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Lake Erie Total Phosphorus Loading Analysis and Update: 1996–2002

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ABSTRACT. *The Lake Erie basin remains one of the most intensely monitored areas in the Great Lakes, largely because of continued interest by government agencies and the public in its trophic status. Total lake phosphorus loading estimates require data from three essential pathways: tributaries, point sources, and the atmosphere. Point source and atmospheric deposition monitoring results are available to allow continued estimation of these components. Several key watersheds are still being monitored, making some tributary load estimation possible. The problem is to make estimates for unmonitored areas, which are now substantially greater than encountered previously. Except for 2 years, the total annual load estimates for 1996–2002 (11,584, 16,853, 12,710, 6,608, 8,456, 7,333, and 9,733 metric tonnes per year, respectively) were near or substantially below the target load set by the Great Lakes Water Quality Agreement of 11,000 metric tonnes per year. The estimates for 1997 and 1998 markedly exceeded the target load due mainly to elevated tributary loads because of heavy precipitation. The margin of error or half-width of approximate 95% confidence intervals varied from 4% to 11% of the total estimated load depending on year. Detailed tables of the yearly (1996–2002) estimates are provided, as well as summaries by Lake Erie sub-basin for 1981–2001.*

INDEX WORDS: *Phosphorus, load estimation, Lake Erie, point source, nonpoint source.*

INTRODUCTION

Cultural eutrophication can be defined as the overproduction of phytoplankton biomass caused by increased anthropogenic nutrient inputs (Bierman *et al.* 1984). This excess algal growth can be linked to various degraded water quality conditions such as increased turbidity, nuisance aesthetic conditions, dissolved oxygen depletion in hypolimnetic waters, and filter-clogging, taste, and odor problems in water supplies. Restoration strategies have been implemented to reverse the impacts of cultural eutrophication, and ecosystem recovery has been documented. In Lake Erie, hypoxia has been directly linked to elevated in-lake total phosphorus concentrations and excessive external total phosphorus loadings (Burns and Ross 1972, El-Shaarawi 1987).

Environmental scientists have argued for decades about the wisdom of monitoring the mass (loads) vs. concentration of pollutants. If the loading rates of a pollutant are low, it seems pointless to attempt to quantify trace concentrations except for academic reasons. If concentrations are high, the money needed for monitoring diverse pollutant sources may be better spent reducing those sources or enforcing existing laws. Thus, when the Lower Lakes Reference Study (IJC 1969) described the degraded conditions in Lake Erie (including elevated total phosphorus concentrations), a major effort was quickly mounted to reduce the known phosphorus sources to the Great Lakes (especially Lakes Erie and Ontario). The principal tools of this effort were to impose a 1 mg/L total phosphorus effluent limit on municipal sewage treatment plants discharging in excess of 3,800 m^3/day and full or partial bans on phosphorus in detergents. However, it was not until the release of the final report of the Pollution from Land Use Activities Reference Group (PLU-

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ARG 1978) that an organized, statistically valid procedure was implemented to monitor and report total phosphorus loads to the Great Lakes. Initially, this was a cumbersome process involving the collection and analysis of millions of data points from the eight Great Lakes states and the Province of Ontario. However, by 1981, the process had been computerized and the reporting of annual total phosphorus loads by lake became routine. These estimated annual loads were compared to the target loads in Annex 3 of the Great Lakes Water Quality Agreement (GLWQA) of 1978. The loads were also used in mass balance modeling studies to examine various hypotheses about the eutrophication process (e.g., Lesht *et al.* 1991).

The restoration of Lake Erie in the early 1990s has been documented extensively. Following achievement of target loads for total phosphorus, yearly concentrations of total phosphorus and dissolved oxygen depletion rates declined significantly (Bertram 1993). Burrowing mayflies returned to the lake (Krieger *et al.* 1996). Reductions in algal biomass were observed, especially in nuisance and eutrophic species (Makarewicz 1993).

In 1991, formal reporting of annual Great Lakes total phosphorus loading ceased. Eutrophication had been replaced by toxic substances as the primary water quality concern for most Great Lakes jurisdictions (GLWQA 1978). Phosphorus concentrations had steadily declined and in some areas (e.g., the eastern basin of Lake Erie) were actually considered too low (Great Lakes Modeling Summit 2000).

Recent indications of returning symptoms of eutrophication (reviewed in Matisoff and Ciborowski 2005) have naturally led to questions about cause and effect. While explanations may not be as simple as new loading sources or backsliding by facilities formerly in compliance, no hypothesis can be scientifically tested without baseline loading information. Even if cultural eutrophication did not appear to have returned as a major water quality problem in Lake Erie, continued monitoring and formal reporting would have been justified based on sound ecosystem management. The $8 billion price tag to achieve the phosphorus reduction in the first place merits the attention of those responsible for Great Lake management, albeit at a reduced level of funding.

Ten years later, the U.S. EPA's Great Lakes National Program Office provided funding to the University of Wisconsin–Green Bay to renew total phosphorus reporting for Lake Erie and bring the annual load record up to date. The objective of this paper is to describe the effort and summarize the results. A summary of all Lake Erie total phosphorus loads for the period 1981-2001 is included in the Appendix.

METHODS

Background

Lake Erie total phosphorus (TP) loadings have been reported since 1967. The same basic sources of data as reported below have been used for the entire reporting period (1967–2002). Further, the same estimation procedures were used throughout this period. The main differences between early (1967–1979) and later (1980–2002) load estimates were due to improved data availability and refined methods for loads from unmonitored areas as prescribed by PLUARG (1978).

Most of the load estimates that were made prior to the study period (pre-1996) have been reported previously. Estimates from 1967 to 1973 were reported by Fraser (1987). These estimates were not broken down by Lake Erie sub-basin. Lesht *et al.* (1991) reported loads from 1974 to 1986 including breakdowns by sub-basin. Dolan (1993) reported the loads from 1986 to 1990. Although never published until now, Dolan and McGunagle (1998, 1999) presented load estimates from the period 1991 to 1995 and made them available to researchers upon request.

Data Sources

All of the data used to estimate Lake Erie TP loads come from government databases except the data from the Lake Erie Tributary Monitoring Program which is maintained by the Heidelberg College Water Quality Laboratory (Baker and Richards 2002). Details of the sources of data may be found in Appendix 2.

Load Estimation

The methods used to estimate TP loads varied by type of source, but the basic calculation involved forming the product of concentration and volume per unit time (flow rate) to produce the mass per unit time (loading rate). This quantity was then averaged over the required time period. For example, to estimate loads from point sources, the following calculations (Dolan 1993) were used to determine annual average point source phosphorus loads:

$$\text{Loading} = (\Sigma C_i Q_i) / n \quad \text{for } i = 1, 2, ..., 12$$

where C_i is the average TP effluent concentration for the *i*th month
Q_i is the mean effluent flow for the *i*th month
and n is the number of months of monitoring.

These calculations were performed on a "per pipe" basis and the estimates summed (for multipipe facilities) to provide loads on a "per facility" basis.

For monitored tributaries, the Stratified Beale's Ratio Estimator (Beale 1962, Tin 1965, Dolan *et al.* 1981) was used. Daily tributary loads were calculated on a yearly basis for each tributary and then these data were stratified into one or more strata depending on the nature of the flow and concentration relationship within each stratum. In general, tributaries with greater than monthly sampling frequency were stratified into at least two strata. The ratio estimator method requires uncensored concentration values for all samples. Tributary TP concentrations reported by Ohio EPA were censored at 0.05 mg/L and those from USGS were censored at 0.01 mg/L. Replacement values were calculated using maximum likelihood estimation (MLE) (El-Shaarawi and Dolan 1989).

Procedures for estimating loads from unmonitored tributaries and the atmosphere were according to Rathke and McCrae (1989). For unmonitored tributaries, a unit area load (UAL) was estimated from nearby monitored tributaries and applied to the unmonitored basin area. For atmospheric loadings, the flux of TP in units of mass per area was estimated from precipitation collectors and applied to the lake area that the collector represents. For each of the years 1996–2002, the average flux of three Canadian sites (Rock Point, St. Clair, and Pelee) was used so that each site represented one-third of the lake surface. All three of these sites are located on the Canadian shore as described by Chan *et al.* (2003). The Rock Point site is on the north shore of the eastern basin in Rock Point Provincial Park. The St. Clair site is on the eastern shore of Lake St. Clair at the St. Clair Wildlife Research Center. The Pelee site is currently in Pelee National Park, which borders the western and central basins.

The base time period for all estimates is the water year (October of the previous year through September of the current year). All previous annual loading estimates for Lake Erie (e.g., Dolan 1993, Rathke and McCrae 1989) used the water year as the base time period. Although the water year was originally chosen to coincide with the availability of published tributary flow reports from USGS, there is some evidence that this time period better captures the contribution of flow events that occur in the winter months (Dolan and Richards 2006).

Approximate two-sided confidence intervals for the true total loading to Lake Erie are estimated by applying the procedure described in Rathke and McCrae (1989). Briefly, this involves estimating the total Lake Erie standard error as the square root of the sum of all of the variances (or mean-square-errors) associated with each source type.

Sub-basin Loading

Various computer programs have been written in SAS and FORTRAN to prepare the data for the load estimation process, estimate the load from individual and area sources, and summarize the resulting loads by type and geographic sub-units (Dolan unpubl).

Segmented Model Analysis

Total phosphorus loadings to the Lake Erie basin apparently have declined to an asymptote since the late 1970s (S. Ludsin, Great Lakes Environmental Research Laboratory, Ann Arbor, *pers. commun.*). Segmented model analysis (Draper and Smith 1998) was used to quantitatively determine whether the temporal pattern of TP loading could be better expressed by two lines of differing slope than by a single negative exponential curve. The log-transformed annual loading data were fitted to a linear model of the form

$$\text{Ln(TP)} = b_0 + b_1 YR_1 + b_2 YR_2 + b_3 A$$

where b_0 is the intercept of the first line
b_1 and b_2 are regression coefficients of two different lines ("before" and "after" the break or point of intersection)
b_3 is the regression coefficient representing the vertical distance between the two lines at the point of intersection
YR_1 is the variable representing year of record up to but not including the point of intersection
YR_2 is variable representing year of record from the point of intersection and later
A is a binary dummy variable (zero if the year of record is before the point of intersection; one if the year of record is at the point of intersection or later)

TABLE 1. Summary of estimated industrial, municipal, and tributary phosphorus loading (MTA) to Lake Erie from point and nonpoint sources (1996–2002)[1,2].

	1996	1997	1998	1999	2000	2001	2002
POINT:							
Direct Industrial Discharge	68	59	54	49	47	53	57
Indirect Industrial Discharge	32	27	25	24	26	17	24
Direct Municipal Discharge	1,266	1,741	1,489	1,370	1,522	1,282	1,399
Indirect Municipal Discharge	631	535	507	505	452	437	512
Point Subtotal	1,997	2,362	2,075	1,948	2,047	1,789	1,992
NONPOINT:							
Monitored Tributary less Indirects	5,613	8,546	6,192	2,007	2,915	2,536	4,332
Unmonitored Adjustment	2,378	4,345	2,669	1,088	1,626	1,391	1,635
Nonpoint Subtotal	7,991	12,891	8,861	3,095	4,541	3,927	5967
Within Lake Total	**9,988**	**15,253**	**10,936**	**5,043**	**6,588**	**5,716**	**7,959**
Atmospheric	**516**	**520**	**694**	**485**	**788**	**537**	**694**
Lake Huron Estimate	**1,080**	**1,080**	**1,080**	**1,080**	**1,080**	**1,080**	**1,080**
TOTAL INPUT TO LAKE ERIE	**11,584**	**16,853**	**12,710**	**6,608**	**8,456**	**7,333**	**9,733**
GLWQA TARGET	**11,000**	**11,000**	**11,000**	**11,000**	**11,000**	**11,000**	**11,000**

NOTES:

1. Includes a constant point source load for Ontario (1996–2000), based on 1995 estimates (64 MTA Direct Municipal, 122 MTA Indirect Municipal, 30 MTA Direct Industrial, less than 1 MTA Indirect Industrial).
2. Includes point source load for Ontario (2001 and 2002), based on updated concentrations for available facilities (45% of total) plus 1995 estimates in NOTE 1, above.

The point of intersection is the year that the segmented model changes from the first line to the second line. This can be found by minimizing the error sum of squares for the segmented model (Draper and Smith 1998). Once the point of intersection has been determined, the relative contribution of point and nonpoint sources to the total loading can be compared before and after the "break." Simple linear regression can be applied to evaluate changes in the percent contribution of municipal plus industrial sources and tributary estimates as suggested by Ludsin (Great Lakes Environmental Research Laboratory, Ann Arbor, *pers. commun.*).

RESULTS

Point Source Loadings

Direct and indirect point sources of TP to Lake Erie have been estimated (Table 1). Direct sources are facilities that have effluents discharging directly to Lakes Erie or St. Clair, the Connecting Channels (Detroit River or St. Clair River), or to unmonitored areas. Indirect sources are facilities that have effluents discharging to monitored areas of tributaries.

The total point source load to Lake Erie was fairly constant at about 2,000 metric tonnes per annum (MTA) with the exception of 1997 when the load was about 2,360 MTA and 2001 when the load was about 1,790 MTA. Most of this load (95% or more) is from municipal sewage treatment plant sources (Table 1).

Tributary Loading

Total phosphorus loadings from tributaries were both greater and much more variable than point source loadings for the period 1996–2002 (Table 1). The combined contribution of monitored and unmonitored tributary loadings varied from a minimum of 3,095 MTA in 1999 (1.6X point source load for that year) to a maximum of 12,891 MTA in 1997 (5.5X the point source load). The inter-annual variation in tributary loadings was due mainly to differences in rainfall and hence tributary flow among years.

TABLE 2. Summary of estimated phosphorus loading (MTA) and 95% confidence limits for Lake Erie (1996–2002).

	1996	1997	1998	1999	2000	2001	2002
Monitored Tributary	6,276	9,108	6,724	2,536	3,393	2,990	4,868
Unmonitored Area	2,378	4,345	2,669	1,088	1,626	1,391	1,635
Atmospheric	516	520	694	485	788	537	694
Direct Industrial	68	59	54	49	47	53	57
Direct Municipal	1,266	1,741	1,489	1,370	1,522	1,282	1,399
Lake Huron	1,080	1,080	1,080	1,080	1,080	1,080	1,080
Total	**11,584**	**16,853**	**12,710**	**6,608**	**8,456**	**7,333**	**9,733**
Target Load (GLWQA)	11,000	11,000	11,000	11,000	11,000	11,000	11,000
Upper 95% Conf. Lim.	12,539	18,665	13,828	6,885	9,035	8,074	10,513
Lower 95% Conf. Lim.	10,629	15,041	11,592	6,331	7,877	6,592	8,953

Atmospheric Loading

The atmospheric TP loads to the surface of Lake Erie were more variable than point source but less variable than tributary loadings (Table 1). Atmospheric loadings ranged from 485 MTA in 1999 to 788 MTA in 2000. Atmospheric loadings always comprised < 10% of the total TP budget.

95% Confidence Intervals for the Total Input to Lake Erie

Approximate 95% confidence limits (two-sided) have been estimated for the total Lake Erie TP load (Table 2). The margin of error or half-width of these confidence intervals varies from 4% to 11% of the total estimated load depending on year. Although not reported here, the tributary standard error usually dominates the estimated variability of the total load (Rathke and McCrae 1989).

Sub-basin Loading

The breakdown of Lake Erie TP loading estimates by sub-basin (western, central, and eastern) is presented in Table A in the Appendix. The western basin loading includes everything upstream to the lake as far as the head of the St. Clair River. The approximate boundary of the western and central basins is Point Pelee and the Lake Erie islands. The approximate boundary of the central and eastern basins is Long Point and Erie, Pennsylvania. Table A is an update of the Lake Erie loadings since 1981, broken down by sub-basin.

These estimates can be used by modelers who wish to include more spatial detail in mass balance or ecosystem models. They can also be used to make inferences about the geographical nature of the loading trends. For example, about 75% of the loadings in any given year come from the western basin. Also, the unmonitored contribution to non-point loadings has increased from about 15–20% in the early 1980s to 50% or more in some lake basins more recently. This, in turn, contributes to increased uncertainty in the estimates.

Segmented Model Analysis

When the 35 years (1967–2001) of TP load estimates are fitted to the segmented linear model described above, the “break” or point of intersection (year that the slope of the line changes) was found to be 1991. This resulted in an error sum of squares of 1.272 ($R^2 = 0.77$, $p < 0.0001$). The slope of the first line (up to but not including 1991) was –0.052 Ln(metric tons) per year ($p < 0.0001$). The slope of the second line (for 1991–2001) was not significantly different from zero ($p = 0.155$). This is illustrated in Figure 1 for the case of the untransformed data. The model fits were virtually identical, but the coefficients are more interpretable for the untransformed case.

For the untransformed case, the results indicate that TP loadings declined from over 25,000 MTA in the late 1960s by about 745 MTA per year and fell below 10,000 MTA in 1987 (breakpoint analysis of line 1, $p < 0.0001$; Fig 1). Subsequent to 1991 (the point of intersection), the change in TP loading with respect to time was not significantly different from zero ($b_2 = -133$ MTA per year ± 705, $p = 0.68$).

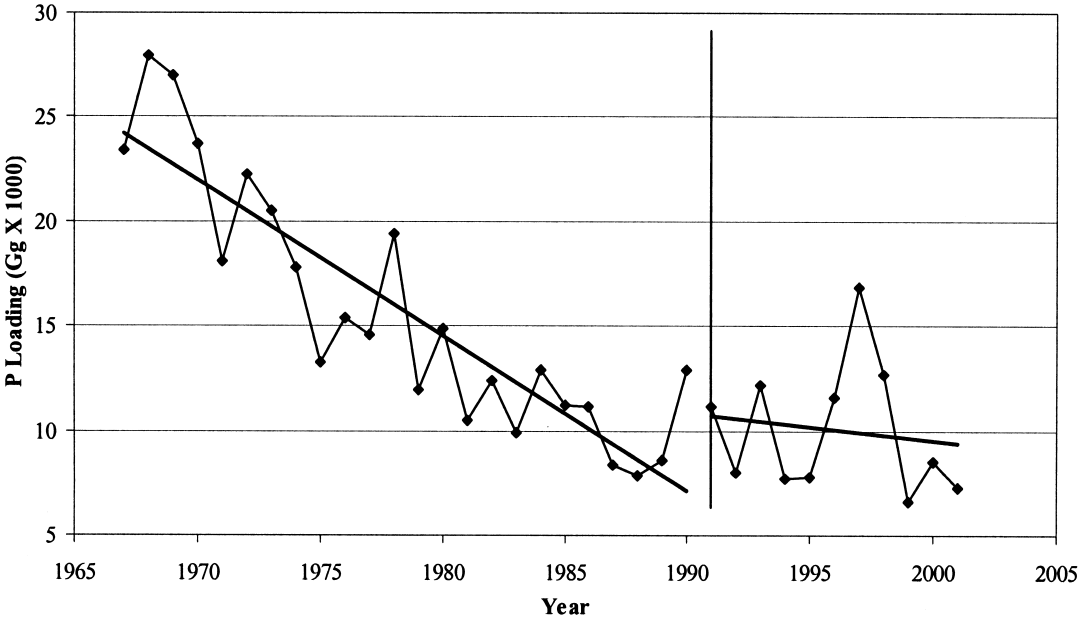

FIG. 1. Segmented model regression for total phosphorus load (thousands of gigagrams (metric tons) per year) vs. year for the period 1967–2001 showing the point of intersection at 1991. Pre-1991 Regression Line: $y = -0.745x + 1{,}490.1$, standard error of the slope = 0.082, $R^2 = 0.7893$, $p < 0.0001$. Post-1990 Regression Line: $y = -0.133x + 275.78$, standard error of the slope = 0.311, $R^2 = 0.0199$, $p = 0.6791$.

Changes in Relative Contribution of Point and Nonpoint Sources

The point of intersection year of 1991 was used to examine the changes in the relative contribution (percent) of point source (municipal and industrial) vs. tributary (monitored and unmonitored) TP load to Lake Erie since 1974 (accurate breakdowns of relative contributions were not available prior to this year). Simple linear regression was used to analyze the slopes of the relationships between these percentages before and after the "break" at 1991 (Fig. 2). Both relationships had slopes that significantly differed from zero ($p < 0.002$) before 1991. Tributary TP loading contribution increased at a rate of 1.56% per year since 1974 while the point source load contribution decreased at roughly the same rate (–1.70%) over the same period. Changes after 1991 in the percentage contribution of either source were not different statistically from zero ($p > 0.35$).

DISCUSSION

Great Lakes TP load reporting ended in 1991. For the period 1967–1985, TP load estimates for all of the Great Lakes were reported to the International Joint Commission by the Great Lakes Water Quality Board (1980, 1981, 1983, 1985, 1987, 1989). For 1986–1991, load estimation continued at the request of the Parties to the GLWQA (EPA and Environment Canada). After 1991, only Lake Erie loads were estimated. Until now, these load estimates were provided by the co-authors to interested investigators by request.

Data Access and Quality Control

Accessing and retrieving point source data continues to be the most time-consuming aspect of TP load estimation. While the U.S. data are all in one database (PCS), the limited retrieval interface and quality of location information necessitates several retrieval jobs for each year of data required. In addition, the quality and quantity of data are highly variable from state to state and this requires numerous quality assurance checks (see Dolan 1993 for details). Problems include inconsistent units, transposition of maxima and averages, internal pipes, missing months of data, etc. The Canadian data (except for some 2001 and 2002 effluent concentrations) could not be obtained despite repeated requests to the Ontario Ministry of the Environment

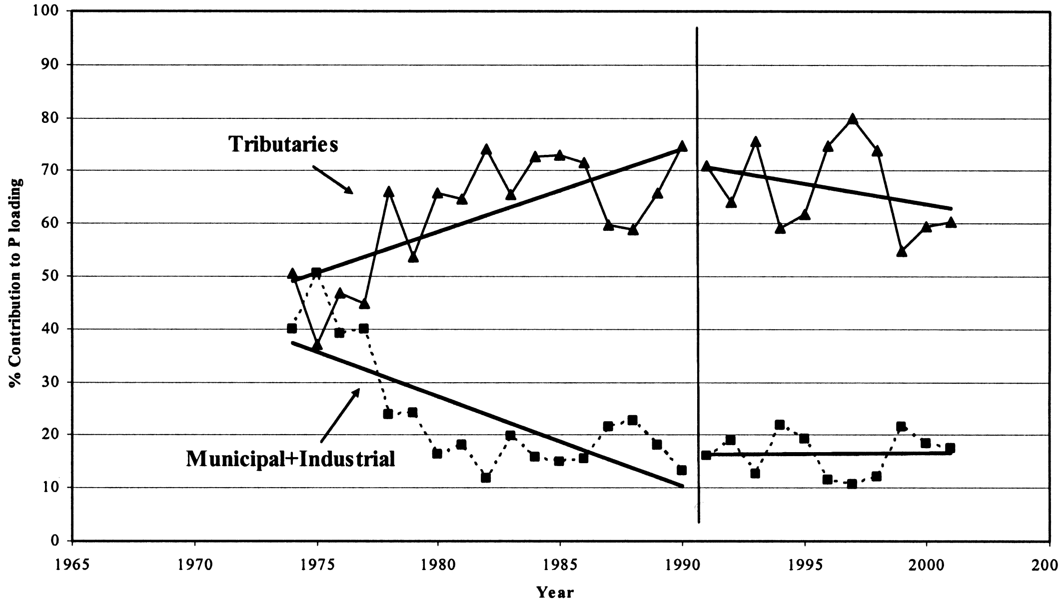

FIG. 2. Simple linear regressions for both percent contribution of point sources (triangles) and tributaries (squares) to total phosphorus load vs. year for the periods 1974–1990 and 1991–2001. Pre-1991 Regression Line for Point Sources: y = –1.70x + 3,393.1, standard error of the slope = 0.38, R^2 = 0.566, p = 0.0005. Post-1990 Regression Line for Point Sources: y = 0.027x – 36.73, standard error of the slope = 0.407, R^2 = 0.0005, p = 0.949. Pre-1991 Regression Line for Tributaries: y = 1.562x – 3,034.99, standard error of the slope = 0.417, R^2 = 0.4836, p = 0.002. Post-1990 Regression Line for Tributaries: y = –0.793x + 1,649.9, standard error of the slope = 0.804, R^2 = 0.0976, p = 0.3497.

and Environment Canada. Complete data were provided for 2003, but these data were not used in this paper. However, past experience suggests that similar problems (with the quality and quantity of point source data) would be encountered if these data (1996–2002) were made available, although the degree of difficulty would probably be less than some of the states (e.g., Michigan and Ohio).

U.S. tributary flows from the USGS website are typically high-quality, dependable data. The only problems encountered are the timeliness of data availability (variable from state to state) and the need to download large amounts of data from the website. Canadian tributary flows from the Water Survey CD-ROM were typically of high quality and easy to work with.

U.S. tributary data come from three diverse sources: state monitoring networks, USGS sampling at NAWQA (National Water-Quality Assessment) sites, and the Heidelberg College network. Formerly, all of these data were stored in STORET Legacy and retrieval was a simple matter of running a batch computer program. Now, as noted in Appendix 2, very little data can actually be obtained from STORET, and data that can be found require downloading from the STORET website. The USGS data are now available on their own website. For the rest of the tributary data, requests made to the individual contacts at the agencies noted above are the only way to obtain the data. Since the data are not referenced anywhere, it is impossible to know if tributaries are "Unmonitored" without polling the contacts for each year. The database, which had become very centralized as a result of PLUARG (1978), is now more dispersed than ever.

Canadian tributary data were received from a personal contact, similar to most US data. The main problem noted with these data is the decline in frequency of monitoring (sample size) on major tributaries and the almost total lack of sampling on the smaller tributaries.

Rainfall amount and quality data were obtained from a personal contact. No problems were encountered with these data except to note that all of the sampling sites are now Canadian, which calls into question the representativeness of flux estimates.

Future Prospects

It is natural to question whether a program that was formally abandoned over 13 years ago is still capable of producing accurate load estimates suitable for management decisions. Despite numerous cutbacks in monitoring throughout the Great Lakes, the two major sources of TP loadings data are still intact. The Ohio Tributary Monitoring Network established by the Water Quality Laboratory at Heidelberg College in Tiffin, Ohio continues to produce high quality tributary monitoring data for five U.S. tributaries to Lake Erie: the Maumee, Sandusky, Grand, and Cuyahoga rivers in Ohio and the River Raisin in Michigan. Not only does this program provide data for accurate estimation of over 38% of the Lake Erie basin, but also it allows estimation of neighboring unmonitored river basins. The other source of continued loading information is the U.S. EPA's Permit Compliance system that contains data for approximately 89% of the point sources of phosphorus in the Lake Erie basin. Most of the results reported above are based on data from these two programs.

Concern has been expressed about the effect of missing data and unmonitored sources of phosphorus. Some estimation of unmonitored sources will always be necessary in lakewide load estimation (PLUARG 1978). Experience with the magnitude and variation of phosphorus loading sources over the period 1980–1994 (prior to major cuts in monitoring and reporting) provides some assurance that the effects of missing data and unmonitored sources are not yet critical. Also, through mass balance modeling, it can be shown that total lake loadings of the magnitude reported in this paper are capable of explaining recently observed TP concentrations in the open waters of Lake Erie (Rockwell *et al.* 2005). Naturally, the effects of unmetered, but large combined sewage overflows (CSOs) and bypasses cannot be assessed with the current load estimation procedures. However, the trend has been for the larger CSOs to be included as point sources in the Permit Compliance System. In addition, an estimate of the contribution of every watershed in the Lake Erie basin has been made, so the effects of unmetered flows have been included in the overall unmonitored area estimate.

Concerted efforts to control point sources of phosphorus to Lake Erie began in 1972 with the signing of the Great Lakes Water Quality Agreement. The major controls that were implemented were the monthly average effluent limit of 1 mg/L TP on all major sewage treatment plants and the ban of phosphorus in detergents. These controls did not show immediate results, but by the mid-1980s, declines in lakewide loadings were obvious (Panek *et al.* 2003). Dolan (1993) reported 95% compliance (on a monthly basis) with the 1 mg/L requirement by the 12 largest municipal sewage treatment plants in the Lake Erie basin for the years 1989 and 1990. Ohio was the last state to implement the phosphorus detergent ban, in 1990 (Hartig *et al.* 1990). The "break" or point of intersection year of 1991 reported in this paper is consistent with the gradual implementation of point source controls of phosphorus over a 20-year period. During this time, the percentage of TP contributed by tributaries to Lake Erie was increasing at roughly the same rate that the point source load percentage was decreasing. Since 1991, no statistically significant change in these percentages or the total load has been observed.

CONCLUSIONS

High quality data are still available to allow reasonable estimates of TP loadings to Lake Erie. Recent (1996–2002) load estimates indicate that the target load of 11,000 metric tons of TP per year is being met for years in which tributary discharge is relatively low. However, considerable variation in this component has led to large total loading in the late 1990s. Changes since 1991 in total lake loads are not significant over the 10-y period. Reductions prior to 1991 were due mainly to the gradual implementation of point source controls.

Recent concern about possible changes in Lake Erie's trophic status should be ample justification for renewed monitoring efforts. Although outside the scope of this study, point source TP estimates from Ontario have been recently made available by the Ministry of the Environment for 2003. Also, recent nonpoint estimates for Canadian watersheds have included more intensive sampling than was available for this study. This renewed information on Canadian sources, coupled with the Ohio Tributary Monitoring Network and the Permit Compliance System discussed above, represents the minimum conditions under which continued TP load estimation for Lake Erie can take place. Additional areas where improvement can occur include more sites for atmospheric monitoring, lower detection limits for tributary sampling in routine monitoring of TP, and occasional sampling of watersheds not normally included in base programs such as those in urban areas that may be affected by unreported CSOs and bypasses. These further improvements would help to verify whether or not assumptions made in the load estimation process continue to be valid.

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APPENDIX 1. ***Table A. Lake Erie total phosphorus loads by basin, 1981–2001.***

	western basin						central basin						eastern basin						
Year	Atm	DID	DMD	TM	UnM	Sub-Total	Atm	DID	DMD	TM	UnM	Sub-Total	Atm	DID	DMD	TM	UnM	Sub-Total	Whole Lake[1]
1981	106	56	1,329	2,848	499	**4,838**	445	0	426	2,116	358	**3,345**	178	2	88	617	306	**1,191**	**10,455**
1982	96	66	897	4,776	728	**6,563**	403	1	409	1,952	686	**3,451**	161	1	81	755	256	**1,254**	**12,349**
1983	53	50	1,222	3,719	648	**5,692**	221	3	485	1,185	310	**2,204**	88	110	100	502	105	**905**	**9,880**
1984	57	30	1,332	4,682	938	**7,039**	239	3	473	2,067	791	**3,573**	96	90	99	697	202	**1,184**	**12,874**
1985	42	23	1,075	4,549	783	**6,472**	178	8	447	1,419	484	**2,536**	71	18	100	785	154	**1,128**	**11,216**
1986	52	17	1,217	3,908	970	**6,164**	218	15	415	1,634	640	**2,922**	87	6	57	659	143	**952**	**11,118**
1987	69	28	1,258	2,006	567	**3,928**	287	12	469	1,129	390	**2,287**	115	4	40	593	336	**1,088**	**8,381**
1988	54	21	1,279	2,114	950	**4,418**	227	10	430	688	80	**1,435**	91	3	31	483	299	**907**	**7,841**
1989	45	25	1,051	3,019	530	**4,670**	189	10	412	1,536	165	**2,312**	76	5	39	252	133	**505**	**8,568**
1990	68	138	1,207	5,062	849	**7,324**	285	16	285	1,351	272	**2,209**	114	5	50	380	1,737	**2,286**	**12,901**
1991	49	128	1,297	4,294	634	**6,402**	203	26	294	1,596	270	**2,389**	81	12	47	757	345	**1,242**	**11,113**
1992	39	43	1,143	3,027	382	**4,634**	161	17	265	1,069	153	**1,665**	64	7	48	373	103	**595**	**7,973**
1993	49	29	1,197	5,394	621	**7,290**	206	14	250	1,564	533	**2,567**	82	6	43	681	389	**1,201**	**12,139**
1994	59	36	1,265	2,310	470	**4,140**	246	9	310	977	341	**1,883**	98	5	56	306	170	**635**	**7,736**
1995	55	52	996	1,993	723	**3,819**	230	31	365	950	672	**2,248**	92	6	53	245	226	**622**	**7,769**
1996	75	49	985	4,233	1,329	**6,671**	315	12	188	1,495	700	**2,710**	126	7	94	548	350	**1,124**	**11,584**
1997	76	38	1,386	6,092	1,996	**9,588**	317	14	257	1,750	882	**3,220**	127	7	98	1,265	1,468	**2,966**	**16,853**
1998	101	39	1,170	5,128	1,599	**8,037**	424	7	226	1,437	879	**2,973**	169	8	93	159	192	**621**	**12,710**
1999	71	36	1,051	1,993	780	**3,931**	296	5	236	471	191	**1,198**	118	7	83	72	116	**397**	**6,608**
2000	115	34	1,150	2,381	839	**4,519**	481	6	273	764	427	**1,951**	192	7	100	248	361	**908**	**8,456**
2001	78	34	990	2,306	1,006	**4,415**	328	11	196	367	167	**1,069**	131	7	95	317	218	**768**	**7,333**

Legend (All loads are in metric tonnes per annum – MTA)
Atm: Atmospheric Loading
DID: Direct Industrial Discharge
DMD: Direct Municipal Discharge
TM: Monitored Tributary Load
UnM: Adjustment for Unmonitored Area

[1] Whole lake estimate includes a constant value of 1,080 MTA upstream (Lake Huron) loading which enters above the western basin.

APPENDIX 2. Data sources.

All of the data used to estimate Lake Erie Total Phosphorus (TP) loads come from government databases except as noted below. Data for U.S. Point Source dischargers in the Lake Erie basin (monthly average effluent flow and TP concentration) are retrieved annually from the Permit Compliance System (PCS) which is a database maintained by the U.S. EPA and updated by the states (New York, Pennsylvania, Ohio, Indiana, and Michigan).

Data for Canadian point source dischargers in the Lake Erie basin are stored in the Municipal and Industrial Strategy for Abatement (MISA) database maintained by the Ontario Ministry of the Environment. Except for limited TP effluent concentration data for 2001 and 2002, these data were not available for the study and previous estimates for 1995 were used and assumed to be representative of the period 1996–2000.

The U.S. daily average tributary flows for gauged Lake Erie tributaries were retrieved from the WATSTORE database maintained by U.S. Geological Survey, Water Division, while the Canadian daily average tributary flows for gauged Lake Erie tributaries were provided on CD-ROM by Environment Canada, Water Survey Canada.

Available U.S. tributary TP concentrations for monitored Lake Erie tributaries were retrieved from STORET, the EPA database for water quality data. Sampling results from state water quality monitoring networks (New York DEC, Ohio EPA, and Michigan DEQ) are stored in this database. STORET is now accessible on the Internet. Data prior to 1999 are available in the STORET Legacy Data Center, and data from 1999 to the present are intended for Modernized STORET. However, no data for the study period currently reside in Modernized STORET. Further, USGS data that were formerly in STORET Legacy have been moved to the USGS water data website where it can be retrieved along with the daily flows referred to above. Data from the Heidelberg College sampling network have not been stored in either version of STORET for the study period but were available directly from Peter Richards (Heidelberg College Water Quality Laboratory, personal communication). Ohio EPA data from 1999 to 2002 were available directly from that agency.

The Canadian tributary TP concentrations for monitored Lake Erie tributaries were available from the Stream Monitoring System database at the Ontario Ministry of the Environment.

The TP concentrations in rainfall and rainfall amounts in the Lake Erie basin were available in spreadsheet format from Environment Canada.

All of the above raw data have been stored in archive form and are available on request from the authors.