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# Fifth Year Review of Canada-United States Great Lakes Water Quality Agreement: Report of Task Group 3: A Technical Group to Review Phosphorus Loadings

International Joint Commission. Task Group 3

J. R. Vallentyne

N. A. Thomas

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# FIFTH YEAR REVIEW
# OF CANADA - UNITED STATES
# GREAT LAKES WATER QUALITY AGREEMENT

## REPORT OF TASK GROUP III

## A TECHNICAL GROUP TO
## REVIEW PHOSPHORUS LOADINGS

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Canada

# FIFTH YEAR REVIEW OF CANADA-UNITED STATES GREAT LAKES WATER QUALITY AGREEMENT

## REPORT OF TASK GROUP III
## A TECHNICAL GROUP TO REVIEW PHOSPHORUS LOADINGS

Canadian Co-Chairman
J. R. Vallentyne, Senior Scientist
Canada Centre for Inland Waters
Burlington, Ontario, Canada L7R 4A6

U.S. Co-Chairman
N.A.Thomas, Chief
Large Lakes Research Station
U. S. Environmental Protection Agency
Grosse Ile, Michigan 48138
U. S. A.

February 1978

The subject report was prepared as background material for the 1978 renegotiation of the Canadian-U.S. Great Lakes Water Quality Agreement. The Task Group that prepared the report did so without regard to agency affiliation, and outside of the International Joint Commission auspices. The publication of the Task Group's findings will benefit those who implement the new Great Lakes Water Quality Agreement.

The Co-chairmen would like to thank all the committee members which include:

A. Beeton, University of Michigan
V. Bierman, U.S. Environmental Protection Agency
S. Chapra, National Oceanic & Atmospheric Administration
P. Dillon, Ministry of the Environment
D. DiToro, Manhattan College
A. Harris, Ministry of the Environment
G. Mills, Ministry of the Environment
S. Munro, Ministry of the Environment
A. Robertson, National Oceanic & Atmospheric Adminstration
S. Salbach, Ministry of the Environment
W. Sonzogni, Great Lakes Basin Commission
G. VanFleet, Ministry of the Environment
R. Vollenweider, Canada Centre for Inland Waters
R. Waybrant, Michigan Department of Natural Resources
S. Yaksich, U.S. Army Corps of Engineers

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Nelson A. Thomas
Nelson A. Thomas,
U.S. Co-Chairman

Jack Vallentyne (NAT)
J.R. Vallentyne,
Canadian Co-Chairman

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## EXECUTIVE SUMMARY AND RECOMMENDATIONS

Task Group III was a technical working group charged with developing total phosphorus loading objectives for each of the Great Lakes as part of the 1978 re-negotiation of the 1972 Water Quality Agreement. The Task Group was directed to address only the technical questions involved.

The general criterion used in developing the objectives was the interference with water use by man. In contrast to the approach used in the 1972 Agreement, the present objectives were based on the resulting water quality corresponding to the phosphorus loads in each basin, as well as on the phosphorus loads themselves.

On the basis of evidence accumulated since 1972, the Task Group is unanimous in endorsing the concept of the phosphorus control program as described in the Agreement. Further, improved information since 1972 has led the Task Group to conclude that a 1 mg per liter (mg/l) effluent requirement for municipal discharges will not be sufficient to achieve desirable water quality in Saginaw Bay, Lake Erie, and Lake Ontario. Some degree of diffuse source control will be required to achieve the recommended water quality objectives for these basins.

It is the recommendation of the Task Group that a non-degradation objective be established for Lake Superior, Lake Huron (exclusive of Saginaw Bay), and Lake Michigan. This recommendation is a reaffirmation that present water quality should be maintained in Lake Superior and Lake Huron. Lake Michigan lies completely within the U.S. border and it is not specifically mentioned in the 1972 Agreement; however, since the outflow from Lake Michigan constitutes an input to Lake Huron, it is not possible to establish an objective for Lake Huron independently of Lake Michigan.

Table A contains a summary of the recommendations for the non-degradation basins. The recommended loads are those which remain after the recommended 1 mg/l effluent standard for municipal discharges greater than 1 million gallons per day (mgd) is fully implemented. The recommended concentrations are estimates of the concentrations that will correspond to these residual loads.

It is the recommendation of the Task Group that substantial phosphorus load reductions be implemented in Saginaw Bay, Lake Erie, and Lake Ontario to achieve desirable water quality. Table B contains a summary of the Task Group recommendations for these basins. This table also contains two of the possible phosphorus treatment strategies which would achieve each of the recommended objectives. An additional treatment strategy would be the further reduction of phosphorus in all commercial and household detergents. Substantial diffuse source phosphorus control must be implemented, even if the present 1 mg/l effluent standard is reduced to 0.5 mg/l.

Investigations by the Task Group have led to the conclusion that for many municipal systems, a 0.5 mg/l treatment level can be achieved with additional settling facilities and/or effluent filtration. In addition, approximately 30 to 50 percent of diffuse loads is believed to be controllable using existing technology where the phosphorus loading rate per unit area is high, such as in the Lower Lakes.

With regard to specific treatment strategies for municipal and diffuse sources, the costs and benefits can be more clearly established over the

## TABLE A. SUMMARY OF TASK GROUP RECOMMENDATIONS FOR NON-DEGRADATION BASINS

| Basin | 1976 Phosphorus Load in Metric Tonnes Per Year | Task Group Recommendation: Phosphorus Load in Metric Tonnes Per Year | Task Group Recommendation: Total Phosphorus Concentration in μg/l |
|---|---|---|---|
| Superior | 3600 | 3400 | 4 |
| Michigan | 6700 | 5600 | 7 |
| Main Lake Huron | 3000 | 2800 | 5 |
| Georgian Bay | 630 | 600 | 4 |
| North Channel | 550 | 520 | 5 |

## TABLE B. SUMMARY OF TASK GROUP RECOMMENDATIONS FOR SAGINAW BAY, LAKE ERIE, AND LAKE ONTARIO

| Basin | Phosphorus Load in Metric Tonnes Per Year |  | Water Quality Objectives | Treatment Strategies |
|---|---|---|---|---|
|  | Base Year | Task Group Recommendation |  |  |
| Saginaw Bay | 870 | 440 | To reduce taste, odor, and filter-clogging at water filtration plants by maintaining a total phosphorus concentration of 15 µg/l. | 1 mg/l + 55% reduction in diffuse sources<br>or<br>0.5 mg/l + 40% reduction in diffuse sources |
| Lake Erie | 20000 | 11000 | Reduction of approximately 90% in the area of anoxia in the Central Basin and prevention of any substantial phosphorus release from the sediments. | 1 mg/l + 50% reduction in diffuse sources<br>or<br>0.5 mg/l + 30% reduction in diffuse sources |
| Lake Ontario | 11000 | 7000 | Minimize degradation of the ecosystem by maintaining a total phosphorus concentration of approximately 10 µg/l. | 1 mg/l + 50% reduction in diffuse sources<br>or<br>0.5 mg/l + 30% reduction in diffuse sources |

---

[1] For Lake Ontario the treatment strategies must be implemented simultaneously in both Lake Erie and Lake Ontario.

next year or so. It is, therefore, recommended that the State and Provincial governments be required to commit themselves within a year from the date of the new Agreement to establishing methods by which the phosphorus loading objectives in Table B are to be achieved. The methodologies to be developed should include a schedule which clearly identifies the time over which the loading objectives would be achieved. Any of the strategies developed will need to reflect the growth of population over time. A minimum of a 1 mg/l phosphorus effluent standard will be required at all municipal treatment plants greater than 1 mgd in the Great Lakes Basin.

next year or so. It is, therefore, recommended that the State and Provincial governments be required to commit themselves within a year from the date of the new Agreement to establishing methods by which the phosphorus loading objectives in Table 4 are to be achieved. The methodologies to be developed should include a schedule which clearly identifies the time over which the loading objectives would be achieved. Any of the strategies developed will need to reflect the growth of population over time. A minimum of a 1 mg/l phosphorus effluent standard will be required at all municipal treatment plants greater than 1 mgd in the Great Lakes Basin.

TABLE 4. SUMMARY OF TASK GROUP RECOMMENDATIONS FOR SAGINAW BAY, LAKE ERIE, AND LAKE ONTARIO

| Region | Phosphorus Load in Metric Tonnes Per Year: Base Year | Phosphorus Load in Metric Tonnes Per Year: Task Group Recommendation | Water Quality Objectives | Treatment Strategies |
|---|---|---|---|---|
| Saginaw Bay | 870 | 440 | To reduce taste, odor, and filter-clogging at water filtration plants by maintaining a total phosphorus concentration of 15 µg/l. | 1 mg/l + [illegible] reduction in diffuse sources<br>0.5 mg/l + [illegible] from diffuse sources |
| Lake Erie | 20000 | 11000 | Reduction of approximately 90% in the area of anoxia in the Central Basin and prevention of any substantial phosphorus release from the sediments. | 1 mg/l + [illegible] reduction in diffuse sources<br>0.5 mg/l + 30% reduction in diffuse sources |
| Lake Ontario | 11000 | 7000 | Minimize degradation of the ecosystem by maintaining a total phosphorus concentration of approximately 10 µg/l. | 1 mg/l + 50% reduction in diffuse sources<br>0.5 mg/l + 20% reduction in diffuse sources |

¹For Lake Ontario the treatment strategies must be implemented simultaneously in both Lake Erie and Lake Ontario.

# INTRODUCTION

The terms of reference for Task Group III, hereafter referred to as TG, were:

1. To prepare a report based on the latest information on "acceptable" total phosphorus loadings to each lake;
2. To provide the best estimates of current phosphorus loadings from each country and each major source, e.g. municipal, industrial, tributary, etc.;
3. To determine what control possibilities exist and what would be the costs of pursuing them;
4. To develop for each lake several phosphorus loading levels and treatment strategies, the conditions which would result from these levels, and estimates of response times of the lakes to these levels;
5. To determine what dissolved oxygen and other water quality objectives would be compatible with the proposed phosphorus loading.

The rationale behind the phosphorus control program of the Great Lakes Water Quality Agreement (WQA) of 1972 was based on evidence from a variety of inland waters. This evidence includes experimental measurements of water from the Lower Great Lakes showing that algal growth and associated aspects of man-made eutrophication could be controlled by reducing phosphorus loading rates to the waters of the Great Lakes system. This evidence was sufficiently compelling to institute a control program; however, no absolute guarantee could be given that the control program would work, nor could the rates of response be predicted. Enough was known to predict with reasonable assurance that even with the recommended control program, additional measures and programs might be required to minimize eutrophication problems in the future.

The phosphorus control program of the WQA had four objectives:

1. Restoration of year-round aerobic conditions in the bottom waters of the central basin of Lake Erie;
2. Reduction in present (1972) levels of algal growth in Lake Erie;
3. Reduction in present (1972) levels of algal growth in Lake Ontario, including the international section of the St. Lawrence River;
4. Stabilization of Lake Superior and Lake Huron in their present (1972) oligotrophic states.

To meet these objectives three measures were proposed in the WQA: (1) municipal waste treatment to achieve less than 1 mg/l of phosphorus in effluents with discharges in excess of 1 mgd into Lake Erie, Lake Ontario and the international section of the St. Lawrence River; (2) maximum practicable reduction of phosphorus from industrial sources discharging wastes into Lake Erie, Lake Ontario and the international section of the St. Lawrence River; and (3) control of phosphorus inputs from animal husbandry operations. Provisions were also included for limiting or eliminating phosphorus from detergents sold or used within the Great Lakes Basin.

The implementation of these control measures did not take place at the rate originally envisioned in the WQA. Phosphorus load reductions are just beginning to be implemented, and the loading objectives have not yet been reached. The program has been almost completely implemented, except for Detroit, which is the largest point source to the Great Lakes. For this reason, it is difficult to evaluate the effects of phosphorus control on the water quality of the Great Lakes.

On the basis of evidence accumulated since 1972, the TG is unanimous in endorsing the concept of the phosphorus control program as described in the WQA. Further, improved information since 1972 has led the TG to conclude that a 1 mg/l effluent requirement for municipal discharges will not be sufficient to achieve desirable water quality in Saginaw Bay, Lake Erie, and Lake Ontario. Some degree of diffuse source phosphorus control will be required to achieve the recommended water quality objectives for these basins.

A number of persistent problems remain which defy easy resolution and which hinder recognition and implementation of the most effective phosphorus control strategies. These are: (1) the large variations associated with phosphorus loading estimates, in part due to sampling inadequacies, year-to-year variations and analytical errors; (2) the difficulty of estimating the availability of phosphorus from different sources and in different chemical forms to various algal species; (3) the difficulty of determining the relative influence on boundary waters of phosphorus discharges at various distances upstream in different tributaries; and (4) the difficulty of estimating the costs and times required for implementation of remedial measures in the case of phosphorus loads from diffuse sources.

In the analysis that follows, objectives are developed for phosphorus loading to each of the major basins in the Great Lakes. The general criterion used in developing the objectives was the interference with water use by man. In contrast to the approach used in the 1972 WQA, the objectives in the present report were based on the resulting water quality corresponding to the phosphorus loads in each basin, as well as on the phosphorus loads themselves. The WQA objectives were based primarily on the phosphorus loads and not on the in-lake concentrations of water quality parameters resulting from these loads.

All references to phosphorus loads and phosphorus concentrations in the present report should be taken to mean total phosphorus. No attempt was made to separate total phosphorus into components which are available or unavailable for algal growth. It was decided by the TG that a meaningful distinction between these components was beyond the present scientific understanding of phosphorus dynamics in lake systems.

It should be recognized that the tabulations for existing phosphorus loads contained in the present report will not necessarily agree with similar tabulations from other sources. This is because phosphorus loads from various sources can be based on varying data sets and on varying methods of calculation. The phosphorus loads in the present report were based on the best current information available.

## SCOPE

Phosphorus loading objectives were developed for ten major basins and sub-basins within the Great Lakes system. Lakes Superior, Huron, Erie, and Ontario were included because these lakes lie along the international border between the U.S. and Canada. Lake Michigan was also included because, although Lake Michigan lies entirely within the U.S. border, the phosphorus load from the Lake Michigan outflow is an important source of phosphorus input to Lake Huron.

The main body of Lake Huron was treated separately from Saginaw Bay, the North Channel, and Georgian Bay. The latter two basins are physically distinct from Lake Huron proper. Saginaw Bay, while not physically distinct, constitutes a western extension of the main body of Lake Huron, and it is highly phosphorus enriched compared with the rest of Lake Huron. The local problems that occur in Saginaw Bay have international ramifications because the outflow from Saginaw Bay constitutes a substantial source of phosphorus loading to Lake Huron across the U.S.-Canada boundary.

Lake Erie was sub-divided into three basins: Western, Central, and Eastern. This was done because of the natural morphometry of Lake Erie and the distinctly different water quality characteristics of the three basins. The Western Basin is shallow, well-mixed, and has a relatively short hydraulic detention time. Most of the external phosphorus input to the lake as a whole comes directly into the Western Basin. The Central Basin is sufficiently deep so that it stratifies into an epilimnion and a hypolimnion during the summer months. This basin constitutes the major depositional area for decaying phytoplankton in the lake. The most notable consequence of phosphorus enrichment in Lake Erie is the depletion of dissolved oxygen in the Central Basin hypolimnion near the end of the summer stratification period. The Eastern Basin is the deepest of the three basins and it receives less of the total external phosphorus load to the whole lake than either the Western or the Central Basins.

## RATIONALE FOR PHOSPHORUS CONTROL IN THE GREAT LAKES

Since the 1972 Water Quality Agreement, there has been increased scientific evidence in support of phosphorus control for the Great Lakes. Bioassay experiments in Lake Huron have shown that phosphorus is the most important nutrient limiting the growth rates of the phytoplankton. Recent work has led to the hypothesis that there are biological mechanisms in lakes which can correct algal deficiencies of carbon and nitrogen. The occurrence of N fixation in Green Bay and in the Western Basin of Lake Erie has been found when dissolved nitrogen levels became extremely low. Carbon has been shown not to be an important limiting nutrient in lake systems which receive large inputs of phosphorus. Even a deficiency in silicon will not necessarily limit phytoplankton crops. It has been hypothesized that increasing silicon depletion in Lake Michigan will lead to a species shift from diatoms to green and blue-green phytoplankton. These latter types do not have a major requirement for silicon.

An intensive study of the depletion of dissolved oxygen was conducted in the Central Basin of Lake Erie. It was found that the rate of phosphorus regeneration from the sediments under anaerobic conditions was eleven (11) times greater than the regeneration rate under aerobic conditions. The decomposition of dead phytoplankton was found to be the major cause of the oxygen depletion in the Central Basin.

Phosphorus is the single element for which all phytoplankton have an absolute requirement, and for which there exists practical control methodology.

Excessive growth of Cladophora, an attached alga, has become an increasing problem in the Great Lakes. Although Cladophora growth is believed to be related to the general level of phosphorus enrichment, there is presently an insufficient scientific understanding of the role of Cladophora in the Great Lakes ecosystem. More research is needed before effective control strategies can be developed.

## PRESENT CONDITIONS AND RECENT TRENDS

In order to describe in-lake conditions it is necessary to define appropriate indicator parameters. The primary indicator used in the present report was total phosphorus concentration. The most important secondary indicator used was chlorophyll a concentration, a substitute for phytoplankton density. Other indicator parameters were used where it was necessary to address specific issues in more detail in certain basins. Dissolved oxygen concentration was used in the Central Basin of Lake Erie. Phytoplankton cell volume data for different functional groups of algae, e.g., diatoms and blue-greens were used in Saginaw Bay instead of chlorophyll a concentration. This was mainly because severe taste and odor problems at the principal water intake plant on Saginaw Bay were found to be statistically correlated with the blue-green component of the total phytoplankton crop. All of these parameters were related to the external phosphorus loads for each of the major basins.

The available data indicate that there have been few significant changes in phosphorus or chlorophyll a concentrations in the Great Lakes during the last ten years. Recent conditions are summarized in Table I. Dobson (1976) investigated possible trends in total phosphorus, chlorophyll a, Secchi depth, and particulate organic carbon using summer data gathered by the Canada Centre for Inland Waters. These data include the period 1968-1975 for Lakes Superior, Huron, Ontario, and the Central Basin of Lake Erie. Dobson reported that only the Secchi depth in Lake Ontario showed a signifi-

TABLE 1. REPRESENTATIVE CONCENTRATIONS USING DATA FROM THE PERIOD 1974-1976

| | Concentration | |
|---|---|---|
| Basin | Annual Average Total Phosphorus (µg/l) | Summer Average Chlorophyll a (µg/l) |
| Superior[1] | 4.6 | 1.0 |
| Michigan[2] | 7.4 | 1.8 |
| Huron[1] | 5.2 | 1.2 |
| Inner Saginaw Bay[3] | 40 | 23 |
| Georgian Bay[4] | 4.5 | 1.2 |
| North Channel[4] | 5.5 | 1.7 |
| Erie[5] | | |
| Western Basin | 44.9 | 12.4 |
| Central Basin | 22.5 | 5.3 |
| Eastern Basin | 23.9 | 3.8 |
| Ontario | 22[5] | 5.3[1] |

[1] Dobson (1976)

[2] Data from 1976 field surveys conducted by the Great Lakes Research Division, University of Michigan, and Region V, United States Environmental Protection Agency, Chicago.

[3] Smith, *et al.* (1977)

[4] Upper Lakes Reference Group, Volume II.

[5] International Joint Commission, Great Lakes Water Quality 1976. Appendix B.

cant increasing trend. All of the other data either indicated no significant trend or showed too much variability for trends to be detected. Insufficient data are available for any trend analysis on Lake Michigan. The Great Lakes Water Quality Board - Appendix B (1976) has reported that the only trend observed anywhere in Lake Erie for phosphorus or chlorophyll a concentrations was a significant upward trend for phosphorus concentration in the Central Basin. The same report indicates that there have been significant increases in both phosphorus and chlorophyll a concentrations in the inner portion of Saginaw Bay between 1974 to 1976.

There is no evidence for any consistent change in the dissolved oxygen conditions in the Central Basin since 1970. Data are available for 1970 (Burns and Ross 1972), and for each year from 1973 to 1976 (Great Lakes Water Quality Board - Appendix B 1976). With the exception of 1975, between 56 percent and 94 percent of the area of the Central Basin hypolimnion became anoxic at the end of the summer stratification period each year. In 1975 only 4 percent of the hypolimnetic area became anoxic at that time. The data support the contention that the conditions in 1975 were an anamoly due to an unusually calm and warm spring period which resulted in the formation of an unusually large hypolimnion. The net oxygen demand of the hypolimnion in terms of mg $O_2$/l/d has remained unchanged since 1970. The net areal oxygen demand of the hypolimnion in terms of mg $O_2$/a/d shows an apparent increase since 1970 (Great Lakes Water Quality Board Report - Appendix B 1976).

The general lack of significant trends for in-lake phosphorus and chlorophyll a concentrations is consistent with a similar lack of significant trends for phosphorus loadings. There has been no significant change in the phosphorus loading to Lake Ontario during the period 1968-1974 (Bierman 1977). Yaksich (1977b) has reported no significant change in the phosphorus loading to Lake Erie during the period 1970-1976. Comprehensive loading data for Saginaw Bay are only available from 1974 to 1976, and they show a high degree of year-to-year variability. Loading data for the other major basins in the Great Lakes are inadequate for meaningful trend analyses.

The lack of significant trends in phosphorus loadings does not necessarily imply that there has been no progress in implementing the objectives of the 1972 Water Quality Agreement. On the contrary, the available data for municipal point source discharges indicate that there have been substantial reductions, especially since 1975 (Great Lakes Water Quality - Appendix C 1976). It is difficult to observe these reductions in the total phosphorus loadings because the annual variations in the tributary loadings are sufficiently large to distort trends which might otherwise be apparent. Dobson (1978) has reported that the winter average total phosphorus concentration in Lake Ontario was 2-3 μg/l lower in 1977 than in 1974. Although the statistical significance of these data has not been shown, except perhaps in certain nearshore areas, it is possible that the change is part of a developing trend in the response of Lake Ontario to reductions in municipal point source loadings. Additional measurements are needed over a longer period of time to confirm any trends in either phosphorus loads or in-lake phosphorus concentrations.

# PHOSPHORUS LOADINGS TO THE GREAT LAKES

## General

To set phosphorus loading objectives for the Great Lakes it was necessary to first establish present phosphorus loadings. Most of the recent information available to the TG was contained in the 1976 Great Lakes Water Quality Board Report - Appendix B. This information was supplemented and, in some cases, revised, by various TG studies. Munro (1977) contains a detailed description of phosphorus loads by individual sources and jurisdictions for all of the major basins considered. This document constituted the primary reference for the summary tables contained in the present report. Any subsequent revisions to the results from Munro (1977) are noted below.

The components of total phosphorus load that appear in conventional tabulations are usually distinguished on the basis of the operational procedures used to reduce the raw data. Some confusion arises because these components are not consistent with components distinguished on the basis of source type. These latter components are more useful when considering various phosphorus control strategies.

The tabulations of existing phosphorus loads in the present report follow the conventional format. It should be recognized that most of the municipal and industrial inputs are included in the components identified as Monitored/Unmonitored Tributary sources. This is because most of the municipal and industrial inputs to the Great Lakes are not discharged directly to the lakes. Instead, they are first discharged to various tributaries which then flow into the lakes.

From the standpoint of phosphorus control strategies, two broad types of loading components have been identified: point loads and non-point loads. Point loads should be taken to include all municipal and industrial sources, both direct and indirect. Non-point loads should be taken to include diffuse loads, atmospheric loads, and loads from inter-lake exchange flows. Diffuse loads include diffuse tributary inputs and possible direct diffuse inputs. The diffuse tributary load is derived from runoff, particularly agricultural and urban, and groundwater flow.

Phosphorus Loads for 1976

Tables II-XIV contain summary information on the existing phosphorus loadings for all of the basins considered. Each table includes a projected loading for the case in which all municipal point discharges greater than 1 mgd achieve a 1 mg/l effluent concentration. This projection includes both direct and indirect municipal discharges. It should be noted that a number of municipalities currently discharge phosphorus at concentrations less than 1 mg/l (Munro 1977).

Loads resulting from shoreline erosion are indicated in the summary tables; however, they are not included in the summation of total loadings to the basins. It was the opinion of the TG that erosion loads were not a significant factor in whole-lake phosphorus dynamics. Neither the total phosphorus from shore erosion nor the estimates of available phosphorus from shore erosion were easily comparable to the phosphorus loadings for other sources. Further, there is no direct comparison between the acid extract-

## TABLE II. 1976 TOTAL PHOSPHORUS LOADING TO LAKE SUPERIOR IN METRIC TONNES PER YEAR

| Source | Minnesota | Wisconsin | Michigan | Ontario | Total |
|---|---|---|---|---|---|
| Direct Industrial | 2[1] | No Data | No Data | 102 | 104[1] |
| Direct Municipal | 12 | 8[1] | 26 | 31 | 77[1] |
| Tributary - Monitored | 143 | 83 | 241 | 1241 | 1708 |
| Tributary - Unmonitored | US 378 | | | 214 | 592 |
| Atmospheric | | | | | 1089 |
| TOTAL (Excluding shore erosion and re-entry from sediments) | | | | | 3570 (3352)[2] |
| Shore Erosion | US (from GLBC) acid extractable[3] | | 2000 | Total | 3800 |
| | Canada (from PLUARG) non apatite | | Not significant | Total | Not significant |

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[1] Indicates value different from that in 1976 GLWQB report - see Munro (1977) for details.

[2] Total load assuming 1 mg/l effluent standard for all municipal discharges greater than 1 mgd.

[3] As determined by extraction in 0.05 normal HCl, not to be confused with available P. The fraction of total P that is available for biological uptake is likely much less than that measured as a 0.05N HCl extraction of shoreline samples.

## TABLE III. 1976 TOTAL PHOSPHORUS LOADINGS TO LAKE MICHIGAN IN METRIC TONNES PER YEAR

| Source | Wisconsin | Michigan | Illinois | Indiana | Total |
|---|---|---|---|---|---|
| Direct Industrial | 4[1] | 6[1] | 3[1] | 32 | 45[1] |
| Direct Municipal | 956 | 19 | 67[1] | No Data | 1042[1] |
| Tributary - Monitored | 870 | 1902 | No Data | 407 | 3179 |
| Tributary - Unmonitored | | | | | 715 |
| Atmospheric | | | | | 1690 |
| TOTAL (Excluding shore erosion and re-entry from sediments) | | | | | 6671 (5553)[2] |
| Shore Erosion (from GLBC) | acid extractable[3] | 1500 | | Total | 3700 |

[1] Indicates value different from that in 1976 GLWQB report - see Munro (1977) for details.

[2] Total load assuming 1 mg/l effluent standard for all municipal discharges greater than 1 mgd.

[3] As determined by extraction in 0.05 normal HCl, not to be confused with available P. The fraction of total P that is available for biological uptake is likely much less than that measured as a 0.05N HCl extraction of shoreline samples.

## TABLE IV. 1976 TOTAL PHOSPHORUS LOADINGS TO GEORGIAN BAY - LAKE HURON IN METRIC TONNES PER YEAR

| Source | Ontario | Total |
|---|---|---|
| Direct Industrial | No Data | - |
| Direct Municipal | 49 | 49 |
| Tributary - Monitored | 263 | 263 |
| Tributary - Unmonitored | 50 | 50 |
| Atmospheric (15108 km$^2$ - 25%) | 266 | 266 |
| TOTAL (Excluding shore erosion and re-entry from sediments) | | 628 (598)[1] |
| Shore Erosion PLUARG estimates no significant erosion contribution | | |

[1] Total load assuming 1 mg/l effluent standard for all municipal discharges greater than 1 mgd.

TABLE V. 1976 TOTAL PHOSPHORUS LOADINGS TO NORTH CHANNEL - LAKE HURON IN METRIC TONNES PER YEAR

| Source | Michigan | Ontario | Total |
|---|---|---|---|
| Direct Industrial | No Data | 6[1] | 6[1] |
| Direct Municipal | 5[2] | 16[2] | 21[2] |
| Tributary - Monitored | | | 237 |
| Tributary - Unmonitored | | | 67 |
| Atmospheric (3950 $km^2$ - 6.6%) | | | 70 |
| St. Mary's River (32%) | | | 129 |
| Georgian Bay (2.6%) | | | 16 |
| TOTAL (Excluding shore erosion and re-entry from sediments) | | | 546 (516)[3] |
| Shore Erosion PLUARG estimates no significant erosion contribution | | | |

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[1] Indicates value different from that in 1976 GLWQB report - see Munro (1977) for details.

[2] Includes 32% of discharge from S.S. Marie, US and S.S. Marie, Canada. Remainder of these discharges is credited to main Lake Huron loading.

[3] Total load assuming 1 mg/l effluent standard for all municipal discharges greater than 1 mgd.

### TABLE VI. 1976 TOTAL PHOSPHORUS LOADINGS TO SAGINAW BAY - LAKE HURON IN METRIC TONNES PER YEAR

| Source | Michigan | Total |
|---|---|---|
| Direct Industrial | 39 | 39 |
| Direct Municipal | No Data | - |
| Tributary - Monitored | 1050 | 1050 |
| Tributary - Unmonitored | 64 | 64 |
| Atmospheric (2500 $km^2$ - 4.2%) | 44 | 44 |
| TOTAL (Excluding shore erosion and re-entry from sediments) | | 1197 (1038)[1] |
| Shore Erosion (from GLBC) acid extractable[2] | 20 | Total 50 |

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[1] Total load assuming 1 mg/l effluent standard for all municipal discharges greater than 1 mgd.

[2] As determined by extraction in 0.05 normal HCl, not to be confused with available P. The fraction of total P that is available for biological uptake is likely much less than that measured as a 0.05N HCl extraction of shoreline samples.

TABLE VII. 1976 TOTAL PHOSPHORUS LOADINGS TO MAIN LAKE HURON
IN METRIC TONNES PER YEAR

| Source | Michigan | Ontario | Total |
|---|---|---|---|
| Direct Industrial | 1 | No Data | 1 |
| Direct Municipal | 18[1] | 42 | 60[1] |
| Tributary - Monitored | | | 409 |
| Tributary - Unmonitored | | | 258 |
| Atmospheric (64.2%) | | | 682 |
| St. Mary's River (68%) | | | 273 |
| Lake Michigan | | | 255 |
| Saginaw Bay (70%) | | | 837 |
| Georgian Bay (8%) | | | 50 |
| North Channel (21%) | | | 127 |
| TOTAL (Excluding shore erosion and re-entry from sediments) | | | 2952 (2781)[2] |
| Shore Erosion US (from GLBC) acid extractable[3] | 80 | | Total 250 |
| Canada (from PLUARG) non apatite | 150 | | Total 416 |

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[1] Indicates value different from that in 1976 GLWQB report - see Munro (1977) for details.

[2] Total load assuming 1 mg/l effluent standard for all municipal discharges greater than 1 mgd.

[3] As determined by extraction in 0.05 normal HCl, not to be confused with available P. The fraction of total P that is available for biological uptake is likely much less than that measured as a 0.05N HCl extraction of shoreline samples.

## TABLE VIII. 1976 TOTAL PHOSPHORUS LOADINGS TO LAKE HURON IN METRIC TONNES PER YEAR

| Source | | | | Total[1] |
|---|---|---|---|---|
| Direct Industrial | | | | 46 |
| Direct Municipal | | | | 130 |
| Tributary - Monitored | | | | 1959 |
| Tributary - Unmonitored | | | | 439 |
| Atmospheric | | | | 1062 |
| St. Mary's River | | | | 402 |
| Lake Michigan | | | | 255 |
| TOTAL[2] (Excluding shore erosion and re-entry from sediments) | | | | 4293 (3903)[3] |
| Shore Erosion | US (from GLBC) | acid extractable[4] | 100 | Total 300 |
| | Canada (from PLUARG) | non apatite | 150 | Total 416 |

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[1] Sum of source contribution from North Channel, Georgian Bay, Saginaw Bay and main Lake Huron.

[2] Total differs from sum of totals for sub-basins because cross loadings, e.g. Georgian Bay loading to main Lake Huron - are excluded.

[3] Total load assuming 1 mg/l effluent standard for all municipal discharges greater than 1 mgd.

[4] As determined by extraction in 0.05 normal HCl, not to be confused with available P. The fraction of total P that is available for biological uptake is likely much less than that measured as a 0.05N HCl extraction of shoreline samples.

## TABLE IX. 1976 TOTAL PHOSPHORUS LOADINGS TO WESTERN BASIN OF LAKE ERIE IN METRIC TONNES PER YEAR

| Source | United States | Canada | Total |
|---|---|---|---|
| Direct Industrial | 111 | 164 | 275 |
| Direct Municipal | 5652 | 73 | 5725 |
| Tributary - Monitored | 4181 | 489 | 4670 |
| Tributary - Unmonitored | 659 | 146 | 805 |
| Atmospheric | | | 134 |
| Lake Huron | | | 1080 |
| TOTAL | | | 12689 (10665)[1] |

[1] Total load assuming 1 mg/l effluent standard for all municipal discharges greater than 1 mgd.

## TABLE X. 1976 TOTAL PHOSPHORUS LOADINGS TO CENTRAL BASIN OF LAKE ERIE IN METRIC TONNES PER YEAR

| Source | United States | Canada | Total |
|---|---|---|---|
| Direct Industrial | 0 | 0 | 0 |
| Direct Municipal | 945 | 5 | 950 |
| Tributary - Monitored | 1760 | 226 | 1986 |
| Tributary - Unmonitored | 499 | 231 | 730 |
| Atmospheric | | | 716 |
| Lake Huron | | | - |
| TOTAL | | | 4382 (2336)[1] |

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[1] Total load assuming 1 mg/l effluent standard for all municipal discharges greater than 1 mgd.

## TABLE XI. 1976 TOTAL PHOSPHORUS LOADINGS TO EASTERN BASIN OF LAKE ERIE IN METRIC TONNES PER YEAR

| Source | United States | Canada | Total |
|---|---|---|---|
| Direct Industrial | 0 | 0 | 0 |
| Direct Municipal | 249 | 3 | 252 |
| Tributary - Monitored | 215 | 1089 | 1304 |
| Tributary - Unmonitored | 417 | 363 | 780 |
| Atmospheric | | | 296 |
| Lake Huron | | | - |
| TOTAL | | | 2605 (1101)[1] |

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[1] Total load assuming 1 mg/l effluent standard for all municipal discharges greater than 1 mgd.

## TABLE XII. 1976 TOTAL PHOSPHORUS LOADINGS TO LAKE ERIE IN METRIC TONNES PER YEAR

| Source | United States | Canada | Total |
|---|---|---|---|
| Direct Industrial | 111 | 164 | 275 |
| Direct Municipal | 6846 | 81 | 6927 |
| Tributary - Monitored | 6156 | 1804 | 7960 |
| Tributary - Unmonitored | 1576 | 740 | 2315 |
| Atmospheric | | | 1119 |
| Lake Huron | | | 1080 |
| TOTAL | | | 19676 (14402)[1] |

[1] Total load assuming 1 mg/l effluent standard for all municipal discharges greater than 1 mgd.

## TABLE XIII. 1976 TOTAL PHOSPHORUS LOADINGS TO LAKE ONTARIO

| Source | New York | Ontario | Total |
|---|---|---|---|
| Direct Industrial | 33 | 51[1] | 84[1] |
| Direct Municipal | 1010[1] | 1129 | 2139[1] |
| Tributary - Monitored | 2123 | 1131 | 3254 |
| Tributary - Unmonitored | 975 | 261 | 1236 |
| Atmospheric | | | 473 |
| Lake Erie (from Hydroscience 1974) | | | 5613 |
| TOTAL (Excluding shore erosion and re-entry from sediments) | | | 12799 (11485)[2] |
| Shore erosion US (from GLBC) acid extractable[3] 180 | | | Total 480 |
| Canada (from PLUARG) non apatite 427 | | | Total 2106 |

[1] Indicates value different from that in 1976 GLWQB report - see Munro (1977) for details.

[2] Total load assuming 1 mg/l effluent standard for all municipal discharges greater than 1 mgd.

[3] As determined by extraction in 0.05 normal HCl, not to be confused with available P. The fraction to total P that is available for biological uptake is likely much less than that measured as 0.05N HCl extraction of shoreline samples.

TABLE XIV. 1976 TOTAL PHOSPHORUS LOADINGS TO THE ST. LAWRENCE RIVER

| Source | New York | Ontario | Total |
|---|---|---|---|
| Direct Industrial | No Data | 42 | 42[1] |
| Direct Municipal | 2[1] | 90 | 92[1] |
| Tributary - Monitored | No Data | 52 | 52 |
| Tributary - Unmonitored | 336 | 36 | 372 |
| Atmospheric | | | Not estimated |
| TOTAL (Excluding shore erosion and re-entry from sediments) | | | 558 (506)[2] |
| Shore erosion | US (from GLBC) acid extractable[3] 20<br>Canada PLUARG estimates to be not significant | Total | 60 |

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[1] Indicates value different from that in 1976 GLWQB report - see Munro (1977) for details.

[2] Total load assuming 1 mg/l effluent standard for all municipal discharges greater than 1 mgd.

[3] As determined by extraction in 0.05 normal HCl, not to be confused with available P. The fraction to total P that is available for biological uptake is likely much less than that measured as 0.05N HCl extraction of shoreline samples.

able phosphorus reported for shoreline erosion on the U.S. side and the non-apatite phosphorus reported for the Canadian side.

The loadings for Saginaw Bay in Table VI have been revised from Munro (1977). The use of additional phosphorus concentration measurements for 1976 from the Saginaw River (EPA-STORET) resulted in a substantially lower value for monitored tributary loading (Clark, 1978, personal communication). In addition, the contribution of Saginaw Bay to Main Lake Huron has been revised to 70 percent in Table VII, as compared with 100 percent reported by Munro (1977). This correction was based on data for net phosphorus accumulation in the sediments in Saginaw Bay. Robbins (1976, personal communication) has reported that the phosphorus accumulation rate in the inner portion of Saginaw Bay is approximately 360 metric tonnes per annum (mta). This constitutes 30 percent of the total load to Saginaw Bay in 1976. Appropriate revisions have been made to the phosphorus loadings in Table VI for Saginaw Bay, and in Tables VII and VIII for Main Lake Huron and Total Lake Huron, respectively. Note that the contributions of Georgian Bay and North Channel to Main Lake Huron were based on estimates from the Upper Lakes Reference Group Report, Volume II.

For some of the basins considered, the projected phosphorus loadings assuming a 1 mg/l effluent standard for municipal discharges greater than 1 mgd were taken from sources other than Munro (1977). For Saginaw Bay, the projected load for 1 mg/l includes a 200 mta contribution from the Flint municipal plant, instead of the 130 mta contribution reported in Munro (1977). Flint did not implement phosphorus removal in 1976 and it did not report an effluent phosphorus concentration in 1976. Munro used the average effluent concentration from all other plants in Michigan to develop the value of 130 mta. The TG decided that a value of 200 mta was more realistic, since many of the Michigan plants have either partially or completely implemented phosphorus removal. For Lake Erie, the projected loads for 1 mg/l were taken from Yaksich (1977a). These values were developed as part of the U.S. Army Corps of Engineers Lake Erie Wastewater Management Study.

Base Year Loads

To define phosphorus loading objectives in a more consistent fashion it was decided to develop base year loads for the systems which were most highly enriched. The purpose was to normalize the annual variations in the non-point components of the total phosphorus loadings. The non-point source components of the base loads were developed using historical average data for tributary flows and inter-lake exchange flows. The point source components and the atmospheric source components of the base loads are the same as in the 1976 loads.

Base year loads were developed for Saginaw Bay (Bierman 1978a) and Lake Erie (Yaksich 1977a) by scaling the present data for tributary sources to correspond to the historical average tributary flows. For Lake Ontario, a base load was developed only for the Lake Erie contribution to the total phosphorus load, and not for the tributaries in the Lake Ontario basin proper (Chapra 1978). Table XV contains a summary of all the base year loads that were developed and projected loadings corresponding to the 1 mg/l treatment level relative to the base year loads. Table XVI contains a percentage breakdown, relative to the base year loads, of the major loading components for each basin.

TABLE XV. SUMMARY OF 1976 AND BASE YEAR TOTAL PHOSPHORUS LOADS

| | Total Phosphorus Load in Metric Tonnes Per Year | | |
|---|---|---|---|
| Basin | 1976 | Base Year | Base Year After 1 mg/l |
| Superior | 3570 | Same as 1976 | 3352 |
| Michigan | 6671 | Same as 1976 | 5553 |
| Huron | 2952 | Same as 1976 | 2781 |
| Saginaw Bay | 1197 | 868 | 715 |
| Georgian Bay | 628 | Same as 1976 | 598 |
| North Channel | 546 | Same as 1976 | 516 |
| Erie | 19676 | 19968 | 15011 |
| Western | 12689 | 14499 | 10290 |
| Central | 4382 | 4007 | 3352 |
| Eastern | 2605 | 1463 | 1370 |
| Ontario | 12795 | 11088 | 9778 |

## TABLE XVI. PERCENTAGE OF BASE YEAR TOTAL PHOSPHORUS LOAD CONSTITUTED BY POINT, TOTAL NON-POINT AND DIFFUSE COMPONENTS

| Basin | Point Sources[1] | Total Non-Point Sources[2] | Diffuse Sources[3] |
|---|---|---|---|
| Superior | 8 | 92 | 61 |
| Michigan | 34 | 66 | 41 |
| Huron | 11 | 89 | 48 |
| Saginaw Bay | 36 | 64 | 59 |
| Georgian Bay | 13 | 87 | 45 |
| North Channel | 10 | 90 | 54 |
| Erie | 43 | 57 | 41 |
| Western | 46 | 54 | 39 |
| Central | 39 | 61 | 43 |
| Eastern | 19 | 81 | 61 |
| Ontario | 27 | 73 | 34 |

[1] Includes only municipal sources for the Upper Lakes and both municipal and industrial sources for the Lower Lakes. Industrial sources do not constitute a substantial portion of total point loads for the Lower Lakes.

[2] Includes diffuse loads, atmospheric loads and loads from inter-lake exchange flows. For Lake Erie, approximately 18% of the total non-point load is contributed by Lake Huron outflow. For Lake Ontario, approximately 48% of the total non-point load is contributed by Lake Erie outflow.

[3] Includes diffuse tributary loads and direct diffuse inputs. Diffuse tributary loads consist of runoff, particularly agricultural and urban, and groundwater flow.

## APPROACH TO LOADING OBJECTIVES

### General

Phosphorus loading objectives were based on the in-lake conditions corresponding to different phosphorus loading levels for each lake. Only the water quality conditions in the open-water zones were considered. Nearshore water quality problems, such as excessive Cladophora growth, were not explicitly considered. Annual average values were used for phosphorus loads and phosphorus concentrations. Values on the appropriate seasonal time scales were used for secondary water quality parameters such as phytoplankton, chlorophyll a, taste and odor, and dissolved oxygen.

The basic problem in developing objectives for phosphorus loadings is to identify the appropriate cause-effect relationships in the lake systems. External phosphorus loads are a cause, and lake responses in the form of phosphorus, chlorophyll a, and dissolved oxygen concentrations, are effects. In order to develop recommendations for objectives, quantitative estimates must be made of lake responses to phosphorus loads that are different from the present loads. In this report, various types of mathematical models were used to make these quantitative estimates for those basins which have the most serious water quality problems.

### Mathematical Models

The models used ranged from simple, empirical correlations between total phosphorus loads and various secondary parameters, to extremely complex mechanistic models which involve dynamic calculations for the major physical, chemical, and biological processes that actually occur in the lakes. In the case of the Great Lakes, all of these models have been tested only against existing conditions. None of the models have been tested for loads other than the present loads because there have been no significant trends in loads during the period of time for which comprehensive in-lake data were available for comparison with model output (5-10 years).

The state-of-the-art of mathematical modeling of the processes associated with eutrophication is still in its infancy. To the best of our knowledge, there have been no documented cases where a mathematical model has been used, a priori, to successfully predict the response of a lake system to a substantial change in phosphorus loads. Some of the simple empirical models have been successful in describing the statistical responses of large numbers of lakes over a wide range of loading conditions; however, such models do not necessarily give correct results for any single lake. On the other hand, complicated mechanistic models which have been developed for specific systems suffer the disadvantage of potential uncertainties when they are used to describe lake responses to loads that are very different from present loads for those systems.

In order to provide the strongest possible scientific basis for the recommendations in the present report, five different models were used. At least three of these models were used on each basin. Comparisons were made among the abilities of the models to describe present conditions and among the predictions of the models under changes in phosphorus loads.

## DESCRIPTION OF MATHEMATICAL MODELS

This section contains a brief description of each of the mathematical models used. The principal characteristics of each model are summarized in Table XVII. For comprehensive details, refer to the primary references cited for each model.

### Vollenweider

The version of the Vollenweider approach used in the present analysis is based on an empirical correlation between phosphorus load and in-lake concentrations of phosphorus and chlorophyll _a_ (Vollenweider 1976), and can be called the Vollenweider loading plot model. The correlations are a function of depth and hydraulic detention time. In developing the correlations, data were used from sixty (60) temperate-zone lakes which represented a range of conditions from oligotrophic to eutrophic.

Conceptually, the Vollenweider loading plot model originated from the solutions of a simplified mass balance model for a mixed reactor (Vollenweider 1969, 1975). In practice, the Vollenweider loading plot model is based on the steady-state solutions of this mixed reactor model. In the steady state, an instantaneous relationship is assumed between total phosphorus load and the corresponding in-lake concentration. The Vollenweider loading plot model can not give information on the response time of a system to a change in phosphorus load; however, it can give an estimate of in-lake conditions after equilibrium has been reached. It

## TABLE XVII. SUMMARY OF PRINCIPAL MODEL CHARACTERISTICS

| | Vollenweider (All Basins) | Chapra (All Basins) | Manhattan College | | Bierman |
|---|---|---|---|---|---|
| | | | Lakes Ontario and Huron | Lake Erie | Saginaw Bay |
| Dynamic | No | Yes | Yes | Yes | Yes |
| Empirical | Yes | Yes | No | No | No |
| State Variables | N/A | Phosphorus | Phosphorus<br>Nitrogen<br>(available and unavailable forms)<br>Chlorophyll *a*<br>Zooplankton | Phosphorus<br>Nitrogen<br>Silicon<br>(available and unavailable forms)<br>Dissolved Oxygen<br>Diatom Chlorophyll<br>Non-Diatom Chlorophyll<br>Zooplankton | Phosphorus<br>Nitrogen<br>Silicon<br>(available and unavailable forms)<br>Phytoplankton biomass for five functional groups (diatoms, greens, non-heterocystous blue-greens, heterocystous blue-green "others"<br>Zooplankton |
| Spatial Segmentation | No | Horizontal by major basin-no vertical | Horizontal and vertical | Horizontal and vertical | No |
| Input Requirements | Phosphorus load<br>Depth<br>Flushing rate | Phosphorus load<br>Depth<br>Flushing rate<br>Volume | Phosphorus load<br>Nitrogen load<br>Temperature<br>Light<br>Depth<br>Flushing rate<br>Volume | Phosphorus load<br>Nitrogen load<br>Silicon load<br>Temperature<br>Light<br>Depth<br>Flushing rate<br>Volume<br>Sediment nutrient release rates | Phosphorus load<br>Nitrogen load<br>Silicon load<br>Temperature<br>Light<br>Depth<br>Flushing rate<br>Volume |
| Output | Phosphorus<br>Chlorophyll *a*<br>(steady state equilibrium values) | Phosphorus (dynamically calculated)<br>Chlorophyll *a*<br>Dissolved oxygen (empirically correlated to phosphorus) | Dynamic concentrations for each state variable | Dynamic concentrations for each state variable | Dynamic concentrations for each state variable |

should be noted that Vollenweider (1969) has also developed time-variable models that can be used to make such calculations.

## Chapra

Chapra (1977) has used Vollenweider's (1969) time-variable approach as the basis for a simple dynamic mass balance model with phosphorus concentration as the principal variable. Total phosphorus is considered to be a nonconservative substance which does not undergo any transformations in the water column, but which is lost from the water column via an apparent settling velocity. Chapra has applied this model to the Great Lakes as a coupled dynamic system of basins. Given phosphorus load, volume, depth and flow, the model calculates in-lake phosphorus concentrations as a function of time, simultaneously for all of the major Great Lakes basins.

Since the Chapra model is a dynamic model, it can estimate both the in-lake concentrations and the response time for these concentrations as a result of changes in phosphorus loads.

The Chapra model contains an empirical component which allows correlations to be made between the dynamically calculated total phosphorus concentrations and various secondary parameters such as chlorophyll a and dissolved oxygen concentrations.

The Chapra model is different than the Vollenweider loading plot model in that Chapra dynamically calculates phosphorus concentration. The Chapra model and the Vollenweider loading plot model are similar in that both models use empirical correlations between phosphorus concentration and chlorophyll a and dissolved oxygen concentrations. Vollenweider has used data from many different lakes to develop his correlations. Chapra has used only Great Lakes data.

### Manhattan College

Manhattan College has developed models for Lake Ontario (Thomann et al. 1975, 1976; Hydroscience 1976), the Lake Huron-Saginaw Bay system (DiToro et al. 1976; DiToro et al. 1978a), and Lake Erie (DiToro et al. 1978b). These are dynamic mass balance models which directly calculate both phosphorus and nitrogen concentrations. In this respect, they are conceptually similar to the Chapra model. The Manhattan models differ from the Chapra model in that they also directly calculate the secondary parameters, chlorophyll a concentration, zooplankton concentration, and, for Lake Erie, dissolved oxygen concentration.

In all of the Manhattan models, phytoplankton growth is a function of phosphorus and nitrogen concentrations, temperature, and light intensity. Zooplankton growth is a function of phytoplankton concentration and temperature.

Manhattan College has applied the same basic conceptual framework to Lake Ontario and to the Lake Huron-Saginaw Bay system. A more advanced framework was applied to Lake Erie. The Lake Erie model includes both diatom and non-diatom phytoplankton types and sediment nutrient release under anaerobic conditions.

### Bierman

The Bierman model is similar to the Manhattan models in that it is a dynamic mass balance model which directly calculates phosphorus, nitrogen, phytoplankton, and zooplankton concentrations (Bierman and Dolan 1976; Bierman et al. 1978b). It differs from all of the above models in that phytoplankton biomass is partitioned into five different functional groups: diatoms, greens, blue-greens ($N_2$-fixing and non-$N_2$-fixing), and "others".

Also, more detailed mechanisms are used to describe phosphorus and nitrogen interactions with the phytoplankton.

The Bierman model gives more information on the biological processes that occur in a lake system; however, the data base requirements for the application of this model are correspondingly greater than for any of the above models. To date, the Bierman model has only been applied to Saginaw Bay.

# MODEL RESULTS

## General

Model results are presented for Inner Saginaw Bay, the Western, Central, and Eastern Basins of Lake Erie, and Lake Ontario. These are the most heavily enriched basins in the Great Lakes. The general format is that an indicator parameter, e.g. total phosphorus, chlorophyll a, dissolved oxygen is plotted versus an external phosphorus load to each system.

All models were first calibrated to the existing conditions in each system. Subsequently, the calibrated models were re-run with reduced phosphorus loads to estimate the responses of the indicator parameters.

In some cases, a range of results is presented corresponding to a given phosphorus load. All of the results for the Chapra model are expressed as ranges with the extreme values corresponding to different assumptions on phosphorus feedback from the sediments. The Vollenweider results for Lake Erie span a range of phosphorus loads, reflecting similar uncertainties in phosphorus release from the sediments. The Bierman results for Saginaw Bay span the range between two different assumptions on the boundary conditions between the inner and outer portions of the bay.

Refer to Table 1 to compare model results to present conditions for phosphorus and chlorophyll a concentrations. It should be noted that exact comparisons can not be made in all cases. There are statistical variations associated with each of the representative average concentrations in Table 1. Further, it is not strictly correct to relate phosphorus load in a given year to the in-lake phosphorus concentration in the same year because of the characteristic lag times for each basin. Refer to the primary references for each model to determine how well the model output corresponds to the field data actually used for model calibration.

Note that the results for the phosphorus load reductions are presented in terms of base year loads. Specifically, the treatment strategies indicated by the arrows in each figure are all referenced to the base year load for each system.

All of the results presented are for equilibrium concentrations. All of the dynamic models were run under the assumption that reductions in phosphorus loads were effected instantaneously in time. These models were then run until steady-state concentrations were obtained with the new phosphorus loads. Response times for each of the basins will be discussed in a later section.

It should be noted that the comparison of results from different models is not always straightforward. Each of the models used was constructed under a different set of assumptions. Spatial segmentation is one of the most important differences among the models. The Bierman model contains no spatial segmentation and it assumes that the inner portion of Saginaw Bay is completely mixed. The Vollenweider and Chapra models include horizontal spatial segmentation, but no vertical spatial segmentation. The Manhattan College models include both horizontal and vertical spatial segmentation. Difficulties can arise in systems where there are important spatial gradients in water quality and where the models being compared do not have the same spatial segmentation.

Inner Saginaw Bay

The inner portion of Saginaw Bay has been operationally defined by a line between Point Lookout and Sand Point (Refer to Smith et al. 1977). Figure 1 contains the model results for phosphorus concentration in the inner bay. The Vollenweider results were calculated by Bierman using the phosphorus equation from Vollenweider (1976) and values of 5.84 meters for mean depth, 0.138 x $10^{10}$ meters$^2$ for surface area, and 0.3 years for hydraulic detention time (Dolan, personal communication). The DiToro and Chapra results were taken from DiToro et al. (1978a) and Chapra (1978), respectively. The Bierman results are the phosphorus concentrations from the model presented in Bierman et al. (1975).

Given the variations in the data and the uncertainties in the complex hydrodynamic interaction between Saginaw Bay and Lake Huron proper, all of the models agree well with present conditions in the bay, and with each other.

Results for chlorophyll a concentrations are not presented. The relationship between phosphorus load and chlorophyll a in Saginaw Bay does not follow the typical pattern observed in most lakes. Vollenweider (1976) has found that summer average chlorophyll a concentration is usually 25 percent to 30 percent of the annual average total phosphorus concentration. In Saginaw Bay, this fraction is greater than 50 percent (Table 1). Dolan et al. (1978) have shown that there are statistically significant differences between chlorophyll a and phytoplankton cell volume in Saginaw Bay, primarily because of a seasonal shift from diatom species to blue-green species. Refer to Bierman et al. (1975) for model output and field data corresponding to the biomass of the major phytoplankton types.

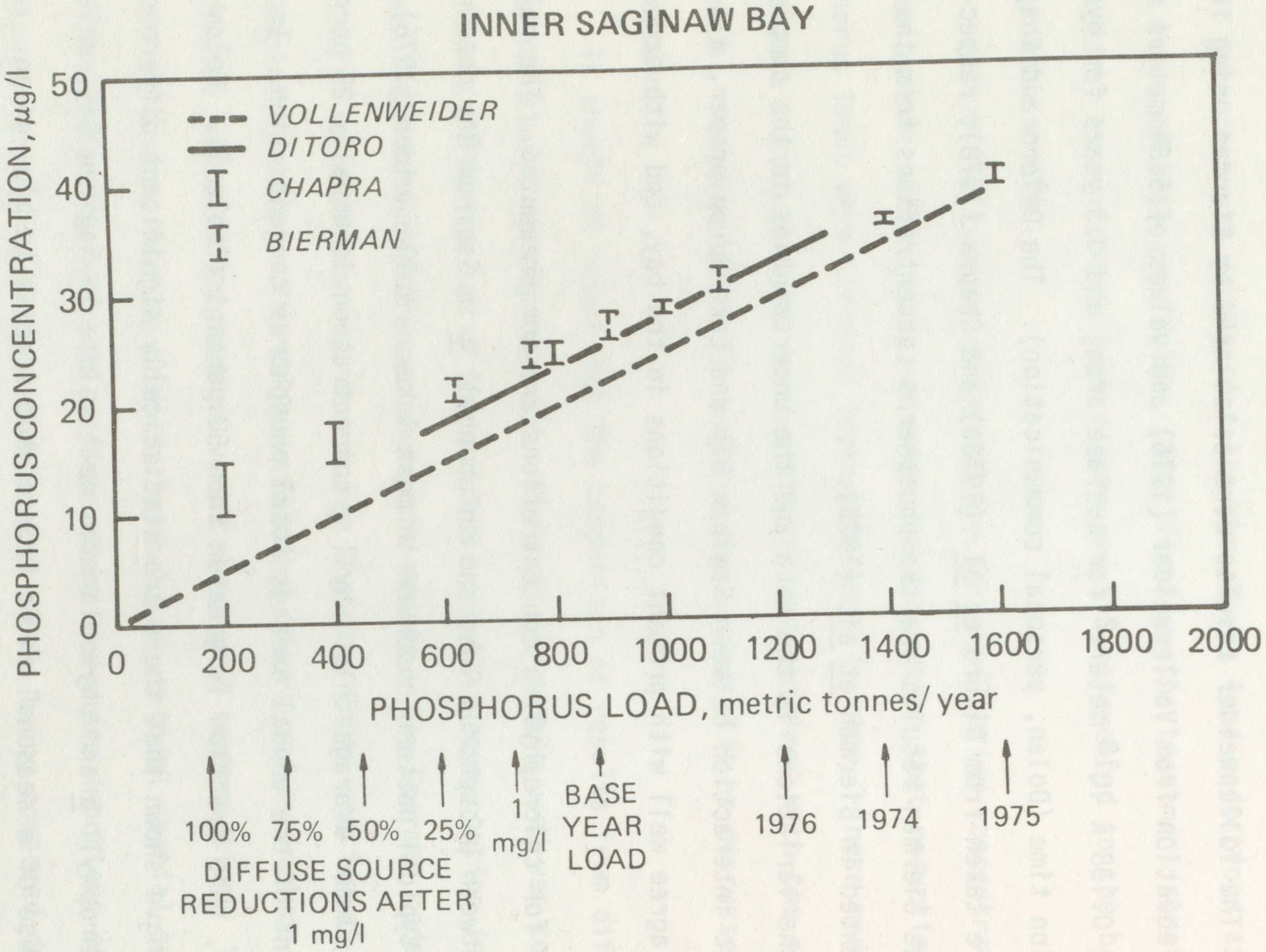

FIGURE 1

Relationship between phosphorus concentration and phosphorus load in Inner Saginaw Bay for the Vollenweider, DiToro, Chapra and Bierman models

Bierman et al. (1978b) have used the data by Chartrand (1973) to develop statistical correlations between measurements for taste and odor and blue-green phytoplankton concentrations at the Saginaw-Midland Water Filtration Plant intake at Whitestone Point. This intake is located in the outer portion of Saginaw Bay; however, Paul (1977) has shown that blue-green phytoplankton produced in the inner bay and transported by water movements to the outer bay are responsible for taste and odor at this intake . Field measurements of blue-green phytoplankton concentrations in the inner bay have been correlated to taste and odor measurements at the Whitestone Point intake (Dolan 1977). The following correlation was found to be statistically significant at the 99 percent confidence level:

$$TO = 2.03 + 1.87\ (BG)$$

where: TO = Threshold Odor Number

BG = Blue-green biomass in mg dry weight/liter.

Using this correlation, the output of the Bierman model for blue-green phytoplankton biomass can be related to taste and odor at the Whitestone Point intake.

### Lake Erie

The model results for Lake Erie are contained in Figures 2-9. The Vollenweider results for phosphorus concentration were taken from Vollenweider (1977b), as revised in a personal communication to Bierman (August 16, 1977). The Vollenweider results for chlorophyll a concentration were calculated by Bierman using the correlation equation between phosphorus and chlorophyll a concentrations from Vollenweider (1976). Vollenweider only presented estimates for loads that correspond to a phosphorus concen-

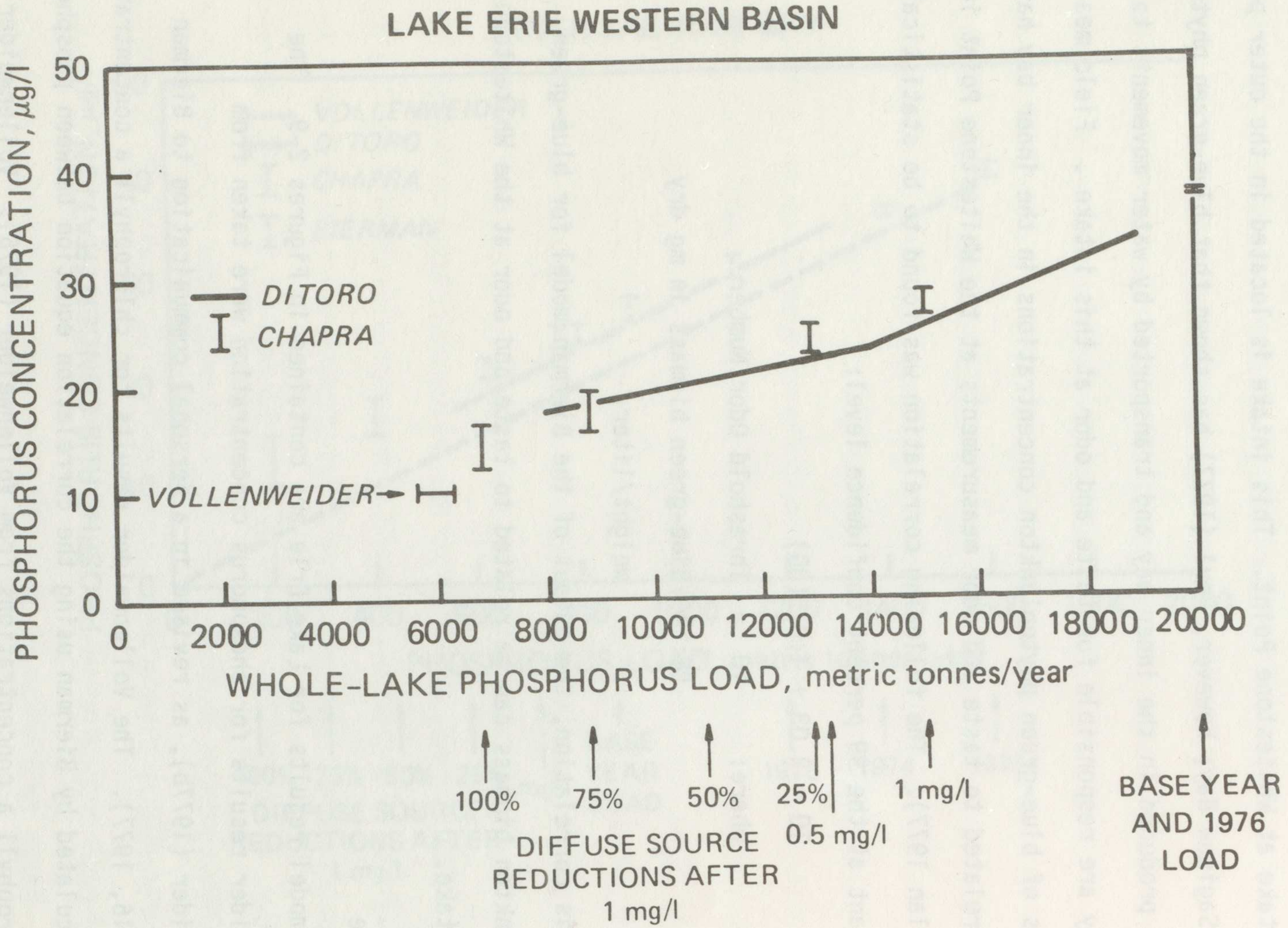

FIGURE 2

Relationship between phosphorus concentration and whole-lake phosphorus load in the Western Basin of Lake Erie for the Vollenweider, DiToro and Chapra models

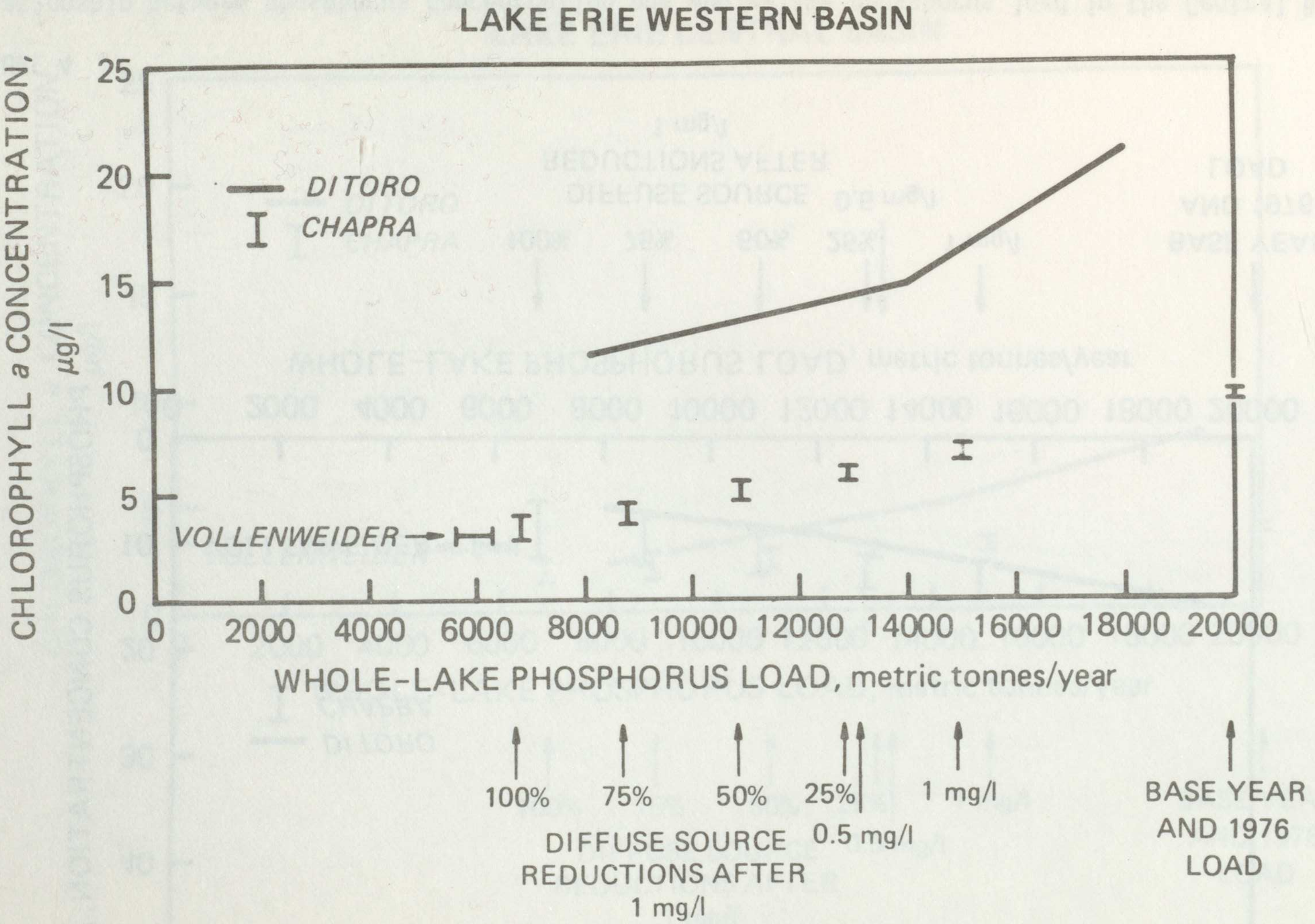

FIGURE 3

Relationship between chlorophyll a concentration and whole-lake phosphorus in the Western Basin of Lake Erie for the Vollenweider, DiToro and Chapra models

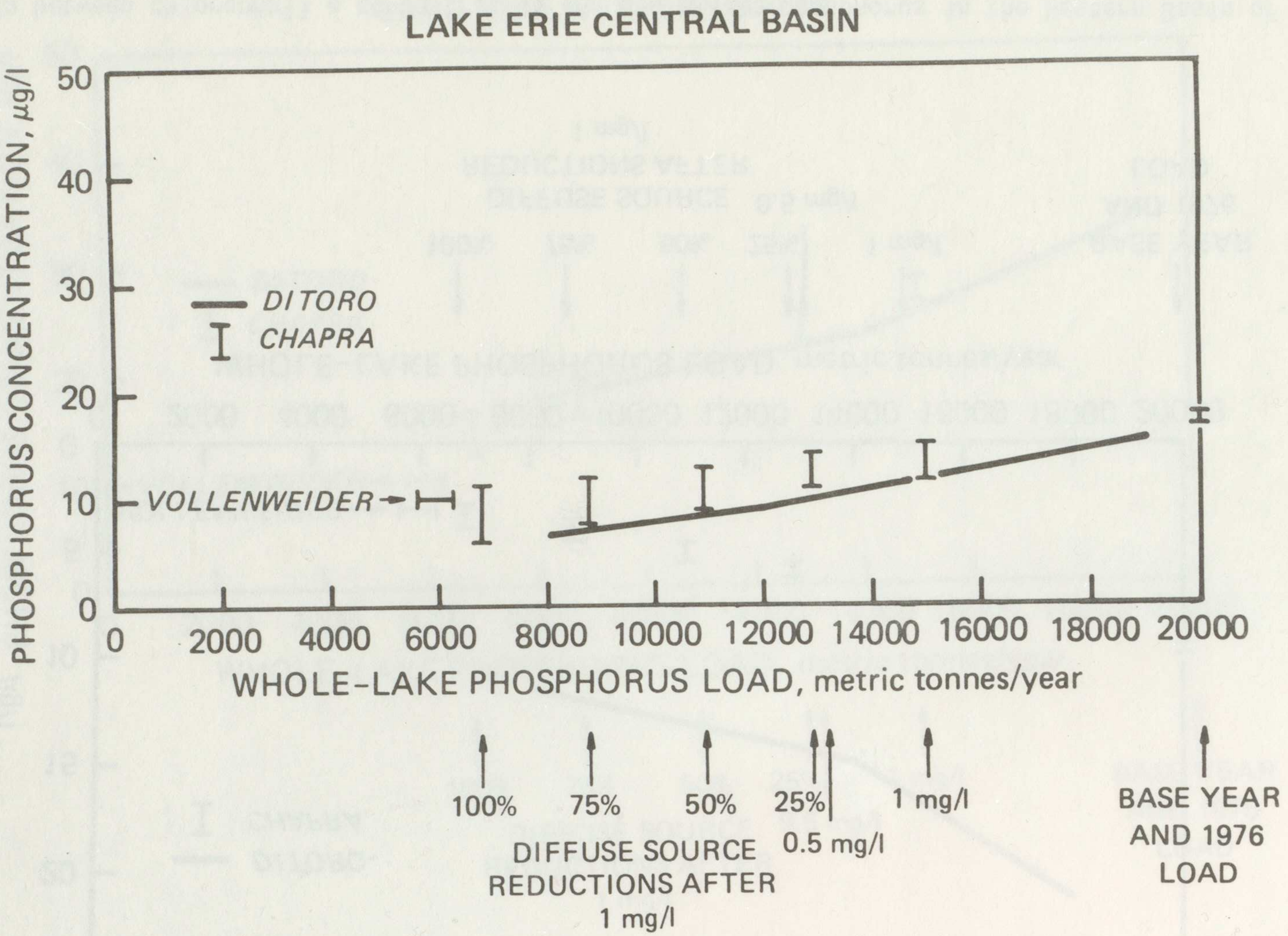

FIGURE 4

Relationship between phosphorus concentration and whole-lake phosphorus load in the Central Basin of Lake Erie for the Vollenweider, DiToro and Chapra models

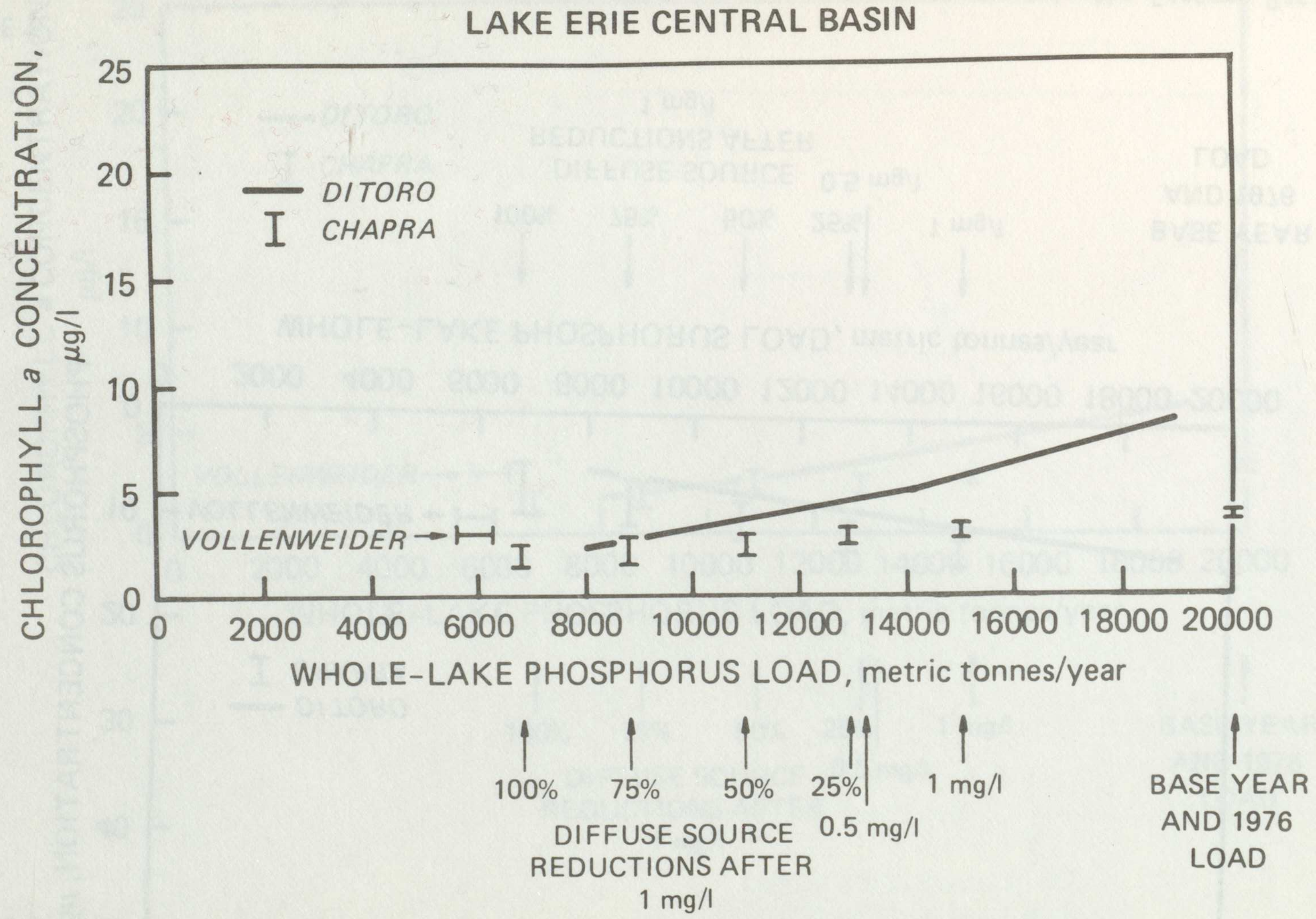

FIGURE 5

Relationship between chlorophyll a concentration and whole-lake phosphorus load in the Central Basin of Lake Erie for the Vollenweider, DiToro and Chapra models

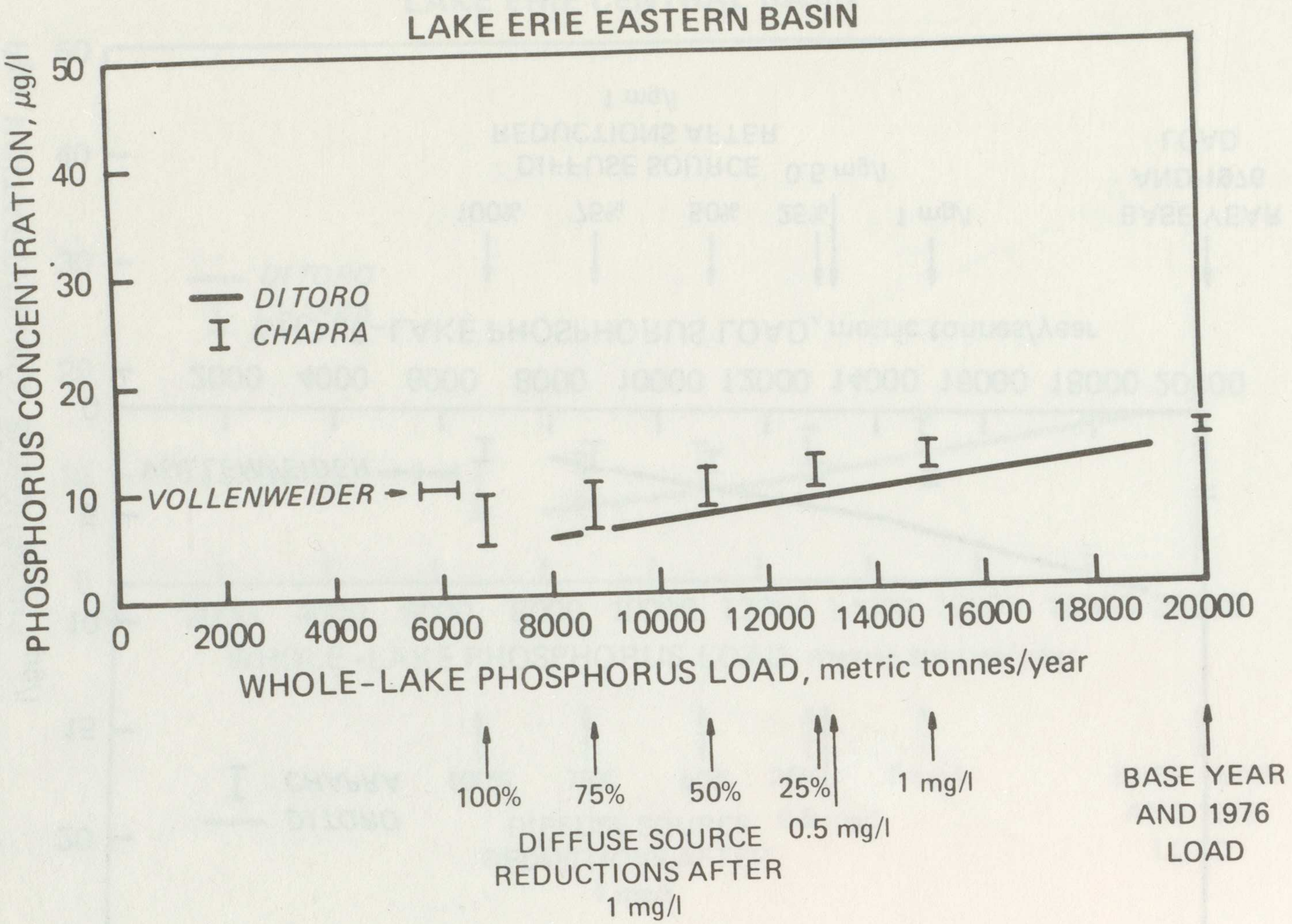

FIGURE 6

Relationship between phosphorus concentration and whole-lake phosphorus load in the Eastern Basin of Lake Erie for the Vollenweider, DiToro and Chapra models

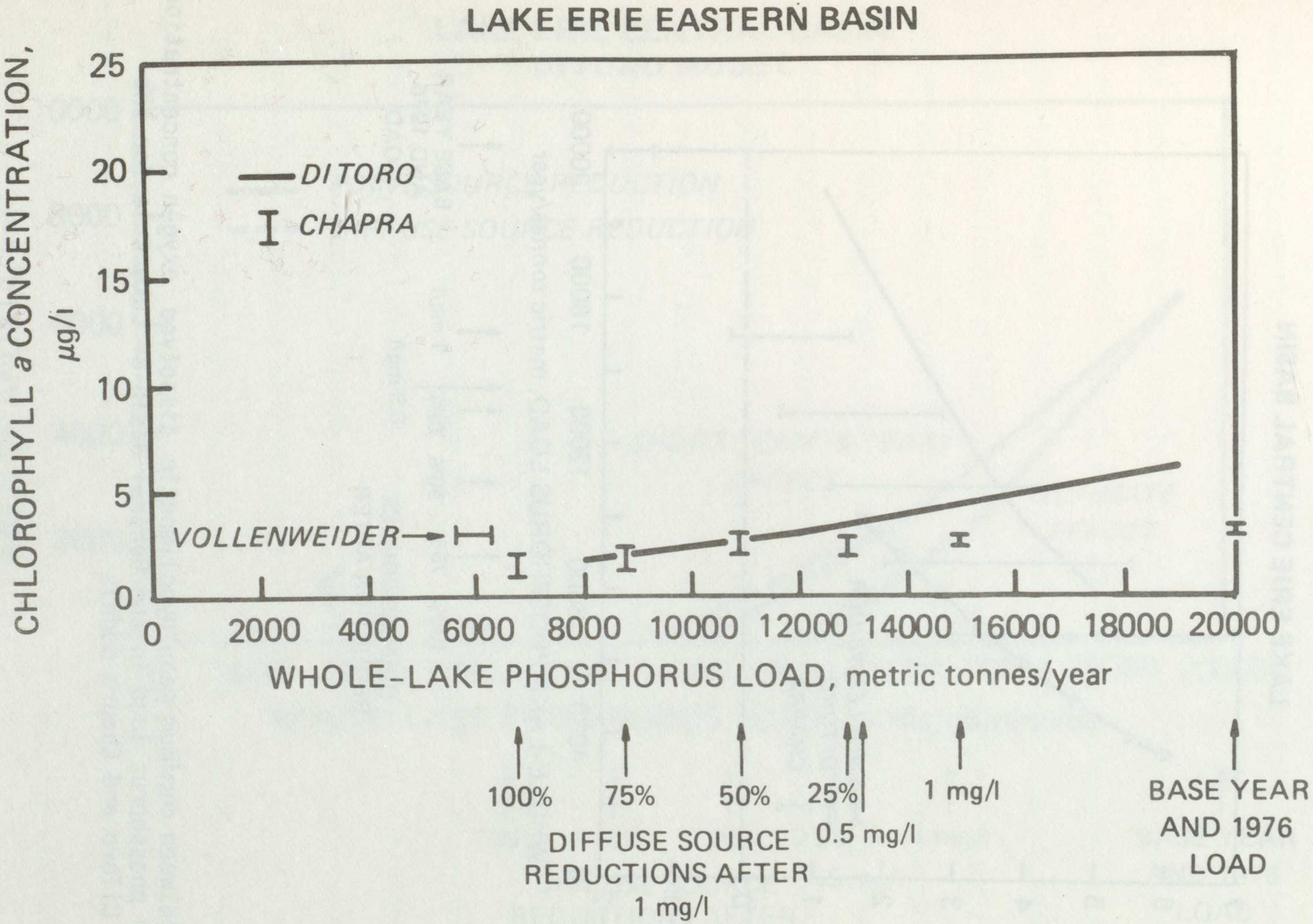

FIGURE 7

Relationship between chlorophyll a concentration and whole-lake phosphorus load in the Eastern Basin of Lake Erie for the Vollenweider, DiToro and Chapra models

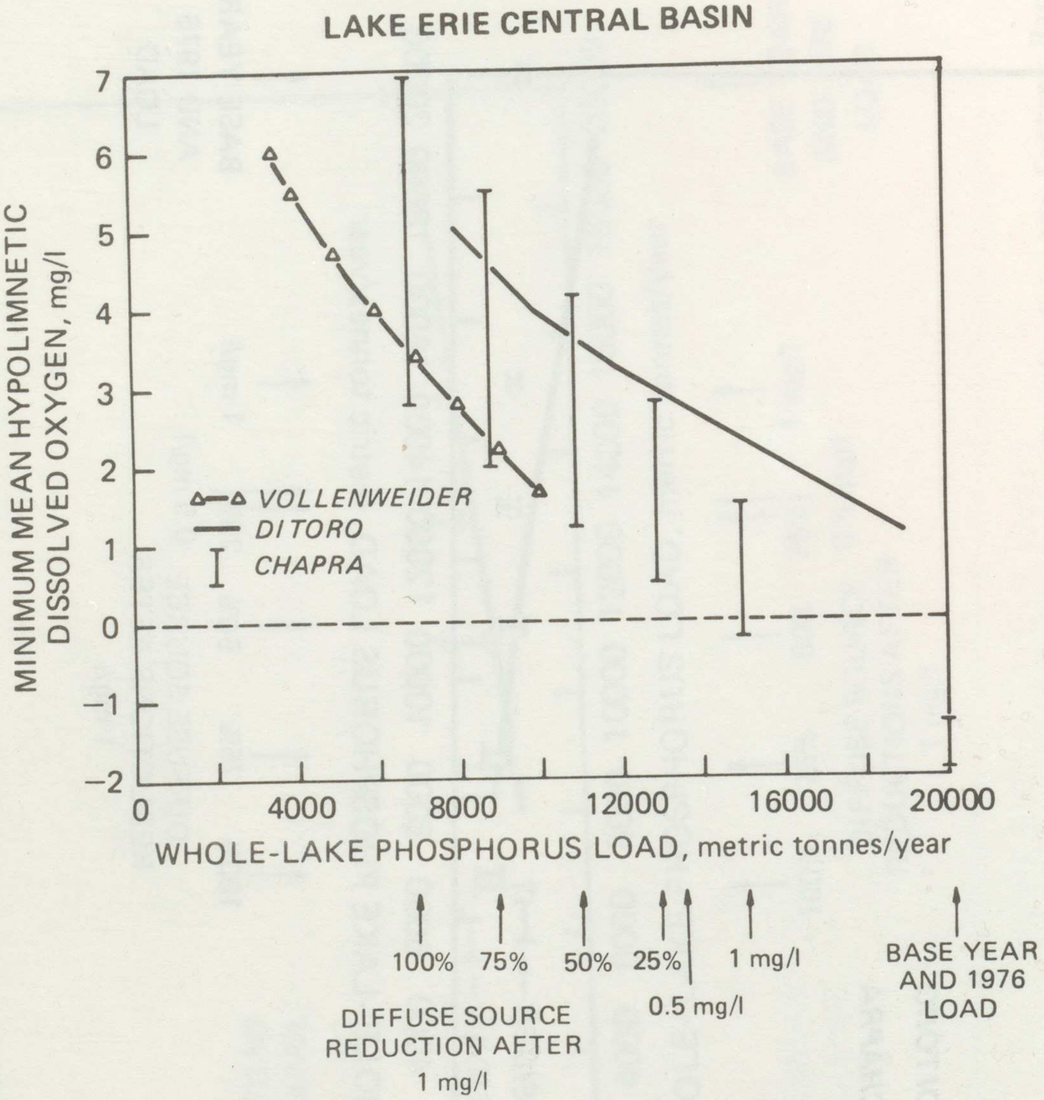

Figure 8

Relationship between minimum mean hypolimnetic dissolved oxygen concentration and whole-lake phosphorus load in the Central Basin of Lake Erie for the Vollenweider, DiToro and Chapra models

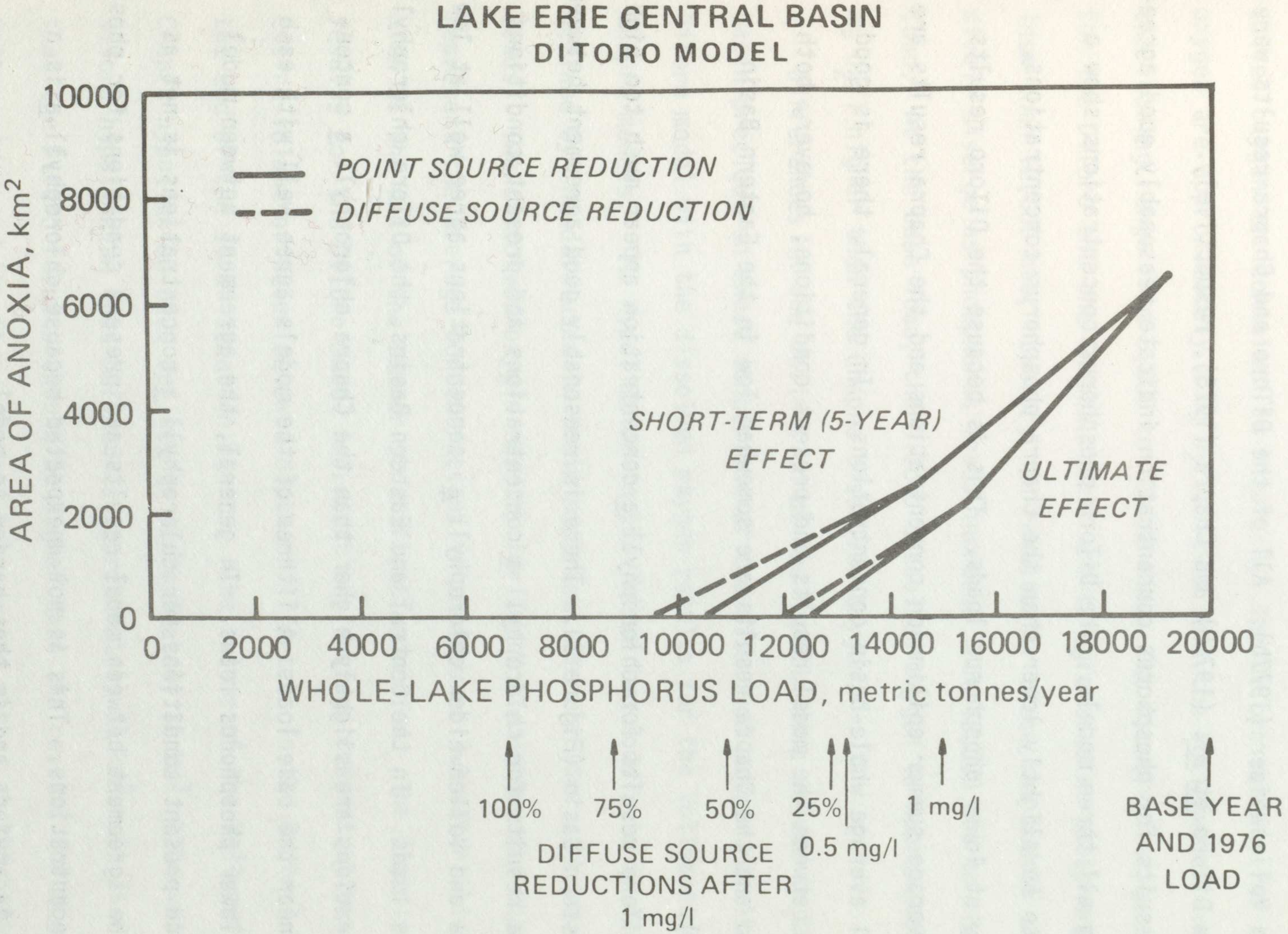

FIGURE 9

Relationship between area of anoxia and whole-lake phosphorus load in the Central Basin of Lake Erie for the DiToro model tration of 10 μg/l in all three of the Lake Erie basins. This range of loading estimates (5600 - 6300 mta) is substantially lower than the base load of 20,000 mta. The Vollenweider results for dissolved oxygen were taken from Vollenweider (1977b). All of the DiToro and Chapra results were taken from DiToro et al. (1978b) and Chapra (1978), respectively.

The results for phosphorus concentration indicate reasonably good agreement among all three models. The DiToro phosphorus concentrations show a tendency to be slightly lower than the Chapra phosphorus concentrations, especially at lower phosphorus loads. This is because the DiToro results are for average summer epilimnion concentrations and the Chapra results are for annual average whole-basin concentrations. In general, there is good agreement between the model results and present conditions; however, both the DiToro and the Chapra results are somewhat low in the Eastern Basin (Figure 6).

The DiToro results for chlorophyll a concentration appear much too high in the Western Basin (Figure 3). There is reasonably good agreement between the Chapra results for chlorophyll a concentrations and present conditions. The Chapra and Vollenweider chlorophyll a concentrations agree well at low phosphorus loads. In the Central and Eastern Basins, the DiToro chlorophyll a concentrations are slightly higher than the Chapra chlorophyll a concentrations near the base load. All three of the models agree well with each other at lower phosphorus loads. In general, the agreement between model results and present conditions for chlorophyll a concentrations is not as good as the agreement between model results and present conditions for phosphorus concentrations. This is not unexpected because chlorophyll a is a secondary parameter, and is thus harder to model.

For the purpose of developing phosphorus loading objectives for Lake Erie, the most important parameter was considered to be dissolved oxygen concentration in the Central Basin hypolimnion. The model results for dissolved oxygen are contained in Figure 8. The DiToro results for dissolved oxygen are approximately 2 mg $O_2$/l higher than the Vollenweider results in the loading range from 8,000 to 10,000 mta. The dissolved oxygen results for the DiToro and the Chapra models are in agreement at phosphorus loads less than 12,000 mta; however, the results for these two models progressively diverge as phosphorus loads increase from 12,000 mta to the base load. At the base load, the DiToro dissolved oxygen is approximately 2-3 mg $O_2$/l higher than the Chapra dissolved oxygen.

Differences in the definition of the hypolimnetic volume in the Central Basin preclude an exact comparison of the dissolved oxygen results for the DiToro model with the dissolved oxygen results for the Vollenweider and Chapra models. The hypolimnion in the latter two models is operationally defined by the data used in their empirical correlations with phosphorus loads. The dissolved oxygen results for the Vollenweider and Chapra models represent the average concentrations in an assumed 3.3 meter thick hypolimnion at the end of the summer stratification period. The dissolved oxygen results for the DiToro model represent the average concentrations in the entire volume of water below a depth of 17 meters in the Central Basin at the end of the stratification period. The volume of the Vollenweider and Chapra hypolimnion thus defined is approximately 38 $km^3$. The volume of the DiToro hypolimnion thus defined is approximately 51 $km^3$. It is expected that the DiToro results should be higher than the results for the Vollenweider and the Chapra models because the waters at the bottom of the hypolimnion near the sediment-water interface become more oxygen-depleted than the waters at the top of the hypolimnion near the 17 meter depth (Burns and Ross 1972).

In order to relate his results more directly to actual conditions in the Central Basin, DiToro has correlated his model output for dissolved oxygen concentrations to the area of anoxia at the end of the summer stratification period (Figure 9). This correlation was developed using measured average dissolved oxygen concentrations for the hypolimnion and the corresponding areal extent of the individual sampling stations that report anoxic values. When the average dissolved oxygen concentration for the hypolimnetic waters below 17 meters becomes less than 4 mg $O_2$/l, then individual stations begin to report zero values for dissolved oxygen. Note that even in the presence of an anoxic area of 6500 km$^2$, the average dissolved oxygen concentration in the hypolimnetic waters below 17 meters is approximately 1 mg $O_2$/l. (Compare Figures 8 and 9). These results are in agreement with field observations.

Lake Ontario

The model results for Lake Ontario are contained in Figures 10-13. The Vollenweider results for phosphorus concentration were taken from Vollenweider (1977b). The Vollenweider results for chlorophyll a concentration were calculated by Bierman using the correlation equation between phosphorus and chlorophyll a concentrations from Vollenweider (1976). The Thomann results were taken from Bierman (1977), and were based on a personal communication from Thomann (March, 1977). Thomann et al. (1976) originally developed load reduction simulations for three different kinetic hypotheses on Lake Ontario. Bierman (1977) has shown that only one these hypotheses, the so-called "optimistic" kinetic assumption, is consistent with the available data. Only the Thomann results corresponding to the "optimistic" assumption have been used in the present report. The results for the Chapra model were taken from Chapra (1978).

In Figures 10 and 11, results are presented for the case where load reduction treatments were assumed to occur only in the Lake Ontario basin. The Lake Erie input was held constant. The phosphorus results for the Thomann model are consistently lower than the phosphorus results for the Vollenweider and Chapra models. Bierman (1977) has shown that during the period from 1968 to 1974, there was a dynamic equilibrium between an average epilimnion phosphorus concentration of 20.5 ± 3.2 μg/l and an average phosphorus load of 14000 ± 2190 mta for Lake Ontario. Using data for the same period, Chapra (personal communication) has determined that the average phosphorus concentration for the whole lake was 21.3 ± 2.5 μg/l. Upon extrapolating the results in Figure 10 to a phosphorus load of 14,000 mta, it appears that the Chapra results are closest to the actual data and that the Vollenweider and Thomann results are near the upper and lower ranges, respectively, of the standard deviations in the data.

The results for chlorophyll a concentration (Figure 11) show more scatter among the models than do the results for phosphorus concentration. The Chapra results appear to be closer to the actual conditions than either the Vollenweider or the Thomann results; however, there is much variation in the chlorophyll a data and the model results are more difficult to interpret than for the case of phosphorus concentration.

Figures 12 and 13 contain the model results for the case where identical load reduction treatments were assumed to occur simultaneously in both Lake

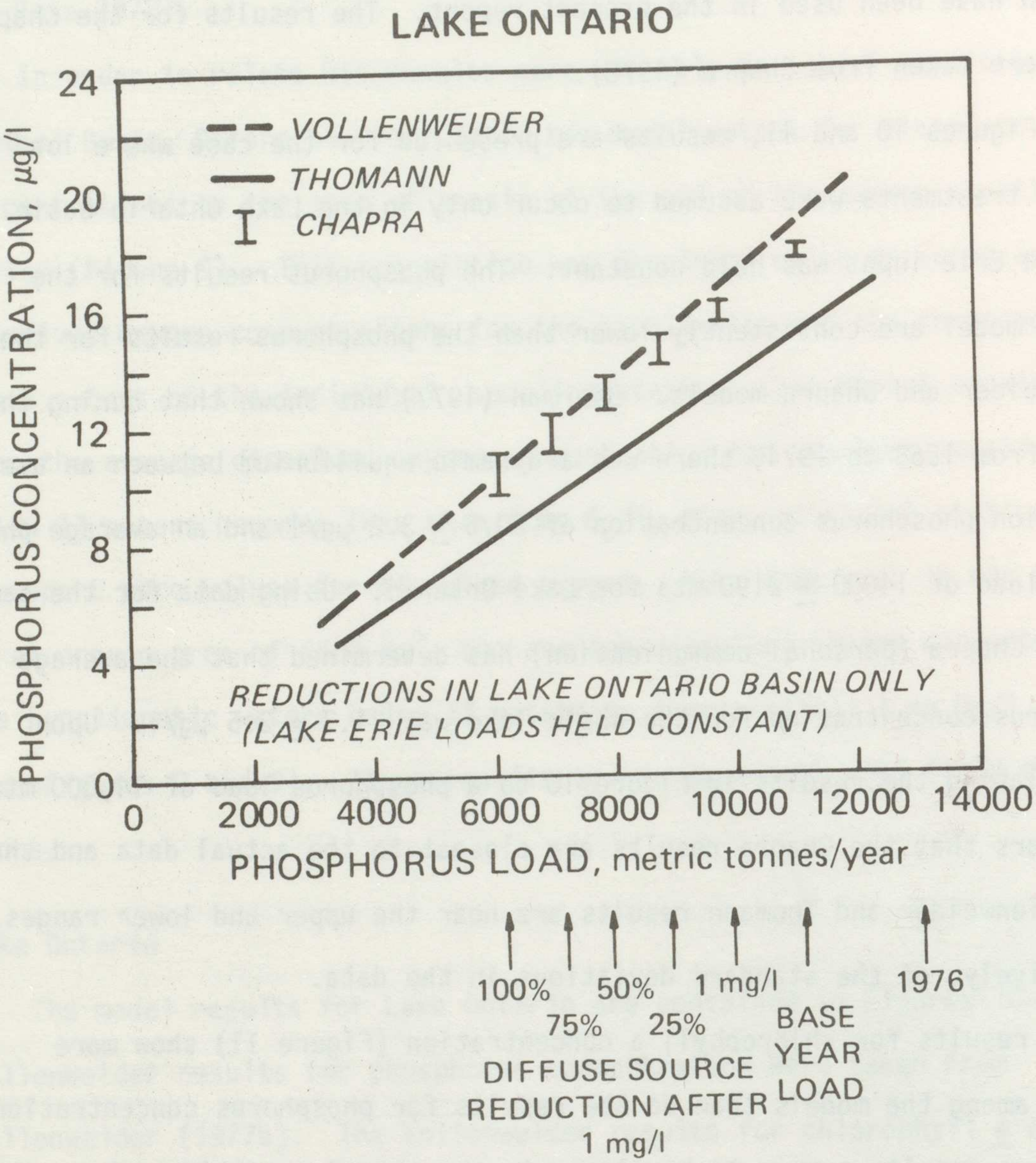

Figure 10

Relationship between phosphorus concentration and phosphorus load in Lake Ontario for the Vollenweider, Thomann and Chapra models for the case where loading input from Lake Erie is held constant

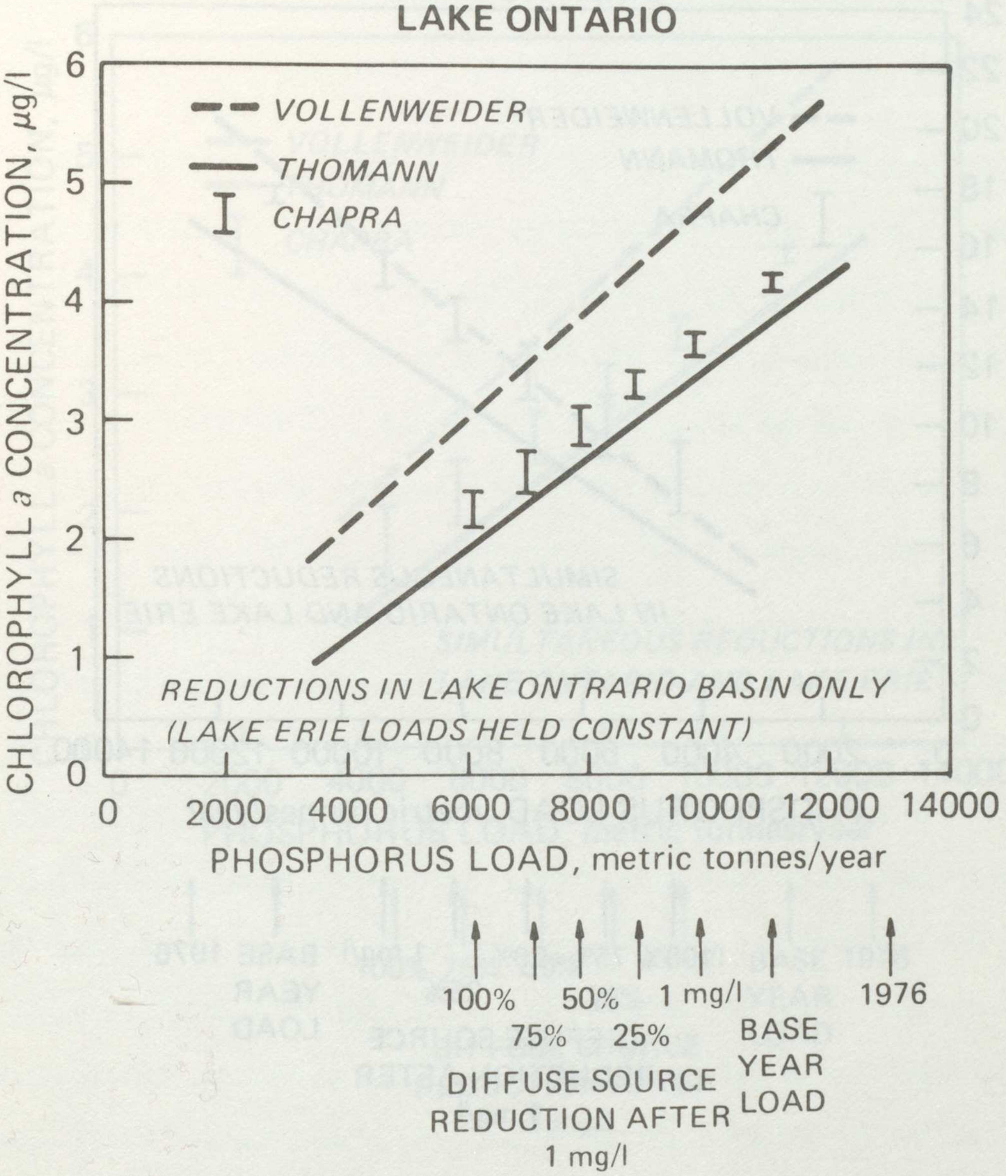

Figure 11

Relationship between chlorophyll a concentration and phosphorus load in Lake Ontario for the Vollenweider, Thomann and Chapra models for the case where loading input from Lake Erie is held constant

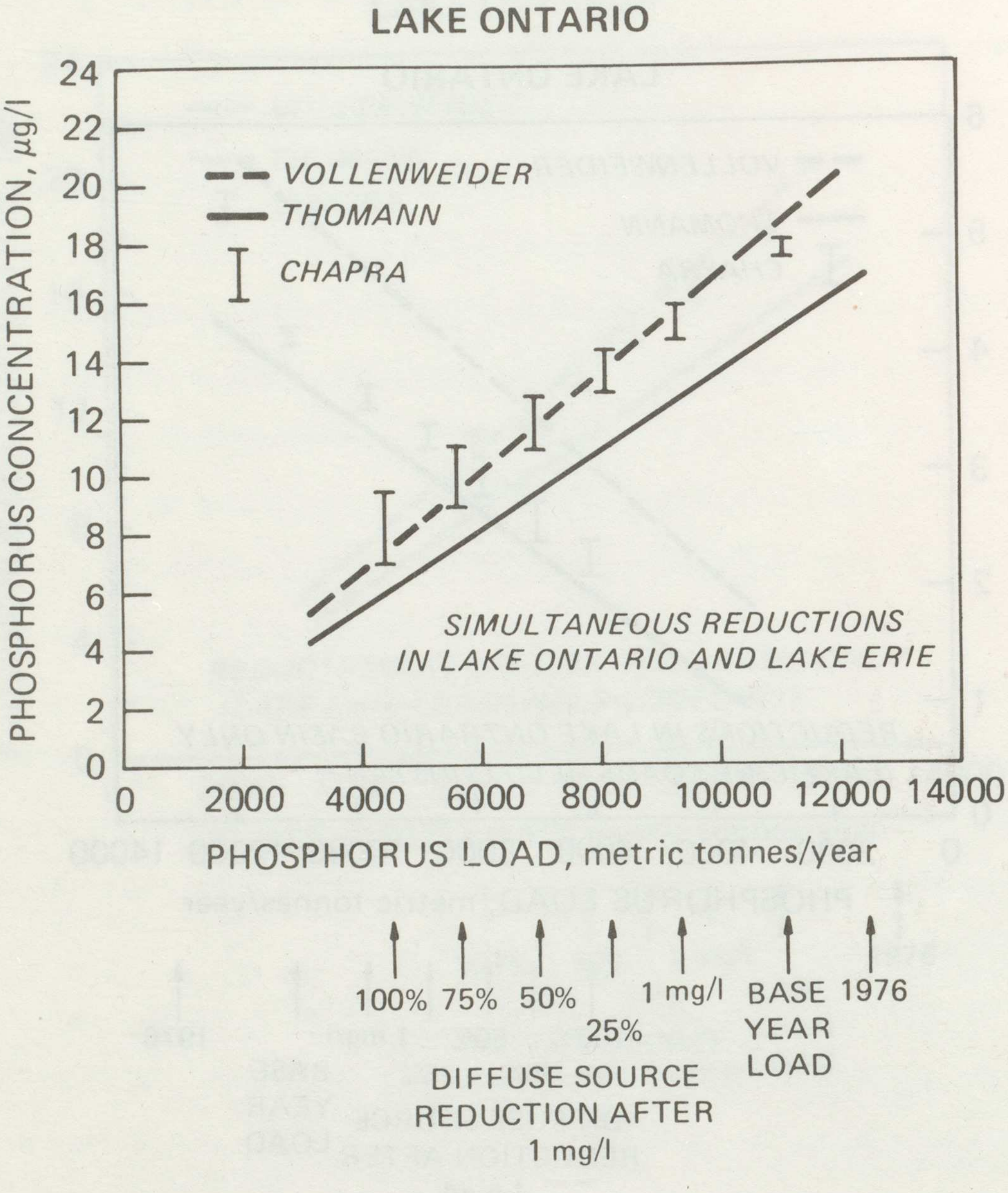

Figure 12

Relationship between phosphorus concentration and phosphorus load in Lake Ontario for the Vollenweider, Thomann and Chapra models for the case where simultaneous load reductions occur in Lakes Erie and Ontario

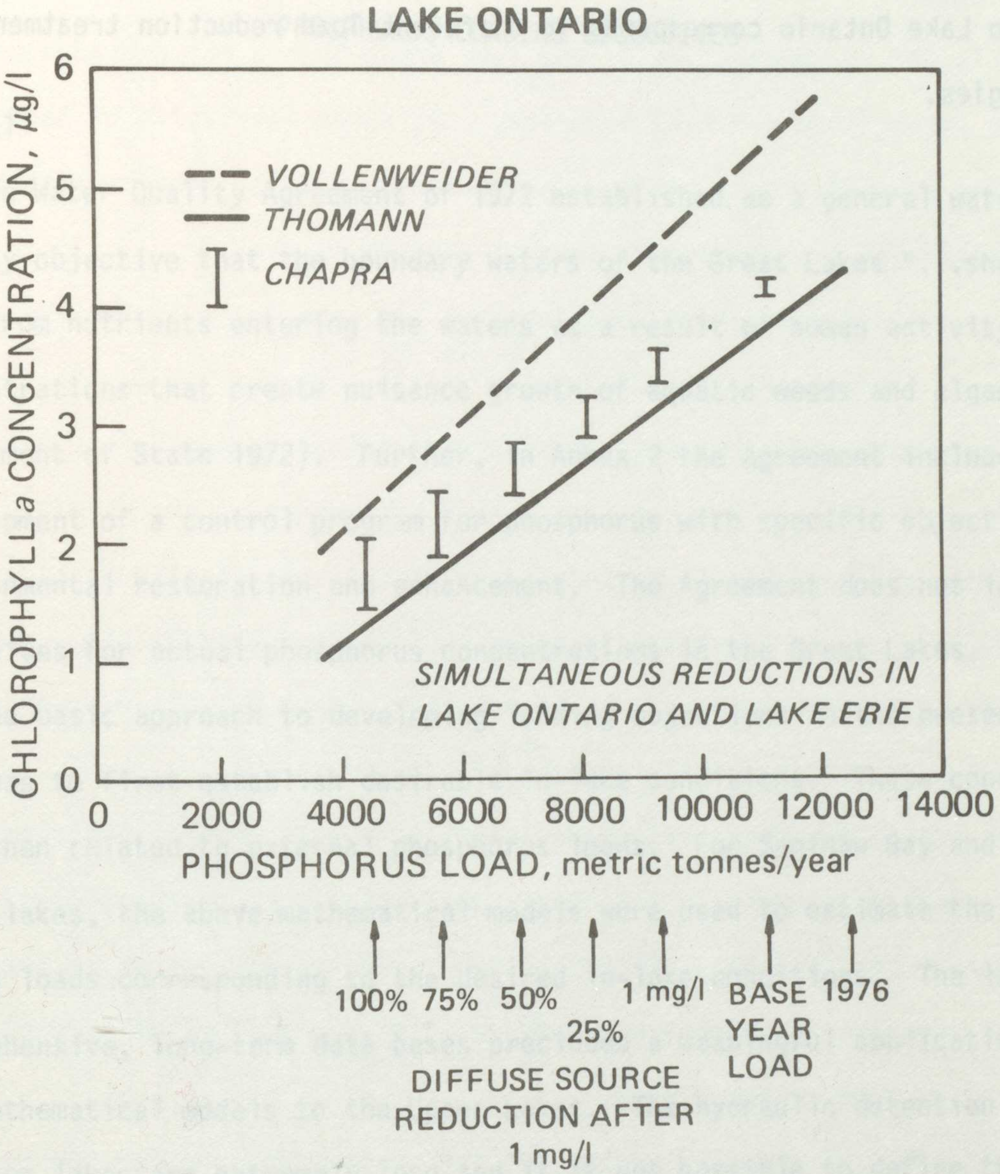

Figure 13

Relationship between chlorophyll a concentration and phosphorus load in Lake Ontario for the Vollenweider, Thomann and Chapra models for the case where simultaneous load reductions occur in Lakes Erie and Ontario

Ontario and Lake Erie. The interpretation of these results is similar to the case where load reductions were assumed to occur only in Lake Ontario. The principal difference between those two cases is that a given phosphorus load to Lake Ontario corresponds to different load reduction treatment strategies.

## PHOSPHORUS LOADING OBJECTIVES

### General

The Water Quality Agreement of 1972 established as a general water quality objective that the boundary waters of the Great Lakes "...should be free from nutrients entering the waters as a result of human activity in concentrations that create nuisance growth of aquatic weeds and algae" (U.S. Department of State 1972). Further, in Annex 2 the Agreement includes the development of a control program for phosphorus with specific objectives for environmental restoration and enhancement. The Agreement does not include objectives for actual phosphorus concentrations in the Great Lakes.

The basic approach to developing loading objectives in the present report was to first establish desirable in-lake conditions. These conditions were then related to external phosphorus loads. For Saginaw Bay and the lower lakes, the above mathematical models were used to estimate the phosphorus loads corresponding to the desired in-lake conditions. The lack of comprehensive, long-term data bases precluded a meaningful application of the mathematical models to the Upper Lakes. The hydraulic detention times of these lakes are extremely long and it is not possible to define the state of the phosphorus dynamics in these lakes with the available data. As a consequence, there are many uncertainties in the responses of the Upper Lakes to changes in phosphorus loads.

Note that all of the example treatment strategies in the present report have been expressed in terms of municipal point loads and diffuse source loads. Recall that diffuse source loads, as defined, do not include atmospheric loads, shore erosion loads, or loads from inter-lake exchange flows.

Upper Lakes

It is the recommendation of the Task Group that a non-degradation objective be established for Lake Superior, Lake Huron (exclusive of Saginaw Bay), and Lake Michigan. Annex 2 of the Water Quality Agreement states that an objective of the phosphorus control program is the:

> "Stabilization of Lake Superior and Lake Huron in their present oligotrophic state."

The recommended objective is a re-affirmation that present water quality should be maintained in Lake Superior and Lake Huron. Lake Michigan lies completely within the U.S. border and it is not specifically mentioned in the 1972 Agreement; however, since the outflow from Lake Michigan constitutes an input to Lake Huron, it is not possible to establish an objective for Lake Huron independently of Lake Michigan.

The reason for the non-degradation objective is that if phosphorus loads are allowed to increase in the Upper Lakes, then the consequences might not be apparent for very long periods of time. If the ecosystems of these lakes become degraded, it is possible that equally long periods of time might be required to reverse the damage.

Table XVIII contains a summary of the recommendations for the non-degradation basins. The recommended loads are those loads which remain after the recommended 1 mg/l effluent standard is fully implemented. The recommended concentrations are estimates of the concentrations that will correspond to these residual loads. It is understood that there will be a degree of statistical variation in both the recommended loads and the recommended

TABLE XVIII. SUMMARY OF OBJECTIVES FOR NON-DEGRADATION BASINS

| Basin | Present Conditions: 1976 Phosphorus Load in Metric Tonnes Per Year | Present Conditions: Annual Average Total Phosphorus Concentration in μg/l | Task Group Recommendations: Phosphorus Load in Metric Tonnes Per Year | Task Group Recommendations: Total Phosphorus Concentration in μg/l |
|---|---|---|---|---|
| Superior | 3570 | 4.6 | 3352 | 4 |
| Michigan | 6671 | 7.4 | 5553 | 7 |
| Huron | 2952 | 5.2 | 2781 | 5 |
| Georgian Bay | 628 | 4.5 | 598 | 4 |
| North Channel | 546 | 5.5 | 516 | 5 |

concentrations on a year-to-year basis. In the absence of any evidence to the contrary, it is assumed that the presently observed phosphorus concentrations in the Upper Lakes are in equilibrium with the presently observed phosphorus loads.

## Saginaw Bay

Three phosphorus loading objectives have been developed for Inner Saginaw Bay (Table XIX). The primary criterion was taste and odor at the Whitestone Point Water Filtration Plant. This plant processes approximately 85 percent of all the water drawn from Saginaw Bay for human use. Secondary criteria were filter-clogging and taste and odor problems at the Pinconning and Bay City Water Filtration Plants in the inner portion of the bay and the degree of degradation of the inner bay ecosystem.

It was estimated that a loading objective of 620 mta would result in minimal compliance with the present taste and odor standard for raw water at the Whitestone Point intake in an average water year. This estimate was based on correlations between the output of the Bierman model for blue-green phytoplankton concentration and taste and odor at the Whitestone Point intake. The results of all the models used on Saginaw Bay indicate that a phosphorus load of 620 mta would correspond to an average annual phosphorus concentration of approximately 20 μg/l (Figure 1).

It was estimated that a loading objective of 440 mta would reduce filter clogging and taste and odor problems at the Pinconning and Bay City Water Filtration Plants in the inner bay, and would reverse some of the degradation to the inner bay ecosystem. The results of the models used indicate that a phosphorus load of 440 mta would correspond to an average annual phosphorus concentration of approximately 15 μg/l (Figure 1). Several in-

TABLE XIX. SUMMARY OF OBJECTIVES FOR SAGINAW BAY

| Objective | Phosphorus Load (metric tonnes/year) | Treatment Strategy |
|---|---|---|
| Obtain compliance with present taste and odor standard for raw water at the Saginaw-Midland Water Filtration Plant intake at Whitestone Point. | 620 | (a) 1 mg/l + 20% reduction in diffuse sources<br>(b) approximately 0.5 mg/l |
| Reduce filter-clogging and taste and odor problems at the Pinconning and Bay City Water Filtration Plant intakes in the inner portion of the bay by maintaining an annual average total phosphorus concentration of 15 μg/l in the inner bay. | 440[1] | (a) 1 mg/l + 55% reduction in diffuse sources<br>(b) 0.5 mg/l + 40% reduction in diffuse sources |
| Essentially eliminate interference with water use and minimize degradation of the ecosystem by maintaining an annual average total phosphorus concentration of 10 μg/l in the inner bay. | 210 | (a) 1 mg/l + 95% reduction in diffuse sources<br>(b) 0.5 mg/l + 80% reduction in diffuse sources |

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[1] Task Group Recommendation.

vestigators (Vollenweider, 1968; Dillon and Rigler, 1975; and Dobson 1976) have suggested 20 μg/l of total phosphorus as a threshold above which the conditions of eutrophication are well advanced. They have also suggested that below 10 μg/l, few of the effects of eutrophication are evident and lakes in this state are usually phosphorus deficient. The loading objective of 440 mta would place Saginaw Bay in a transition state between nutrient-deficient and nutrient-rich conditions.

It was estimated that a loading objective of 210 mta would essentially eliminate interference with water uses in Saginaw Bay, and would minimize degradation of the ecosystem. The results of the models used indicate that a phosphorus load of 210 mta would correspond to an annual average phosphorus concentration of approximately 10 μg/l (Figure 1). The loading objective of 210 mta would place Saginaw Bay at the lower threshold for the undesirable consequences of phosphorus enrichment.

It is recommended that a phosphorus loading objective of 440 mta be established for Saginaw Bay. The ideal phosphorus loading objective for Saginaw Bay would be 210 mta to lower the average annual phosphorus concentration to 10 μg/l; however, it was decided that this would not be a practical objective because of the large diffuse source reduction that would be required to achieve it.

For an average water year it is estimated that the loading objective of 440 mta could be achieved with either of two treatment strategies (Table XIX):

(a) 1 mg/l effluent standard for all municipal point discharges greater than 1 mgd plus 55 percent reduction in diffuse sources.

(b) 0.5 mg/l effluent standard for all municipal point discharges greater than 1 mgd plus 40 percent reduction in diffuse sources.

It should be noted that there will not exist a "tolerance" for future load increases elsewhere in the Lake Huron basin after loading reductions occur in Saginaw Bay. Model results (DiToro et al. 1978a; Chapra 1978) indicate that the annual average phosphorus concentration in Lake Huron (exclusive of Saginaw Bay) will not be significantly different from the recommended objective of 5 μg/l after the Saginaw Bay reductions.

## Lake Erie

Four different loading objectives were developed for Lake Erie (Table XX). The primary criteria were the area of anoxia in the Central Basin and the dissolved oxygen concentration in the Central Basin hypolimnion. Results were used from Figures 8 and 9 for the Vollenweider, DiToro, and Chapra models. In all cases, only the short term (5 years) results for area of anoxia were used from the DiToro model. This was because of the considerable uncertainties involved in attempting to estimate long-term sediment responses to reductions in phosphorus loads.

To reduce the area of anoxia by approximately 50 percent, it was estimated that a phosphorus load of 15,000 mta would be required. The Chapra results for dissolved oxygen concentration are consistent with the DiToro estimate for area of anoxia in the sense that the range of results for dissolved oxygen concentration in the lower hypolimnetic waters from the Chapra model spans both negative and positive values. A load of 15,000 mta corresponds to the present program for a 1 mg/l effluent standard for all municipal point dischargers greater than 1 mgd, assuming an average water year.

## TABLE XX. SUMMARY OF OBJECTIVES FOR LAKE ERIE

| Objective | Phosphorus Load (metric tonnes/year) | Treatment Strategy |
|---|---|---|
| Reduction of approximately 50% in area of anoxia | 15000 | 1 mg/l (corresponds to present programs) |
| Reduction of approximately 75% in area of anoxia | 13200 | (a) 1 mg/l + 20% reduction in diffuse sources<br>(b) 0.5 mg/l |
| Reduction of approximately 90% in area of anoxia | 10900[1] | (a) 1 mg/l + 50% reduction in diffuse sources<br>(b) 0.5 mg/l + 30% reduction in diffuse sources |
| Prevention of any substantial nutrient release from the sediments. | | |
| Essentially eliminate area of anoxia | 9500 | (a) 1 mg/l + 65% reduction in diffuse sources<br>(b) 0.5 mg/l + 45% reduction in diffuse sources |
| Maintain optimum dissolved oxygen concentration for fish in the Central Basin hypolimnion | | |

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[1] Task Group Recommendation.

To reduce the area of anoxia by 75 percent, it was estimated that a phosphorus load of 13,200 mta would be required. The dissolved oxygen concentrations of the DiToro and Chapra models have converged somewhat at this lower phosphorus load; however, a direct comparison of the two models is difficult.

To reduce the area of anoxia by 90 percent and to prevent any substantial amount of phosphorus release from the sediments, it was estimated that a phosphorus load of 10,900 mta would be required. At this phosphorus load, the dissolved oxygen concentrations for the DiToro and the Chapra models lie within the same range. This convergence is consistent with the different assumptions contained in each model. As the anoxic area decreases, it is expected that there should be less difference between the dissolved oxygen concentrations in the upper and lower layers of the hypolimnion.

To completely eliminate the area of anoxic and to ensure optimum dissolved oxygen conditions for fish in the hypolimnion (at least 4 mg $O_2$/l), it was estimated that a phosphorus load of 9500 mta would be required. The dissolved oxygen concentrations for the Vollenweider, DiToro, and Chapra models are all in the same range at this load.

It is recommended that a phosphorus loading objective of 10,900 mta be established for Lake Erie to eliminate 90 percent of the anoxic area in the Central Basin. The ideal phosphorus loading objective for Lake Erie would be 9500 mta to ensure optimum conditions for fish in the Central Basin hypolimnion; however, it was decided that this would not be a practical objective because of the large diffuse source reduction that would be required to achieve it.

For an average water year it is estimated that the loading objective of 10,900 mta could be achieved with either of two treatment strategies (Table XX):

(a) 1 mg/l effluent standard for all municipal point discharges greater than 1 mgd plus 50 percent reduction in diffuse sources (all three basins).

(b) 0.5 mg/l effluent standard for all municipal point discharges greater than 1 mgd plus 30 percent reduction in diffuse sources (all three basins).

Note that these strategies are not unique in that different combinations of point and diffuse source control among the three basins can be used to achieve the 10,900 mta loading objective for the whole lake.

All of the available scientific evidence leads to the conclusion that substantial diffuse source control is required in the Lake Erie basin to significantly improve the present dissolved oxygen conditions.

Lake Ontario

Two different loading objectives were developed for Lake Ontario (Table XXI). The primary criterion was degradation of the ecosystem in the lake. The principal indicator parameter used was annual average total phosphorus concentration.

The present phosphorus concentration in Lake Ontario is approximately 21 g/l. This value is indicative of a nutrient-rich system. The recently completed International Field Year for the Great Lakes (IFYGL) program has revealed the severe deterioration that has occurred in Lake Ontario. Detailed studies by Stoermer et al. (1975) on the phytoplankton and McNaught and Buzzard (1973) and McNaught et al. (1975) on the zooplankton have shown

## TABLE XXI. SUMMARY OF OBJECTIVES FOR LAKE ONTARIO

| Objective | Phosphorus Load (metric tonnes/year) | Simultaneous Treatment Strategies Required in Lake Ontario and Erie | Comments |
|---|---|---|---|
| Reduce degradation of the ecosystem by maintaining an annual average total phosphorus concentration of 15 μg/l. | 9700 | 1 mg/l (corresponds to present programs - more than adequate) | |
| Minimize degradation of the ecosystem by maintaining an annual average total phosphorus concentration of approximately 10 μg/l. | 6800[1] | (a) 1 mg/l + 50% reduction in diffuse sources<br>(b) 0.5 mg/l + 30% reduction in diffuse sources | These treatments correspond to the 10900 mta loading objective in Lake Erie. |

[1] Task Group Recommendation.

that the lake is presently inhabited largely by species that are tolerant of phosphorus enrichment. These investigators believe that Lake Ontario's original condition and biota were characteristic of a much less eutrophic situation.

To reduce degradation of the ecosystem in Lake Ontario and to maintain an annual average total phosphorus concentration of 15 µg/l, it was estimated that a phosphorus loading objective of 9700 mta would be required. This was based on the average of the results for the Vollenweider, Thomann, and Chapra models (Figures 10 or 12). For a phosphorus load of 9700 mta, Lake Ontario would be in the transition state between nutrient-deficient and nutrient-rich conditions. The present 1 mg/l effluent standard for all municipal point discharges greater than 1 mgd in the Lake Erie and Lake Ontario basins would be more than sufficient to meet this objective.

To minimize degradation of the ecosystem in Lake Ontario and to maintain an annual average total phosphorus concentration of approximately 10 µg/l, it was estimated that a phosphorus loading objective of 6800 mta would be required. Again, this was based on the average of the results for the three models used (Figures 10 or 12). For a phosphorus load of 6800 mta, conditions in Lake Ontario would be at the lower threshold for the undesirable consequences of phosphorus enrichment.

It is recommended that a phosphorus loading objective of 6800 mta be established for Lake Ontario to minimize degradation of the ecosystem.

For an average water year, if the phosphorus load from Lake Erie to Lake Ontario were held constant, the recommended loading objective of 6800 mta for Lake Ontario could not be met without reducing more than 50 percent of the diffuse sources in the Lake Ontario basin (Figure 10). This is not a practical treatment strategy. The treatment strategy required to achieve the recommended loading objective for Lake Ontario must include some simultaneous treatment for Lake Erie.

For an average water year, it is estimated that the loading objective of 6800 mta for Lake Ontario could be achieved with either of two simultaneous treatment strategies in Lake Ontario and in Lake Erie (Table XXI):

(a) 1 mg/l effluent standard for all municipal point discharges greater than 1 mgd plus 50 percent reduction in diffuse sources.

(b) 0.5 mg/l effluent standard for all municipal point discharges greater than 1 mgd plus 30 percent reduction in diffuse sources.

Each of these treatment strategies corresponds to the recommended loading objective of 10,900 mta for Lake Erie.

## Response Times

An important consideration in the implementation of phosphorus control strategies is the time required for the phosphorus concentrations in a system to respond to changes in the external phosphorus loads. The response time of a given system depends on the following:

1. The schedule for phosphorus load reductions.
2. The characteristic phosphorus residence time in the system.
3. The dynamic state of the system between the present phosphorus load and the present phosphorus concentration.

An informative treatment of lake responses to changes in phosphorus loadings is given by Sonzogni *et al.* (1976).

No attempt has been made in the present report to estimate actual schedules for implementing the recommended phosphorus load objectives. Instead, comparative estimates of system response times were made by assuming that the loading objectives were carried out as instantaneous step-reductions. It is recognized that this is not likely to occur. In actual practice, however, changes that occur in a given year for a given system are likely to fall within the range of the year-to-year variation in either the phosphorus loads, the in-lake phosphorus concentrations, or both. For this reason, long-term, comprehensive measurements of loads and in-lake concentrations are usually necessary to accurately determine the response of a system.

The effects of the characteristic phosphorus residence times for the various basins are implicitly included in all of the dynamic models used. Recall that the Vollenweider loading plot model is an equilibrium model, and thus it cannot be used to estimate response time. Recently, however, Vollenweider has developed a set of dynamic calculations for estimating the response time of Lake Ontario to changes in phosphorus loads (Vollenweider 1977a).

It was assumed that the presently-observed phosphorus concentrations in Inner Saginaw Bay, Lake Erie, and Lake Ontario are in dynamic equilibrium with the presently observed external phosphorus loads. The basis for this assumption in Lake Erie and Lake Ontario has been discussed earlier in this report. The equilibrium assumption is valid for Saginaw Bay because of its very short (3-4 months) hydraulic detention time.

For Inner Saginaw Bay, all of the dynamic models used indicate that the response time to a change in phosphorus load will be less than one year. Such a result is typical for a system with the short hydraulic detention time of Saginaw Bay. Essentially, the phosphorus concentration observed in

Saginaw Bay in a given year is largely a function of the phosphorus load for that year.

The response time for Lake Erie is expected to be somewhat longer than for Saginaw Bay because the hydraulic detention time of Lake Erie is approximately 2.6 years. The Chapra model indicates thast the 90 percent response time of Lake Erie to a change in phosphorus load will be one to two years. This is the time required for 90 percent of the expected change in phosphorus concentration to occur. The DiToro model indicates that essentially 100 percent of the new equilibrium concentration would be achieved in five years after a change in phosphorus load. The Chapra and DiToro results are not inconsistent when it is realized that the 95 percent response time for a given water body is 30 percent longer than the 90 percent response time, and that the 100 percent response time is longer still (Sonzogni et al. 1976). Since the variability in the actual data is usually at least 10 to 20 percent, it is more practical to state that the response time of Lake Erie to a change in phosphorus load will be one to two years.

The response time for Lake Ontario is expected to be relatively long because the hydraulic detention time of this system is 8.1 years. All of the models used for Lake Ontario indicate that the 90 percent response time will be approximately six years. The results ranged from the Thomann estimate of 5.8 years (Bierman 1977) to the Vollenweider estimate of six to seven years (Vollenweider 1977a). The Chapra estimate was 5.9 years (Chapra 1978).

The above estimates for response times must be used with great caution. There are many uncertainties in the scientific understanding of the factors affecting phosphorus residence times in lakes. Phosphorus feedback from the sediments and changes in the proportion of dissolved and particulate phosphorus forms in the water column can potentially modify the response time of a lake as the external phosphorus loads are changed.

## Comparison with 1972 WQA Objectives

Table XXII contains a comparison between the loading results of the TG and the 1976 target loads from the 1972 WQA. Detailed comparisons are difficult because atmospheric sources were not included in the WQA loads and because the TG recommendations for Saginaw Bay, Lake Erie and Lake Ontario were developed using the concept of base year loads.

TABLE XXII. COMPARISON BETWEEN THE LOADING RESULTS OF TASK GROUP III AND THE 1976 TARGET LOADS FROM THE 1972 WQA - ALL VALUES IN METRIC TONNES PER YEAR

| Basin | 1976 Target Load From 1972 WQA[1] | Actual 1976 Load | Base Year Load | Task Group Recommendation |
|---|---|---|---|---|
| Superior | 1796 | 3570 | Same as 1976 | 3352 |
| Michigan | 5350 | 6671 | Same as 1976 | 5553 |
| Main Lake Huron | 3088[2] | 2952 | Same as 1976 | 2781 |
| Saginaw Bay | - | 1197 | 868 | 440 |
| Georgian Bay | - | 628 | Same as 1976 | 598 |
| North Channel | - | 546 | Same as 1976 | 516 |
| Lake Erie | 14603 | 19676 | 19968 | 10900 |
| Western | - | 12689 | 14499 | - |
| Central | - | 4382 | 4007 | - |
| Eastern | - | 2605 | 1463 | - |
| Ontario | 9070 | 12795 | 11088 | 6800 |

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[1] Not including loads from atmospheric sources.

[2] WQA target load for entire Lake Huron basin.

## CONTROL OF PHOSPHORUS SOURCES

### General

With regard to control strategies for municipal and diffuse sources, the costs and benfits can be more clearly established over the next year or so. It is, therefore, recommended that the State and Provincial governments be required to commit themselves within a year from the date of the new Agreement on the methods by which the phosphorus loading objectives in Tables XVIII-XXI would be achieved. The methodologies to be developed should include a schedule which clearly identifies the time frame over which the loading objectives would be achieved. Any of the strategies will need to reflect the growth of population over time. A minimum of a 1 mg/l phosphorus effluent standard will be required at all municipal treatment plants greater than 1 mgd in the Great Lakes Basin.

### Municipal Point Sources

It has been demonstrated that it is possible to control phosphorus from municipal point discharges down to 0.1 mg/l. It is estimated that the 0.1 mg/l treatment level costs approximately ten times that of the 1.0 mg/l treatment level. For many municipal systems, a 0.5 mg/l treatment level can be achieved with additional settling facilities and/or effluent filtration. The additional cost of such treatment should be evaluated in terms of cost effectiveness of the strategies to achieve the phosphorus loading objectives for each basin.

## Industrial Point Sources

Industrial point sources constitute a small proportion of the phosphorus loadings to the Great Lakes. Control of phosphorus loadings from industrial point sources is not economically feasible because loads generally consist of large volumes and low phosphorus concentrations (Munro 1977).

## Diffuse Sources

The diffuse loads consist of diffuse tributary inputs as well as possible direct diffuse inputs. The diffuse tributary load is derived from runoff, particularly agricultural and urban, and groundwater flow. While urban land may contribute large amounts of phosphorus per unit area, because of the relatively small amount of urban area in the Great Lakes Basin the urban runoff load is significantly less than the agricultural runoff load. Combined sewer overflows can be significant in certain densely populated areas and can contribute to the diffuse load.

Most of the total phosphorus load to the Great Lakes is delivered by the tributaries. Diffuse sources account for a large proportion of the total tributary load (See Table XVI). Approximately 30 to 50 percent of the diffuse load is believed to be controllable using existing technology where the phosphorus loading rate per unit area is high, such as in the Lower Lakes. This technology includes improved conservation practices and specialized land cultivation techniques. If diffuse source controls are deemed necessary, then decisions should be made as soon as possible because implementation will probably be a lengthy process.

### Atmospheric Sources

Atmospheric phosphorus loadings result mainly from industrial emissions and wind erosion. Control of phosphorus loadings from these sources appears to be difficult; however, land management techniques might help control the component due to wind erosion.

### Shoreline Erosion

Since shoreline erosion is primarily a natural process, control of phosphorus from shoreline erosion is not considered necessary. Control of shoreline erosion for shore protection purposes probably has little effect on the overall phosphorus load from shoreline erosion.

### Detergent Phosphorus

Detergent phosphorus control would be effective in reducing those inputs which do not presently receive effective phosphorus treatment. These include most municipal sewage plants in the Upper Great Lakes, some of the plants with capacities greater than 1 mgd, plants without phosphorus removal, with capacities less than 1 mgd in the Lake Ontario and Lake Erie drainage basins, and septic tanks in general. The degree of effectiveness depends on the presently enforced phosphorus content limitations in detergents. It is not possible with available technical data to accurately quantify the reduction of phosphorus inputs as a result of detergent phosphorus control. However, as it appears quite feasible to reformulate detergents without seriously affecting their use, the TG favors the further reduction of phosphorus in commercial and household detergents as one of the control strategies to achieve the recommended loadings for each of the Great Lakes basins.

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