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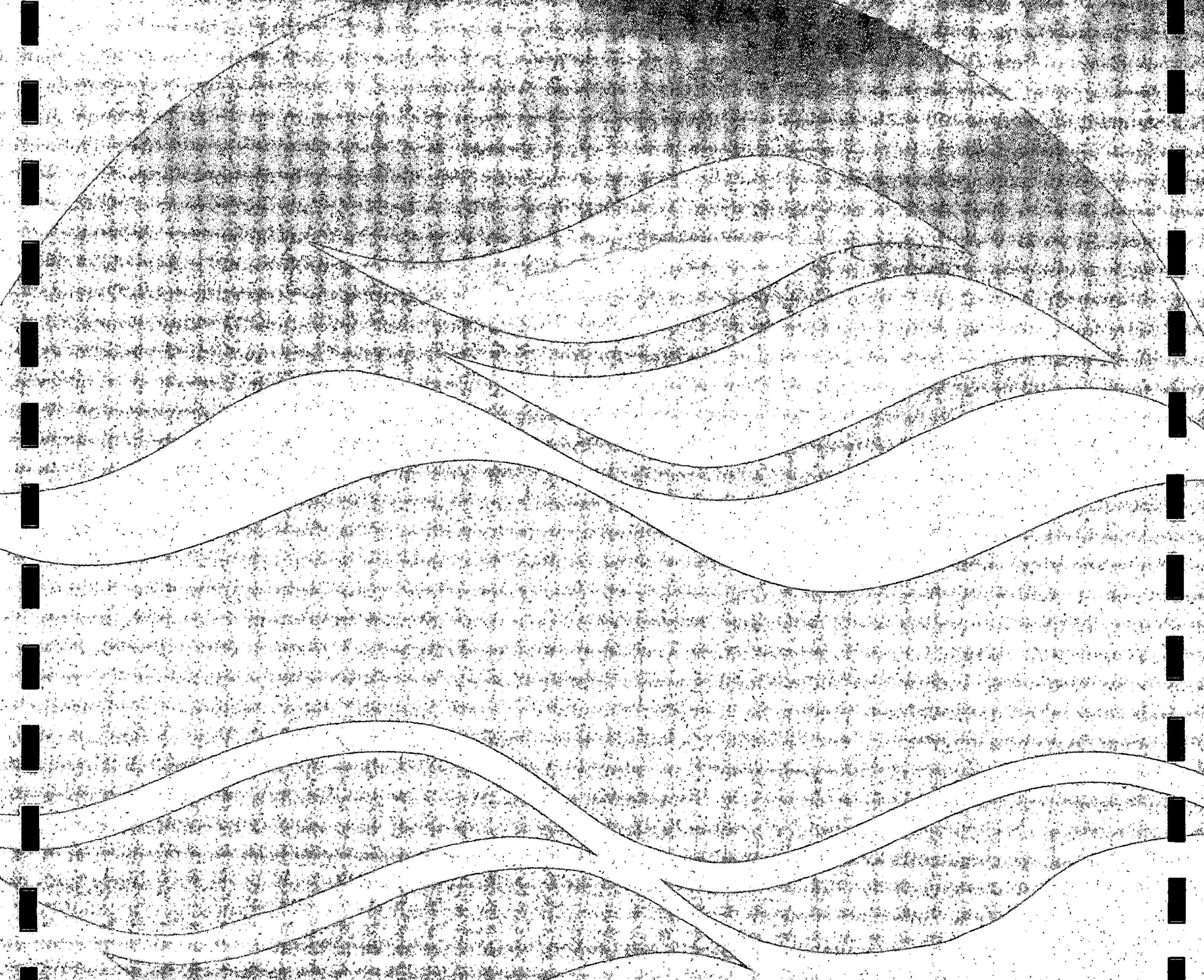

Lake Erie in transition: the 1990's

by

M.N. Charlton, R. Le Sage and J.E. Milne

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Management Perspective

Great Lakes 2000, Lake Erie LaMP, phosphorus management policy, fisheries.

Lake Erie's response to GLWQA nutrient load controls and zebra mussels was assessed with data between 1968 and 1997. Nutrient load reductions caused a reduction by about 50% in chlorophyll (algae) in the central and east basins before mussels arrived. Larger changes occurred in the west basin. A previous relationship between algae population and photosynthesis was used to predict that lake production fell, in the central and east areas, 35%-46% due to lower nutrients and a further 12%-15% due to mussels. Phosphorus decreased in the central and east basins after Zebra mussels but most of the loss has been recovered in 1996 and 1997. Relative to demands for more fish production, moderate relaxation of nutrient restrictions would have little benefit and would likely stimulate blue green algae and exacerbate the problem of filamentous algae on shorelines. Advises continuation of present phosphorus management policy.

Publish in scientific journal, communicate to LaMP process.

This Management Perspective is currently being translated into French.

ABSTRACT

The initial scientific work on Lake Erie in the late 1920s was conducted due to concerns about declining fisheries and water quality. Following sporadic surveys in the 1950s and early 1960s intensive monitoring and research was begun in the late 1960s. Intensive eutrophication was found in the lower Great Lakes and the Great Lakes Water Quality Agreement (GLWQA) between Canada and the U.S. was signed in 1972. The phosphorus load into Lake Erie was halved as a result. Effects were regional with more relative change in the more damaged west end of the lake. In the majority of the lake the results show a small but significant reduction in nutrient and chlorophyll concentrations. About the time the nutrient load goals were achieved in the mid-1980s the exotic Dreissena sp. mussels were introduced. Since then there have been statements that the mussels can filter the whole lake in a short period or that they have cleaned up the whole lake by their filtering actions. In addition, there have been suggestions that nutrient controls should be relaxed in order to stimulate the food chain and produce more fish. The long term data show how little could be accomplished in most of the lake with moderate reversal of phosphorus removal policy. The long term data also show that, except in the west basin, lake turbidity hasn't changed much due to the mussels. A lack of nearshore data however hampers assessment of the mussels where they may have the most effect. Nevertheless the long term data are very useful for elucidating lake changes, sorting fact from fiction, and managing expectations of the Lake Erie ecosystem.

This Abstract is currently being translated in French.

Lake Erie in transition: the 1990's

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1. Introduction

Lake Erie has been damaged by sewage pollution, agricultural runoff, industrial contamination, and fisheries over-exploitation. In the early 1970's the Great Lakes Water Quality Agreement (GLWQA) between Canada and the United States of America brought about reductions in nutrient pollution and toxic chemical contamination. The goals for target nutrient loads were achieved in the mid 1980's. Phosphorus concentrations were reduced by 50% in the west basin and contamination of biota decreased while better fisheries management enabled recovery of the valuable walleye population.

While the GLWQA was successful in pollution control, the objective of protecting and restoring 'ecosystem integrity' was undermined by introductions of exotic species at increased rates in the last 20 years. The introductions of *Bythotrephes cederstroemi*, *Dreissena sp.*, gobies, and the inevitable arrival of the ruffe are and will change the lake. Change will continue; Lake Erie will not recover from the invasions of exotic species. Some years ago the ability of the exotic mussels to alter the existing phosphorus-algae-oxygen paradigm was recognized. (Makarewitz and Bertram, 1991; Charlton *et al.*, 1993; Charlton, 1994). The spread of the mussels over soft sediment continues (Coakley *et al.*, 1997) and this will continue to change the lake. Ultimately, the mussels and other exotics together with the nutrient load reductions and exploitation management are causing *a lake in transition*. In this paper we report on the nutrient status of Lake Erie and the changes in water quality measured by recent research.

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2. Methods

Samples were collected aboard CSS Limnos at up to 60 stations (figure 1) with depths greater than 15 m in the central and east basins and throughout the west basin during 1997. The dates of the sampling cruises in 1997 are shown in Table 1 and these are typical of work in 1990, 93, 94, 95 and 96. 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 0-10M in the west basin. Sample aliquots were placed in bottles immediately for total phosphorus (TP-UF) and were filtered immediately and placed in bottles and stored at 4 C for later analyses for soluble reactive phosphorus (SRP), nitrate plus nitrite (NO_3NO_2-F) and filtered phosphorus (TP-F). Samples for uncorrected chlorophyll-a (UncorCHLa or Chlorophyll-a) were filtered immediately and the filters were stored frozen until analysis. Samples were analysed (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. Contour maps were computed by the 'RAISON' software package (Lam *et al.*, 1994).

Data for trend presentations were obtained from files of the National Water Research Institute (NWRI) in the CCIW, Burlington, Ontario. For purposes of comparability, only Canadian data were used (Charlton *et al.*, 1993). Data for surface water from either discrete depth samples up to 10 m deep or integrated from 0 to 10 m were used for June, July, and August. Restriction of the analysis to the June, July, August summer period is a way to minimize interference caused by gradually reduced sampling efforts since 1970. Station depths were greater than 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 early June data which sometimes represent spring conditions. To illustrate changes in the lake the data were summarized in Tables 8 to 12 as means for the periods 1968 to 1972, 1984 to 1988, and 1994 to 1996. Tables 8 to 12 show the means for June, July, and August as well as the mean for the summer period as well as the probability associated with a 't' test between the summer data in the successive periods.

3. Results

3.1. Conditions in 1997

Phosphorus concentrations in all three basins were greater than the GLWQA targets of 10 μgP l^{-1} (central and east basins) and 15 μgP l^{-1} (west basin) in the spring and declined until very low values occurred in July. Figure 2 shows the seasonal variation in mean total phosphorus (TP-UF) for surface water in the four basin areas in 1997. The highest datum in early July in the west basin was due to one high value of 79 μgP l^{-1}. Otherwise, values were surprisingly low in the west basin. Although most of the cruise means were similar to those of the mid 1980's in the central basin the values that occurred in early July were unprecedented. Previously,

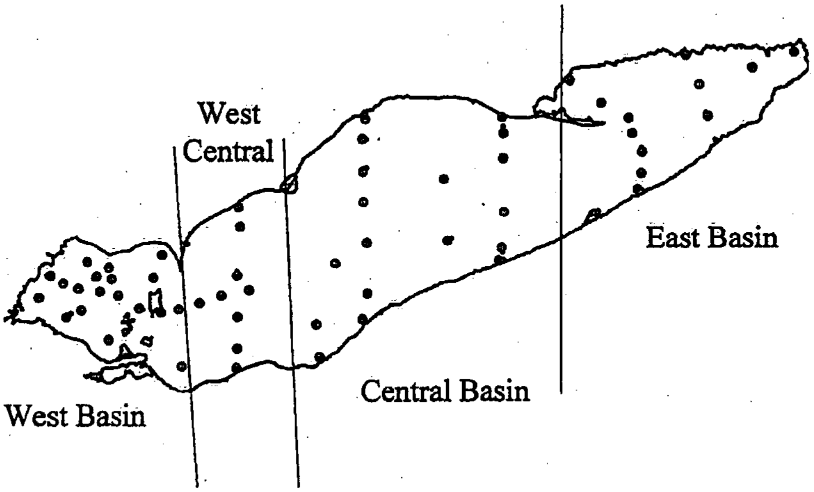

Fig. 1. Map of station locations in 1997.

Table 1. Dates of sampling cruises in 1997.

Cruise #	CCIW Cruise #	Dates
1	02	6-9 May, 1997
2	04	2-5 June, 1997
3	06	30 June–3 July, 1997
4	08	28 July–1 August, 1997
5	10	25-29 August, 1997

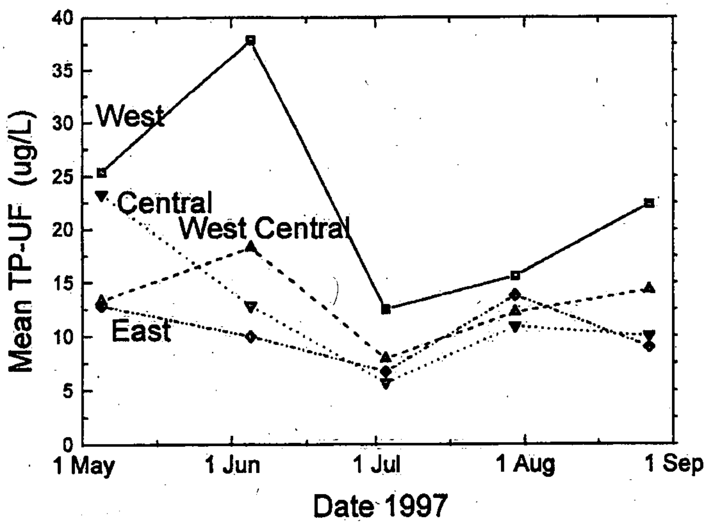

Fig. 2. Season cruise means of total phosphorus in 1997.

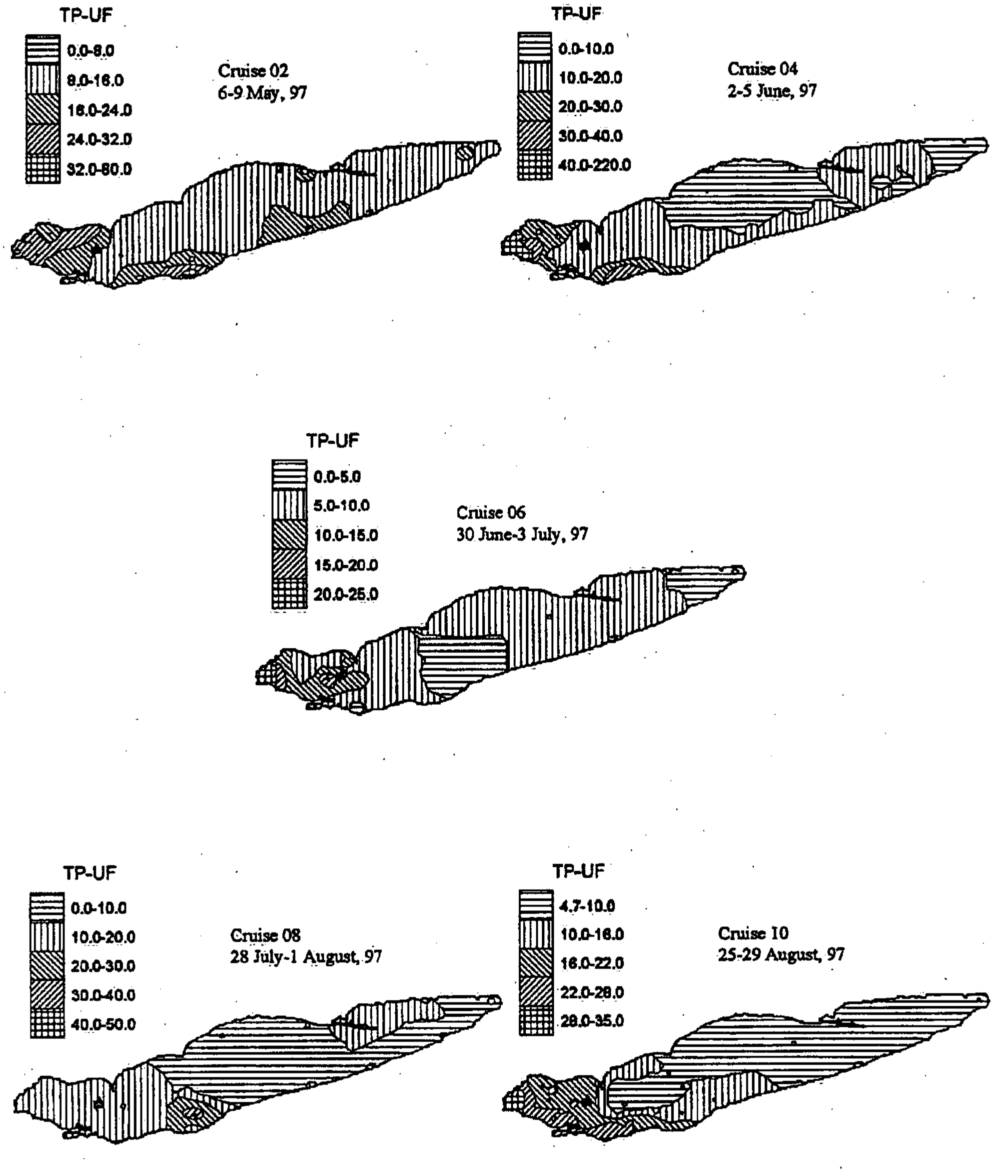

Fig. 3. Spatial distribution of total phosphorus (μgP l^{-1}) in 1997.

Table 2. Total phosphorus in 1997 (µgL^{-1}) average and standard deviation.

	Basin							
Cruise	East		Central		W. Central		West	
	avg	std	avg	std	avg	std	avg	std
1	13.3	9.0	11.7	5.2	12.2	4.5	25.4	8.0
2	1.6	2.7	9.6	2.4	17.3	9.8	34.9	49.4
3	6.5	2.3	5.2	1.7	6.1	0.9	12.5	6.1
4	9.9	2.2	11.4	10.9	12.0	1.4	14.8	2.8
5	8.9	0.8	9.0	3.0	11.9	5.7	21.8	6.2
Mean	9.8	3.2	9.6	5.8	12.1	6.5	22.6	26.6

East n=9; Central n=11; W. Central n=6; West n=15

the lowest cruise means were 7.5 to 8.0 µgP l^{-1}. In early July 1997 the minima in the east, central, west central and west basins were 4.9, 2.9, 3.7. and 5.1 µgP l^{-1} respectively; corresponding means were 7.1, 5.7, 7.9, and 12.5 µgP l^{-1} respectively.

Spatial contouring of the water quality data is a useful way to summarize both the area corresponding to concentration ranges and the location of high concentration sources. Figure 3 shows spatial distribution patterns of TP-UF generated by a contouring algorithm in the software package 'RAISON' (Lam *et al.*, 1994). The shapes constructed by the software are arbitrary but the areas corresponding to ranges of data represent the data well. The algorithm was adjusted to render a compromise between unusual data and the need to portray widespread spatial trends. Thus, outstanding data were not suppressed but the areas they were allowed to represent were minimized. For example, in May, there was one TP-UF value of 79 µg l^{-1} near Cleveland and this elevated the mean for the central basin to 23 µg l^{-1} whereas the mean for west central stations was 13 µg l^{-1} and the map shows that most of the basin TP-UF values ranged 8 to 16 µg l^{-1}. Similarly, there was a very high value of 215 µgP l^{-1} near Toledo in early June and this raised the basin mean to 37.9 µgP l^{-1} whereas as typical values were about 20 µgP l^{-1}.

Typically, there was a strong west to east gradient in chemical parameters consistent with the existence of substantial loads in the west basin. By early June (figure 3) there were substantial areas of the central and east basins with total phosphorus less than 10 µgP l^{-1} but also there were large areas from 10 to 20 µg l^{-1}. By the end of June all of the central and east basins was below 10 µgP l^{-1} and much of the west basin was below 20 µgP l^{-1}. By the end of July most of the central and east basins had less than 10 µgP l^{-1} (Table 2) and phosphorus concentrations in the west basin and part of the east basin ranged from 10 to 20 µgP l^{-1}. In late August, central and east basin total phosphorus concentrations were typically near 10 µgP l^{-1} whereas concentrations were slightly higher in the west central areas and were near 20 µgP l^{-1} in the west basin.

There did not appear to be a fundamental difference between the basins or the surveys in the proportion of phosphorus that was particulate matter (TP-UF – TP-F)/(TP-UF) during the surveys (Table 3). There was, however, a consistent mini-

Table 3. Percentage particulate phosphorus of total phosphorus (cruise averages) in 1997.

	Basin			
Cruise	East	Central	W. Central	West
1	32	56	63	68
2	58	56	49	59
3	21	38	29	18
4	54	71	67	57
5	61	60	33	58

Table 4. Cruise averages and standard deviation of Nitrate+Nitrite (mgN l^{-1}) in 1997.

	Basin							
Cruise	East		Central		W. Central		West	
	avg	std	avg	std	avg	std	avg	std
1	.40	.05	.34	.13	.30	.14	.60	.09
2	.40	.06	.33	.11	.41	.15	1.13	1.41
4	.29	.02	.32	.05	.47	.07	.42	.19
5	.26	.02	.28	.03	.24	.03	.42	.21
Mean	.33	.08	.31	.09	.36	.14	.62	.77

East n=10; Central n=11; W. Central n=6; West n=10

Table 5. Cruise averages and standard deviation of Soluble Reactive Phosphorus (μgP l^{-1}) in 1997.

	Basin							
Cruise	East		Central		W. Central		West	
	avg	std	avg	std	avg	std	avg	std
1	.68	.19	.54	.25	.50	.30	1.30	.10
2	.27	.05	.30	.12	.20	n/a	7.20	14.9
4	.36	.16	.43	.30	.30	.15	.60	.13
5	.87	1.18	1.6	2.30	.20	n/a	3.50	4.40
Mean	.52	.56	.65	.65	.40	.20	3.60	8.60

East n=10; Central n=9 W. Central n=4 West n=8

Table 6. Chlorophyll to phosphorus ratio, cruise averages and standard deviation in 1997.

	Basin							
Cruise	East		Central		W. Central		West	
	avg	std	avg	std	avg	std	avg	std
1	.14	.09	.31	.12	.46	.20	.17	.11
2	.27	.17	.28	.09	.31	.19	.20	.15
3	.21	.13	.21	.13	.16	.03	.41	.12
4	.25	.11	.33	.17	.41	.06	.38	.12
5	.35	.12	.36	.15	.42	.07	.32	.16
Mean	.25	.14	.30	.14	.36	.17	.28	.17

East n=10; Central n=13; W. Central n=6; West n=13

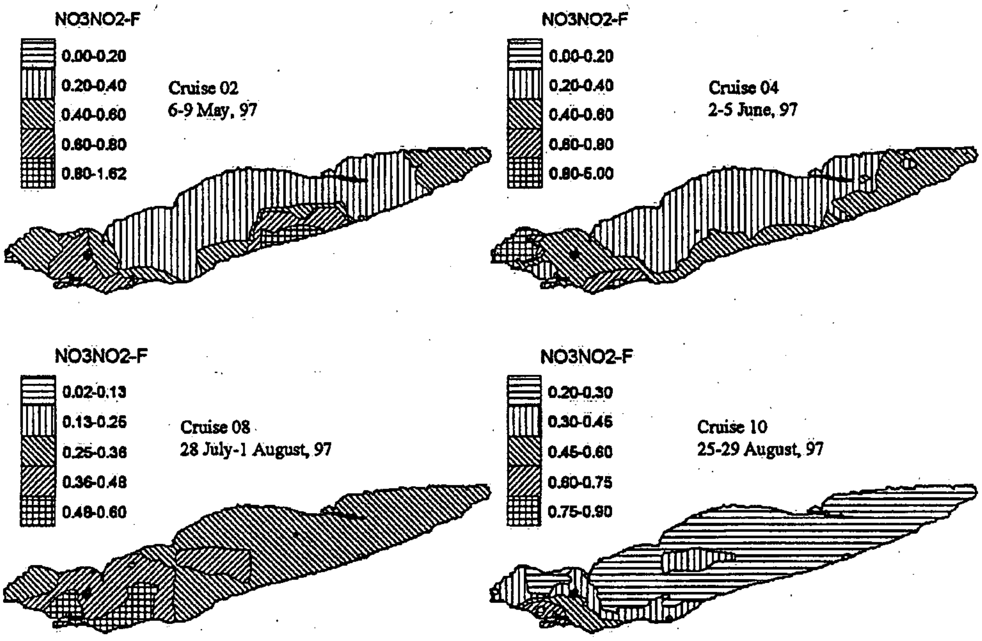

Fig. 4. Spatial distribution of dissolved nitrogen (nitrate + nitrite mgN l^{-1}) in 1997.

mum in the middle of the summer. Compared to data in 1970, (Charlton, 1994) there seems to be no systematic change in these data.

The spatial pattern for nitrate + nitrite (NO_3NO_2-F) was similar to that of total phosphorus (figure 4). Again, there tended to be a west to east gradient and there was one very high value near Toledo in the early June survey. Soluble nutrients tended to be somewhat higher in the early part of the season (Tables 4 and 5) during 1997. Generally, soluble nitrogen tended to be in the range 0.24 to 1.13 mgN l^{-1} and SRP was almost non-existent with many values less than 1 µgP l^{-1} except in the west basin where mean values were as high as 7.2 µgP^{-1}. A notable exception was in the west basin during the second cruise when, again, one sample near Toledo had very high total and soluble nitrogen and phosphorus concentrations. Nevertheless both SRP and nitrogen tended to be highest in the west basin and this may reflect loads and recycling by mussels in the shallow water.

The spatial distribution of chlorophyll in 1997 followed that of the nutrients with a west to east gradient and a tendency for higher concentrations along the south shore of the central basin in early June (figure 5). In early June the east and central areas had 1 to 6 µgChla l^{-1}. By the end of June the entire east and central basin area had chlorophyll concentrations of less than 2 µg l^{-1}. In late July, chlorophyll increased somewhat in the north part of the east basin and the west part of the central basin.

There was a typical decrease in chlorophyll in the central and east basins in midsummer 1997 (figure 6). Standard deviations for the cruise averages in figure 6 are

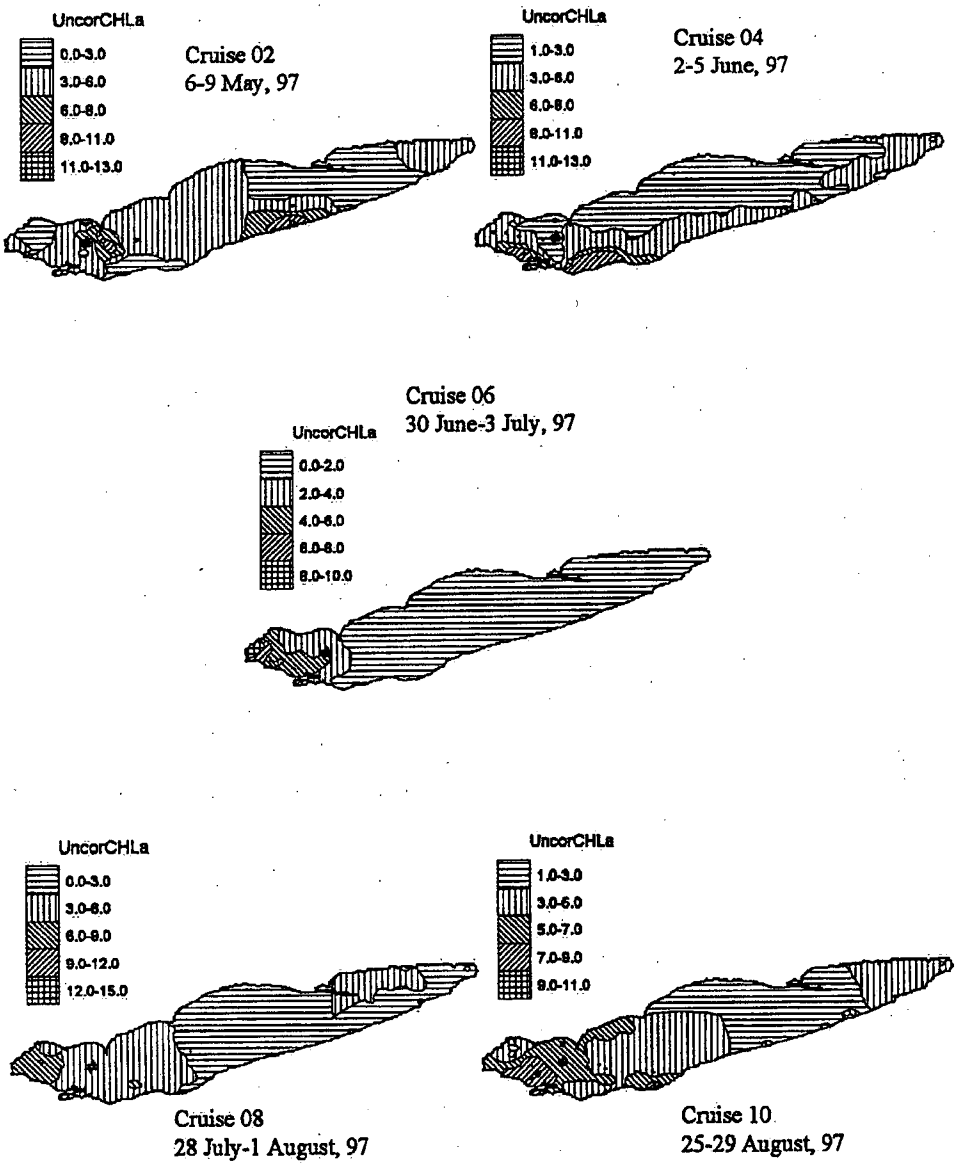

Fig. 5. Spatial distribution of Chlorophyll-a (μg l^{-1}) in 1997.

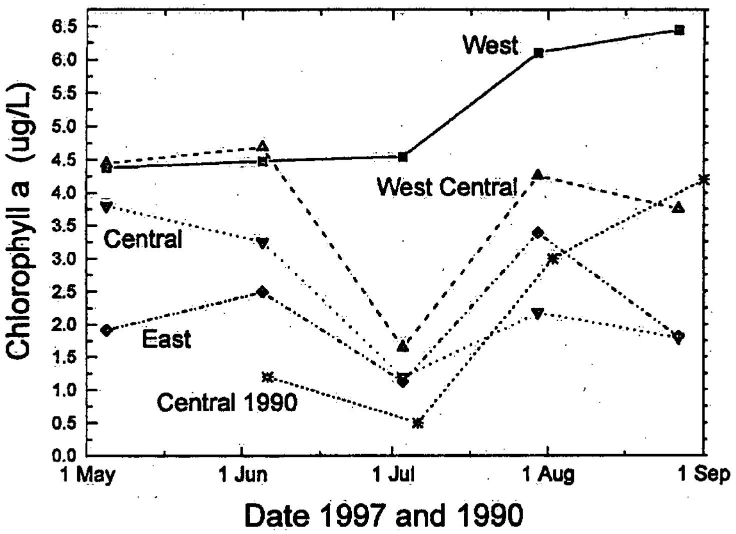

Fig. 6. Seasonal change in Chlorophyll-a in the four basin areas in 1997 and in the central basin in 1990.

on the order of 2 μg l^{-1} for the east and central basins and 5 μg l^{-1} for the west basin. Data from 1990 were included in figure 6 for comparison. For much of the summer period, chlorophyll in 1990 was lower than in 1997.

Unlike the systematic west to east gradient in nutrient concentrations there wasn't a spatial trend in the of the ratio of chlorophyll to total phosphorus during 1997 (figure 7). Indeed, relative to other measures, the distribution of the ratio was patchy. At higher TP concentrations early in the 1990 season (Charlton *et al.*, 1993) the ratios were lower. In late July and August in both 1990 and 1997 the ratios were similar. The lowest Chl-a to TP ratios tended to be in the east basin although similar ratios were found in other basins (table 6). The lowest values of 0.15 and 0.16 in the east basin and 0.17 in the west basin are in the range thought to indicate a high degree of grazing (Graham *et al.*, 1996).

The spatial pattern of Secchi depth had the typical west to east gradient (figure 8). Extremely clear water occurred in the eastern end of the central basin during the third cruise with a maximum Secchi disk visibility of 12 m. Clarity at west central basin stations tended to be intermediate between west basin and central basin stations (Table 7). Relatively clear water occurred in the west basin during the third and fourth cruises. Spatial differences occurred in and between basins.

3.2. Trends

Trend data are summarized in a series of figures (9 to 13) and tables (8 to 12). In general, changes in the data were of the same scale or less than the error bars surrounding data in any one month. The tables show changes between the pre and post-nutrient reduction periods and the subsequent period post-mussels. The more sig-

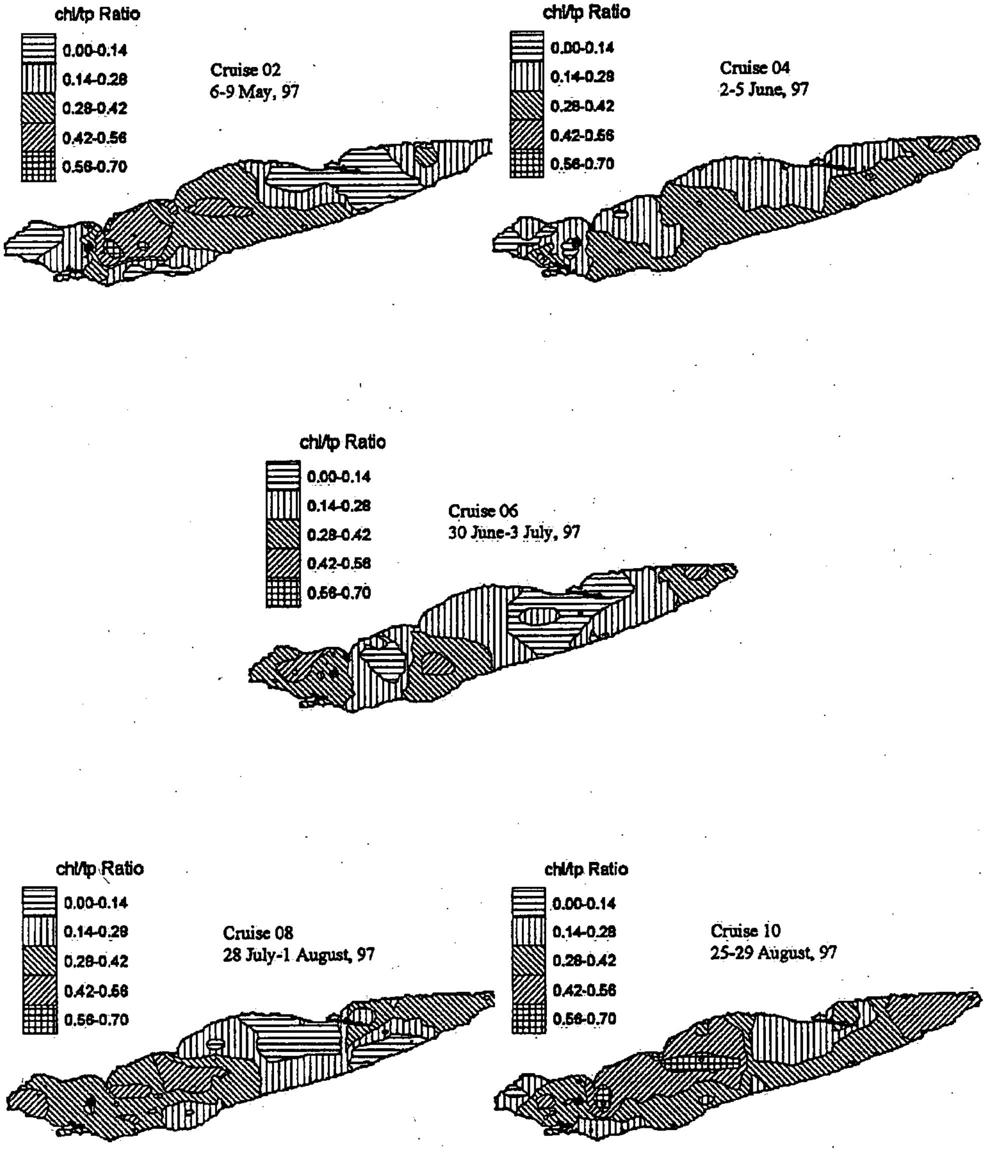

Fig. 7. Spatial distribution of Chlorophyll to total phosphorus ratio in 1997.

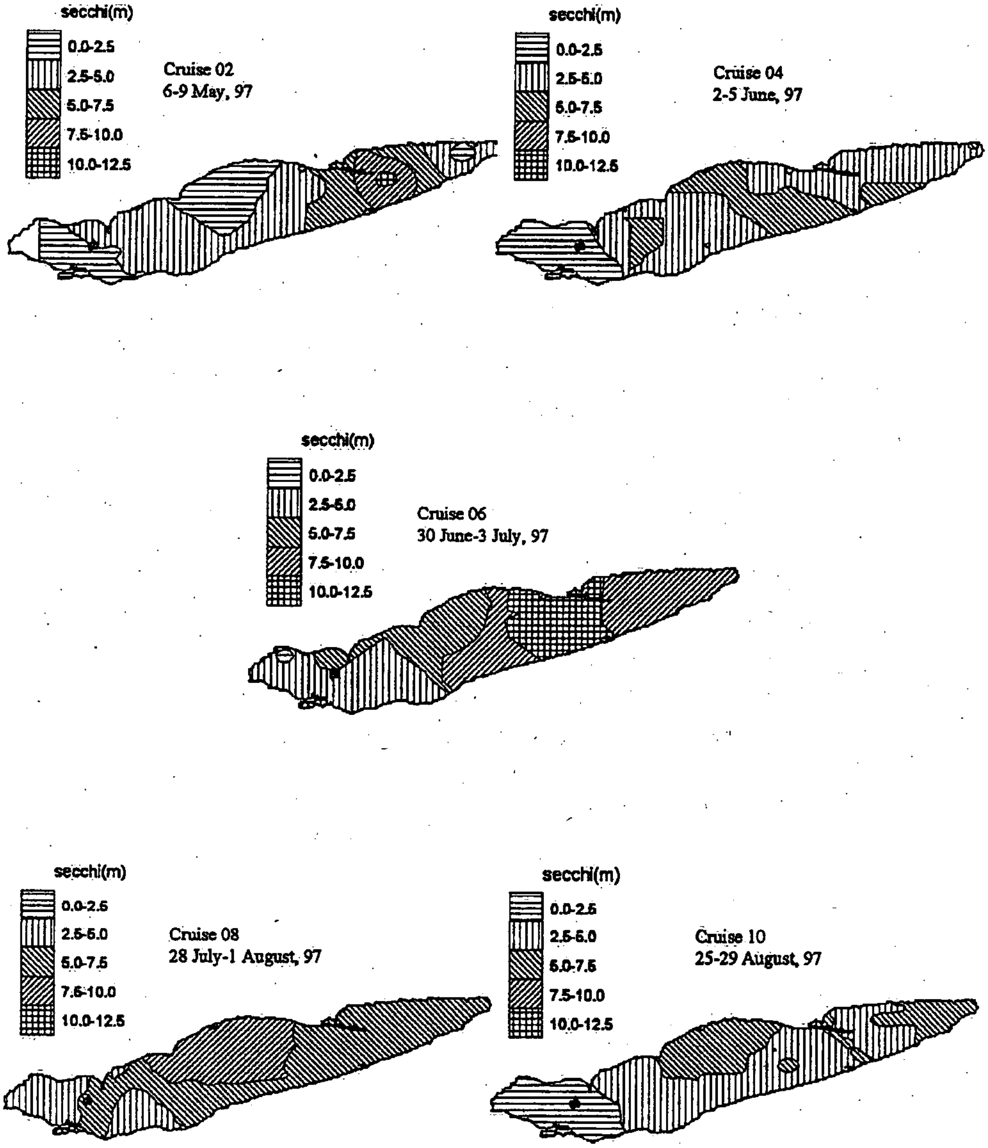

Fig. 8. Spatial distribution of Secchi depth (m) in 1997.

Table 7. Secchi depths cruise averages and standard deviation in 1997 (m).

	Basin							
Cruise	East		Central		W. Central		West	
	avg	std	avg	std	avg	std	avg	std
1	1.0	n/a	2.6	1.6	3.6	1.1	n/a	n/a
2	5.5	0.5	4.1	1.5	2.8	2.3	0.9	0.7
3	7.4	1.3	7.5	3.6	n/a	n/a	3.8	1.3
4	6.9	01	7.8	1.2	4.3	03	3.0	n/a
5	5.8	1.0	3.5	2.1	4.0	n/a	1.2	0.3
Mean	6.2	1.7	4.9	2.6	3.4	1.3	1.9	1.5

East n=5; Central n=8; W. Central n=2; West n=9

nificant changes were associated with 't' test probabilities that would cause rejection of the hypothesis that the changes happened by chance.

Phosphorus decreased in the east basin during the nutrient load reductions and there was a further decrease and subsequent increase following the mussel invasion. The trend in total phosphorus in the four basin areas is shown in figure 9 A, B, C, D. In the East basin (figure 9A) there was a tendency for the highest monthly means to become lower. Interestingly, there were many instances of fairly low cruise means in the range of 10 to 12 μg l^{-1} even at the beginning of the data set. It is difficult to judge the magnitude of the phosphorus decrease due to the GLWQA from the graphs because the change is within the standard deviations of the cruise average data. The data are compared for trends in a series of tables that compare the period 1968 to 1972 with the period 1984 to 1988 (pre-mussels). A subsequent comparison is made between 1984 to 1988 and 1994 to 1996 (post-mussels). A relative decrease of about 2.8 μgP l^{-1} occurred up to 1988 (Table 8). In 1994 and 1995 very low phosphorus concentrations occurred with means in 1995 in the range of 5 to 6 μgP l^{-1}. In 1996 and 1997 phosphorus increased again to a mean of 9.8 μgP l^{-1} which is close to the GLWQA spring goal of 10 μgP l^{-1} in springtime.

Phosphorus also decreased in the central basin (figure 9B) similar to the east basin (Table 8) in the era of load reductions until the mid 1980's. There was a decrease that bottomed out with one cruise mean of 5 μgP l^{-1} in 1995 after the mussel invasion. In 1996 and 1997 phosphorus increased with a return to means in the range 9.0 to 11.7 in 1997 (Table 2). The frequency of high values has decreased with time. Similar changes occurred with less definition in the west central area (figure 9c).

The largest change in phosphorus loads occurred in the west basin and concentrations there ought to follow the loads. From typical mean concentrations of 41 μgP l^{-1} in the 1970's, the nutrient controls in the GLWQA reduced the concentration of phosphorus to 35.5 μgP l^{-1} in our data according to the analysis in Table 8. Other data in figure 9 are consistent with a decrease to 20 μgP l^{-1} or less according to the more numerous data of Lesht *et al.*, (1991) and Williams *et al.*, (1998) by the mid 1980's. In the mid 1990's, concentrations have decreased so that mean concentrations of 12.5 to 25.4 μgP l^{-1} that occurred in 1997 are typical. Some cruise means

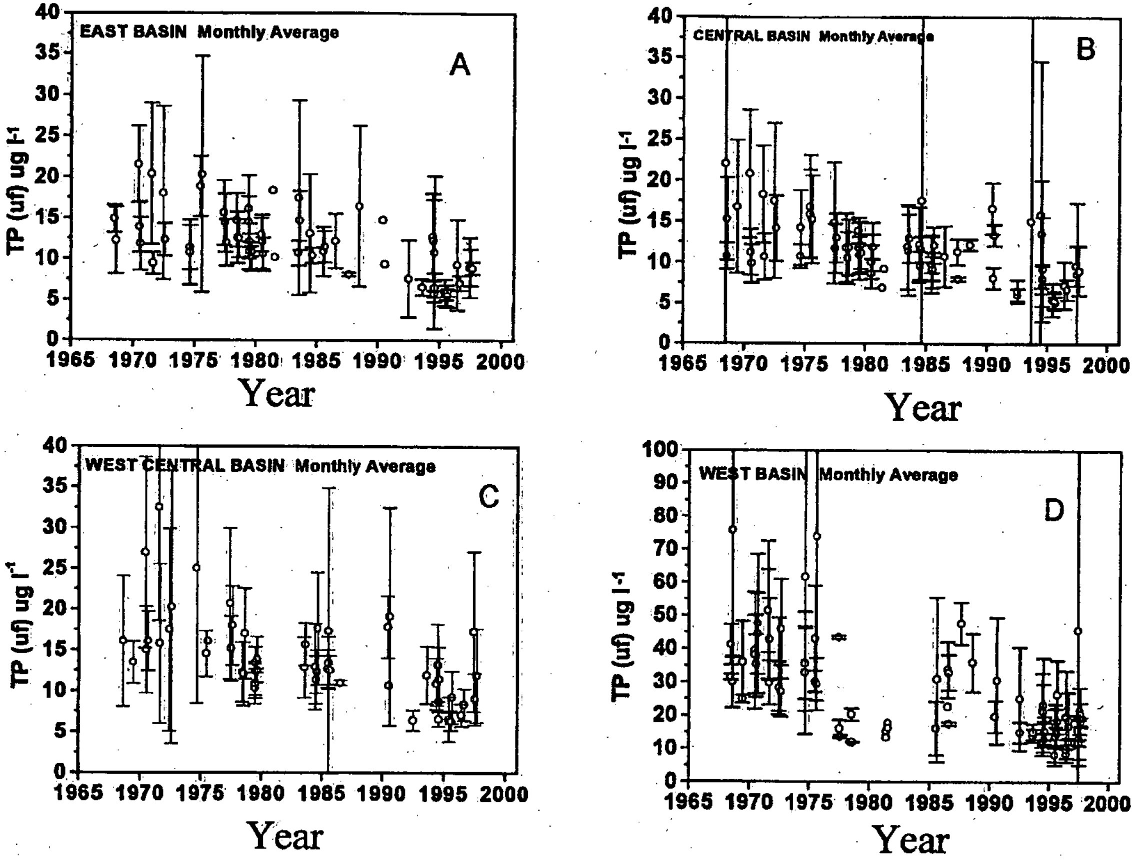

Fig. 9. Trend of total phosphorus (TP-UF µgP l^{-1}) in Lake Erie. Circles are monthly means for June, July, and August, bars represent standard deviation.

Table 8. Change in total phosphorus between 1968-72 and 1984-88 and 1994-96 ($\mu g l^{-1}$).

Basin	Period	June	July	August	Summer	Change	P (t test)
EB	68-72	18.7	15.5	11.2	14.7		
EB	84-88	12.8	12.6	10.2	11.9	-2.8	0.003
EB	94-96	9.0	8.9	6.2	8.0	-3.9	<0.001
CB	68-72	19.0	12.2	11.6	14.1		
CB	84-88	11.5	9.9	11.0	10.9	-3.2	<0.001
CB	94-96	9.0	9.6	6.6	8.4	-2.5	<0.001
WC	68-72	21.3	19.0	17.9	19.3		
WC	84-88	12.5	15.5	14.8	14.2	-5.1	0.008
WC	94-96	8.3	10.2	9.1	9.0	-5.2	<0.001
WB	68-72	34.6	41.3	41.2	41.2		
WB	84-88		29.3	33.5	35.5	-5.7	0.003
WB	94-96	16.3	18.2	17.4	17.7	-17.9	<0.001

Table 9. Change in nitrate plus nitrite between 1968-72 and 1984-88 and 1994-96 ($mg l^{-1}$)

Basin	Period	June	July	August	Summer	Change	P (t test)
EB	68-72	0.11	0.03	0.03	0.04		
EB	84-88	0.19	0.16	0.16	0.17	+0.13	<0.001
EB	94-96	0.27	0.20	0.15	0.22	+0.09	<0.001
CB	68-72	0.12	0.38	0.03	0.05		
CB	84-88	0.23	0.22	0.24	0.22	+0.17	<0.001
CB	94-96	0.30	0.18	0.17	0.23	+0.01	0.817
WC	68-72	0.16	0.07	0.04	0.08		
WC	84-88	0.13	0.36	0.25	0.27	+0.19	<0.001
WC	94-96	0.41	0.25	0.31	0.33	+0.06	0.179
WB	68-72	0.21	0.09	0.10	0.12		
WB	84-88		0.12	0.15	0.14	+0.02	0.125
WB	94-96	0.82	0.38	0.31	0.56	+0.42	<0.001

Table 10. Change in chlorophyll between 1968-72 and 1984-88 and 1994-96 ($\mu g l^{-1}$)

Basin	Period	June	July	August	Summer	Change	P (t test)
EB	68-72	5.5	5.1	3.6	4.9		
EB	84-88	1.8	2.1	3.5	2.8	-2.1	0.005
EB	94-96	2.3	2.0	2.1	2.1	-0.7	0.311
CB	68-72	6.9	3.5	3.6	5.0		
CB	84-88	2.5	1.8	2.3	2.3	-2.7	<0.001
CB	94-96	1.2	2.1	2.3	1.8	-0.4	<0.001
WC	68-72	4.6	4.1	9.6	6.6		
WC	84-88	2.0	2.4	3.0	2.5	-4.0	<0.001
WC	94-96	1.5	3.2	4.3	2.8	+0.2	<0.414
WB	68-72	12.0	13.5	16.1	13.8		
WB	84-88		8.4	8.3	8.3	-5.5	<0.001
WB	94-96	3.8	5.5	7.5	5.6	-2.8	<0.001

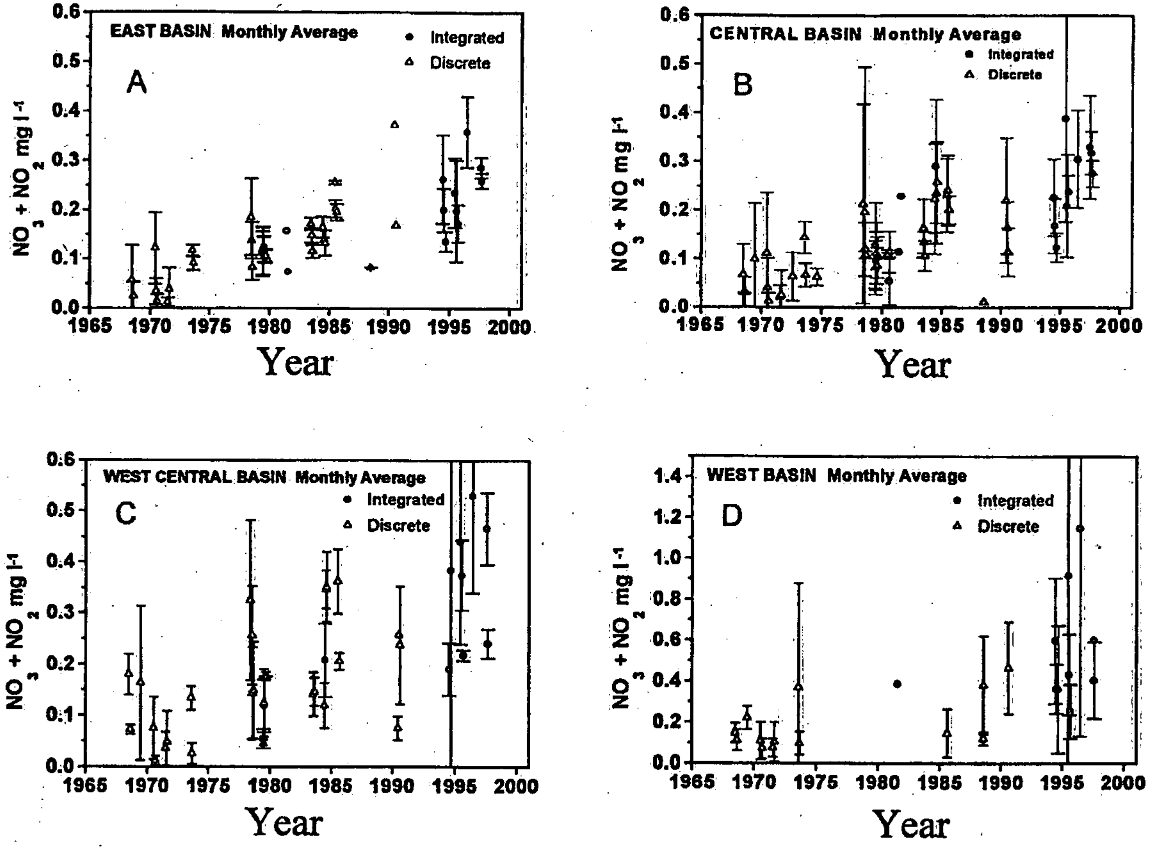

Fig. 10. Trend in nitrate + nitrite concentrations in offshore stations of the four basin areas in June, July, and August. Circles are monthly means for June, July, and August, bars represent standard deviation.

were near or slightly below 10 μgP l^{-1} which was normally thought to occur in the central and east basins.

There has been a trend to higher summer nitrate+nitrate concentrations in all four areas since the late 1960's. Figure 10 shows the available cruise mean nitrate+nitrite data for samples in June July and August in Lake Erie. Table 9 enumerates the changes in nitrate + nitrate that occurred over the period of nutrient reductions and then during the mussel invasion. The concentration of summer nitrate+nitrate increased roughly by a factor of four or more in all areas of Lake Erie except the west basin during nutrient load reductions. A large nitrate+nitrite increase occurred in the west basin coincident with the mussel invasion according to our data. The highest nitrate+nitrite concentrations now occur in the west basin and this is consistent with the sewage treatment practices, which mainly remove phosphorus but not nitrogen.

Algal populations as indicated by chlorophyll concentrations have decreased during the phosphorus loading reductions until the mid 1980's. Cruise mean data for chlorophyll in the four basin areas are shown in figure 11. Present data in the mid-1990's strongly overlap data in the 1970's. Nevertheless, chlorophyll has decreased by about 50% in the central and east basins and by about 40% in the west basin during the nutrient reductions (Table 10). Interestingly, chlorophyll in the mid 1990's is similar to the mid 1980's. Typical concentrations now in summer are around 2 μg l^{-1} in the east and central basins and around 5 μg l^{-1} in the west basin. In a few samples, chlorophyll was almost non-existent in the central and east basins in 1997. On the other hand, very low chlorophyll concentrations have been observed in each basin area since 1985 which was before the mussel invasion.

Secchi depths measured in summer increased by 2 to 2.4 m in the east and central basins and hardly at all in the west basin during the nutrient reductions (Table 11 and figure 12). There has been a decrease in low Secchi observations in the east basin but the upper range of typical observations now appears similar to that of the mid 1980's. Secchi depths changed from 4 to 5 m to about 6.5 m in the central and east basins during the nutrient load reduction up to the 1980's.. The tendency for increased frequency of west basin Secchi depths greater than 3 m post-mussels noted by 1993 (Charlton, 1994) has continued and this has resulted in a mean increase of 2.2 m. Paradoxically, many recent observations in the west basin are similar to those in the 1970's.

The available data for chlorophyll and total phosphorus are combined as a ratio of chlorophyll to phosphorus in figure 13. Low numbers for the ratio are thought to indicate excessive grazing of phytoplankton; this is of great interest now due to the recent invasion of *Dreissena sp.* Figure 13 shows there have always been ratios lower than the 0.14 to 0.17 thought to indicate excessive grazing in nearshore (1993-94) east basin stations (Graham *et al.*, 1996). More typical offshore ratios of 0.23 to 0.31 found in 1993 and 1994 by Graham *et al.*, (1996) are representative of the middle of the range found historically in our offshore data in figure 13. Interestingly, there was a decrease in the chla/tp ratio associated with nutrient reductions and an increase in the ratio for these offshore data in the period following the mussel invasion of the central and east basins (Table 12).

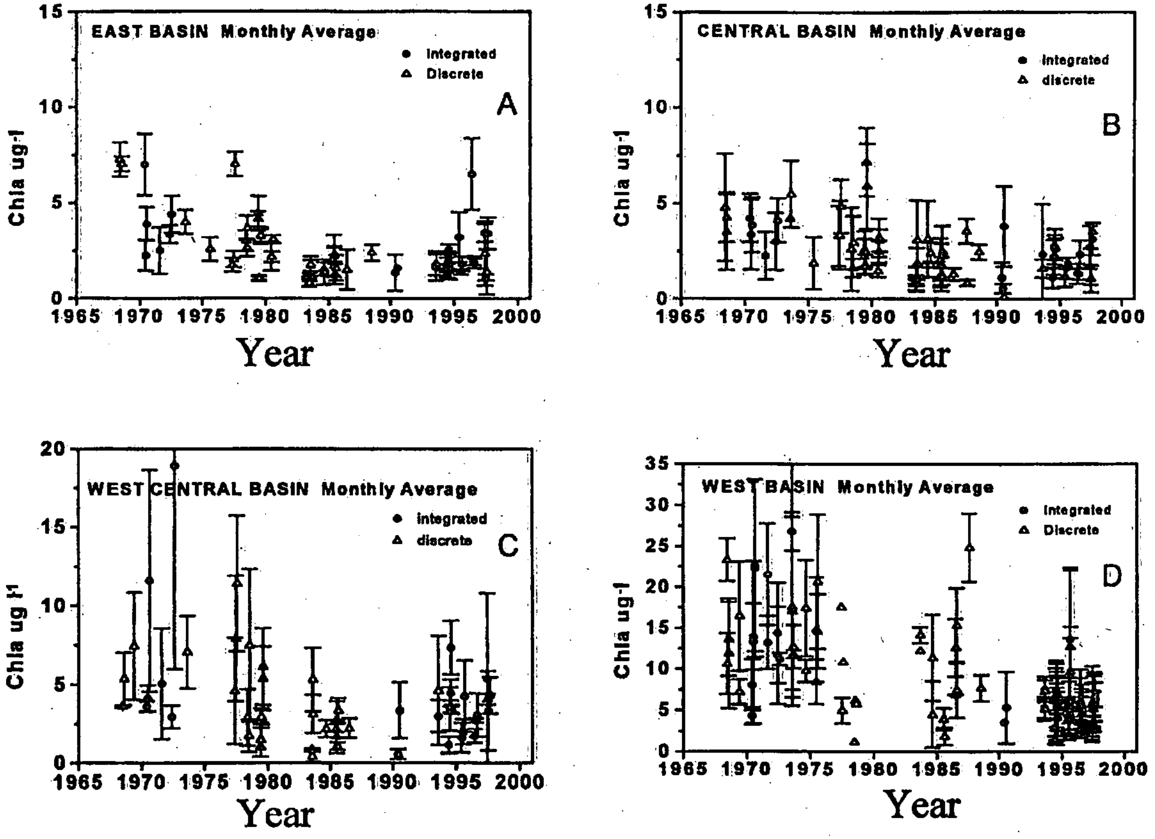

Fig. 11. Trend in Chlorophyll-a concentrations in offshore stations of the four basin areas in June, July, and August. Circles are monthly means for June, July, and August, bars represent standard deviation.

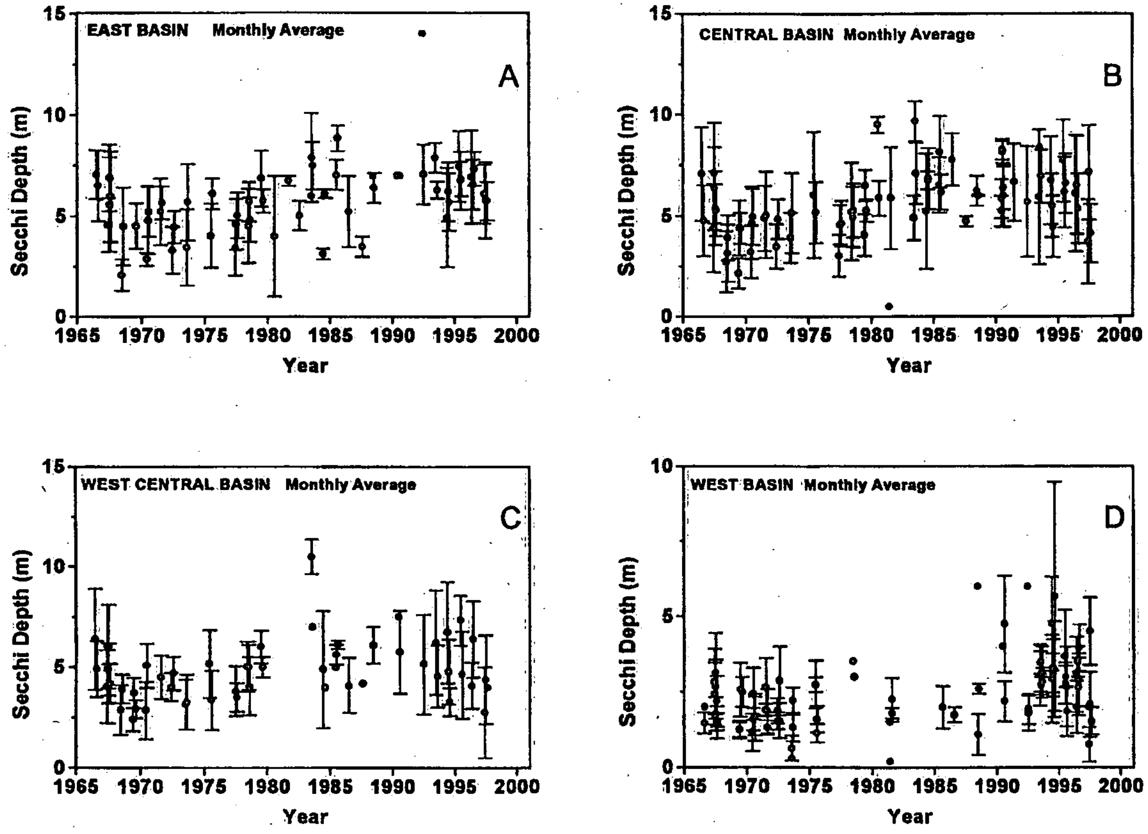

Fig. 12. Trend in Secchi depth observations in offshore stations of the four basin areas in June, July, and August. Circles are monthly means for June, July, and August, bars represent standard deviation.

Table 11. Change in Secchi depth between 1968-72 and 1984-88 and 1994-96 (m)

Basin	Period	June	July	August	Summer	Change	P (t test)
EB	68-72	2.8	4.7	4.9	4.2		
EB	84-88	4.7	6.3	6.5	6.2	+2.0	<0.001
EB	94-96	6.9	6.4	6.6	6.7	+0.5	0.083
CB	68-72	2.9	4.5	4.5	4.1		
CB	84-88	5.6	7.6	6.5	6.5	+2.4	<0.001
CB	94-96	6.7	6.0	5.7	6.2	-0.3	0.149
WC	68-72	3.0	4.3	4.0	3.8		
WC	84-88	5.0	5.2	5.2	5.2	+1.4	<0.001
WC	94-96	5.9	5.5	4.1	5.2	0.0	0.868
WB	68-72	1.5	2.1	1.8	1.8		
WB	84-88	1.3	2.5	1.9	1.9	+0.1	0.456
WB	94-96	3.1	3.1	3.0	3.1	+2.2	<0.001

Table 12. Change in chlorophyll to phosphorus ratio between 1968-72 and 1984-88 and 1994-96.

Basin	Period	June	July	August	Summer	Change	P (t test)
EB	68-72	0.26	0.24	0.32	0.28		
EB	84-88	0.17	0.16	0.16	0.16	-0.12	<0.001
EB	94-96	0.21	0.33	0.25	0.26	+0.10	<0.001
CB	68-72	0.32	0.32	0.31	0.32		
CB	84-88	0.20	0.16	0.24	0.20	-0.12	<0.001
CB	94-96	0.16	0.25	0.34	0.24	+0.04	<0.001
WC	68-72	0.28	0.32	0.66	0.43		
WC	84-88	0.18	0.18	0.29	0.20	-0.23	<0.001
WC	94-96	0.19	0.35	0.43	0.31	+0.11	<0.001
WB	68-72	0.37	0.36	0.41	0.38		
WB	84-88	n/a	0.29	0.28	0.28	-0.10	0.008
WB	94-96	0.24	0.35	0.35	0.31	+0.03	0.097

3.3. Dissolved oxygen

Hypolimnion dissolved oxygen was measured by electronic profiling during a series of cruises in 1990, 93, 94, 95, 96 and 97. Beginning in 1993 (Charlton, 1994) the oxygen depletion rates in the central basin have been around 0.07 mg/L/d. This represents a decreased rate from the usual 0.10 mg/L/d which occurred as recently as 1990. At the same time, central basin hypolimnion tended to be thicker than usual. Mean oxygen concentrations in the central basin hypolimnion at the end of August or even mid September have, since 1993, been 2–6 mg/L. In late August 1998, however, hypolimnion oxygen concentrations were less than 1 mgl^{-1} over most of the central basin and concentrations as low as 0.15 mgl^{-1} were found (Charlton unpublished data). Oxygen depletion rates in the east basin appear to have changed little. A full report on the changing oxygen situation will be made elsewhere.

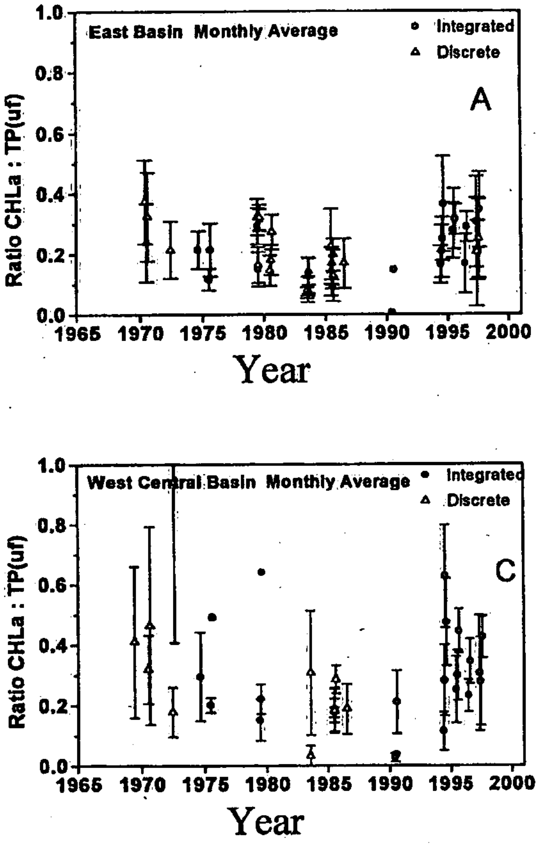

Fig. 13. Trend in Chlorophyll-a/total phosphorus ratios in offshore stations of the four basin areas in June, July, and August. Circles are monthly means for June, July, and August, bars represent standard deviation.

4. Discussion

The GLWQA nutrient controls were designed to reduce nuisance growths of algae and weeds and to restore year round aerobic conditions in the central basin hypolimnion. By the mid 1980's target phosphorus loads of about half the maximum had been reached (Lesht *et al.*, 1991) and phosphorus concentrations declined in the west basin. Assessment of the effects of the GLWQA has been complicated by the invasion of *Bythotrephes*, zebra mussels (*Dreissena sp.*) and a growing list of other exotic species. The most obvious effects expected at this time are from zebra mussels which arrived about the same time as target nutrient loads were achieved. Clearly, however, the data (figures 9 and 11 and in Lesht (1991) and Nicholls and Hopkins (1993) and Nicholls (1997)) indicate that major changes in the nutrient and algal status of the west basin were associated with nutrient reductions before the zebra mussel invasion.

Phosphorus was controlled by better techniques at sewage plants but there generally has been little attention given to nitrogen removal. Coupled with increasing population and decreased algal demand for nitrogen due to phosphorus reductions, nitrogen concentrations have increased throughout the lake during the summertime. The increase in nitrogen approaching 0.25 mg NO_3+NO_2 l^{-1} is one of the largest man made changes ever seen in the lake. The increase is largest in the west basin which is consistent with the preponderance of sewage and agricultural sources there. Paradoxically, the changes in summer nitrate + nitrite are not mirrored by the trend data for springtime when there has been little change in the west and east basins and a moderate increase in the central basin (Williams *et al.*, 1998). Thus, the summer nitrogen data may indicate the gradually changing lake metabolism brought about by phosphorus controls.

Although Secchi depth improved over the nutrient control period there is still the question of why relatively good depths occurred in 1966 and 1967 followed by a rapid decrease in 1968-1969. Many of the Secchi depths recorded recently are similar to those in the mid-1960's and this has not been explained. The occurrences of Secchi depths greater than 3 m in the west basin have clearly increased since the mussel invasion. Surprisingly, though, many of the recent Secchi observations are similar to those decades earlier. Thus, the impact of the mussels on the whole west basin ecosystem is complicated and unclear. In 1994, there was a distinct north south gradient in Secchi depth and algal populations. The north area of the west basin contained *Microcystis sp.* colonies and had Secchi depths 3 m or more whereas the south area had little or no *Microcystis* but were dominated by smaller algae and had less Secchi depth (Charlton, unpublished data). Some of these effects may be caused by the effects of the mussels in upstream Lake St. Clair. Some of the west basin spatial gradients were present in our maps of the 1997 data. There is little difference between pre-and post-mussel Secchi depths in offshore waters of the central and east basins (figure 12 and Table 11). This is contrary to popular opinion that the mussels have 'cleaned up Lake Erie'. Instead, mussels are likely to have the most effect on clarity in nearshore waters where they can access the entire water column and where lay persons are most likely to make observations. Indeed, at a site 10 m deep 1.3 km offshore near Fort Erie in the east basin, Secchi depths increased from 4 m to 6 to 7 m coincident with the mussel invasion (Howell *et al.*, 1996). This underscores the assertion in Nicholls (1997) that long term data sets are important to provide the facts with which to make management decisions.

Phosphorus declined in response to the load reductions by about 3 μgP l^{-1} in the central and east basins (Table 8). Of particular interest though is the remarkable stability of the low cruise means in each year. A fruitful research topic may be the causes of the mid summer phosphorus values of about 10 μgP l^{-1} throughout the time series despite load changes. Do these data represent the real response of the central and east basins to the load reductions free of variable sampling bias or is there some fundamental reason for the stability?

Our data show that after the zebra mussel invasion of the central and east basins in 1989 and 1990 (Nicholls and Hopkins, 1993) summer phosphorus declined by as much as 5 μgP l^{-1}. For this we have no definite explanation. We suggest a hypothesis that mussels may be responsible for the gyrations in ambient phosphorus by altering sedimentation characteristics. The mussels contribute veliger larvae to the plankton and these graze as well as sink out of the water column. Once the basins stratify each year a period of net loss from the epilimnion occurs and this results in summertime minima in surface waters. Thus, the pattern of net sedimentation during the summer may be accentuated by the mussel larvae. The abundance of the larvae can vary widely between years (Graham *et al.*, 1996) thus, the variability in veliger numbers may alter sedimentation of phosphorus. Summer phosphorus seems to have reached a minimum in 1995 in the central and east basins.

Summer phosphorus in the central and east basins has increased since 1995 (figure 9). The increases in 1996 and 1997 have restored much of the loss that occurred after the invasion of mussels. On a basin wide basis, the seasonal total phosphorus means in 1997 were 9.8, 9.6, 12.1, and 22.6 μgP l^{-1} for the east, central, west central, and west basin areas respectively. These data for 1997 are somewhat lower than means reported for 1986 of 11.5, 13.3, and 20.1 μgP l^{-1} for the east, central, and west basins in Lesht *et al.* (1991). The 1997 summer data for the central and east basins are consistent with GLWQA goal for spring phosphorus of 10 μgP l^{-1} whereas the goal of 15 μgP l^{-1} was exceeded in the west basin.

The spatial distribution maps are a useful way to illustrate the degree of heterogeneity in the lake. For example, the maps show the typical west-to-east gradients of nutrients in the lake. Ideally, there should be more data with which to construct the contours. Nevertheless, the maps provide an accurate impression of the spatial distribution patterns even though the shapes produced by the contouring program are somewhat arbitrary. Perhaps the most interesting display shows the ratio of chlorophyll to total phosphorus in figure 7. The distribution of the ratio is far more patchy than other measures. This patchiness may indicate variability in grazing or sedimentation losses.

The effect of mussel grazing on algal populations and the emergence of different phosphorus/chlorophyll and phosphorus/production relationships (Graham *et al.*, 1996, Millard *et al.*, 1998) raises the question of how much historical variability there is in the chlorophyll to phosphorus ratio data. The historic data of the chlorophyll to phosphorus ratio in offshore waters decreased during nutrient reductions and now there seems to be a tendency to higher ratios (Table 12). Low ratios may be caused by mussel grazing in shallower water so that some of the phosphorus in the grazed algae is excreted while the chlorophyll is destroyed. In the offshore water the grazing losses by zooplankton may be augmented by grazing and sedimentation by mussel larvae. When the larvae have grown sufficiently they settle through the thermocline and thereby remove their accumulated phosphorus from the epilimnion. Relatively less effect on the Chl-a to TP ratio would occur compared to effects of adult mussels in shallow water seen by Graham *et al.* (1996). In addition, occasional low ratios in the past may have been associated with heavy zooplankton grazing.. Thus, these offshore ratio data are not unexpected.

Chlorophyll declined in all three basins following nutrient load reductions. Most of the decline occurred before the arrival of *Dreissena sp*. Seasonal mean chlorophyll was 2.1, 2.4, 3.8 and 5.2 μg l^{-1} in the east, central, west central, and west basin areas in 1997. In comparison, chlorophyll seasonal means in 1970 were 4.3 and 5.5 μg l^{-1} in the east and central basins respectively (Burns, 1976). Thus, the nutrient loading reductions of 50% have caused a reduction of chlorophyll of about 50% (Table 10). There has been a subsequent loss of 0.4 to 0.7 μg CHLa l^{-1} with equivocal statistical significance (Table 10) since the mussel invasion. Mussels and the continuing effects of the nutrient reductions may not have removed much chlorophyll in these offshore waters but the recent losses represent a change of a quarter to a third of the chlorophyll present in the late 1980's (Table. 10). There has been a loss of a third of the west basin chlorophyll coincident with the mussel invasion (Table 10).

One of the important questions now is the extent to which lake productivity decreased due to nutrient load reduction compared to the later effects of mussels. The paucity of actual measurements of primary production with which to make the comparison has been noted by Millard *et al.*, (1998), However, an impression of the productivity changes can be derived by applying the changes in chlorophyll to known relationships between chlorophyll and primary production. According to a relationship between primary production and chlorophyll (Vollenweider *et al.*, 1974) the productivity of the central and east basins would have decreased by 46% and 35% respectively in the summer due to the chlorophyll decreases (Table 10) during the nutrient reduction period. Similar projections result from a more recent relationship in Graham *et al.* (1996). The subsequent losses of chlorophyll in the period 1994 to 1996 would be consistent with a further loss of 12% to 15% of the primary production compared to the period 1968 to 1972 in the central and east basins respectively. Based on actual measurements, Millard *et al.* (1998) found that annual primary production in 1993 (post-mussels) compared to that of 1970 was reduced by 22% and 55% in the central and east basins. Thus, accepting the differences between the various estimates of decrease and assuming lake function has not totally changed, a large portion of the decrease in production of the lake today likely occurred due to nutrient load reductions by the late 1980's before the mussel invasion.

Oxygen in the central basin hypolimnion has changed and changed again. Since the first report of improved conditions in 1993 (Charlton, 1994) the tendency for higher than usual concentrations continued until 1997. In 1998, however, lower, more typical, concentrations of less than 1 mgl^{-1} were found in late August As recently as 1990, the oxygen situation was similar to that of 1970. By the end of summer 1990, the hypolimnion was essentially anoxic to the extent that significant sediment phosphorus regeneration occurred (Charlton *et al.*, 1993). While much has been discussed about the response of the oxygen situation to nutrient loads (see review in Charlton *et al.*, 1993) we propose that the lake is now a different system that renders the discussions of the past partially irrelevant. Cessation of sediment phosphorus regeneration due to oxic conditions is not the cause of fluctuating phosphorus concentrations in the lake. In many years P regeneration did not occur despite low oxygen. In recent years, the hypolimnion has been unusually thick and this may have contributed to the better oxygen concentrations but we do not have an explanation as to why so many years would have been unusual. On the other hand it seems somewhat optimistic that the oxygen situation could have fundamentally improved so quickly since 1990. At this time the situation appears variable and an investigation is underway to find whether the recent oxygen depletion phenomena can be explained by variations in factors such as hypolimnion thickness, temperature, chlorophyll and advection. A full account of the oxygen situation, which is beyond the scope of this report, will appear elsewhere.

Recently, management of the phosphorus loads in the lake has been questioned. Fluctuations and declines of some fish species in the east and central basins have been noted by the commercial and sport fishery industries. On the other hand the food web is changing with the emergence of a mussel-goby-bass food chain. The appropriateness of the GLWQA loading targets has been questioned in light of the changing lake ecology brought about by exotic species. Unprecedented low phosphorus values have occurred in the east and central basins since the *Dreissena sp.* invasion. These concentrations were lowest in 1995 and have increased in 1996 and 1997. Moreover, chlorophyll concentrations do not seem to have changed much in the offshore waters of the central and east basins coincident with the *Dreissena* invasion compared to the decrease that occurred earlier due to nutrient reduction. Thus, the occurrence of low chlorophyll pre-1995 should be taken into account. In addition, there may be lag effects of the achievement of the nutrient load targets that reinforce, or are even more important than, the effects of mussels The mussels can cause pronounced effects in nearshore areas (Graham *et al.*, 1996, Millard *et al.*, 1998) and this may be where the early life stages of the fish are most susceptible to grazing induced lack of food. When the phosphorus minima occur offshore in the summer the concentrations of phosphorus are still higher than those in Lake Huron and this reflects the nutrient load and morphometry of Lake Erie. Lake Huron still has a fishery. Thus, there is probably no threat to the survival of fish in Lake Erie from today's phosphorus concentrations. Instead, the amount and type of fish harvest that is sustainable may be affected.

One hypothetical solution for low fish production, suggested by some fishing interests, might be relaxation of phosphorus removal by precipitation reaction during winter months at sewage plants. The historical data shown in figure 9 indicate that the nutrient loading reduction caused a decrease of around 3 $\mu gP\ l^{-1}$ in the central and east basins. This is consistent with other analyses (Rosa, 1987). Therefore, assuming the lake functions as before, a return to nutrient load pollution levels of the 1960's would be needed to increase phosphorus by a similar amount. Much of the phosphorus load reduction, however, resulted from control of raw sewage and partially treated sewage. Therefore, only a portion of the difference between pre-and-post phosphorus control loads would be made available by any simple shift in technology such as cessation of phosphorus precipitation at sewage plants. Most of the sewage phosphorus load now under control which might be made available is discharged in the west basin. Increasing west basin loads would have little effect on phosphorus in the central and east basins unless a return to gross pollution were allowed. Concerns with this idea would be the practicality from an operational point of view at sewage plants, the effects on landowners, drinking water quality, beach quality, and the co-emission of toxic chemicals which may be removed along with phosphorus. In addition, more nutrient loading may have other deleterious effects by stimulating production of blue-green algae which now seem to be favoured in the west basin. Of course, the conditions of tributaries and the effects of more nutrients on shoreline properties already beset by *Cladophora sp.* accumulations (T. Howell, Ont. Min. Environment, personal communication) would have to be taken into account if an attempt were made to fertilize the nearshore areas or even the lake as a whole. Apparently, fishing was adequate in the period 1985 to 1990 when offshore chlorophyll was almost as low as in the recent years. Thus, it is doubtful that whole basin nutrient additions from sewage would be sufficient to significantly influence fish production now. A fruitful line of research may be to focus on how and whether the mussels may be affecting particularly vulnerable life stages of fish that may inhabit shallow areas. The success of the mussels varies greatly between the years and the presence of the veliger larvae varies as well and there may be the possibility that mussel populations will decline over time. This, in addition to the recent increase in phosphorus, indicates that more years of experience with the changing species composition and their effect on the lake are needed to fully understand effects and potential for management. The authors believe that a change in phosphorus management policy is not advisable at this time.

Because the present sewage loading limits are regulated on an effluent concentration basis the load of phosphorus to Lake Erie can gradually increase due to population growth. Fortunately, more diligent application of present phosphorus removal techniques can be applied in order to maintain or lower loads from sewage. Amelioration of local eutrophication problems in 'areas of concern' (identified in the GLWQA) would cause a nutrient load reduction to the lake. Non-point sources are numerically very important now and these will decline if objectives to ameliorate conditions in tributaries and to prevent loss of valuable soil are successful. Non-point phosphorus loads are mainly poorly available to algae because the phosphorus is bound in soils except immediately following rain when fields have just been fertilized. Thus, although the total phosphorus load to the lake may decrease further due to non-point controls, only a small part of that decrease would potentially affect lake productivity. The GLWQA sought to limit productivity of Lake Erie as a way of improving water quality, beach quality and fish habitat while preventing auto fertilization of the lake from phosphorus regeneration. Some decline in lake productivity would be expected (see other papers in this issue) but at this time we do not know whether this will be ameliorated or exacerbated by the food chain shift to benthic populations.

5. Summary

We have collected samples and data for the purpose of examining the response of Lake Erie to nutrient loading restrictions and the recent invasions of exotic species.

Phosphorus and algae populations were most affected in the west basin by nutrient reductions. Algae (chlorophyll) and probably lake productivity were reduced more in the central and east basins prior to the invasion of *Dreissena sp.* than after the invasion. Water clarity has increased in parts of the west basin but has not changed in the offshore waters of the central and east basins after the mussel invasion. Chlorophyll to phosphorus ratios have changed in offshore waters but the distribution is relatively patchy. Nitrate plus Nitrite has been increasing in the summer since the 1960's. Since the *Dreissena sp.* invasion phosphorus concentrations reached a minimum in 1995 in the east and central basins and have increased in 1996 and 1997. There is desire to optimize fish production in light of exotic species invasions. The response of the lake to nutrient reductions shows that minor relaxation of whole lake nutrient controls is unlikely to increase production. Fertilization of nearshore areas to increase fish production may exacerbate existing problems of *Cladophora* accumulations on shorelines. The Lake Erie ecosystem has changed and is changing. Lake Erie in the 90's is a *lake in transition.*

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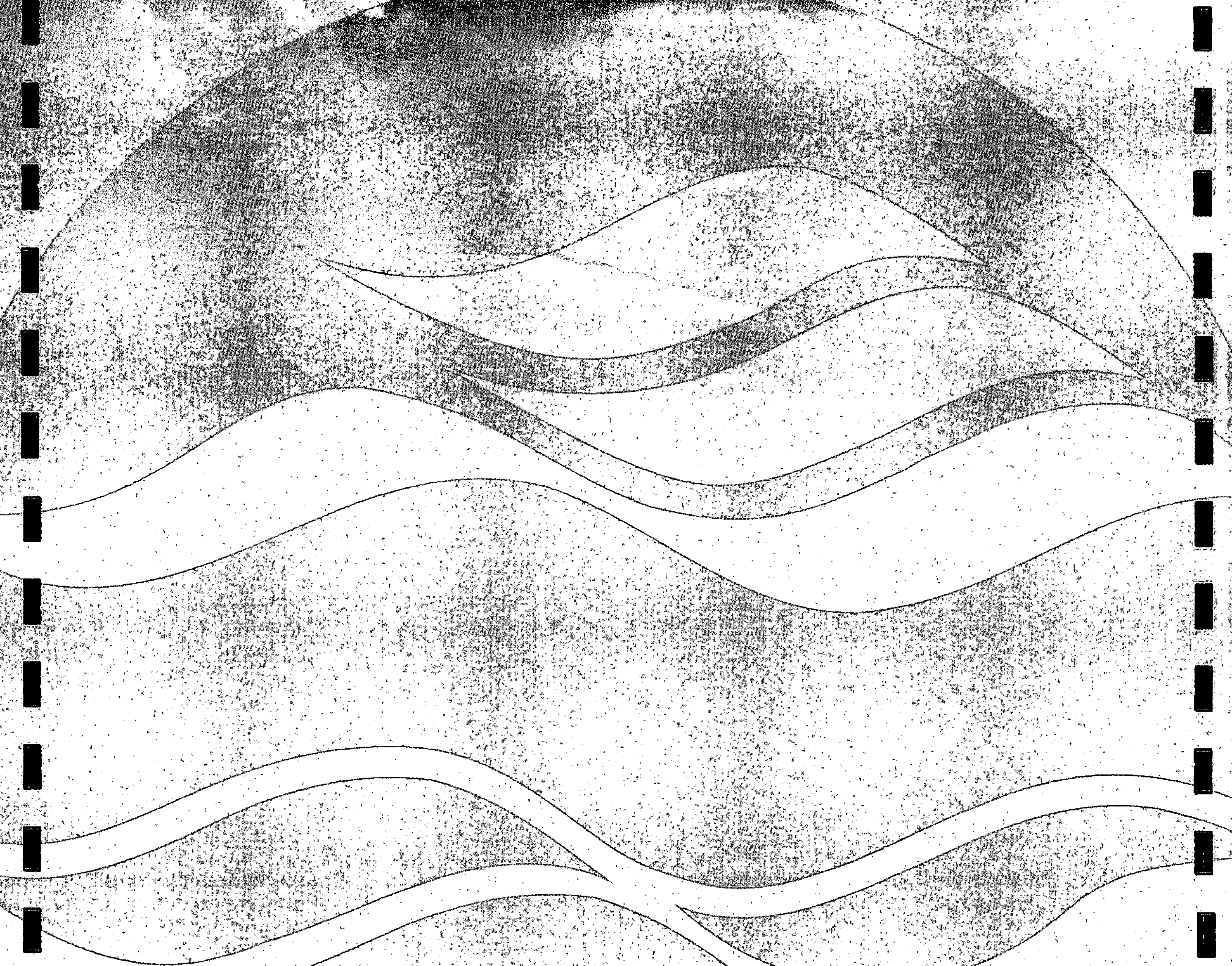

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