

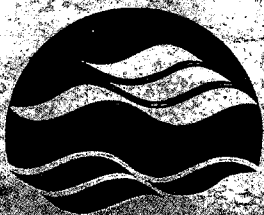
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Review of Eutrophication and Undesirable Algae in Lake Erie

BY:

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NWRI Contribution No. 01-177

Review of Eutrophication and Undesirable Algae in Lake Erie

Technical Report 10
Prepared for the Lake Erie LaMP
Preliminary Beneficial Use Impairment Assessment

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Management Perspective

Review of Eutrophication and Undesirable Algae in Lake Erie

Charlton, M., L'Italien, S., Howell, T., Bertram, P., Zarull, M., Thoma, R., and Culver, D. 2001. Review of Eutrophication and Undesirable Algae in Lake Erie.

This review was prepared for the Lake Erie Lake wide Management Plan (LaMP) process (Great Lakes 2020). The audience is practitioners of science on Lake Erie, officials in Canada and the U.S. involved in the LaMP process, and the concerned public.

Criteria and indicators of impairment are reviewed consistent with the current version of the Great Lakes Water Quality Agreement. Impairments due to eutrophication and undesirable algae are occurring in Lake Erie despite nutrient loads reduced to targets in the Great Lakes Water Quality Agreement.

Abstract:

Lake Erie still has impairment due to eutrophication and algae. Oxygen conditions are still low in the central basin bottom water in summer. Noxious filamentous algae still wash up on shores in the central and east basin. The west basin is experiencing a reoccurrence of blue-green algae blooms which are producing hazardous toxins. Most rivers contain phosphorus well above guideline concentrations. Fish populations are degraded in impaired downstream sections of larger rivers. Large increases in the ratio of nitrogen to phosphorus have occurred in the lake since the beginning of phosphorus controls in the early 1970. Atmospheric loads, fertilisers, and municipal sources of nitrogen have not been controlled as much as phosphorus. The changing N:P ratio may have unforeseen effects on stimulating nuisance algae. Zebra mussels have tended to clear up the water near shores and this can allow more growth of macrophytes and attached algae not subject to the mussels' grazing. Meanwhile, the water offshore has had good clarity for twenty years.

Étude de l'eutrophisation et des algues nuisibles dans le lac Érié

Charlton, M., S. L'Italien, T. Howell, P. Bertram, M. Zarull, R. Thoma et D. Culver

Sommaire à l'intention de la direction

Cette étude, réalisée dans le cadre du plan d'aménagement panlacustre du lac Érié (PAP) (Grands Lacs 2020), s'adresse aux chercheurs qui étudient le lac Érié et aux fonctionnaires du Canada et des États-Unis qui collaborent au PAP, ainsi qu'aux autres personnes qui s'intéressent à ce sujet.

On examine les critères et les indicateurs de dégradation en fonction de la version actuelle de l'Accord relatif à la qualité de l'eau dans les Grands Lacs. On note des cas de dégradation dus à l'eutrophisation et à des algues nuisibles dans le lac Érié, malgré la réduction des charges de nutriments à des valeurs correspondant aux objectifs de l'Accord.

Résumé

On observe encore des cas de dégradation des eaux du lac Érié due à l'eutrophisation et aux algues. Les conditions d'oxygénation restent mauvaises dans l'eau du fond du bassin central en été. Des algues filamenteuses nuisibles sont encore rejetées sur les rivages des bassins centre et est. Dans le bassin ouest, on note de nouvelles proliférations d'algues bleues qui produisent des toxines dangereuses. La plupart des cours d'eau contiennent des concentrations de phosphore très supérieures aux lignes directrices. Les populations de poissons sont touchées dans les sections aval altérées des grands cours d'eau. On a noté de fortes augmentations du rapport azote-phosphore dans le lac depuis l'application des mesures de réduction du phosphore au début des années 70, parce qu'on n'a pas réduit aussi efficacement les sources d'azote (charges atmosphériques, fertilisants et eaux usées municipales). Cette variation du rapport N : P peut avoir des effets imprévus qui stimulent la croissance d'algues nocives. La présence des moules zébrées, qui semble augmenter la limpidité de l'eau du rivage, pourrait favoriser la croissance des macrophytes et des algues fixes qu'elles ne consomment pas. Pour leur part, les eaux du large sont demeurées assez limpides depuis 20 ans.

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Section 10

Eutrophication or Undesirable Algae

10.1 Listing Criteria

According to the International Joint Commission (IJC), a eutrophication or undesirable algae impairment exists when there are **persistent** water quality problems (for example, dissolved oxygen depletion of bottom waters, nuisance algal blooms or accumulation, decreased water clarity, etc...) attributed to cultural (man-induced) eutrophication (IJC, 1989). The Lake Erie Lake Wide Management Plan (LaMP) process has adopted the IJC listing criteria and the objectives and indicators from the Great Lakes Water Quality Agreement (GLWQA) for evaluating eutrophication, with one exception. Evidence suggests that intermittent anoxia is an inherent property of the central basin. Therefore, use of dissolved oxygen depletion of bottom waters in the central basin as an indicator of impairment must be evaluated very carefully in Lake Erie and should not be used **on its own** as an indicator of eutrophication. The GLWQA objectives and indicators (section 10.2) drive our interpretation and application of the IJC listing criteria.

10.2 Bi-national Lake Erie Phosphorus Reduction Objectives and Indicators

In 1996, the IJC stated a general objective on phosphorus for the Great Lakes: "there shall be an absence of excess phosphorus entering the water as a result of human activity" (IJC, 1996). Cultural eutrophication in Lake Erie has been and continues to be due to phosphorus loading. In 1972, the United States and Canada signed the Great Lakes Water Quality Agreement (GLWQA) which focused on reducing phosphorus inputs to the Great Lakes (IJC, 1972). Updated phosphorus loading targets for Lake Erie were incorporated into the renegotiated GLWQA in 1978. These target loads (indicators) were based on achieving average annual in-lake phosphorus concentrations (objectives) for each of Lake Erie's three basins (Vallentyne and Thomas 1978), as shown below:

Phosphorus target load and spring total phosphorus objectives.

		<u>Objectives</u>
Lake Erie	11000 (metric t/yr)	
Western Basin		15 (ug/L)
Central Basin		10 (ug/L)

Target loads of the 1978 GLWQA are currently met (see Figure 1). Actual phosphorus loads to Lake Erie are now directly related to the amount of precipitation falling in the basin since the major phosphorus inputs come from the tributaries to the lake. Nevertheless, municipal treated sewage phosphorus can still cause problems due its concentration and availability to algae of phosphorus. Average in-lake spring total phosphorus concentrations presently meet the GLWQA objectives for the eastern and the central basins, while in the western basin, exceedences are still occurring periodically. The GLWQA objective for the restoration of year-round aerobic conditions in the hypolimnion of the central basin was not used as a criterion to define a eutrophication problem because historical evidence suggests that intermittent anoxia is an inherent property of the basin (section 10.4.5).

10.3 Indicators of Eutrophication

Chemical, physical and biological indicators are used to assess trophic status of aquatic ecosystems. They can be interpreted individually, but they provide a better assessment of the trophic status of an ecosystem when they are considered simultaneously because they are inter-dependent, i.e. when abiotic conditions vary (physical and chemical), a response in biological characteristics usually follows. Some of these indicators are specific to the nearshore waters, while others are applicable to both the nearshore and the open lake waters. Table 1 summarizes the range of proposed values for different indicators of lake trophic state. Scientists from several disciplines have proposed different ranges of values for the same indicator. These ranges of values are subjective but generally tend to converge. Table 2 summarizes the Lake Erie's trophic status by indicator and basin. A brief description of each of those indicators follows:

Total Phosphorus (TP)

This chemical indicator can be used to measure the progress in meeting GLWQA target loadings based on average annual phosphorus concentrations in the open lake waters (sections 10.2 and 10.4.1). Total phosphorus can also be used as a nearshore indicator. The Ontario Interim Provincial Water Quality Objectives for TP are considered as general guidelines to avoid nuisance concentrations of algae in lakes and excessive plant growth in rivers (section 10.5.1).

Soluble Reactive Phosphorus (SRP)

This chemical indicator is a measure of the amount of phosphorus available to primary

producers (algae) in both the nearshore and open lake waters. Spring SRP trends generally follow those of total phosphorus concentrations (section 10.4.2). SRP tends to overestimate the amount of P available to algae; thus, SRP is controversial as an indicator. Nevertheless, in the absence of P sources, SRP in lake waters tends to zero in the summer and this means that intense recycling and little new net growth occurs. Measuring SRP in the spring when levels are highest minimizes this overestimation.

Chlorophyll a

This biological indicator is a measure of the quantity of phytoplankton (algae). Chlorophyll data reflect the nearshore and open lake responses to the reductions in phosphorus loading and spring concentrations, as recommended by the GLWQA. Recent studies in Lake Erie indicate that zebra mussels have caused reductions in the phytoplankton biomass. Therefore, there has likely been a change in the expected relationship between nutrient availability and chlorophyll a concentrations (section 10.4.3).

Secchi Disk

The Secchi Disk depth is a physical measurement. As a visual indication of the relative clarity of water the Secchi depth is simply the depth at which a white disk, lowered from a boat, disappears from sight. It can be used for both nearshore and open lake waters (sections 10.4.4, 10.5.1 and 10.5.2). The recent invasion of zebra mussels resulted in decreased plankton abundance and an increased water clarity in some areas of the lake. In offshore waters away from sediment sources the Secchi depth is related mainly to the concentration and type of algae in the water. The apparent change in trophic status is related to a combination of reduced nutrient inputs and the effect of zebra mussels. The Secchi disk produces consistent measurement but it has limitations due to the fact that it is very sensitive to the number of particles scattering light. Therefore, the effect of particles on transparency is not one of a simple contribution to the downward attenuation of light by interception in addition to the adsorption by dissolved colored substances (Edmonston, 1980). The vertical light extinction coefficient is a better long-term measure of changes in transparency but data for this parameter are difficult to obtain and consequently not available over the long-term. Nevertheless, Secchi depth is used world wide as a practical indicator of water quality.

Dissolved Oxygen (DO)

This chemical indicator is a fundamental determinant of the survival of biota. Low dissolved oxygen in the hypolimnion (bottom) waters of the central basin in late summer can be stressful or can be insufficient for survival of biota. Successive DO measurements during the summer can be used to calculate dissolved oxygen depletion rates in the hypolimnion. This oxygen depletion results from sediment oxygen demand, which has been enhanced by cultural eutrophication, and a small hypolimnetic volume. In general, reduced dissolved oxygen depletion rates seem to be associated with lower spring total phosphorus levels (section 10.4.5).

Nitrogen:Phosphorus ratio (N:P ratio)

This chemical indicator can be used to measure potential algal species composition for both nearshore and open lake waters. The N:P ratio is calculated as total nitrogen (Kjeldahl + nitrate + nitrite) divided by total phosphorus (Dahl *et al.*, 1995). When the N:P ratio exceeds 29, there may be a shift in dominance from blue-green to green algae and diatoms. Blue-green algae composed much of the "nuisance algae" referred to in the GLWQA (section 10.4.6).

Hexagenia limbata

The occurrence of the nymph of the mayfly *Hexagenia* is a biological indicator that can be used for both nearshore and open lake waters. It is a benthic indicator of dissolved oxygen levels (section 10.4.5), and of the trophic state of an aquatic system.

Abundance of Omnivorous Fish

The Ohio EPA uses omnivorous fish as a biological indicator of the trophic status of the fish community (section 10.5.5). With the exception of Maumee Bay, the abundance of omnivorous fish indicator is currently only applicable to the lake effect zones of Ohio tributaries and the Ohio Lake Erie shoreline. Due to lack of data, omnivore dynamics in offshore Lake Erie are not well understood and therefore this indicator is used in nearshore areas only.

Abundance of *Cladophora*

This biological indicator measures excessive levels of *Cladophora* (filamentous algae) causing fouling of the shoreline due to sloughing and decomposition in the nearshore waters. The

concentration of P in *Cladophora* tissue is a good indicator of the level of P sufficiency and a predictor of growth rate (sections 10.5.1 and 10.5.3).

Milbrink Index

The Milbrink Index is a biological indicator. It is a benthic indicator of the trophic status based on the species composition and absolute abundance of oligochaetes (worms) living in the sediment. Invertebrate components of the ecosystem are affected by nutrient conditions. Extremely high numbers of dreissenid mussels may confound the interpretation of the index value. The Milbrink Index has been applied in this report as a nearshore benthic indicator (section 10.5.4).

Diatom abundance

The estimation of this parameter is a biological (algae) indication of the relative abundance of eutrophic, mesotrophic, and oligotrophic diatoms (sections 10.4.6 and 10.4.7).

10.4 Recent Measurable Changes in the Open Lake

10.4.1 Total Phosphorus

Figure 2 presents the trends in open lake total phosphorus concentrations for the period 1971 to 1999 measured during spring cruises. Nutrient concentrations are usually greatest in early spring, and concentrations at this time determine the limits of algal growth during the summer.

In the western basin, average spring total phosphorus concentrations continue to be highly variable, subject to sampling locations, influence of seasonal tributary loading and sediment resuspension from storms. During the period 1983-1985, average spring phosphorus concentrations were typically 20-25 ug/L, although in 1984 one survey averaged 69.3 ug/L. During 1990 and 1992, spring averages were reduced to 12.2 and 10.9 ug/L, respectively, but the 1991 average (27.5 ug/L) and subsequent data in the late 1990s demonstrate the continuing variability of the western basin.

Since 1970, average spring concentrations in the central basin have generally declined, dropping below the guideline of 10 ug/L during 1988-1990. Concentrations were slightly above the

guidelines during 1991-92. However, annual fluctuations are common, in part due to the influence of resuspended sediments from storms, but average concentrations remain around the guideline.

In the eastern basin, phosphorus concentrations declined from greater than 20 ug/L in the early 1970's to below the objective of 10 ug/L in 1987. Spring concentrations remained below the guideline through 1990, but slightly exceeded it in 1991 and 1992.

Environment Canada's Great Lakes Surveillance Program has surveyed Lake Erie in 1994 and 1995. Three annual cruises were carried out, in the spring (end of April), in the summer (July-August) and in the fall (mid-October).

Total phosphorus (TP) concentrations measured in the spring of 1994 and 1995 in the western basin (see Figures 3 and 4) exceeded the GLWQA guideline (15 ug/L), as well as the Ontario Interim Provincial Water Quality Objective (20 ug/L). In the summer of 1994, TP concentrations were lower than 20 ug/L, except at one station (see figure 5). In the fall, TP concentrations were again exceeding the 20 ug/L at several locations in the western and in the central basins (see Figure 6). Summer phosphorus concentrations in the east and central basins declined to around 5 ug/L in the mid 1990s. Concentrations largely recovered to near 10 ug/L by 1997 (Charlton et al., 1999).

10.4.2 Soluble Reactive Phosphorus

Soluble reactive phosphorus (SRP) represents that fraction of the total phosphorus which is directly available to the primary producers (plants and algae). Generally, spring SRP trends followed those of total phosphorus concentrations. Variations larger than 2 ug/L were observed in both the central and eastern basins of Lake Erie; however, concentrations have remained below 5 ug/L since 1974 (see Figure 7).

During periods of excessive nutrient enrichment in the 1970's and 1980's, large odoriferous masses of decaying *Cladophora* created problems along the shoreline of Lake Erie. The decline in phosphorus concentrations, especially SRP, has resulted in noticeable changes, both nearshore (section 10.5.3) and offshore.

Environment Canada's Great Lakes Surveillance Program reported soluble reactive phosphorus (SRP) concentrations in the spring of 1994 and 1995 that were greater than 2 ug/L in some nearshore areas and in the western basin (see Figures 8 and 9). These concentrations were high

enough to promote the sustained growth of *Cladophora* (section 10.5.1). In the eastern basin, SRP concentrations exceeded the 2 ug/L level in the spring of 1995 only.

10.4.3 Chlorophyll a

Green plants and algae contain chlorophyll, a pigment that is easily measurable as an indicator of the quantity of algae in the water column (algal biomass). The chlorophyll data reflect the offshore responses of planktonic algae to the reductions in phosphorus loadings and spring concentrations. Using the most restrictive of the many proposed trophic status indicators in the literature (Forsberg and Ryding 1980), Rast and Lee (1978) have suggested that chlorophyll a concentrations below 2.0 mg/L are indicative of oligotrophic conditions. Reductions in chlorophyll concentrations in the offshore waters of Lake Erie indicate a trend from mesotrophy toward oligotrophy over the period 1980-1990 (section 10.7.1)

Data sets for the open waters of the eastern basin indicate stable summer chlorophyll concentrations from 1983 to 1988, and show that mean concentrations have decreased by 80% between 1988 and 1990, from 1.6 to 0.3 ug/L (Neilson et al. 1995). Leach (1993) showed decreases in chlorophyll of 27% in the west central basin between 1988 and 1990. In the central basin, Neilson et al. (1995) reported that chlorophyll decreased by 66%, from 1.9 ug/L in 1988 to 0.6 ug/L in 1990. Dahl et al. (1995) reported a spring/summer mean concentration of 1.4 ug/L for 1993, substantially higher than those reported for 1990. These short term variations are important but they should be considered in light of long term changes in the lake.

Figure 10 shows a long term data set from 1968 to 1997 for the months of June, July, and August (Charlton et al. 1999). Chlorophyll decreased by 2.1, 2.7 and 5.5 ug/L in the east, central and west basins respectively between 1968 and 1988 during nutrient controls. Further chlorophyll decreases of 0.7, 0.4 and 2.8 ug/L occurred between 1988 and 1996 after zebra mussels invaded the system (Charlton et al. 1999).

Chlorophyll a concentrations measured by Environment Canada's Great Lakes Surveillance Program for August 1994 and 1995 are presented in Figures 11 and 12. Samples integrated over the epilimnion, from the surface of the lake to the appropriate depth up to a maximum of 20 metres, were used to produce these figures. In 1994 and 1995, chlorophyll a concentrations in the eastern and the east central basins rarely exceeded 2 ug/L indicating oligotrophic conditions (Rast and Lee, 1978). In the western and west central basins, chlorophyll a concentrations generally ranged from 2 to 6.8 ug/L with a maximum of 11.2 ug/L, indicating mesotrophic conditions.

Recent studies in Lake Erie indicate that zebra mussels have caused reductions in nearshore phytoplankton biomass (Nicholls and Hopkins 1993; Nicholls et al. 1999; Hebert et al. 1989; Griffiths et al. 1991; Leach 1993) and changes in the species composition of phytoplankton communities (Dahl et al., 1995) (section 10.4.7). Chlorophyll decreases in the central and east basin open waters since the mussel invasion have been minor compared to decreases caused by nutrient load reductions (Charlton et al. 1999). The changing relationship between total phosphorus and chlorophyll depends on whether phosphorus is lost proportionate to algal biomass due to zebra mussels filtering. There are indications that this may differ between lakes but at least in the eastern basin of Lake Erie phosphorus is recycled back into the water column such that chlorophyll levels decline but total phosphorus does not. The resultant decrease in the chlorophyll to phosphorus ratio indicates an uncoupling, or at least a different relationship, between phosphorus and algae concentrations. This has led to the dilemma of whether to use phosphorus levels (the driver) or chlorophyll (the response) as the indicator of trophic status. Meanwhile chlorophyll to phosphorus ratios were unchanged or actually increased in much of the open waters of the lake (Charlton et al. 1999).

Eutrophication and/or undesirable algae, however, continued to present problems in areas identified by the IJC as having the worst problems (section 10.6). Remedial action plans (RAPs) are being developed individually for those "Areas of Concern".

10.4.4 Secchi Disk

Secchi disk measurements made in 1993 by Dahl et al. (1995) showed oligotrophic conditions in the open waters of the central and eastern basins, and in the nearshore of the eastern basin. In the western basin, mesotrophic conditions were determined in the open waters, and in the nearshore areas, they were classified as eutrophic. Zebra mussels have had little effect on Secchi depth in the offshore waters of the east and central basins but a large effect did occur in the west basin (Charlton et al. 1999).

10.4.5 Dissolved Oxygen Depletion

Figure 13 illustrates that dissolved oxygen concentrations in the bottom waters (hypolimnion) of the central basin of Lake Erie have continued to decline during the summer season throughout the period 1988 to 1993 (see Bertram 1993). Charlton et al. (1993) observed a similar pattern as far back as 1979. As recently as 1998 the central basin hypolimnion was nearly anoxic Charlton et al., (1999). Episodes of anoxia in the late summer continue to exist in some areas of the central

basin. At fall overturn, oxygenated waters again extend from surface to bottom. However, bottom dwelling invertebrates, such as the mayfly (*Hexagenia limbata*), are sensitive to low oxygen concentrations, and even short periods of anoxia quickly kill the organisms. Prior to 1953, mayflies were the most abundant species in the benthic community of the western basin (Reynoldson and Hamilton 1993). However, two particularly long warm calm spells in both 1953 and 1955 produced anoxic conditions in the western basin, and mayflies have been essentially absent since.

Vollenweider and Janus (1981) determined that lake phosphorus loads would have to be reduced to about 5000 metric t/y for the desired effect on oxygen and that, consequently, the goal of year-round aerobic conditions in Lake Erie should be reconsidered. There is also evidence to suggest that there were brief periods of anoxia in some areas of the central basin of Lake Erie for hundreds of years, prior to European colonization and the onset of cultural eutrophication (Charlton 1980; Delorme 1982; Reynoldson and Hamilton 1993). This anoxia results from a high sediment oxygen demand, which has been enhanced by cultural eutrophication, and a small hypolimnetic volume.

In 1989, the rate at which dissolved oxygen was depleted throughout the summer (corrected for hypolimnion temperature and thickness, vertical mixing and seasonal effects) was the lowest measured in 20 years. This would suggest that, under some weather conditions, the hypolimnion may be capable of sustaining aerobic waters for the entire season. However, the depletion rates for 1990 through 1992 were more typical of the rates calculated for the late 1970's and early 1980's. This is not unexpected, given the lake morphometry and variability in the weather. In general, reduced dissolved oxygen depletion rates seem to be associated with lower spring total phosphorus levels (Bertram 1993), suggesting that phosphorus loading reduction strategies are producing the desired effect in Lake Erie. Some lapse of time between achievement of phosphorus loading targets and the maintenance of aerobic conditions in the central basin was predicted at the time that the loading targets were determined (DiToro and Connolly 1980). Indeed, the full impact of peak phosphorus loads may not have developed fully. Nutrient load reductions then may have prevented some damage and thus improvements may not be proportional to load,

Recent observations of oxygen in the central basin were made by the National Water Research Institute (M. Charlton, NWRI, Burlington, Ontario). A series of research cruises were conducted in 1990, 93, 94, 95 and 96 to help follow the progress of the lake's water quality. Oxygen was measured by a continuous profiler from the CSS Limnos. Figures 14a and 14b for 1994 and 1995 respectively show that recent mean depletion rates have been 0.7 - 0.8 mg/L/day. These

recent rates are less than the rates of around 1 mg/L/day observed since the 1970's. Typical of the mid-1990s has been a hypolimnion thickness of 5m or more. Previously, typical thicknesses were around 3m. The increased mean oxygen in the central basin is consistent with the effect of hypolimnion thickness pointed out by Charlton (1979, 1980). In other words, at the present chlorophyll levels lower oxygen conditions would be expected if the thermocline were to be at a usual depth and if the lake were actually functioning as before. We do not know yet whether the recent thermocline depths represent some systematic change in the thermal regime caused by changing transparency or whether they are simply an unusual coincidence. The distribution of data points in Figure 14a reinforces the notion that somewhere in the central basin there would be near zero oxygen even if the mean end of summer concentration was near 4 mg/L (DiToro and Connolly 1980). Indeed, on June 27, 1996 a deep station (# 962) had 8 mg/L near the bottom (see figure 15a). Figure 15b shows that on the same day in early summer 1996 there was a station (# 963) with only 3 mg/L on the bottom. This station would be anoxic later. The temperature in figure 15a is consistent with the relationship derived by Charlton (1979) between hypolimnion thickness and temperature. Cooler temperatures are associated with higher oxygen. What is different is the peak of oxygen in the thermocline which now occurs at some stations. This may be an indicator of changing lake function as the effects of introduced species develop. In 1998, the situation reverted to more typical late August oxygen concentrations of less than 1 mg/L with some sites at 0.15 mg/L (Charlton et al. 1999).

Anoxic area may seem to be a good indicator of the oxygen situation but, in reality, recent surveys do not have enough stations with which to calculate an affected area. In addition the area affected by low oxygen is partially determined by the date of the survey, the time of stratification, and thermocline depth each year; these physical variations make it difficult to conduct adequate sampling for anoxic area. In summary, the oxygen situation, although perhaps not critical to impaired uses, is worth following to increase understanding of the lake. In particular, the recent thermal structure has been unusual and the implications need to be researched. Unfortunately, we cannot say how the post zebra mussel observations relate to earlier times with regard to response to nutrient controls. Even when oxic conditions are present on average year round, there are still observations of near zero oxygen in the data. There is a strong influence of lake morphometry and annual weather in the oxygen depletion pattern. Thus, as argued by Charlton (1979), oxygen is not a good indicator of water quality and the goal of year round oxic conditions may be unobtainable even when average oxygen and other water quality measures are acceptable.

10.4.6 Nitrogen:Phosphorus Ratios

Nitrate-plus-nitrite is also an important nutrient in water systems. In the central and eastern

basins of Lake Erie, levels of nitrate-plus-nitrite have risen from 1968 to 1986, decreased until 1990, then regained their maximal levels of 1986 and 1987 (see Figure 16) (Stevens and Neilson 1987; Williams 1992, Charlton *et al.* 1999). In the western basin, the nitrate-plus-nitrite concentrations followed trends similar to those of the other basins, except that they were 3 times higher. Current open lake concentrations do not create a public health concern, as they are at least 20 times lower than the guideline for protection of drinking water (10 mg/L). In Lake Erie, increased use of chemical fertilizers and gaseous emission of nitrogen compounds within the drainage basin are believed to be the major causes of rising nitrogen concentrations in the water. Nitrogen fertilizer sales in the Lake Erie basin increased by roughly 50% between 1974 and 1980, continuing an increasing trend which began at least as early as 1970 (Richards and Baker, 1993). Recently, the nitrogen fertilizer sales in Ontario which peaked in 1985 at 237,409 tonnes, have been declining annually to reach 166,211 tonnes in 1994. Over the last decade, there has been an ongoing decrease in the amount of nitrogen fertilizer sold. There is, however, roughly as much nitrogen as phosphorus in sewage. In the last 30 years, about 90% of the phosphorus in sewage has been removed by treatment. This has caused less demand for nitrogen by algae but the discharge of nitrogen has continued relatively unabated and this may be the reason for some of the trend to increasing concentrations.

Changes in the ratio of nitrogen to phosphorus (N:P ratio) can affect algal species composition. Under phosphorus-rich conditions, when nitrogen may be limited, some blue-green algae have a competitive advantage because many can utilize ("fix") nitrogen (gaseous N_2) directly, whereas other types of algae cannot. Blue-green algae composed much of the "nuisance algae" referred to in the GLWQA. Smith (1983) has observed that, when the N:P ratio exceeds 29, there is a shift in dominance from blue-green to green algae and diatoms. Nitrogen to phosphorus ratios for the summer during three different time periods are shown below (data in Charlton *et al.* 1999).

Basin	N:P 1968-72	N:P 1984-88	N:P 1994-96
West	3	4	32
West Central	4	19	37
Central	4	20	27
East	3	14	28

Ratios began to rise by the 1984 -88 period coincident with controls on phosphorus in all areas except the west basin. By the mid 1990s the N:P ratios had risen further to levels that would be far less likely to stimulate dominance by blue-green algae. Nevertheless, blooms of blue-green algae, *Microcystis sp.* appeared in 1994, 1995 and 1996 covering much of the western basin (section 10.4.7). The cause of the *Microcystis* blooms is speculative at this time but they

correspond with development of the exotic mussel population which is able to select against the larger colonies of blue-greens while filtering out smaller algae. This emerging issue must be investigated in future years.

The combination of reductions in phosphorus concentrations and increases in nitrogen concentrations have served to not only reduce the total quantity of algae in the water (i.e., reduced chlorophyll and *Cladophora* levels), but also to shift the species composition away from nuisance blue-greens and toward more desirable, and historically prevalent, diatoms. This shift will likely cause a change in zooplankton species and density. Trends in increasing nitrogen compounds in Lake Erie may warrant continued monitoring, but they do not appear to be cause for alarm at this time.

10.4.7 Changes in Species Composition

Several studies reported increased nuisance and eutrophic indicator species with progressing eutrophication through the 1960's and early 1970's. Verduin (1964) stated that the mesotrophic species *Asterionella formosa*, *Tabellaria fenestra* and *Melosira ambigua* dominated the western basin prior to 1950 and subsequently disappeared with increasing phosphorus enrichment up to the late 1960's. Phosphorus control measures under the Great Lakes Water Quality Agreement (section 10.2) have reversed some of these trends by causing a gradual reduction in the abundance of eutrophic indicator species.

Changes in phytoplankton abundance and species in Lake Erie from 1970 through the mid-1980's were consistent with the expected impacts of reduced nutrient loading (Makarewicz and Bertram 1991). For example, the mean algal biomass during this period declined by 65% (from 3.4 g/m³ to 1.18 g/m³) and the nuisance blue-green algae *Aphanizomenon flos-aquae* decreased 89% (from 2 g/m³ to 0.22 g/m³) (Makarewicz, 1993).

The number of dominant eutrophic diatom species decreased in the western basin, whereas the number of dominant mesotrophic species increased (Makarewicz, 1993). Eutrophic species of the genus *Stephanodiscus* (*S. binderanus*, *S. niagarae* and *S. tenuis*) were present at levels reduced by 70-98% compared to those recorded before phosphorus was controlled. The densities of *Asterionella formosa* and *Rhizosolenia eriensis* from 1983-87 were comparable to those measured in the 1930's and 1940's indicating a return to mesotrophic conditions (Makarewicz, 1993). Data collected in 1991, 1993, and 1995 (Krieger *et al.*, 1996) indicate that nymphs of the insect *Hexagenia limbata* are recolonizing rapidly lakeward from the inshore areas of the western

basin, showing a tendency toward mesotrophic benthic conditions (Reynoldson et al., 1989).

The recent invasion by zebra and quagga mussels has caused impacts on the water quality and the food web. Zebra mussels filter-feed all particles, including large chain-forming diatoms, and even some relatively large zooplankton organisms (Ten Winkle and Davids, 1982; MacIsaac et al., 1991; Dahl et al., 1995). Recent studies in Lake Erie indicate that zebra mussels have caused reductions in phytoplankton biomass (Nicholls and Hopkins 1993; Hebert et al. 1989; Griffiths et al. 1991; Leach 1993), while, at the same time enhancing water clarity in the shallow waters, where they are found in greatest numbers (Charlton 1994). This clearing effect has direct implications for walleye, which prefer to dwell in more turbid, mesotrophic waters.

Dahl et al. (1995) reported changes in the species composition of phytoplankton communities. In the western basin, changes in phytoplankton were attributed to filtration by *Dreissena*, which however did not seem to influence the zooplankton. The presence of large daphnids in the western basin indicated that planktivory was not excessive. Diatoms were still the dominant group, however biomass declined 68% compared to the 1983-1987 period studied by Makarewicz (1993). The reduction in diatoms may have alleviated the competition for nutrients, allowing for a 60% increase in Chrysophycean biomass observed in 1993. The shift toward smaller phytoplanktonic species indicates a shift to a more oligotrophic state (Wetzel, 1993). In 1993, the western basin appeared to be less eutrophic because the indicator species, *Fragilaria capucina* and *Stephanodiscus tenuis* were not present. Benthic production and community structure in the western basin have been affected by *Dreissena polymorpha*. Production is almost exclusively dominated by *Dreissena polymorpha* which accounts for 90% of the annual benthic production and wet shell-free biomass in the lake. The only benthic taxa which is replaced by *Dreissena polymorpha* in the western basin, are the native clams, both *Unionidae* and *Sphaeriidae*. Throughout the nearshore areas of the lake, *Gammarus* populations have dramatically increased since the establishment of *Dreissena polymorpha*.

In late August 1994 a bloom of *Microcystis* occurred in the north half of the west basin (Charlton, unpublished observations). In mid-August 1995, *Microcystis* (*sp. aeruginosa*) was found floating on water near Rattlesnake Island, two miles west of Put-in-Bay (Appendix A), and by mid-September the bloom spread, covering much of the western basin. In May of 1996, the bloom appeared again in the western basin. *Microcystis* and other blue-green algae can produce toxins that are harmful to wildlife and humans. This is an emerging issue since we do not know if it will continue to be a problem in the future. This bloom was not expected to occur with the recent phosphorus concentrations and the presence of zebra mussels. Nonetheless, in 1995 and 1996, there was a nuisance algal bloom and therefore the algal biomass had not been

reduced to a level below nuisance conditions. Research currently underway (Appendix A) will determine the cause of the bloom and whether it can be expected to continue in future years. The results of this research should allow us to evaluate whether the presence of *Microcystis* in the western basin is causing a eutrophication impairment.

In the central basin, Makarewicz (1993) observed similar patterns as in the western basin for *Stephanodiscus*, dominant in 1970 but almost absent from 1983-1987. Dahl *et al.* (1995) showed that the community structure had changed little since 1987 although an increase in the eutrophic indicator *Melosira granulata* was observed. However, several species of *Cyclotella*, indicators of oligotrophic conditions were also present.

In the eastern basin, the relative importance of dinoflagellates (*Gymnodinium helveticum* and *G. Ubertimum*) in the total biomass was greater before phosphorus control compared to the rest of the lake, while diatoms were less important (Munawar & Munawar, 1976) (section 13.4.5.3). Dahl *et al.* (1995) concluded that the species composition in the eastern basin had not changed drastically since the 1983-87 study of Makarewicz (1993) with a few notable exceptions. Biomass of *Rhodomonas* has not changed but its relative proportion has increased since the total biomass has declined. The most significant changes observed may be the appearance and at times significant biomass (>10%) of *Dinobryon* which was not observed in the 1983-87 study. Short-lived peaks were reported in diatom biomass which were higher than those in Makarewicz's study. Throughout the rest of the stratified period, diatom biomass was low. The eutrophic species *Stephanodiscus niagarae* and *Ceratium hirundella* have disappeared since 1983-87. Their absence and that of *Melosira binderana* coupled to an increase in smaller phytoplankton species and the presence of *Dinobryon* indicate a shift toward oligotrophic conditions.

10.5 Recent Measurable Changes in the Lake Erie Nearshore

10.5.1 Water Intakes

The Ontario Ministry of the Environment (OME) monitors raw water quality at a number of water treatment plants which use Lake Erie as source water (Figure 17). Nutrient chemistry and chlorophyll levels are monitored weekly on a year-round basis at five plants on Lake Erie in the Great Lakes Intakes program. The Rosehill (west of Fort Erie) and Dunnville (west of the Grand River) plants draw from the eastern basin, the Elgin (east of Port Stanley) and Blenheim (west of Rondeau Bay) plants draw from the central basin and the Union (west of Leamington) plant

draws from the western basin. The water intakes which vary in depth from 3 to 10 m are located from 0.5 to 1.2 km from shore in the main body of the lake.

The median total phosphorus (TP) concentrations in raw water over the period 1988-1994 ranged from 12 to 20 ug/L among the five plants (Table 3). The 90% quantile, the concentration below which 90% of the results fall, for TP concentration varied from 29 to 133 ug/L among the intakes. Median concentration and the 90% quantile were similar or slightly lower if either the April to October data for 1988-1994, or, the two year period from 1993 to 1994 are considered (Table 3). The Ontario Interim Provincial Water Quality Objectives for TP are 20 and 30 ug/L (averaged over the ice-free period) for lakes and rivers, respectively (OMEE 1994). Due to insufficient scientific evidence to develop firm objectives, the interim objectives are considered as general guidelines to avoid nuisance concentrations of algae in lakes and excessive plant growth in rivers (OMEE 1994).

The median soluble reactive phosphorus (SRP) concentrations for the period 1988 to the end of 1994 were similar among intakes varying from 2 to 4 ug/L among intakes, however, the 90% quantiles varied among intakes ranging from 9 to 20ug/L.

The median levels of SRP were above the concentration which needed to sustain the growth of *Cladophora*. Jackson and Hamdy (1982) used an empirical relationship between SRP in water and the P concentration in *Cladophora* tissue among sites in Georgian Bay to infer that a SRP concentration of 2 ug/l was adequate to promote growth of *Cladophora*, albeit under P limited conditions. The concentration of P in *Cladophora* tissue is a good indicator of the level of P sufficiency and predictor of growth rate (Auer and Canale 1982). Model-based predictions of *Cladophora* tissue P derived from P concentration in the environment developed by Painter and Jackson (1986,1989) support Jackson and Hamdy's (1982) predictions.

The median concentration of chlorophyll *a* (total) over the period 1988-1994 was very low (<1 ug/L) at all intakes. Likewise the 90% quantiles were low, under 6 ug/L in all cases. Nicholls and Hopkins (1993) documented a dramatic decline in chlorophyll *a* and algal density at four of these intakes during 1988-1990 which they suggested was likely due to a zebra mussel effect.

Nicholls and Hopkins (1993) also described a progressive decline in algal density between 1970-1985 at the Union intake in the western basin which was attributed to a corresponding decrease in P loading to the western basin.

The interpretation of trophic status based on the intakes data is not straightforward. Chlorophyll

a is an indicator of algal biomass in the water (section 10.4.3). The potentially high rate of removal of phytoplankton from the water column by the filter-feeding of dreissenid mussels has likely resulted in a change in the expected nutrient concentration vs. chlorophyll a relationships which have been used in the past to identify trophic boundaries based on chlorophyll a. For example, the validity of 2 ug/L chlorophyll a as an upper threshold for oligotrophic conditions (Gregor and Rast 1979) is uncertain. Using this criterion the intakes data suggest that oligotrophic conditions prevailed at all sites. In contrast, the phosphorus data suggest oligo-mesotrophic to mesotrophic conditions (based on a oligotrophic-mesotrophic boundary of 15 ug/L (Gregor and Rast 1979). The annual averages of chlorophyll over the April to September period for the Union, Blenheim, Elgin and Dunnville plants for the years 1985-1988 presented by Nicholls and Hopkins (1993) ranged from approximately 5-8, 2-6, 2-7, and 3-5 ug/L respectively suggesting oligo-mesotrophic to mesotrophic conditions using the criterion of 2 ug/L chlorophyll a as the oligo-mesotrophic boundary.

Holland *et al.* (1994) raise the issue of whether algal biomass as the symptom of eutrophication or nutrient concentration as the determinant of trophic status should be used as the basis of assessing trophic conditions. Phosphorus levels indicate the potential for a certain level of productivity. The biological response being the variable of interest, productivity should take precedence over phosphorus levels as the basis of assessment of trophic status. In most lakes, the two are inextricably linked but the presence of zebra mussels has shifted the emphasis from the pelagia to the benthos. Researchers in Saginaw Bay concluded that the focus had to include more than the pelagia because the mussels cause more energy and nutrient flow to the benthos. In the case of eutrophic Hatchery Bay in the western basin, they suggest that, because nutrient levels were unchanged, recently decreased plankton abundance and increased water clarity, thought to be mediated by zebra mussels, should not be interpreted as signs of oligotrophication.

10.5.2 Harbours and Embayments

Localized areas of elevated nutrients likely exist along the perimeter of the north shore at tributary mouths. In 1988 and 1989, OME conducted a synoptic survey of water quality at nine nearshore areas, either embayments (small craft harbours) or river mouths along the north shore. Nutrient levels at four of the survey areas at the time of sampling suggested that nutrient enriched conditions may have existed (ie. TP > 30 ug/L) (Table 4). The areas with elevated TP, total inorganic nitrogen (TIN) and chlorophyll a included Port Maitland at the mouth of the Grand River, Port Burwell at the mouth of Big Otter Creek, Port Stanley at the mouth of Kettle Creek and Sturgeon Creek. The concentration of TP and chlorophyll a, averaged over sites within the survey area, exceeded 30 ug/L and 10 ug/L, respectively at these locations. Nutrient

concentrations directly outside these areas were lower, however, only limited sampling was conducted precluding any resolution of the nutrient gradients from the land to the open lake.

While the harbours and embayments data suggest nutrient enriched conditions occurred at a number of locations, the inferences which can be made with respect to the issue of eutrophication are limited. There was no information collected on the occurrence of undesirable proliferation of algae at the time of the surveys. Because of the high turbidity in some of the areas (Table 4) it is not clear whether there would be adequate light to sustain extensive algal growth despite the high nutrient levels. Since the water samples contained moderate to high levels of suspended sediments in many cases, it is probable that a portion of the TP would have occurred as a mineral complex and would not be biologically available. If algal growth in these turbid waters is light-limited and chlorophyll levels are not high, eutrophication cannot be concluded based on high phosphorus levels alone. Nonetheless, this turbidity effect should not preclude us from concluding that these areas appeared eutrophic at the time of survey.

10.5.3 Shoreline *Cladophora* Surveys

Evidence suggesting localized areas of nutrient enrichment on the north shore comes from recent observations on the fouling of shoreline by *Cladophora*, a symptom of nutrient enrichment. Historically, the fouling of beaches by *Cladophora* was a problem in parts of Lake Erie. The extent of the problem, while directly related to nutrient enrichment, is greatly modified by the amount of rocky shoreline available for colonization. Monitoring data for *Cladophora* are available for the late 1970's and early 1980's, however, there appears to be little information available for recent years. Painter and McCabe (1987) provide data on the concentrations of P in *Cladophora* tissue for a number of sites in eastern Lake Erie sampled in 1985. They also provided limited information on the percent cover of *Cladophora*. They reported that growth and abundance was minimal at most locations and that heavy growth was confined to the mouth of the Grand River and unidentified locations where there were point sources of nutrients. In the past, the eastern basin of Lake Erie was particularly afflicted by shoreline fouling by *Cladophora* because of the extensive area of rocky shoreline in the basin.

In 1995 the Ontario Ministry of Environment and Energy conducted a synoptic survey of the occurrence of *Cladophora* along the shoreline of the eastern basin of Lake Erie (Table 5). Location of the stations surveyed is given in Fig. 17. In 1995 fouling by *Cladophora* was observed at four of the locations surveyed including west of the Grand River mouth, Featherstone Point, east of Sandusk Creek and Peacock Point (east of Nanticoke). *Cladophora* was abundant in the littoral zone of 16 areas surveyed between Fort Erie and Port Dover. The surface coverage

and median thickness of *Cladophora* over rocky bottom in the 0.5 to 1.5 depth band ranged from 60 to 100% and 4.4 to 20 cm, respectively, among sites (Table 5).

The explanation for the wide spread abundance of *Cladophora* in the shallow littoral zone in July 1995 is unclear. The minimum phosphorus concentrations predicted to sustain growth of *Cladophora* are relatively low (Jackson and Hamdy, 1982). Neilson *et al.* (1995) predicted that SRP concentrations in the nearshore of Lake Erie were sufficient to sustain *Cladophora* growth. Local shoreline or tributary inputs to the littoral zone likely contributed to the greater than average abundance of *Cladophora* in some areas, however, the extent to which local sources of nutrients were a factor in the overall abundance of *Cladophora* is not known. Increased water clarity in the eastern basin may also be a factor contributing to the observed abundance of *Cladophora* by reducing the degree of light limitation on growth. A more speculative question is whether *Cladophora* benefits from the presence of dreissenid mussels by scavenging nutrients released from the waste products (urine, faeces and pseudofaeces) of mussels. Recent data from 1998 are presented in Appendix B.

The growth of *Cladophora* in the littoral zone does not necessarily indicate that there is a nuisance algal problem. The die-back and sloughing of *Cladophora* in early to mid summer and the subsequent accumulation and decomposition of *Cladophora* around the lake perimeter is the primary factor associated with use impairment. Based on the limited information, shoreline fouling appears to be a localized problem.

10.5.4 Benthic Invertebrate Trophic Index

Invertebrate components of the ecosystem are affected by nutrient conditions and can also be used as trophic indicators. The composition of benthic invertebrates has been used as an indicator of trophic levels in the Great Lakes. In 1993 OME assessed environmental conditions at six stations along the north shore of Lake Erie including, the determination of the composition of benthic invertebrates as indicators of environmental condition and trophic status. The data collected over three surveys were used to calculate the Milbrink index (Milbrink 1983), a trophic index based on the species composition and absolute abundance of oligochaetes living in the sediment (Table 6). Index values at three sites were at or slightly above 1, the mesotrophic to eutrophic boundary (Leamington-Point Pelee area, Pointe aux Pins, and Fort Erie). The Fort Erie station had extremely high numbers of dreissenid mussels, which may confound the interpretation of the index value. A Milbrink value of 2 suggesting eutrophic conditions was calculated for a station ~3 km offshore of the mouth of the Grand River. Milbrink values under 0.6, the oligotrophic to mesotrophic boundary, were calculated for two stations, east of Port

Stanley and Peacock Point, east of Nanticoke, respectively.

10.5.5 Omnivorous Fish Trophic Index

The Ohio EPA uses omnivorous fish as an indicator of fish community trophic status in the lake effect (lacustuary) and shoreline zones of Lake Erie, based on their experiences sampling fish community composition throughout Ohio. A lacustuary is a transition zone in a river that flows into a freshwater lake and is the portion of river affected by the water level of the lake.

Lacustuaries begin where lotic conditions end in the river and end where the lake proper begins. They are hydrologically similar to estuaries in that they are lentic habitats affected by water level variations caused by seiches and wind set-up. Lacustuaries differ from estuaries in that they are less saline with gradients going from higher upstream to lower at the lake interface.

Table 7 lists the fish species considered omnivorous by the Ohio EPA (Ohio EPA, 1989). In areas that Ohio EPA has studied where nutrient enrichment is an issue, elevated nutrients are always associated with increases in the percentage of fish in the omnivore category. However, some portion of the elevated omnivore levels may also be a response to chemical pollution from industrial activities and habitat degradation, not just nutrient enrichment. Therefore, results must be evaluated carefully to determine if nutrients are the *overriding* cause of the levels of omnivorous fish found in a given location. In addition, like many of the other indicators in this report, levels of omnivorous fish indicate the trophic condition of a given location—oligotrophic, mesotrophic or eutrophic. However, the fact that a location is eutrophic, does not necessarily mean that there is an impairment. Some evidence of cultural eutrophication must be present to confirm impairment.

Ohio EPA uses a standardized method (Ohio EPA, 1988) of determining how strongly an individual ecosystem component (such as omnivores) deviates from conditions one would expect to find in an undisturbed community. This method follows the guidelines of Karr (1981) and Karr *et al.* (1986). A summary of all of the metrics, including omnivorous fish, used in evaluating the index of biotic integrity in Lake Erie shoreline and lacustuary fish communities is given in Appendix C.

Recent work using the above method indicates that for the lake shore areas, strong deviation from an undisturbed community occurs at the 11% omnivore level and moderate deviation occurs at 5.5%. Lacustuaries strongly deviate at 44% and moderately deviate at 22%. Strong deviation is considered reflective of eutrophic conditions and moderate deviation is considered reflective of mesotrophic conditions (see Figures 18 and 19). The designation of trophic state with the use of

the omnivorous fish trophic index does not apply to open lake waters.

Within Ohio Lake Erie basin tributaries, the most abundant populations of omnivores are found in Lucas County. In addition, all but two of the Ohio tributaries in the entire basin (Grand and Ashtabula) have omnivore percentages greater than 20%. Four areas exhibit levels greater than 40% (eutrophic)†the Maumee River/Ottawa River, Sandusky River/Little Muddy Creek, Cuyahoga and Chagrin Rivers (Northeast Ohio Regional Sewer District, 1994).

Most of the Cuyahoga River lacustrary has been dredged to 7.6 m to accommodate lake freighter traffic and most of the shores are lined by seawalls constructed of steel sheet piling or concrete. Lack of any littoral habitat would constrain the fish community to less demanding species. The Chagrin River is eutrophic from urban runoff and (the greater factor) disturbance from recreational boat traffic. The Maumee and Sandusky areas have both become eutrophic principally in response to agricultural activities. The Maumee area also has an added nutrient load from municipal sewage (section 10.6.1).

The remaining lacustraries, ranging from 20 to 40% omnivores, (Portage River, Huron River, Old Woman Creek, Vermillion River, Black River, Rocky River, and Conneaut Creek) are considered mesotrophic. These streams are suffering from a variety of adverse impacts, principally in the categories of agricultural runoff, habitat destruction (mostly for marinas), and urban runoff (especially sewage overflows). In contrast, the Grand River and Ashtabula River have large undisturbed areas of watershed and minimal urbanization.

Along the Ohio Lake Erie shoreline, the Lorain and Cuyahoga county areas show elevated omnivore levels. Both of these counties have large urban areas in their vicinity and this factor is reflected in the fish community composition. And finally, in the Ohio nearshore, the Maumee Bay portion of the western basin is decidedly eutrophic based on percent omnivores.

10.6 Areas of Concern

Hartig and Law (1994) have stated that there was an impairment due to eutrophication or the presence of undesirable algae in the Clinton, Rouge, Maumee and Cuyahoga River Areas of Concern in the Lake Erie Basin. For the purpose of our beneficial use impairment assessment the Clinton and Rouge Rivers AOCs are not included because they are not direct tributaries of Lake Erie.

10.6.1 Maumee River

The Maumee River is the largest single tributary source of phosphorus to Lake Erie from Ohio comprising over 40% of the total annual load. The sources and causes of these inputs are agricultural land uses, waste water treatment plants, urban runoff, package treatment plants, combined sewer overflows (CSOs) and on-site wastewater treatment systems (Maumee River Remedial Action Plan Advisory Committee, 1990). There is an impairment due to eutrophication or the presence of undesirable algae in the Maumee River AOC (Hartig and Law, 1994).

10.6.2 Cuyahoga River

The Cuyahoga River Stage 1 Report (Cuyahoga River Remedial Action Plan, 1992), has identified a eutrophication impairment in the nearshore area of Cleveland. Data on trends and trophic state for the Area of Concern is limited. A 1984 study by the Argonne National Laboratories has determined eutrophic conditions. The Edgewater Yacht Club reported an algae growth problem during the summer of 1990.

The navigation channel (River Mile 5.6 to the mouth) is impaired due to severe oxygen depletion which occurs temporarily and under conditions combining extended periods of warm weather with low flow. This problem is more a result of low flow (slow time of travel) and very little aeration rather than input of raw sewage. A very deep, narrow channel allows little surface for aeration. The Cuyahoga River flows through two heavily urbanized areas (i.e., Akron and Cleveland) and drains an area with an extremely high proportion of impervious land surface.

The resulting extreme fluctuation in flow velocities has a much greater impact on the degree of erosion than any failure to implement control measures that may have been effective in less urbanized setting. Water clarity problems are a function of sediment loss and limited erosion control efforts, and, to a lesser extent, of heavy boat traffic and dredging. Dry weather and monitoring done during the months of June, July and August on the Cuyahoga River by OEPA and NEORSD do not show high contributions (all analysis show levels of less than 1.0 mg/L) of total phosphorus. Point sources are required to meet 1.0 mg/L as a maximum and phosphorus in detergents is controlled in the Northeast Ohio area under the Ohio Revised Code. Phosphorus originates mostly from non-point sources.

A 1994 study performed by the Northeast Ohio Regional Sewer District determined that, within the district's jurisdictional area, total loadings of ortho-phosphates from stormwater exceeded total loadings of ortho-phosphorus from combined sewer overflows (CSO). Studies have shown

that even if all point sources of BOD were removed there would still be a DO problem in the navigational channel due to channel morphology (Northeast Ohio Coordinating Agency, 1995). Therefore, the Cuyahoga River RAP Stage 1 Update Report (Cuyahoga River RAP Coordinating Committee, 1996) does not identify severe oxygen depletion in the Navigation Channel as an impairment related to eutrophication.

10.7 Trophic Status

10.7.1 Open Lake

The spring TP concentrations measured in the offshore eastern and central basins decreased from the early 1970's to presently reach the objective of 10 ug/L set by the GLWQA, with a brief period of exceedence during 1991 and 1992. In 1991, the mean value for the western basin was 27.5 ug/L, and in the spring of 1994 and 1995, it still exceeded the GLWQA guideline (15 mg/L).

Recent trends suggest that offshore nutrient and chlorophyll concentrations tend toward oligotrophic conditions for the eastern and central basins. More variable levels in the western basin are related to the massive inputs from the Detroit, Maumee and Sandusky rivers associated with spring run-off, precipitation, and resuspension of sediment during storm events. Mesotrophic conditions seem to be presently prevailing in the offshore waters of the western basin.

Chlorophyll changes in the offshore, combined with the nearshore *Cladophora* trends (section 10.5.3), indicate that the GLWQA goal of reduction in the present level of algal biomass to a level below that of a "nuisance condition" has been partially achieved. Localized nuisance algal problems (blooms and fouling due to excessive *Cladophora*) in some nearshore areas are still occurring on the northern shoreline, and therefore neither the GLWQA objective or the delisting criteria have been met.

The oxygen depletion rate in the hypolimnion of Lake Erie's central basin has declined from 1987 to 1991, with 1989 being the lowest in 20 years. In 1990 and 1992, the depletion rates were similar to those estimated in the 1970's and 1980's. The goal of establishing year-round aerobic conditions in the hypolimnion of Lake Erie's central basin has not been realized. Perhaps intermittent anoxia is an inherent property of the basin, and the use of dissolved oxygen as an indicator of eutrophication is not recommended.

Changes in phytoplankton abundance and species in Lake Erie (section 10.4.7) were also consistent with the expected impacts of reduced nutrient loadings initiated under the Great Lakes Water Quality Agreement. Recent studies indicate that zebra mussels have caused reductions in phytoplankton biomass, while, at the same time enhancing water clarity in the shallow waters, where they are found in greatest numbers.

The management of water quality has direct implications for fisheries management, because the composition of the fish community will vary with lake trophic state (Colby *et al.*, 1972; Leach *et al.*, 1977; Ryder and Kerr, 1978; Marshall and Ryan, 1987). Cold-water salmonids dominate communities in oligotrophic lakes, cool-water percids dominate communities in mesotrophic lakes and warm-water centrarchids dominate the fish communities in eutrophic lakes. Lake Erie's fish community changed following this pattern as the lake became eutrophic and many of the changes were reversed after phosphorus loading controls were established in 1972. After reaching target loads in the 1980's, phosphorus loading has been somewhat above or below the goal depending on water supply. The effect of loading reductions has been enhanced by the biological oligotrophication of *Dreissena* (Holland *et al.* 1994).

10.7.2 Nearshore

In the central basin, persistent problems (July through September) with excessive *Cladophora* and shoreline fouling are occurring in Rondeau Bay, Ontario (Shepley, 1996).

Recent *Cladophora* data collected in the eastern basin suggests that there are localized areas where adequate nutrients to promote undesirable levels of algal growth occur. The shoreline adjacent to the Grand River (Ontario), Featherstone Point, Sandusk Creek and Peacock Point were afflicted with *Cladophora* fouling in 1995. Limited nutrient chemistry data collected in 1988 and 1989 suggests that elevated nutrient levels may occur at some of the tributary mouths to the lake including Grand River (Ontario), Big Otter Creek, Kettle Creek, and Sturgeon Creek. However, given the limited data, it is difficult to accurately report to what extent undesirable symptoms of eutrophication occur.

In the case of the Grand River (Ontario), the benthic invertebrate data collected at a station offshore from the river mouth indicated nutrient enrichment. In the nearshore the total phosphorus (TP) levels measured extensively at the five intakes were at or below the 20 ug/L Interim Provincial Water Quality Objective, suggesting that undesirable levels of algal growth should be avoided.

Based on both data showing elevated abundance of omnivorous fishes and the beneficial use impairment assessment for the Maumee Area of Concern Remedial Action Plan, Maumee Bay and the Ottawa and Maumee rivers are decidedly eutrophic (Thoma 1996; Maumee RAP, 1990).

Turtle, Muddy and Old Woman Creeks and the Portage, Sandusky, Vermilion, Black, Rocky, Cuyahoga and Chagrin Rivers all show potential for eutrophication problems based on elevated levels of omnivorous fish and associated phosphorus data. However, because the U.S. has no water quality standards for nutrients, it is not possible to definitively interpret nutrient levels as indicative of cultural eutrophication. This, along with uncertainty about other factors affecting the fish community health, such as chemical pollution and habitat degradation, meant that the subcommittee did not feel comfortable with a definite ~~✱impaired✱~~ decision. However, there was enough evidence to suggest the need for continued monitoring of the situation, therefore, the conclusion was ~~✱potentially impaired✱~~.

10.8 **Impairment Conclusions**

Eastern Basin

OPEN LAKE - No impairment. Phosphorus and chlorophyll a concentrations in offshore waters are presently indicating oligotrophic conditions.

NEARSHORE - Impairment: *Cladophora* data collected in 1995 by the Ontario Ministry of Environment and Energy in the eastern basin suggest that there are still adequate nutrients in at least portions of the shoreline to promote undesirable levels of algal growth. At a minimum, *Cladophora* fouling occurred in 1995 along the shoreline adjacent to the Grand River (Ontario), Featherstone Point, Sandusk Creek and Peacock Point. Heavy *Cladophora* growth was noted in 12 other areas, but no evidence of fouling was seen in these areas in 1995.

Cladophora fouling is an impairment when it is persistent. The 1995 fouling is indicative of impairment, but monitoring data are generally not available for the years previous to 1995 or for 1996. The exception is the Grand River (Ontario) mouth where limited water quality monitoring in 1989 and benthic invertebrate collections in 1993 were consistent with nutrient enriched conditions. In 1998, *Cladophora* windrows on shore and accumulations in water that were in some locations heavy occurred in several locations in the east basin. Three of the areas affected in 1995 and three other areas were affected in 1998 (Appendix B). Thus, *Cladophora* accumulation is a recurring problem. In summary, despite limited data, it appears that *Cladophora* causes an impairment.

Central Basin

OPEN LAKE - No impairment (based on phosphorus and chlorophyll *a* concentrations)/ Inconclusive (based on dissolved oxygen levels). Phosphorus and chlorophyll *a* concentrations in offshore waters are presently indicating oligotrophic conditions. Episodes of anoxia continue to exist in some areas of the central basin in late summer. Ecosystem objectives that identify desired dissolved oxygen conditions and associated aquatic communities in the central basin nearshore are needed before an impairment conclusion can be drawn for oxygen depletion in this area of the Lake.

NEARSHORE - Potentially impaired in Rondeau Bay Ontario based on *Cladophora* fouling problems. *Cladophora* fouling was not a problem in 1998 but these are insufficient data with which to make a firm conclusion.

LAKE EFFECT ZONE - Potentially impaired in Old Woman Creek, the Vermilion, Rocky, Huron, Black, Chagrin and Cuyahoga Rivers based on elevated levels of omnivorous fish. In addition, elevated concentrations of total phosphorus, total inorganic nitrogen and chlorophyll *a* were measured at Port Burwell at the mouth of Big Otter Creek, and at Port Stanley at the mouth of Kettle Creek and Sturgeon Creek in 1988 and 1989. If persistent, these conditions could be indicative of impairment. Impairment is indicated by tributary phosphorus data well above Provincial Water Quality Objectives (PWQOs, Appendix D)

Western Basin

OPEN LAKE - No impairment. Phosphorus and chlorophyll *a* concentrations in offshore waters are presently indicating mesotrophic conditions. An emerging issue is *Microcystis* blooms in 1994, 1995, 1996, and 1998.

NEARSHORE - Impaired. Data from the Maumee AOC beneficial use impairment and percentages of omnivorous fish are presently indicating highly eutrophic conditions in Maumee Bay (Maumee AOC). Potentially impaired in lake effect zones of the Toussaint, Portage and Sandusky Rivers and Turtle and Muddy Creeks in Ohio.

LAKE EFFECT ZONE- Potentially impaired for the Toussaint, Portage and Sandusky Rivers and Muddy and Turtle Creeks based on elevated levels of omnivorous fish.

Emerging Issue

In late August 1994, mid-August 1995 and again in May of 1996, *Microcystis* (*sp. aeruginosa*) blooms appeared in the western basin of Lake Erie. By mid-September the bloom covered much of the western basin. Research currently underway will determine the cause of the bloom and whether it can be expected to continue in future years (Appendix A). The results of this research should allow us to evaluate whether the presence of *Microcystis* in the western basin is causing an impairment. Historically, the lake has had Cyanobacteria blooms, including *Microcystis*, and the absence of such blooms for a few years followed by their resurgence suggest major ecological change in the lake. These changes are a reflection of weather effects on external phosphorus loading, selective grazing by zebra mussels, and contribution by zebra mussels to the internal loading of nutrients in the lake (David Culver, Ohio State University, pers. comm., Dec. 1996).

Causes of Impairment

Historically, phosphorus levels in Lake Erie have been the primary cause of impairment. In the eastern basin of Lake Erie, phosphorus levels are linked to the *Cladophora* growth and fouling along some portions of the north shore.

More variable levels of phosphorus in the western basin are related to massive inputs from the Detroit, Maumee and Sandusky Rivers during storm events. The Maumee River is the largest single tributary source of phosphorus to Lake Erie from Ohio, comprising over 40% of the total annual load. The phosphorus loads from sewage plants are still 25 to 50 times more concentrated than west basin water. The ability to predict phosphorus levels in the western basin is limited by the unpredictable nature of weather patterns. The sources and causes of phosphorus inputs from western basin tributaries are agricultural land uses, wastewater treatment plants, urban run-off, combined sewer overflows, and onsite wastewater treatment systems.

10.9 Recommendations

It is recommended that additional monitoring and research be conducted in central and eastern basin locations where current limited data indicates potential impairment. In addition, other jurisdictions have expressed an interest in further development of the omnivorous fish indicator, so that it could be more definitively used to identify cultural eutrophication impairments.

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Appendix A

Toxicity, Ecological Impact, Monitoring, Causes and Public Awareness of Microcystis Blooms in Lake Erie

March 31, 1999

D. Culver, The Ohio State University

Summary of Conclusions

Problem Identification - The large blooms of *Microcystis* that occurred in the western basin of Lake Erie during August- October 1995 were unexpected. Over the last 25 years cyanobacterial blooms have decreased in frequency while water quality of Lake Erie has increased (Makarewicz, 1993). While levels of nitrogen-fixing cyanobacteria genera such as *Anabaena*, *Aphanizomenon*, *Nostoc* and *Nodularia* have remained low since 1990, *Microcystis aeruginosa*, a non-nitrogen-fixing species has suddenly increased suggesting that one or more factors having to do with phosphorus or N/P ratio changes, and/or activities by filter-feeding zebra mussels may be involved. Because *Microcystis* can produce virulent toxins that may affect Lake Erie's ecosystem, including man, we prepared a collaborative, comprehensive study plan to delineate the interactions of this alga and its toxins with Lake Erie, monitor the frequency and distribution of the blooms, examine their causes, and communicate the results of our research to the lay public, Lake Erie managers, and the scientific community. This report summarizes the results of that study as of December 1998, but many of the research initiatives begun with this collaboration are continuing in the laboratories of the research partners.

Goal III. Monitor the Occurrence of Blooms of *Microcystis* and Other Toxic Algae

- ✂ *Aphanizomenon* and *Anabaena* were much reduced from 1970 levels by 1983, whereas *Microcystis* has bloomed at least twice (1995 and 1998) since zebra mussels have become established. The first two taxa are nitrogen fixers, whereas *Microcystis* is not.
- ✂ High abundance of cyanophytes (including *Microcystis*) in Lake Erie in 1996 was associated with stations with total inorganic Nitrogen to total Phosphorus ratios below 25, and total inorganic Nitrogen to soluble reactive phosphorus levels below 400. Highest abundances occurred in August and September, when prevailing water temperatures were highest.
- ✂ A near real-time display of daily surface reflectance (related to surface algae and other particulate matter) for all of Lake Erie, based on AVHRR satellite data has been made available via a NOAA web site (<http://www.glerl.noaa.gov/cw/cw.html>).
- ✂ Calibration of 1995 satellite data with ground truth data enabled following the development in August and disappearance in October of the 1995 *Microcystis* bloom; this showed that the AVHRR satellite data provide an inexpensive means of monitoring the extent of surface blooms in Lake Erie. The SeaWiFS satellite may also be useful for this purpose, since it detects light near the fluorescence wavelength of chlorophyll.

Goal IV. Determine the Causes of *Microcystis* Blooms in Lake Erie.

- ✂ Low nitrate to ammonia ratios and warm water temperatures in August and September may have helped initiate the *Microcystis* bloom in 1995, but these conditions were also found in four other years without blooms in Hatchery Bay, South Bass Island.
- ✂ External loading of phosphorus and nitrogen was not correlated with the occurrence of a bloom of *Microcystis* in 1995.
- ✂ Algae growing near zebra mussels are less phosphorus-limited than are those living further away, suggesting that phosphorus excretion (recycling) by zebra mussels may in part stimulate algal growth and *Microcystis* blooms.
- ✂ Nitrogen excretion by zebra mussels in Lake Erie were 1.3 to 2.9 times that in Saginaw Bay, while their phosphorus excretion was 20 to 80 times higher than that of Saginaw Bay mussels. Lake Erie zebra mussels excreted N and P at N:P ratios lower than the seston being consumed.
- ✂ High light reaching the bottom of the lake may trigger growth of *Microcystis* cells lying on the bottom, initiating a bloom.

Appendix B

Cladophora in Lake Erie 1998

Todd Howell, Ontario Ministry of the Environment

Excessive growth of benthic algae (typically *Cladophora*) stemming from cultural eutrophication and resulting in aesthetically unpleasing accumulations of algae on shore has plagued parts of Lake Erie in the past. In recent years there has been renewed concern that *Cladophora* remains abundant in parts of the lake for reasons that are not well understood. In July of 1998 a survey of the occurrence of *Cladophora* along the north shore of Lake Erie was completed by the Ontario Ministry of the Environment (MOE) following up on an earlier survey completed in 1995 (Howell 1998). Observations on the accumulation of *Cladophora* washed on shore were made at 29, 16 and 7 locations in the east, central and western basins, respectively (Figure 1). Measurements of surface cover, thickness and biomass of *Cladophora* growing in the littoral zone (waterline to 2 m depth) were made at 10 locations in the eastern basin, nine of which were surveyed in 1995 (Figure 2).

Little algae was found washed up onshore at the sites examined in the central and western basins. Variable amounts of *Cladophora* were found attached to hard substrata (shoreline groins, breakwalls, and rocks), however, the amount of algae growing along the lakeshore appeared to be strongly limited by availability of suitable substrate over the areas examined. *Cladophora* is typically found growing attached to hard and stable surfaces.

Not surprisingly, *Cladophora* was more abundant at the sites in the eastern basin, many of which are along rocky shoreline, than at sites elsewhere in the lake. Variable amounts of algae, occurring as windrows on shore, or as material pooled along the waters edge were observed at many sites. The amounts of algae washed up on shore at the time of the survey appeared to be lighter than observed over a similar period in 1995. The shoreline accumulations were considered to be mildly unpleasant at several locations, however, even at these sites the areas affected by heavy accumulations were very localized and limited in extent. Areas where patches of affected shoreline were detected include: west of the Grand River mouth

in Splatt Bay, mouths of Sandusk Creek and Hemlock Creek, west of Low Point, Featherstone Point, east of Rathfon Point, and west of Nantiocoke. These observations are highly subjective and based on one or two occasions, so they should be treated with a suitable degree of caution.

The quantity of algae growing in the shallow littoral zone of the eastern basin, as judged by visually estimating surface cover and thickness of the *Cladophora* lawn, was lower at most locations at the time of the 1998 survey than compared with similar measurements in 1995. In 1998 the median thickness of the *Cladophora* lawns over the 0.5 to 1.5 m depth ranged from 1 to 9 cm among sites compared with a range of 6 to 20 cm over approximately the same sites in 1995 (Figure 2). The average surface cover over the 0.5 to 1.5 meter depth ranged 38 to 93%. Percent cover was greater than 70% at half of the sites. While *Cladophora* remained a prominent feature of the shallow littoral zone, its abundance at most sites appeared to be lower than observed in 1995. It should be noted that the abundance of *Cladophora* is known to be highly variable from year to year in response to undetermined environmental factors. The results provided here should not be taken as evidence of a change in nutrient conditions without further monitoring and investigation. In the eastern basin it has been suggested that *Cladophora* is more abundant in low water years than in high water years (e.g. Moore 1975), however, there does not appear to be any conclusive evidence to support this contention.

Water quality surveys conducted by MOE in the spring of 1998 in the nearshore of Lake Erie adjacent to the mouth of the Grand River and along the shoreline between Sandusk Creek and Port Dover provide insights into environmental conditions that may be important for *Cladophora*. Measurements made in April of water temperatures indicated that there were areas of warming along shore associated with tributary mouths and shallow depths. In several cases, areas with temperatures suitable for *Cladophora* growth (>10 CE) coincided with areas where total phosphorus (TP) levels were elevated due to tributary or shoreline inputs of TP (Figure 3 & 4). The data support the hypothesis that in early spring there may be areas along shore with good conditions for growth of *Cladophora*, and that these areas may be localized and not evident later in the season when tributary flows decline and water temperatures increase.

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Credits: Basemaps in Figures 3 & 4 derived from Ontario Ministry of Natural Resources OBMs

Figure Captions:

Figure 1: Locations in Lake Erie where observation were made on the wash-up of algae on shore during July 1998.

Figure 2: Median thickness of the lawns of *Cladophora* growing at 0.5 to 1.5 depths at sites in eastern Lake Erie in 1995 and 1998. Thickness refers to height of the lawn as it sits in the water.

Figure 3: Surface water temperature (1.5 m depth) and total phosphorus concentrations in surface samples (1.5 m) near the mouth of Sandusk Creek in April 1998.

Figure 4: Surface water temperature (1.5 m depth) and total phosphorus concentrations in surface samples (1.5 m) near the mouth of the Grand River in April 1998.

Median Thickness of Cladophora over bedrock
> over depth range (0.5 to 1.5 m)

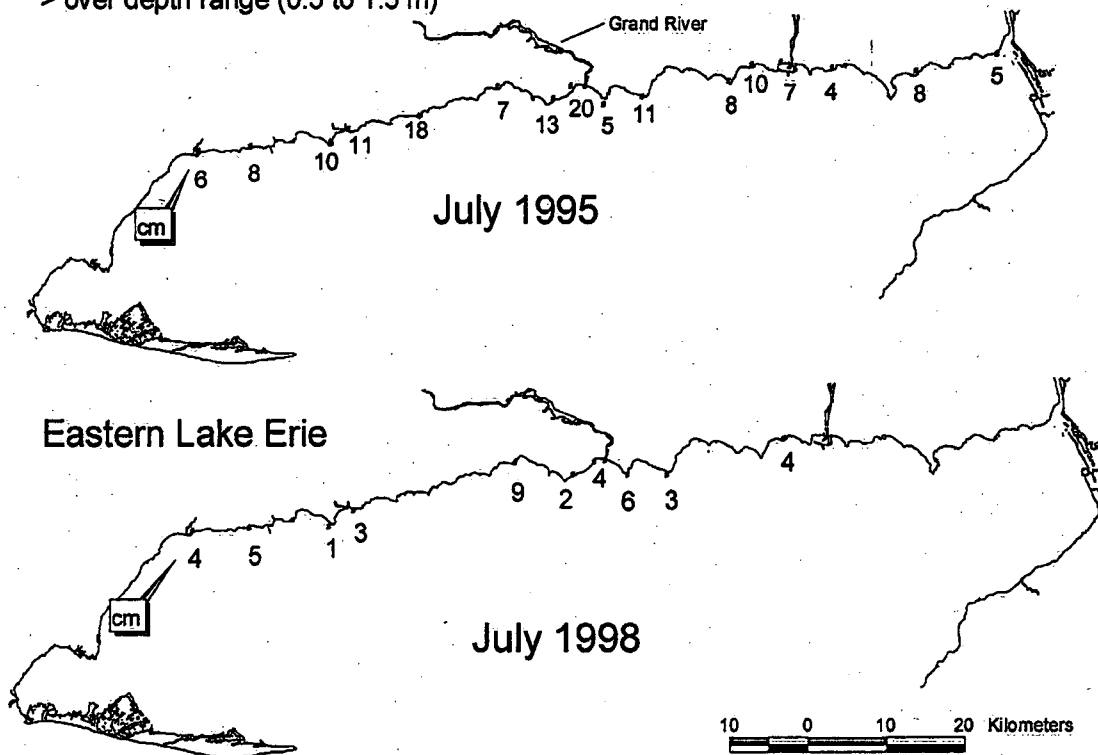


Figure 2

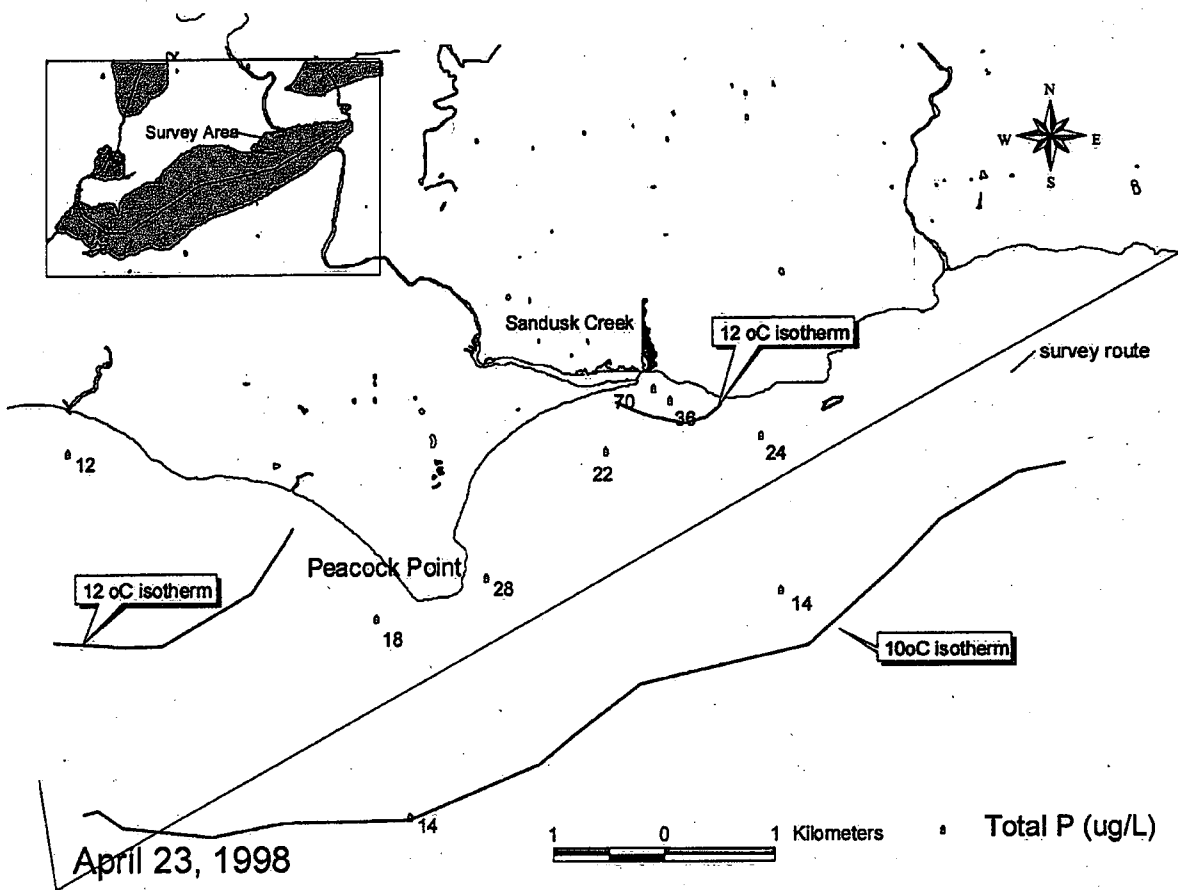


Figure 3

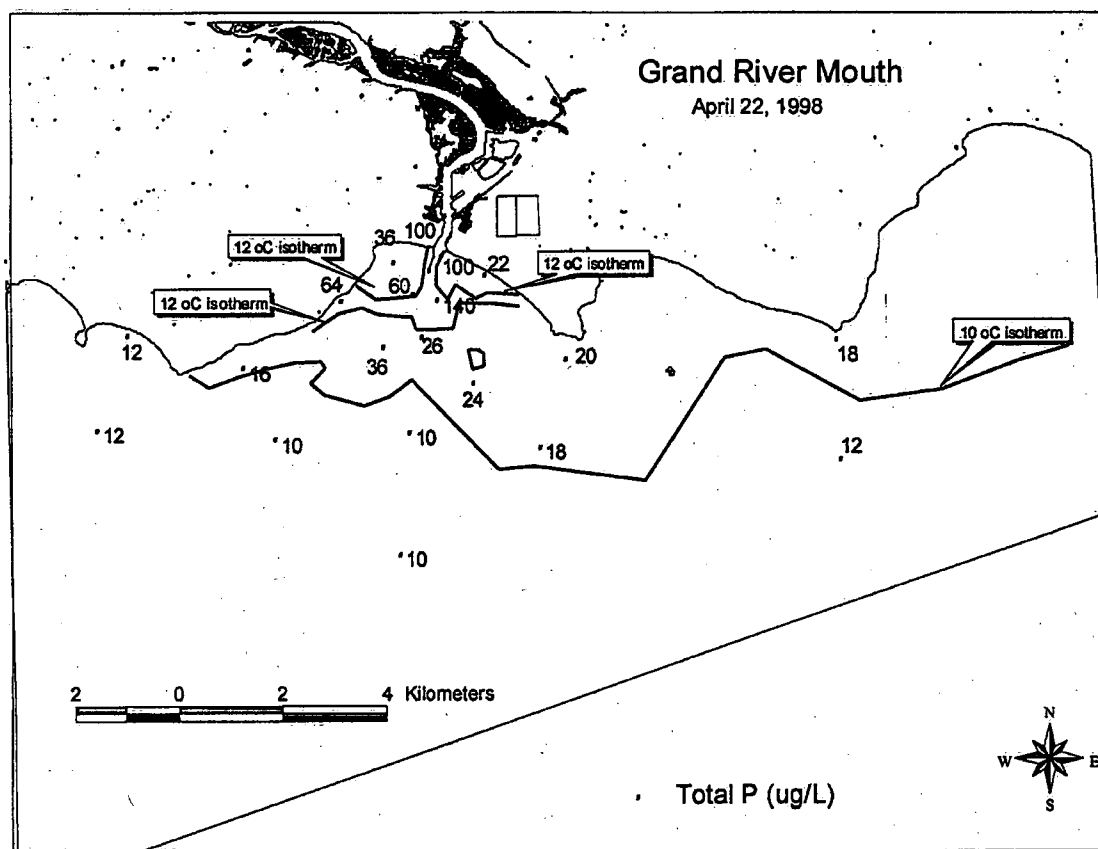


Figure 4

Appendix C-

Summary of Ohio EPA Metrics Used in Evaluating Index of Biotic Integrity (Ohio EPA, 1999)

Lake Erie Shoreline Metrics

Lacustrary Metrics

Species Number Metrics

Number of species
Number of sunfish species
Number of Phytophilic species
Number of Benthic species

Number of species
Number of sunfish species
Number of Cyprinid species
Number of Benthic species

Behavior/trophic guild metrics

% Lake associated individuals
% Top carnivores
Number of Intolerant species
% Omnivore individuals
% Nonindigenous individuals
% Tolerant individuals

% Phtophilic individuals
% Top carnivores
Number of intolerant species
% Omnivore individuals
% Nonindigenous individuals
% Tolerant individuals

Community health metrics

% DELT*
Relative numbers**

%DEL T
Relative numbers**

* Externally observable deformities, eroded fins, lesions, and tumors

** Includes nonindigenous species and excludes gizzard shad

Appendix D

Phosphorus in Tributaries

Monitoring of tributaries is conducted by agencies in both countries. There is now sufficient data available to gain an impression of not only the nutrient status of the tributaries but also whether or not changes have occurred.

Phosphorus data were retrieved from the U.S. STORET system and from Environment Canada and the Ontario Ministry of the Environment (PWQMN). After restricting the data to those from lower river and nearshore river mouth sites 4092 observations from 47 sites were used.

Data were grouped into two time periods, 1986 to 1989 and 1993 to 1996. The data as shown as colored dots in Figs 1 and 2.

Most data were higher than State or Provincial guidelines in both the 1986-1989 and 1993 to 1996 periods.

A statistical analysis was conducted on the data of the two groups to see if sites had changed or not:

Phosphorus decreased at 19 stations.

Phosphorus increased at 3 stations.

Phosphorus was unchanged at 25 stations.

Although there has been some progress in reducing phosphorus concentrations in tributaries most of the data are still higher than guidelines and this indicates more work is needed on sources. The guidelines are based on observations that total phosphorus levels higher than 30 ugP/L are associated with problem algal problems in streams. Thus even though some of the phosphorus is from eroded soils and the availability to algae has not been determined the 30 ug/L is a practical guideline which is exceeded in many cases.

The timing and amount of anthropogenic phosphorus loads creates nearshore pollution problems. Excess phosphorus comes from natural erosion, erosion of fertilized soils, fertilizer P dissolved in runoff, and treated sewage from municipal sources as well as from septic systems and manure storage and spreading. Before intense anthropogenic impacts the phosphorus load to the lake was mainly by erosion and flushing of wetlands during snow melt freshets. The lake would exist on a burst of phosphorus load that occurred in spring. Now, anthropogenic loads occur daily in the form of human and livestock waste and routinely when rainfall washes material from denuded landscapes. These loads enter the lake in low velocity streams and rivers that tend to pollute nearshore areas before mixing into the whole lake.

The source of the

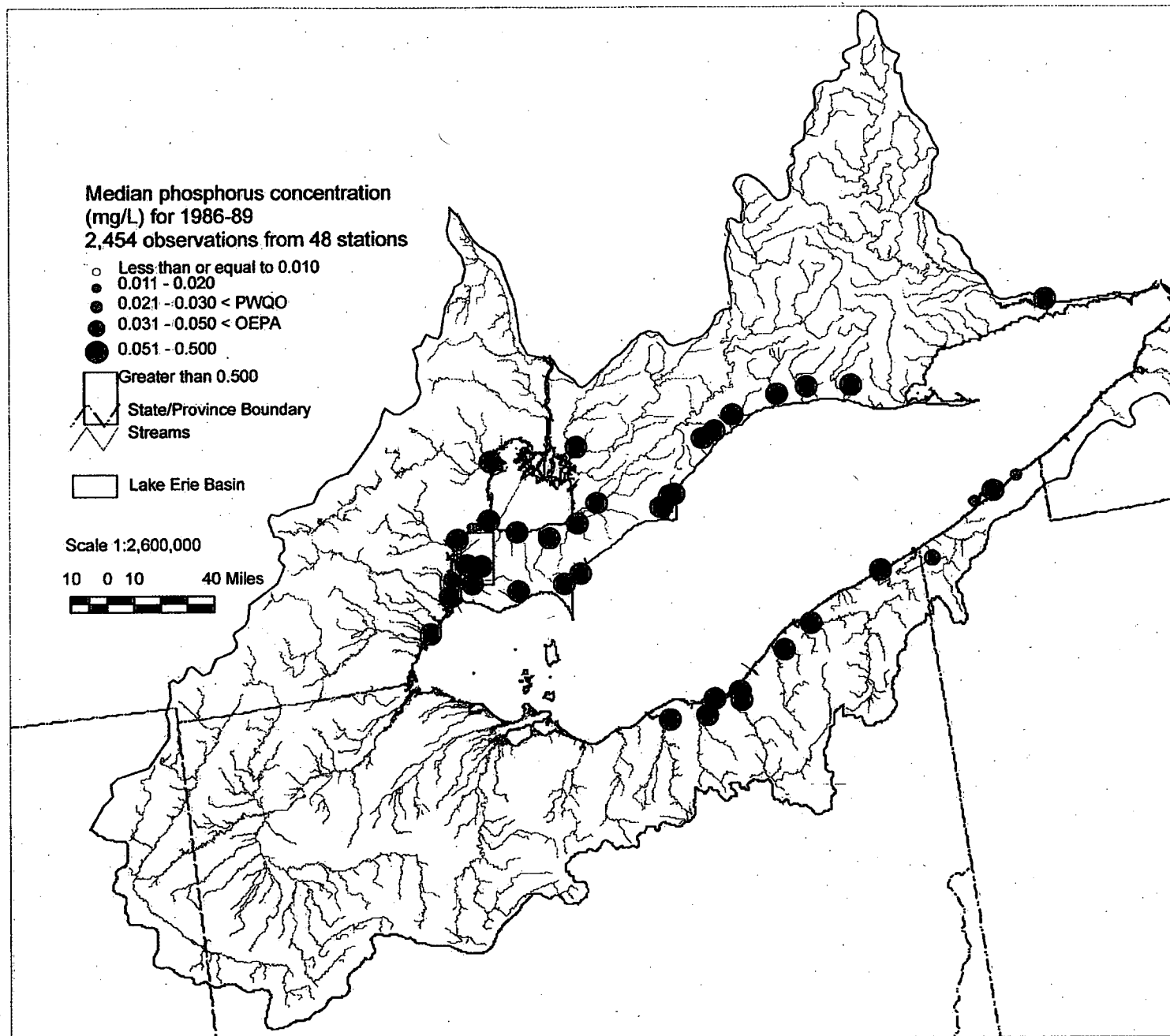


Figure 1. Median ambient phosphorus concentrations at 48 stations in the Lake Erie basin, United States and Canada, 1986-1989.

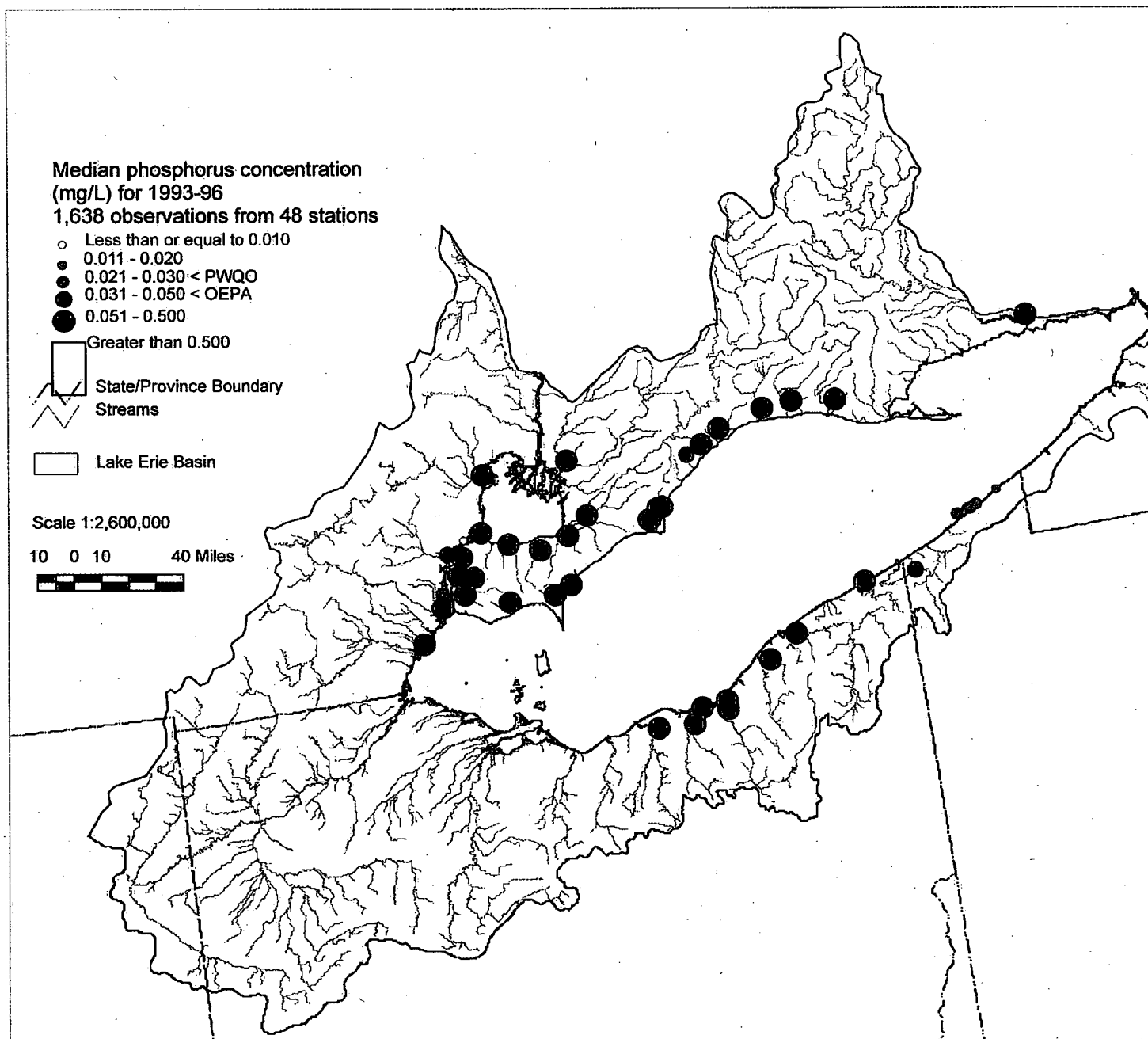


Figure 2. Median ambient phosphorus concentrations at 48 stations in the Lake Erie basin, United States and Canada, 1993-1996.

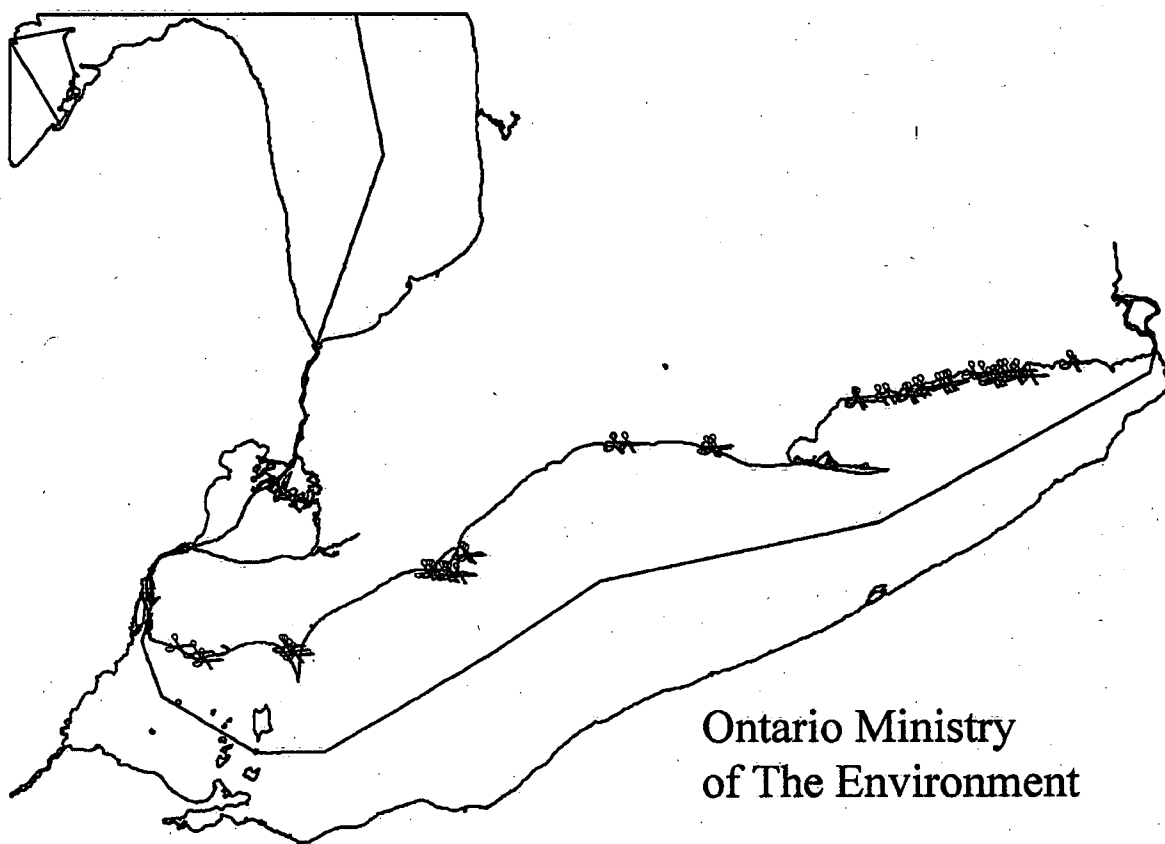


Figure 1, Cladophora sampling sites in 1998

Figure 1

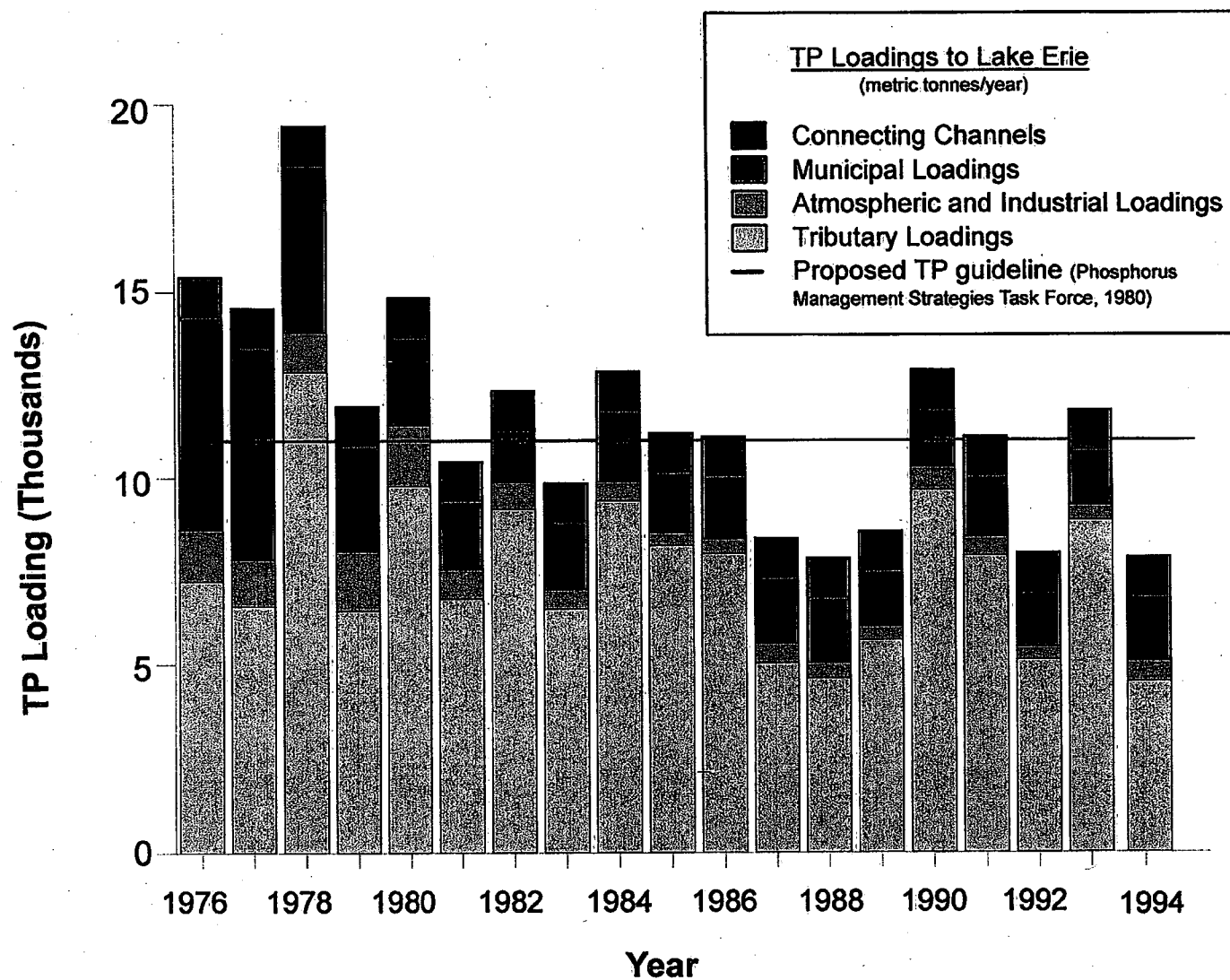


Figure 1: Total Phosphorus Load to Lake Erie (metric tonnes)

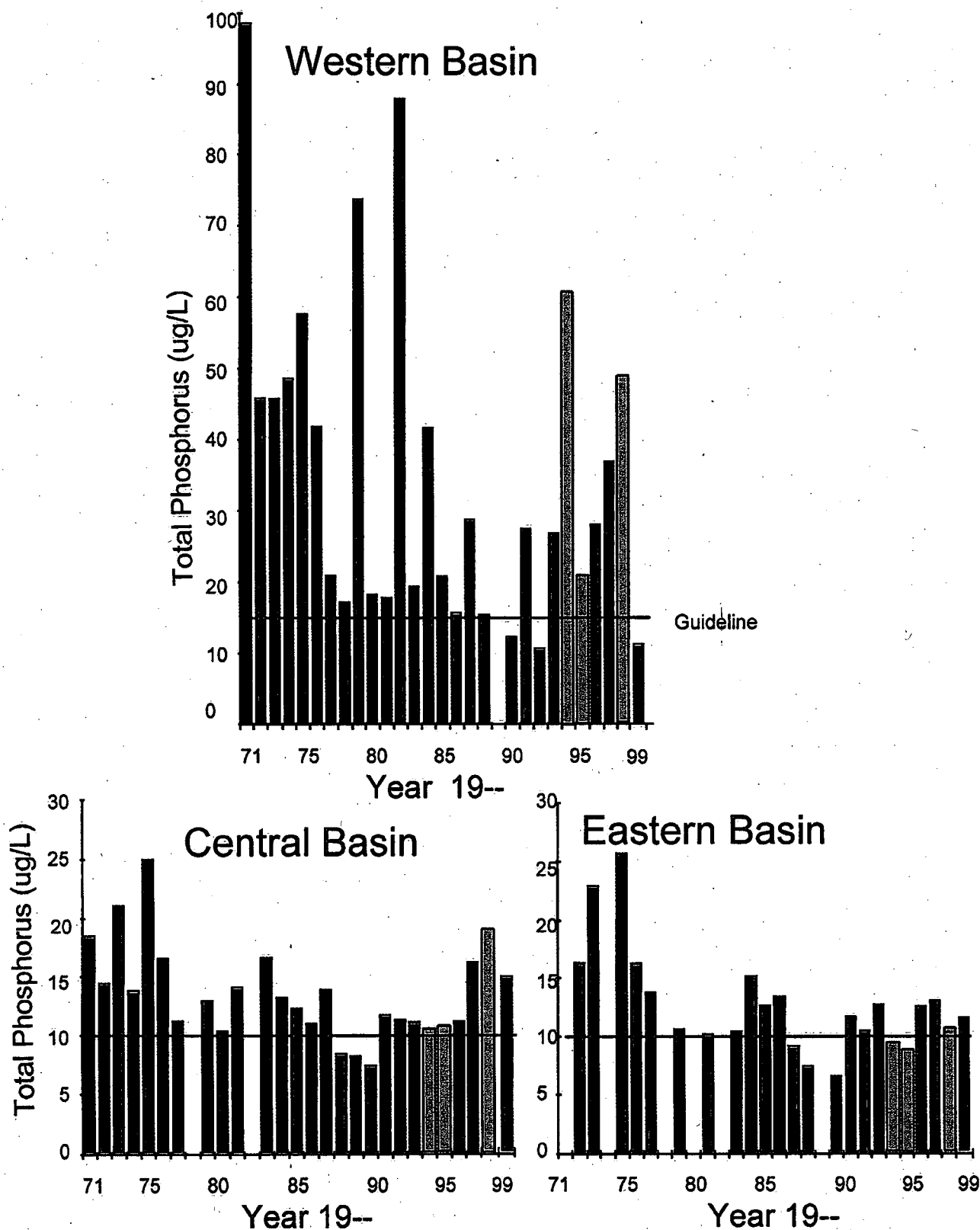
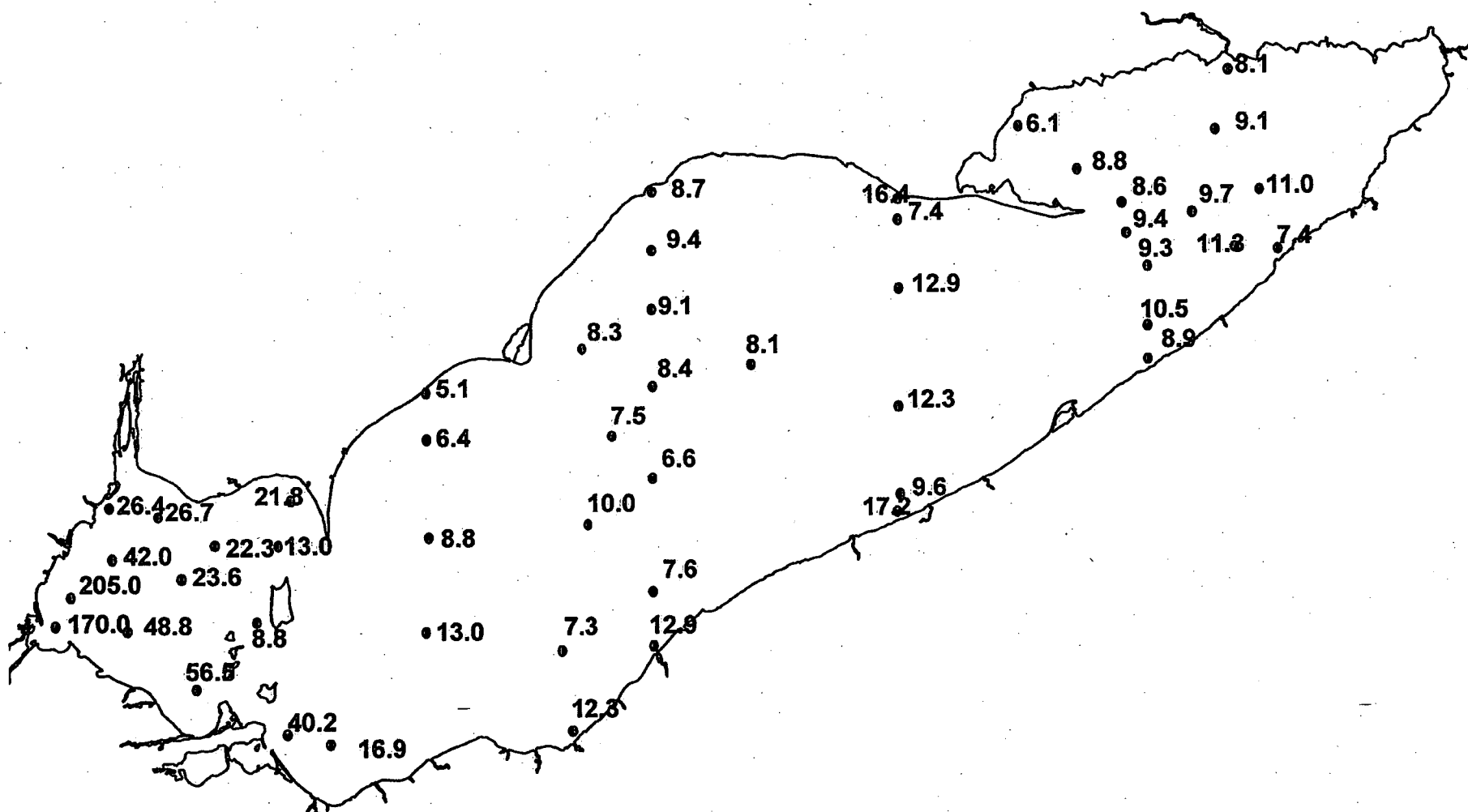
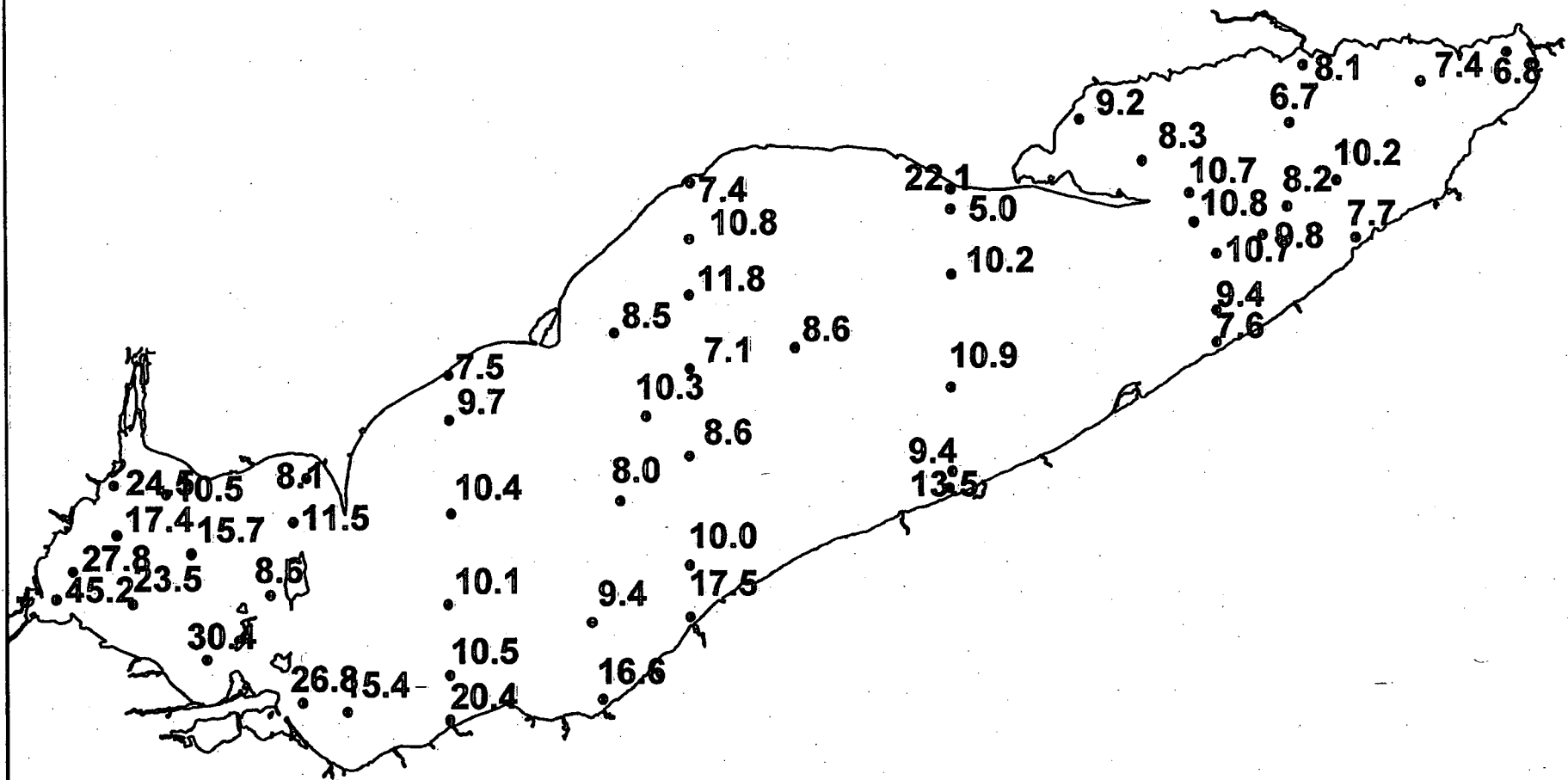


Figure 2, Spring Mean Total Phosphorus Trends in Lake Erie (Spring, Open Lake, Surface). Data from Great Lakes National Program Office US EPA and Environment Canada (gray bars).



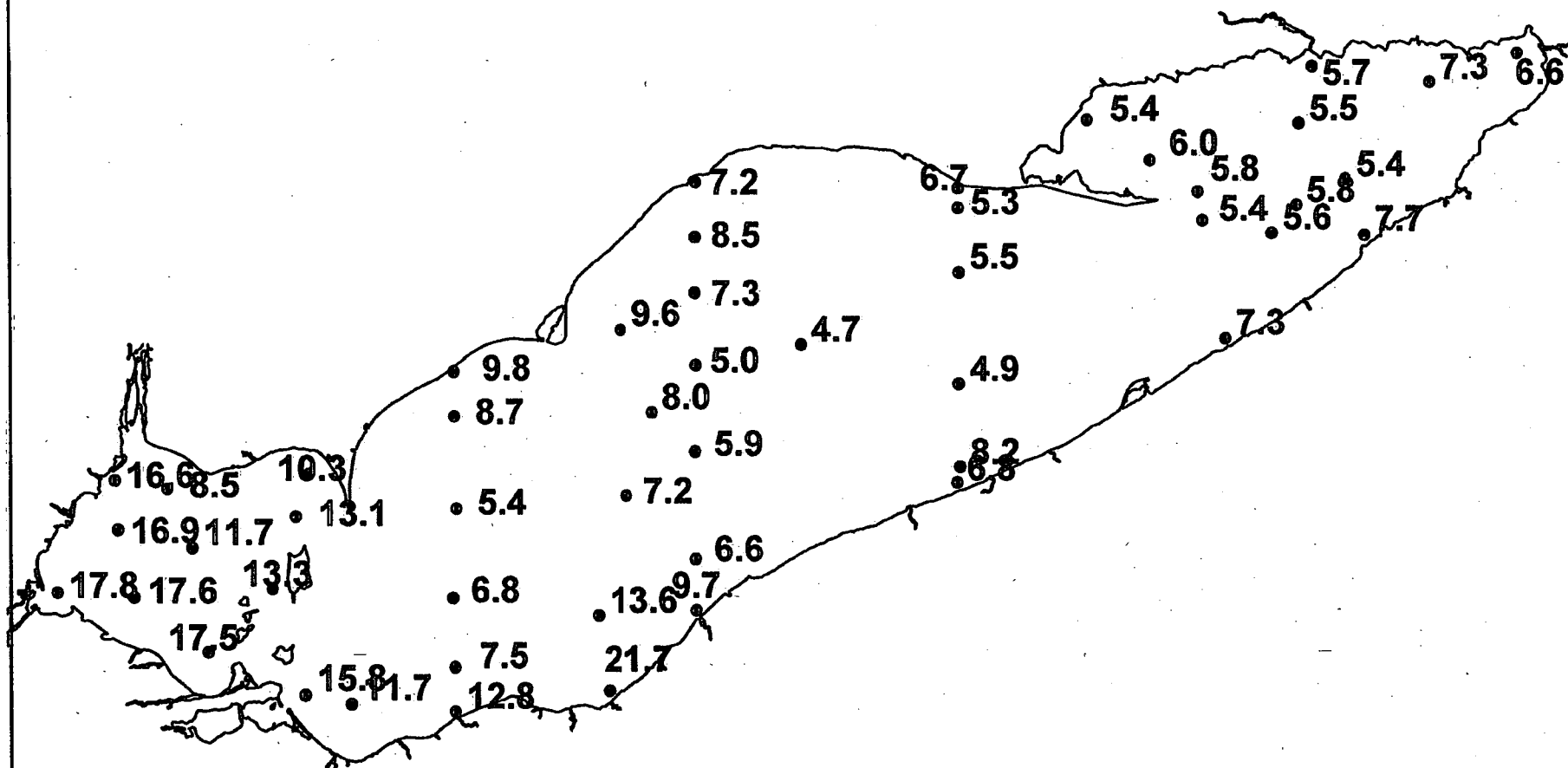
Data Source: Environmental Conservation Branch/ Environment Canada.

Figure 3 . Total phosphorus in Lake Erie (1m depth), spring 1994 (ug/L).



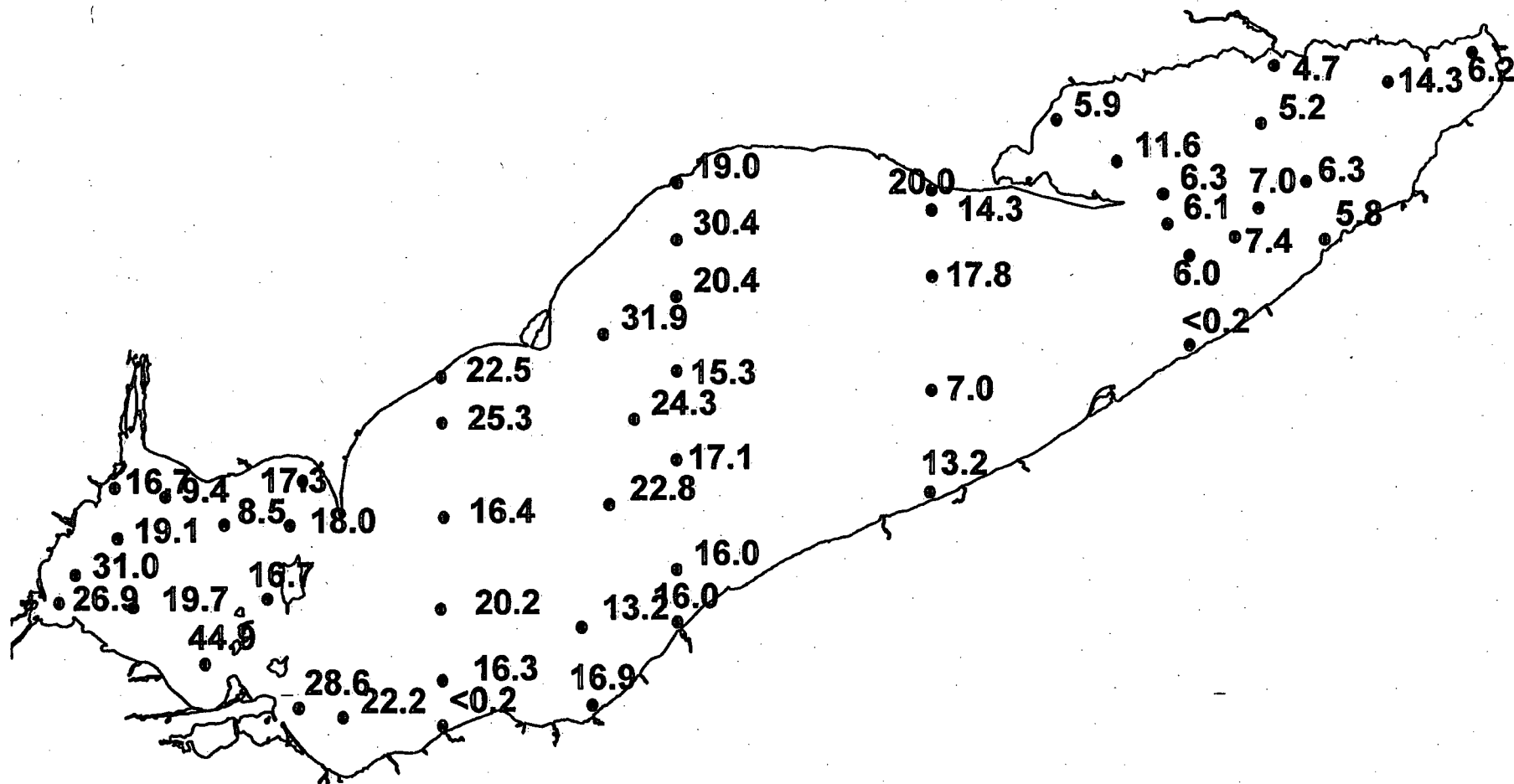
Data Source: Environmental Conservation Branch/ Environment Canada.

figure 4. Total phosphorus in Lake Erie (1m depth), spring 1995 (ug/L).



Data Source: Environmental Conservation Branch/ Environment Canada.

Figure 5. Total phosphorus in Lake Erie (1m depth), summer 1994 (ug/L).



Data Source: Environmental Conservation Branch/ Environment Canada.

Figure 6. Total phosphorus in Lake Erie (1m depth), fall 1994 (ug/L).

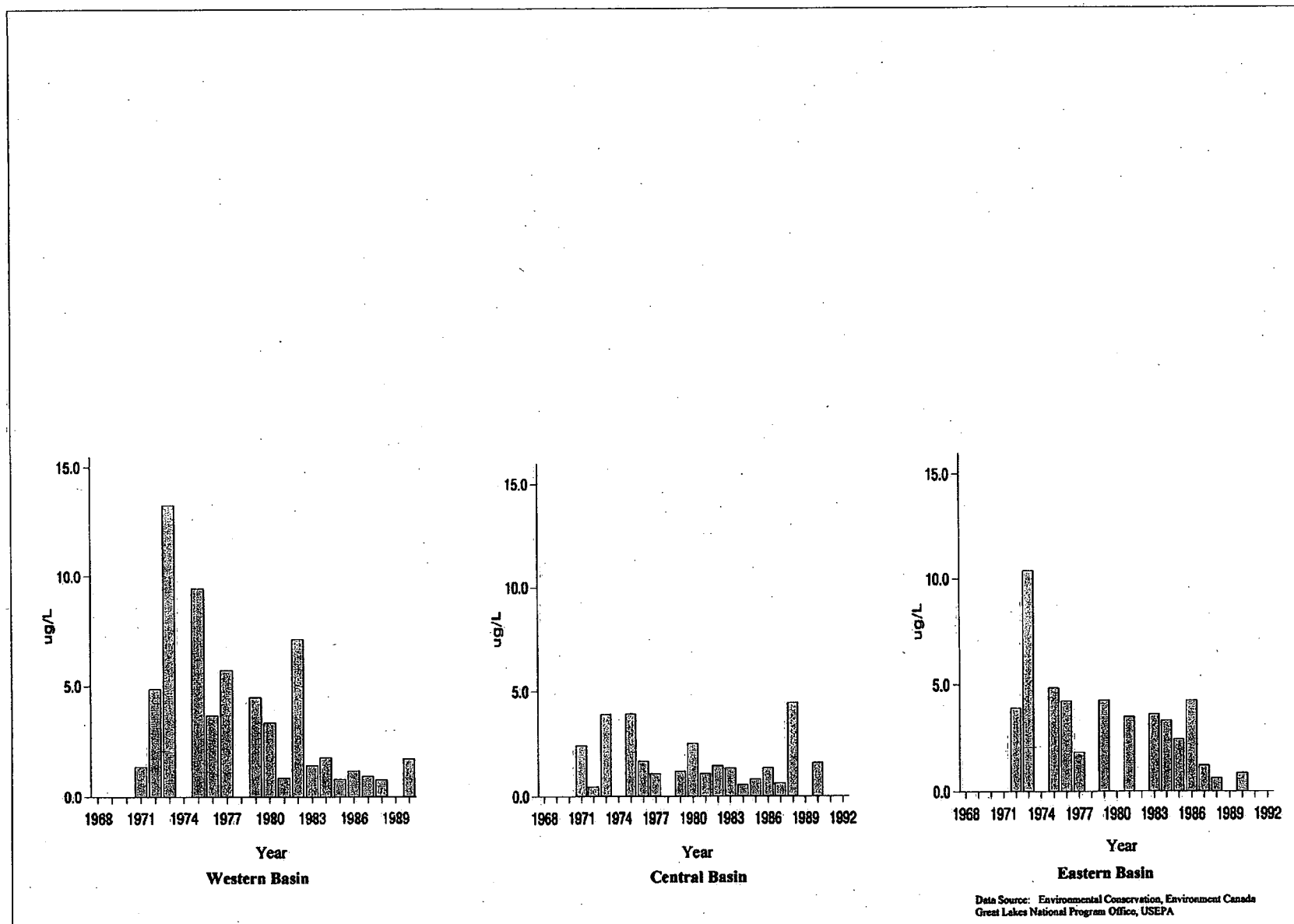


Figure 7. Soluble reactive phosphorus levels in Lake Erie, 1968 - 1992.

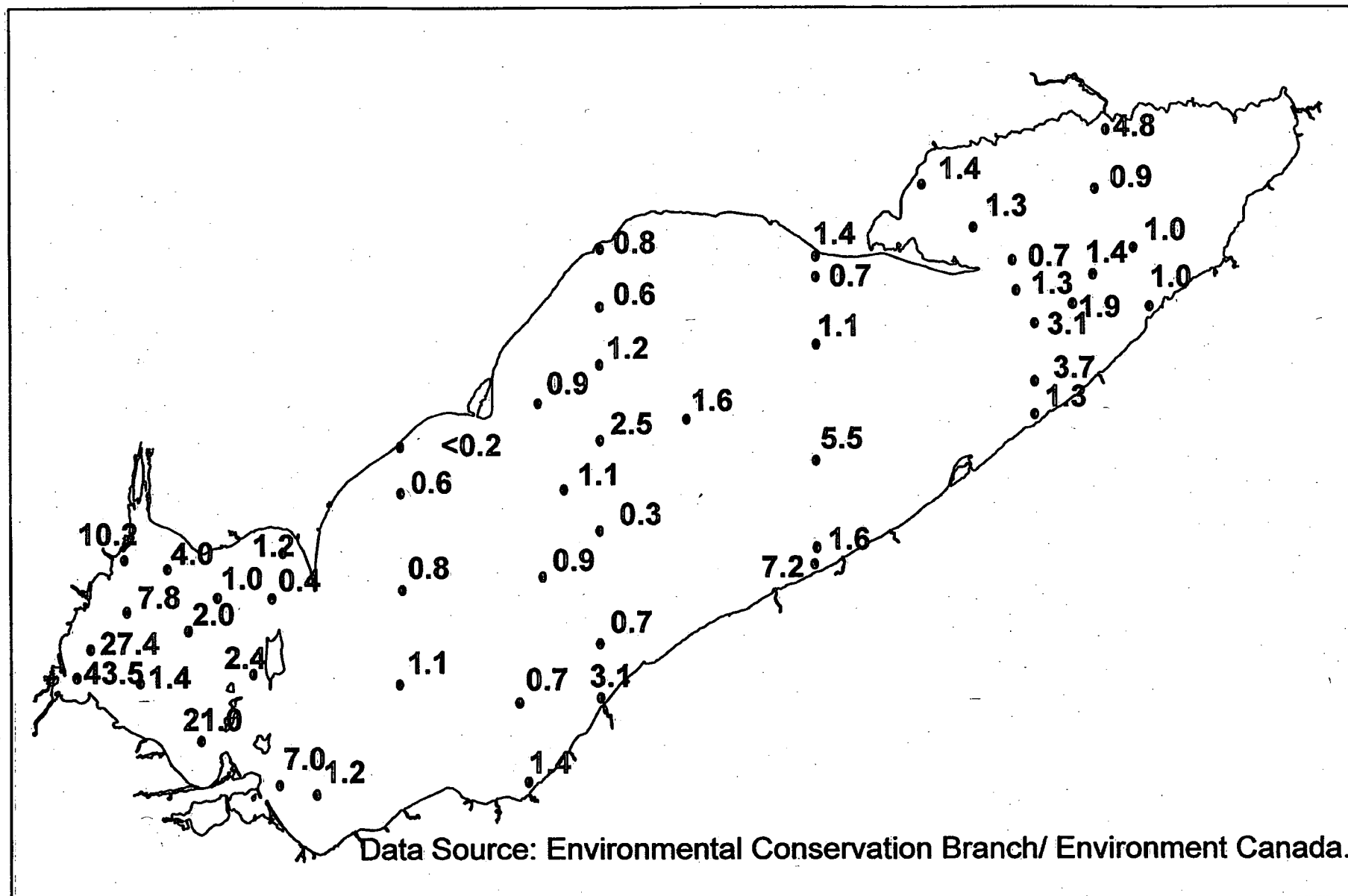
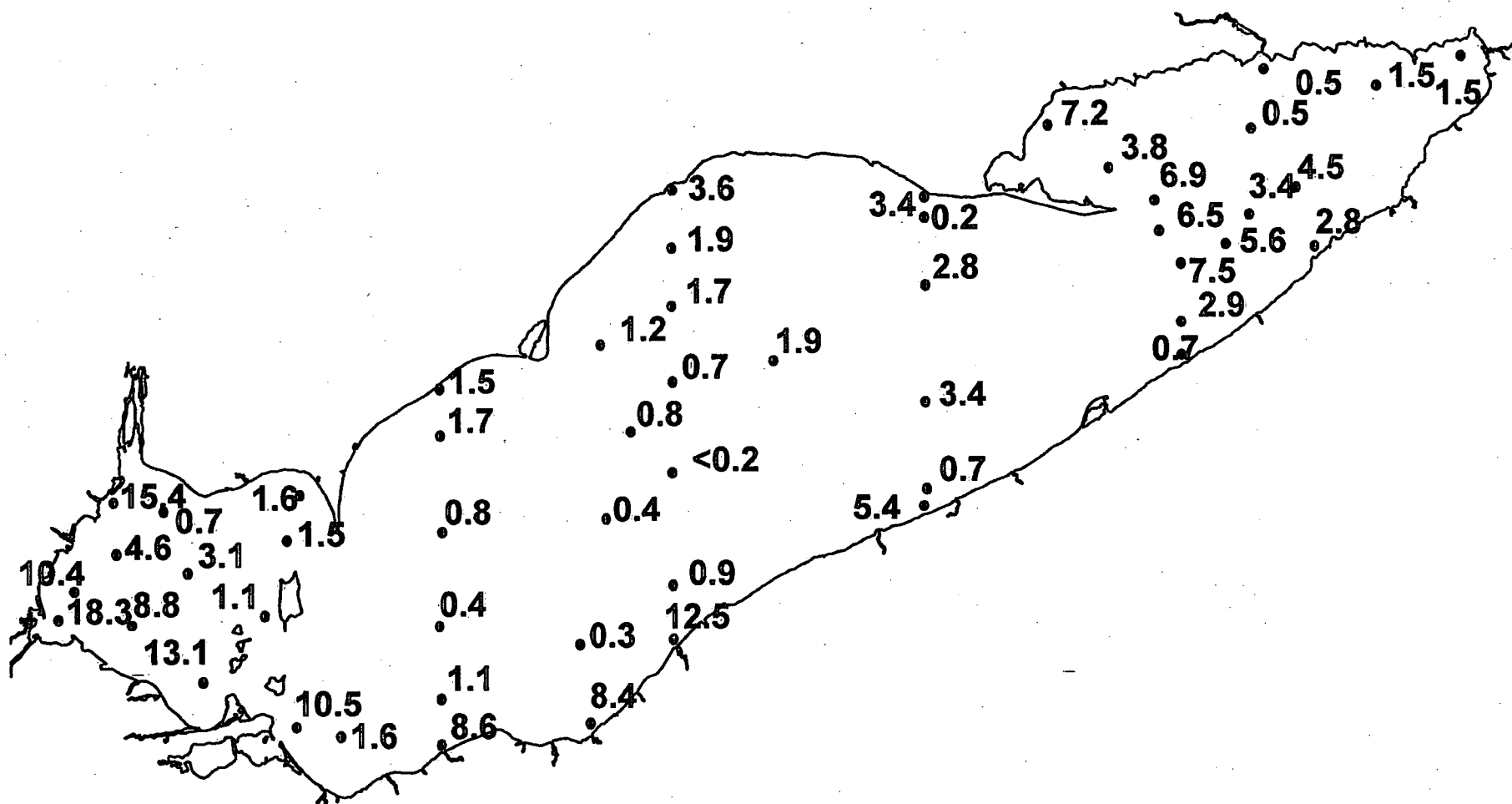


Figure 8. Soluble reactive phosphorus in Lake Erie (1m depth), spring 1994 (ug/L).



Data Source: Environmental Conservation Branch/ Environment Canada.

Figure 9. Soluble reactive phosphorus in Lake Erie (1m depth), spring 1995 (ug/L).

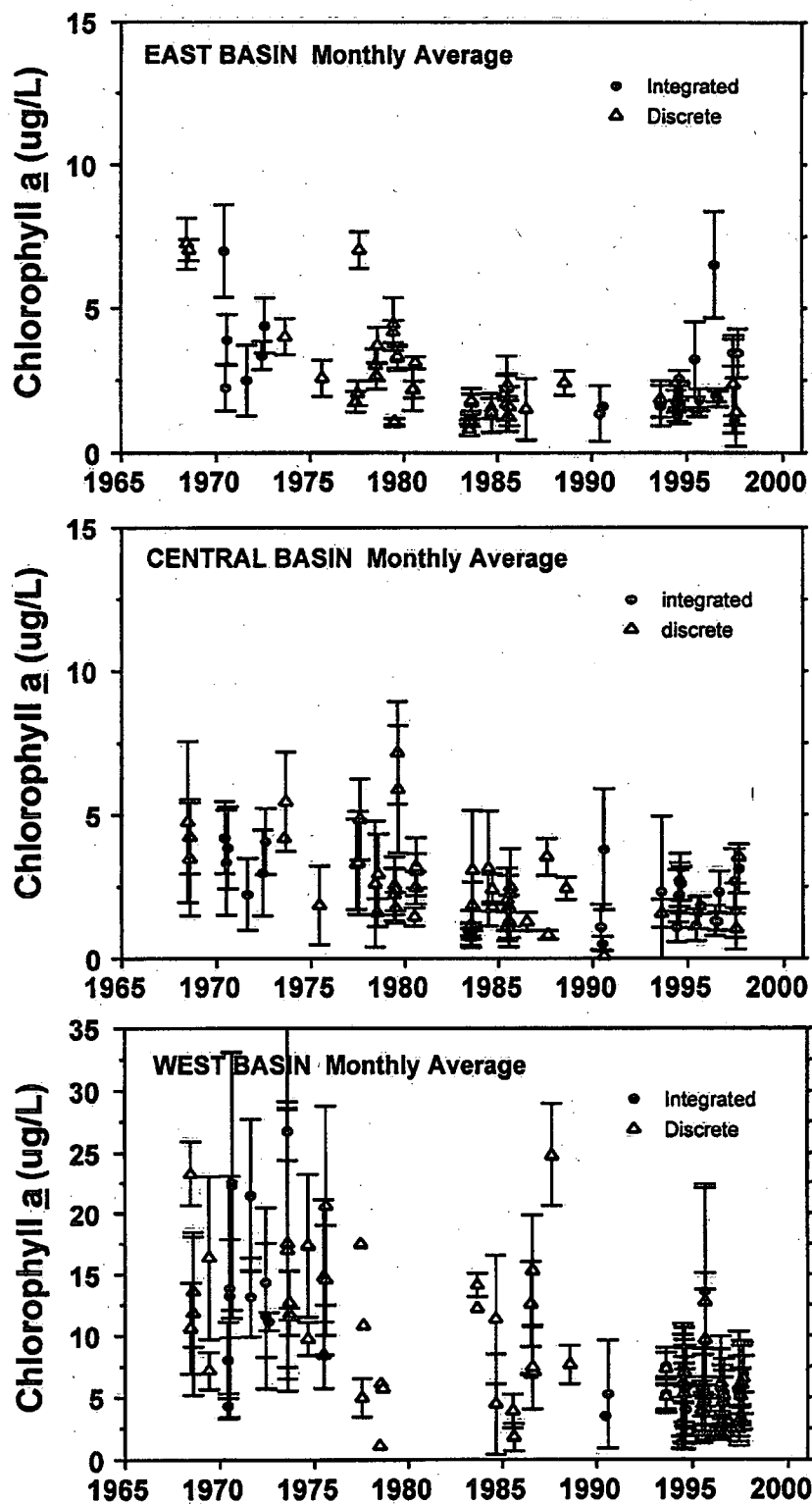
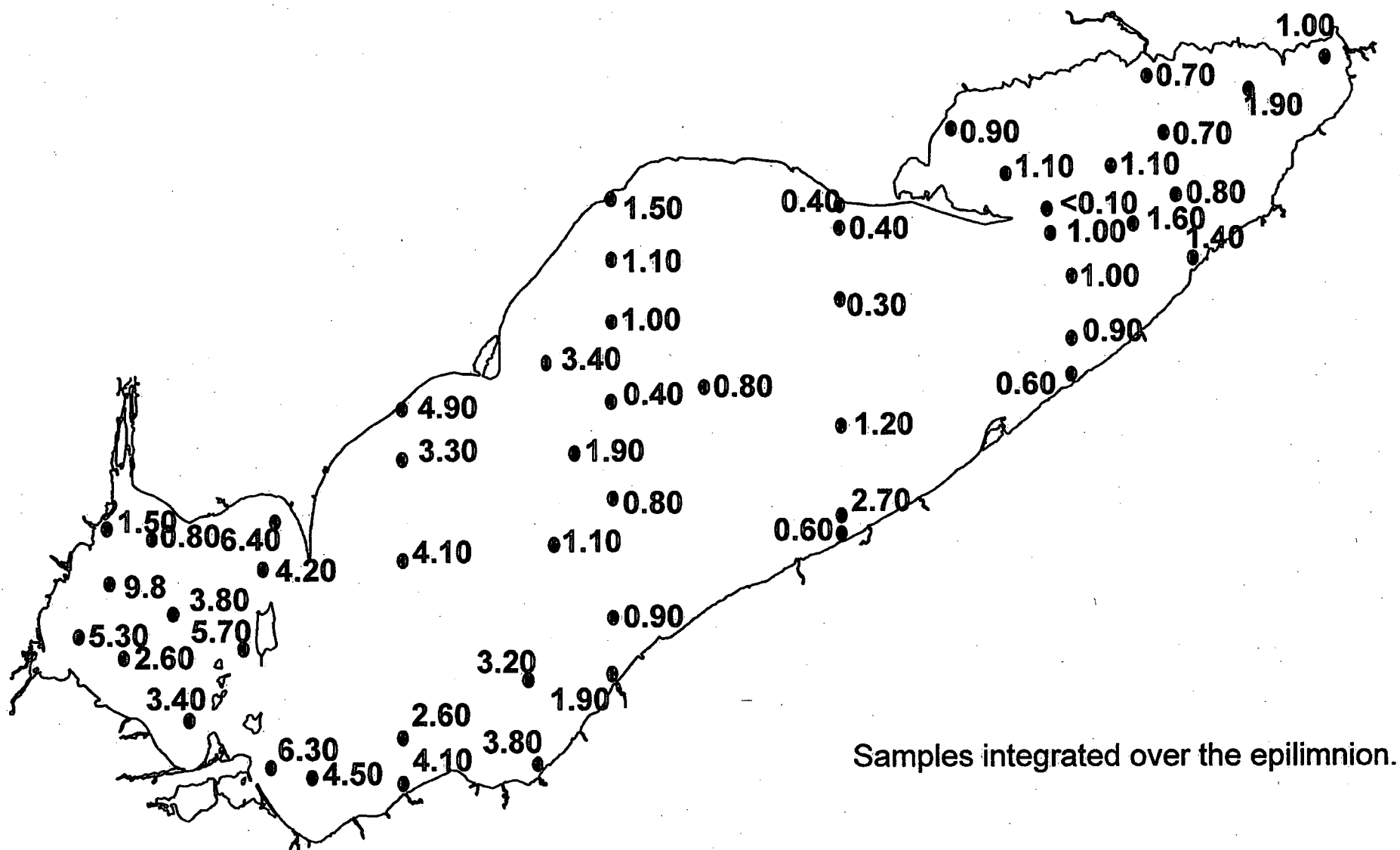


Figure 10, Chlorophyll \bar{a} trends (mean \pm standard deviation) in Lake Erie, June July, August (redrawn from Charlton et al. 1999)



Samples integrated over the epilimnion.

Data source: Environmental Conservation Branch/Environment Canada.

figure 11. Chlorophyll *a* concentrations in August 1994 (ug/L).

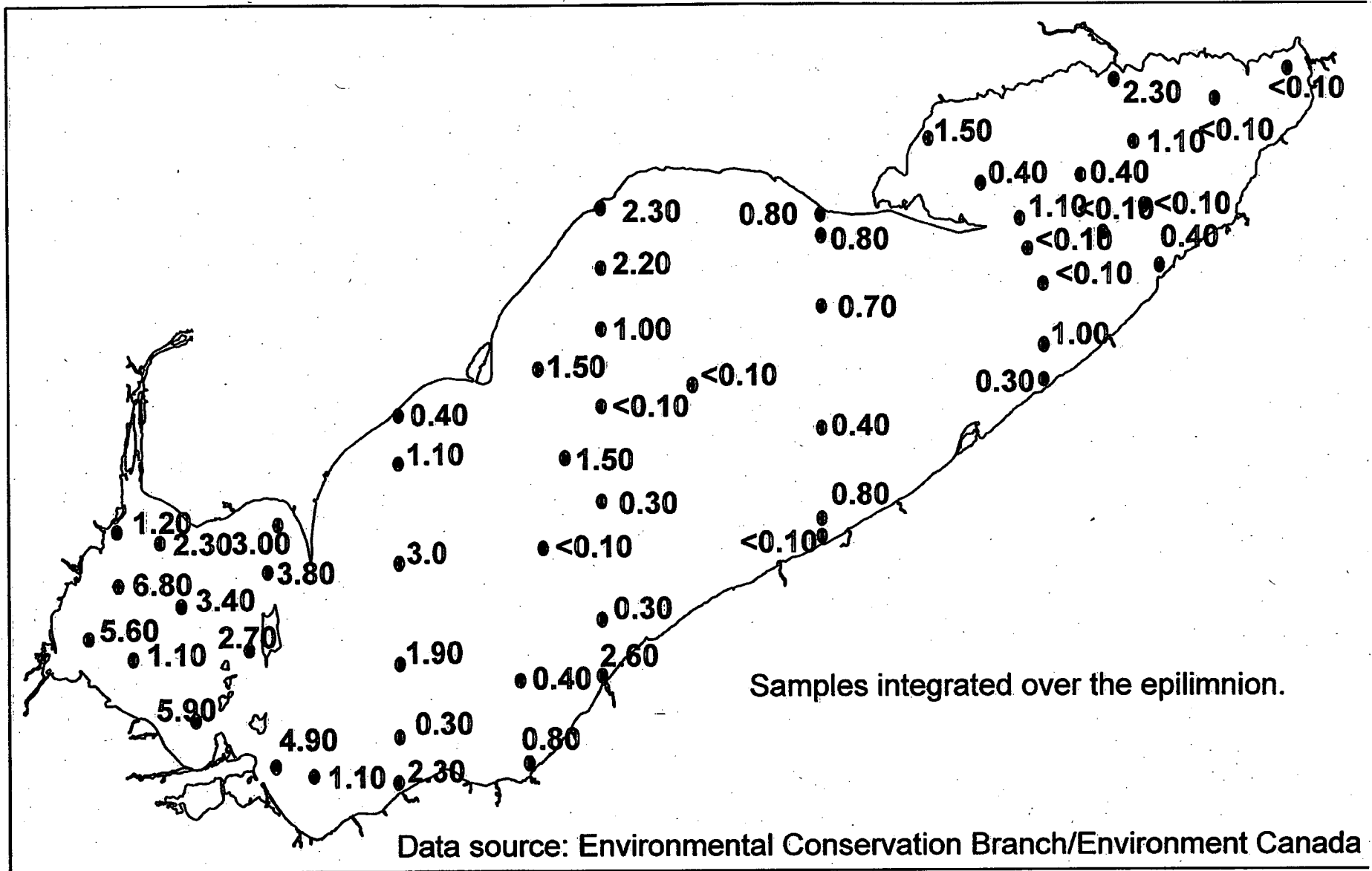


Figure 12

Chlorophyll *a* concentrations in August 1995 (ug/L).

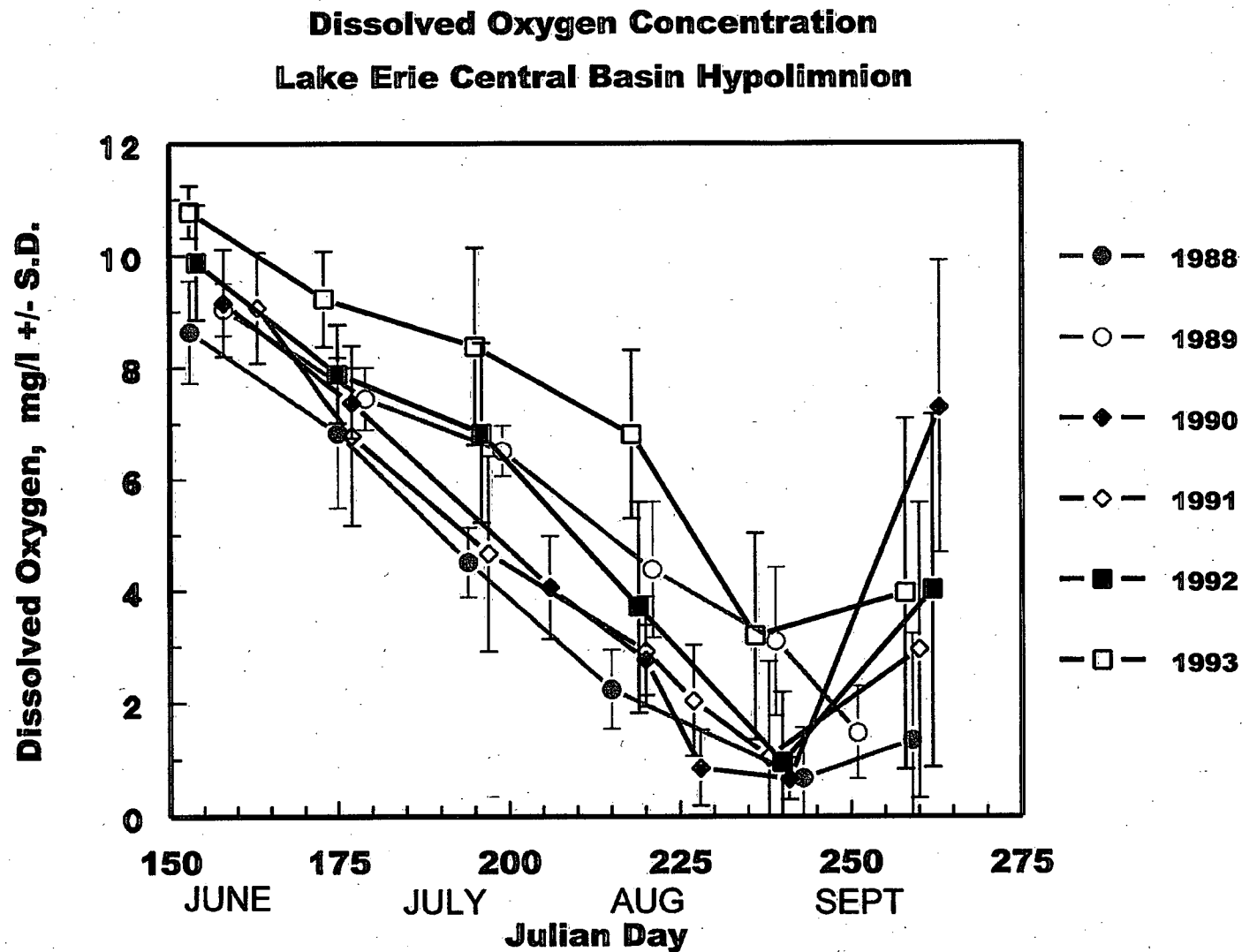


Figure 13. Hypolimnetic dissolved oxygen concentrations (mean \pm 1 standard deviation) in the Central Basin 1988 to 1993 (U.S. EPA).

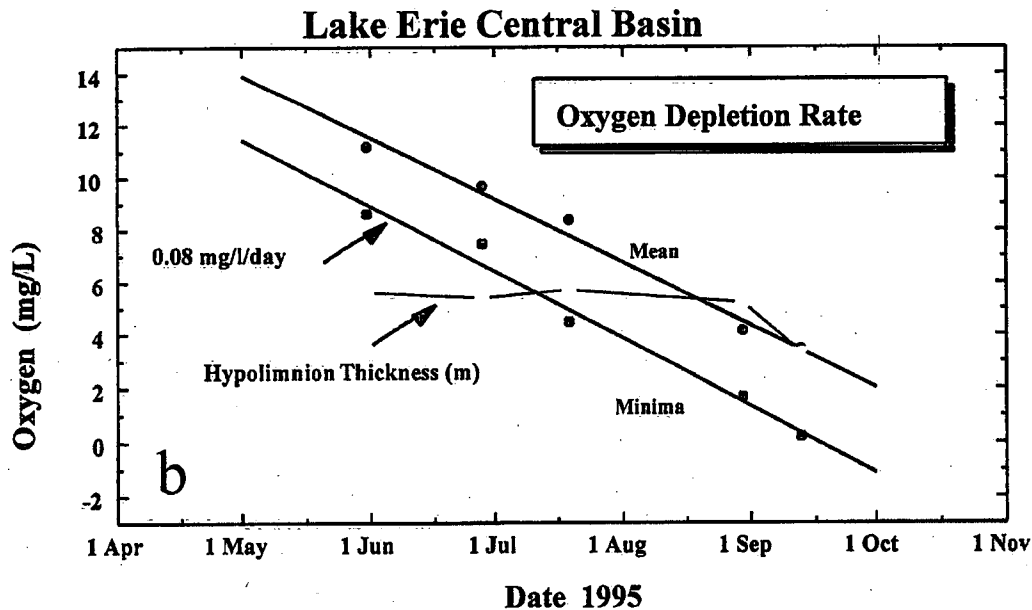
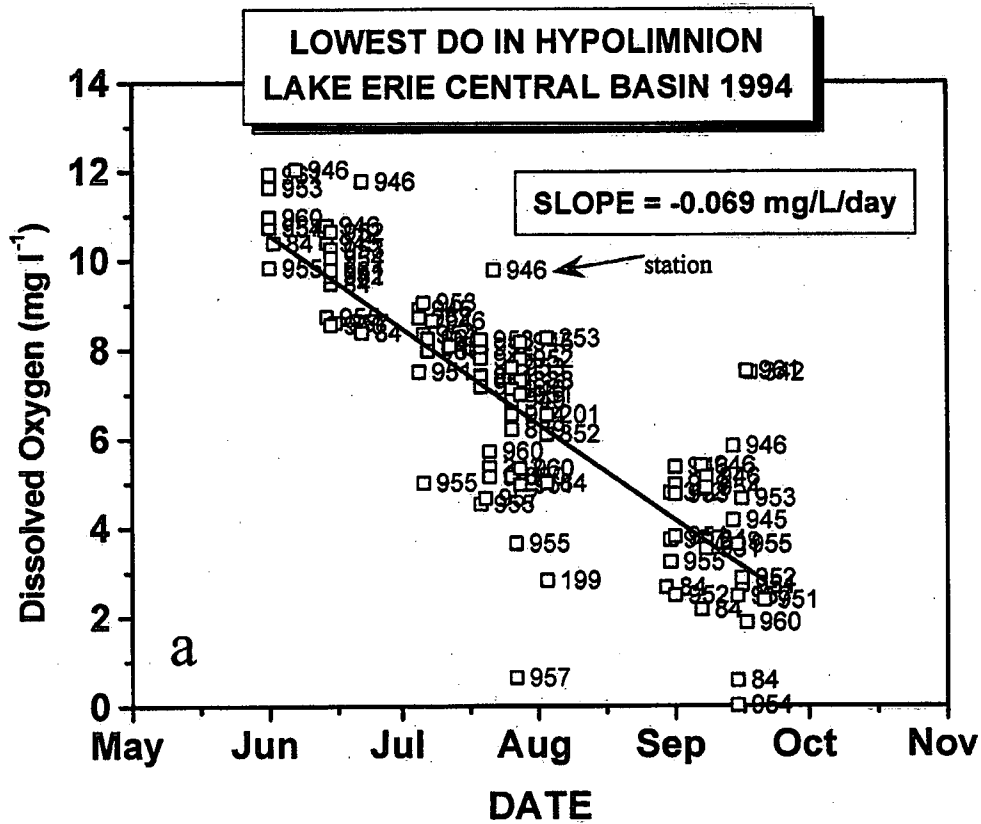


Figure 14a,b. Oxygen variability and depletion rate in Lake Erie central basin in 1994 and 1995

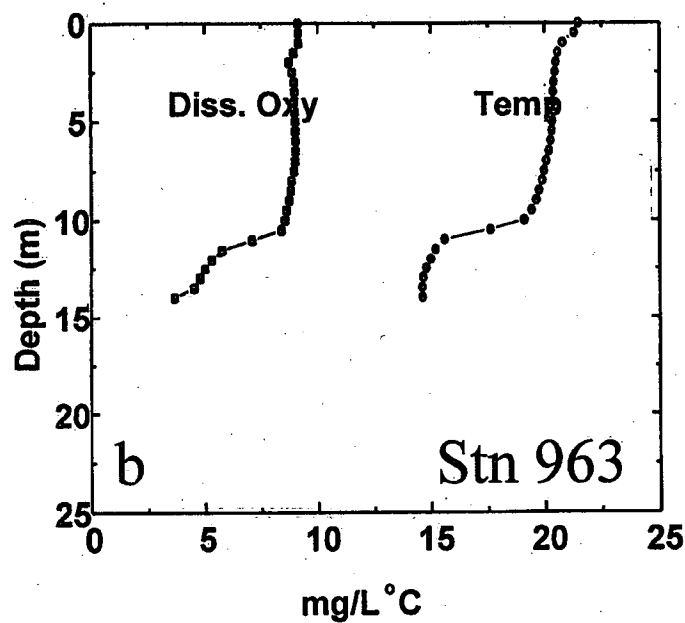
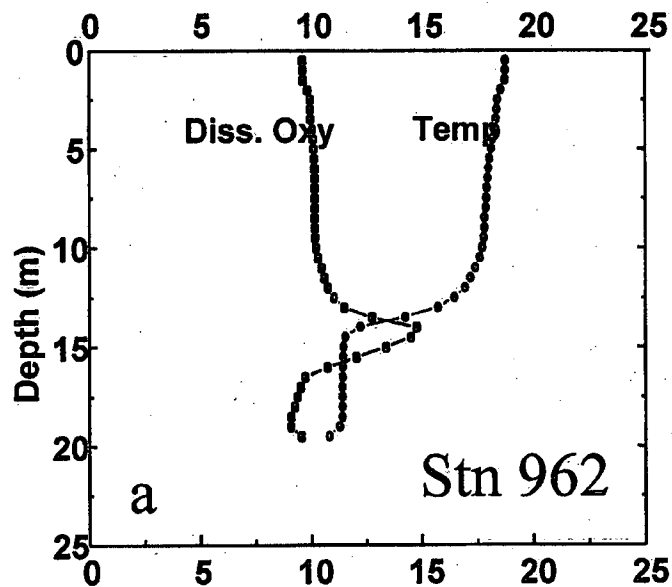


Figure 15a,b. Lake Erie Oxygen and Temperature Profiles June 27, 1996.

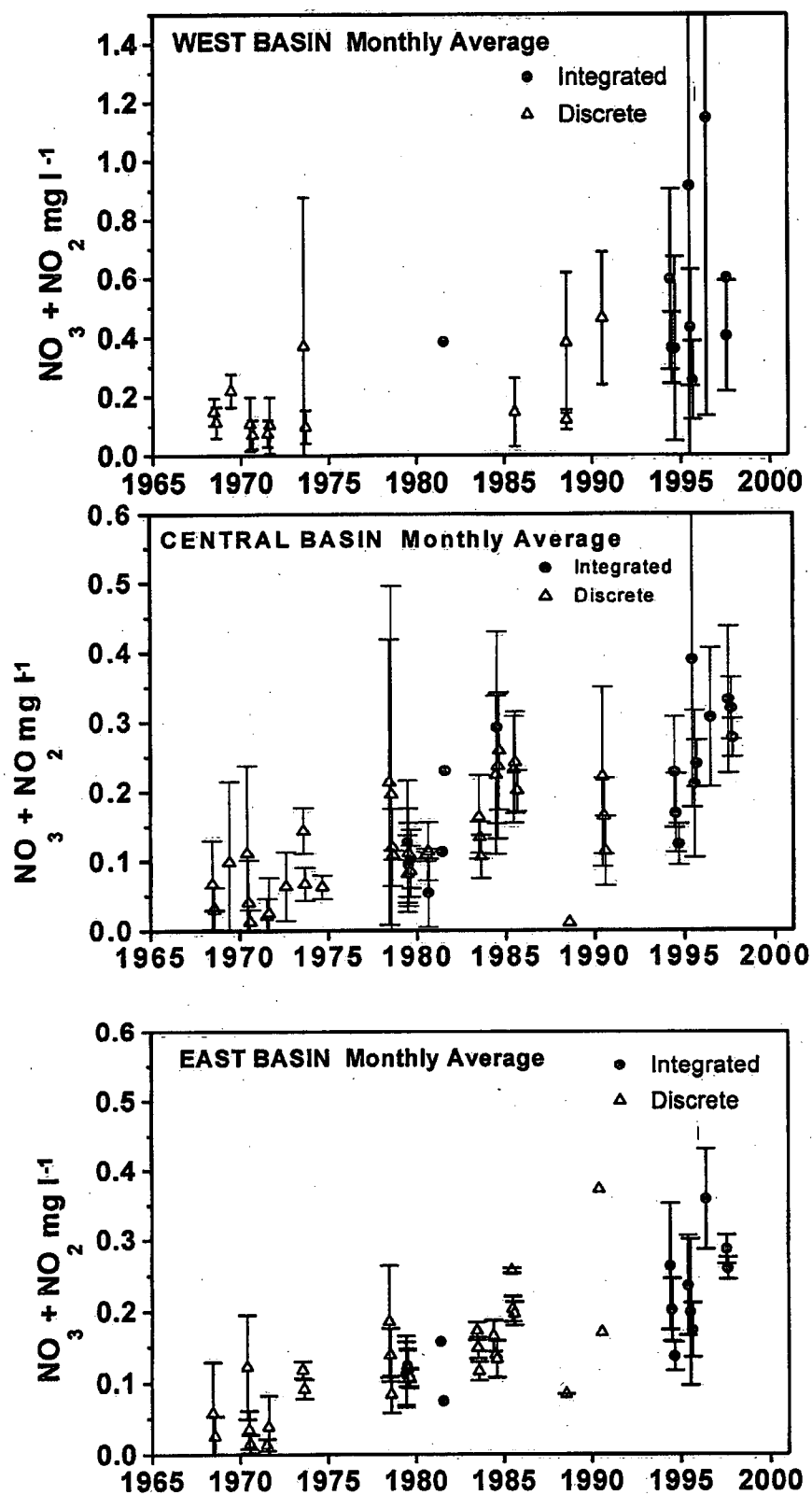


Figure 16. Summer nitrate plus nitrite trends (mean \pm standard deviation) for Lake Erie 1968-1997 (redrawn from Charlton *et al.* 1999)

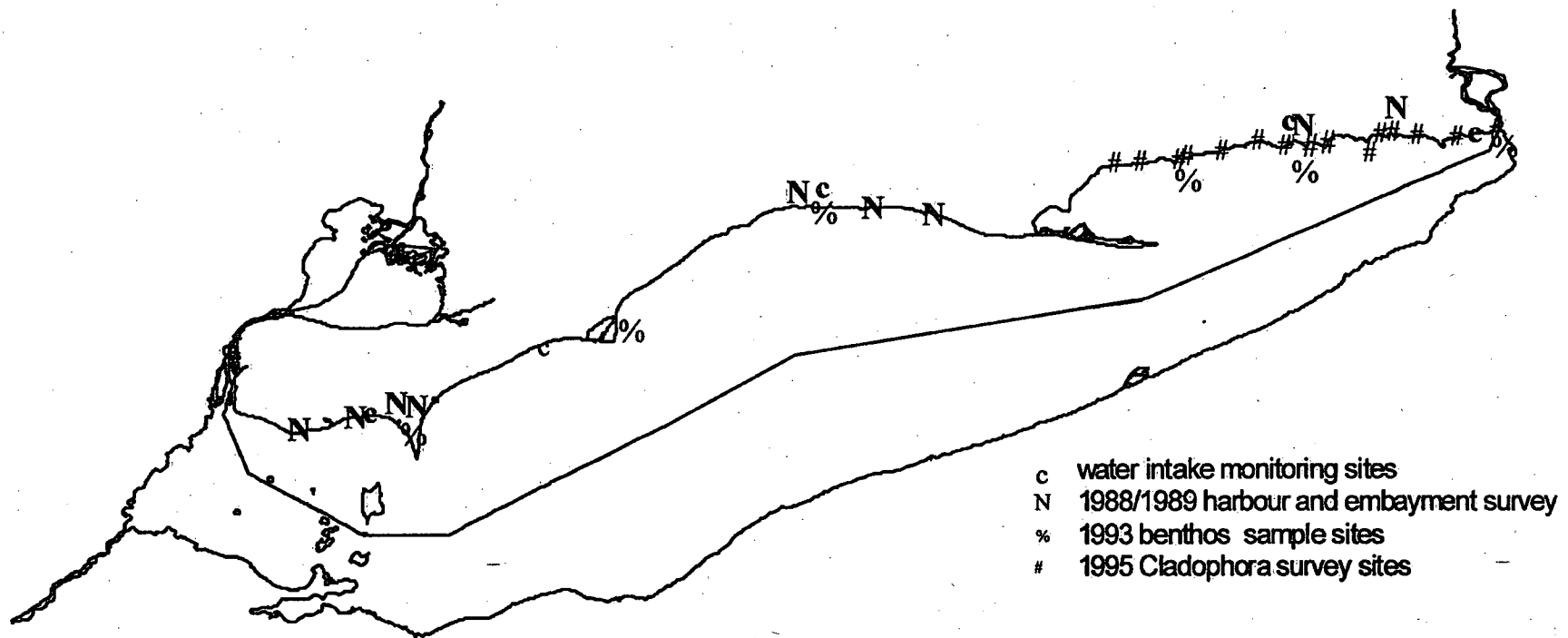
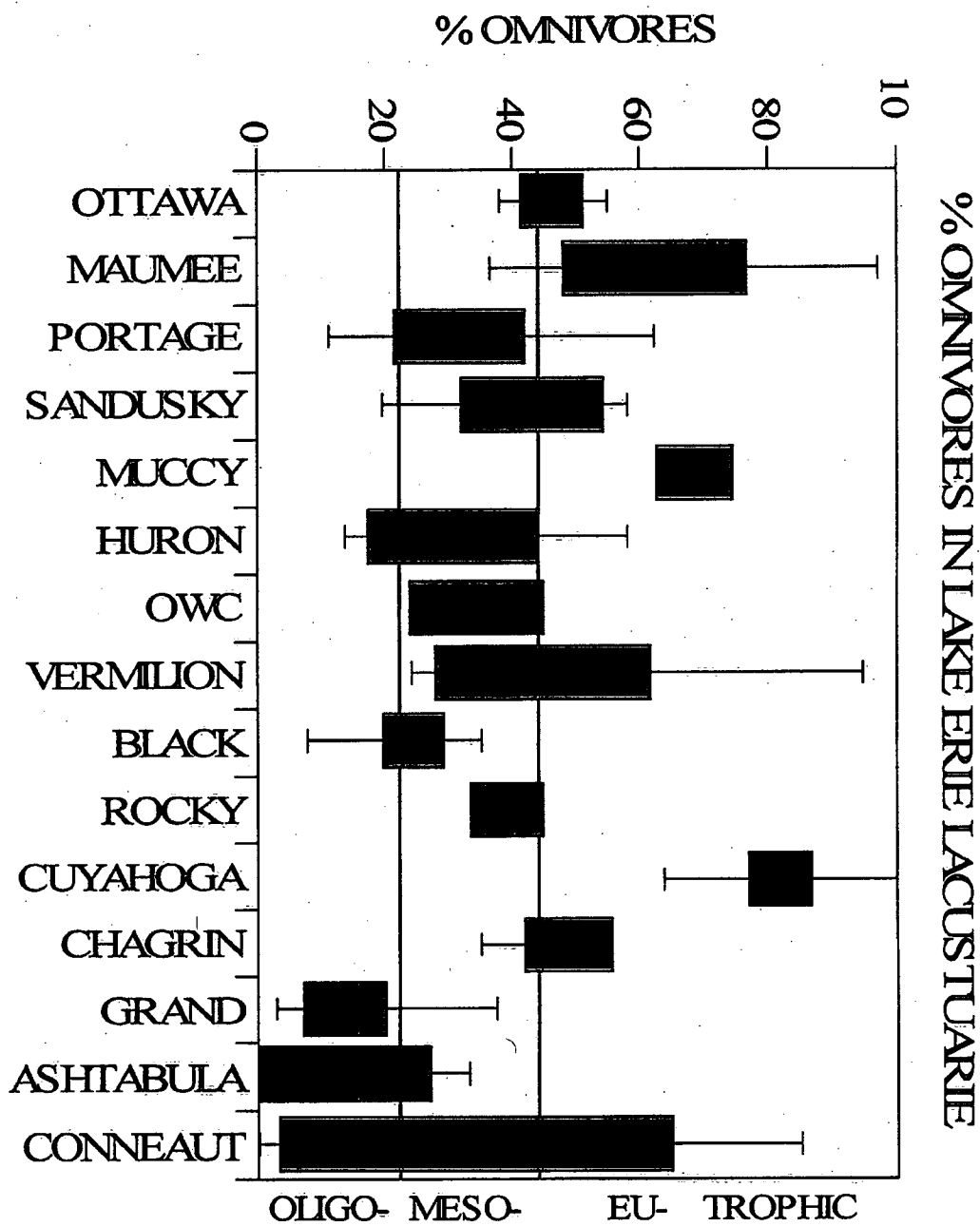


Figure 17. Location of stations for the Ontario Ministry of the Environment monitoring information



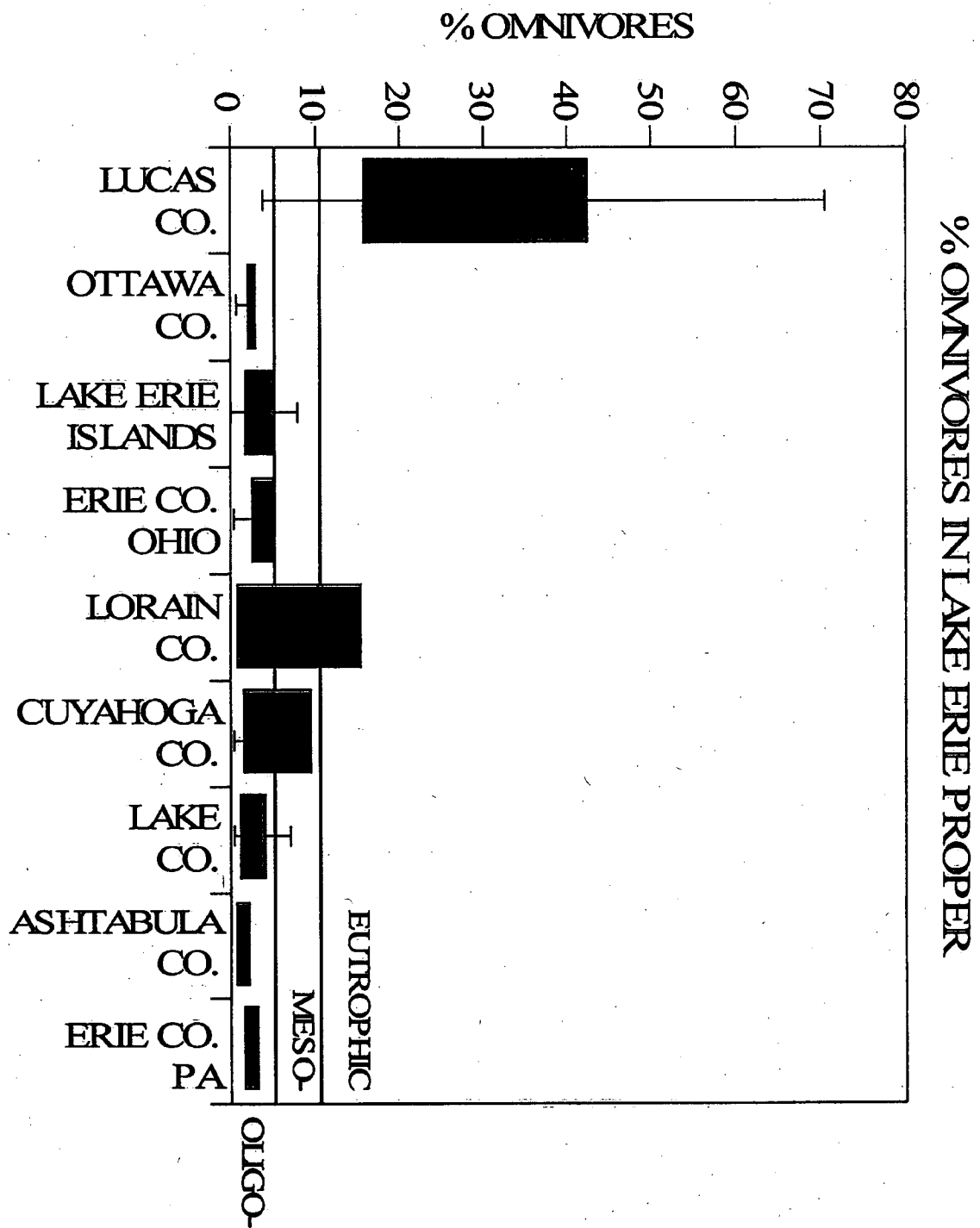


Table 1. Values used to characterize lake trophic state (Edwards and Ryder, 1990).

Parameter	Lake Trophic State		
	Oligotrophic	Mesotrophic	Eutrophic
Secchi Disk (m)	>5 >6 >3.7	5-3 6-3 2-3.7	<3 ^a <3 ^b <2 ^m
Chlorophyll a (:g/L)	<3 <4.3 0.3-2.5 0-4 <7 <2 ^g	3-7 4.3-8.88 1-15 4-10 7-12	>7 ^c >8.8 ^d 5-140 ^k >10 ^l >12 ^m
Total Phosphorus (:g/L)	<10 <15 4.3-11.5 <10	10-20 15-25 11.5-37.5 10-20	>20 ^e >25 ^c >37.5 ^f >20 ^m >20-30 ^j
Soluble Reactive Phosphorus (:g/L)	0.5-1.2	1.2-8	>8 ^f
N:P ratio		>29 green algae and diatoms	<29 ^h blue-green algae
Milbrink index	0-0.6	0.6-1.0	1.0-3.0 ^j

- a Chapra and Dobson 1981
- b Vallentyne et al. 1969
- c Forsberg and Ryding 1980
- d Dobson et al. 1974
- e Chapra and Robertson 1977
- f Auer et al. 1986
- g Rast and Lee 1978
- h Smith 1983
- i OMOEE 1994
- j Milbrink 1983
- k Sakamoto 1966
- l National Academy
- m US EPA

Table 2. Lake Erie trophic Status by Indicator and Basin.

	Criteria used for Table 5	W. Basin Nearshore	W. Basin Open Waters	C. Basin Nearshore	C. Basin Open Waters	E. Basin Nearshore	E. Basin Open Waters
Secchi Disk (1) (m)	US EPA	Eutrophic (1.7)	Mesotrophic (2.3 - 2.7)	NA NA	Oligotrophic (4.7 - 5.5)	Oligotrophic (4.6)	Oligotrophic (6.5 - 6.7)
Total Phosphorus (2 and 3) (ug/L)	Chapra and Robertson	Eutrophic (>20)	Meso-Eutrophic (>15 - 20)	Mesotrophic (10 - 20)	Oligotrophic (<10)	Oligotrophic (<10)	Oligotrophic (<10)
SRP (4 and 5) (ug/L)	Auer et al.	Eutrophic (10 - 40)	Meso-Eutrophic (1 - 30)	Meso-Eutrophic (1 - 12)	Oligo-Mesotrophic (0 - 5.5)	Oligo-Mesotrophic (0.5 - 7.2)	Oligo-Mesotrophic (0.5 - 7.5)
Chlorophyll a (6 and 7) (ug/L)	Rast and Lee	Mesotrophic	Meso-Eutrophic (1.1 - 11.2)	Meso-Eutrophic	Oligo-Mesotrophic (0.4 - 4.9)	Oligotrophic	Oligotrophic (0 - 1.4)
N:P ratio (14)	Smith	<29(Sept.-Oct.) >29(May-Aug.)	<29(Sept.-Oct.) >29(May-Aug.)	<29(Sept.-Oct.) >29(May-Aug.)	<29(Sept.-Oct.) >29(May-Aug.)	>29(May-Aug.)	<29(Oct.) >29(May-Aug.)
Dissolved Oxygen (8 and 15)							
Milbrink Index (9)	OME	Meso-Eutrophic	NA	Oligo-Mesotrophic	NA	Oligo-Mesotrophic	NA
Abundance Omnivorous Fish(10)	Ohio EPA	Meso-Eutrophic (a)	NA	NA	NA	NA	NA
Abundance of Cladophora (11)		NA (a)	NA	NA	NA	Inconclusive	NA
Hexagenia limbata (12)		Mesotrophic	Mesotrophic	NA	NA	NA	NA
Abundance of Diatoms (13)		Mesotrophic	Mesotrophic	Oligotrophic	Oligotrophic	Oligotrophic	Oligotrophic

Study time period

1: Seasonal weighted mean	Dahl et al (1995)	1993
2: Spring mean concentrations	GLNPO, US EPA	1971-1992
3: Seasonal concentrations	EC/ECB/EHD	1994-1995
4: Spring mean concentrations	GLNPO, US EPA	1971-1992
5: Seasonal concentrations	EC/ECB/EHD	1994-1995
6: Summer concentrations	GLNPO, US EPA	1971-1992
7: Summer concentrations	EC/ECB/EHD	1994-1995
8: Monthly concentrations	GLNPO, US EPA	1987-1991
9: Oligochaetes	OME	1993
10: Abundance of omnivorous fish	Ohio EPA (b)	
11: Abundance of Cladophora	OME	1995
12: Presence of Hexagenia limbata	Krieger et al. (1996)	1993-1995
13: Abundance of Diatoms	Dahl et al. (1995)	1993
14: N:P ratio (1993) data	Dahl et al. (1995)	1993
15: Oxygen concentrations (1994-96)	Charlton (pers. Comm.)	1994-1996

(a) NA: No recent data available.

(b) With the exception of Maumee Bay, the abundance of omnivorous fish indicator is currently only applicable to the lake effect zones of Ohio tributaries and the Ohio Lake Erie shoreline.

Table 3: Summary of nutrient concentrations in 'raw' water collected at water plants on the north shore of Lake Erie from 1988-1994 in the Great Lakes Intake Monitoring Program. OME unpublished data.

Water Plant (Lake Basin given in brackets)	Intake Length (m)	Depth (m)	Total Phosphorus (ug/L) First value is median, second value is 90 % quantile			Filtered Reactive P (ug/L) First value is median, second value is 90 % quantile			Total Inorganic Nitrogen (ug/L) First value is median, second value is 90 % quantile			Chlorophyll a (total) (ug/L) First value is median, second value is 90 % quantile		
			1988- 1994	April - October 1988-1994	1993 - 1994	1988 - 1994	April - October 1988- 1994	1993 - 1994	1988 - 1994	April - October 1988-1994	1993 - 1994	1988 - 1994	April - October 1988 - 1994	1993 - 1994
Rosehill(E)	549	6.4	12(29)	10(23)	10(19)	2(9)	1.5(5.5)	2.5(9.5)	253(379)	223(346)	309(383)	0.9(3.8)	0.9(3.4)	0.5(1.6)
Dunville (E)	488	7.3	14(37)	12.5(26)	14(29)	4(13)	2.5(7.5)	6(14.5)	255(684)	226(540)	328(929)	0.6(4.5)	0.6(3.8)	0.3(0.7)
Elgin 8	1249	8.5	20(133)	15(43)	16(56)	4(20)	2.0(11)	5.5(18)	260(440)	257(380)	290(466)	0.9(5.6)	0.8(4.7)	0.6(1.7)
Blenheim 8	805	9.1	14(38)	13(36)	12(24)	4(16)	3(18)	3.5(14)	251(468)	233(385)	260(362)	0.6(5.1)	0.5(4.2)	0.4(1.0)
Union (W)	1) 457 2) 1079	2.5 -3.0	18(61)	18(58)	14(38)	4(17)	3(13)	3.0(13.5)	490(877)	417(709)	451(700)	0.9(4.5)	0.9(4.7)	0.8(2.5)

Table 4: Nutrient, chlorophyll a and suspended solids concentration and secchi depth at embayments and river mouths along the north shore of Lake Erie in 1988 and 1989. OME unpublished data.

	Date	Sites	Total P (:g/L) mean (range)	Chl a (:g/L) mean (range)	TIN (:g/L) mean (range)	Secchi depth (m) mean (range)	Suspended Solids (mg/L) mean (range)
Port Colborne							
Gravelly Bay - harbour	1988/05/05	6	12(11-14)	3.2(3.0-3.7)	160(133-190)	2.8(1.5-3.5)	2.3(1.7-2.9)
Gravelly Bay - harbour	1988/10/13	6	14(9-20)	3.4(3.1-4.0)	108(104-116)	1.4(1.0-1.8)	6.0(3.8-10.3)
Outside Harbour	1988/05/05	1	10	2.7	194	4	1.5
Outside Harbour	1988/10/13	1	13	3.7	109	1.8	4.3
Grand River/ Port Maitland							
lower reach of Grand River	1989/06/23	5	109(104-105)	35(29-39)	1804(1780-1847)	0.3(0.3-0.4)	23.1(22.3-26.1)
mouth of Grand River in Lake Erie	1989/06/23	2	57(44-70)	20.5(14.0-27.1)	969(757-1180)	1.1(0.4-1.9)	10.1(10.0-10.1)
Port Burwell							
Lower reach of Big Otter Creek	1989/06/22	4	179(162-205)	14.7(13.4-16.5)	2275(2248-2293)	0.2(0.2-0.2)	125(92-166)
off Port Burwell breakwall in Lake Erie	1989/06/22	2	168(31-304)	2.3(1.0-3.5)	685(319-1050)	1.6(0.5-2.8)	9.1(7.8-10.4)
Port Bruce							
lower reach of Catfish Creek	1989/06/21	4	22(22-23)	6.7(4.5-9.0)	5353(3808-7246)	0.2(0.2-0.2)	97(81-129)
off breakwall in Lake Erie	1989/06/21	2	32(15-50)	24.8(5.5-4.4)	198(164-230)	0.5(0.2-0.8)	16.3(2.1-30.6)
Port Stanley							
lower reach of Kettle Creek	1988/09/01	5	71(27-95)	11.0(7.3-19.0)	822(223-1197)	0.5(0.5-0.6)	39.6(16.4-72.4)
lower reach of Kettle Creek	1989/06/20	5	264(63-360)	25.4(9.1-46.6)	3869(771-5305)	0.2(0.1-0.5)	91.4(12.5-143)
off breakwall in Lake Erie	1988/09/01	1	3	4.6	102	1.0	4.9
off breakwall in Lake Erie	1989/06/20	2	25(17-33)	1.0(0.7-1.3)	257(230-285)	1.3(0.6-2.0)	3.7(2.5-4.9)
Sturgeon Creek							
lower reach of Sturgeon Creek	1988/08/29	4	83(46-131)	18.8(13.5-28.0)	211(141-308)	0.4(0.3-0.5)	34.9(20.4-53.8)
off breakwall in Lake Erie	1988/08/29	1	31	21.0	635	0.9	10.7
Leamington							
Leamington Harbour	1998/08/31	4	21(19-21)	7.0(3.1-9.4)	147(132-154)	1.0(0.9-1.0)	9.2(7.4-14.1)
off breakwall in Lake Erie	1988/08/31	3	19(18-21)	11.0(8.6-15.5)	124(96-141)	1.2(1.1-1.3)	7.0(5.7-9.4)
Kingsville							
Kingsville Harbour	1988/08/30	3	38(26-50)	5.1(4.4-5.5)	214(178-260)	0.6(0.5-0.7)	14.9(9.3-18.2)
off breakwall in Lake Erie	1988/08/30	2	28(21-35)	8.8(6.2-11.4)	164(113-216)	0.9(0.6-1.2)	9.7(6.9-12.5)
Colchester							
Colchester Harbour	1988/08/30	4	17(12-21)	2.4(2.0-3.4)	171(161-180)	0.8(0.5-1.3)	9.9(5.0-17.4)
off breakwall in Lake Erie	1988/08/30	1	10	2.7	181	1.9	3.8

Table 5: Median thickness and percentage cover of *Cladophora* over the 0.5 to 1.5 m depth on rocky substratum in eastern Lake Erie, July 1995. The number of 0.25 m² quadrant surveyed is given by n. The values in brackets give the range of values. OME unpublished data.

Survey Area	Median Thickness (cm)	Percent Cover (%)
Bertie Bay (n=18)	5.4 (4-8)	89 (50-100)
Windmill Point (n=10)	7.7 (6-11)	98 (90-100)
Whiteman's Point (n=10)	4.4 (2-7)	92 (60-100)
Sugar Loaf Point (n=10)	6.5 (6-7)	98 (80-100)
Rafhton Point (n=10)	9.7 (7-11)	91 (70-100)
Morgan's Point (n=10)	8.0 (6-10)	96 (60-100)
Mohawk Point (n=9)	10.9 (6-15)	94 (80-100)
Rock Point (n=10)	5.4 (4-7)	60 (20-90)
Spatt's Bay (Grand R.) (n=6)	20 (10-28)	100
Grant Point (n=10)	13.4 (8-17)	94 (40-100)
West of Low Point (n=10)	7.4 (4-12)	91 (40-100)
Featherstone Point (n=10)	18.0 (16-20)	100
Sandusk Creek Mouth (n=10)	10.8 (7-17)	98 (90-100)
Peacock Point (n=3)	10.3 (8-13)	100
Nanticoke (n=10)	7.6 (5-10)	76 (50-100)
Port Dover (n=10)	5.8 (4-7)	94 (60-100)

Note: Median thickness is the median height of the top of the *Cladophora* lawn.

Table 6: Milbrink Index values for six nearshore index stations in Lake Erie (north shore) surveyed in the spring, summer and fall of 1993. The Milbrink index is an indicator of trophic status based on the composition and abundance of oligochaete worms living in bottom sediments. MOEE unpublished data.

Area	Coordinates ²	Depth (m)	Milbrink Index ¹ mean (range)
Leamington -Point Pelee (W)	41°58'01"N 82°33'36"W	11	1.4 (1.0-1.8)
Pointe Aux Pins X	42°16'55"N 81°49'42"W	11	1.5 (1.2-1.7)
Port Stanley X	42°38'16"N 81°11'08"W	12	0.3 (0.2-0.4)
Peacock Point (E)	42°46'30"N 79°58'57"W	12	0.5 (0.4-0.6)
Grand River (E)	42°50'26"N 79°35'25"W	11	2.0 (1.7-2.4)
Fort Erie (E)	42°52'13"N 78°55'49"W	9-10	1.1 (0.6-1.6)

Note:

1) Milbrink Index trophic boundaries:

- * 0 to 0.6 - Oligotrophic
- * 0.6 to 1.0 - Mesotrophic
- * 1.0 to 3.0 - Eutrophic

2) average over surveys.

Table 7. Fish species considered omnivorous by the Ohio EPA (Ohio EPA, 1989).

Gizzard Shad	(<i>Dorosoma cepedianum</i>)
Threadfin Shad	(<i>Dorosoma petenense</i>)
Quillback Carpsucker	(<i>Carpionodes cyprinus</i>)
River Carpsucker	(<i>Carpionodes carpio</i>)
Highfin Carpsucker	(<i>Carpionodes velifer</i>)
White Sucker	(<i>Catostomus commersoni</i>)
Common Carp	(<i>Cyprinus carpio</i>)
Goldfish	(<i>Carassius auratus</i>)
Carp X Goldfish hybrids	
Bullhead Minnow	(<i>Pimephales vigilax</i>)
Fathead Minnow	(<i>Pimephales promelas</i>)
Bluntnose Minnow	(<i>Pimephales notatus</i>)

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