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Background Paper

Nutrients:
Trends and System Response

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NUTRIENTS: TRENDS AND SYSTEM RESPONSE

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NOTICE TO READER

These Background Papers are intended to provide a concise overview of the status of conditions in the Great Lakes. The information they present has been selected as representative of the much greater volume of data. They therefore do not present all research or monitoring information available. The Papers were prepared with input from many individuals representing diverse sectors of society.

The Background Papers were first released as Working Papers to provide the basis for discussions at the first State of the Lakes Ecosystem Conference (SOLEC) in October, 1994. Information provided by SOLEC discussants was incorporated into the these final SOLEC background papers. SOLEC was intended to provide key information required by managers to make better environmental decisions.

EXECUTIVE SUMMARY

Reductions in annual phosphorus loadings have been achieved in all five Great Lakes, with current loads clearly below the target loads of the 1978 Canada-U.S. Great Lakes Water Quality Agreement for lakes Superior, Huron and Michigan, and at or near the target limits for lakes Erie and Ontario. Phosphorus concentrations are likewise below the expected open-lake concentrations that reflect achievement of loadings limits for the Upper Lakes. In Lake Ontario, expected phosphorus concentrations have been achieved for several recent years. In central and eastern Lake Erie, phosphorus concentrations have been achieved, but some annual fluctuations around the objective still exist. In western Lake Erie, annual phosphorus concentrations are highly variable, although spring averages below the objective have been reported in at least two recent years.

Soluble reactive phosphorus (SRP) represents that fraction of the total phosphorus which is directly available to the primary producers (plants and algae). Generally, for all of the Great Lakes, spring SRP trends followed those of total phosphorus concentrations. The decline in SRP concentrations has resulted in noticeable changes, both nearshore and offshore. The nearshore effects were observable in the reduction in *Cladophora* growth. In the offshore, concentrations of chlorophyll a (an indirect measure of productivity) indicate that the Upper Lakes have remained oligotrophic, while the Lower Lakes (particularly Lake Ontario) are tending towards oligotrophic conditions.

Nitrate-plus-nitrite is also an important nutrient in water systems. Major sources of nitrogen to the lakes are agricultural runoff, municipal sewage treatment plants and atmospheric deposition. Increasing levels of nitrate-plus-nitrite have been reported in the Great Lakes for the past two decades, particularly in Lake Ontario. 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). 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.

Phosphorus controls appear to have been successful in lowering the loadings into the lakes, and consequently reducing, to varying extents, the resultant open lake concentrations of total and soluble reactive phosphorus. However, the goal of establishing year-round aerobic conditions in the hypolimnion of Lake Erie's Central Basin has not been realized. It has been determined that lake phosphorus loads would have to be reduced to about 5000 metric t/y to achieve the desired effect on oxygen. 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. Perhaps intermittent anoxia is an inherent property of the basin, and management to achieve a state where anoxia does not occur is not a realistic goal for lake managers.

What impact have nutrient controls had on the food web? Zooplankton are the pivotal trophic level in lake ecosystems, responding to both salmonid stocking (top-down) and phosphorus abatement (bottom-up) management strategies. In Lake Ontario, zooplankton composition has not changed systematically or substantially throughout the 1980's, although zooplankton abundance declined as of 1983-84, particularly in the eastern basin. This has been attributed to a combination of stable fish predation and reduced food supply.

Zooplankton comprise almost the entire diet of alewife, and are a significant component of the diet of smelt. The reduction in abundance of zooplankton, therefore, could only result in lower production of alewife and smelt. Alewife and smelt biomass indices have declined since the early 1980's. At the same time, the numbers of hatchery-reared salmon and trout stocked in Lake Ontario steadily increased from just over 1 million in 1972 to approximately 8.2 million in 1984. As the stocked fish continued to grow and accumulate, the total weight of salmon and trout reached a peak in 1986 and, since then, has remained high. Alewife and smelt populations in Lake Ontario are under stress from both ends of the food chain. How much stocking is too much?

In an attempt to restore the balance between stocked predators and prey in Lake Ontario, the two agencies responsible for fisheries management agreed to revise their Lake Ontario fish stocking plans, using a two-year phased-in approach, beginning in 1993. For 1993, the two agencies set a target for predator demand which is 35% lower than 1991 levels. In 1994, additional stocking reductions are expected to bring about a total reduction of 47% in predator demand from the 1991 level.

Fisheries and water quality management strategies have evolved independently in the Great Lakes. In general, these strategies operate from different ends of the management spectrum -- bottom-up (phosphorus control) and top-down (massive fish stocking). A more ecologically oriented approach, which recognizes the interactions between fisheries and water quality, will be required to manage the Great Lakes.

1.0 Introduction

In the 1960's, severe degradation of the Lower Lakes and several embayment areas of the Upper Lakes aroused public concern. Enormous algal blooms were frequently observed and normal aquatic life disappeared from waters adjacent to densely industrialized and populated areas. In the Central Basin of Lake Erie, Saginaw Bay and Green Bay, bacterial decomposition of large quantities of algae that had settled to the sediment surface lead to anoxia (lack of oxygen) in the bottom waters (hypolimnion). Decomposing filamentous algae (*Cladophora*) also piled up on some beaches. Taste and odor problems appeared in drinking water due to blue-green algae.

In the late 1960's, a review of the state of the Lower Lakes by the International Joint Commission (IJC 1969), based on the results of special studies by Canada and the U.S., identified eutrophication as a problem due to excessive inputs of nutrients. Phosphorus was subsequently identified as the key nutrient controlling eutrophication. If cultural eutrophication of the Great Lakes was to be reversed, phosphorus would need to be controlled. The major sources of phosphorus were municipal and industrial wastes, and urban and agricultural runoff. In 1972 the United States and Canada signed the Great Lakes Water Quality Agreement (GLWQA). The GLWQA focused on reducing phosphorus inputs to the lakes in order to:

a) substantially eliminate nuisance algal growth in the Lower Lakes and the International Section of the St. Lawrence River;
b) restore year-round aerobic conditions in the hypolimnion of Lake Erie's Central Basin; and
c) maintain Lake Superior's and Lake Huron's oligotrophic state.

Municipal wastes containing phosphate detergents contributed 70% of total inputs of phosphorus. Programs that were implemented to reduce phosphorus loads to the Great Lakes included improving major municipal wastewater treatment facilities (those discharging more than 3800 m^3/d or 1 million gallons/d) so their effluents contained no more than 1 mg P/liter, limiting P content in household detergents used in the Great Lakes Basin, requiring industries to remove P from their discharges to the maximum extent practicable, and controlling P loadings from agricultural operations.

Restrictions on the P content of household detergents was considered one of the most effective early actions that could be taken to reduce phosphorus loadings. The Canadian federal government chose to implement such restrictions in 1972, and several of the U.S. states did so soon thereafter. The U.S. federal government also encouraged engineering solutions to phosphorus removal from sewage. U.S. federal grants to states and local municipalities for construction or upgrading of sewage treatment plants was a highly visible, costly part of a nationwide program to improve the level of sewage treatment. However, in many cases around the Great Lakes, the targeted load reductions forced the consideration of phosphorus removal in the engineering designs that otherwise might not have been included.

Updated phosphorus loading targets for each lake were incorporated into the renegotiated GLWQA in 1978. These target loads were based on achieving average annual in-lake phosphorus concentrations [guidelines] (Vallentyne and Thomas 1978), as shown in Table 1. These loading values were subsequently confirmed (Phosphorus Management Strategies Task Force 1980), and were incorporated into the revised GLWQA in 1978. Later, the Aquatic Ecosystem Objectives Committee of the IJC recommended that the phosphorus concentration guidelines be based on spring open-lake concentrations, since these largely influence summer phytoplankton biomass (Great Lakes Science Advisory Board 1980).

Table 1. Phosphorus target loads (metric t/yr) and spring total phosphorus guidelines (μg/L).

Basin	Phosphorus Target Load	Guideline
Lake Superior	3400	5
Lake Michigan	5600	7
Lake Huron	4300	5
Lake Erie	11000	
Western Basin		15
Central Basin		10
Eastern Basin		10
Lake Ontario	7000	10

In recognition that phosphorus loading targets had not yet been attained in lakes Erie and Ontario, a Phosphorus Load Reduction Supplement was added to the Agreement in 1983 which identified loading reductions of 2,000 and 430 metric tonnes/yr for lakes Erie and Ontario, respectively, still to be achieved. The allocation of reductions to meet target loads for Lake Erie were further defined as 300 metric t/yr from Canadian sources, and 1700 metric t/yr from U.S. sources. The U.S further apportioned load reduction goals by state. At this point, the loadings were expected to be achieved mainly through non-point source (agricultural) programs.

This paper discusses the progress in controlling phosphorus loads to the lakes and the resulting responses of each of the Great Lakes. Emphasis is placed on concentrations and long-term trends of phosphorus, nitrogen and chlorophyll a in the offshore waters and on the hypolimnetic oxygen depletion in Lake Erie. Some nearshore Areas of Concern are impacted by problems related to excessive nutrients (Figure 1), but a detailed discussion of these areas is beyond the scope of this paper.

2.0 Status and Trends of Total phosphorus in the Great Lakes

2.1 Reductions in Historic Loadings

The combination of phosphorus-detergent restrictions and improved sewage treatment facilities was successful in reducing phosphorus loadings. By 1985, 85% of the 40 largest municipal discharges in the Great Lakes basin were in compliance with the 1 mg/L phosphorus limit, including the 9 largest dischargers.

Non-point source programs were intended to assist farmers through combined incentive programs, education and research, and they included conservation farming practices, installation of structural soil erosion control measures and environmentally appropriate animal waste handling practices. Cropping and tillage practice changes were expected to account for most of the phosphorus reductions from agricultural non-point sources. In the U.S., the non-point source programs have involved a number of approaches and jurisdictions, including numerous federal grants for projects. Participation by farmers and other landowners is still voluntary, but many successful projects have fostered continuing interest in improved agricultural practices. These programs in the states bordering Lake Erie have reduced phosphorus loadings by approximately 1100 metric t/yr (of the 1700 metric t/yr targeted reductions). For Lake Ontario, estimated reductions of 404 metric t/yr exceed the 1983 goal of 235 metric t/yr. The Canadian federal and provincial governments conducted the Soil and Water Environmental Enhancement Program (SWEEP) for Lake Erie from 1985 through 1993. Results from the SWEEP program indicate that Canada has met or exceeded its agricultural non-point source phosphorus loading reduction targets for Lake Erie.

Estimates of phosphorus loadings from tributaries, municipal and industrial point sources, atmospheric sources and the connecting channels have been calculated for each lake on an annual basis by the Regional Office of the International Joint Commission, and reported by the Water Quality Board. Results for 1976 to 1991 are presented in Figure 2. Figure 3 presents the trends in open lake total phosphorus concentrations for the period 1971 to 1992 measured during spring cruises conducted by Environment Canada (lakes Superior, Huron/Georgian Bay and Ontario) and the Great Lakes National Program Office of U.S. EPA (lakes Michigan and Erie). Nutrient concentrations are usually greatest in early spring, and concentrations at this time determine the limits of algal growth during the summer.

2.2 Current Status

Reductions in annual phosphorus loadings have been achieved in all five Great Lakes, with current loads clearly below the target loads of the 1978 Agreement for lakes Superior, Huron and Michigan, and at or near the target limits for lakes Erie and Ontario.

Phosphorus concentrations are likewise below the expected open lake concentrations that reflect achievement of loadings limits for the Upper Lakes. In Lake Ontario, expected phosphorus concentrations have been achieved for several recent years. In Central and Eastern Lake Erie, phosphorus concentrations have been achieved, but some annual fluctuations around the objective still exist. In Western Lake Erie, annual phosphorus concentrations are highly variable, although spring averages below the objective have been reported in at least two recent years.

Lake Superior: Since 1985, loadings have been below the target (3400 metric t/y). During the period of record, 1983 to 1992, open lake concentrations were always well below the 5 µg/L guideline. The most recent data for the lake indicate that higher concentrations are found only in the Duluth-Superior Harbor region in the western arm of the lake.

Lake Michigan: Since 1981, loadings have been below target (5600 metric t/y). Tributary loadings, which account for the bulk of the load, have varied over the period of record. Atmospheric loadings, however, appeared to decline an order of magnitude between 1980 and 1981. Beginning in 1981, more accurate estimates of atmospheric loadings became available through U.S. and Canadian atmospheric monitoring networks, and subsequent total load estimates have reflected the better atmospheric data. Since 1976, lakewide total phosphorus concentrations have consistently been below the 7 µg/L guideline, with concentrations of approximately 5 µg/L.

Lake Huron: With the exception of 1982 and 1985, loadings have been below target (4300 metric t/y) since 1981, also reflecting the better atmospheric data available. In 1985, tributary loadings doubled, coincident with record (1900-1993) average Lake Huron basin precipitation (National Oceanic and Atmospheric Administration, NOAA). Open lake total phosphorus levels have remained below the 5 µg/L guideline from 1980 to 1991, except in 1987 when 5.5 µg/L was observed. Localized problems persist in Saginaw Bay (see Figures 4a and 4b) and along the Ontario shore of southern Lake Huron.

Lake Erie: Phosphorus loadings demonstrated a general decreasing trend during the period 1976-1991. Municipal loadings showed a decrease between 1976 and 1981, but have remained fairly constant since then. While Lake Erie receives the largest municipal load of any of the Great Lakes (Dolan 1993), 100% of the largest plants are in compliance with the 1 mg/L effluent limitations. For the decade 1981-1991, loadings were equal to or below the target except for the years 1982, 1984 and 1990. Phosphorus loads to Lake Erie are directly related to the amount of precipitation falling in the basin since the major phosphorus inputs come from the tributaries to the lakes. Thus 1990, the wettest year on record (NOAA) for Lake Erie, caused an approximate doubling of tributary loads, resulting in the highest recorded phosphorus load since 1980.

In the Western Basin, average spring phosphorus concentrations continue to be highly variable, subject to sampling locations, influence of seasonal tributary loadings and sediment resuspension from storms. During the period 1983-1985, average spring phosphorus concentrations were typically 20-25 µg/L, although in 1984 one survey averaged 69.3 µg/L. During 1990 and 1992, spring averages were reduced to 12.2 and 10.9 µg/L, respectively, but the 1991 average (27.5 µg/L) demonstrates the continuing variable nature of the Western Basin.

Since 1970, average spring concentrations in the Central Basin have generally declined, dropping below the guideline of 10 µg/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 µg/L in the early 1970's to below the guideline of 10 µg/L in 1987. Spring concentrations remained below the guideline through 1990, but slightly exceeded it in 1991 and 1992.

Lake Ontario: Phosphorus loadings decreased from about 15,000 metric t/y in 1972 to the target of 7,000 metric t/y in 1981. Since that time, annual loadings have fluctuated near the target, but were below targeted limits only during the years 1983, 1988 and 1989. Prior to 1983, loadings from the Niagara River were comparable to those from all other tributaries combined. Tributary loadings have declined such that Niagara River loadings now dominate.

Lakewide concentrations of total phosphorus have decreased significantly over the past 20 years. Levels exceeded 20 µg/L during 1971-1977, but have declined to be at or below the guideline of 10 µg/L since 1986. During 1991 and 1992, mid-lake spring total phosphorus concentrations were below 10 µg/L. In 1991/92, values above the recommended guideline were only found in very confined regions along the shoreline, a sharp contrast to conditions observed in 1980 (Figures 4a, 4b).

3.0 System Response

3.1 Soluble Reactive Phosphorus and Algal Growth

Soluble reactive phosphorus (SRP) represents that fraction of the total phosphorus which is directly available to the primary producers (plants and algae). Generally, for all of the Great Lakes, spring SRP trends followed those of total phosphorus concentrations. In the Upper Lakes (Superior, Huron and Michigan), concentrations of SRP have fluctuated mildly, never exceeding 2 µg/L (Figure 5). Larger variations were observed in both the Central and Eastern Basins of Lake Erie; however, concentrations have remained below 5 µg/L since 1974. The greatest decline in open lake concentrations occurred in Lake Ontario, where SRP concentrations as high as 15 µg/L in 1974 have now been reduced to 3 µg/L.

The decline in phosphorus concentrations, especially SRP, has resulted in noticeable changes, both nearshore and offshore. Nearshore effects are observable in the reduction in *Cladophora* growth. During periods of excessive nutrient enrichment, large odoriferous masses of decaying *Cladophora* created problems along the shoreline of the Lower Lakes. Between 1972 and 1983, however, the amount of *Cladophora* in Lake Ontario decreased by 58% (Painter and Kamaitis 1987).

Cladophora growth rates have been modelled as a function of light, temperature, and phosphorus by Auer and Canale (1982), and Painter and Jackson (1989). Based on model projections, estimated SRP concentrations in the nearshore areas of Lake Ontario and Lake Erie are sufficient to sustain *Cladophora* growth. *Cladophora* growth in the Upper Lakes is a localized problem responding to local inputs. SRP will have to be monitored carefully in areas such as Georgian Bay to ensure that a *Cladophora* problem does not arise. Jackson and Hamdy (1982) have suggested that a 1 µg/L increase in total phosphorus could result in nuisance growths in the Thirty Thousand Islands area of Georgian Bay.

Green plants and algae contain chlorophyll, a pigment that is easily measurable and thus can be used to estimate the quantity of algae in the water. The chlorophyll data reflect the offshore responses to the reductions in phosphorus loadings and spring concentrations. It is measured in the summer, at the peak of the primary production of a lake. 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 µg/L are indicative of oligotrophic conditions. Using this criteria, the Upper Lakes have been oligotrophic at least since 1980 (the 1989 value for Lake Michigan notwithstanding, Figure 6). This is consistent with the goals of phosphorus reduction programs, as outlined in the GLWQA. Reductions in chlorophyll concentrations in the offshore waters of lakes Erie and Ontario indicate a trend from mesotrophy toward oligotrophy over the period 1980-1990. Chlorophyll changes in the offshore, combined with the nearshore *Cladophora* trends, 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 achieved.

Eutrophication and/or undesirable algae, however, continued to present problems in 18 of the 43 areas in the Great Lakes identified by the IJC as having the worst problems (see Figure 1). Remedial action plans to address these problems are being developed individually for each of these "Areas of Concern".

3.2 Lake Erie Dissolved Oxygen Depletion

Figure 7 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 1987 to 1991 (Bertram 1993). Charlton et al (1993) observed a similar pattern as far back as 1979. 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.

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 for 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 1970s and early 1980s. 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).

3.3 Nitrate-plus-nitrite

Nitrate-plus-nitrite is also an important nutrient in water systems. Major sources of nitrogen to the lakes are agricultural runoff, municipal sewage treatment plants and atmospheric deposition. The contribution of nitrogen and phosphorus from septic systems is unknown, but may be significant in some areas. Increasing levels of nitrate-plus-nitrite have been reported in the Great Lakes for the past two decades (Stevens and Neilson 1987; Williams 1992), particularly in Lake Ontario (Figure 8). 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).

However, nitrate may be a predisposing factor in several diseases in fish (Colt and Armstrong 1981).

Atmospheric deposition is suspected of being the major cause of nitrogen increases in the Upper Lakes because of their large surface-area-to-drainage-basin ratio, lower population densities and relatively fewer municipal and industrial dischargers. It has been estimated that 58% of the total nitrogen load to Lake Superior is due to precipitation (Hartig and Gannon 1986; Bennett, 1986). 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. 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).

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, blue-green algae have a competitive advantage because they can utilize ("fix") nitrogen directly, whereas other types of algae cannot. Blue-green algae composed much of the "nuisance algae" referred to in the GLWQA. When the N:P ratio exceeds 29, there is a shift in dominance from blue-green to green algae and diatoms (Smith 1983). Hartig et al (1991) have postulated that it is likely that until about 1982-83 (when the N:P ratio crossed the 29:1 threshold), Lake Ontario's summer phytoplankton biomass was actually limited by nitrogen. This would explain why chlorophyll a levels only began to respond to further phosphorus reductions after this time.

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 the Great Lakes may warrant continued monitoring, but they do not appear to be cause for alarm at this time.

4.0 Where Do We Go From Here?

Phosphorus controls appear to have been successful in lowering the loadings into the lakes, and consequently reducing, to varying extents, the resultant open lake concentrations of total and soluble reactive phosphorus. The desired response in algal biomass, as indicated by chlorophyll a concentrations, was finally observed in Lake Ontario in 1985 when a 50% decrease occurred. However, the goal of establishing year-round aerobic conditions in the hypolimnion of Lake Erie's Central Basin has not been realized. 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). Perhaps intermittent anoxia is an inherent property of the basin, and management to achieve a state where anoxia does not occur is not a realistic goal for lake managers.

What impact have nutrient controls had on the food web? Zooplankton are the pivotal trophic level in lake ecosystems, stressed by both salmonid stocking (top-down) and phosphorus abatement (bottom-up) management strategies. Johannsson et al (1991) compared nearshore and offshore zooplankton in Lake Ontario between 1981 and 1988 and reported that zooplankton abundance had declined as of 1983-84, particularly in the eastern basin, but the species composition did not change appreciably. They suggested these changes could have resulted from a reduced phytoplankton food supply, as a result of lower phosphorus concentrations, combined with continued levels of predation by alewife.

Changes in phytoplankton abundance and species in Lake Erie from 1970 through the mid-1980s were also consistent with the expected impacts of reduced nutrient loadings (Makarewicz and Bertram 1991). For example, the mean algal biomass during this period declined by 65% (from 3.4 g/m^3 to 1.18 g/m^3); the nuisance blue-green algae *Aphanizomenon flos-aquae* decreased 89% (from 2 g/m^3 to 0.22 g/m^3); and the number of dominant eutrophic diatom species decreased in the western basin, whereas the number of dominant mesotrophic species increased (from 1 to 4).

Not all changes in the lower food web are attributable to changes in phosphorus concentrations. For example, zooplankton standing stocks in the nearshore region of Lake Michigan declined 10-fold during 1982-84, although phosphorus concentrations in the offshore waters had not declined appreciably (Evans 1986). Predation by yellow perch, which confine themselves to the nearshore regions, was suggested as the likely cause. In Lake Erie, the recovery of the walleye fishery and the introduction of a new salmonid fishery also have had a cascading effect on trophic structure. As top-level predators increased in abundance, forage fish abundance decreased, perhaps contributing to the establishment of the large predaceous spiny water flea by 1985, and allowing larger zooplankton to dominate the community structure. Grazing pressure from these larger zooplankton appears to have caused a further decrease in algal abundance (Makarewicz and

Bertram 1991).

Although the desired reductions in phosphorus have been achieved, which have lead to positive changes in the plankton communities, the question remains, "What level of fishery can be sustained by the resultant food base?" Zooplankton comprise almost the entire diet of alewife, and are a significant component of the diet of smelt. A reduction in the abundance of zooplankton, therefore, could only result in reduced populations of alewife and smelt. The Great Lakes Fishery Commission reports that alewife and smelt biomass indices have declined since the early 1980's (GLFC 1992). At the same time, the numbers of hatchery-reared salmon and trout stocked in Lake Ontario steadily increased from just over 1 million in 1972 to approximately 8.2 million in 1984. As the stocked fish continued to grow and accumulate, the total weight of salmon and trout reached a peak in 1986 and, since then, has remained high. Alewife and smelt populations in Lake Ontario are under stress from both ends of the food chain. How much stocking is too much?

The issue of restoring the balance between stocked predators and their prey was the subject of discussion at a series of public meetings held in 1992 by the agencies responsible for the fish stocking program in Lake Ontario: the Ontario Ministry of Natural Resources (OMNR) and New York State Department of Environmental Conservation (NYDEC). There emerged consensus that alewives be maintained as the dominant forage species, so that a diverse fishery could be maintained. A scientific task force, established by the Lake Ontario Committee of the Great Lakes Fishery Commission, recommended reduction of predator numbers to stabilize the predator/prey balance. In response, both OMNR and NYDEC agreed to revise their Lake Ontario fish stocking plans, using a two-year phased-in approach, beginning in 1993. For 1993, the two agencies set a target for predator demand which was 35% lower than 1991 levels. In 1994, additional stocking reductions were expected to bring about a total reduction of 47% in predator demand from the 1991 level. OMNR and NYDEC set targets to stock 5.1 million fish in Lake Ontario in 1993, and 4.5 million in 1994. To further reduce the demand for food by predators already in the system, OMNR also encouraged increased harvesting of salmon and trout.

Having seen changes in Lake Michigan's food web now starting to appear in Lake Ontario (eg., changes in zooplankton species and standing stock; a decline in alewife abundance and a resurgence of walleye, whitefish and yellow perch), the participants at the International Joint Commission's Food Web II Workshop, which focussed on Lake Ontario (Hartig et al 1991), recommended that water quality and fisheries agencies: (1) standardize monitoring techniques and establish and maintain compatible, long-term, limnological data sets, (2) cooperate on research (eg. controlled, mesoscale, whole-system experiments) designed to quantify the rates (eg. growth, predation, etc.) of food web interactions (emphasis must be placed on an interdisciplinary approach that explicitly accounts for time and spatial scale effects), and (3) promote initiatives which quantify the impact of changes in food web dynamics on reduction of toxic substances levels in Great Lakes fishes. Water quality and fisheries agencies are coming to recognize the need to act on these recommendations.

In order to understand the effects of nutrient and food web controls in lakes Michigan, Ontario and Erie, research should be focussed on quantifying fluxes of energy, and collecting more information on feeding habits and rates for important species so that food web models can be constructed. Of course, this will be complicated by the recent invasion by zebra mussels (and, in Lake Erie, quagga mussels), and their associated impacts on water quality and the food web. Drinking water impairment (taste and odor problems), loss of fish habitat, and the production and edibility of fish are all potential issues of concern related to zebra mussels.

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). 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; Holland 1993; Leach 1993), and they have enhanced water clarity in shallow waters, where they are found in greatest numbers (Charlton 1994). The diversion of plankton from pelagic to benthic food pathways by zebra mussels could also affect the biomagnification of toxic organic contaminants through higher trophic levels (Bruner et al 1994), and could result in increased concentrations of PCBs and other contaminants in desired sport fish. The combination of the clearing effect and the potential for higher concentrations of contaminants in fish species has particular direct implications for the walleye fishery in Lake Erie. There are currently a number of initiatives, such as the binational Lake Erie Trophic Transfer project, that are beginning to address the impact of zebra mussels on the Great Lakes ecosystem.

In conclusion, fisheries and water quality management strategies have evolved independently in the Great Lakes. In general, these strategies operate from different ends of the management spectrum -- bottom-up (phosphorus control) and top-down (massive fish stocking). A more ecologically oriented approach, which recognizes the interactions between fisheries and water quality, will be required to effectively manage the Great Lakes.

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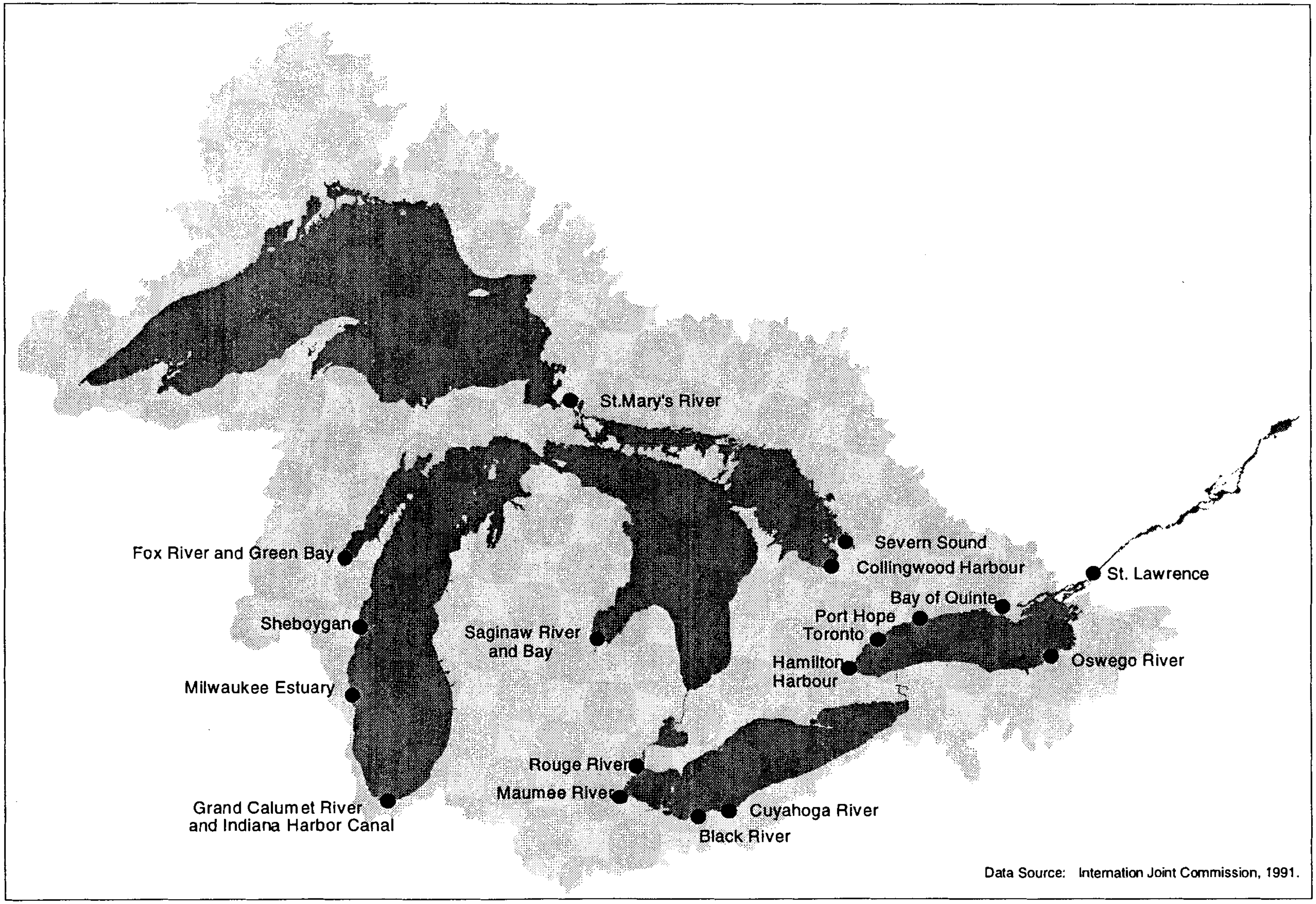
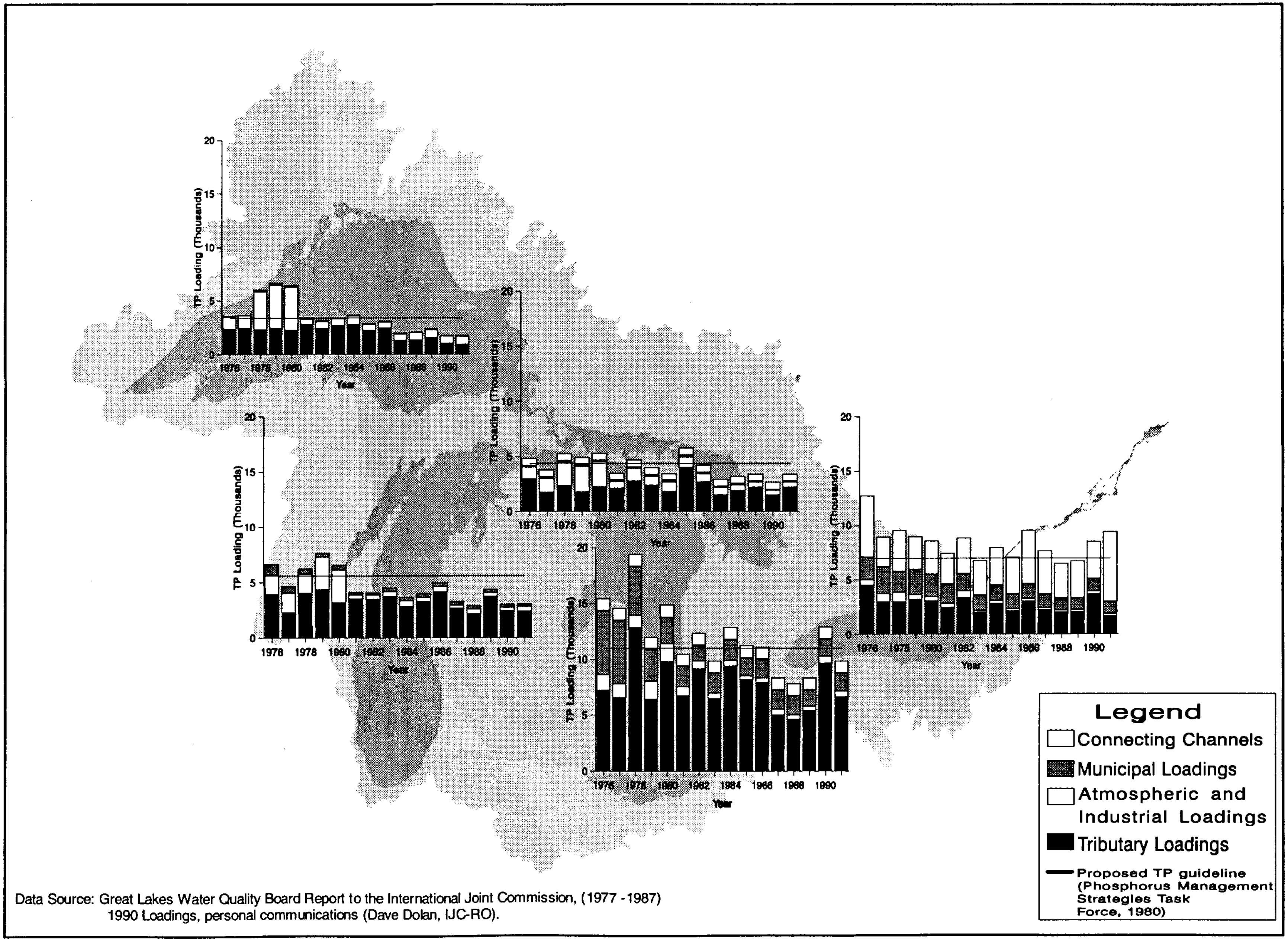


Figure 1. Areas of Concern with eutrophication - or undesirable algae-related impairments



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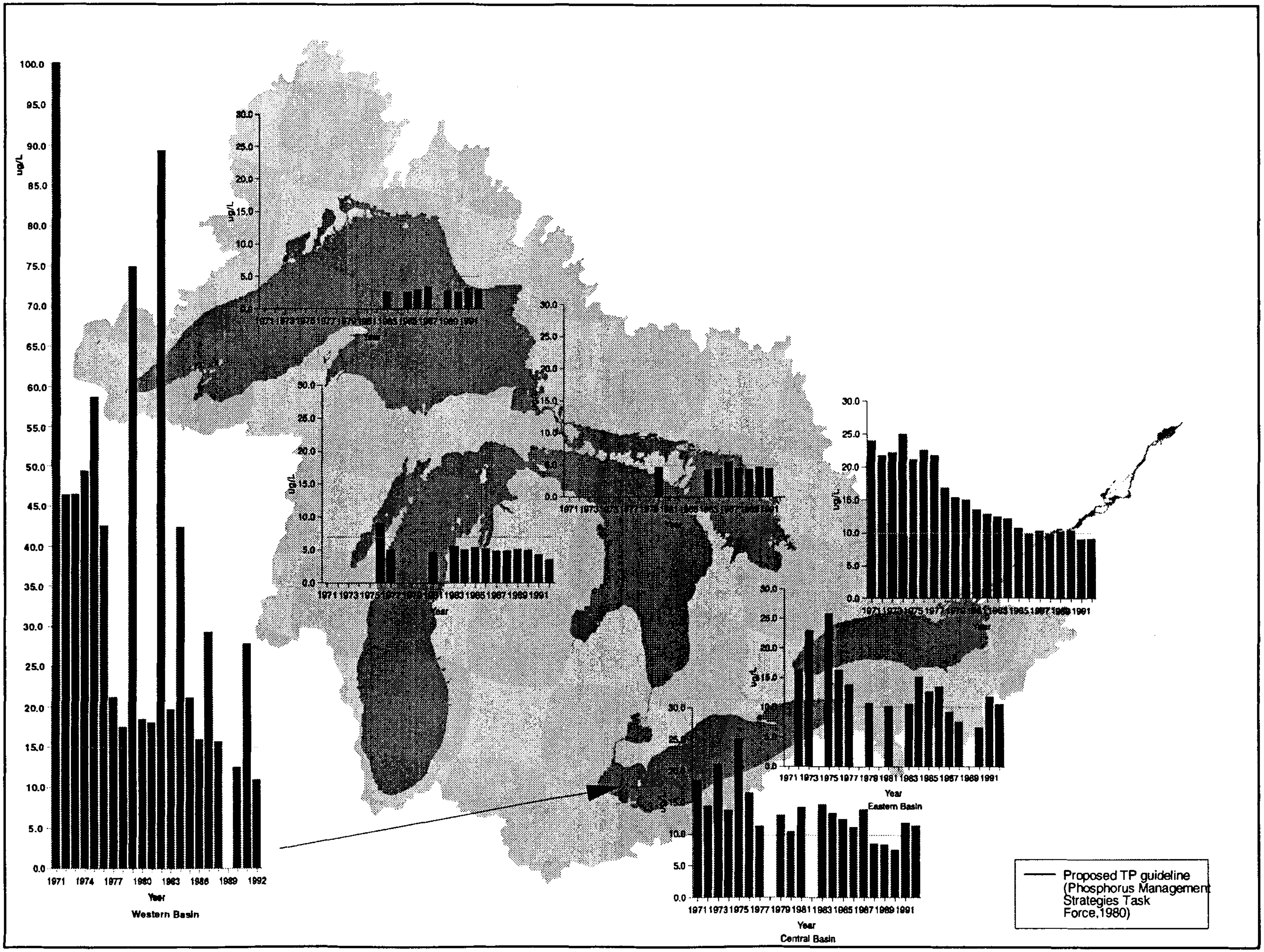

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Data Source: Environmental Conservation Branch, Environment Canada
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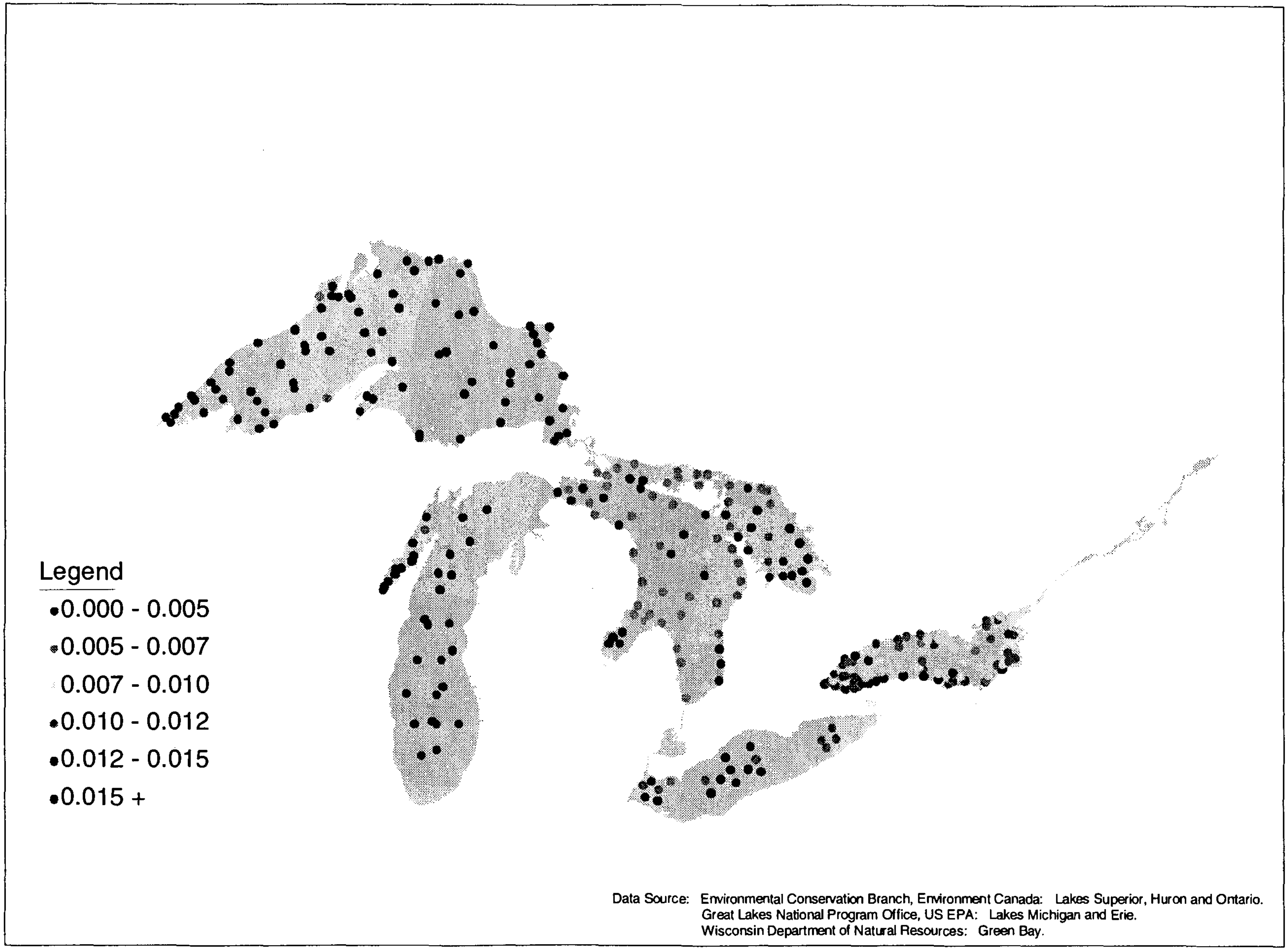

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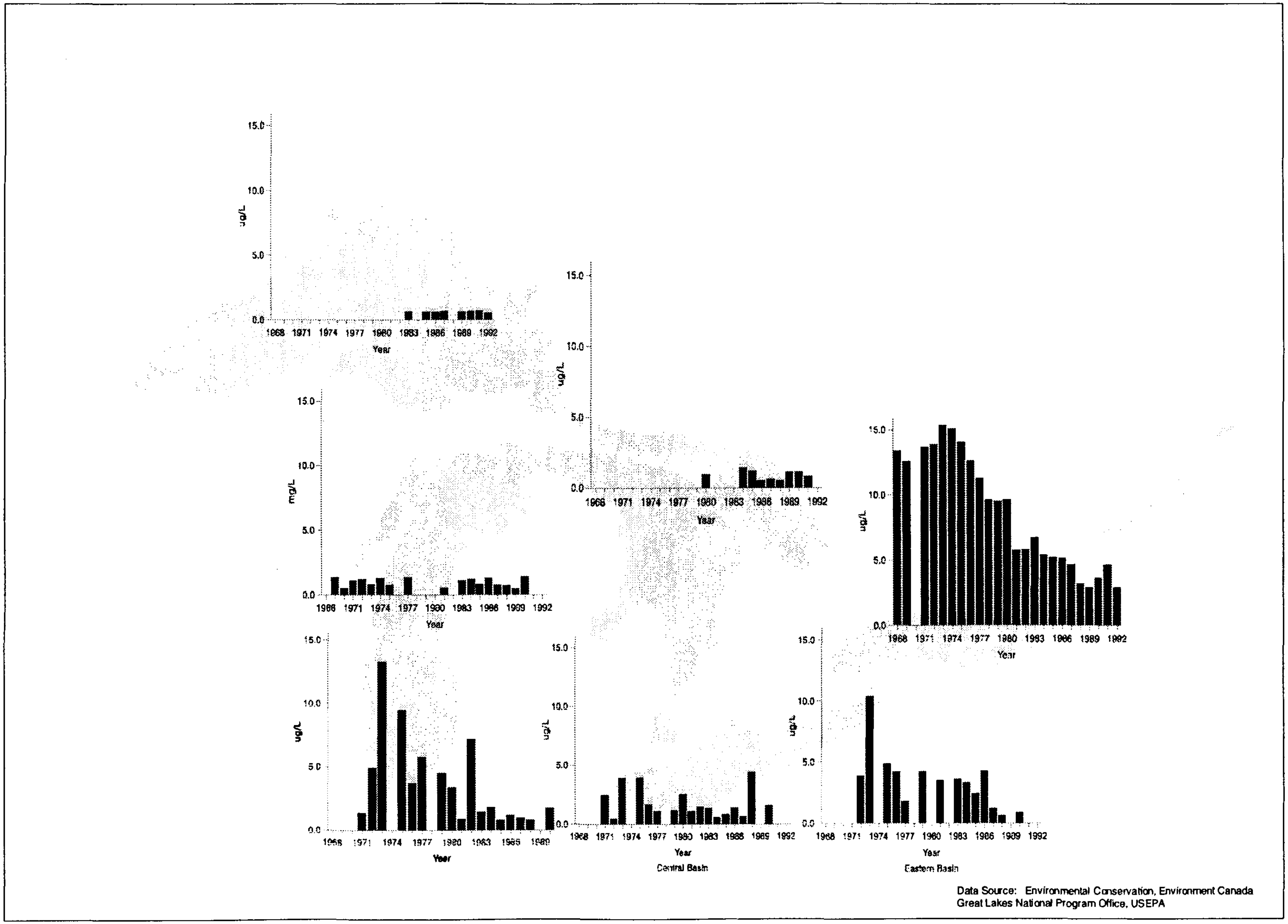

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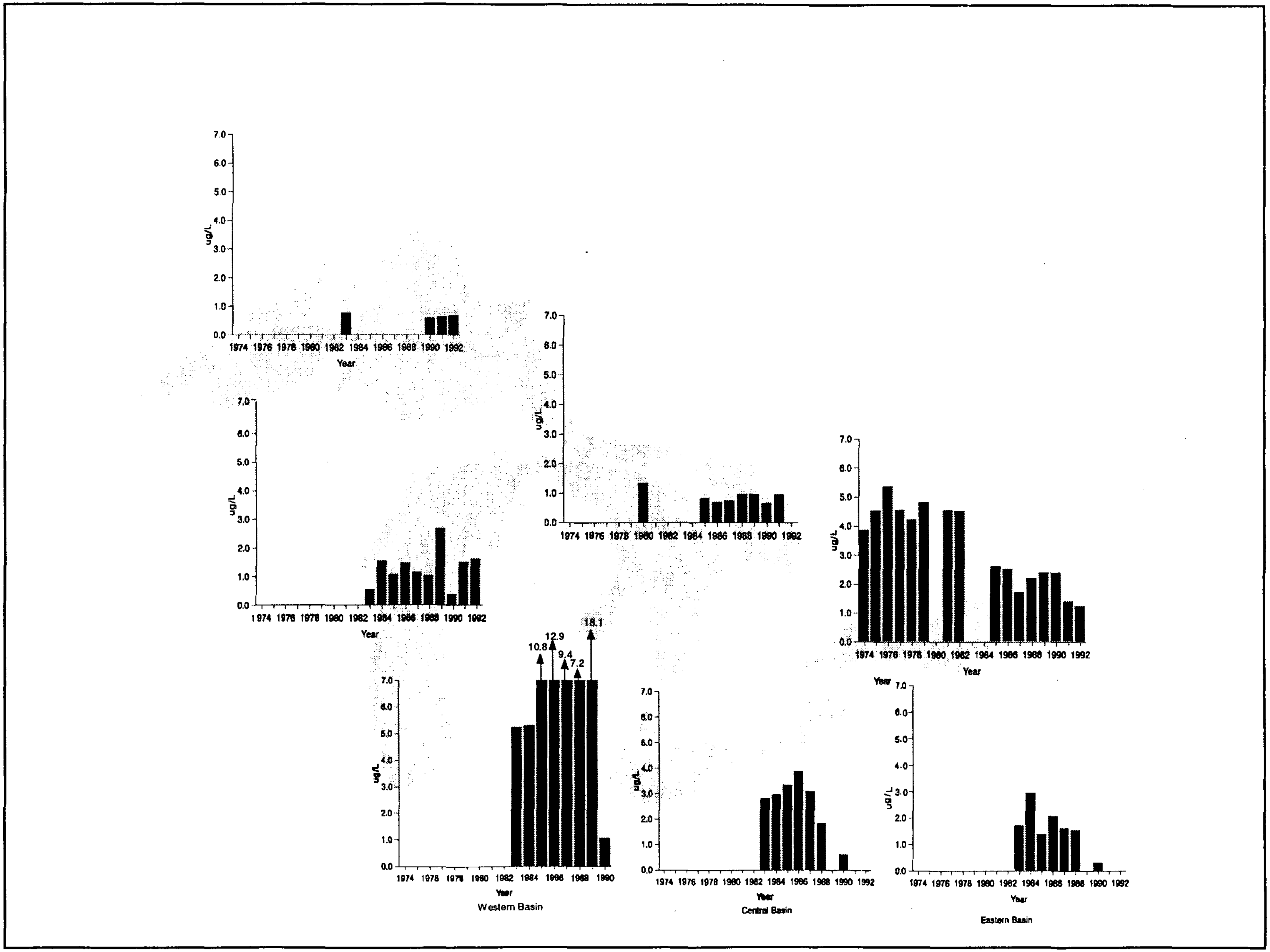

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Data Source: Environmental Conservation Branch, Environment Canada
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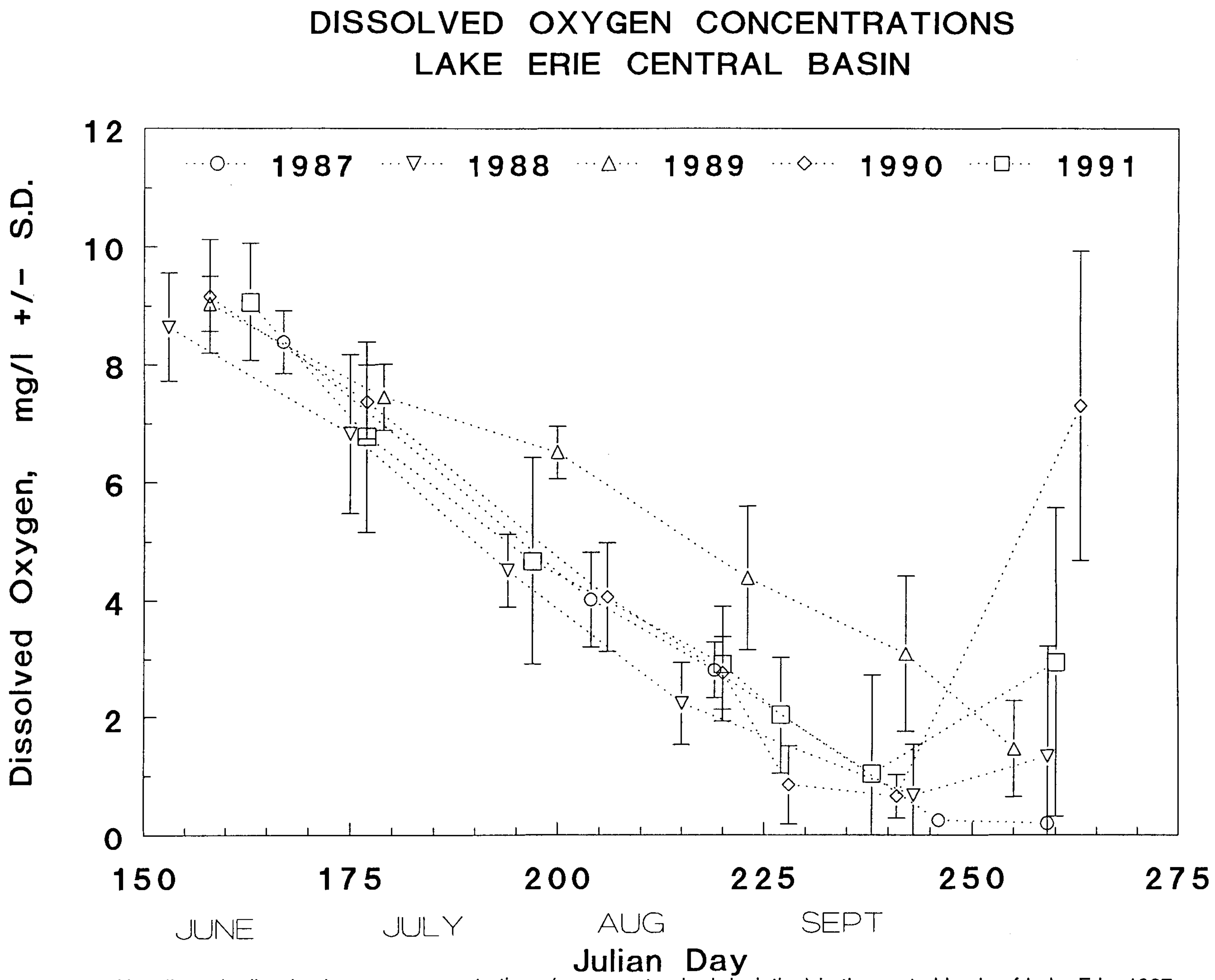

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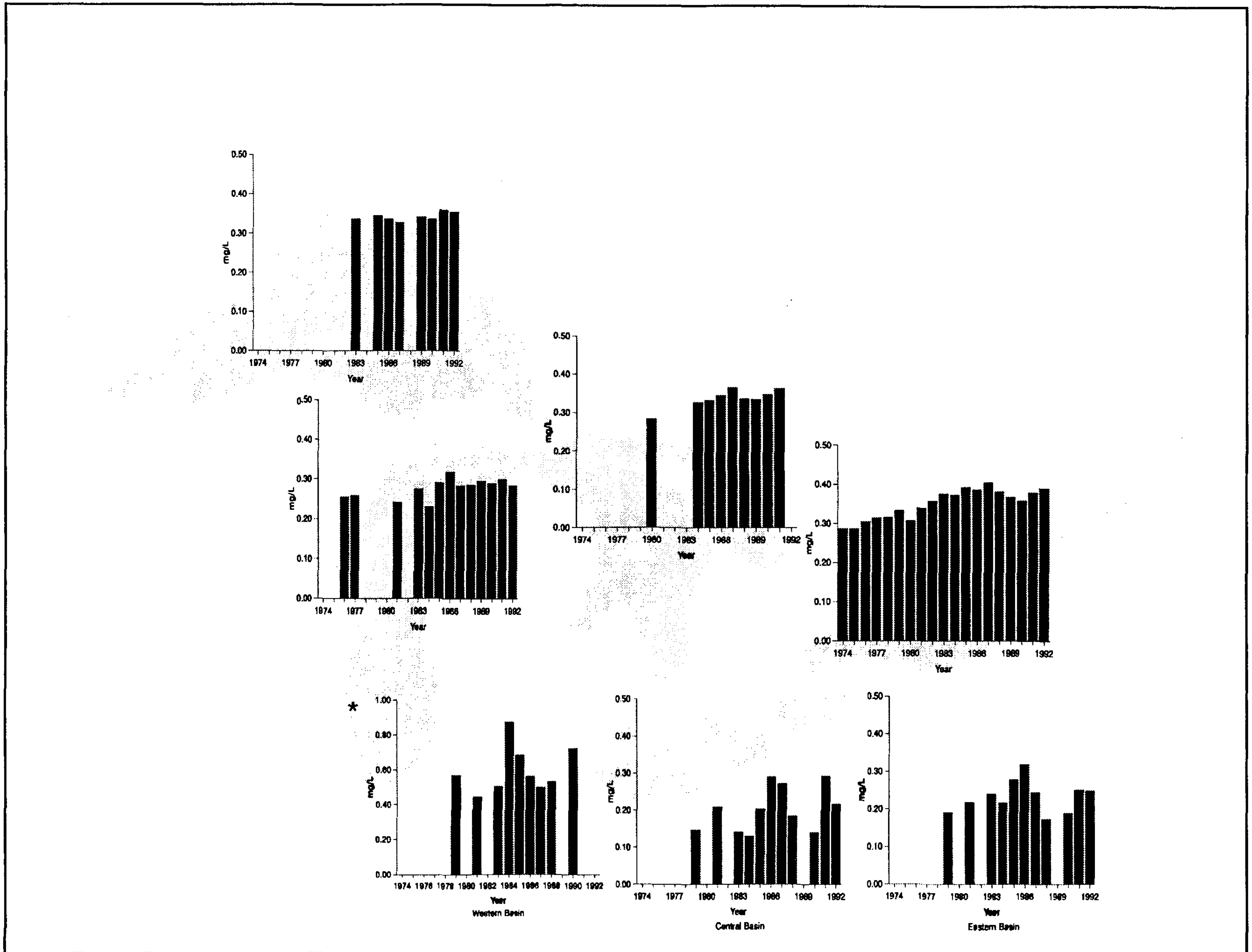

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