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on Great Lakes Water Quality

COMPARISON OF ACTUAL AND SIMULATED WATER QUALITY RESPONSES TO PHOSPHORUS LOADING SCENARIOS IN LAKE ONTARIO AND LAKE ERIE

By

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EXECUTIVE SUMMARY

Numerical systems simulation models that were developed under the Great Lakes Water Quality Program (GLWQP) by the National Water Research Institute for management level predictions of lake, water quality response to loading controls may also serve to assess the benefits that have been achieved from in-place loading controls. This report presents the simulation of the water quality of Lakes Erie and Ontario that would have been expected had phosphorus loading controls not been established under the GLWQP.

The simulation indicates that, with population growth that has been experienced, the epilimnion total phosphorus concentrations during the spring maximum for Lake Ontario would have been about 38 μg/ℓ in the absence of controls as compared to the 20 μg/ℓ that presently prevails under the control program. For Lake Erie, the volume of anoxic hypolimnion to be expected with the climatic conditions that were experienced are modelled using the controlled phosphorus loading and a constant loading at 1972 levels. While some degree of anoxia may be expected on "poor" climatic years under the control loadings, the reduction in anoxia volume is shown to be 50% or greater.

This report was prepared for the Phosphorus Management Task Force of the Canada-Ontario Agreement on Great Lakes Water Quality.

RÉSUMÉ ADMINISTRATIF

Dans le cadre de son programme de la qualité de l'eau des Grand Lacs, l'Institut national de recherche sur les eaux a mis au point des modèles de simulation numérique afin de pouvoir prédire le niveau des lacs, aux fins de leur gestion, et les résultats enregistrés en matière de qualité des eaux à la suite de mesures de réduction des charges polluantes. Cette modélisation peut aussi servir à évaluer les avantages qui ont été retirés des mécanismes déjà en place. Le rapport fait état des expériences de simulation de la qualité de l'eau des lacs Érié et Ontario et des résultats qu'elles auraient donnés si des mesures de contrôle des charges de phosphore n'avaient pas été établies en vertu du programme de la qualité de l'eau des Grands Lacs.

La simulation révèle qu'avec la poussée démographique enregistrée, on aurait eu des concentrations de phosphore total dans l'épilimnion au cours de la période de crue du printemps dans le lac Ontario d'environ 38 µg/L en l'absence de tout contrôle au lieu de celle de 20 µg/L qui prévaut actuellement grâce au programme de réduction. Quant au lac Érié, on est à établir des modèles du volume auquel il faudrait s'attendre dans un hypolimnion dépourvu d'oxygène, compte tenu des conditions climatiques que nous avons connues, en se servant des niveaux de 1972 pour les émissions de phosphore contrôlés et les charges constantes. Même si l'on peut s'attendre à un certain appauvrissement d'oxygène pendant les années pour lesquelles le climat a laissé à désirer et que les émissions polluantes étaient assujetties à des contrôles, on obtient une baisse du volume d'anoxie de 50 p. 100 ou plus.

Le rapport a été préparé par le Groupe de travail sur la gestion du phosphore en vertu de l'Accord Canada-Ontario sur la qualité de l'eau des Grands Lacs.

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ABSTRACT

Water quality models developed at the Canada Centre for Inland Waters are used to simulate the effect of various phosphorus loading scenarios in Lake Ontario and Lake Erie. Simulation results are compared to actual conditions resulting from the institution of phosphorus remedial measures.

In Lake Ontario the maximum and minimum trends in epilimnion SRP, OP and TP concentrations are outlined for hypothetical phosphorus loading changes ranging from -50 to +50% in the period 1972 to 1983. Assuming a +10% loading change in this period, a difference in the simulated maximum TP epilimnion concentration in year 1983 is as much as 10 µg/L higher than the results representative of current values attributable to the program of phosphorus loading abatement (about -50% change).

In Lake Erie the effect of a constant total phosphorus loading in the period 1967 to 1982 was contrasted against water quality responses using actual total phosphorus loading reductions. A measure of the difference was expressed in terms of the 'prevalence' of anoxia occurrence. Cumulation of simulated hypolimnion volumes over the period of anoxia (oxygen concentration < 1.5 mg/L) dramatically illustrates that the effect of remedial measures has been to substantially reduce the 'prevalence' of anoxia in comparison to scenarios without phosphorus reduction.

COMPARAISON DES RÉSULTATS ESCOMPTÉS ET RÉELS EN MATIÈRE DE QUALITÉ DE L'EAU, SELON LES DIVERS SCÉNARIOS DE CHARGE DE PHOSPHORE DANS LES LACS ONTARIO ET ÉRIÉ

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RÉSUMÉ

Les modèles de qualité de l'eau qui sont élaborés au Centre canadien des eaux intérieures servent à simuler les résultats que divers scénarios axés sur la charge de phosphore pourraient avoir dans les lacs Ontario et Érié. Ces résultats sont ensuite comparés aux conditions qui prévalent à la suite des mesures mises en place pour réduire la teneur en phosphore.

Dans le lac Ontario, pour la période allant de 1972 à 1983, on a établi les tendances extrêmes des concentrations du phosphore réactif soluble, des profils d'oxygène et du phosphore total dans l'épilimnion et ainsi dressé la gamme hypothétique complète des changements dans les charges en phosphore, allant d'une réduction de 50 p. 100 de la teneur à une augmentation de 50 p. 100 de celle-ci. Par exemple, si le scénario prévoit que la charge a augmenté de 10 p. 100 au cours de la période, la concentration maximale du phosphore total dans l'épilimnion prévue dans le modèle pour 1983 pourra être supérieure de 10 µg/L aux valeurs enregistrées, car le programme de réduction de phosphore a, dans les faits, entraîné une baisse de 50 p. 100.

Pour le lac Érié, on a comparé l'effet d'une charge constante de phosphore total au cours de la période allant de 1967 à 1982 aux résultats enregistrés dans la qualité de l'eau à la suite des mesures concrètes prises pour réduire le phosphore total. L'écart a été exprimé en termes de "prévalence" de l'anoxie. Les volumes simulés des concentrations dans l'hypolimnion pendant la période anoxique (où la concentration de l'oxygène était inférieure à 1,5 µg/l) démontrent que les mesures de dépollution ont nettement réduit la "prévalence" de l'anoxie par rapport aux scénarios qui ne préconisaient pas de réduction de la teneur en phosphore.

INTRODUCTION

Eutrophication of the Lower Great Lakes was demonstrated to be related to nutrient enrichment. The consequences of such artificial enrichment included the proliferation of aquatic weeds such as cladophora and the occurrence of anoxia especially in the Central Basin of Lake Erie. Total phosphorus was determined as the nutrient responsible for the continued enrichment (Burns and Ross, 1972) and in an effort to reduce the water quality problems in the lakes, a phosphorus loading reduction program was instituted in Canada and the United States (IJC, 1978). The program was fully initiated in 1972 and included such measures as reductions of phosphates in detergents and introduction of secondary sewage treatment.

The phosphorus reduction program has been in effect for approximately 12 years and observations have shown decreases in concentrations within the lakes. The following discussion details a comparison of actual and simulated water quality responses to various scenarios of total phosphorus loading changes for Lake Ontario and Lake Erie. Water quality models are used to derive simulations of the trends in concentration in response to specified loading changes.

WATER QUALITY MODEL

The water quality models used to simulate the effects of total phosphorus loading changes in Lake Ontario (Simons, 1978) and in Lake Erie (Lam, Schertzer and Fraser, 1983) are illustrated schematically in Figure 1. In general, the Lake Ontario model is a two-layer system (epilimnion and hypolimnion) in which a physical system and chemical processes are incorporated to effect a mass balance of SRP and OP between compartments. The Lake Erie model is similar in concept to the Lake Ontario model except that a third compartment representing a transition zone (i.e. mesolimnion) is included as well as a third component which is dissolved oxygen.

An example of the application of the water quality model for Lake Erie is given in Figure 2. Simulation of the seasonal cycle of West Basin epilimnion total phosphorus concentrations and the Central Basin hypolimnion dissolved oxygen concentration show good correspondence with measured values. Additional simulations for temperature, SRP, TP and dissolved oxygen for epilimnion, mesolimnion and hypolimnion layers is shown in (Lam, Schertzer and Fraser, 1983).

SIMULATION OF ACTUAL PHOSPHORUS CONCENTRATIONS

Actual total phosphorus loadings to Lake Ontario and Lake Erie are given in Figure 3 and 6 for the years 1967 to 1972 (Fraser and

Willson, 1981: Lam et al, 1983). Simulation of the Lake Ontario epilimnion phosphorus concentrations proceeds by initializing the water quality model. Using the 1972 TP loading value and initial specification of the epilmnion and hypolimnion SRP and OP (OP=TP-SRP) concentrations (Neilson and Stevens, 1983) with estimates of settling and repiration rates, a simulation of the seasonal SRP and OP concentrations are possible for each layer.

Figure 4 shows a sample simulation of actual epilimnion SRP concentrations for Lake Ontario compared with observations (Neilson and Stevens, 1983). In these simulations a linear decrease in annual loading is assumed. An annual trend to the computed results is illustrated by connecting the annual maximum and minimum seasonal simulations. For most years the seasonal simulations are in good agreement with observations. In this simulation of actual epilimnion SRP concentration, the trend to decreasing maximum concentrations from 1972 to 1983 is indicative of the positive effects of the phosphorus removal program. In a large measure, some of the reductions are also due to decreased TP loadings from Lake Erie. Similar simulations of Lake Erie phosphorus concentrations are also possible (as shown in Figure 2). Again, good agreement between computed and observed results is obtained and renders us the confidence to apply the models operationally (e.g. Lam and Hansen, 1983) to hypothetical scenarios for management analyses.

SIMULATION RESULTS FOR HYPOTHETICAL TOTAL PHOSPHORUS LOADING CHANGES

Lake Ontario

As indicated previously, phosphorus remedial measures in Lake Ontario were fully implemented in 1972. For the purposes of this discussion, total phosphorus loads in 1972 (13.6 MT) are used as the initial load for input to the Lake Ontario water quality model. Figure 3 shows initial TP loading in 1972 and hypothetical TP loading changes over the period 1972 to 1983. Five hypothetical scenarios are considered which are loading changes of -50, 0, +10, +25 and +50 percent over the 12 year simulation period. All other input parameters, such as settling and respiration rates, are held constant. The results for all five scenarios are given as trends in Figure 5 for epilimnion SRP, OP and TP maximum and minimum concentrations.

The simulated trends for the case -50 percent phosphorus loading reduction (Figure 5) closely resembles the actual loading decrease as depicted in Figure 3. Consequently, the results for the other four scenarios (0, +10, +25 and +50 percent) can be compared to this result to indicate the effect of the remedial measures. In the case of TP epilimnion concentrations, a comparison of maximum concentrations for the cases of -50 and 0 percent TP loading change over the 12 year simulation period shows that in 1983 as much as 9.9 μg/L difference

would be expected. Larger differences are apparent in comparing the -50 percent result with the other scenarios. The differences in maximums for the year 1983 are (10 µg/L, +10% increase): (13 µg/L, +25% increase) and (17 µg/L, +50% increase) for the remaining scenarios. Results for epilimnion SRP and OP concentrations are also given for each scenario.

Lake Erie

In Lake Erie, a measure of the effectiveness of the phosphorus removal program is the extent of and occurrence of Central Basin anoxia. Reductions in the available nutrient total phosphorus would be expected to result in an alleviation of the anoxic problem in Lake Erie. Previous studies (Charlton, 1980; Lam, Schertzer and Fraser, 1983) have indicated that meteorological factors which influence the hypolimnion thickness also have a significant effect upon the formation of anoxia within the hypolimnion. The Lake Erie water quality model incorporates a complex physical submodel which defines the hypolimnion thickness (Figure 1b). In this discussion, we combine the results of the physical regime and the simulated dissolved oxygen from the water quality model to define how 'prevalent' anoxia is from one year to another. Since the computation of dissolved oxygen concentrations is dependent on the loadings of total phosphorus to the system, different scenarios can be tested to demonstrate the effects

of phosphorus reductions on the water quality of Lake Erie. In the discussion which follows, we consider the results as determined from actual total phosphorus loading reductions in the period 1967 to 1983 contrasted against a scenario in which there is a constant total phosphorus loading in the simulation period.

Figure 7a graphically represents the 'prevalence' of anoxia based on computed hypolimnion volume and dissolved oxygen concentrations. Cumulative anoxic volume is defined as the sum of the computed daily hypolimnion volume over the period in which hypolimnion dissolved oxygen concentration is less than 1.5 mg/L. In another calculation we attempt to normalize this value by determining the ratio between the cumulative anoxic volume and the total hypolimnion volume determined when the upper interface is greater than 19 m, terminating when the dissolved oxygen concentration is again larger than 1.5 mg/L. The depth 19 m is chosen as it relates to the mean depth of the lake and is correlated with the occurrence of anoxia (Lam and Schertzer, 1984).

Figures 7b and 7c show the 'prevalence' of anoxia in the Central Basin of Lake Erie over the period 1967 to 1982 for the actual loading reduction (shading) and for the constant loading scenario (no shading). The diagrams illustrate that the years 1967, 1969, 1970, 1974 and 1977 to 1980 have the most prevalent anoxic occurrences) over the 16 year simulations. In contrast to the results using actual loading reductions, the effect of using a constant total phosphorus

loading at a high value of 28 MT/year (Figure 6) is to increase the 'prevalence' of anoxia in the Central Basin by extending the time in which the computed dissolved oxygen concentration is less than 1.5 mg/L. Note that for the recent years (1978-1983) anoxic conditions could have been much more severe (Figure 7b and 7c) had there not been the phosphorus reduction program.

CONCLUSION

The responses of Lake Ontario and Lake Erie to phosphorus loading reduction were determined for various scenarios through simulations incorporating water quality models developed at CCIW. By accounting for physical and chemical processes, these water quality models demonstrate that simulations of seasonal concentrations in phosphorus and dissolved oxygen for various compartments is possible and that these compare well with observations. By determining the trend in computed long-term simulations for phosphorus components, a comparison of various phosphorus loading scenarios demonstrates that the phosphorus reduction programs instituted in 1972 have had a significant effect in reducing phosphorus concentrations in Lake Ontario. In the simulation period 1972 to 1983 a constant loading scenario for phosphorus to Lake Ontario in the absence of the remedial programs would have resulted in maximum TP concentrations in 1983 in the range of 9 µg/L higher than current values. In Lake Erie the adoption of a phosphorus removal program appears to have had the

effect of reducing the 'prevalence' of Central Basin anoxia. Using the two measures of the prevalence of anoxia (Figure 7a and 7b), simulations using a high constant TP loading over the period 1967 to 1983 indicate that episodes of anoxia without remedial programs were 85 to 100 percent more prevalent compared to results with the phosphorus reduction program.

As the models have been verified and post-audited with 12 years of data in the case of Lake Ontario and with 16 years of data in the case of Lake Erie, the application of these models for operational use is justified and has been carried out. For future projections, estimates of the lake responses to further management strategies can be obtained from the scenario results presented or from a more refined run.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Figure 1 Schematic representation of the Lake Ontario (2-layer ; 2-component) and the Lake Erie 3-layer ; 3-component) Water Quality Models.

Figure 2a Comparison of computed (——) and observed (—■—) dissolved oxygen for the Central Basin hypolimnion of Lake Erie from 1967 to 1982.

Figure 2b Comparison of computed (——) and observed (—■—) total phosphorus concentration for the Western Basin of Lake Erie from 1967 to 1982.

Figure 3 Actual total phosphorus loading to Lake Ontario (O) from 1967 to 1983 and illustration of various total phosphorus loading scenarios (----) from 1972 to 1983.

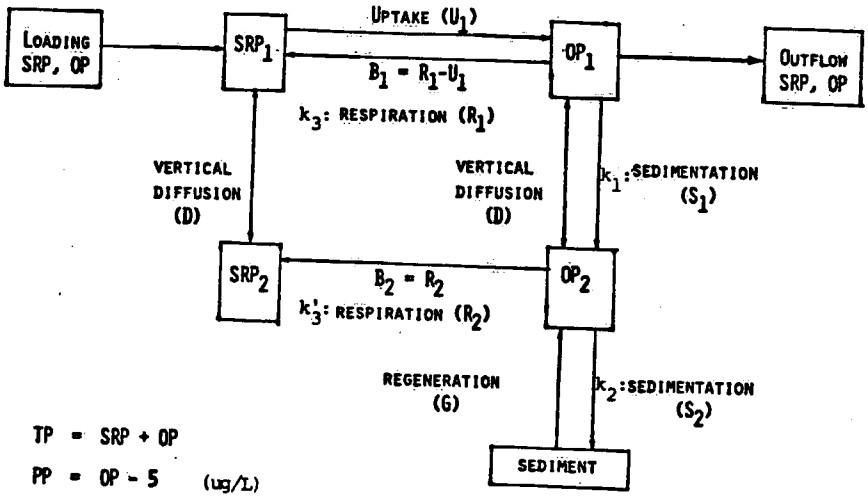
Figure 4 Application of the Lake Ontario operational water quality model to simulate seasonal epilimnion soluble reactive phosphorus concentrations (——) and comparison of results with observations (●) in the period 1972 to 1983.

Figure 5 Maximum and minimum trends in computed epilimnion SRP, OP, and TP concentrations for various total phosphorus loading scenarios in lake Ontario from 1972 to 1983.

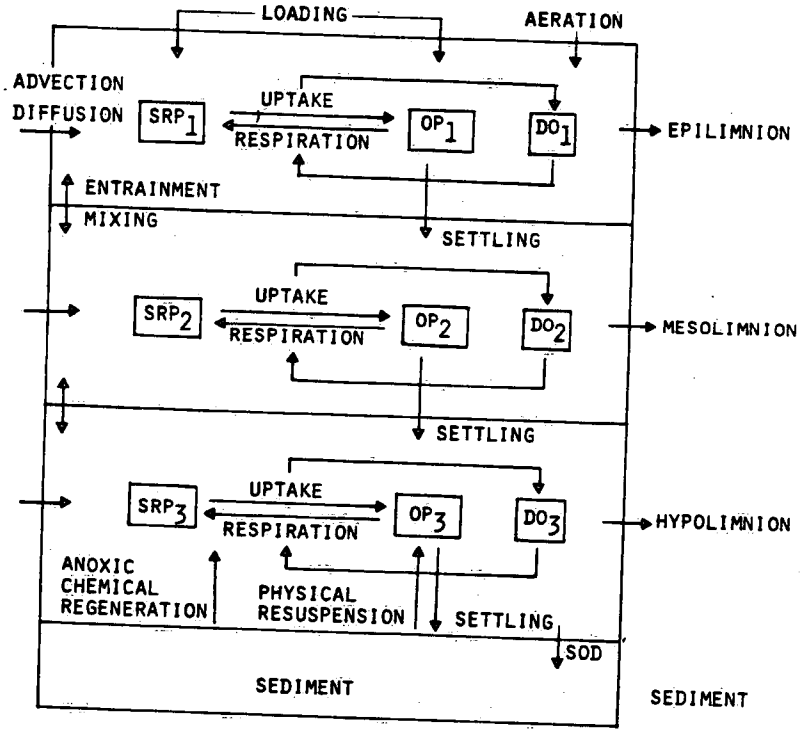
Figure 6 Actual total phosphorus loading to Lake Erie (O) from 1967 to 1982 and illustration of a high constant total phosphorus loading scenario (----).

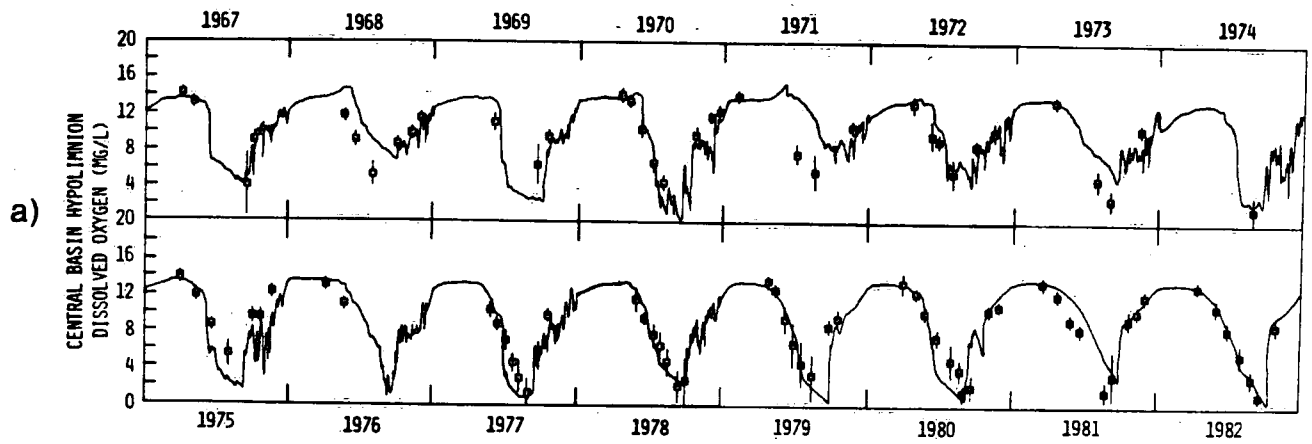
Figure 7 Comparison of the 'prevalence' of Lake Erie Central Basin anoxia from 1967 to 1982 for simulations using the actual total phosphorus loading (shading) and for a high total phosphorus loading scenario (no shading). Figure 7a is a schematic representation of the integration of meteorological effects (simulated hypolimnion depth) with chemical processes (simulated dissolved oxygen concentration) to derive an index to illustrate the 'prevalence' of anoxia using, (b) cumulative anoxic volumes and (c) the ratio between computed anoxic volumes and the total volume.

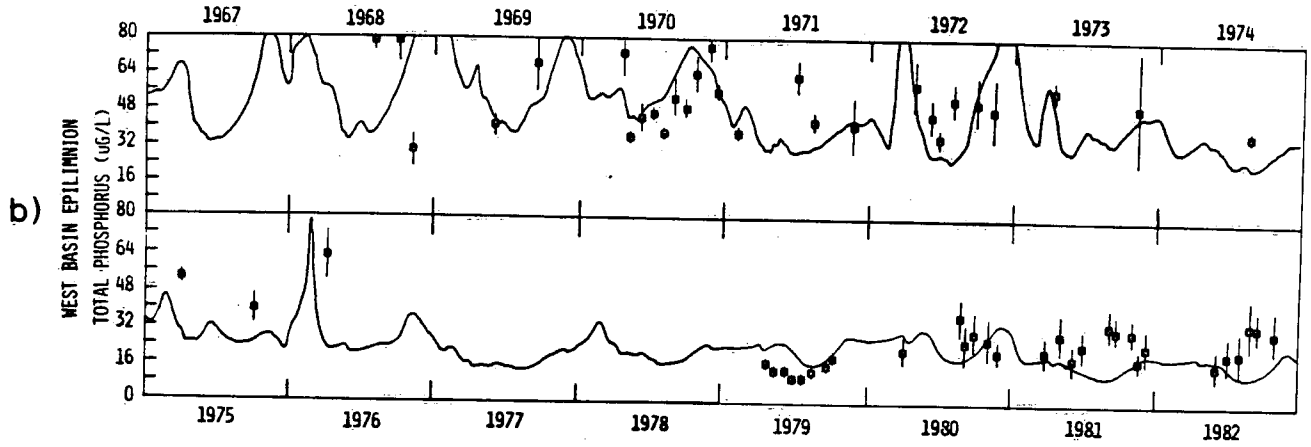
a) LAKE ONTARIO WATER QUALITY MODEL

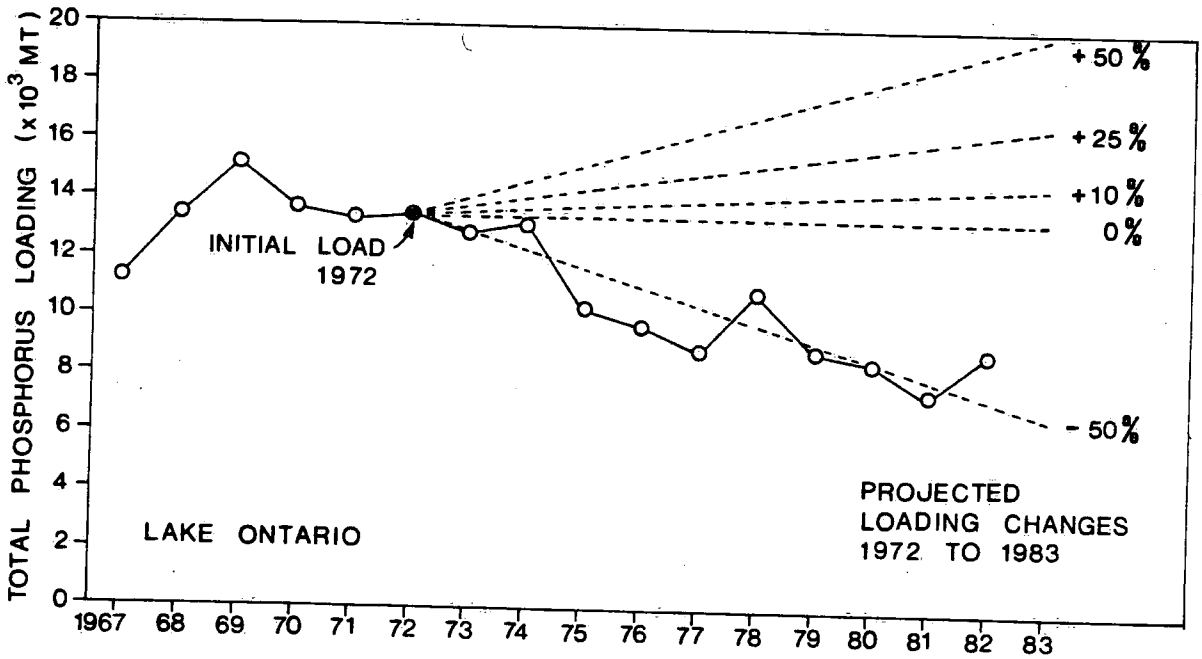


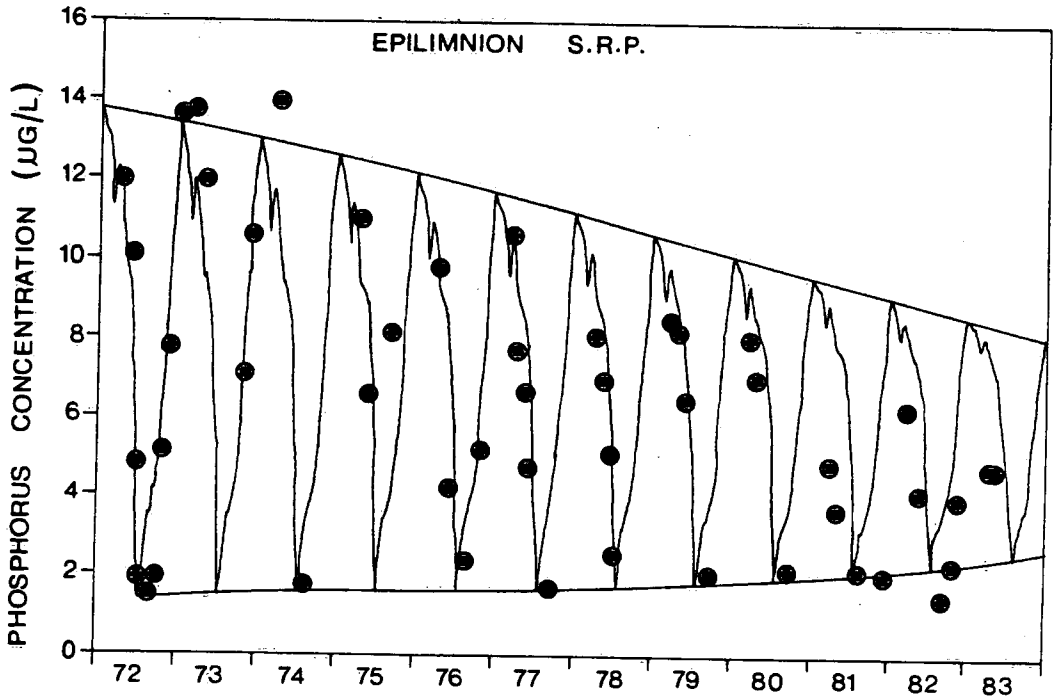
b) LAKE ERIE WATER QUALITY MODEL

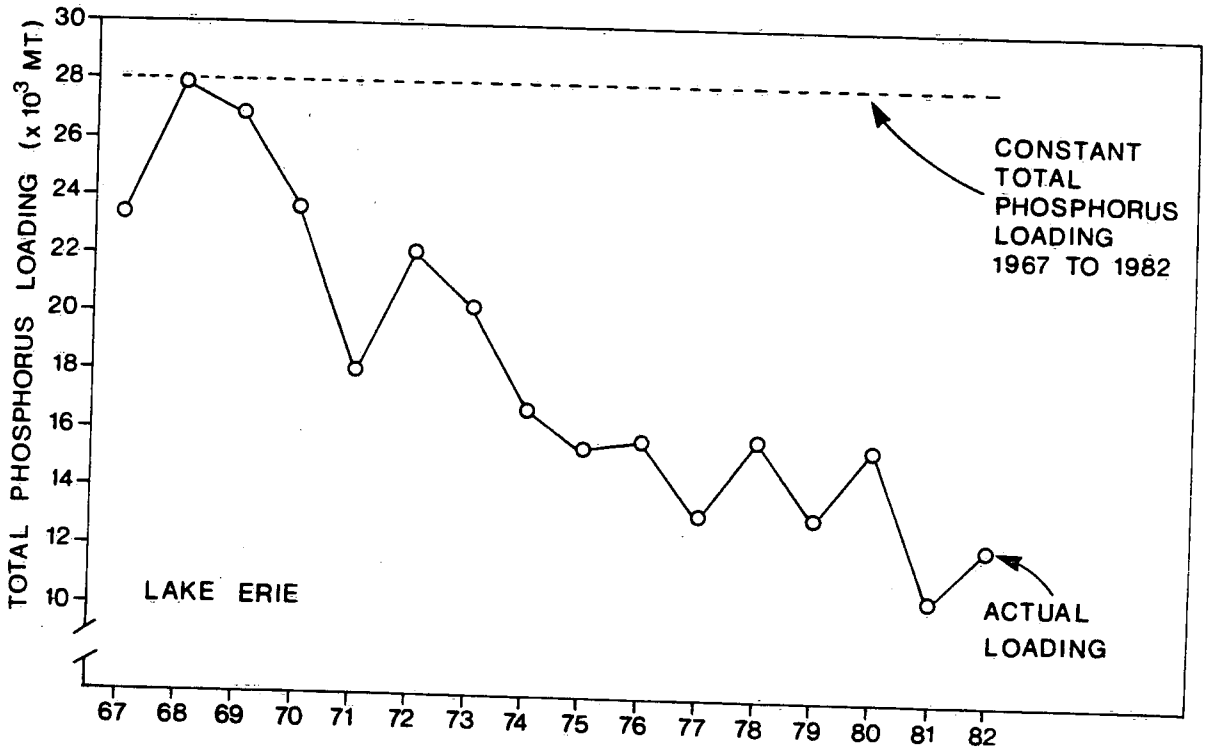


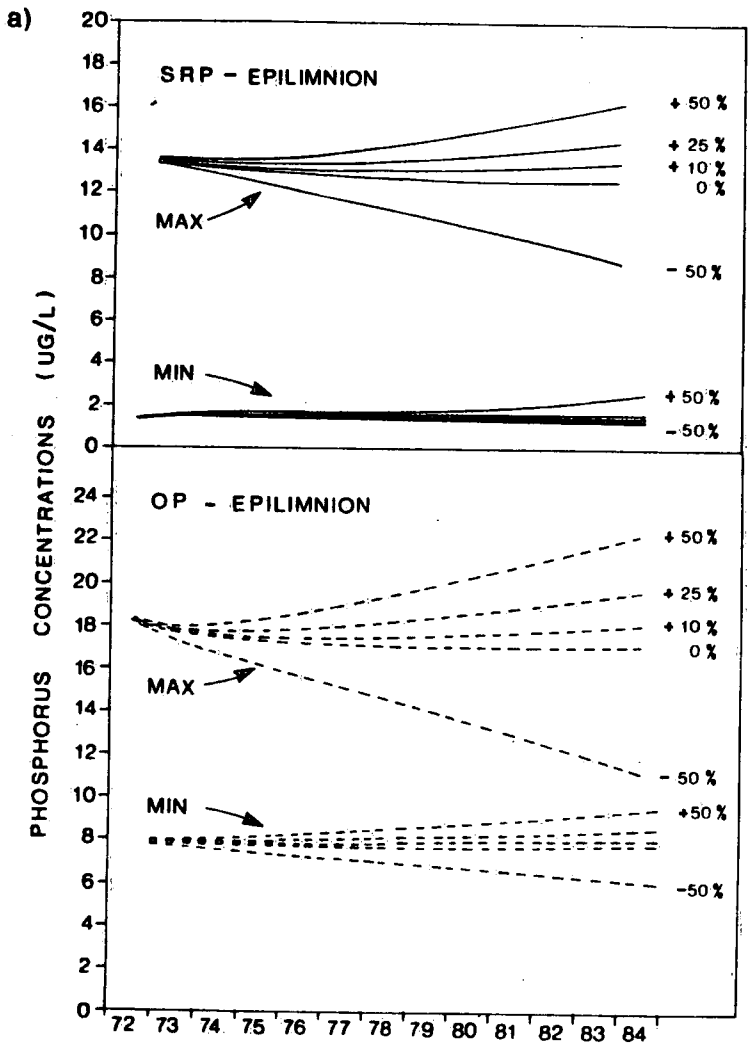

a)
CENTRAL BASIN HYPOLIMNION
DISSOLVED OXYGEN (MG/L)
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982

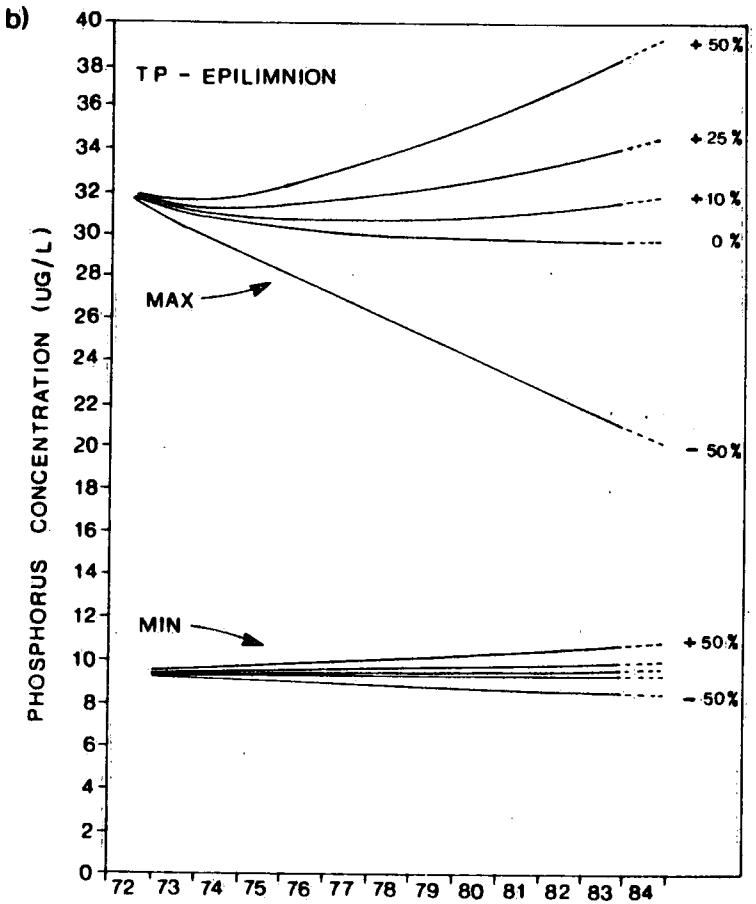

b)
WEST BASIN EPILIMNION
TOTAL PHOSPHORUS (uG/L)
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982

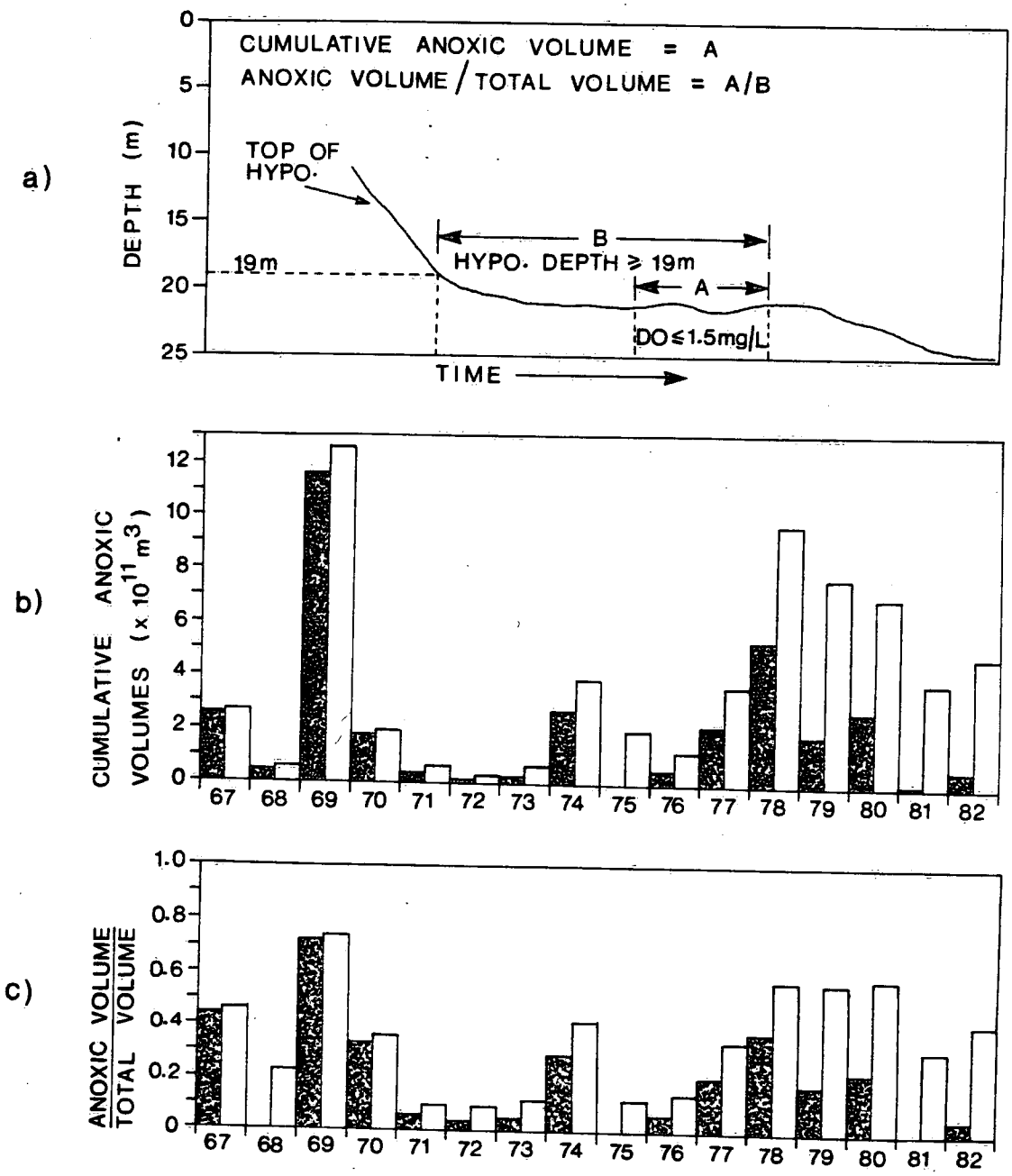

TOTAL PHOSPHORUS LOADING (x 10³ MT)
20
18
16
14
12
10
8
6
4
2
0
1967
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
INITIAL LOAD
1972
+50 %
+25 %
+10 %
0 %
- 50 %
LAKE ONTARIO
PROJECTED
LOADING CHANGES
1972 TO 1983


EPILIMNION S.R.P.
PHOSPHORUS CONCENTRATION (µG/L)
16
14
12
10
8
6
4
2
0
72
73
74
75
76
77
78
79
80
81
82
83


TOTAL PHOSPHORUS LOADING (x 10³ MT)
30
28
26
24
22
20
18
16
14
12
10
LAKE ERIE
CONSTANT TOTAL PHOSPHORUS LOADING 1967 TO 1982
ACTUAL LOADING
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82


a)
SRP - EPILIMNION
+ 50 %
+ 25 %
+ 10 %
0 %
- 50 %
MAX
MIN
+ 50 %
- 50 %
OP - EPILIMNION
+ 50 %
+ 25 %
+ 10 %
0 %
MAX
- 50 %
MIN
+50 %
-50 %
PHOSPHORUS CONCENTRATIONS (UG/L)
0 2 4 6 8 10 12 14 16 18 20 22 24
72 73 74 75 76 77 78 79 80 81 82 83 84


b)
TP - EPILIMNION
+ 50 %
+ 25 %
+ 10 %
0 %
MAX
- 50 %
MIN
+ 50 %
- 50 %
PHOSPHORUS CONCENTRATION (UG/L)
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40
72 73 74 75 76 77 78 79 80 81 82 83 84


a)
CUMULATIVE ANOXIC VOLUME = A
ANOXIC VOLUME / TOTAL VOLUME = A/B
TOP OF HYPO.
DEPTH (m)
19m
B
HYPO. DEPTH ≥ 19m
A
DO ≤ 1.5mg/L
TIME
b)
CUMULATIVE ANOXIC VOLUMES (x 10^11 m^3)
c)
ANOXIC VOLUME / TOTAL VOLUME
67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82

Ro 154