

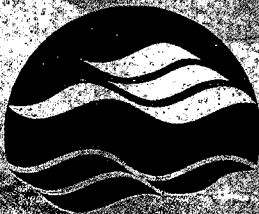
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REVIEW OF THIRTY YEARS OF CHANGE IN LAKE ERIE WATER QUALITY

M.N. Charlton and J.E. Milne

NWRI Contribution No. 04-167

**REVIEW OF THIRTY YEARS OF CHANGE
IN LAKE ERIE WATER QUALITY**

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Review of Thirty Years of Change in Lake Erie Water Quality

Murray N. Charlton, Jacqui E. Milne

Abstract:

Three main events have occurred since the beginning of popular environmental interest in Lake Erie over 30 years ago. First, the near demise of the walleye in the 1950s and 1960s, resulted in development of fisheries management techniques to ensure recovery and attempt sustainability. Second, loadings of toxic chemicals and phosphorus were controlled under the Canada-U.S. Great Lakes Water Quality Agreement (GLWQA). Third, an invasion of exotic species became apparent in the 1980s and continues today. Nutrient management was thought to be the most important event and controls took time to develop. During that time interest in "ecosystem integrity" revealed that changes in lake biota could themselves affect water quality. Thus, changes in water quality over the years, which should indicate aspects of the nutrient control program may also be affected by exotic species and perhaps even the recovery of the walleye population. Phosphorus loadings were brought under control, producing large concentration changes in the west basin and minor changes in the central and east basins. The hoped-for elimination of low oxygen in the central basin hypolimnion has not occurred. Relatively large increases in nitrogen continue. Recently, a decrease in phosphorus concentrations around 1995 has been reversed as concentrations have rebounded through 2000-2001. These phenomena are not explained with the data and scientific effort presently available. Thus, there is a need to augment science programs in order to provide understanding needed to manage the chaotically changing ecosystem.

Trente ans de changements dans la qualité des eaux du lac Érié

Murray N. Charlton et Jacqui E. Milne

Résumé

Trois grands phénomènes se sont produits depuis que le public a commencé à s'intéresser à la situation environnementale du lac Érié, il y a plus de trente ans. D'abord, durant les années 50 et 60, avec la disparition quasi complète du doré jaune, il a fallu mettre au point des techniques de gestion des pêches permettant de rétablir l'espèce et d'en rendre l'exploitation plus durable. Deuxièmement, les charges de substances toxiques et de phosphore ont été maîtrisées grâce à l'Accord entre le Canada et les États-Unis relatif à la qualité de l'eau dans les Grands Lacs. Troisièmement, l'envahissement des eaux par des espèces exotiques est devenu manifeste durant les années 80 et se poursuit encore aujourd'hui. On a estimé que la gestion des éléments nutritifs importait le plus, et il a fallu du temps pour élaborer les mesures voulues. Durant cette période, avec l'attention accordée à l'intégrité des écosystèmes, on a pu constater que les changements survenant dans la flore et la faune du lac pouvaient eux-mêmes influencer sur la qualité de l'eau. Par conséquent, les changements survenant dans la qualité de l'eau au cours des années, qui devraient refléter certains aspects du programme de contrôle des éléments nutritifs, pourraient également être affectés par les espèces exotiques ou même par le rétablissement de la population de doré. Les charges de phosphore ont été maîtrisées, ce qui a produit de grands changements de concentration dans le bassin ouest et des changements mineurs dans le bassin central et le bassin est. On n'a pas réussi à contrer, comme on l'espérait, la raréfaction de l'oxygène dans l'hypolimnion du bassin central. On observe encore des augmentations relativement grandes de la concentration d'azote. La diminution des concentrations de phosphore observée vers 1995 a été suivie d'une augmentation en 2000 et 2001. Or, tous ces phénomènes ne peuvent être expliqués au moyen des données et travaux scientifiques actuellement disponibles. Il faudrait donc accroître les programmes de recherche, afin de disposer de toute l'information voulue pour bien gérer cet écosystème connaissant des changements chaotiques.

NWRI RESEARCH SUMMARY

Plain language title

Review of Thirty Years of Lake Erie Water Quality

What is the problem and what do scientists already know about it?

Water quality was controlled by nutrient reductions, alien mussels confuse the results, the oxygen depletion goal has not been met – there is confusion as to why.

Why did NWRI do this study?

To present a long term data set to help clarify response of the lake.

What were the results?

Nutrient reductions and alien mussels had the most effect in the west end of the lake. Water quality indicators seem little changed except for phosphorus perturbations in the central and east basins, the oxygen situation seem mostly unchanged but should be watched.

How will these results be used?

To advise governments and recommend further research.

Who were our main partners in the study?

DFO OME.

Sommaire des recherches de l'INRE

Titre en langage clair

Trente ans de changements dans la qualité des eaux du lac Érié

Quel est le problème et que savent les chercheurs à ce sujet?

La qualité des eaux a été maîtrisée par une réduction des concentrations d'éléments nutritifs; les moules exotiques rendent les résultats difficiles à interpréter; l'objectif relatif à la raréfaction de l'oxygène n'a pas été atteint, et une confusion règne quant aux raisons de cet échec.

Pourquoi l'INRE a-t-il effectué cette étude?

Un ensemble de données à long terme pourrait aider à élucider la réaction du lac.

Quels sont les résultats?

C'est dans le bassin ouest du lac que la réduction des concentrations d'éléments nutritifs et l'envahissement par les moules exotiques ont eu le plus d'effet. Les indicateurs de la qualité des eaux semblent avoir peu changé, sauf pour les perturbations du phosphore observées dans le bassin central et le bassin est; la situation de l'oxygène semble avoir peu changé mais mériterait d'être surveillée.

Comment ces résultats seront-ils utilisés?

Conseiller les gouvernements et recommander des recherches plus approfondies.

Quels étaient nos principaux partenaires dans cette étude?

MPO MEO.

Review of Thirty Years of Change in Lake Erie Water Quality

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NWRI Contribution No. 04-167

Abstract:

Three main events have occurred since the beginning of popular environmental interest in Lake Erie over 30 years ago. First, the near demise of the walleye in the 1950s and 1960s, resulted in development of fisheries management techniques to ensure recovery and attempt sustainability. Second, loadings of toxic chemicals and phosphorus were controlled under the Canada-U.S. Great Lakes Water Quality Agreement (GLWQA). Third, an invasion of exotic species became apparent in the 1980s and continues today. Nutrient management was thought to be the most important event, and controls took time to develop. During that time interest in "ecosystem integrity" revealed that changes in lake biota could themselves affect water quality. Thus, changes in water quality over the years, which should indicate aspects of the nutrient control program may also be affected by exotic species and perhaps even the recovery of the walleye population. Phosphorus loadings were brought under control, producing large concentration changes in the west basin and minor changes in the central and east basins. The hoped-for elimination of low oxygen in the central basin hypolimnion has not occurred. Relatively large increases in nitrogen continue. Recently, a decrease in phosphorus concentrations around 1995 has been reversed as concentrations have rebounded through 2000-2001. These phenomena are not explained with the data and scientific effort presently available. Thus, there is a need to augment science programs in order to provide understanding needed to manage the chaotically changing ecosystem.

Introduction

During the 1990s unprecedented change occurred in Lake Erie. Up to 1997 the lake was thought to be in transition due to combined effects of fisheries perturbations, nutrient controls, and an ongoing invasion of exotic species (Charlton et al. 1999). This report updates to 2000 water quality data for the west and central basins, and to 2001 for the east basin and reviews some of the long term data for Lake Erie.

Methods

Sample Collection

Samples were collected at a series of up to 60 stations in all three basins aboard a variety of vessels, with most sampling done from CSS Limnos (later the CGS Limnos) from 1970 to 2001. An integrating sampler collected water from 0-20 m or from the surface to the top of the thermocline in the central and east basins and 0-10 m in the west basin. Samples were placed in bottles immediately. Those designated for total phosphorus (Tp-uf) analysis were placed in bottles and preserved with the addition of 30% sulphuric acid. Samples designated for soluble reactive phosphorus (SRP) and nitrate plus nitrite ($\text{NO}_3 + \text{NO}_2$) were filtered immediately and placed in bottles and stored at 4°C. Samples designated for uncorrected chlorophyll-a (Chla) analysis were filtered immediately and the filters were stored frozen at -14°C until analysis.

Samples were analyzed (Environment Canada 1979) at the National Laboratory for Environmental Testing (NLET) at the Canada Centre for Inland Waters (CCIW) where continuity of methods can be traced back to 1970.

Profiles of temperature, light transmission, pH, dissolved oxygen, and conductivity were measured with a Seabird™ apparatus held in a calibration bath between stations. Electronic oxygen recordings were supplemented by water samples and Winkler oxygen analyses.

Data Analysis:

Data for trend presentations were obtained from files of the National Water Research Institute (NWRI) since 1979, mainly gathered by the senior author, and Environment Canada, Ontario Region, at CCIW. For purposes of comparability, only Canadian data were used (Charlton et al. 1993). Recent data from 1999 and 2000 are highlighted. Monthly mean and standard deviation data for surface water from either discrete depth samples up to 10 m deep or integrated 0-10 m were used for the months of June, July, and August. Usually, only one cruise occurred per month but occasionally there were two and the data were averaged. Stations were located at least 1 km offshore at depths >15 m in the east and central basins. The selection processes are similar to those in Charlton et al, (1993) but some additional variability has been introduced by the inclusion of June data which sometimes represent spring conditions. Restriction of the analysis to the summer period is a way of minimizing interference caused by gradually reduced sampling efforts since 1970 of the periods of greater resuspension of sediments which occur in the windier spring and fall periods. Thus, we hope the probability of detecting changes in long term data is maximized regardless of the cause.

Results

Total Phosphorus

Phosphorus concentration continues to change in Lake Erie. From cruise mean lows of 5-6 $\mu\text{g/L}$ TP/in 1995, total phosphorus concentrations rebounded somewhat in the late 1990s (Fig. 1). Recent east basin summer total phosphorus concentrations for 1999, 2000 and 2001 were 7.3, 9.7 and 6.2 $\mu\text{g/L}$, respectively (Table 1).

Changes have been greater in the central basin (Fig.1B). Monthly mean lows around 5 $\mu\text{g/L}$ were followed by values in the range of 9.0 to 11.7 in 1996 and 1997. The rate of increase slowed somewhat in 1999 with a season mean of 8.7 $\mu\text{g/L}$, but this was followed by cruise means in the range of 12.1 to 16.4 in 2000. Except for 1999, the increase in total phosphorus concentrations in the central basin appeared to be steady since 1995, resulting in an increase from 8.4 to 14 $\mu\text{g/L}$ by 2000.

In the west basin, total phosphorus concentration increased from about 17.7 $\mu\text{g/L}$ in 1994-96 to 25.0 and 23.2 in 1999 and 2000, respectively. Although the Y-axis scale is relatively compressed in the west basin portion of Fig. 1C, an appreciation of the phosphorus increase can be had from the lowest monthly means each year. Thus, between the mid-1990s and 2000 there has been an increase of 6 to 7 $\mu\text{g/L}$ TP in the west and central basins.

Soluble Reactive Phosphorus

Soluble reactive phosphorus (SRP) is generally thought to be an indicator of phosphorus forms available for algal uptake (Lee et al. 1980). When phosphorus loading restrictions called for in the Canada U.S Great Lakes Water Quality Agreement (GLWQA) were achieved in the mid 1980s, SRP concentrations appeared to decrease to below 1 $\mu\text{g/L}$ in the east and central basins (Fig. 2A,2B). Typical SRP cruise means in 1999 and 2000 were between 0.3 and 2.0 $\mu\text{g/L}$ in the east and central basins (Table 1).

Soluble reactive phosphorus concentration has always been higher in the west basin, reflecting perhaps sources of point and non-point loading as well as internal recycling. In 1999 and 2000, typical west basin monthly means were in the range of 1.0 to 6.0 $\mu\text{g/L}$ SRP. Clearly, the SRP concentrations are low and variable, and we do not intend to imply that any major changes have occurred. Nevertheless, there is an impression that the concentrations are beginning to sporadically increase perhaps, consistently with increases in total phosphorus.

Chlorophyll *a*

Chlorophyll *a* (CHLa) as an indicator of algal populations has been measured with consistent methods for many years. Although changing species composition and physiological states of algal populations may not be well described by chlorophyll *a*, this measure is an economical way to derive some baseline information on the primary production potential of the water.

East basin CHLa means ranged from 0.7 to 1.6 $\mu\text{g/L}$ in 1999, 2000, and 2001 (Table 1). Although these values overlap some of those obtained before the dreissenid mussel invasion (mid 1980s, Fig.3), they seem to be relatively low. Central basin means in 1999 and 2000 were somewhat higher with a range of 0.4 to 2.6 $\mu\text{g/L}$. Recent central basin CHLa concentrations overlap previous values observed in the mid 1980s and still vary by a factor of two between closely adjacent pairs of years (e.g., 1997-98 compared to 1999 and 2000). Still, implementation of nutrient controls clearly coincided with a decline in CHLa concentrations, whereas the effects of the dreissenid mussel invasion were smaller and may still be developing (Charlton et al. 1999).

West basin CHLa concentration decreased strongly with the advent of nutrient controls (Fig.3C). Although some of the recent mean values overlap those of the mid 1980s, the variability seems to be generally reduced and the frequency of low values seems to have increased. In 1999 and 2000, the means ranged from 2.7 to 7.1 $\mu\text{g/L}$. These are chlorophyll concentrations formerly associated with conditions thought to be problematic in the central basin during 1970 (Munawar and Burns, 1976).

Dissolved Nitrogen

Increases in nitrate+nitrite concentrations represent some of the largest anthropogenic changes in Lake Erie - on the order of hundreds of $\mu\text{g/L}$ between 1970 and the late 1990s. Lately, the increase seems to have slowed or even may have stopped and reversed according to the data we show in Figure 4 and Table 1. The amount of increase was somewhat greater in the central basin compared to the east basin. The increase was larger still in the west basin and there is the impression that concentrations may still be increasing there.

Nitrate and nitrite can come from agricultural sources, urban runoff, atmospheric deposition, and municipal sewage (Wetzel, 1983). The western end of the central basin has intermediate concentrations (Charlton et al. 1999). Thus, there is an apparent west to east gradient, which is consistent with large loading effects in the west basin. Although the concentrations do not approach the upper limits for drinking water guidelines, they are of concern because no specific control program exists for nitrogen.

Water Clarity (Secchi Depth)

Secchi depths are perhaps not as elegant a measure of water clarity as in-situ light extinction coefficients, but they offer a history of data not available with other measures. Water clarity was one of the concerns to be addressed by the nutrient controls in the 1970's because much of the turbidity was thought to be controlled by algae (Vollenweider et al. 1980). Early in the records (Fig. 5) some relatively high Secchi depth readings occurred in the central and east basins (8-10 m). Perhaps, in retrospect, the Secchi depth values of 1966 and 1967 might have been inconvenient for promotion of nutrient controls. By 1969 and 1970, however, clarity had decreased and from then on water clarity began to increase consistent with expectations of the effects of ongoing nutrient controls. Still, the anomalously clear water of 1966 and 1967 at the time of peak nutrient loading to Lake Erie remains an enigma. Why was the water so clear? Was the response to increasing nutrient pollution just developing in the central and east basins? Nevertheless, the trend to increased clarity culminated with maximal Secchi values around 1985 as the nutrient-loading goals were achieved and just before the arrival of *Dreissena* mussels.

The Dreissenid mussel invasion was accompanied by much popular literature that stated that the mussels 'cleaned up' Lake Erie. The Secchi depth data for the east and central basins offer little support for this notion (Fig. 5). We suspect that observations in the nearshore frequented by the public are not as representative of the whole lake as are our data. Present day (1999 and 2000) Secchi depth values were achieved before the mussels arrived. Moreover, there seems to be an indication of decreasing Secchi depths in the central basin. Indeed, in the western portion of the central basin Secchi depths averaged 5.2 m in 1994-1996 (Charlton et al. 1999). However, values declined to approximately 3 m for the same area in 2000 (Table 1). The appearance of Dreissenid mussels in the west basin in the late 1980s coincided with an increase in Secchi depths up until the mid-1990s (Fig. 5C). Subsequently, there seems to be a trend toward lower Secchi depths in the west basin consistent with those observed in the west central basin. One reason for this may be the resurgence of the burrowing mayfly *Hexagenia* in the west basin (Edsall et al. 1999). The mayflies are important bioturbators (Matisoff and Wang, 2000, J. Ciborowski, University of Windsor, personal communication) that have developed a large population since the mussels arrived. This may partly explain the west basin's decreasing water clarity in the absence of increasing chlorophyll.

Hypolimnion Oxygen

Dissolved oxygen is an important aspect of the requirements of aquatic organisms. Lake Erie generally exhibits little hypoxia except in the central basin hypolimnion at the end of the summer (Charlton, 1979, 1980a). Anoxic

conditions in the late 1960s and early 1970s resulted in sediment phosphorus regeneration in the central basin that exacerbated the nutrient concentrations (Burns and Ross 1972). There was concern about the loss of such a large area of the lake as fish habitat (Regier et al. 1969). "Restoration of year-round aerobic conditions in the bottom waters of the central basin" became one of the goals of the original 1972 GLWQA.

We have gathered oxygen data since the late 1970s in order to document the response of the lake to nutrient loading restrictions. Data from 1990, 93, 94, 95, 96, 97, 98, 99 and 2000 are shown in Fig.6. As an example of recent information, hypolimnion oxygen data we gathered in 2000 are shown in Figure 6. By the end of June, one station was approaching the danger limit for fish (4 mg/L), and oxygen at many stations had declined to this level by mid-July. By mid August and into September many stations were functionally anoxic (≤ 1 mg/L). We calculated oxygen depletion rates by linear regression. We have calculated an oxygen depletion rate for 2000 of 0.08 mg/L/d for all the data in Figure 6. We suspect the rate calculated in 2000 was biased low by higher data points in the latter surveys which may have been caused by our use of water samples and Winkler analyses while our profiler was unavailable (see discussion in Charlton et al. 1993). Supporting this is the observation that some stations had reached near-zero values in mid August and thereafter could not contribute to further depletion or were no longer stratified. This is a common occurrence in thin hypolimnion years with low oxygen and has been shown here to illustrate some of the problems in these data. Thus, the depletion rate in 2000 was likely up to 0.12 mg/L/d omitting the last data set in Fig. 6.

Relatively good oxygen conditions occurred in the central basin hypolimnion in 1993 (Charlton 1994) 1994, 1996, and 1997 in our data. Ideally, however, data collection would continue until de-stratification in order to determine ultimate oxygen concentrations and duration of the conditions. Anoxia or near anoxia occurred in 1990, 1995, 1998, 1999, and 2000. The highest depletion rates in 1990 and 2000 (Table 2) were associated with the thinnest hypolimnia of close to 3m as noted in Charlton (1980a). Conversely, low depletion rates tended to be associated with hypolimnion thickness of close to or more than 4m. Overall, the hypolimnion thickness is only one of the factors affecting oxygen rate each year; duration of stratification is also important. Thus, even though the depletion rate in 1995 was not high a considerable period of low oxygen concentrations occurred extending into mid September. Hypolimnion oxygen depletion in the east basin is less rapid than in the central basin (Table 2). The difference in mean depth between the east and central basins as illustrated by hypolimnion thickness is shown in Table 2. The greater mean depth of the east basin allows a thicker hypolimnion, which results in less oxygen depletion for a given level of productivity (Charlton 1980b). East basin depletion rates do not seem to have changed since earlier calculations (Charlton, 1979). A transient feature in some of our east basin profiles is a depression in oxygen concentrations in the thermocline; sometimes these concentrations are in the range to affect fish habitat (levels of 4 mg/L or lower).

General Discussion and Research Recommendations

The recent increase in total phosphorus in the central basin is as large as the decrease brought about by the nutrient loading controls. Increases in total phosphorus concentrations in Lake Erie's open waters are disconcerting because there is no apparent explanation. Data on loading of phosphorus to the lake do not seem to explain the phenomenon. Recent advances in monitoring municipal waste loads and the realization that sewage plant bypasses may not be monitored may call into question reported loads (Dolan & McGunagle, this volume). Some understanding of whether phosphorus concentration changes were caused by nutrient loads or changes in biota or other factors would be desirable.

Changes in sediment fluxes might be responsible for changes in water column phosphorus concentrations. We hypothesize that changes in sediment fluxes may be caused by varying numbers of adult *Dreissena* (Nicholls et al. 1999a) as well as veligers that grow for a few weeks and then settle from the plankton (Johannsson et al. 1999, Lewandowski, K. 1982, Mackie et al. 1989). The rapid growth of the dreissenid population may have removed phosphorus from the lake (Nicholls et al. 1999a) that may be now returning if their lake-wide population growth rate is beginning to taper off as available substrate becomes colonized. Unfortunately, data to test this hypothesis are not available. At the same time the introduction of predacious zooplankton (*Bythotrephes* and *Cercopagis* sp.) can affect the abundance of filter feeding zooplankton (Johannsson et al. 1999) that would affect water quality. Some introduced forage fish populations, which suffer large population fluctuations because they are ill-adapted for cold water may also affect zooplankton populations (Ryan et al. 1999). For the most part, investigations of the lake biology, physics, and chemistry have been inadequate to allow understanding of recent changes in water quality. An enthusiastically funded science program could provide annual background data.

A variety of research and monitoring efforts can provide insight into important lake function. The present work has concentrated on sampling Lake Erie's offshore areas during summer in an effort to minimize expenses and to avoid weather related resuspension events and nearshore variability. On the other hand, the water intake program of the Province of Ontario provides an even more economical source of data from the nearshore areas of the lakes that are the most variable and most likely to be affected by the dreissenid invasion (Nicholls et al. 2001). Average intake (nearshore) phosphorus concentration in 1996-1999 was 21.3 ug/L in the west basin, which is similar to our results. In the central basin, however, nearshore phosphorus concentrations were 25.0 and 31.8 ug/L at two locations; these levels were substantially higher than the offshore values we observed for the similar period. Similarly, phosphorus concentration at two east basin intakes was 20.3 and 15.7 ug/L, again, substantially higher than our offshore concentrations between 1996 and 1999 (Fig. 1, Table 1). Nearshore phosphorus concentrations should reflect nearshore

sources such as shore erosion, agricultural runoff, and municipal sewage thus we expect some higher concentrations than in the offshore. Particulate phosphorus, which consists of much abiotic material, can recycle up and down in the nearshore water column while the net movement is slowly offshore. Thus, the same nearshore phosphorus can be measured repeatedly with each resuspension event partially independently of changes in managed phosphorus loads.

In the offshore area, biotic particles are more dominant and net sedimentation seems to prevail with less return once particles reach the bottom. The nearshore is also the area of greatest mussel abundance (Dermott et al. 1993, Dermott and Kerec 1997,). Thus, the mussels may be harvesting particulate phosphorus from circulating water and causing a new flux of phosphorus from the offshore to the nearshore that may explain maintenance of nearshore concentrations as well as gyrations in phosphorus concentrations offshore.

Chlorophyll:phosphorus ratios are of interest because Dreissenid mussels can potentially graze planktonic algae and release phosphorus, from accumulations of biomass and faecal material thereby changing traditional relationships between chlorophyll and phosphorus (Nicholls et al. 1999a). Nicholls et al. (2001) reported nearshore chlorophyll *a* concentrations in the range of 0.13 to 0.19 ugCHLa/ ugTP before mussels arrived. These medians are at the lower part of the range of our data (Fig. 7, Table 1) but are within a factor of two of our means. The nearshore median CHLa:TP ratios after the mussels (Nicholls et al. 2001) are fundamentally different than our offshore data. Nearshore ratios after establishment of Dreissenid mussels were 0.02 to 0.05 , whereas our offshore mean data are in the range of 0.11 to 0.33. Not only are the nearshore ratios much lower than in the offshore zone, but they changed quickly with the appearance of the mussels (Nicholls et al. 1999b). This rapid reduction in the ratio was not apparent in our offshore data. Indeed, there may even have been an increase in the ratio, which is perhaps consistent with an increase in abundance of some phytoplankton groups (Makarewicz et al. 1999). The difference between the two data sets possibly reflects different metabolism and different effects of the new biota on the lake, dependent on depth, stratification, and perhaps substrate type. Our data on offshore ratios may indicate a trend of decreasing values in 2000 and 2001.

Even offshore algal populations assessed by enumeration show different trajectories and little or no change, compared to nearshore populations, where Dreissenid mussels are expected to exert their greatest response (Makarewicz et al. 1999). Clearly, the nearshore data do not well represent the majority of the lake in the offshore area. Still, the nearshore data describe conditions in a habitat thought to be key for the survival of many species of young fish (Ryan et al. 1999). Thus, the nearshore data are important to interpretation of events.

Hypothetically, a decline in chlorophyll per unit phosphorus could be reason for us to alter (i.e., reduce) phosphorus control strategies in that loading

changes would have less impact than would have been expected before the mussel invasion (Nicholls et al. 1999b). However, because there has been no clear change in CHL_a:TP ratio offshore, and because nearshore *Cladophora* growth continues to be a problem (Charlton et al. 2000), any change in phosphorus control strategies would need other justification.

Charlton (1979, 1980a, 1980b, 1993) showed that the supposedly strong relationship between Lake Erie's central basin oxygen budget and phosphorus load was clouded by the sporadic nature of the data set and even biases of the early sampling apparatus. In addition, in-lake factors such as hypolimnion thickness and temperature confused the picture but were as important as the trophic status. Simple modelling (Charlton, 1980b) showed that interannual variation in hypoxia in Lake Erie was part of a natural continuum, and that significant oxygen depletion could be occasionally expected even with very low chlorophyll concentrations. Simple models indicated that the success of the GLWQA would be seen in terms of improved/preserved surface water quality, that hypolimnetic oxygen conditions should improve but not to the extent of eliminating anoxia or habitat problems every year unless phosphorus loads were much lower than at present, that oxygen should not be used as a trophic status indicator without consideration of lake morphology, and that the basis (oxygen depletion) of target phosphorus loads in the GLWQA should be reviewed (Charlton 1979, 1980b; Vollenweider et al. 1980). The present oxygen data are not inconsistent with the predictions of the simple models, given the reservations expressed over 20 years ago (Charlton, 1980a;1980b) although this may be perhaps fortuitous given all the changes Lake Erie has undergone. Recently, the re-appearance of low oxygen conditions following a few better years in the early 1990s has been interpreted by some to mean that conditions have changed for the worse. This would have required an improvement in the first place. Although we have shown that the differences between years is largely a function of physical factors the most telling argument against the proposed changes is the proximity of the 1990 year, with oxygen and P regeneration similar to 1970, (Charlton et al. 1993) to the supposedly improved years in the early 1990s. Such a recovery speed is unlikely. The nutrient loading reductions called for in the GLWQA have had desired water quality effects that were expected except, so far, in central basin oxygen. Thus, it may be time to reconsider the suggestion in Vollenweider et al. (1980) that phosphorus loading targets should be formulated on the basis of surface water characteristics as was done in the other Great Lakes. Nevertheless, surface water quality is good over most of the lake and there is no need at the moment to adjust loads except perhaps in areas impacted by nearshore algae problems Charlton (1999), Charlton et al. (2000).

Research Needs:

Several predictive modelling efforts have been made to take into account various physical factors, nutrient load, and productivity in an effort to project, with little data, the lake's oxygen metabolism and surface water quality as a

consequence of controls on phosphorus loading (for example: Chapra, 1980; Di Toro, 1980, Lam et al. 1987a,b.) Such modeling efforts are valuable as a means to increase understanding and to provide a framework for future in-lake research. However, we feel that expectations of continuing efforts to apply predictive models to current oxygen and phosphorus data should be carefully assessed for two reasons. Firstly, there are now enough data that the Lake Erie oxygen story is self evident up to this time - low oxygen concentrations have not yet disappeared as desired in the GLWQA. Thus, models need to be modified to explain the data already collected. Secondly, the biology of the lake has changed in ways never imagined when monitoring was begun. The appearances of new predacious zooplankton species, mollusc veliger larvae that sink out of the water column, immense populations of adult Dreissenids, and the introduction of gobies have changed energy flow in the ecosystem in ways that may make historical comparisons and assessment of model predictions subject to significant uncertainty. Although oxygen depletion in 1990, before alien mussels could have an effect, was hardly changed from that of 1970 despite 20 years of nutrient reductions and variation has not changed since then it may be tempting to blame the mussels for prolonging the oxygen depletion phenomenon. We see no support for this notion in the data we have. Recently, the NWRI nine-box model (Lam et al. 1987b) has been used to assess the impact of Dreissenids in Lake Erie (Lam et al. 2002). The main findings were that the mussels have had no effect on the dissolved oxygen regime of the central basin. Nutrient concentrations in the west basin were affected most by loads whereas adjustments to model parameters for uptake and sedimentation in the central and east basins were required to account for variation in P concentrations since the arrival of Dreissenids. Refinement of predictive models for Lake Erie would require much more biological work than has been done recently to take into account the present biota in the lake and the continuing introductions of exotic species. Judging from the discrepancies in data between offshore and inshore data more work is required in the nearshore to understand the effects of the mussels and this is where we have concentrated our efforts since 2000 in the east basin. We hope that realization of unexplained phenomena such as the phosphorus perturbations in this paper will help stimulate increased commitment to research needed to understand the lake.

Although the models may need development to provide the means to take into account these changes in lake biota, fundamental regulating factors of hypolimnion thickness, temperature, and primary productivity remain undiminished in importance. Consequently, gross effects of environmental change can be anticipated in general terms. For example, if regional climate change causes Lake Erie to become shallower and warmer (Quinn and Croley II, 1999), we expect, other things being equal, thinner hypolimnia and higher water temperatures to exacerbate the tendency towards oxygen depletion (Atkinson et al. 1999). At the same time, long range climate change may also include effects such as reduced wind speeds, less ice cover, increased duration of stratification,

and a shallower upper mixed layer (Schertzer and Croley II, 1999) which may need more understanding to predict effects on hypolimnion oxygen. Clearly, an understanding of lake physics will be an ongoing requirement if we are to understand other aspects of the lake..

Much of the information on Lake Erie has been gathered in the last thirty years during a period of abundant rainfall and relatively high water levels. The main cohort of present Lake Erie limnologists began their careers at the beginning of this period. The lake seems to be entering a period of lower or more variable levels as has happened several times in the past but this period will coincide with the retirement of a large proportion of present day scientists. A new cohort may be faced with lower lake levels and will develop new information and perhaps new paradigms. Thus, overlap of employment and transfer of experience may be crucial to understanding the emerging state of the lake. Presently, the lake seems to be in transition towards a new ecosystem. The situation has never been so chaotic and yet so exciting for scientific investigations. We lack guidelines to indicate when the accelerating perturbations of the last 50 years will finally even out (if ever). However, management of the lake is crucial if we are to balance our multiple uses of Lake Erie, and this needs scientific information:

- 1) Confirm that municipal phosphorus loads are measured and reported accurately;
- 2) Measure and model nitrogen fluxes to understand the dynamics apparent in the lake and their effect on biota;
- 3) Continue measurements of non-point source loads and determination of their effects on the lake;
- 4) Investigate planktivory and zooplankton effects on water quality;
- 5) Measure dreissenid mussel populations in the whole lake for several years;
- 6) Determine effects of dreissenid mussels on water quality and food webs regionally around the lake;
- 7 Measure sedimentation coefficients of the three basins;
- 8 Determine the factors responsible for the reappearance of *Hexagenia* populations in the west basin and their effects on water quality;.
- 10 Continue to assess hypolimnetic oxygen concentrations in the central basin;.

11 Augment biological studies and training so taxonomists important for assessing the biotic resources are able to maintain an ongoing inventory;.

12 Determine why attached algae continue to dominate some shorelines, resulting in beach closings despite generally good water quality offshore;.

Captions:

Fig. 1. Mean±SD total phosphorus, unfiltered concentrations (TP_{uf}, ug/L) in Lake Erie: monthly mean and standard deviation in June, July, and August.

Fig 2. Mean±SD soluble reactive phosphorus concentrations (SRP, mg/L) in Lake Erie: monthly mean and standard deviation in June, July, and August.

Fig. 3. Mean±SD chlorophyll-a concentrations (ug/L) in Lake Erie: monthly mean and standard deviation in June, July, and August.

Fig. 4. Mean±SD Nitrate plus Nitrite concentrations (mg/L) in Lake Erie: monthly mean and standard deviation in June, July, and August.

Fig. 5 Mean±SD Secchi depth (M) in Lake Erie: monthly mean and standard deviation in June, July, and August.

Fig. 6 Dissolved oxygen concentrations in the central basin hypolimnion (depletion rates determined by linear regression).

Fig. 7. Mean±SD Chlorophyll a : Ltotal phosphorus ratios in Lake Erie, 1970 to 2000.

References

- Atkinson, J.F., DePinto, J.V. and Lam, D.C.L. 1999. Water Quality. *In*: Lam, D.C.L. and Schertzer, W.M. (Eds) Potential climate change effects on Great Lakes hydrodynamics and water quality. National Water Research Institute contribution No. 99-059, Environment Canada.
- Burns, N.M. and Ross, C. 1972. Project Hypo: An intensive study of the Lake Erie central basin hypolimnion and related surface water phenomena. Canada Centre for Inland Waters, Paper No. 6.
- Chapra, S.C. 1980. Application of the phosphorus loading concept to the Great Lakes. *In*: Loehr, R.C., Martin, C.S., Rast, W. (Eds) Phosphorus management strategies for lakes. Ann Arbor Science Publishers inc., 1980 pp 135-152.
- Charlton, M.N., 1979. Hypolimnion oxygen depletion in central Lake Erie: has there been any change? Inland Waters Directorate Scientific Series No. 110, Ottawa, 1979.
- Charlton, M.N., 1980a. Oxygen depletion in Lake Erie: has there been any change? Can. J. Fish. Aquat. Sci. 37:72-81.
- Charlton, M.N. 1980b. Hypolimnion oxygen consumption in lakes: discussion of productivity and morphometry effects. Can. J. Fish. Aquat. Sci. 37: 1531-1539.
- Charlton, M.N., Milne, J.E., Booth, W.G. and Chiocchio, F. 1993. Lake Erie offshore in 1990: restoration and resilience in the central basin. J. Great Lakes Res. 19(2):291-309.
- Charlton, M.N., 1994. The case for research on the effects of zebra mussels in Lake Erie: visualization of information from August and September 1993. Journal of biological Systems. 2(4):467-480.
- Charlton, M.N., LeSage, R., and Milne, J.E. 1999. Lake Erie in transition: the 1990s. State of Lake Erie (SOLE) - Past, Present and Future, pp 97-123. Edited by M. Munawar, T. Edsall & I.F. Munawar, Ecovision World Monograph series, Backhuys Publishers, Leiden, The Netherlands.
- Charlton, M.N., S. L'Italien, T. Howell, P. Bertram, M. Zarull, R. Thoma, D. Culver. 2000. Review of Eutrophication and Undesirable Algae: Preliminary Beneficial Use Impairment Assessment (Lake Erie). Technical Report No. 10, Lake Erie Lakewide Management Plan.

Dermott, R. Mitchell, J., Murray, I., and Fear, E. 1993. Biomass and production of zebra mussels (*Dreissena polymorpha*) in shallow waters of northeastern Lake Erie. *In* Zebra mussels: biology, impacts, and control. Edited by T.F. Nalepa and D.W. Schloesser. Lewis Publishers, Boca Raton, Fla. Pp 399-413.

Dermott, R. and Kerec, D. 1997. Changes to the deepwater benthos of eastern Lake Erie since the invasion of *Dreissena*: 1979-1993. *Can. J. Fish. Aquat. Sci.* 54: 922-930.

Di Toro, D.M. 1980. The effect of phosphorus loadings on dissolved oxygen in Lake Erie. *In*: Loehr, R.C., Martin, C.S., Rast, W. (Eds) Phosphorus management strategies for lakes. Ann Arbor Science Publishers inc., 1980 pp 191-205.

Edsall, T.A., Madenjian, C.P., and Manny, B.A. 1999. Burrowing Mayflies in Lake Erie - a review. *State of Lake Erie (SOLE) - Past Present and Future*, pp. 219-231. Edited by M. Munawar, T. Edsall & I.F. Munawar. Ecovision World Monograph Series, Backhuys Publishers, Leiden, The Netherlands.

Environment Canada. 1979. Analytical Methods Manual. Inland Waters Directorate, Ottawa, Ontario.

Johannsson, O.E., Graham, D.M., Einhouse, D.W.E., and Mills, E.L. 1999. Historical and recent changes in the Lake Erie zooplankton community and their relationship to ecosystem function. *In*: *State of Lake Erie (SOLE) Past, Present, and Future*, pp 169-196. Edited by M. Munawar, T. Edsall & I.F. Munawar. Ecovision World Monograph Series. Backhuys Publishers, Leiden, The Netherlands.

Lam, D.C.L, Schertzer, W.M., and Fraser, A.S. 1987a. Oxygen depletion in Lake Erie: modeling the physical, chemical, and biological interactions, 1972 and 1979. *J. Great Lakes Res.* 13(4): 770-769.

Lam, D.C.L, Schertzer, W.M., and Fraser, A.S. 1987b. Post audit analysis of the NWRI nine-box water quality model for Lake Erie. *J. Great Lakes Res.* 13 (4): 782-800.

Lam, D.C.L., Schertzer, W.M. and McCrimmon, R.C. 2002. Modelling changes in phosphorus and dissolved oxygen pre- and post- zebra mussel arrival in Lake Erie. NWRI Contribution No. 02-198. National Water Research Institute, Environment Canada, Burlington, Ontario.

Lee, G.F., Jones, R.A., and Rast, W. 1980. Availability of phosphorus to phytoplankton and its implications for phosphorus management strategies. *In*:

Phosphorus management strategies for lakes. Loehr, R.C., Martin, C.S., Rast, W. (Eds) (Ann Arbor Science Publishers inc., 1980) pp 259-308.

Lewandowski, K. 1982. The role of early developmental life stages in the dynamics of *Dreissena polymorpha* (Pall.) (Bivalvata) populations in lakes. *Ekologia Polska*, 30, 1-2, 81-109.

Mackie, G.L., Gibbons, W.N., Muncaster, B.W., and Gray, I.M. 1989. The zebra mussel *Dreissena polymorpha*: a synthesis of European experiences and a preview for North America. Water Resources Branch, Ontario Ministry of the Environment . ISBN 0-7729-5647-2, Queen's Printer for Ontario.

Makarewicz, J.C., Lewis, T. W., and Bertram, P. 1999. Phytoplankton composition and biomass in the offshore waters of Lake Erie: pre - and post - *Dreissena* introduction (1983-1993). *J. Great Lakes Res.* 25(1):135-148.

Matisoff, G., and Wang, X. 2000. Particle mixing by freshwater infaunal bioirrigators: midges (Chironomidae: Diptera) and mayflies (Ephemeroidea: Ephemeroptera). *J. Great Lakes Res.* 26:174-182.

Munawar, M., and Burns, N. M. 1976. Relationships of phytoplankton biomass with soluble nutrients, primary production, and chlorophyll a in Lake Erie, 1970. *J. Fish. Res. Board Can.* 33:601-611.

Nicholls, K.H., Standke, S.J., and Hopkins, G.J. 1999a. Effects of dreissinid mussels on nitrogen and phosphorus in north shore waters of Lake Erie. *State of Lake Erie (SOLE) Past, Present, and Future*, pp 323-336. Edited by M. Munawar, T. Edsall & I.F. Munawar. Ecovision World Monograph Series. Backhuys Publishers, Leiden, The Netherlands.

Nicholls, K.H., Hopkins, G.J., Standke, S.J., and Nakamoto, L. 2001. Trends in total phosphorus in Canadian near-shore waters of the Laurentian Great Lakes: 1976-1999. *J. Great Lakes Res.* 27(4):402-422.

Nicholls, K.H., Hopkins, G.J. and Standke, S.J. 1999b. Reduced chlorophyll to phosphorus ratios in nearshore Great Lakes waters coincide with the establishment of dreissenid mussels. *Can. J. Fish. Aquat. Sci.* 56: 153-161.

Quinn, F.H. and Croley II, T.E. 1999. Potential climate change impacts in Lake Erie. *In: State of Lake Erie (SOLE) Past, Present, and Future*, pp 23-30. Edited by M. Munawar, T. Edsall & I.F. Munawar. Ecovision World Monograph Series. Backhuys Publishers, Leiden, The Netherlands.

Regier, H.A., Applegate, V.C. and Ryder, R.A. 1969. The ecology and management of the walleye in western Lake Erie. Great Lakes Fish. Comm. Tech. Rep. No. 15, 101p.

Ryan, P.A., Witzel, L.D., Paine, J. Freeman, M., Hardy, M., Scholten, S., Sztramko, L., and MacGregor, R. 1999. Recent Trends in fish populations in eastern Lake Erie in relation to changing lake trophic state and food web. State of Lake Erie (SOLE) Past, Present, and Future, pp 241-289. Edited by M. Munawar, T. Edsall & I.F. Munawar. Ecovision World Monograph Series. Backhuys jPublishers, Leiden, The Netherlands.

Schertzer, W.M., and Croley II, T.E. 1999. Climate and lake responses. *In*: Lam, D.C.L. and Schertzer, W.M. (Eds) Potential climate change effects on Great Lakes hydrodynamics and water quality. National Water Research Institute contribution No. 99-059, Environment Canada.

Vollenweider, R.A., Rast, W. and Kerekes, J. 1980. The phosphorus loading concept and Great Lakes eutrophication. *In*: Loehr, R.C., Martin, C.S., Rast, W. (Eds) Phosphorus management strategies for lakes. Ann Arbor Science Publishers inc., 1980 pp 207-234.

Wetzel, R.G. 1983. Limnology. Saunders College Publishing

TABLE 1. Monthly means of total phosphorus (Tp(uf) ug/L), soluble reactive phosphorus (SRP mg/L), Secchi depth (M), Nitrate plus Nitrate (NO²+NO³ mg/L), Chlorophyll-a (Chla ug/L), and Chlorophyll to Total Phosphorus ratio (Chla:Tp) in the east, central, and west basins 1999, 2000 and 2001.

East Basin						
1999	Tp(uf)	SRP	Secchi	NO ² +NO ³	Chla	Chla:Tp ratio
June	6.4	0.0003	7.6	0.22	0.7	0.11
July	8.3	N/A	7.8	0.18	N/A	
August	7.3	0.0010	7.9	0.11	0.8	0.11
2000						
June	9.0	0.0018	5.8	0.27	1.1	0.11
July	9.3	0.0009	5.3	0.16	1.6	0.22
August	10.9	0.0015	5.5	0.16	N/A	0.21
2001						
June	6.6	0.0007	6.4	0.20	1.6	0.23
July	5.7	0.0005	6.6	0.17	1.5	0.21
August	6.4	N/A	N/A	N/A	N/A	N/A
Central Basin						
1999	Tp(uf)	SRP	Secchi	NO ² +NO ³	Chla	TP:Chla ratio
June	7.0	0.0005	4.9	0.26	0.4	0.06
July	10.3	N/A	6.0	0.25	N/A	
August	8.7	0.0012	7.1	0.19	1.1	0.13
2000						
June	16.4	0.0020	5.5	0.19	1.8	0.11
July	12.1	0.0007	4.8	0.20	2.1	0.18
August	13.4	0.0016	4.7	0.19	2.6	0.19
2001						
June	No sampling					
July						
August						
West Basin						
1999	Tp(uf)	SRP	Secchi	NO ² +NO ³	Chla	TP:Chla ratio
June	36.5	0.003	3.1	0.69	2.7	0.13
July	16.0	N/A	3.5	0.35	4.4	0.27
August	22.6	0.002	2.4	0.87	8.1	0.33
2000						
June	29.4	0.006	1.8	1.3	4.6	0.18
July	21.4	0.001	2.6	0.81	1.9	0.11
August	18.1	0.002	1.9	0.65	7.1	N/A
2001						
June	No sampling					
July						
August						

Table 2. Oxygen depletion rates derived by linear regression and hypolimnion thicknesses for the eastern and central basins 1983 to 2001.

Year	EAST BASIN		CENTRAL BASIN	
	Slope (mg/L/day)	Hypolimnion Thickness (m)	Slope (mg/L/day)	Hypolimnion Thickness (m)
1983	-0.06	17.2	-0.08	4.4
1984	-0.05	21.7	-0.10	4.5
1985	-0.04	21.5	-0.08	2.2
1990	n/a	n/a	-0.13	3.1
1993	-0.04	13.5	-0.07	5.1
1994	-0.04	11.0	-0.07	4.0
1995	-0.06	13.3	-0.07	4.4
1996	-0.04	14.0	-0.07	5.8
1997	-0.05	12.7	-0.07	3.8
1998	-0.04	11.6	-0.09	3.4
1999	-0.06	8.7	-0.09	3.7
2000	-0.07	7.7	-0.12/-0.09	3.0
2001	-0.05	14.1	n/a	n/a

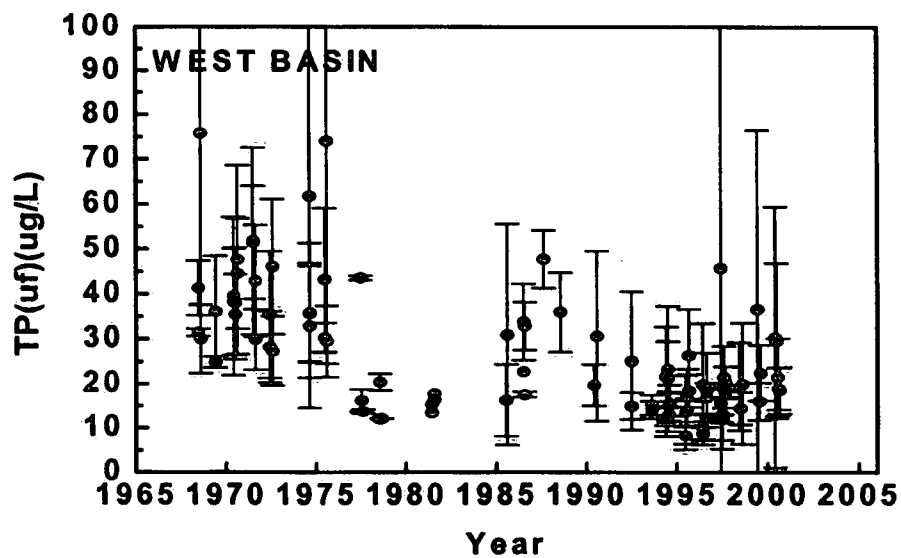
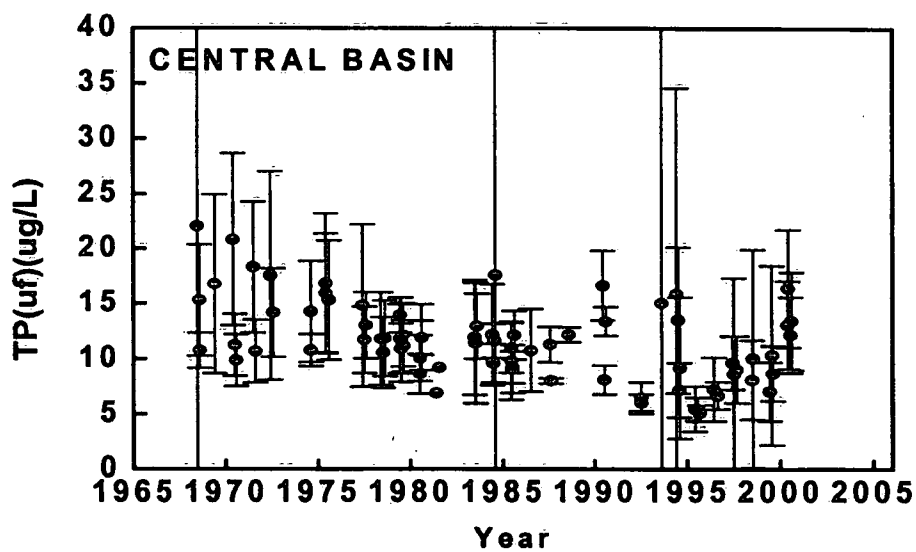
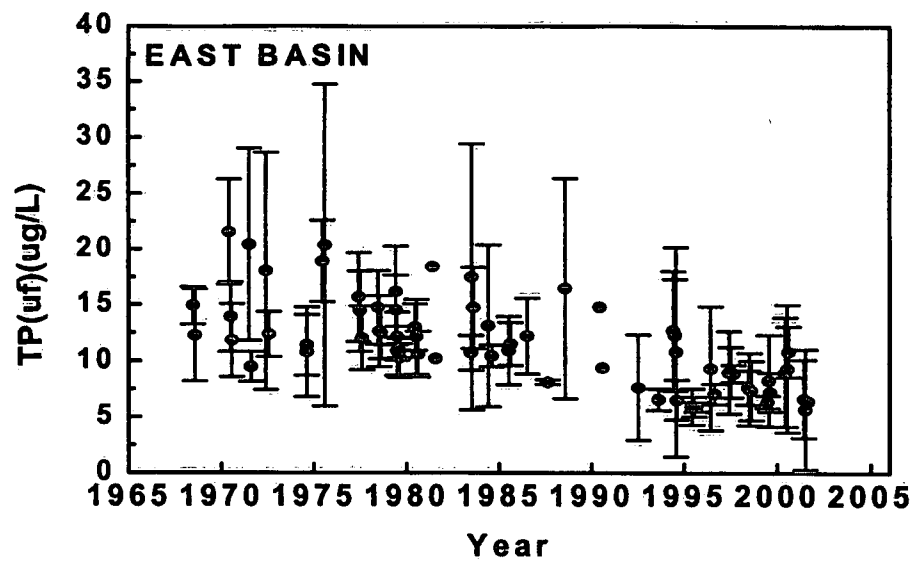


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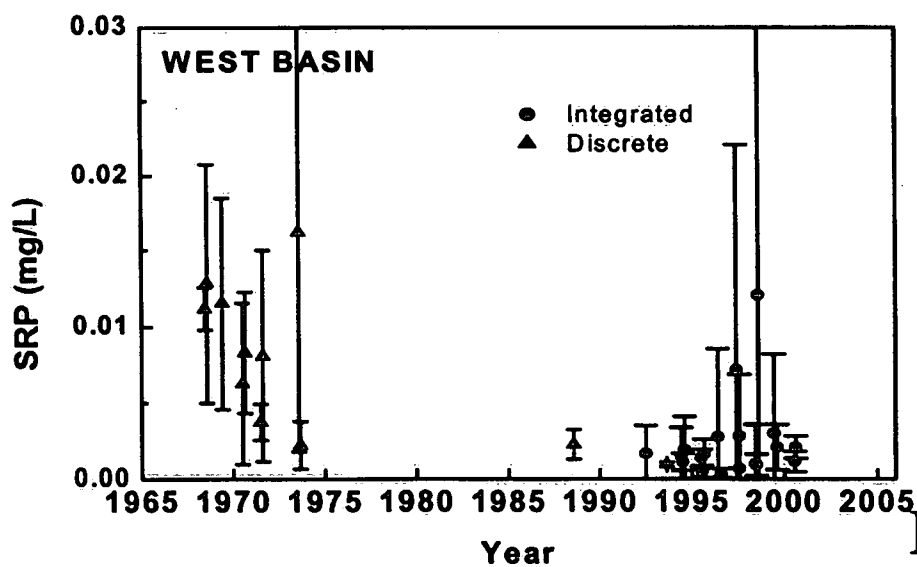
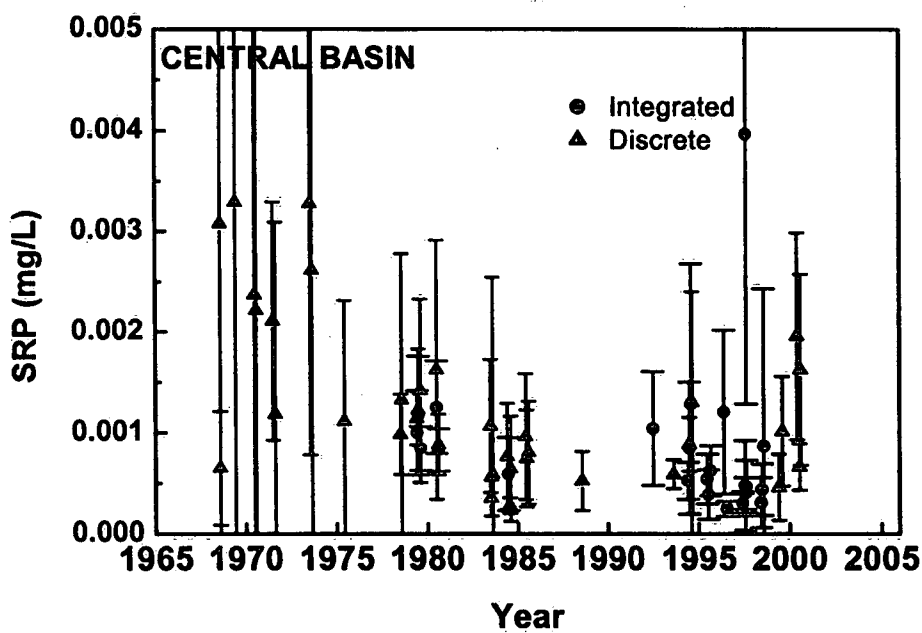
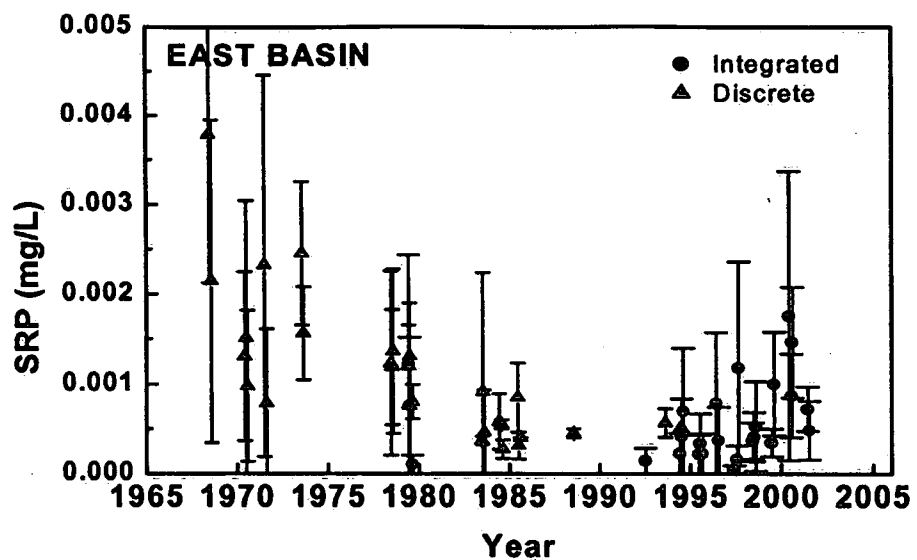


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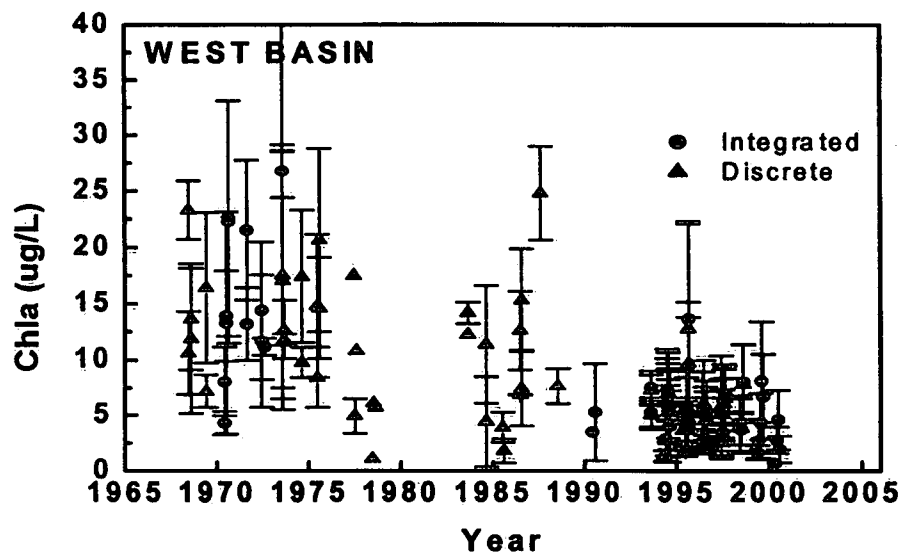
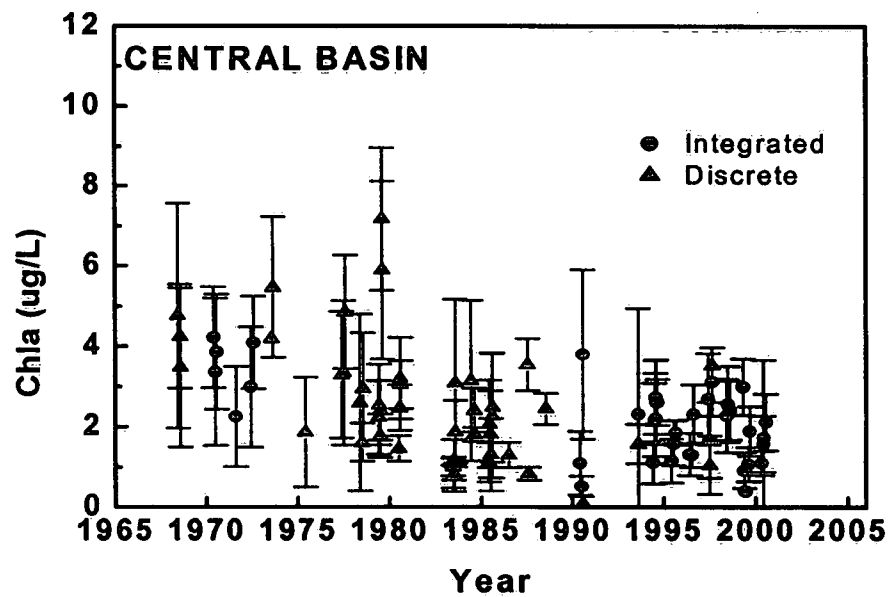
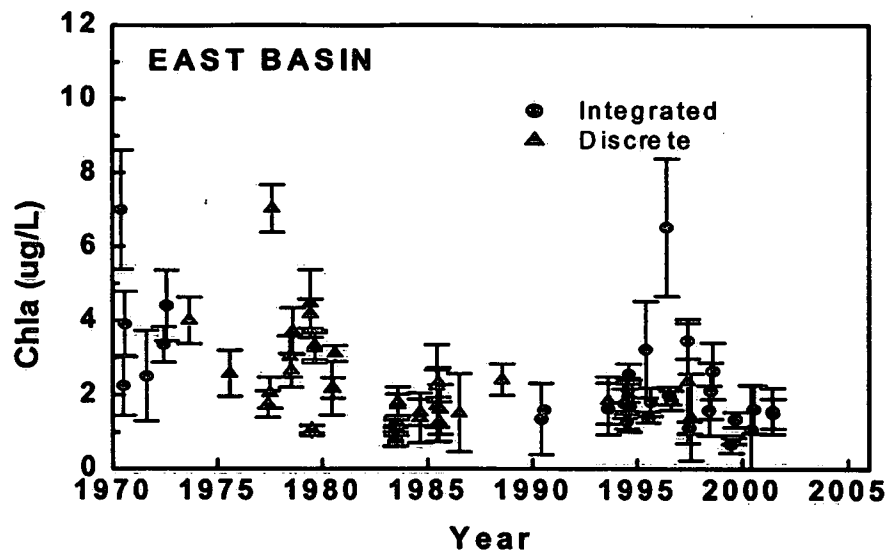


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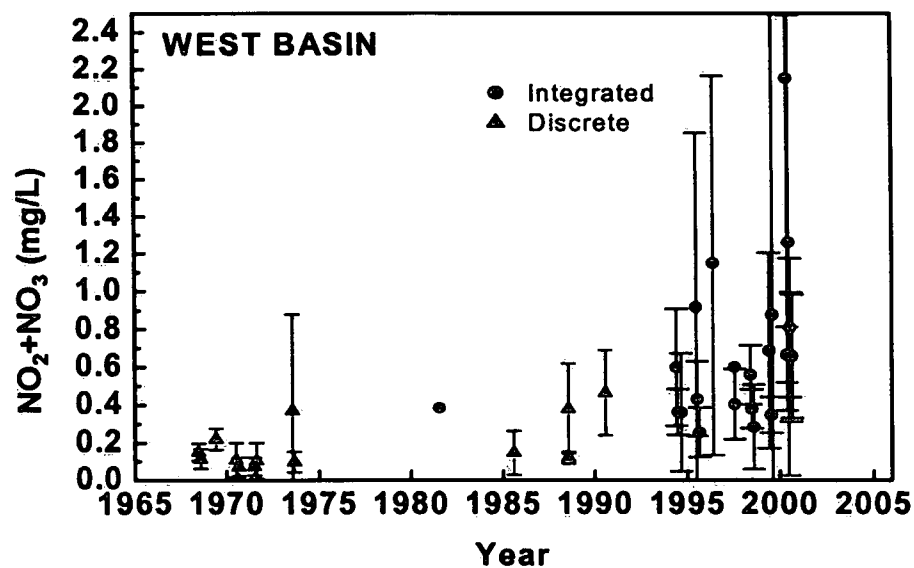
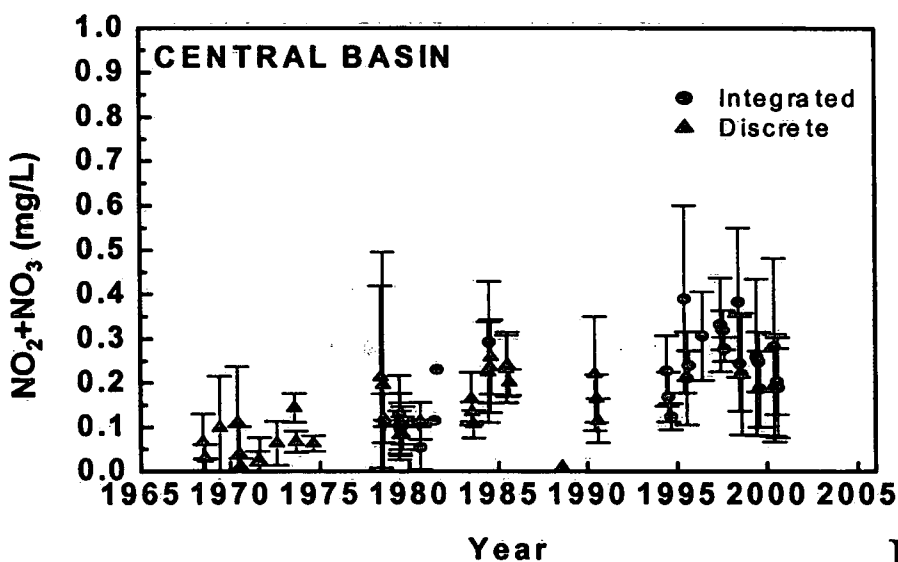
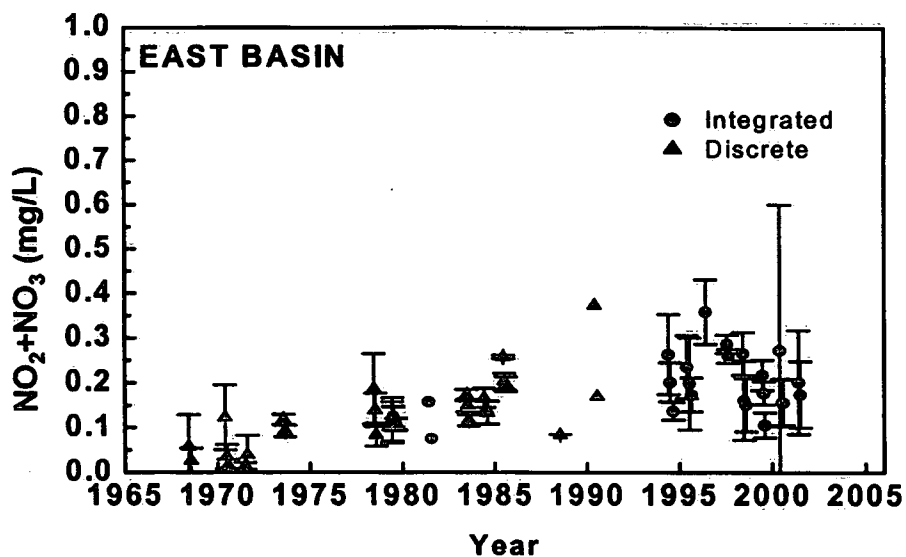


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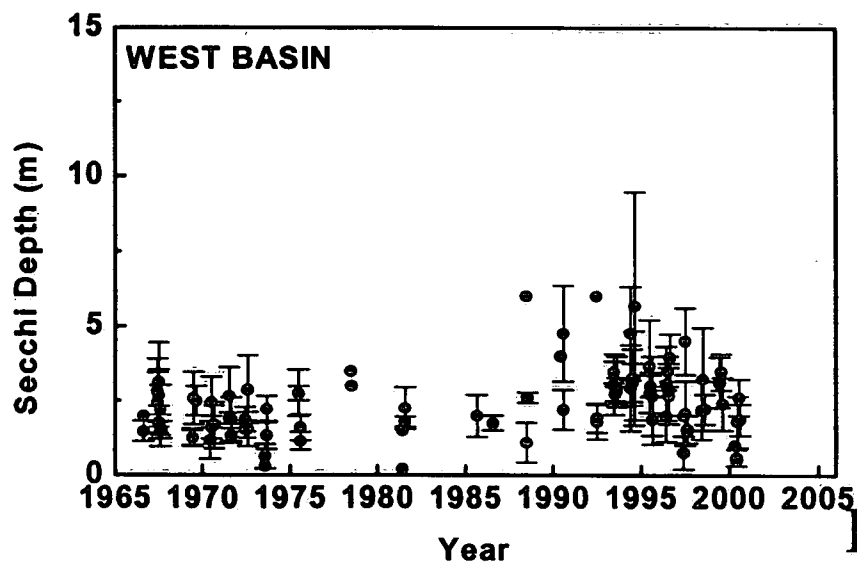
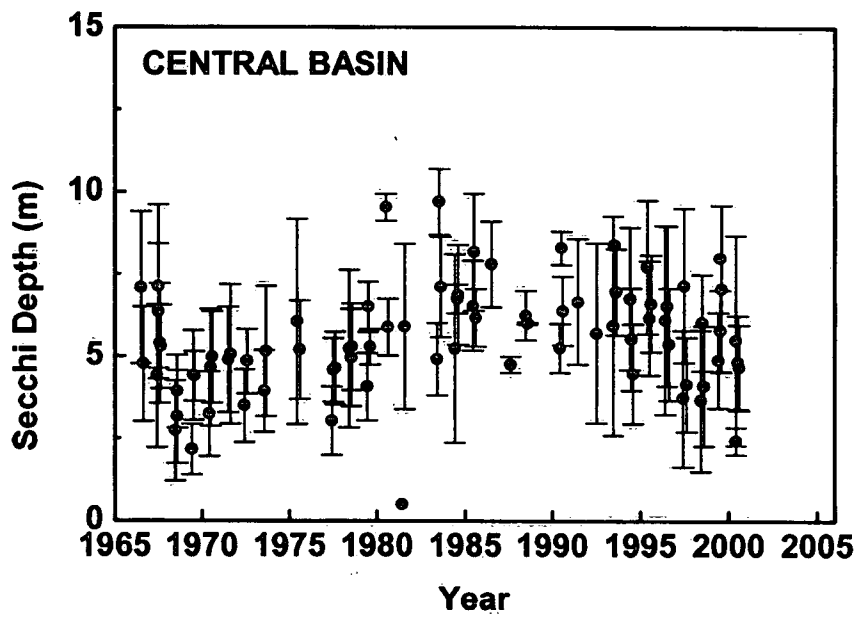
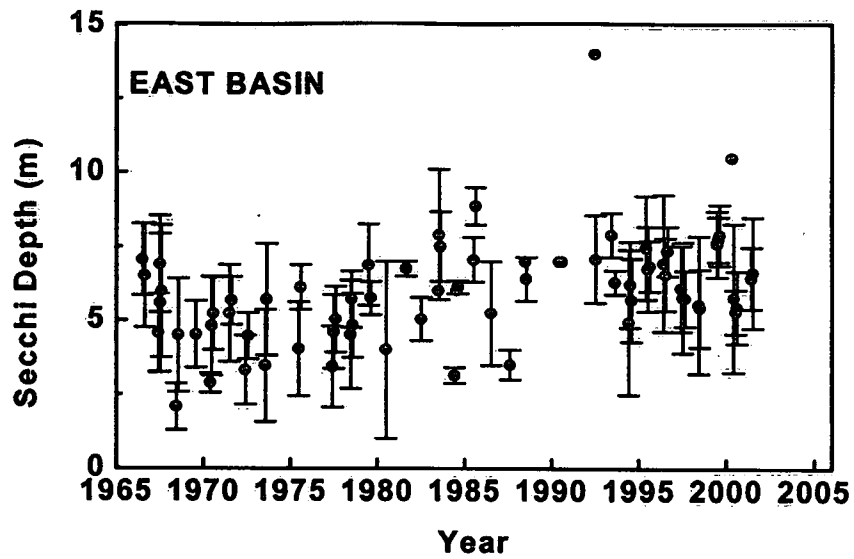


Figure 5

Lake Erie Central Basin Dissolved Oxygen

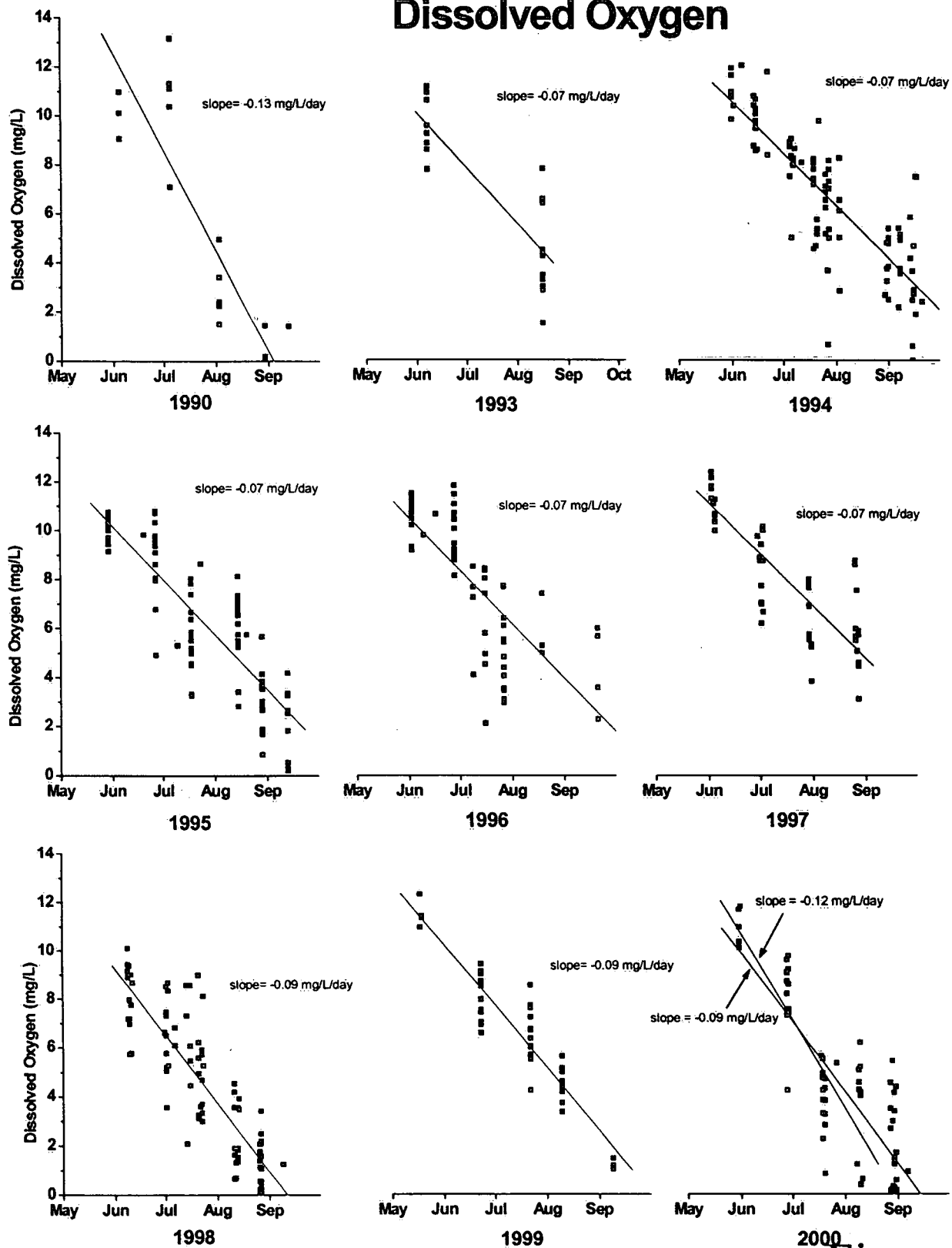


Figure 6

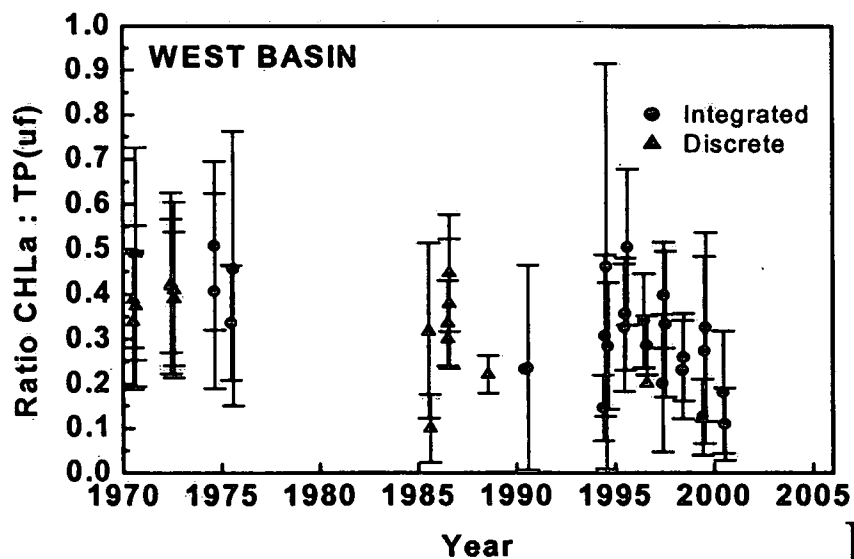
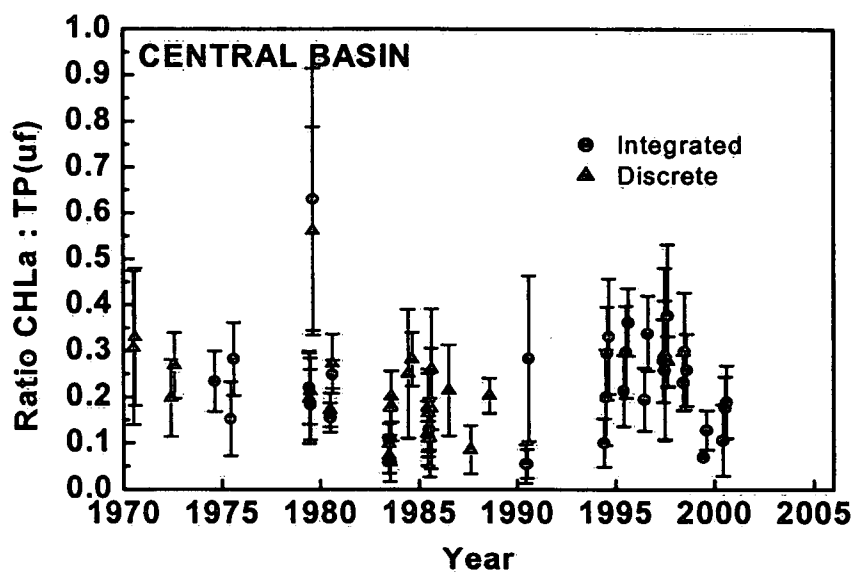
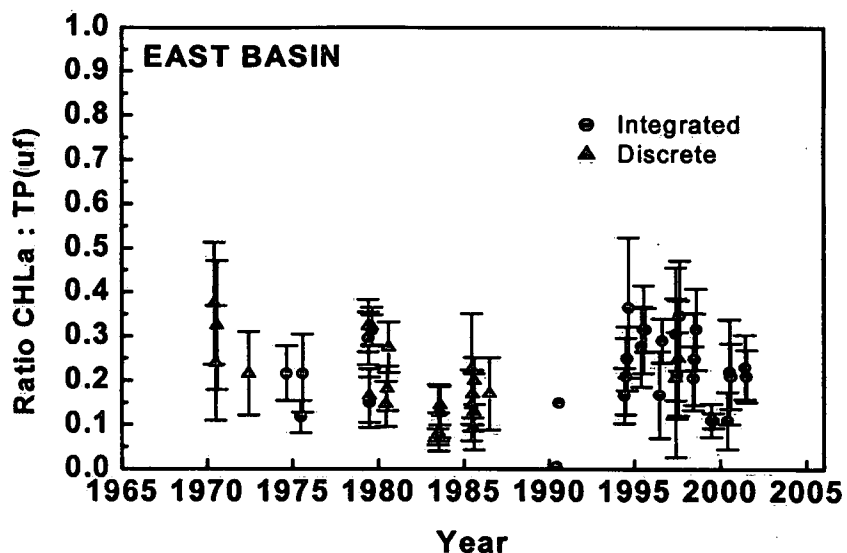


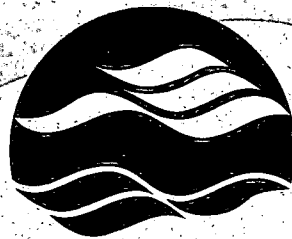
Figure 7

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