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SIMULATION OF RECENT AND PROJECTED TOTAL PHOSPHORUS TRENDS IN LAKE ONTARIO[1]

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ABSTRACT. Recent trends (1965 through 1978) of total phosphorus were analyzed with a time-variable, nutrient budget model of Lake Ontario. Future conditions were also simulated to estimate the effect of anticipated control measures on the lake's water quality.

The analysis suggests that recent improvements in Lake Ontario's total phosphorus concentration are attributable to point source reductions due to detergent limitations and waste treatment by the Province of Ontario and the State of New York. Projections show that present point source controls will maintain the lake at the upper level of mesotrophy (15-20 μgP/L) to the year 2000, whereas the absence of controls would result in eutrophy (∿30 μgP/L). Further indications are that some diffuse source reduction may be required if oligotrophy (<10 μgP/L) is the ultimate goal and that Lake Ontario's fate is closely related to that of Lake Erie.

An attempt is made to assess the effect of model uncertainty and phosphorus availability on the projections. In general, the inclusion of uncertainty indicates that more stringent load reductions will be needed to meet water quality objectives with greater than 50% certainty. Inclusion of availability tends to improve prospects for lake restoration and to enhance point as opposed to diffuse source controls.

INTRODUCTION

Since the early 1970s, Canada and the United States have attempted to reverse Great Lakes eutrophication by reducing phosphorus loadings. While the control program for the entire basin is by no means complete, there are several reasons why rapid and measurable improvement would be expected in Lake Ontario. First, both governments bordering the lake (the Province of Ontario and the State of New York) imposed strict limitations on detergent phosphorus early in the decade. Since estimates (Casey and Salbach 1974, Hydroscience Inc. 1976, PLUARG 1978) indicate that domestic sources constitute a sizeable fraction of the lake's loading, such an action should have substantial impact. Second, because the lake has a high flow-to-volume ratio (relative to most of the other Great Lakes), it should respond rapidly to load changes. Chapra (1977) estimates a 90% response time of less than a decade for total phosphorus load reductions. Finally, because of its great depth, Lake Ontario's hypolimnion is always rich in oxygen. Thus anaerobic feedback of phosphorus, which is often cited as a major cause of retarded recovery, would be unlikely to occur.

In fact, measurements of spring total phosphorus concentration since approximately 1973 seem to show an improvement (H. F. H. Dobson, Canada Centre for Inland Waters, Burlington, Ontario, personal communication). There are several reasons, however, why it is difficult to analyze these trends directly and to determine their underlying causes. First, the effect of natural, year-to-year physical variations must be estimated and separated from man's impact on the system. For example, the 1970s were particularly wet years, with an inordinately high volume of water flowing through Lake Ontario. Second, the variety of human uses and natural processes that contribute to a lake's total phosphorus loading somewhat complicates the connection of a response with its antecedent cause (or causes). Finally, because of its great size, Lake Ontario is difficult and costly to measure. Thus, while surveillance programs have provided several years of information on in-lake conditions, adequate time series of loadings are unavailable.

For the above reasons, the present exercise uses a mathematical model to reconstruct and

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analyze the recent trends in the loading and response of Lake Ontario. The model calculates lake loading on a year-to-year basis as a function of variables that reflect human and natural effects in the drainage basin. A nutrient budget model, which also accounts for year-to-year flow variations, is then used to translate the calculated loadings into time-variable, in-lake total phosphorus concentrations. Thus, the model starts with variables related to cultural and natural perturbations of the watershed and ends with a variable reflecting the effect on the lake. The major conclusion of the present study is that recent changes in total phosphorus concentration in Lake Ontario are what would be expected on the basis of simple mass balance calculations. The analysis implies that phosphorus control has had an impact on the water quality of Lake Ontario, particularly as a preventive measure, but that additional reductions, including the rehabilitation of Lake Erie and land runoff control, may be needed if oligotrophy is the ultimate objective.

THE MODEL

Waste Source Model

Phosphorus inputs to Lake Ontario from Lake Erie, the atmosphere, domestic sources, and land runoff are calculated as follows (all concentrations and loadings are for total phosphorus expressed as phosphorus):

$$W(t) = Q_e(t)p_e + W_a + \sum_{i=1}^{2} \left\{ [C_{di}(t) + C_h(t)] \, S_i[1 - T_i(t)] \, P_i(t) + Q_{ti}(t)p_{ti} \right\} \qquad (1)$$

where

$W(t)$ = rate of mass loading of total phosphorus to Lake Ontario (tonnes/yr), with the (t) denoting that the parameter varies from year-to-year,
$Q_e(t)$ = water flow out of Lake Erie (km^3/yr),
p_e = total phosphorus concentration in Eastern Lake Erie (μg/L),
W_a = atmospheric loading (tonnes/yr),
i = index designating the two countries bordering Lake Ontario, 1 and 2 denoting the United States and Canada, respectively,
$C_{di}(t)$ = annual per capita generation rate of total phosphorus due to detergents [kg/(capita yr)],
$C_h(t)$ = annual per capita generation rate of total phosphorus due to domestic waste other than detergents [kg/(capita yr)],
S_i = fraction of population served by sewers,
$T_i(t)$ = fraction of total phosphorus in sewered wastewater removed by treatment,
$P_i(t)$ = human population (thousand capita),
$Q_{ti}(t)$ = tributary water flow to Lake Ontario (km^3/yr), and
p_{ti} = total phosphorus concentration in Lake Ontario tributaries due to land runoff (μg/L).

Note that tributary phosphorus concentrations are constant over the period of the simulation. This connotes that (a) flow and concentration are not correlated on a year-to-year basis and that (b) land use characteristics and manipulative practices did not change significantly over the period of the simulation. While the former may not be true for all watersheds, available data does not allow the development of a statistically valid flow-concentration relationship at this time (Hydroscience 1976).

Phosphorus Budget Model

A total phosphorus budget model (Vollenweider 1969, as modified by Chapra 1975) can be written for Lake Ontario as

$$V \frac{dp}{dt} = W(t) - Q(t)p - vA_sp \qquad (2)$$

where

V = volume (km^3),
p = mean annual total phosphorus concentration (μg/L),
t = time (years),
$Q(t)$ = outflow (km^3/yr),
v = apparent settling velocity of total phosphorus (km/yr), and
A_s = surface area (km^2).

The model [Equations (1) and (2)] is similar to a previous attempt to model Great Lakes total phosphorus budgets (Chapra 1977), with the exception that in the previous application many of the coefficients were time-invariant. In the present exercise, additional coefficients are varied in time to account for year-to-year changes in the system characteristics (e.g., the high water flows in the mid-1970s).

With appropriate initial conditions, Equation (2) can be solved numerically for total phosphorus concentration as a function of time. Since the concentration in Lake Ontario for 1965 is unknown, the simulation is started in 1950 with an initial condition of 10 μg/L. In this way the model generates its own initial conditions consistent with the historical trends of population and hydrology that existed in the late 1950s and early 1960s.

Since for many recent years there were not enough surveillance cruises to develop accurate annual average total phosphorus concentrations, more data are available for spring total phosphorus. The following conversion (Chapra and Tarapchak 1976) is, therefore, used to convert mean annual to spring total phosphorus concentration:

$$p_v = 1.1\,p \tag{3}$$

where

p_v = total phosphorus concentration in Lake Ontario in spring (μg/L).

DATA

Physical Factors

Long-term hydrologic and morphometric information for Lake Ontario is summarized in Table 1.

TABLE 1. Long-term means of physical variables for Lake Ontario.

Parameter	Symbol	Value
Mean depth	z	86 m
Surface area	A_s	19000 km^2
Volume	V	1634 km^3
Inflow from Erie	Q_e	182.0 km^3 yr^{-1}
Tributary flow	Q_t	26.6 km^3 yr^{-1}
U.S.	Q_{t1}	16.9 km^3 yr^{-1}
Canada	Q_{t2}	9.7 km^3 yr^{-1}
Outflow	Q	208.6 km^3 yr^{-1}

Flows for 1965 through 1978, along with long-term means, are displayed in Figure 1. Note that since 1968 the system has experienced above-average inflows and outflows, with a peak in 1973 that was well over 2 standard deviations above the mean. Particularly high U.S. tributary flows occurred in 1972 and 1976.

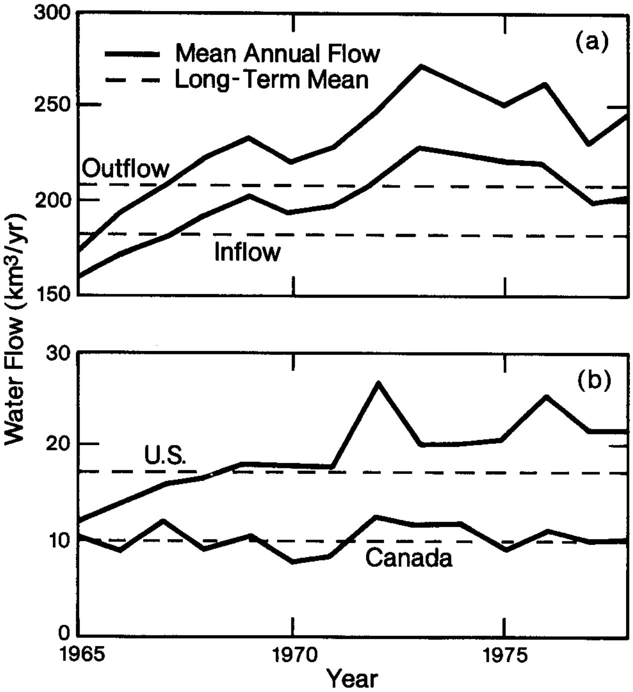

FIG. 1. Lake Ontario hydrology from 1965 through 1978: (a) inflow from Lake Erie and outflow and (b) runoff in km^3/yr. Solid lines are mean annual flows and dashed lines are long-term means. Note the high flows in the 1970s.

Human Factors

Population

Population data and projections are taken from a variety of sources (Canada Centre for Inland Waters 1972, U.S. Bureau of the Census 1971, U.S. Water Resources Council 1974, and R. Kogler, Ontario Ministry of the Environment, personal communication) and are presented in Figure 2. If present trends continue, the basin population will approach 10 million by the year 2000, representing about a 30% increase over present levels.

Per Capita Generation Rates

Reviews by Vollenweider (1968), Hetling and Carcich (1973), and Ligman, Hutzler, and Boyle (1974) have been used to develop the historical rates in Figure 3. Prior to 1945, values of 0.5 and 0.0 kg/(capita yr) were used for non-detergent and detergent domestic sources, respectively. Linear trends for both coefficients from 1945 to values of 0.8 kg/(capita yr) in 1970 indicate the growth of detergent use as well as of non-detergent phosphorus (e.g., garbage disposals) during this time period. Values were assumed to remain at 1970 levels until detergent limitations were imposed

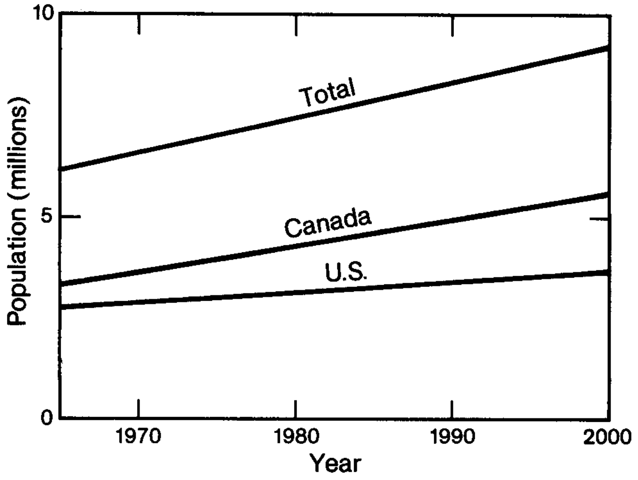

FIG. 2. Lake Ontario Basin population data and projections.

by Ontario (detergent phosphorus content of 8.8% in 1971 and 2.2% in 1973) and the State of New York (0.5% in mid-1973). Since prelimitation detergents contained approximately 12% phosphorus (Sawyer and McCarty 1967) the post-limitation rates are 0.587 kg/(capita yr) in 1971 and 0.147 kg/(capita yr) in 1973 for Ontario, and 0.033 kg/(capita yr) in mid-1973 for New York. Non-detergent rates are assumed to continue at 1970 levels [0.8 kg/(capita yr)] into the future.

Sewering

The 1970 values of 0.90 and 0.85 for the United States and Canada, respectively (Great Lakes Water Quality Board 1974) are assumed to apply for the entire simulation period.

Treatment

In the United States in the late 1960s, treatment, if any, was of the primary type (International Joint Commission 1969). Presently, secondary treatment is predominant (Great Lakes Water Quality Board 1978b). Since the transition between the two is unclear, the increase is assumed to have occurred linearly from 1972 (when amendments to the Federal Water Pollution Control Act mandated increased treatment) to 1975.

In Canada, most plants used secondary treatment in the late 1960s (International Joint Commission 1969) and many were upgraded to tertiary treatment in 1975 (Great Lakes Water Quality Board 1978b). Using Sawyer's (1973) removal efficiencies (0.05, 0.25 and 0.90 for primary, secondary, and tertiary, respectively) and treatment plant information results in the factors in Figure 4.

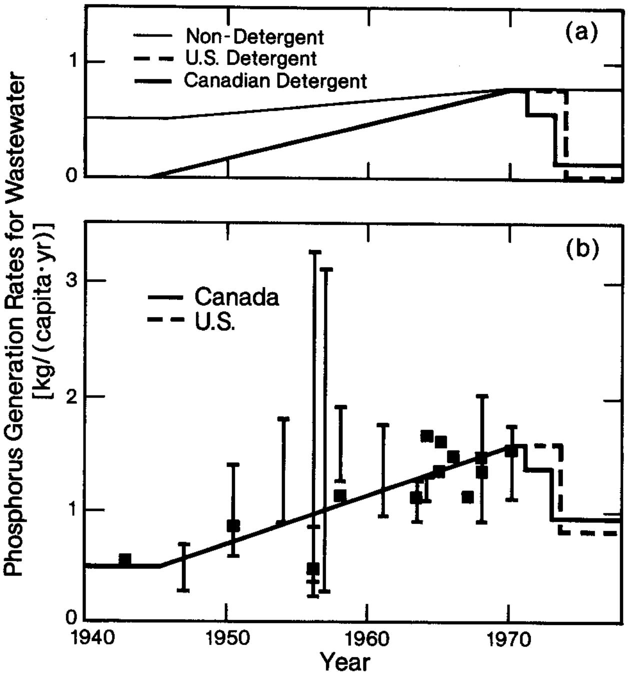

FIG. 3. Per capita generation rates of total phosphorus [kg/(capita yr)] from domestic wastewater: (a) components and (b) total rate, with data from Hetling and Carcich (1973). Symbols and bars designate average values and ranges, respectively.

Sewage Flow

Since legislation to limit point sources of total phosphorus in the Great Lakes has been expressed as mass per volume (e.g., the 1 mg/L effluent), it is necessary to determine the average per capita water use rate. Values in the Lake Ontario Basin are generally 700 L/(capita d) (International Joint Commission 1969), which is approximately 25% higher than the national average for the United States (Metcalf and Eddy Inc. 1972). The higher flows are probably due to industrial contributions to municipal sewage systems.

Other Factors

Lake Erie Phosphorus Concentration

Calculation of the Eastern Lake Erie concentration is complicated by the fact that the value of 25 μg/L

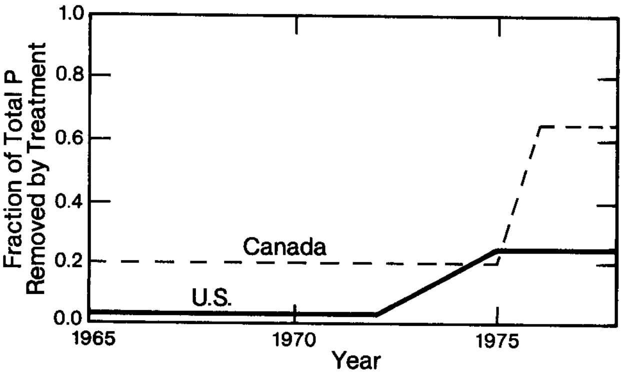

FIG. 4. Fraction of total phosphorus in sewered wastewater removed by treatment in the Lake Ontario basin.

(Hydroscience Inc. 1976) measured at the outlet is higher than the mid-lake value of 17.2 μg/L (Chapra and Sonzogni 1979). In the present exercise, the excess is assumed to originate in shoreline erosion and will not be included when calculating the eastern Erie contribution. Since this is a critical assumption, amounting to a 1000-2000 tonne/yr difference in the Lake Erie contribution, its effect on projections will be investigated in a subsequent section.

Tributary Phosphorus Concentration

Values of 81 and 96 μg/L for the United States and Canada, respectively, were determined by dividing measured tributary loadings (corrected for point sources) from PLUARG (1978) by tributary water flow for the year 1976.

Atmospheric Inputs

Atmospheric loadings are maintained at a constant level of 588 tonnes/yr (PLUARG 1978) for all simulations.

Apparent Settling Velocity

An apparent settling velocity of 0.0214 km/yr is determined by minimizing the sum of the squares of the residuals between phosphorus concentration data from 1969 through 1978 and model calculations. Using a relationship derived by Chapra (1975), this apparent settling velocity can be expressed as a retention coefficient of 0.62. This value falls between estimates calculated from empirical equations by Kirchner and Dillon (1975) and Larsen and Mercier (1976) of 0.52 and 0.72, respectively.

Aside from providing an estimate of in-lake losses to the sediments, the calculation also yields an estimate of the model's uncertainty in the form of the calibration's residual standard error. The value of 1.5 μg/L will be used in a subsequent section in an effort to include probabilistic information in model predictions.

1965 THROUGH 1978 SIMULATIONS

Loadings

Figure 5 depicts calculated loadings in several ways. Figure 5a shows mass loadings broken down into components. Prior to 1972, point sources accounted for over 50% of the total mass loading which ranged from 11,000 to 14,000 tonnes/yr. Point source control through detergent limitations and treatment has resulted in the present level of approximately 9,000 tonnes/yr. Note that Lake Erie's contribution represents 40% of the present load.

Inflow concentration (i.e., mass loading divided by total water inflow) is presented in Figure 5b since it more closely reflects the impact of load changes on the lake by accounting for both mass and flow variability (Larsen and Mercier 1976). Thus, although during high flow periods increased mass of a nutrient may be delivered to a lake, a higher flushing rate would partially compensate for the increase. A comparison of Figures 5a and b illustrates that high mass loadings in the early 1970s were partly due to high flows. More importantly, while mass loadings may show a decrease when flows return to normal or below average levels, a concomitant lake response might not occur.

Since the present point source control strategy is expressed in terms of the concentration of sewage effluent, Figure 5c compares calculated effluent concentrations with measured values (International Joint Commission 1969, Great Lakes Water Quality Board 1978b). Detergent reductions and treatment have reduced effluent concentrations from approximately 6 mg/L in the late 1960s to present levels of about 2 mg/L.

A breakdown of loadings just prior to the onset of major efforts to reduce phosphorus inputs (1970) and for a recent year when loading data are available (1976) is presented in Table 2. Note that in 1970 point sources were predominant, whereas in 1976 land runoff and Lake Erie were at comparable levels. The comparison with measurements is good, with a total difference of approximately 5% between the calculations and the data in 1976.

Finally, a comparison of the calculated loadings with estimates of other investigations (Figure 6)

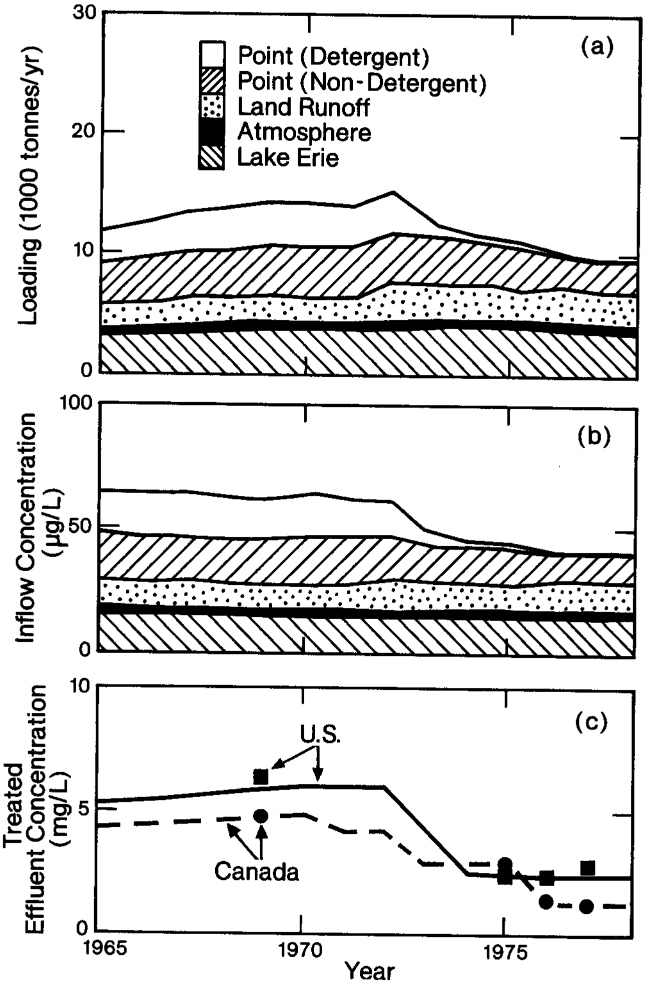

FIG. 5. Simulation of recent (a) mass loadings in thousand tonnes/yr, (b) inflow concentration (i.e., total loading divided by flow from Lake Erie and runoff flow) in μg/L, and (c) wastewater effluent in mg/L. Data are from International Joint Commission (1969) and Great Lakes Water Quality Board (1978b).

indicates that the present calculation generally yields lower values. This is primarily due to the fact that the model uses the mid-lake rather than the outlet concentration to determine the loadings from Lake Erie. This amounts to a difference of approximately 1600 metric tons/yr which, if added to the present calculation, would make the loading estimates comparable. Of more interest is the fact that the two long-term estimates that are available (Hydroscience Inc. 1976, Great Lakes Water Quality Board 1974-1979) show peak loadings occurring prior to 1972. A closer examination of the Hydroscience Inc. (1976) estimate suggests that a major reason for its 1969 peak is that a major drop in direct municipal loadings occurred in 1970. The explanation for the drop is not described in detail but if it were the result of a major treatment effort, it could be included in the present model.

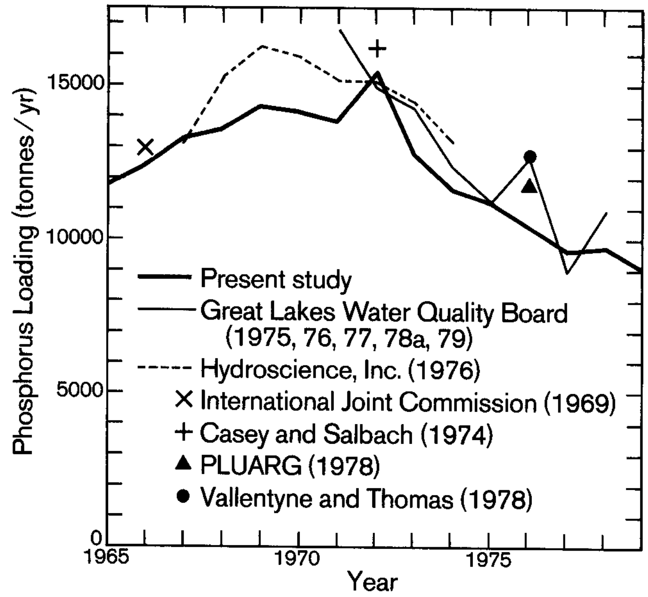

FIG. 6. Comparison of recent mass loadings of total phosphorus to Lake Ontario (as calculated in the present study) with estimates by other investigators.

Lake Response

Figure 7 presents results for spring total phosphorus concentration along with data from the Canada Centre for Inland Waters (H. F. H. Dobson, Canada Centre for Inland Waters, personal communication). In addition, the present levels in several other parts of the Great Lakes (Chapra and Sonzogni 1979) and approximate bounds for mesotrophy (Chapra and Dobson 1979) are included to assist interpretation. The simulation results generally show the same response as the data, with a peak value in the spring of 1973 (∼24-25 μg/L) followed by a gradual decline to 1978 levels of approximately 18 μg/L.

Figure 8 compares the present study's calculation of lake response with those of several other models that were used to support the recent review of the Great Lakes Water Quality Agreement between the United States and Canada (Vallentyne and Thomas 1978). Interestingly, all of the models (including Thomann's non-linear phytoplankton-phosphorus model) are linear with respect to loading changes. Thus, much of the difference between the predictions is a function of the particular data set used to calibrate each model.

TABLE 2. Components of loading for Lake Ontario as calculated for 1970 and 1976 along with data from PLUARG (1978) for 1976. Values in tonnes/year with percent of total loading in parentheses. Bracketed values refer to Lake Erie estimates based on Lake Erie outlet rather than mid-lake concentration.

	Calculated				
	1970		1976		Observed 1976
	tonnes/yr	(%)	tonnes/yr	(%)	tonnes/yr
Domestic	8100	(57)	2900	(28)	2900
United States	4100	(29)	1700	(16)	1600
Detergent	2050	(14.5)	100	(1)	
Non-Detergent	2050	(14.5)	1600	(15)	
Canada	4000	(28)	1200	(12)	1300
Detergent	2000	(14)	200	(2)	
Non-Detergent	2000	(14)	1000	(10)	
Land Runoff	2300	(16)	3200	(31)	3300
United States	1500	(10)	2100	(20)	2200
Canada	800	(6)	1100	(11)	1100
Atmospheric	500	(4)	500	(5)	500
Lake Erie	3300 [4800]	(23)	3800 [5500]	(36)	[4800]
Total	14200 [15700]		10400 [12100]		[11500]

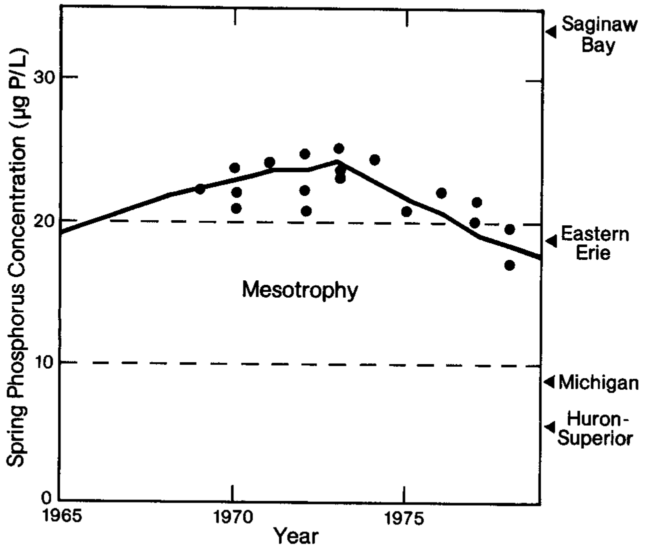

FIG. 7. Simulation of recent in-lake, spring concentration of total phosphorus (μg/L) with data from the Canada Centre for Inland Waters (Dobson, personal communication). Each data point represents a cruise-mean; note that in some years more than one surveillance cruise was conducted.

PROJECTIONS

A number of loading scenarios (Table 3) have been developed as idealizations of anticipated phosphorus control measures. They include the 1 mg/L point source effluent restriction that is presently mandated, as well as a 0.5 mg/L restriction and a 30% land runoff reduction that have been recommended. In addition, a lowering of eastern Lake Erie's phosphorus level to 10 μg/L is included, as well as a "no treatment" scenario to ascertain what would have occurred had nothing been done to control phosphorus after 1970. Finally, a scenario is included to estimate the effect of relying solely on detergent reductions.

The results are presented in Figure 9, along with loadings and concentrations for the year 2000 as presented in Table 3. The immediate observation from the future simulations is that point source controls (of which detergent limitations are a sizeable fraction) lower the lake to the upper level of mesotrophy, whereas it would have become solidly eutrophic had no controls been implemented (scenario I). The consequence of the

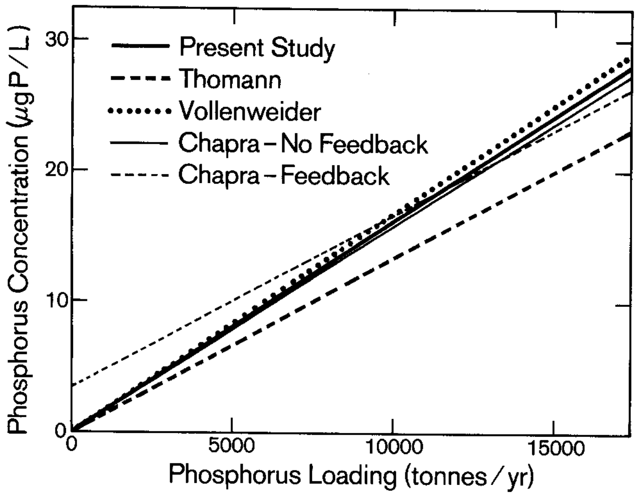

FIG. 8. Comparison of prediction using the present model and those used to support the Fifth Year Review of the Canada-United States Great Lakes Water Quality Agreement (Vallentyne and Thomas 1978). The plot shows mean annual total phosphorus concentration as a function of loading.

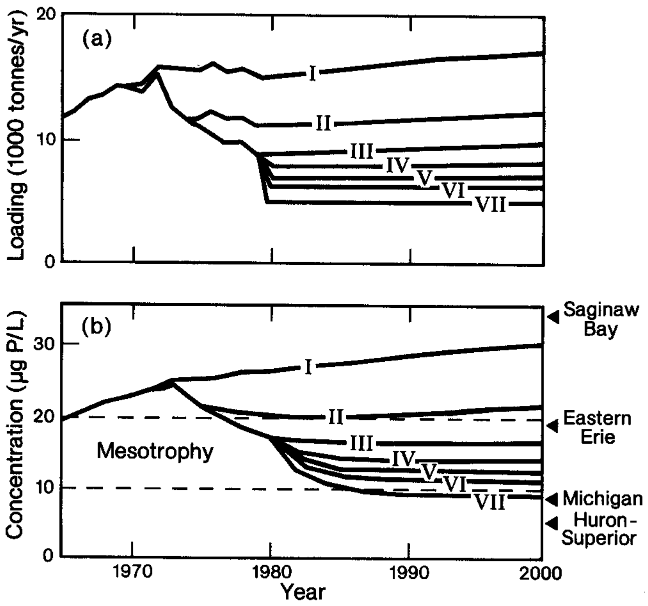

FIG. 9. Simulation of future (a) loadings and (b) response of Lake Ontario to several scenarios of phosphorus control. (See Table 3 for explanation of scenarios.)

TABLE 3. Scenarios representing idealized versions of anticipated control programs for Lake Ontario with corresponding loadings (metric tons/year) and steady-state spring phosphorus concentrations (μg/L) for the year 2000.

Scenario	Description	Year 2000 Loading (tonnes/yr)	Year 2000 Concentration (mg/L)
I No Control	No additional phosphorus control after 1970.	17,300	31.0
II Detergent Control	Just detergent limitations after 1970.	12,300	22.1
III Present Control	Continuation of 1977 control level into the future.	9,700	17.3
IV 1 mg/L Effluent	Imposition of a 1 mg/L effluent restriction on all domestic sources in 1980.	8,100	14.4
V 0.5 mg/L Effluent	Imposition of a 0.5 mg/L effluent restriction on all domestic sources in 1980.	7,000	12.6
VI 30% Land Runoff Reduction	Same as V but with an additional 30% reduction of land runoff sources in 1980.	6,300	11.3
VII Lake Erie Reduction	Same as VI but with Eastern Lake Erie's mid-lake concentration reduced to 10 μg/L in 1980.	5,000	9.0

"no treatment" scenario can be appreciated by realizing that it would have brought Lake Ontario's total phosphorus concentration up to levels comparable to those in Saginaw Bay. The additional scenarios beyond present controls each amount to ~ 2 μg/L improvements, with scenario VII reducing the load to 5000 tonnes/yr and the concentration to 9 μg/L. Note that land runoff and Lake Erie reductions are necessary if the upper level of oligotrophy (~ 10 μg/L) is taken as the water quality objective. This conclusion is reinforced when the uncertainty of the projection is considered as in the following section.

DISCUSSION

Since the model is merely an approximation of reality, the following should be considered for a balanced interpretation of the preceding analysis.

Space and Time Scales

The assumption of complete mixing ignores localized areas of enrichment, such as nearshore areas and embayments where human use and contact is intense. Similarly, the model's use of annual or spring values for its variables may ignore important temporal variations or shorter time scales. While it is beyond the scope of the present study, the analysis of finer scales should be considered in a complete assessment of Lake Ontario's eutrophication control program; other models have been designed for this purpose (Thomann *et al.* 1975; Chen, Lorenzen, and Smith 1975).

Phosphorus Availability

The model assumes that water quality is directly proportional to the lake's total phosphorus level. While, in a broad sense, this seems to be a good approximation [e.g., Vollenweider's (1968, 1975) phosphorus loading plots], when finer distinctions are made the possibility that all of the total phosphorus may not be available for algal assimilation must be considered. One implication of availability is that the present analysis might be pessimistic since less stringent loading reductions might be adequate to reach water quality goals if the available fraction of the loading could be determined and selectively treated. As a corollary, care should be exercised in reducing total phosphorus since removal of the unavailable fraction might be useless or possibly detrimental to the attainment of water quality objectives. For example, total phosphorus associated with fine-grained sediments could presently (a) reduce water clarity and inhibit phytoplankton production and (b) through adsorption, actually compete with phytoplankton for available phosphorus (Fitzgerald 1970).

Recently, Schaffner and Oglesby (1978 and Oglesby and Schaffner 1978) have attempted to include availability in lake loading and response calculations. While their approach has yet to be tested against an independent data set, it provides a first estimate of the effect of availability on Lake Ontario water quality predictions. Because there are a number of problems with the direct application of the Schaffner-Oglesby method to the present context (e.g., their correlations yield negative values at low levels of loading), a modified version is applied here. This modification is based on the fact that the critical difference between conventional total phosphorus models and the Schaffner-Oglesby method is that the latter yields lower estimates of land runoff loading. This is due to Schaffner and Oglesby's (1978) contention that a fraction of the phosphorus in land runoff is adsorbed on soil particles and is thus unavailable for phytoplankton assimilation. The other components of the loading (point, atmospheric, and loading from another lake) are assumed to be totally available. In addition, while other aspects of the Schaffner-Oglesby approach (e.g., normalization of loading to the mixed depth of the lake) may be useful in explaining lake-to-lake variability, they are unnecessary for explaining year-to-year variations in a single lake.

Therefore, the present paper uses Schaffner and Oglesby's (1978) land export factors and Lake Ontario land use and runoff data to calculate "biologically available" tributary phosphorus concentrations of 30.2 and 41.1 μg/L for the United States and Canada, respectively. Note that these values represent over a 50% decrease in the land runoff loading as compared with the original estimates for total phosphorus. These available land runoff loadings, along with the other components of the loading, are used to recalibrate the model for the period from 1969 through 1978 and then to make projections. This assumes that the non-biologically available phosphorus that enters the lake immediately settles out at the tributary mouth.

The results of this and three other versions of the model are shown in Figure 10. The other cases are as follows:

1) The total phosphorus model with Lake Erie's contribution calculated on the basis of the eastern Lake Erie mid-lake concentration (p_e = 17.2 μg/L). This is the model that has been used throughout the preceding parts of the paper; it will be called the "base model."
2) The total phosphorus model with Lake Erie's contribution calculated on the basis of the concentration at its outlet (p_e = 25.0 μg/L). This is called the "high Erie model."
3) It has been suggested that some of the point source phosphorus discharged to tributary streams may be lost in transit and never affect the lake (Baker and Kramer 1973). As a test of the model's sensitivity to this hypothesis, a version has been developed that considers only point sources that originate in counties contiguous with the lake. All tributary loadings are, therefore, assumed to be the result of land runoff. In addition, the higher Lake Erie contribution is also used. This version is called the "on-lake point model." Note that in all four versions the 30% land runoff reduction is 700 tonnes/year as was determined for the base model.

In general, Figure 10 indicates that with decreasing availability, the response to control measures that affect available phosphorus is heightened. Thus, point source control becomes somewhat more advantageous. In addition, the Schaffner-Oglesby approach increases the prospects for rehabilitation since less of the total phosphorus loading affects the lake's water quality. Therefore, less of a reduction in loading is necessary to attain water quality objectives.

Uncertainty

A complete assessment of phosphorus control strategies must consider the uncertainty of the predictions. In the present analysis, this will be done by assuming that the residual standard error of 1.5 μg/L determined from the model calibration is a valid approximation of the error of subsequent predictions. If the error is normally distributed (because of the small sample in the present case, this cannot be substantiated), this amounts to an additional reduction of about 1.0 μg/L to reach a particular phosphorus concentration goal with 75% certainty. Thus, a predicted concentration of 9.0 μg/L would have to be sought in order to be 75% certain that the lake was less than 10 μg/L. If higher certainty is desired, the target concentration would have to be lowered further (e.g., 8.1 μg/L to be 90% certain). These results are graphically depicted in Figure 11.

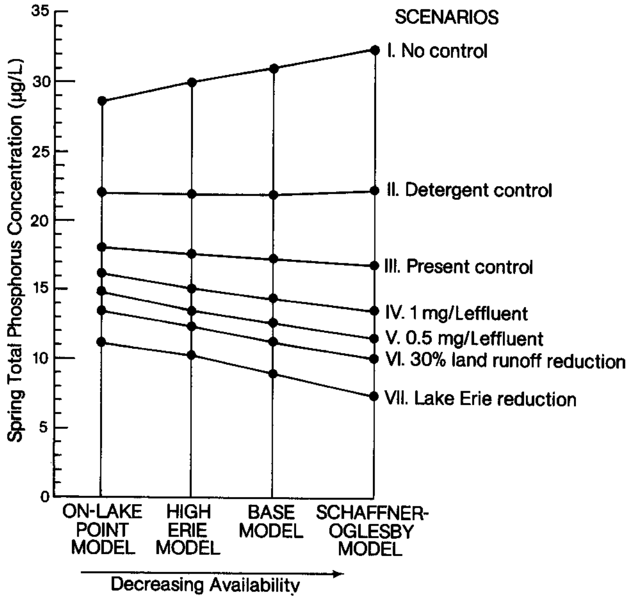

FIG. 10. The effect of availability on model predictions. Spring total phosphorus concentrations in the year 2000 as calculated by four versions of the model with decreasing availability of phosphorus to phytoplankton. Note that with decreasing availability, the predictions are more responsive to control measures since less of the loading plays a part in controlling lake response.

There are several weaknesses related to the validity of using the standard error as an estimate of prediction uncertainty. These relate to model and parameter error, as well as to measurement error of both the independent and dependent variables (see Chapra and Reckhow 1979 for a preliminary discussion of these problems). Therefore, the preceding analysis is not intended as a rigorous treatment of the subject. Rather, it is meant to draw the general conclusion that more stringent loading reductions will be required in order to meet water quality objectives with greater than 50% certainty.

CONCLUSIONS

Since large sums of money have been expended to reduce loadings, there is a natural tendency to expect these efforts to yield immediate response in Lake Ontario. As shown in the present paper, there are two reasons why such expectations can be both frustrating and futile. First, Lake Ontario responds to phosphorus load changes on a time

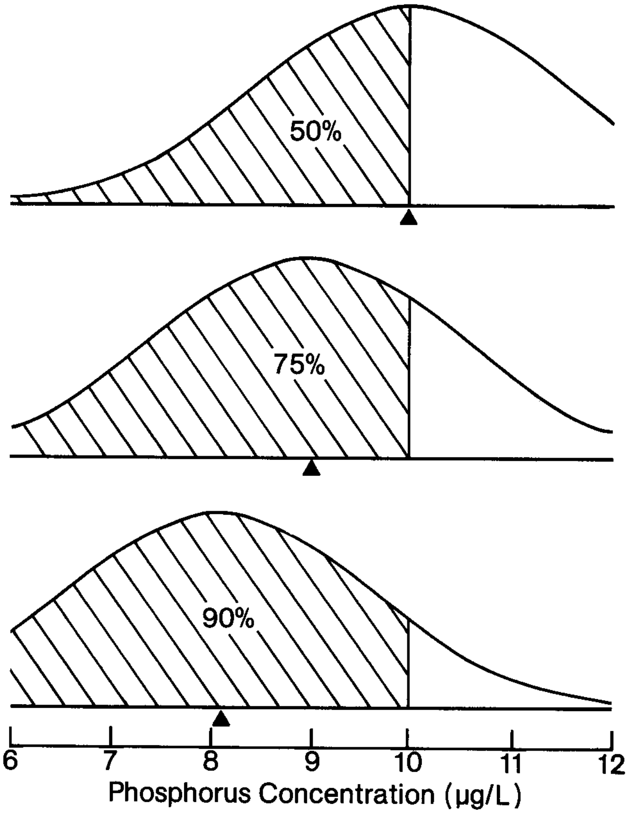

FIG. 11. The effect of probability of model predictions. The arrows designate the mean phosphorus level that must be attained to ensure an in-lake concentration of 10 µg/L with a specified degree (%) of certainty. Thus, if more certainty is required, lower target levels are needed.

frame of 5-10 years, rather than on an annual basis. Second, sizeable year-to-year changes due to natural variability and to measurement error are superimposed on the long-term trend. Thus, while the lake may be undergoing a significant, though gradual, shift on the broader scale, those interested in lake water quality can alternate between optimism and pessimism when evaluating the short-term fluctuation. At the worst, this sort of myopia could lead to the abandonment of what would be perceived as an ineffective abatement program. The median phosphorus response time of the Great Lakes is on the order of a decade or two (Chapra and Sonzogni 1979). Since this is approximately a human generation, it suggests that relaxation of treatment objectives due to frustration with short-term improvements could result in handing our problems down to our children. It is hoped that the present analysis demonstrates that a broader perspective is needed when evaluating water quality trends for a system as large and important as Lake Ontario.

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