Lake Erie Regulation Study
Water Quality Research

FIRST DRAFT

AN ANALYSIS OF CERTAIN ASPECTS OF WATER QUALITY AND CHANGES WHICH MIGHT RESULT FROM THE REGULATION OF LAKE ERIE.

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TABLE OF CONTENTS

SUMMARIES

Chapter 1

The regulation plans are discussed, and hydrographs and plots of frequency of occurrence of levels are shown, comparing BOC with the extreme Plan 6.

Chapter 4

The effect of regulation on phosphorus in the lower lakes is discussed. It is shown that open lake changes would be small. The major change expected would result from the change in quantity of shoreline erosion. The fraction of available phosphorus in eroded bluff material is very small, and so the effects of this change lakewide would be trivial, but of some significance in the nearshore zones.

Chapter 5

Regulation would seem likely to have a noticeable effect decreasing nearshore water turbidity, particularly in Lake Erie central and eastern basins. In the shallow western basin of Lake Erie, and in Lake St. Clair, regulation might cause increased turbidity as a result of more frequent resuspension of bottom sediments.

Open lake turbidities would not change by a large amount.

Chapter 6

The effect of regulation on hypolimnetic temperature and oxygen is discussed. Even for the particular case of Lake Erie central basin, these effects are likely to be small. Further work may be necessary to consider the problem of more frequent containment of Lake Erie central basin hypolimnion by the Pennsylvania Ridge.

N.B.

Throughout this report the effects of regulation are considered with reference to the change in mean lake levels. As Chapter 1 shows, natural fluctuations of lake level are considerably greater than any perturbations which might result from human interference. The purpose of this study is to assess long term changes which might be expected to follow regulation.

THE EFFECTS ON WATER QUALITY OF REGULATING THE LEVEL OF LAKE ERIE

Introduction

A proposal has been made to regulate the level of Lake Erie by allowing more water to flow out of the Niagara River when high levels on Lake Erie are expected. This proposal was made in response to concerns about shoreline erosion, which is particularly severe during the coincidence of storms and high water levels. As moderation of the weather is not yet feasible on the necessary scale, a suggestion has been made to decrease the likelihood of shore damage by reducing the frequency of high water levels. It is desirable to estimate the full impact of this manipulation of the natural regime, including changes to water quality, before a decision is made about this proposal.

How Might Lake Level Regulation Affect Water Quality?

The proposed changes in lake level, though small compared with the natural fluctuations, may have various effects on water quality, particularly inshore water quality, though some of these changes may be so slight as to be insignificant. If regulation were successful in preventing excessive shoreline erosion, a change might be observed in water clarity, and in concentrations of constituents of bluff material, of which phosphorus may be the most immediately important. Other effects of regulation to be considered include changes in heating and oxygen consumption, changes in inshore conditions, particularly as outfall dispersion and intake quality may be affected, changes in marshland water quality, changes in water quality in embayments, and the possible need for dredging and construction and how this might affect water quality.

Phosphorus

During recent decades, considerable attention has been given to phosphorus in water bodies - its concentration, speciation, supply, utilization, and cycling. In many temperate natural waters, it has been shown that phosphorus is the limiting nutrient for algal growth. Plants are the first and key stage in all food chains, and in open water phytoplankton (free-floating, microscopic plants) growth is frequently dependent on the availability of phosphorus. It is therefore necessary to consider how lake level regulation might affect the phosphorus budget, as changes in the amount of available phosphorus will, if this nutrient is limiting, and if conditions for growth are otherwise met, result in changes in the algal population, with direct effects on water clarity and on the trophic status of the whole lake.

REGULATION OF LAKE ERIE AND HOW IT WOULD AFFECT LAKE LEVELS IN LAKES ST. CLAIR, ERIE, AND ONTARIO

1.1 Introduction

Various plans of regulation of Lake Erie are being considered, but for this simple overview, only the extreme version will be described: Plan 6.

Plan 6 is a scheme based on water supply in the upper lakes whereby, when high levels in Lake Erie seem likely, extra water will be allowed to flow out of Lake Erie through the Niagara River to a maximum of 30 TCFS in excess of the unregulated flow. The mean flow through the Niagara River before regulation is 210 TCFS. The proposals include no capacity for holding back water. When excess water is released, the level falls, the head of water at the outfall decreases, and the resultant outflow becomes smaller than it would have been had no prior regulation taken place. The actual lake levels for the years 1900-1976 have been taken, adjusted to allow for human interference during that time, and these adjusted values taken as the Basis of Comparison (BOC) for all regulation plans. This chapter deals very briefly with the major differences between the BOC and Plan 6 for each lake.

1.2 Approach

The hydrographs (Figs. 1-4) show the predicted lake levels for the 77-year period. The data were also sorted into level order and, from this assemblage, Figs. 5-7 were plotted, showing frequency of occurrence of monthly mean levels at 0.5-foot intervals. Table 1 shows the ranges and means which would result from regulation.

1.3 Discussion

The data in the figures presented in this chapter show clearly that regulation of Lake Erie would have the effect, in Lakes St. Clair and Erie, of decreasing the frequency of occurrence of high water levels (those associated with particularly excessive shoreline erosion), of slightly increasing the frequency of low water levels, and of increasing the frequency of occurrence of levels close to the mean. In Lake Ontario, which is regulated at Cornwall, the mean would be unchanged by the changing inflow from Lake Erie, but extreme high or low levels would occur more

TABLE 1

Lake Levels (feet) before and after Regulation.

	BOC	PLAN 6
Lake Erie		
Mean	570.76	570.05
Maximum	573.74	572.47
Minimum	567.96	567.65
Range	5.78	4.82
Lake Ontario (with deviation)		
Mean	244.72	244.72
Maximum	248.52	248.69
Minimum	241.27	240.92
Range	7.25	7.77

Figure 5 Frequency of occurrence of monthly mean lake levels
LAKE ST CLAIR 1900-1976

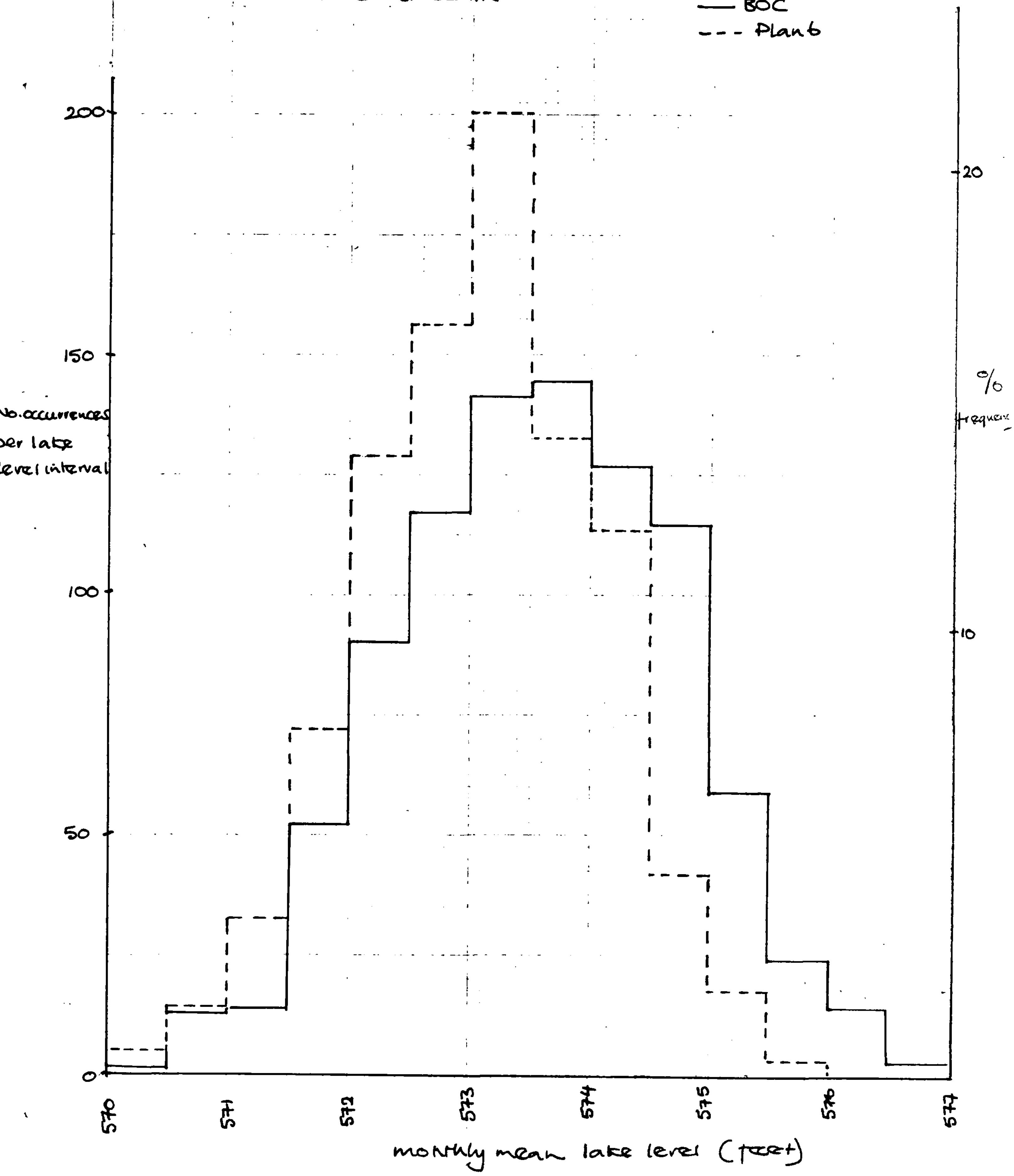


Figure 6 Frequency of occurrence of monthly mean lake levels
LAKE ERIE 1900-1976

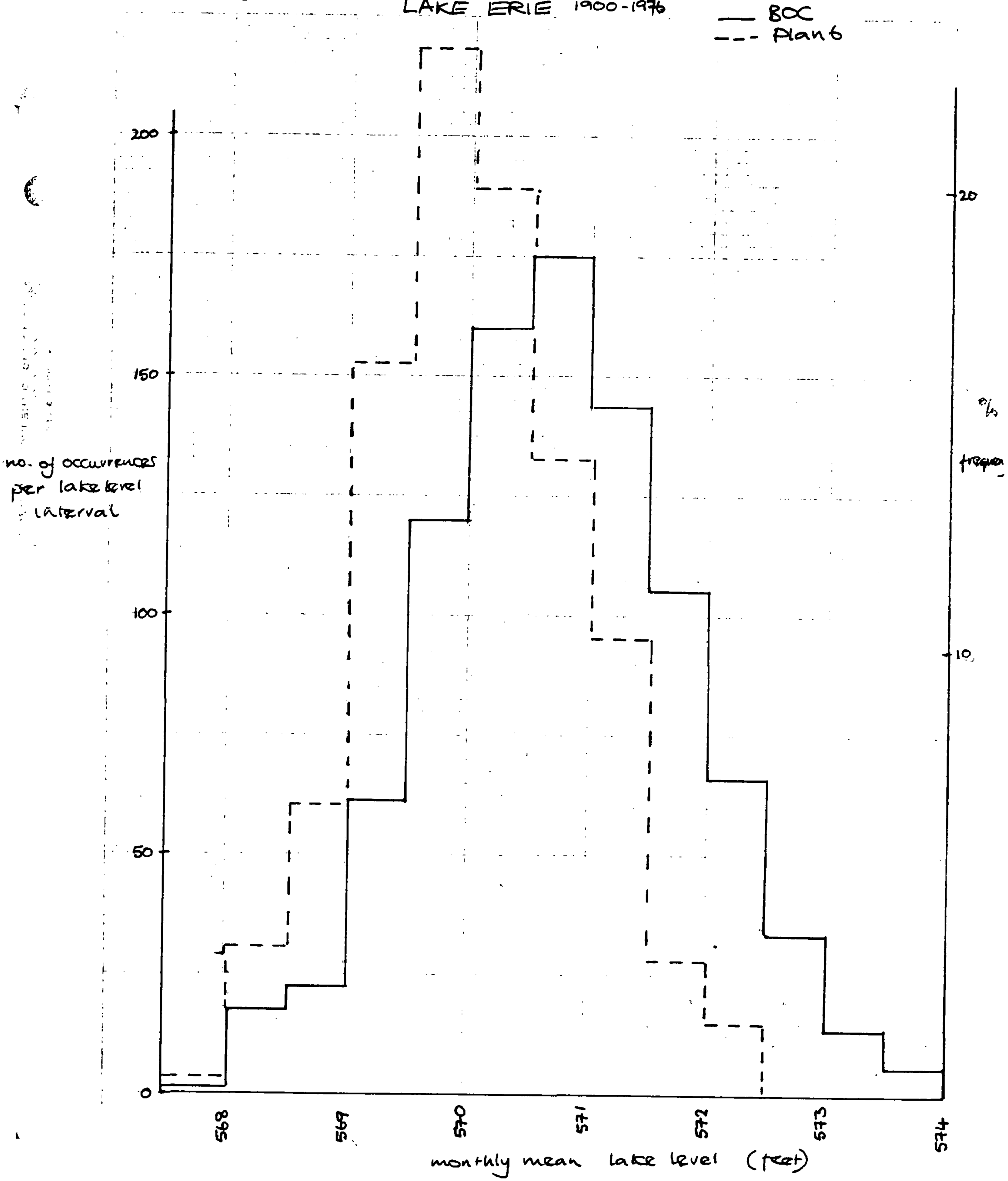
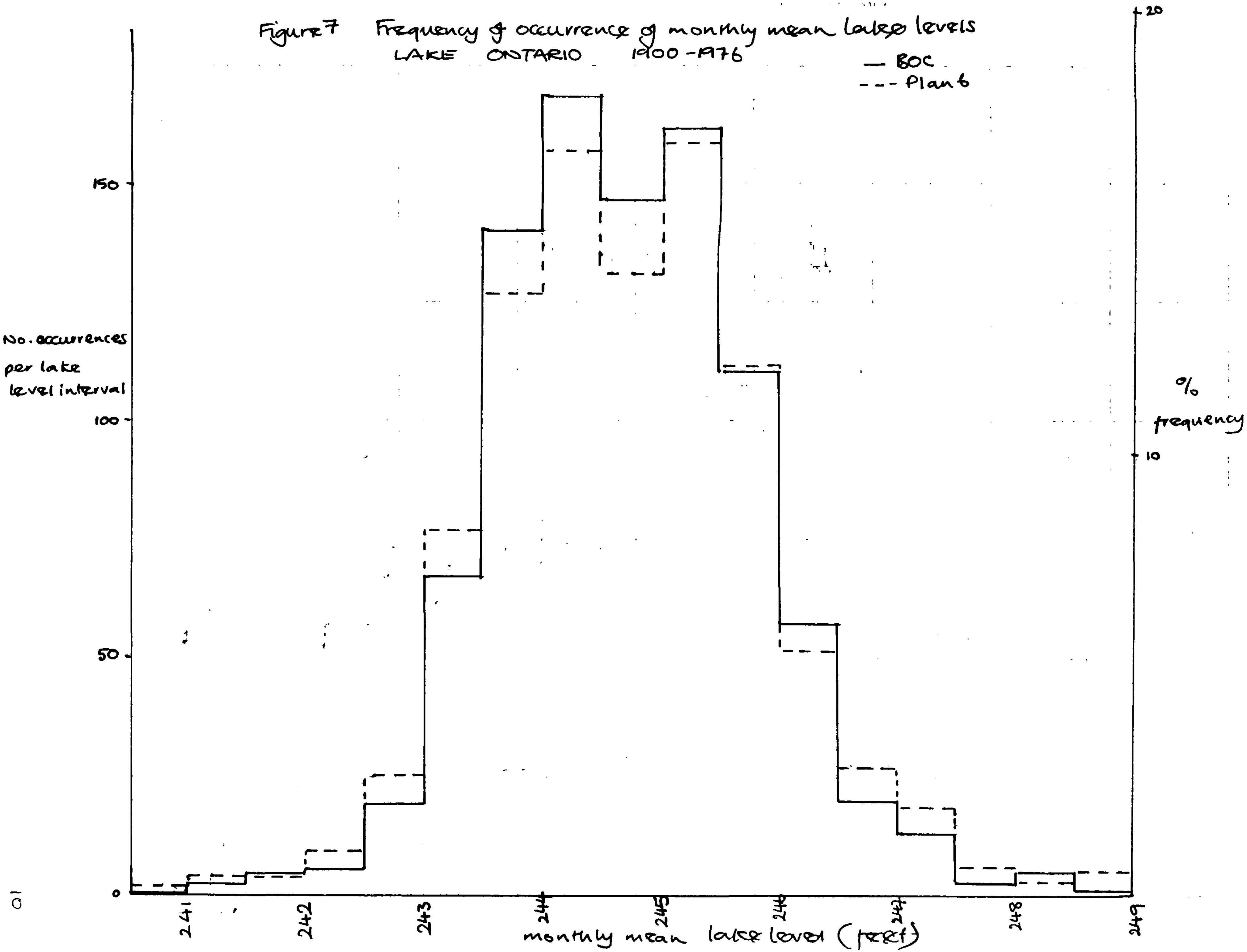


Figure 7 Frequency of occurrence of monthly mean lake levels
LAKE ONTARIO 1900-1976



frequently following regulation. Figures 5-7 show that, in percentage terms, changes to the extreme high or low level frequencies are small, though changes around the mean levels are more significant.

4. THE EFFECT OF LAKE LEVEL REGULATION ON PHOSPHORUS CONCENTRATIONS

4.1 Introduction

Regulation of the level of Lake Erie might have an effect on the concentrations of phosphorus in Lakes St. Clair, Erie, and Ontario. As phosphorus is one of the limiting nutrients in these lakes, changes in its concentration would result in other trophic changes, and thus this problem is one that must be addressed.

The concentration of any substance dissolved in lake water depends on certain simple factors; the supply of that substance to the lake, the volume and turnover time of the lake, and the proportion of that substance which is removed from solution within the lake. The supply includes all sources of the material in question; precipitation, leaching from rocks and soils in the watershed, human, agricultural and industrial waste, inflow from upstream lakes and erosion from the shoreline of the lake. The volume and turnover time of the lake determine the amount of water available in a unit of time in which the supply of that substance may dissolve or be diluted. The proportion of the substance removed within a lake depends on the characteristics of both the substance and the lake: certain dissolved species may be a~~b~~dsorbed onto settled or suspended sediment and trapped at the bottom of the lake, others may be nutrients which are incorporated into biomass and removed from the lake (e.g., by fishing) or sedimented as detritus, others may undergo chemical change into unsoluble forms which fall to the sediment. A conservative substance is one which is not subject to physical, biological, or chemical change, and its concentration is a function only of the supply and water flow.

Phosphorus is supplied to lakes from natural and anthropogenic sources. The natural sources include precipitation, runoff, leaching and erosion, while direct anthropogenic sources are sewage, industrial effluent, urban drainage, and indirect sources are agricultural effluents and increased runoff and increased erosion. Phosphorus is not a conservative element. In the forms in which it is present in natural water, it binds readily with clays and organic particles, and some is removed from solution by this means. Phosphorus is also an important plant nutrient and is used by phytoplankton in lakes. A proportion of the phosphorus bound in biological material reaches the sediments in organic detritus and debris and is thus removed from solution, though much is returned to solution after decomposition of the organic material.

When considering the effects of lake level regualtion on a lake's phosphorus concentration, it is apparent that three factors must be considered; supply, water budget, and retention of phosphorus in the lake.

PLUARG (PLUARG, 1978) data for phosphorus loading to Lakes Erie and Ontario are reproduced (Table 1). From this, it can be seen that those loadings which might be altered by the regulation of Lake Erie are the shoreline erosion loading to each of the lakes and on the upstream loading to Lake Ontario. As regulation of Lake Erie is designed to alleviate high levels, occurrences of maximum changes due to regualtion will coincide, to some extent, with higher than average precipitation. It will be instructive to consider which loadings are affected by changes in precipitation and calculate the effect of heavy precipitation and increased water budget on the phosphorus budgets, with and without the added effects of regulation. Loading data for Lake St. Clair, gathered from various sources, are shown in Table 2. The contribution of direct urban loading is an estimate derived by comparison with the Lake Erie data in Table 1. It should be noted that the PLUARG data in Table 1 treats as Lake Erie both Lake Erie and Lake St. Clair.

Regulation of Lake Erie entails the release of greater volumes of water from Lake Erie at certain strategic times. This regulation, and the resultant changes in lake level, will alter the volume and flow through time of the lakes but not the overall waterflow through the system.

Phosphorus retention in a lake can be measured as a difference between input and output of that element. Theoretical prediction of retention has not been attained, though various empirical relationships between retention and water budgets have been proposed. If small changes in phosphorus budgets are being considered, it can be assumed that the proportion of phosphorus retained will not change markedly, but this would not be true if major changes to the water and phosphorus loadings were being postulated.

	metric tons/yr							
	LAKE ONTARIO				LAKE ERIE			
SOURCE	CANADA	U.S.	TOTAL	[PERCENT]	CANADA	U.S.	TOTAL	[PERCENT]
Direct Municipal Sewage Treatment Plants[b]	1,079	968	2,047	[17]	70	5,588	5,658	[32]
Tributary Municipal Sewage Treatment[c] Plants	155	613	768	[7]	185	985	1,170	[7]
Direct Industrial[d]	47	33	80	[<1]	164	111	275	[2]
Tributary Industrial[d]	4	18	22	[<1]	0	72	72	[<1]
Urban Nonpoint Direct[e]	324	•	324	[3]	44	•	44	[<1]
Tributary Diffuse[f] (Tributary Total)	1,088 (1,247)	2,169 (2,800)	3,257 (4,047)	[28]	1,726 (1,911)	6,675 (7,732)	8,401 (9,643)	[48]
Sub-Total	2,697	3,801	6,498	[55]	2,189	13,431	15,620	[89]
Atmospheric[g]	—	—	488	[4]	—	—	774	[4]
Load From Upstream Lake	—	—	4,769	[41]	—	—	1,080	[6]
Total			11,755	[100]			17,474	[100]
Shoreline Erosion[i] (Not Included in Total)	777	538	1,315		5,912	1,024	6,936	

TABLE 1: Summary of 1976 Total Phosphorus Loads to the Great Lakes

TABLE 2

Phosphorus Loading to Lake St. Clair
(metric tons/year)

	(total)	(per cent)
* Direct (STPs, industrial, urban runoff)	1,000	21
# Tributary	1,070	22
⌿ Atmospheric	35	1
+ Upstream	2,450	51
TOTALS	4,555	100

* Data unavailable; this value is an estimate based on a comparison of the shorelines of Lakes Erie and St. Clair.

\# U.S. and Canadian tributary loadings, summed.
Data obtained from 1) Sonzogni et al., 1978, and
2) Ongley, 1978.

⌿ Based on an areal pro-rated comparison of Lakes Ontario and Erie data in Table 1.

\+ Data from 1) Ontario MOE, 1972, and
2) Leach, 1972.

Changes in water budgets are considered in detail in Appendix A. The average volume of Lakes Erie and St. Clair would be decreased by regulation, in Lake Erie by less than 1%, and in Lake St. Clair by about 6%, resulting in shorter water residence times in those lakes. Total water budgets cannot be altered however.

4.2 Changes in Phosphorus Loading

4.2.1 Shoreline Erosion

Table 1 indicates that shoreline erosion contributes a considerable load of phosphorus to Lakes Erie and Ontario. Few data are available for Lake St. Clair. Boulden (1975) includes information about the southern shore of that lake which indicates that the overall loss to the lake from the Canadian shore may be small. In this smaller lake of short fetch, erosion would be likely to be less of a problem.

Thomas and Haras (1978) discuss the contribution of erosion to the phosphorus budgets of the lakes and conclude that, although the phosphorus entering Lake Erie from shoreline erosion is a large fraction of the total phosphorus supply, very little will be biologically available. While it is assumed that all other phosphorus entering a lake is potentially available for algal uptake, apatite phosphorus is unsoluble, and in a form in which it cannot be used for algal growth if other phosphorus is present. They cite the work of Williams et al (1976) on the non-availability of apatite phosphorus; most of the erosional phosphorus being in the form of apatite (see Table 3).

TABLE 3

Apatite phosphorus (as a percentage of total phosphorus) in Canadian shoreline bluffs (from Thomas and Haras, 1978)

Lake Erie :	Whole Lake	86
	Western Basin	81
	Central Basin	86
	Eastern Basin	83
Lake Ontario:	Whole Lake	80

Dr. Williams (personal communication) has indicated that further, as yet unpublished, work verifies his earlier data on the non-availability of apatite phosphorus. This recent work indicates that, for bluffs material entering Lakes Erie and Ontario, about 75% of the non-apatite inorganic phosphorus (NAIP) is available and utilized by algae, but that very little of the apatite phosphorus is taken up. NAIP, as quantified by Williams, can be related to the extractable P fractions reported by other workers (NaOH extractable P, Armstrong and Lee; resin extractable P, Schroeder, NTA extractable P, Golterman), all of which give a good indication of the cell growth associated with that material. As the non-apatite fraction of total phosphorus includes non-apatite inorganic phosphorus, organic phosphorus and phosphorus bound with minerals, it is apparent that of the total erosional P entering the lakes, less than 10% would be utilized in Lake Erie, and less than 15% in Lake Ontario.

Thomas and Haras (1978) compared the contribution of total and available phosphorus from erosion, using both long-term (20-year) and short-term (1-year) data, to the total loading of phosphorus to the lakes. Table 4 shows the contribution to the phosphorus budgets of eroded material as included in Table 1. Their data were based on the assumption that all non-apatite phosphorus in eroded material would be available. This has since been discounted by the work of Williams and Armstrong (personal communication).

which indicates only 3-5% total eroded phosphorus is available.

The effect of lake level regulation would be to reduce the frequency of occurrence of high lake levels in Lakes Erie and St. Clair, though in Lake Ontario higher levels would occur a little more often (see earlier section). The relationship between lake level and shoreline erosion is not absolutely defined but, in general, along reaches where bluffs are normally protected from wave attack by a beach, temporarily high lake levels will surmount this protection, allowing attack and erosion to occur. Of particular importance is the coincidence of high water levels with onshore storms, when most shoreline damage will occur or be instigated. Seibel et al. (1976) present a review of work correlating lake level with erosion and conclude that the incidence and duration of high water level are important and that there may be a critical low water level below which beach-protected bluffs suffer no damage. It would appear that Lake Erie regulation would have the effect of reducting erosion in Lake Erie and Lake St. Clair, both by reducing the frequency of high water levels and by increasing the frequency of lower water levels. Mr. D. Brown (personal communication) has estimated that regulation might reduce shoreline damage in Lake Erie by about one half. For the purposes of this assessment, it will be assumed that mean annual erosion after regulation would be 50% of the 1970 values in Lake Erie, and 110% of 1976 values in Lake Ontario. Thus, from the data in Table 4, the change in the available phosphorus loadings would be as shown in Table 5. It can be seen that these changes are very small percentages of the total phosphorus budgets.

TABLE 4

Eroded shoreline phosphorus loading.
(metric tons/year)

	Lake Erie	Lake Ontario
Total P	6,936	1,315
Available P = 5% total P	347	66

* data from Thomas and Haras (1978)

TABLE 5

Contribution of available phosphorus from shoreline erosion: probable effect of lake level regulation.

	Loading of Available Phosphorus (mt)	
	Without Regulation	With Regulation≠
Lake Erie	347.0	174.0
Erosional P as % of total available loading	2.0	1.0
Lake Ontario	66.0	73.0
Erosional P as % of total available loading	0.5	0.6

≠ Assuming regulation decreases erosion by 50% in Lake Erie and increases erosion of 10% in Lake Ontario, and assuming all non-erosional phosphorus loading is available for biological uptake.

4.2.2 Upstream Loading

The upstream loading is an important fraction of the loading to Lake Ontario, but a much smaller proportion of the loading to Lake Erie (Table 1). In Lake St. Clair, the principal loadings are through the inflowing rivers. Mean total phosphorus concentrations in the St. Clair and Thames Rivers (the latter is the major tributary source to the lake; see Table 6) are similar (about 0.014 mgP/l, Ontario MOE, 1972, 1975), and as the St. Clair River accounts for most of the water budget, it is obviously a major factor in the phosphorus budget also. Upstream loading to Lakes St. Clair and Erie will not be affected by regulation of Lake Erie, but the loading to Lake Ontario may undergo some changes, as a result of changes in the phosphorus budget of Lake Erie. When considering the effects of these changes, it must be borne in mind that the proposed regulation of Lake Erie will result in a change in the seasonal pattern of outflow of water from Lake Erie, which, though not changing the mean annual phosphorus budget, might significantly affect the trophic state of the lake. Thus, when other changes to the phosphorus budgets of the lakes have been evaluated, the change in the upstream loading to Lake Ontario must be considered. As the supply to Lake Ontario from Lake Erie and the Niagara River constitutes such a large proportion of that lake's total phosphorus budget, this factor may be significant.

TABLE 6

Tributary loadings to Lake St. Clair, metric tons P/yr

* U.S. :	Clinton River	260	
	Swan Creek	60	320
† Canada:	Little River	73	
	Pike Creek	6	
	Puce Creek	10	
	Belle River	16	
	Ruscom River	10	
	Thames River	492	
	Sydenham River	143	750
TOTAL			1,070

* from Sonzogni et al., 1978.
† from Ongley, 1978.

4.2.3 Changes in the Phosphorus Budgets Resulting from Water Budget Fluctuations.

Regulation of Lake Erie is intended to prevent the occurrence of exceptionally high water levels. The proposed regulation plan allows for the release of extra flow through the Niagara River when periods of high precipitation have brought about high water loading in the Upper Lakes which will eventually result in high inflows and levels in Lake Erie. Thus, assuming annual fluctuations in precipitation are felt over the whole Great Lakes basin, regulation will coincide with and follow high precipitation.

In order to assess the effects of regulation it is necessary also to assess the effects of high precipitation. If the background against which changes resulting from regulation occur itself undergoes changes, predicted changes would not be observed. This section deals with the ranges of these "background" changes associated with high precipitation.

Phosphorus loadings which are directly related to precipitation are those listed in Table 1 as "tributary diffuse", urban non-point source ("Tributary diffuse" loadings include land runoff and any other loadings to tributary streams which are not identified as point sources. Urban non-point source loadings include urban runoff through storm sewers.), atmospheric and, to some extent, upstream. Bennett (MS) shows that, for a conservative substance, high water flow will result in dilution, as loading will be fairly constant but flow through will increase. Phosphorus loading can be affected as precipitation chemistry and stream chemistry change with variations in volume of precipitation.

Pearson and Fisher (1971) suggest that the constituents of precipitation can be considered as those which are particulates washed out of the atmosphere, froming a constant annual loading, and those which result from the solution of an aerosol, whose loading increases with increasing precipitation. The former group includes the ions Na^+, CL^-, Mg^{2+}, K^+, Ca^{2+}, $HCO3^-$, NH_4^+, NO_3^-, as well as total nitrogen and, probably, phosphorus. Hydrogen (H^+) and sulphate (SO_4^{2-}) result mainly from the atmospheric oxidation of sulphur compounds, and loadings of these increase as precipitation increases. It would seem probable that phosphorus loading is independent of quantity of precipitation, but the data presented by Pearson and Fisher, though indicative of this, are too sparse to provide verification. For this assessment of the problem, however, the assumption will be made that phosphorus loading from the atmosphere is independent of temporal fluctuations in the quantity of precipitation.

Data in the Lake Erie Wastewater Management Study Preliminary Feasibility Report (USACE, 1975, Vol. III) for the Maumee River in Ohio show a positive correlation between total phosphorus concentration and flow (see attached figure 1). This is verification of what might be expected; increased precipitation would cause not merely increased runoff but higher runoff volumes which would have a comparatively greater scouring and carrying capacity. Such a relationship is a function of the size, topography, land use and soil type of the watershed, and thus cannot be extrapolated to fit the general case. For most watersheds, however, it can be said that phosphorus concentration is a function of discharge, and tributary diffuse phosphorus loadings will increase as the water loading increases. Urban storm drainage would similarly tend to carry a higher phosphorus load during periods of heavy runoff.

With an increased water loading, the volume entering from upstream will increase, but the concentration of phosphorus in this water will depend on the balance of precipitation and stream loading to that lake.

4.3 Phosphorus Retention

When calculating phosphorus concentrations in lakes, it is necessary to know what proportion of the incoming phosphorus remains in solution and what proportion settles out of the system. Various empirical relationships have been proposed, but do not apply too well to the Great Lakes. These are discussed in Appendix B. For this exercise, known inflow and outflow values will be used to obtain an estimate of the proportion of phosphorus retained, and the assumption is made that the changes in loading envisaged will be sufficiently small that this proportionate retention will remain unaltered.

The retention coefficients calculated from inflow and outflow data are shown in Table 7 - these coefficients indicate the proportion (or multiplied by 100, the percentage) of phosphorus that is removed from solution within the lake.

MAUMEE RIVER AT WATERVILLE, OHIO

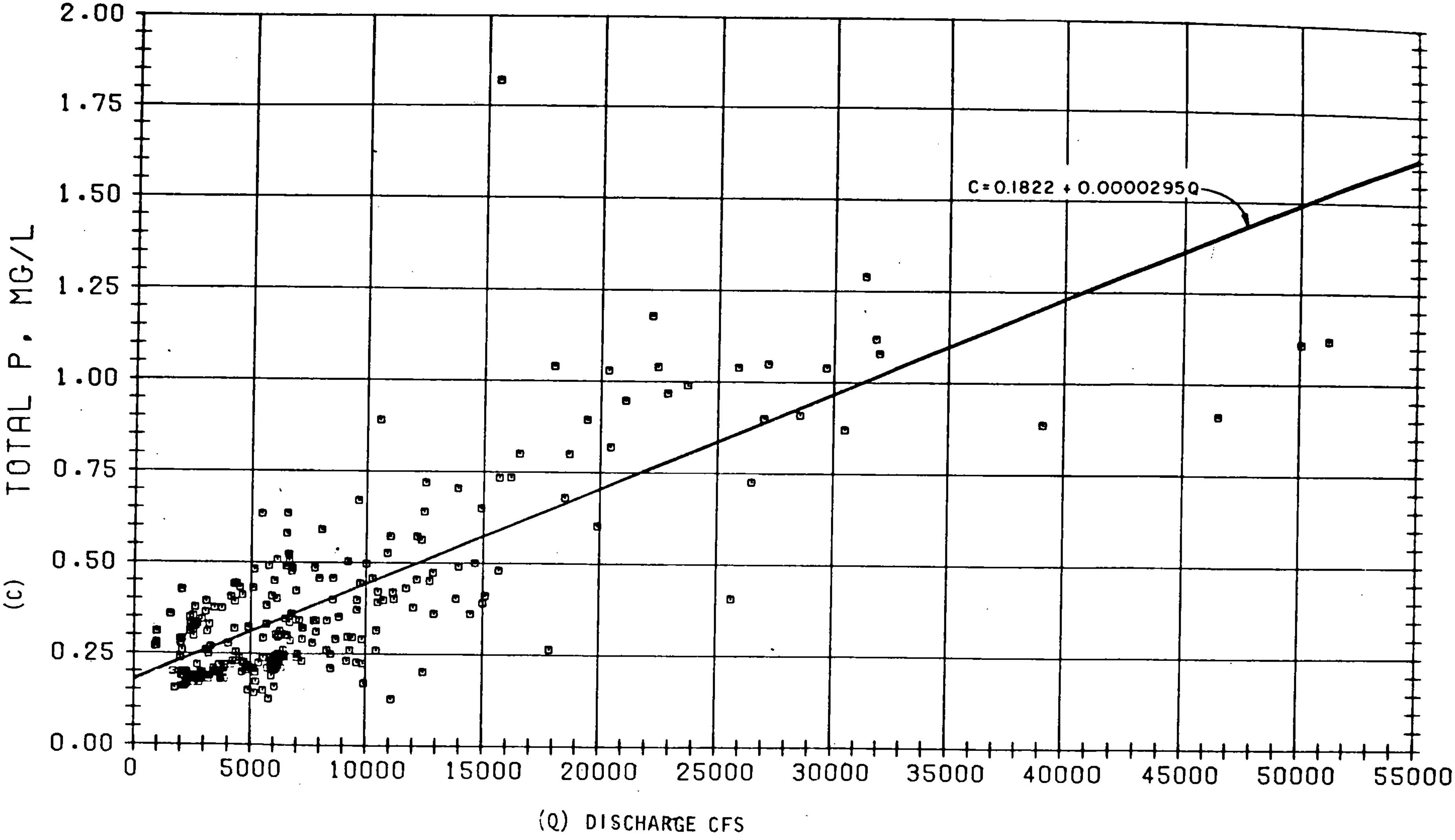


TABLE 7

Phosphorus Retention Coefficients
(See Appendix B for Calculations)

Lake St. Clair	.35
Lake Erie	.79
Lake Ontario	.60

In Lake St. Clair, a smaller proportion of the total available phosphorus seems to be retained in the lake than in the other lower lakes. The work of Thomas (1974) indicates that the sediment is washed out of Lake St. Clair into Lake Erie, and this may be reflected in the higher concentrations of total phosphorus recorded in the outflow (Ontario MOE, 1972 a) than in the open lake (Leach, 1972).

4.4 Calculation of the Effects of Lake Erie Regulation on the Phosphorus Budgets of Lakes St. Clair, Erie, and Ontario.

4.4.1 Introduction

The concentration of phosphorus in a lake is a function of the amount of phosphorus supplied to that lake. This can be expressed as:

$$(P) = f\ (J)$$

where: (P) = concentration of phosphorus; and
(J) = phosphorus loading.

As the supply of phosphorus to the lake increases, the concentration of phosphorus in the lake will also increase if the loading of phosphorus is not parallelled by an increase in water flow. Whether or not the two increases will be proportional depends on the physical relationship embodied in equation (1).

A considerable body of work about phosphorus concentrations in lakes has been built up in which a lake is assumed to be a completely mixed body of water. The relationship between the annual supply of phosphorus to the lake and the concentration of phosphorus in the lake is then a fairly simple one, which includes a measure of the volume and rate of flow through of water and a "retention" factor, which accounts for the proportion of phosphorus which enters the lake but is removed from solution. In this model, the conditions at the outflow are the same as elsewhere in the lake, and so the "retained" phosphorus is the difference between the inflow and outflow quantities.

The frequently used form of this relationship is that proposed by Vollenweider (1968) and modified by Dillion (see e.g., Dillon and Rigler, 1975):

$$(P) = \frac{J\ (1-R)}{V \times \rho} \qquad (2)$$

where: R = the retention coefficient*;

v = the lake volume; and

ρ = the flushing rate.

As ρ = Q/v, where Q = outflow rate, equation (2) can be rewritten as:

$$(P) = \frac{J\ (1-R)}{Q} \qquad (3)$$

Certain assumptions are inherent in this model which, differing from reality, must be examined carefully. The model assumes the lake to be completely mixed, so that the effect of any input of soluble material will be felt equally at all points in the lake. In fact, in the Great Lakes, thermal stratification occurs during summer, preventing complete vertical mixing, while the lakes' size also hinders mixing. The model also assumes that seasonal changes in water or nutrient loading will not be large enough to affect the model - that the average (P) calculated from the model will be closely similar to the (P) found in the lake. Dillon's model is claimed to predict (P) in spring, at which time algal growth (which is probably limited by (P) available) is likely to be most rapid. Spring is the season of maximum water inflow and, in many lakes, maximum phosphorus loading. The spring phosphorus concentration may not equal the annual mean phosphorus concentration, which is predicted by this method. When considering the Great Lakes, the model can best be used as as indicator of possible overall, long-term changes which might occur as a result of definite perturbations in the system. Because of the lakes' size and, for Erie and Ontario, comparatively long water residence time (Table 8), mean spring values of (P) before thermal stratification is set up can be fairly accurately predicted by the model. Lake St. Clair is a much smaller lake, too shallow to stratify, wind disturbed though not completely mixed, with a very short water residence time (Table 8). Here too, the model can be used to predict long-term averages, although, for

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* A retention coefficient of 1 would indicate that all phosphorus entering the lake remained in that lake basin and none was lost through an outfall. A retention coefficient of 0, which is found for unreactive, conservative substances, occurs when the outflowing quantity equals the inflowing quantity. A negative retention coefficient is possible if the lake basin contributes to the budget.

all the lakes, spatial and temporal variations may be considerable.

TABLE 8

Water Residence Times (years)
(for details of calculations, see Appendix A)

	BOC	Plan 6
Lake St. Clair	0.21	0.20
Lake Erie	2.70	2.68
Lake Ontario	7.85	7.85

4.4.2 An Estimate of the Influence of regulation on the Retention of Phosphorus within the Lakes.

The proportion of inflowing phosphorus retained in a lake system can be measured in two ways; either as the difference between loading and outflow, or as the amount being sedimented. The latter method is subject to problems, and few reliable data of this sort are available; certainly insufficient to allow change to be related to water level. For the lower Great Lakes, complete data on loadings, water flow, lake level and phosphorus concentrations are not available for enough years for the relationship of retention with lake level to be determined.

In order to determine the probable changes in retention which might result from regulation, the empirical relationship shown below can be employed (see Appendix B, Table B1).

$$R = 0.482 - 0.112 \ln \rho$$

where:
R = retention coefficient
ρ = flushing rate = $\frac{Q}{V}$ (yr.$^{-1}$)
Q = outflow rate Km^3/yr.
V = volume km^3

Thus:
$$R = 0.482 - 0.112 \ln (\frac{Q}{V})$$
$$R = 0.482 - 0.112 \ln Q + 0.112 \ln V$$

It is assumed that for the mean case, Q is constant, then:

$$R = K + 0.112 \ln V.$$

If lake volume undergoes or change from V_1 (BOC) to V_2 (Plan 6) then the ~~remittant~~ resultant change in R will be (ΔR)

$$\Delta R = 0.112 \text{ in } V_1 - 0.112 \ln V_2$$
$$\Delta R = 0.112 \text{ in } \frac{V_1}{V_2}$$

Using the data on lake volumes (Table A4, Appendix A), the values for ΔR shown below are obtained. These are shown as a percentage of the values of R (Table ( ): see Table 9.

TABLE 9

Changes in the Retention Coefficients Resulting from Regulation

	ΔR	R	% Change
Lake St. Clair	0.0068	0.35	2.0
Lake Erie	0.0009	0.79	0.1

Thus, it seems likely that the changes in phosphorus retention will be very small, and for the most part, insignificant.

4.4.3 Changes in Mid-Lake Phosphorus Concentrations which might Result from Lake Erie Regulation.

These calculations will be based on equation (3):

$$(P) = \frac{J\ (1-R)}{Q}$$

It has been shown, however, that R will change very little as a result of regulation, and Q remains unchanged. Equation (3) can then be rewritten as:

$$(P) = K\ J$$

where: K is a constant, $= \frac{(1-R)}{Q}$

This relationship will first be tested with existing data (no regulation) to check the closeness of the predicted (P) with the measured values. Necessary data are reiterated in Table 10.

TABLE 10

Data Necessary for Phosphorus Budget Calculations

	Lake St. Clair	Lake Erie	Lake Ontario
J total loading of available P, excluding erosional P (mgP/yr) (see Table 1)	$4{,}555\times10^9$	$17{,}474\times10^9$	$11{,}755\times10^9$
R retention coefficient (see Table 7)	0.35	0.79	0.60
(1-R)	0.65	0.21	0.40
Q outflow rate (m^3/yr.) (see Appendix A)	164×10^9	181×10^9	213×10^9
$K = \frac{(1-R)}{Q}$	106.6×10^9	38.0×10^9	85.2×10^9
(P) calculated from eq. (3) mg/m^3	18	20	22
(P) measured mg/m^3	4+	20#	22≠

+ from Leach, 1972

\# from Burns, 1976 a)

≠ from Allen, 1977

The predicted concentrations of phosphorus are equal to those measured in the outflows (Ontario, MOE, 1972 a) and b)) because these were used to calculate values for R (see Appendix B). The discrepancy between outflow and open lake concentrations in Lake St. Clair has been discussed in a previous section.

When the effects of shoreline erosion are considered, the value of J will change. The data in Table 10 do not take into account the available fraction of the erosional phosphorus. Table 11 shows the loadings, including this fraction. It can be seen that J changes by only one percent as a result of regulation, and thus a similar small change must result for the concentration of phosphorus. Table 12 shows the predicted concentrations following Lake Erie regulation (based on the PLUARG data, Table 1).

TABLE 11

Loadings of Phosphorus to Lakes Erie and Ontario, taking into account the biologically available phosphorus in eroded shoreline material (mgP/yr).

	Lake Erie	Lake Ontario
a) J (Table 9)	$17,474 \times 10^9$	$11,755 \times 10^9$
b) Eroded Material: Total P	$6,936 \times 10^9$	$1,315 \times 10^9$
c) Available P in eroded material = 5% total P in eroded material	347×10^9	66×10^9
d) Total available P = (a+c)	$17,821 \times 10^9$	$11,821 \times 10^9$
e) Eroded material after regulation, total P (50% of b in Lake Erie) (110% of b in Lake Ontario)	$3,468 \times 10^9$	$1,447 \times 10^9$
f) Available P in eroded material after regulation = 5% total P in eroded material	174×10^9	72×10^9
g) Total available P after regulation = (a+f)	$17,648 \times 10^9$	$11,827 \times 10^9$
a) as % of d)	98	99
g) as % of d)	99	100

TABLE 12

Predicted concentrations of phosphorus (mg/m^3) when the available fraction of phosphorus in eroded material is considered.

	BOC	PLAN 6
Lake Erie	21	20
Lake Ontario	22	22

Tables 11 and 12 indicate that the effect of erosion on the phosphorus budgets of Lakes Erie and Ontario is small, when the work of Williams on the non-availability of apatite is considered. Though some uncertainty remains about the change in erosion resulting from regulation, this does not appear to be important when considering whole lake phosphorus budgets.

4.4.4 The Influence of Regulation on Mid-Lake Phosphorus Concentrations during a Period of High Precipitation.

This will be approached by considering the effects of precipitation which is 10% higher than the average. For this simple calculation, it will be assumed that there is no time lag - no finite flow-through time, and so the effects of precipitation upstream will coincide with the effects on the downstream lakes. A change in volume of precipitation will affect, particularly, the tributary loadings. Figure 1 shows an example of total phosphorus concentration in tributary streams increasing with increased flow. From this, it is apparent that the stream loading (concentration x flow) will increase with increasing flow proportionally more than does flow. Tables 1 and 2 are partially reproduced in Table 13 and possible changes in loading resulting from an increase in precipitation of 10% are included (The data in Tables 1 and 2 are 1975 and 1976 data - years of high precipitation. These will suffice, however, for the exercise in hand.). The assumption has been made that tributary runoff loadings would remain unchanged and that the load into Lake St. Clair from the upstream lake (Lake Huron) would also remain unchanged. This last assumption is based on loading data for Lake Huron, taken from the same source as Table 1, which indicates that about 50% of the loading is "tributary diffuse". If this 50% increases by 115%, while the other loadings remain constant, and the water loading increase by 10%, the overall change in phosphorus concentration would be a small decrease:

$$\left(\frac{50 \times 1.15 + 50 \times 1.0}{110} = 98 \right)$$

TABLE 13

Phosphorus loading to Lakes St. Clair, Erie and Ontario (a), and changes which might result from a Season of Precipitation 10% above normal (b) (metric tons P/yr.)

		DIRECT	TRIBUTARY (+15 %)	ATMOSPHERE	UPSTREAM	TOTAL
Lake St. Clair	a)	1000	1070	35	2450	4555
	b)	1000	1230	35	2450	4715
Lake Erie	a)	7219	8401	774	1080	17474
	b)	7219	9661	774	1118	18772
Lake Ontario	a)	3241	3257	488	4769	11755
	b)	3241	3746	488	5123	12598

The upstream loadings to lakes Erie and Ontario are calculated as:

$$\text{Upstream loading (b)} = \text{Upstream loading (a)} \times f$$

$$\text{Where } f = \frac{\text{total loading to upstream lake (b)}}{\text{total loading to upstream lake (a)}}$$

The mid-lake concentration changes can be ascertained by comparing the ratios of total loading (a) /100 and total loading (b) / 110. These changes are shown in Table 14.

TABLE 14

Predicted changes to Mid-Lake Phosphorus Concentrations resulting from 10% heavier Precipitation

	Predicted (a) *†	Predicted (b)†	% Change
Lake St. Clair	18	17	-6%
Lake Erie	20	20	-2%
Lake Ontario	22	22	-3%

* from Table 9

† mgP/m^3

When these changes are considered with the changes predicted in Section 4.4.3, it can be seen that the effects of both high precipitation and regulation would seem to be too small to be measurable, and both would tend to improve open lake water quality very slightly.

4.4.5 The Effect of Regulation on the Mid-Basin Phosphorus Concentrations in each Basin in Lake Erie.

Burns (1976,b) includes data for the water and phosphorus loadings to the different basins of Lake Erie, which are summarized in Table 15. Burns, following Williams et al (1976) work, does not consider the contribution of bluffs material to be significant in terms of available phosphorus.

TABLE 15

	J Metric tons P/yr.*		Q km^3/yr.†	R
Detroit River	18,075		183	
West Basin	5,723	23,798	189	0.77^x
Central Basin	5,769		193	0.65^x
East Basin	2,494		196	0.35^x

* From Table 4, Burns 1976 b)

† From Table 1, Burns 1976 b)

x From Table 7, Burns 1976 b)

Most of the erosion along the Lake Erie Canadian shore occurs in the Central Basin. The contribution of this to the phosphorus budget of that basin and the east basin can be calculated, and then the effects of regulation can be gauged.

Using Equation (3), $[P] = \frac{J\ (1-R)}{Q}$

The mean phosphorus concentrations can be calculated, using the data in Table 15.

TABLE 16

Phosphorus Loading and Calculated Concentrations in Lake Erie

	WEST (1-R) = .23	CENTRAL (1-R) = .35	EAST (1-R) = .65
(a) Phosphorus Loading as shown in Table 14.			
1) Loading mg P/yr	23,798	11,243	6,429
2) (P) mg P/m^3	29	20	21
3) mean (p) mg P/m^3 April, 1970 - April, 1971. †	44	20	18
(b) a) + available P from shoreline erosion * (Table 10)			
1) Loading mg P/yr	23,798	11,590	6,550
2) (P) mg P/m^3	29	21	22
(c) a) + available P from shoreline erosion after regulation			
1) loading mg P/yr	23,798	11,417	6,490
2) (P) mg P/m^3	29	21	22

* Using data from Table 11, assuming entire load of available P from erosion enters the Central Basin.

† From Burns, 1976 b), Table 8.

These data show that even on an individual basin basis, the contribution of eroded bluff material to the available phosphorus budget is slight, and the effect of regulation in reducing shoreline erosion would be difficult to measure.

4.4.6 The Effect of Regulation on Nearshore Phosphorus Concentrations.

While it has been shown that the contribution of eroded shoreline material to the phosphorus budgets of open water is small, and thus regulation of Lake Erie will have a barely noticeable effect on this aspect of the lake systems, the nearshore zone should also be considered.

The nearshore zone may be defined in various ways, and encompassing various portions of the nearshore water. The 10 m contour has been chosen for the purpose of this exercise, as enclosing that region of highest concentration gradients, and being intermediate in the range sometimes considered. (See Appendix C). The volume of this zone has been calculated (see Appendix C) in both Lakes Erie and Lake Ontario, these values are reproduced in Table 17.

TABLE 17

Morphometric Data of Nearshore Zones
of Lakes Erie and Ontario
(see Appendix C)

	Lake Erie	Lake Ontario
Volume Km^3	24.8	4.5
Area Km^2	4,080	980
Mean Depth m	6.1	4.6

Any attempt to consider nearshore conditions is complicated by the lack of present knowledge about these important zones, when the simple equation describing the relationship between phosphorus loading and concentration and water budget in a mixed container is considered:

$$(P) = \frac{J\ (1-R)}{Q}$$

It can be seen that two of the valuables are not readily estimated in the nearshore zone (R,Q).

The problems associated with the determination of R for whole lakes have been discussed (Appendix B). In the nearshore zone these are magnified; inflow and outflow are less well defined than for an entire lake, and difficult to measure, and measurements of the settling of particulate phosphorus are comfounded by resuspension. For the purpose of this exercise it will be assumed that, in the nearshore zone, R = 0, that is, that no retention of phosphorus occurs within that zone. While it is possible that more retention occurs in deep basins, where particulate phosphorus can settle without resuspension, phosphorus in the nearshore zone may be removed from solution by absorption onto the heavy particulate load in that zone, and the larger particles, particularly some of those resulting from erosion, may settle and remain in that zone. The assumption of zero R results in extreme estimates of phosphorus concentration, which would be unlikely to be attained in fact.

Q the outflow rate (or the flushing rate, $= \frac{Q}{V}$ where V = volume) is particularly difficult to quantify. Water flow through the nearshore zone may be of three kinds: flow off land to the open lake (tributary and runoff water loading), along-shore exchange and exchange with the open lake. The exchange between different regions of the nearshore zone need not be considered when the general case of the mean nearshore zone is approached. Exchange across the artificial boundary between the nearshore zone and the open lake is probably the most important factor affecting water turnover time, and the least easy to quantify. If the water flow is taken as only that from land to lake (total water loading less upstream flow and precipitation), the residence times in the nearshore zones are shorter than those for water in the whole lakes. (Tables 18,19).

Phosphorus in the lakes can then be considered as a balance of the upstream and atmospheric contribution to the open lake, the tributary loading to the nearshore zone, the mixing between these zones and the additional loading from erosion to the nearshore zone. This simple model can apply only to large lakes in which a significant proportion of the water and phosphorus loadings are from one major upstream lake. Smaller or headwater lakes could not be considered in these terms. Comprehension and relevant data about the interactions of offshore and nearshore water are very limited.

TABLE 18

Water Budgets for Lakes Erie and Ontario, Showing Quantity of Water Entering Lakes Per Length of Shoreline. (Km^3/yr.)*

	Lake Erie	Lake Ontario
Total Inflow	196.5	219.2
Upstream Flow	183.3	181.3
Tributary Flow = Q nearshore	13.2	27.9

* See Appendix A

TABLE 19

Water Residence Times (yr.)

	Lake Erie	Lake Ontario
Whole Lake	2.70	7.85
10 m Nearshore Zone, Tributary Flow	1.88	0.16

In this general approach an approximate measure of dilution of nearshore water by open lake water will be estimated by comparison with measured concentrations. The effects of changes to shoreline erosion, brought about by regulation, on water quality, can then perhaps be assessed. The computations are shown in Table 20.

The source concentrations predicted for nearshore Lake Erie are improbably high. Those for Lake Ontario, while far higher than, are likely to be found along most shorelines, as approximate conditions near the major sewage treatment plant outfalls. Figure 2 shows a plot of distance offshore against phosphorus concentration, using data for April, 1976 (IJC 1978). The high nearshore concentrations implied by this plot are found only in the vicinity of STP outfalls and other point sources of phosphorus, and this shows the shortcomings of this line of inquiry.

Following this line of reasoning, it would seem that the impact of regulation on the erosional component of nearshore phosphorus concentration would be impeneptible - a change of about 1%, but such a conclusion must be considered in the light of the difference between predicted and ambient concentrations.

One of the major flaws in the approach just described is the assumption that tributary loading of water and phosphorus has a direct effect on the overall nearshore zone. Most tributary and point source loadings will affect a small section of the nearshore zone only, contributing more to the overall water quality of the lake. It seems more reasonable to consider the nearshore zone as being affected only by direct runoff and by erosion of the shoreline.

When this latter approach is taken, the problem arises as to how the residence time of water in the nearshore zone can then be defined. In the absence of data, the assumption will be made that the residence time of water is uniform throughout the lake. Flow through the nearshore zone can then be calculated:

For the whole lake flushing rate $= \frac{Q}{V}$

Figure 2 Dilution of phosphorus in the vicinity of Humber Bay STP

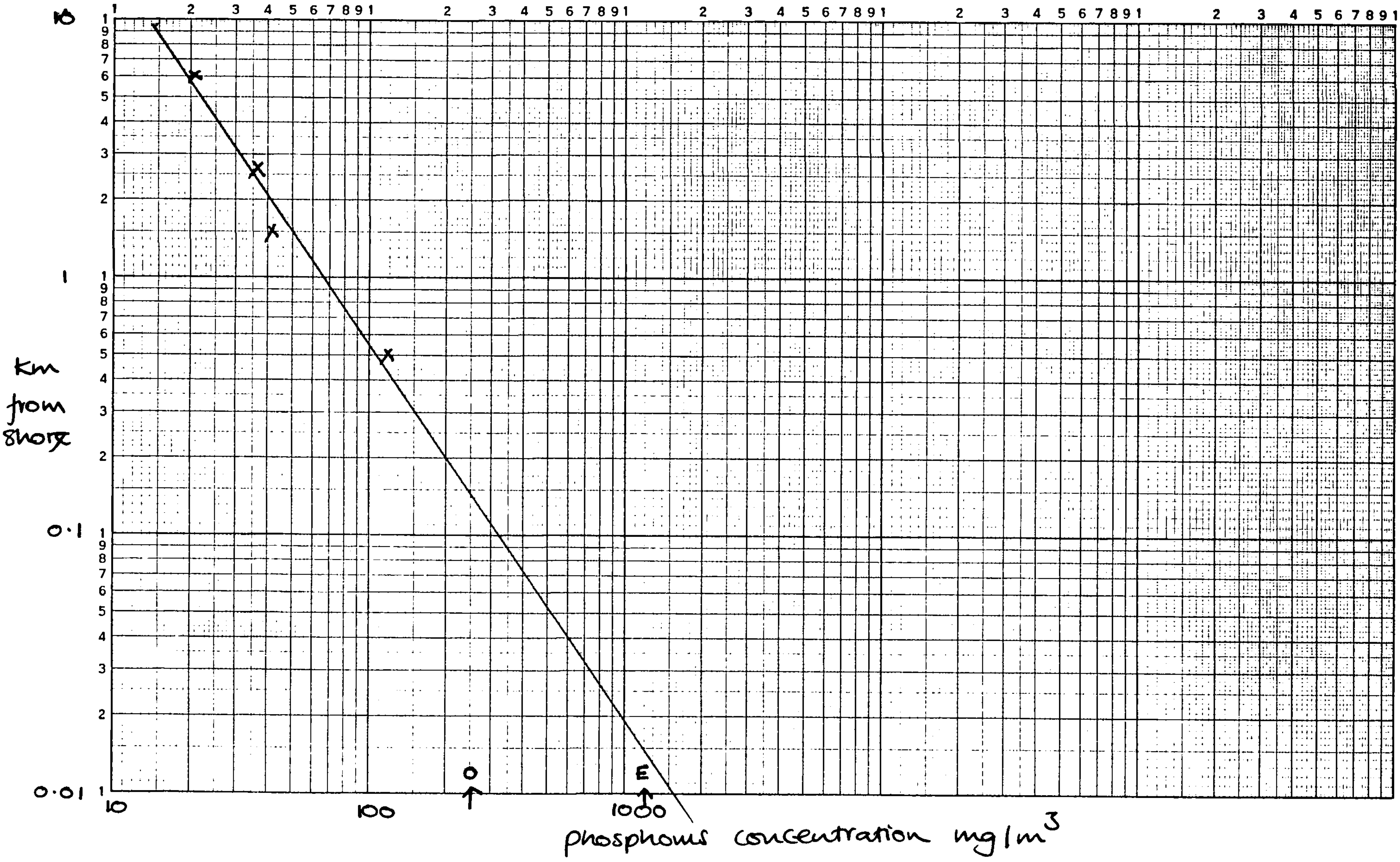


TABLE 20

A Consideration of Phosphorus Zonation

	Lake Erie	Lake Ontario
Entire Lake		
R	0.79	0.60
Q km^3/yr	181	213
Nearshore		
$Q_N km^3/yr$	13.2	27.9
Loading $J 10^3 kgP/yr$		
a) Upstream & atmospheric = J_A	1,854	5,257
b) Tributary = J_B	15,620	6,498
c) Erosion, = J_C no regulation	347	66
d) Erosion, = J_D after regulation	174	72
(P) mgP/m^3		
Open Lake		
a) $(P) = \frac{J_A(1-R)}{Q}$	2.3	10.9
Entering Nearshore		
b) $(P) = \frac{J_B}{Q_N}$	1,183	233
c) $(P) = \frac{J_B + J_C}{Q_N}$	1,210	235
d) $(P) = \frac{J_B + J_D}{Q_N}$	1,197	236

Assume P is constant for the nearshore zone

$$Q = p \times V \text{ nearshore}$$

The necessary data are shown in Table 21. From these, predictions of the contribution of eroded material to the nearshore phosphorus concentrations have been made: Table 22. These calculations have been based on the equation:

$$(P) = \frac{J\ (1-R)}{Q}$$

Assuming R for the nearshore zone is either zero or same as for the whole lake. When considering only phosphorus from eroded material, a nearshore retention coefficient of zero, as employed in the previous approach would not seem valid, eroded bluff material comprising coarse particles which settle rapidly, without reaching equilibrium with the water. Table 22 contains predictions of phosphorus concentrations made using both lakewide and zero values of R. The predicted concentrations are considerably higher than mean nearshore concentrations. This may be in part, the result of an inappropriate choice of size of nearshore zone or of water residence time in that zone. It is possible that the residence time of the coarser eroded particles is insufficient for even that portion of the phosphorus considered "available" to enter the water. The percentage changes resulting from regulation would thus be less than those shown in Table 22, but these calculations do indicate that there would be a measurable, beneficial effect in Lake Erie, and a smaller but undesirable effect in Lake Erie, and a smaller but undesirable effect in Lake Ontario.

These two approaches to the problem of the effects of regulation on nearshore phosphorus concentrations have not led to a definite conclusion. The layer appears to be a more convincing approximation of reality. The next section will examine recorded changes in nearshore and open water during a period of changing levels, in an attempt to discern trends applicable to this study.

TABLE 21

Data Necessary for the Calculation of Inshore Phosphorus Concentration

	Lake Erie	Lake Ontario
† Lake Volume V km^3	489	1671
* Outflow Rate Q km^3/yr	181	213
Flushing Rate p yr-1	0.37	0.13
Nearshore Volume V nearshore km^3	24.8	4.5
Q Nearshore km^3/yr	9.18	0.57
Phosphorus Retention Coefficient R	0.79	0.60
* J Total Loading of Available P Excluding Erosional P (kg P/yr)	$17,474 \times 10^3$	$11,755 \times 10^3$
* Available P in Eroded Material kg P/yr	347×10^3	66×10^3
† Available P in Eroded Material after Regulation kg P/yr	174×10^3	72×10^3

* See Table 10

† See Table A4

[illegible]

TABLE 22

Calculated Phosphorus Concentration mg P/m^3

	Lake Erie		Lake Ontario	
Mid-lake concentration predicted from total non-erosional loadings.	20		22	
	R = 0	R = .79	R = 0	R = .60
Additional nearshore concentration predicted from contribution of available P from erosion.	38	8	115	46
Additional nearshore concentration predicted from contribution of available P from reduced erosion (after regulation).	14	4	126	50
Total nearshore concentration				
1) before regulation	58	28	137	68
2) after regulation	34	24	148	72
% Change in phosphorus concentration following regulation.	-24	-14	+8	+6

4.5 Observed Changes in Phosphorus Concentrations During Period of Naturally Changing Lake Levels.

The work of Gregor and Ongley (1978) provides a valuable analysis of Ontario MOE nearshore data for the years 1967-1973, during which Lake Erie underent considerable natural fluctuations. (Fig. 3). The report on the Great Lakes Water Quality, 1977 (IJC 1978) furnishes information on observed changes in both nearshore and mid-lake waters. Nicholls et al (1977) described trends in nearshore water constituents which were later re-interpreted (Nicholls, 1979, personal communication).

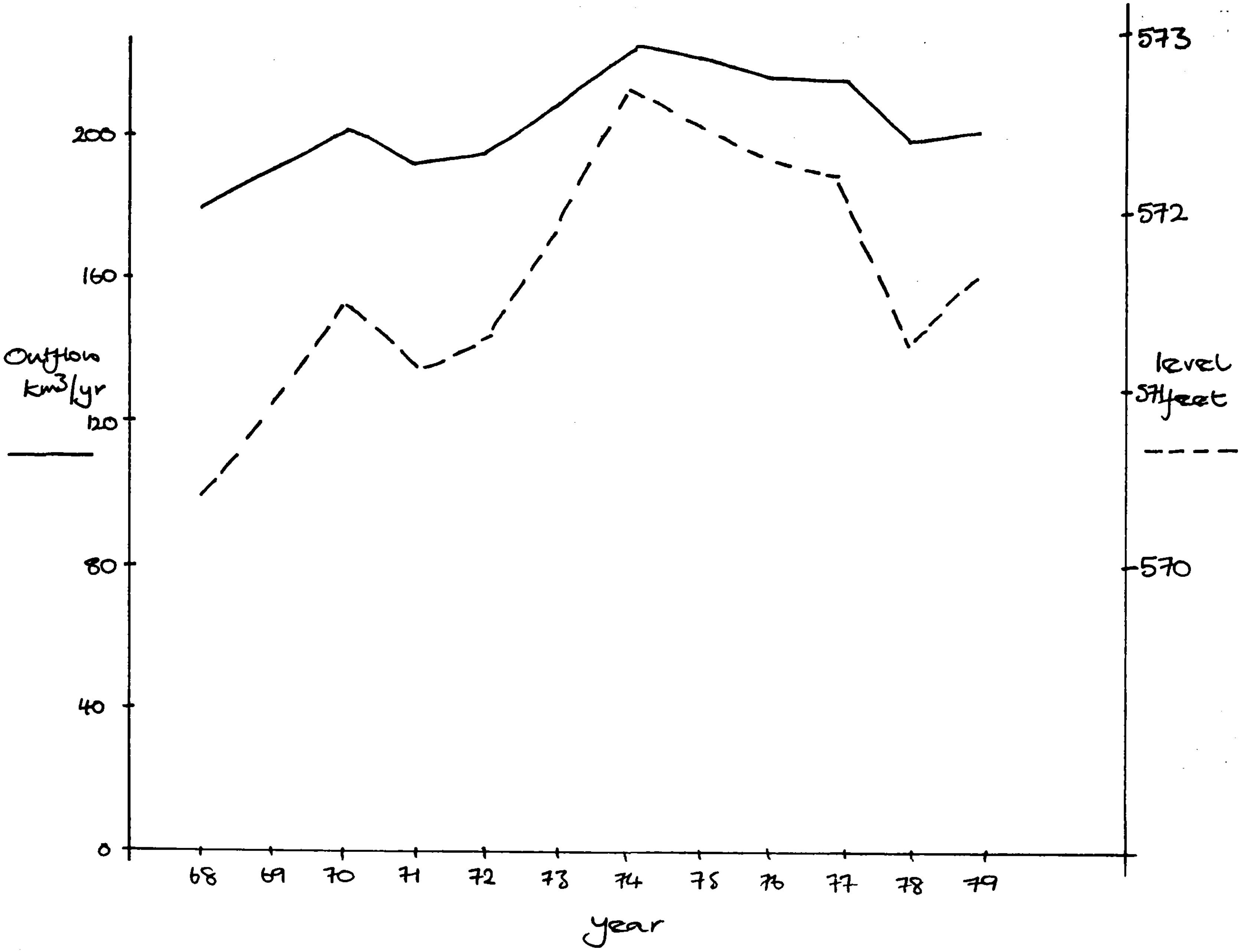
For the years 1967-1973 during which time water levels in both Lakes Erie and Ontario rose (Fig. 3), Gregor and Ongley (1978) found that total phosphorus concentrations decreased in the nearshore zone of both Lake Erie and Ontario. During this same period phosphorus loading diminished following the reduction of the phosphate content of detergents, and improved water treatment and this was considered to be the cause of the observed decline in nearshore phosphorus concentrations. (See eg. Nicholls et al 1977).

In most of the nearshore areas of Lake Ontario, and in the nearshore water, is the western basin of Lake Erie. This decline continued through 1977 (IJC 1978). In Lake Erie this could be attributed in part to a continuing improvement in the water quality of the Detroit River.

Mid-lake phosphorus concentrations in Lake Ontario showed no significant changes during the years 1970-1977, though a significant decline was observed in lake-wide means during this time. In Lake Erie the mean concentrations in the central basin continued to fall until 1974, and then rose markedly during the following three years (IJC 1978). These data appeared to show some relationship with lake level.

At this point, an important difference must be noted between changes in lake level due to natural fluctuations in the hydrological cycle and changes in lake level due to regulation. The former reflect variations in the water budget: a high level is associated with a high outflow rate. The latter do not involve a change in outflow: regulation does not affect the supply of water to the lake. In order to assess changes in phosphorus resulting from lake level as such, it is therefore necessary to determine what changes might be expected to result from the comcomitant change in flow. When the standard

Figure 3 Lake Erie mean annual level and outflow 1967 - 1978



relationship:

$$(P) = \frac{J\,(1-R)}{Q}$$

is considered, the importance of Outflow Q is immediately apparent. Table 23 shows that the outflow rate has changed considerably during the latter years. Using the empirical relationship of flow with phosphorus retention.

$$R = 0.86 - 0.143 \ln qs$$

(see Appendix B)

where: $qs = \frac{Q}{A}$

Values for A, qs and R can then be obtained for different values of lake level outflow: see Table 24.

TABLE 23

Mean Recorded Outflows and
Lake Levels in Lake Erie
1967-1978.

Year	Lake Level m	Outflow km^3/yr.	Outflow as % of mean outflow
1967	570.4	180	99
1968	570.9	191	106
1969	571.5	202	112
1970	571.1	193	107
1971	571.3	196	108
1972	571.9	210	116
1973	572.7	227	125
1974	572.5	224	125
1975	572.3	219	121
1976	572.2	218	120
1977	571.2	199	110
1978	571.6	202	112
Mean, 1900-1977.			

TABLE 24

Calculated Values of A (area, km^2), as (water load, m/year) and R Pretention Coefficient) for Lake Erie, 1967-1978, Based on the Measured Lake Levels and Outflows.

Year	A $\times 10^3$	$qs=\frac{Q}{A}$	R=0.86-0.143 ln qs
Mean 1900-1977	25.32	7.148	
1967	25.32	7.109	0.58
1968	25.34	7.537	0.57
1969	25.39	7.957	0.56
1970	25.37	7.609	0.57
1971	25.37	7.727	0.57
1972	25.41	8.265	0.56
1973	25.48	8.910	0.55
1974	25.48	8.793	0.55
1975	25.45	8.604	0.55
1976	25.45	8.564	0.57
1977	25.39	7.839	0.56
1978	25.39	7.957	0.58

* See Appendix C

If loading of phosphorus to the lake is considered constant, the predicted phosphorus concentration

$$(P) = \frac{J\ (1-R)}{Q}$$

then becomes a function of water flow and the dependent valuables described above. Table 25 shows how the factor $\frac{(1-R)}{Q}$ varied for the period considered (R calculated from qs, not R measured), and indicates the range from the expected mean (assuming J constant).

TABLE 25

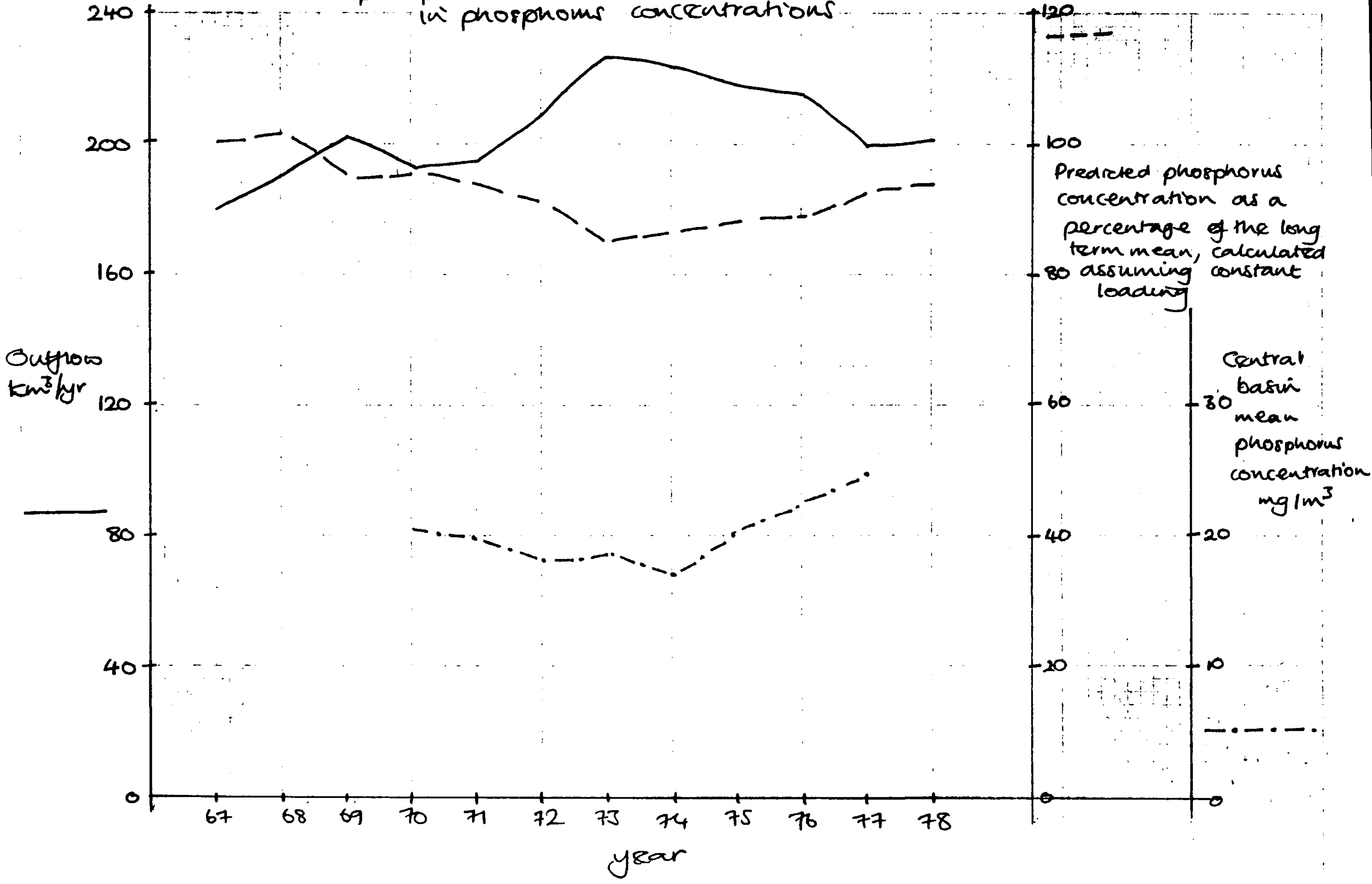
The Predicted Range of Mean Phosphorus Concentrations, Assuming a Constant Loading J.

Year	$\frac{(1-R)}{Q} \times 10^{-3}$	$(P)=J\frac{(1-R)}{Q}$ as a Percentage of Predicted Mean
Mean 1900-1977	2.32	100
1967	2.33	100
1968	2.35	101
1969	2.18	94
1970	2.23	96
1971	2.19	94
1972	2.10	91
1973	1.98	85
1974	2.01	85
1975	2.05	88
1976	2.06	89
1977	2.16	93
1978	2.18	94

This is illustrated in Fig. 4, which shows that the predicted trends in phosphorus concentration do minor the changes in recorded outflow, and are not dissimilar to the changes observed in mean annual phosphorus concentrations in Lake Erie central basin.

Thus it seems that mid-lake phosphorus concentrations in Lake Erie are strongly influenced by changes in flow, which can account for a good part of the fluctuations observed. In the western basin of Lake Erie the decreasing phosphorus loading of the Detroit River appears to be the major influence. In this basin, bluff erosion is not an important factor, though

Figure 4 Lake Erie recorded outflow, recorded phosphorus concentrations and predicted changes in phosphorus concentrations



resuspension of sediments must be considered in the detailed phosphorus budget there. Nicholls (1979, personal communication) found that the analyses of water from union water intake in the western basin showed that though clear trends in phosphorus concentrations could not be discerned, in the years since 1975 the diatom population has increased. Nicholls speculates that this is related to falling lake level and probably to the changes in resuspension rather than to changes in phosphorus loading.

In Lake Ontario, the statistically significant decreases in nearshore phosphorus concentrations were observed along the populous north west shoreline (IJC 1978). That same report shows high concentrations of phosphorus emanating from major sewage treatment plants rather than for the bluff shoreline east of Toronto. The lack of influence of bluffs material is also indicated by apparent lack of any relationship of nearshore phosphorus concentrations with lake level.

Thus reported data seem to confirm the findings of this chapter that changes in open lake phosphorus concentrations resulting from lake level changes will be small, and indicate that even in nearshore zones, changes may not be significant.

4.6 Conclusions

This chapter has set out to qualify possible changes which might occur in phosphorus concentrations as a result of lake level regulation. It appears that regulation of Lake Erie would have a very small effect on open lake phosphorus concentrations. The diminution of erosion of shoreline bluff material which is expected to be a result of regulation might be reflected in lowered phosphorus concentrations in certain nearshore areas, but analysis of water quality data suggests there would not be a marked change. As changes predicted for Lake Erie seem small, it is unlikely that the change in upstream loading to Lake Ontario will be significant.

Thus it seems likely that regulation will not have a significant effect on phosphorus concentrations in the lower Great Lakes.

APPENDIX A

Changes in Water Budgets

APPENDIX A

Changes in Water Budgets

Summary water budgets for the Lakes are reproduced from Leach (1972), Burns (1976,b) and Allen (1977) in Table A1.

TABLE A1

Water Budgets for Lakes St. Clair, Erie and Ontario

a) Lake St. Clair †

Volume		$3.4\ km^3$
Inflow:	St. Clair River	$5300\ m^3/sec$
	Thames River	$<200\ m^3/sec$ *
Outflow:	Detroit River	$5400\ m^3/sec$

* From Hamdy et al, (1977)
† From Leach, (1972)

b) Lake Erie †

Detroit River Input	183.267
Western Basin Rivers	5.683
Central Basin Rivers	4.228
Eastern Basin Rivers	3.297
Total Input	196.475
Net Storage	3.06
Estimated Output	193.39
Measured Output	187.88
Difference	5.51
Net Evaporation Due to Difference ($cm\ yr^{-1}$)	21.9

† From Burns (1976,b), Table 3)

c) Lake Ontario[+]

Water Source	m^3/sec	INPUT	(cfs)
Niagara River Basin (US and CAN)	5,750		(203,000)
Oswego River (US)	176		(6,200)
Trent River (CAN)	118		(4,200)
Black River (US)	108		(3,800)
Genesee River (US)	77		(2,700)
Other tributaries, waste discharges	208		(7,300)
Atmospheric Precipitation	516		(18,200)
Total, all sources	6,950		(245,400)
Water Sink		OUTPUT	
St. Lawrence River	6,420		(226,600)
Evaporation*	530		(18,800)

+ From Allen (1977)

When these data are used in conjunction with the data on mean levels (Table A2), some estimate can be made of the changes in water budgets which would result from regulation and which might affect phosphorus budgets.

TABLE A2

Mean Lake Levels (feet) to be Expected
With No Regulation (B.O.C.) or Maximum
Regulation (Plan 6).

	BOC	Plan 6
Lake St. Clair	573.59	573.09
Lake Erie	570.76	570.05
Lake Ontario	244.72	244.72

The data in Table A1 are valuable for the information they give about major sources and outflows, but for the purposes of calculation, the data in Table A2, based on mean records of the years 1900-1977 (Environment Canada) are better suited.

TABLE A3

Mean Recorded Outflows of Lakes
St. Clair, Erie and Ontario.

(More recent estimates than those in Table A1)

	TCFS	$Km^3/yr.$
Lake St. Clair	184 ✓	164
Lake Erie	203 ✓	181
Lake Ontario	238 ✓	213

Flows must, on average, remain the same (regulation will alter the seasonal pattern of flow from Lake Erie, but cannot change the mean water flow through the Great Lakes system) and so the turnover times of water in the lakes will change. These can be deduced from the changes in volume resulting from the lake level changes. (Tables A4, A5).

TABLE A4

Volumes of Lakes (km^3) St. Clair, Erie
and Ontario be Expected with no Regulation
(BOC) or Maximum Regulation (Plan 6)

	BOC	PLAN 6
Lake St. Clair	3.4	3.2
Lake Erie	489	485
*Lake Ontario with deviation	1671	1671

TABLE A5

Flow Through Times (Years) for Lakes St. Clair,
Erie and Ontario to be Expected with no Regulation
(BOC) or Maximum Regulation (BOC) or Maximum
Regulation (Plan 6)

	BOC	PLAN 6
Lake St. Clair	0.0207	0.0195
Lake Erie	2.70	2.68
*Lake Ontario with deviation	7.85	7.85

* With deviation - this means that the plan of regulation of Lake Ontario at Cornwall may not be adhered to at times of extreme variation in lake level.

Thus regulation of Lake Erie would have the effect of decreasing the residence time of water in Lakes St. Clair and Erie.

APPENDIX B

Phosphorus Retention

APPENDIX B

Phosphorus Retention

When phosphorus, or any material which undergoes some reaction within a lake, moves through a lake system, the quantities entering and leaving the system may not be equal. Most frequently, a proportion of the material remains in the system, so that less leaves than enters, and measurable retention has occurred. Negative retention may be found if the lake acts as a source rather than as a sink, but this is a less common occurrence.

Phosphorus retention in lakes comes about because phosphorus is assimilated into biomass, some of which falls to the lake sediment removing phosphorus from the cycle, some of which may be removed entirely from the lake (eg. by fishing). Phosphorus in soluble form is also readily removed from water by physical adsorption onto sedimenting particulate material. Though phosphorus may be returned to the water during the settling and sedimentation process, part may become buried in the sediments, and unavailable for further utilization.

When attempting to produce simple models of phosphorus cycles in lakes, a value for the retained proportion must be available. Phosphorus retention can be measured directly as the difference between loading and outflow. When seeking to apply modelling techniques on a wide scale, it is often desirable to make predictive models without field data, gathering these later to provide verification. Loading of phosphorus and the water budget for a lake can be predicted from a consideration of the topography and land use of the lake's watershed. Consequently attempts have been made to find relationships between measured water budgets and phosphorus retention values which could be used as predictive tools, enabling lakes' phosphorus budgets to be assessed without expensive field surveys.

Larsen and Mercier (1976) presented six empirical expressions: (See Table B1).

TABLE B1

Expressions for the Derivation of R, the
Phosphorus Retention Coefficient (from
Larsen and Mercier, 1976).

1. $R = \frac{\nu}{\nu + qs}$

   based on [Chapra (1975) and Dillon and Kirchner (1975), where ν = apparent settling velocity (m/yr) and qs = area water loading (m/yr)]. Chapra's value for ν of 16m/yr was used with success by Scavia and Chapra (1977) when comparing models for Lake Ontario, but Larsen and Mercier used a value of 11.73.

2. $R = 0.86 - 0.143 \ln qs$.

3. $R = 0.482 - 0.112 \ln p$, where p = flushing rate

4. $R = \frac{1}{1 + \alpha \rho^{\beta}}$

   where $\alpha = 1.3$ and $\beta = 0.4$.

5. $R = \frac{1}{1 + \rho^{1/2}}$

6. $R = 0.426 \exp(-0.271\ qs) + 0.574 \exp(-0.00949\ qs)$ (Kirchner and Dillon, 1975).

For Lakes Erie and Ontario, values for R have been calculated using these expressions, and compared with the measured values. The data necessary for the computations are shown in Table B2 and the calculated R's in Table B3.

TABLE B2

Hydrologic, Morphometric and Phosphorus Loading Data for Lakes Erie and Ontario

		Erie	Ontario
[1]Area	A km^2	25,666	19,594
[1]Mean Depth	$\bar{z}$ m	17	86
[1]Volume	V km^3	458	1,636
[1]Outflow Rate	Q km^3/yr	175	209
Flushing Rate	$\rho = \frac{Q}{V}$ yr^{-1}	0.382	0.128
Water Load	$q_s = \frac{Q}{A}$ m/yr	6.8	10.7
[x]Phosphorus Load	J Kg P/yr	$17{,}474 \times 10^3$	$11{,}755 \times 10^3$
[ƒ]Mean Outflow Phosphorus Level	$[P]$outflow mg/m^3	25	22

1. Derived from Chandler, 1964.

x. From PLUARG 1978: Total Loading of Phosphorus excluding the contribution of shoreline erosion.

ƒ. Ontario MOE 1972 a,b.

TABLE B3

Phosphorus Retention Coefficient

	Erie	Ontario
A. Derived from measured loading and outflow	0.750	0.609
B. Derived from relationships shown in Table 1.		
1a. $R = \nu/\nu+q_s$, $= 16$	0.702	0.600
1b. $R = \nu/\nu+qs$, $= 11.73$	0.633	0.524
2. $R = 0.86 - 0.143 \ln q_s$	0.586	0.522
3. $R = 0.482 - 0.112 \ln \rho$	0.590	0.712
4. $R = 1/1+1.3\rho^{0.4}$	0.531	0.636
5. $R = 1/1+\rho^{1/2}$	0.618	0.737
6. $R = 0.426 \exp(-0.271qs) + 0.574 \exp(-0.00949qs)$	0.623	0.542
MEAN	0.881	0.610

It can be seen from Table B3 that the various empirical relationships give rise to many different estimates of retention of phosphorus, particularly for Lake Erie. This arises because these functions were developed from data for rather different lakes. The model assumes complete mixing and takes no account of seasonal or local effects. In calculations of phosphorus concentration, using the Dillon and Rigler (1975) equation (derived from Vollenweider's work, 1968):

$$(P) = \frac{J\ (1-R)}{Q}$$

The values for R derived from measured loading and outflow will be used. Though this results in a tautology, for the exercise in hand these values are more reliable than those predicted in Table B3.

The data necessary for calculating R by difference are shown in Table B4.

Table B4

	Lake St. Clair	Lake Erie	Lake Ontario
Loading J mgP/yr x 10^{-9}	4,555(1)	17,474(2)	11,755 (2)
Outflow Q Km^3/yr	164(3)	181 (3)	213 (3)
Measured Outflow Concentration MgP/	18(4)	20(5)	22 (5)

(1) Chapter 4 Table 2
(2) Chapter 4 Table 1
(3) Appendix A Table A2
(4) Ontario MOE 1972 a)
(5) Ontario MOE 1972 b)

These data lead to the retention coefficients shown in Table B5.

Table B5

Phosphorus Retention Coefficient Calculated from Measured Loading and Outflow.

Lake St. Clair	0.35
Lake Erie	0.79
Lake Ontario	0.60

APPENDIX C

Changes in Lake Area and Volume Resulting from Lake Erie Regulation.

APPENDIX C

Changes in Lake Area and Volume Resulting from Lake Erie Regulation.

Mr. D. G. Robertson (personal communication) supplied the data in Table C1 from which changes can be estimated. These data are referenced to the IGL data (Lake Erie 173.31 m, Lake Ontario 74.01 m : see Robertson and Jordan, 1977). They were derived from hydrographic charts, 1 m depth being that depth at which some water is shown on the charts. These data are thus less than ideal for use in predicting small actual changes, but can be used to estimate proportional differences which might result from lake level regulation.

When the surface 4 m of each lake are considered, it can be calculated that the changes in areas and volumes with depth are those shown in Table C2.

TABLE C2

Changes in Area and Volume with Depth, in the surface 4 m of Lakes Erie and Ontario.

	Lake Erie	Lake Ontario
Change in area with depth km^2/m	223	141
Change in volume with depth km^3/m	24.8840	18.1747
% change in area per m change in depth	0.88	0.76
% change in total lake volume per m change in depth	5.26	1.09
% change in area per m change in depth if lake a straight sided container	0.00	0.00
% change in total lake volume per m change in depth if lake a straight sided container	5.35	1.11

TABLE C1A(A)

LAKE ERIE

ACCUMULATIVE VOLUMES(CU.M.) FROM THE SURFACE VS DEPTH

Z(M.)	ACC VOL(CU M)	Z(M.)	ACC VOL(CU M)	Z(M.)	ACC VOL(CU M)	Z(M.)	ACC VOL(CU M)	Z(M.)	ACC VOL(CU M)	Z(M.)	ACC VOL(CU M)
1	0.253200E+11	2	0.504000E+11	3	0.753200E+11	4	0.999720E+11	5	0.124360E+12	6	0.148060E+12
7	0.171308E+12	8	0.194040E+12	9	0.215932E+12	10	0.237172E+12	11	0.257396E+12	12	0.276856E+12
13	0.295884E+12	14	0.314080E+12	15	0.331544E+12	16	0.347708E+12	17	0.362880E+12	18	0.377116E+12
19	0.390184E+12	20	0.402416E+12	21	0.412004E+12	22	0.420440E+12	23	0.426140E+12	24	0.430776E+12
25	0.434088E+12	26	0.436904E+12	27	0.439492E+12	28	0.441940E+12	29	0.444288E+12	30	0.446548E+12
31	0.448728E+12	32	0.450804E+12	33	0.452780E+12	34	0.454628E+12	35	0.456360E+12	36	0.457984E+12
37	0.459500E+12	38	0.460892E+12	39	0.462152E+12	40	0.463336E+12	41	0.464472E+12	42	0.465512E+12
43	0.466456E+12	44	0.467296E+12	45	0.468040E+12	46	0.468716E+12	47	0.469308E+12	48	0.469848E+12
49	0.470316E+12	50	0.470732E+12	51	0.471116E+12	52	0.471480E+12	53	0.471800E+12	54	0.472084E+12
55	0.472348E+12	56	0.472556E+12	57	0.472688E+12	58	0.472800E+12	59	0.472888E+12	60	0.472956E+12
61	0.472989E+12	62	0.473004E+12	63	0.473015E+12	64	0.473020E+12				

AKE ERIE

YPSOMETRIC DATA DEPTH(METRES) VS AREA(SQ.KM.)

(M)	A(SQKM)	Z(M)	A(SQKM)	Z(M)	A(SQKM)	Z(M)	A(SQKM)	Z(M)	A(SQKM)	Z(M)	A(SQKM)	Z(M)	A(SQKM)	Z(M)	A(SQKM)	Z(M)	A(SQKM)	Z(M)	A(SQKM)
1	25320.0	2	25080.0	3	24920.0	4	24652.0	5	24388.0	6	23700.0	7	23248.0	8	22732.0	9	21892.0	10	21240.0
11	20224.0	12	19460.0	13	19028.0	14	18196.0	15	17464.0	16	16164.0	17	15172.0	18	14236.0	19	13068.0	20	12232.0
21	9588.0	22	8436.0	23	5700.0	24	4636.0	25	3312.0	26	2816.0	27	2588.0	28	2448.0	29	2348.0	30	2260.0
31	2180.0	32	2076.0	33	1976.0	34	1848.0	35	1732.0	36	1624.0	37	1516.0	38	1392.0	39	1260.0	40	1184.0
41	1136.0	42	1040.0	43	944.0	44	840.0	45	744.0	46	676.0	47	592.0	48	540.0	49	468.0	50	416.0
51	384.0	52	364.0	53	320.0	54	284.0	55	264.0	56	208.0	57	132.0	58	112.0	59	88.0	60	68.0

LAKE ERIE

VOLUME= 0.473020E+12(CUBIC METRES)
MEAN GEOMETRIC DEPTH= 18.68(METRES)
DEPTH OF HALF VOLUME= 9.97(METRES)
CONICAL RATIO= 0.29

HYPSOMETRIC DATA DEPTH(METRES) VS AREA(SQ.KM.)

TABLE C1 (B)

```
Z(M)  A(SQKM)Z(M)   A(SQKM)Z(M)   A(SQKM)Z(M)   A(SQKM)Z(M)   A(SQKM)Z(M)   A(SQKM)Z(M)   A(SQKM)Z(M)   A(SQKM)Z(M)   A(SQKM)Z(M)   A(SQKM)

   1  18484.0   2  18320.0   3  18144.0   4  18060.0   5  17980.0   6  17860.0   7  17800.0   8  17724.0   9  17624.0  10  17504.0
  11  17192.0  12  17066.0  13  16900.0  14  16808.0  15  16712.0  16  16496.0  17  16428.0  18  16352.0  19  16220.0  20  16064.0
  21  15752.0  22  15608.0  23  15440.0  24  15280.0  25  15184.0  26  15040.0  27  14992.0  28  14912.0  29  14824.0  30  14708.0
  31  14500.0  32  14336.0  33  14164.0  34  14060.0  35  13988.0  36  13812.0  37  13756.0  38  13704.0  39  13584.0  40  13496.0
  41  13300.0  42  13200.0  43  13092.0  44  13016.0  45  12952.0  46  12832.0  47  12776.0  48  12654.0  49  12624.0  50  12520.0
  51  12344.0  52  12268.0  53  12188.0  54  12124.0  55  12044.0  56  11944.0  57  11900.0  58  11868.0  59  11804.0  60  11732.0
  61  11568.0  62  11496.0  63  11380.0  64  11280.0  65  11224.0  66  11116.0  67  11052.0  68  10972.0  69  10868.0  70  10735.0
  71  10628.0  72  10528.0  73  10432.0  74  10316.0  75  10224.0  76  10156.0  77  10084.0  78  10012.0  79   9892.0  80   98[illegible]4.0
  81   9664.0  82   9588.0  83   9508.0  84   9440.0  85   9388.0  86   9320.0  87   9254.0  88   9216.0  89   9132.0  90   9040.0
  91   8916.0  92   8812.0  93   8716.0  94   8664.0  95   8596.0  96   8512.0  97   8464.0  98   8400.0  99   8330.0 100   8152.0
 101   8028.0 102   7940.0 103   7864.0 104   7764.0 105   7704.0 106   7620.0 107   7535.0 108   7456.0 109   7316.0 110   7228.0
 111   7140.0 112   7056.0 113   6948.0 114   6860.0 115   6776.0 116   6696.0 117   6624.0 118   6516.0 119   6420.0 120   6300.0
 121   6136.0 122   6100.0 123   6024.0 124   5964.0 125   5892.0 126   5812.0 127   5732.0 128   5672.0 129   5576.0 130   5472.0
 131   5340.0 132   5216.0 133   5120.0 134   5052.0 135   4956.0 136   4860.0 137   4808.0 138   4732.0 139   4640.0 140   4568.0
 141   4452.0 142   4384.0 143   4276.0 144   4216.0 145   4144.0 146   4052.0 147   3984.0 148   3920.0 149   3856.0 150   3800.0
 151   3664.0 152   3560.0 153   3504.0 154   3452.0 155   3384.0 156   3308.0 157   3280.0 158   3216.0 159   3136.0 160   3040.0
 161   2940.0 162   2864.0 163   2756.0 164   2668.0 165   2612.0 166   2552.0 167   2488.0 168   2432.0 169   2304.0 170   2252.0
 171   2104.0 172   1972.0 173   1868.0 174   1752.0 175   1660.0 176   1596.0 177   1524.0 178   1496.0 179   1420.0 180   1336.0
 181   1256.0 182   1168.0 183   1120.0 184   1084.0 185   1036.0 186   1000.0 187    980.0 188    948.0 189    924.0 190    880.0
 191    816.0 192    772.0 193    736.0 194    716.0 195    704.0 196    684.0 197    656.0 198    636.0 199    592.0 200    544.0
 201    484.0 202    444.0 203    416.0 204    380.0 205    348.0 206    340.0 207    336.0 208    320.0 209    300.0 210    272.0
 211    216.0 212    180.0 213    164.0 214    160.0 215    156.0 216    156.0 217    152.0 218    152.0 219    128.0 220    104.0
 221     76.0 222     56.0 223     48.0 224     40.0 225     36.0 226     32.0 227     32.0 228     32.0 229     28.0 230     24.0
 231     20.0 232     16.0 233      8.0 234      8.0 235      4.0 236      4.0 237      4.0
```

```
LAKE ONTARIO

                 VOLUME=    0.167067E+13(CUBIC METRES)
  MEAN GEOMETRIC DEPTH=          90.38(METRES)
  DEPTH OF HALF VOLUME=          55.71(METRES)
         CONICAL RATIO=           0.38
```

TABLE C1 (C)

KE ONTARIO

CUMULATIVE VOLUMES(CU.M.) FROM THE SURFACE VS DEPTH

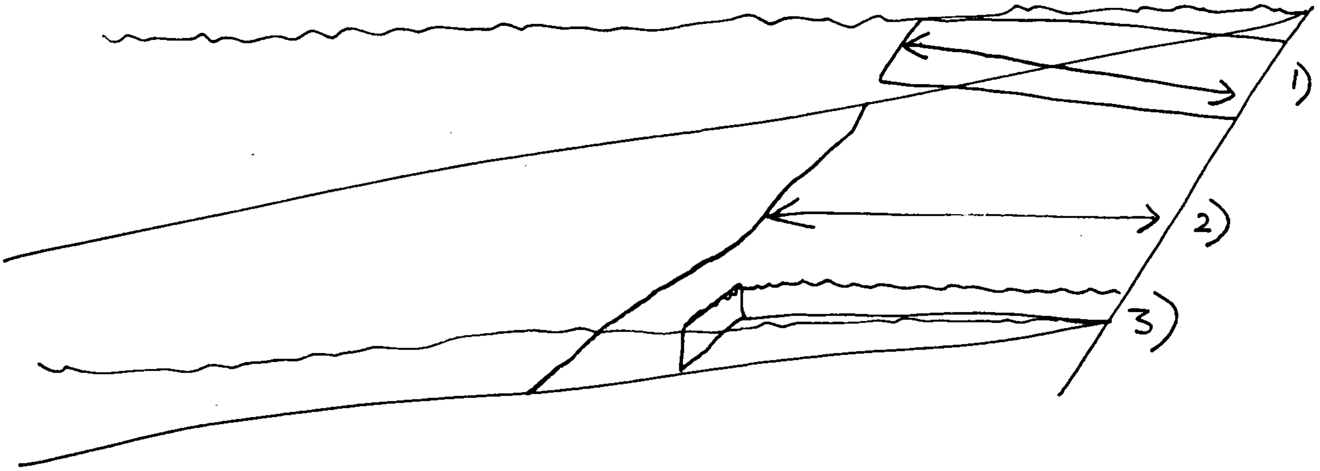
Z(M.)	ACC VOL(CU M)	Z(M.)	ACC VOL(CU M)	Z(M.)	ACC VOL(CU M)	Z(M.)	ACC VOL(CU M)	Z(M.)	ACC VOL(CU M)	Z(M.)	ACC VOL(CU M)
1	0.184840E+11	2	0.368040E+11	3	0.549460E+11	4	0.730080E+11	5	0.909880E+11	6	0.108848E+12
7	0.126648E+12	8	0.144372E+12	9	0.161996E+12	10	0.179500E+12	11	0.196692E+12	12	0.213760E+12
13	0.230660E+12	14	0.247468E+12	15	0.264180E+12	16	0.280676E+12	17	0.297104E+12	18	0.313456E+12
19	0.329676E+12	20	0.345740E+12	21	0.361492E+12	22	0.377100E+12	23	0.392540E+12	24	0.407820E+12
25	0.423004E+12	26	0.438044E+12	27	0.453036E+12	28	0.467948E+12	29	0.482772E+12	30	0.497460E+12
31	0.511960E+12	32	0.526316E+12	33	0.540480E+12	34	0.554540E+12	35	0.568528E+12	36	0.582340E+12
37	0.596096E+12	38	0.609800E+12	39	0.623364E+12	40	0.636880E+12	41	0.650180E+12	42	0.663350E+12
43	0.676472E+12	44	0.689488E+12	45	0.702440E+12	46	0.715272E+12	47	0.728048E+12	48	0.740732E+12
49	0.753356E+12	50	0.765875E+12	51	0.778220E+12	52	0.790488E+12	53	0.802676E+12	54	0.814800E+12
55	0.826844E+12	56	0.838788E+12	57	0.850688E+12	58	0.862556E+12	59	0.874360E+12	60	0.886092E+12
61	0.897660E+12	62	0.909156E+12	63	0.920536E+12	64	0.931816E+12	65	0.943040E+12	66	0.954156E+12
67	0.965208E+12	68	0.976160E+12	69	0.987048E+12	70	0.997784E+12	71	0.100841E+13	72	0.101894E+13
73	0.102937E+13	74	0.103969E+13	75	0.104991E+13	76	0.106007E+13	77	0.107015E+13	78	0.108016E+13
79	0.109006E+13	80	0.109986E+13	81	0.110952E+13	82	0.111911E+13	83	0.112862E+13	84	0.113806E+13
85	0.114745E+13	86	0.115677E+13	87	0.116603E+13	88	0.117525E+13	89	0.118438E+13	90	0.119342E+13
91	0.120234E+13	92	0.121115E+13	93	0.121986E+13	94	0.122853E+13	95	0.123712E+13	96	0.124564E+13
97	0.125410E+13	98	0.126250E+13	99	0.127080E+13	100	0.127899E+13	101	0.128702E+13	102	0.129495E+13
103	0.130282E+13	104	0.131059E+13	105	0.131829E+13	106	0.132591E+13	107	0.133345E+13	108	0.134090E+13
109	0.134822E+13	110	0.135545E+13	111	0.136259E+13	112	0.136964E+13	113	0.137659E+13	114	0.138345E+13
115	0.139023E+13	116	0.139692E+13	117	0.140355E+13	118	0.141006E+13	119	0.141648E+13	120	0.142278E+13
121	0.142898E+13	122	0.143508E+13	123	0.144110E+13	124	0.144707E+13	125	0.145295E+13	126	0.145877E+13
127	0.146450E+13	128	0.147018E+13	129	0.147575E+13	130	0.148122E+13	131	0.148656E+13	132	0.149178E+13
133	0.149690E+13	134	0.150195E+13	135	0.150691E+13	136	0.151177E+13	137	0.151658E+13	138	0.152131E+13
139	0.152595E+13	140	0.153052E+13	141	0.153497E+13	142	0.153935E+13	143	0.154363E+13	144	0.154784E+13
145	0.155199E+13	146	0.155604E+13	147	0.156002E+13	148	0.156394E+13	149	0.156780E+13	150	0.157160E+13
151	0.157527E+13	152	0.157883E+13	153	0.158233E+13	154	0.158578E+13	155	0.158917E+13	156	0.159248E+13
157	0.159576E+13	158	0.159897E+13	159	0.160211E+13	160	0.160515E+13	161	0.160809E+13	162	0.161095E+13
163	0.161371E+13	164	0.161638E+13	165	0.161899E+13	166	0.162154E+13	167	0.162403E+13	168	0.162646E+13
169	0.162876E+13	170	0.163102E+13	171	0.163312E+13	172	0.163509E+13	173	0.163695E+13	174	0.163871E+13
175	0.164037E+13	176	0.164197E+13	177	0.164349E+13	178	0.164499E+13	179	0.164641E+13	180	0.164774E+13
181	0.164900E+13	182	0.165017E+13	183	0.165129E+13	184	0.165237E+13	185	0.165341E+13	186	0.165441E+13
187	0.165539E+13	188	0.165634E+13	189	0.165726E+13	190	0.165814E+13	191	0.165895E+13	192	0.165973E+13
193	0.166046E+13	194	0.166118E+13	195	0.166188E+13	196	0.166257E+13	197	0.166322E+13	198	0.166386E+13
199	0.166445E+13	200	0.166500E+13	201	0.166548E+13	202	0.166592E+13	203	0.166634E+13	204	0.166672E+13
205	0.166707E+13	206	0.166741E+13	207	0.166774E+13	208	0.166806E+13	209	0.166835E+13	210	0.166864E+13
211	0.166885E+13	212	0.166903E+13	213	0.166920E+13	214	0.166936E+13	215	0.166951E+13	216	0.166967E+13
217	0.166982E+13	218	0.166997E+13	219	0.167010E+13	220	0.167020E+13	221	0.167028E+13	222	0.167034E+13
223	0.167038E+13	224	0.167042E+13	225	0.167046E+13	226	0.167049E+13	227	0.167052E+13	228	0.167056E+13
229	0.167058E+13	230	0.167061E+13	231	0.167063E+13	232	0.167064E+13	233	0.167065E+13	234	0.167066E+13
235	0.167066E+13	236	0.167067E+13	237	0.167067E+13						

The disparity between areal and volumetric proportional changes occurs because the lakes are effectively straight sided - see the additional data in Table C2.

The changes in mean depth which would result from regulation of Lake Erie are 0.22 m (difference between BOC and Plan 6) and 0 m in Lake Ontario Thus in Lake Erie, regulation would cause a decrease in mean surface area of 49 km^2 (0.19%) and a decrease in mean volume of 5.47 km^3 (1.16%).

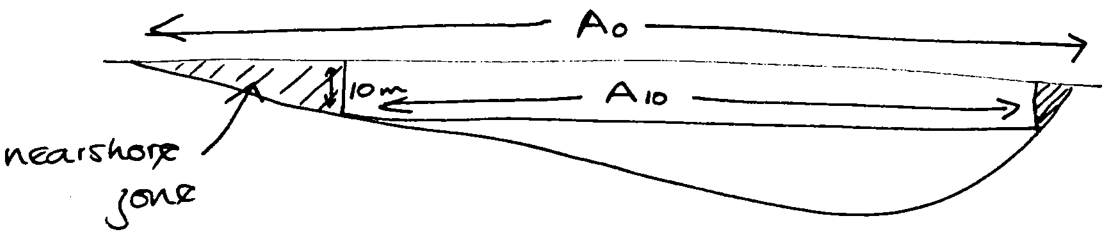
NEARSHORE ZONE

The definition of nearshore zone is a matter of choice, often depending on historical sampling procedures rather than general definitions. For the purpose of this study, in which general effects are considered as well as specific sites, some definition of nearshore zone must be decided upon. The zone can be considered as that zone; 1) within a certain distance of shore, or 2) within a certain depth contour, or 3) containing a certain volume of water/unit length of shoreline:



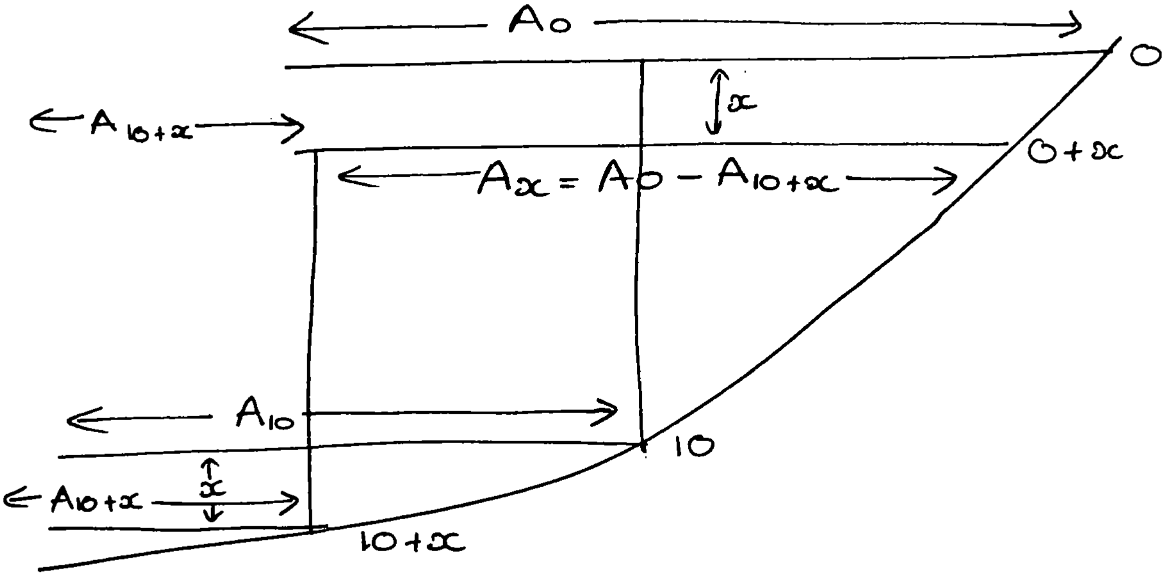
For ease of manipulation, definition 3) is less practicable than definitions 1) or 2). The choice of K or D, and the choice of 1) or 2), depend on the purpose for which the zone is being defined, and the variability of the nearshore slope. If the mean slope is constant along the shoreline, the methods are comparable, and only the extent of the zone must be considered. When considering the region affected by wave action, the zone will be much smaller than when considering the region in which diffusion and dispersion of nutrients will occur.

A nearshore zone defined by the 10m depth contour will be considered.



The area of this zone is the difference between the surface area and the area at 10m depth. The volume is the difference between the volume above 10m and the volume above 10m enclosed by the 10m contour.

Changes in the nearshore zone of Lake Erie resulting from the mean change in water level are calculated below:



change in surface area = $A_x - A_n$

$A_0 = 25,320 \text{ km}^2$
$A_{10} = 21,240 \text{ km}^2$
$A_n = A_0 - A_{10} = 4,080 \text{ km}^2$

change in area with depth 0m = 200 km^2/m
10m = 834 km^2/m

Therefore, A(10+x) = A10 -834x
= 21,240 - 184 (x = 0.22 m)
= 21,056 km^2

Ax = A_0 - A(10+x) = 25,320 - 21,056
= 4,264 km^2

Thus, change in surface area = $A_X - A_n$ = 4,264 - 4,080
= 184 km^2

Change in volume with depth 0m 25.00 km^3/m
10m 20.73 km^3/m

Volume of lowered zone =
Volume above (10+x) - volume enclosed by 10x(10+x) m contour - volume above x m contour.

Volume above 10m = 237.17 km^3.

Volume above (10+x) contour
= 237.17 + .22 x 20.73
= 237.17 + 4.56
= 241.73 km^3

Volume enclosed by (10+x) contour, to 10m above it
= 210.56 km^3.

Volume above x m contour
= .22 x 25.00 = 5.5 km^3.

Therefore, volume of lowered zone = 241.73 - 210.56 -5.5
= 25.67 km^3

Therefore, increase in volume = 0.9 km^3.

TABLE C3

Morphometric data (Robertson, personal communication)

	Lake Erie	Lake Ontario
Area at surface km^2	25,320	18,484
Area at 10m km^2	21,240	17,504
Volume above 10m km^3	237.17	179.50
Change in area with depth km^2/m		
at surface*	200	170
at 10m†	834	216
Change in volume with depth km^3/m		
at surface*	25.00	18.23
at 10m†	20.73	17.35
Area of nearshore zone km^2 (within 10m contour)	4,080	980
Volume of nearshore zone km^3 (within 10m contour)	24.77	4.46
Mean depth of nearshore zone m	6.07	4.55
Change in area (km^2) if zone lowered by regulation	+184 (4.5%)	-
Change in volume (km^3) if zone km^3 lowered by regulation	+0.9 (3.6%)	-

* mean of values 1-3 m

† mean of values 9-11 m

The preceding calculations describe the changes which might result from regulation, to a nearshore zone defined by the 10 m contour. The choice of the extent of the nearshore zone depends on the purpose of the investigation: wave action may be felt only in shallow water, while a measurable gradient of dissolved substances may be observed into much deeper water.

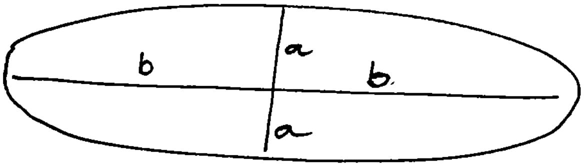
Dr. Herdendorf (personal communication), defining the nearshore zone as that region of high concentrations of dissolved substance and high variability of these concentrations, considers that in the Western basin of Lake Erie the nearshore is 1 - 2 km off the southern shore, 15 km off shore at Maumee Bay and 4 km off the Michigan shoreline. These distances correspond to depths of about 5 m. Chesters and Delfino (1978) when examining resuspension, took the nearshore zone as that region with the 18 m contour. These two examples give an indication of the range of definitions of "nearshore". As it may be desirable to consider different "nearshore" zones, data for these are included here: Table C4, based on the data in Table C1.

TABLE C4

Dimensions of Near-Shore Zones in Lake Erie

Depth of Defining Contour D (m)	Volume of Nearshore Zone Vn (km^3)	Area of Boundary* with open lake En (km^2)
2	0.24	1.89
3	0.56	2.83
4	1.36	3.75
5	2.42	4.67
10	24.77	8.71
15	69.58	11.85
20	157.78	13.22

* This value En was obtained by considering Lake Erie to be eliptical in shape, with the long axis 5.5 x the short axis. The circumference of each depth layer was then calculated from the area of that layer, and this multiplied by the depth gave the area of the interface.



circumference $2\pi\sqrt{\frac{a^2 + b^2}{2}} = C$

area $= \pi ab = A$

$b = 5.5\,a$

En $= C \times D$

Hence $C = \sqrt{35.7A}$

An Estimate of the Effects of Lake Level Regulation on Certain Specific Regions of Lake Erie.

While attempts have been made to predict the effects of lake level regulation on water quality in general terms, it is instructive, when data are available, to consider particular regions. Such exercises will demonstrate the sufficiency of both the available information and the chosen approach, and will provide numbers which may facilitate the evaluation of the proposed regulation.

Regulation of Lake Erie water level will have a direct effect on Lakes Erie and St. Clair, and some slight effect on Lake Ontario. Earlier chapters have shown that shoreline erosion is the factor influencing water quality which is most likely to be altered by changes in water level. Three regions in Lake Erie, subject to light, moderate and heavy bluff erosion, will therefore be considered. Gregor and Ongley (1978), in an analysis of Ontario Ministry of Environment's nearshore water quality data, divided the nearshore areas of Lake Erie into 22 zones, (see Figure 1). Three of these will be considered here: Region 16, around Port Alma and Port Crewe, Region 11, around Port Burwell and Region 14, around Port Glasgow. Information in Boulden (1975) shows that Region 16 is one of moderate net erosion rates (0.5 - 2.0 m^3/m/m/yr.) while most of Region 11 is subject to heavy erosion ($>$ 2.0 m^3/m/m/yr.) and erosion rates in Region 14 are low ($<$ 0.5 m^3/m/m/yr.). Gregor and Ongley examined MOE data for the period 1967-1973, and their mean data are reporduced in Table 1. They classified data by season, taking, for Lake Erie, spring as April 1 - June 21, summer as June 22 - September 21 and fall as September 22 - November 30. These periods have been used to calculate the mean recorded lake levels: See Table 2.

During the period of data analysed by Gregor and Ongley, annual mean lake levels rose each year. It is therefore tempting to look for trends in their data which may be related to lake level changes. This of course can take no account of other changes occurring during those years, such as the more efficient treatment of sewage and concomitant reduction in phosphorus loading. By 1974, it was considered in some circles that this reduced phosphorus loading was the cause of an observed improvement in certain aspects of Lake Erie water quality. Data gathered in the following years showed a reversal of this trend, and it became apparent that lake level changes may have been more significant than changes in phosphorus loading. (e.g. Hamdy, Nicholls: presentations to the Lake Erie Workshop, Windsor, March 20-21, 1979).

Figure 2a shows a plot of Secchi depth against lake level, using the data in Tables 1 and 2. When these data are plotted separately by zone, it can be seen (Figure 2b-d) that the fall values show the most consistent relationships between Secchi depth and water level. Fall is the season of most severe storms, when erosion is likely to be greatest. When the fall values for the three zones are plotted (Figure 2e) three points emerge: at the highest water levels very high turbidities were recorded, with very little difference between zones; at the lower water levels the range of values increased, and there was no consistent difference between the zones. This latter point is particularly curious, as it implies that close inshore the turbidity of the water is not a function of the quantity of erodable material on that stretch of shoreline. This is obviously not true in general, and here serves to emphasize the risks involved in working with small quantities of pre-worked data. It does obviate the possibility of deducing separate relationships between turbidity and water level for each zone, from which the effects of regulation could have been calculated. These data refer to years when water level was close to or above the mean. Because of the greater spread of the data at lower water levels, the extrapolation to the lower mean (Plan 6) is fraught with error. It would appear that an improvement in Secchi transparency of about 1 m might result from the regulation of Lake Erie, but differenceces between areas cannot be predicted. Some indication of the expected difference between zones can be seen on Figure 2a, where the data points for zone 11 tend to be closer to the axes than do the other values, but though Secchi depths are lower in zone 11, changes with lake level are not significantly different.

When the data are used to examine the relationships between secchi depth and chlorophyll a (Figure 3a) it is clear that though the general envelope lies around the usual curve (e.g. Carlson, 1977), there is a very wide scatter, and differences between zones are not marked. It might be expected that the belt fit would be found when algal growth is most vigorous and when inorganic turbidity is least. In fact, only the spring data show a reasonable relationship (Figure 3b). Were eroded material an important contributor to the Secchi turbidity, it would be expected that the plot for zone 11 would be closest to the axes, and the plot for zone 14 further from the axes. While zone 11 data do tend to follow this trend, the other data are indistinguishable (see Figure 3a) and all lie on the axes side of Carlson's (1977) empirical equation $\ln SD = 2.04 - 0.68 \ln(\text{chlorophyll } \underline{a})$, indicating turbidity due to suspended sediment in all samples. This is in keeping with the inferences drawn from

Figure 7.1 Lake Erie - Nearshore Geographic Regions

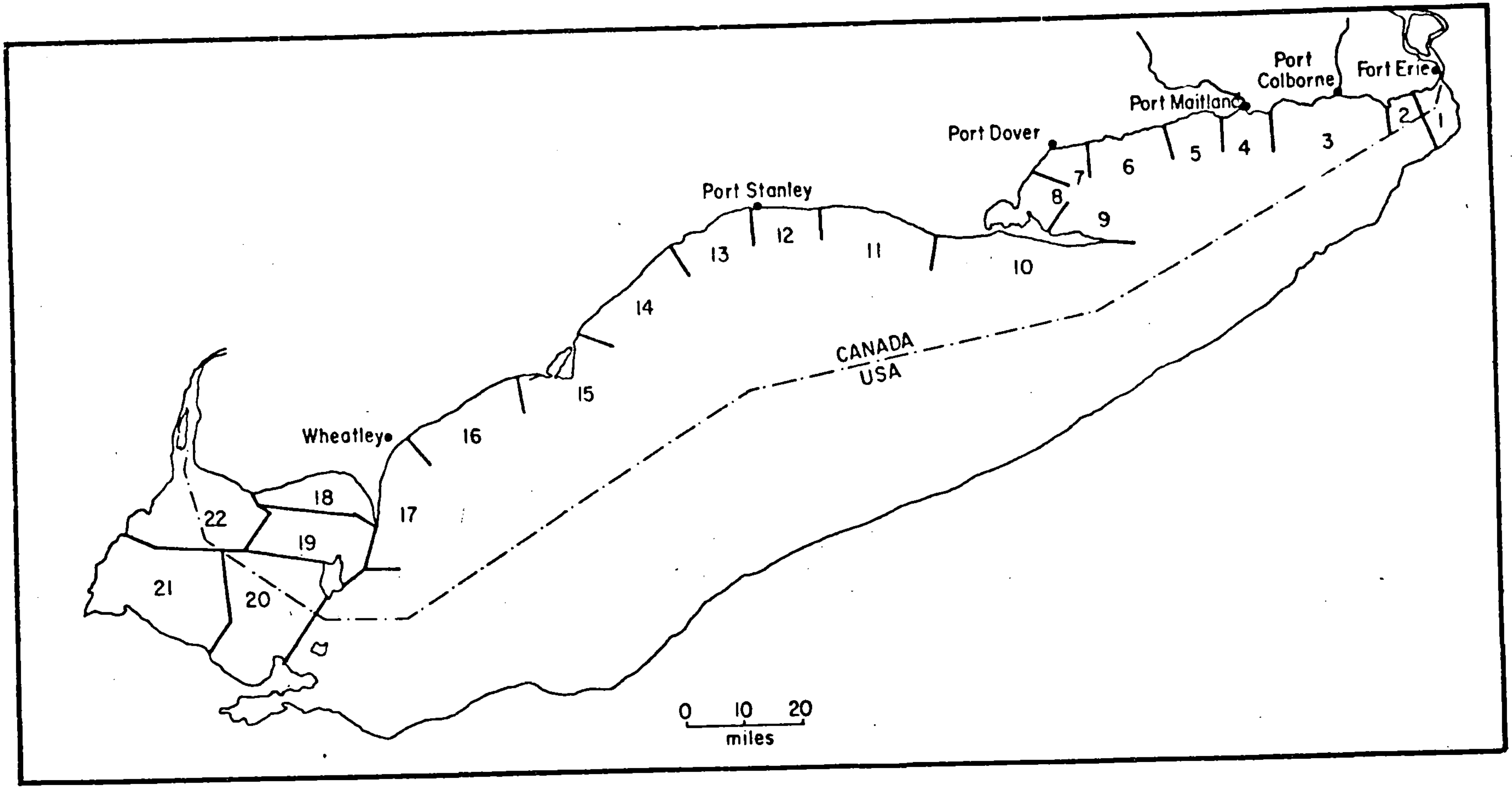


Figure 1

Figure 2 Plots of Secchi disc depth against lake level

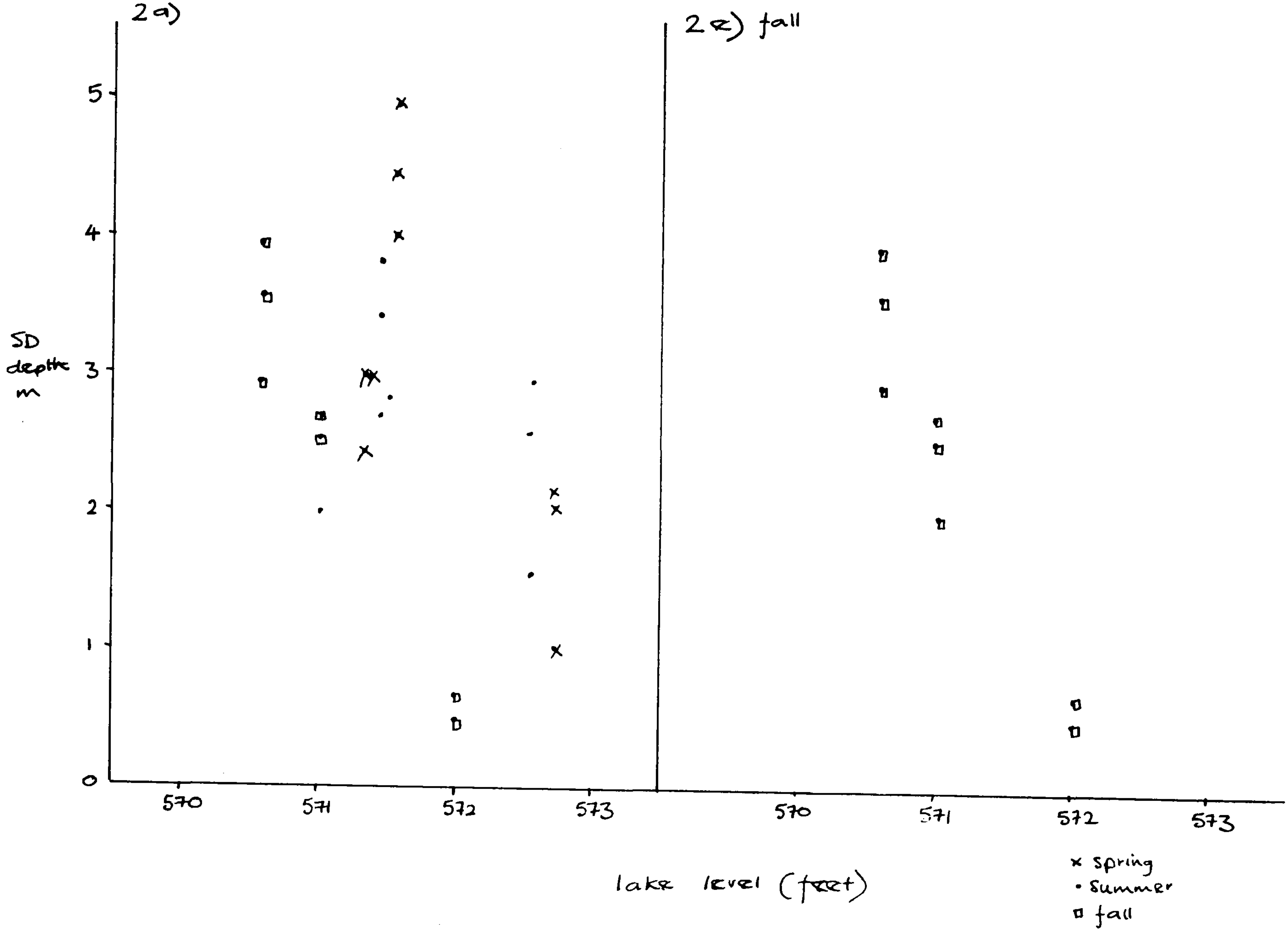


Figure 2

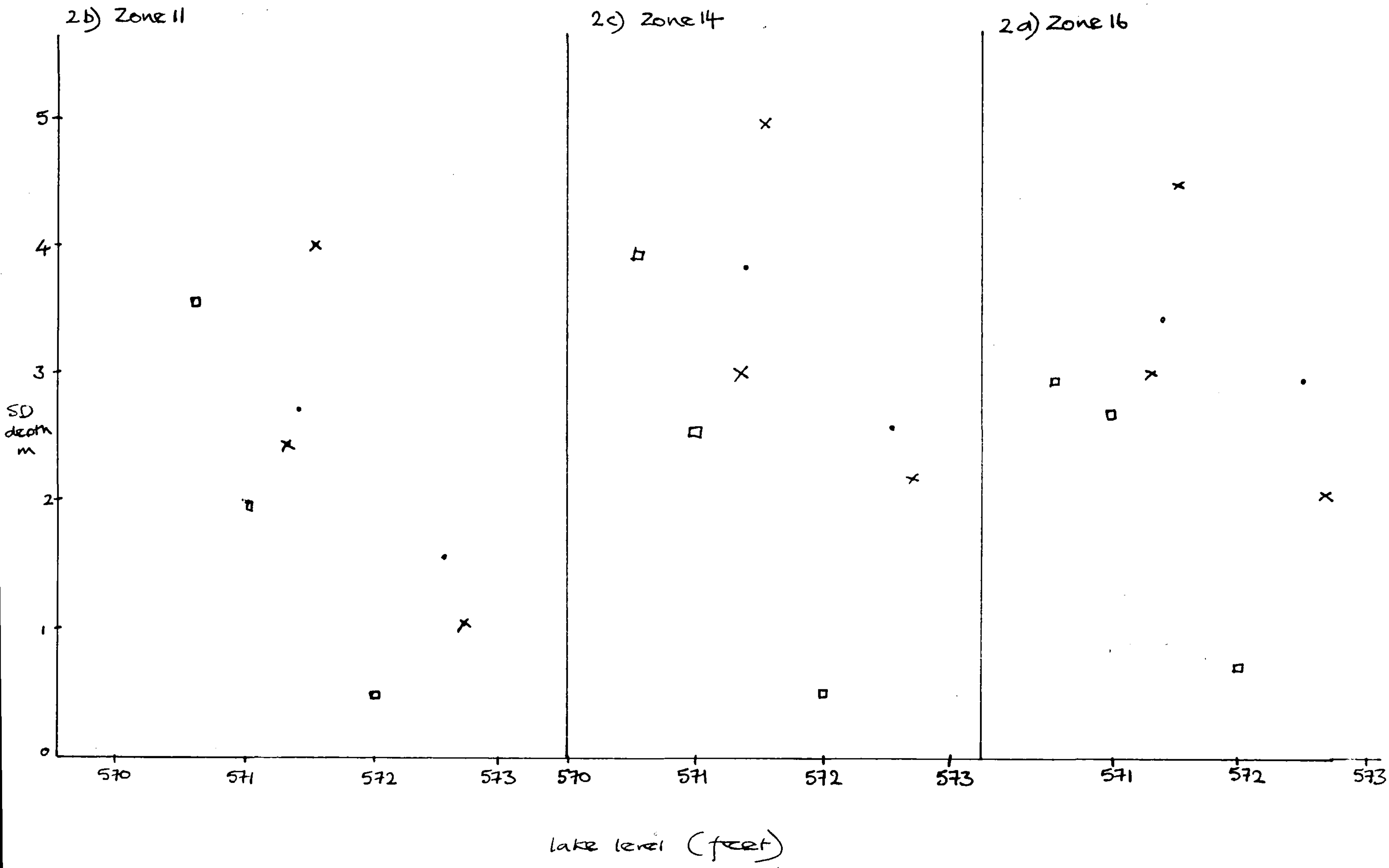

2b) Zone 11
2c) Zone 14
2a) Zone 16
SD depth m
0
1
2
3
4
5
570
571
572
573
570
571
572
573
571
572
573
lake level (feet)

Figure 3 Plots of Secchi disc depth against chlorophyll a concentration

3a)

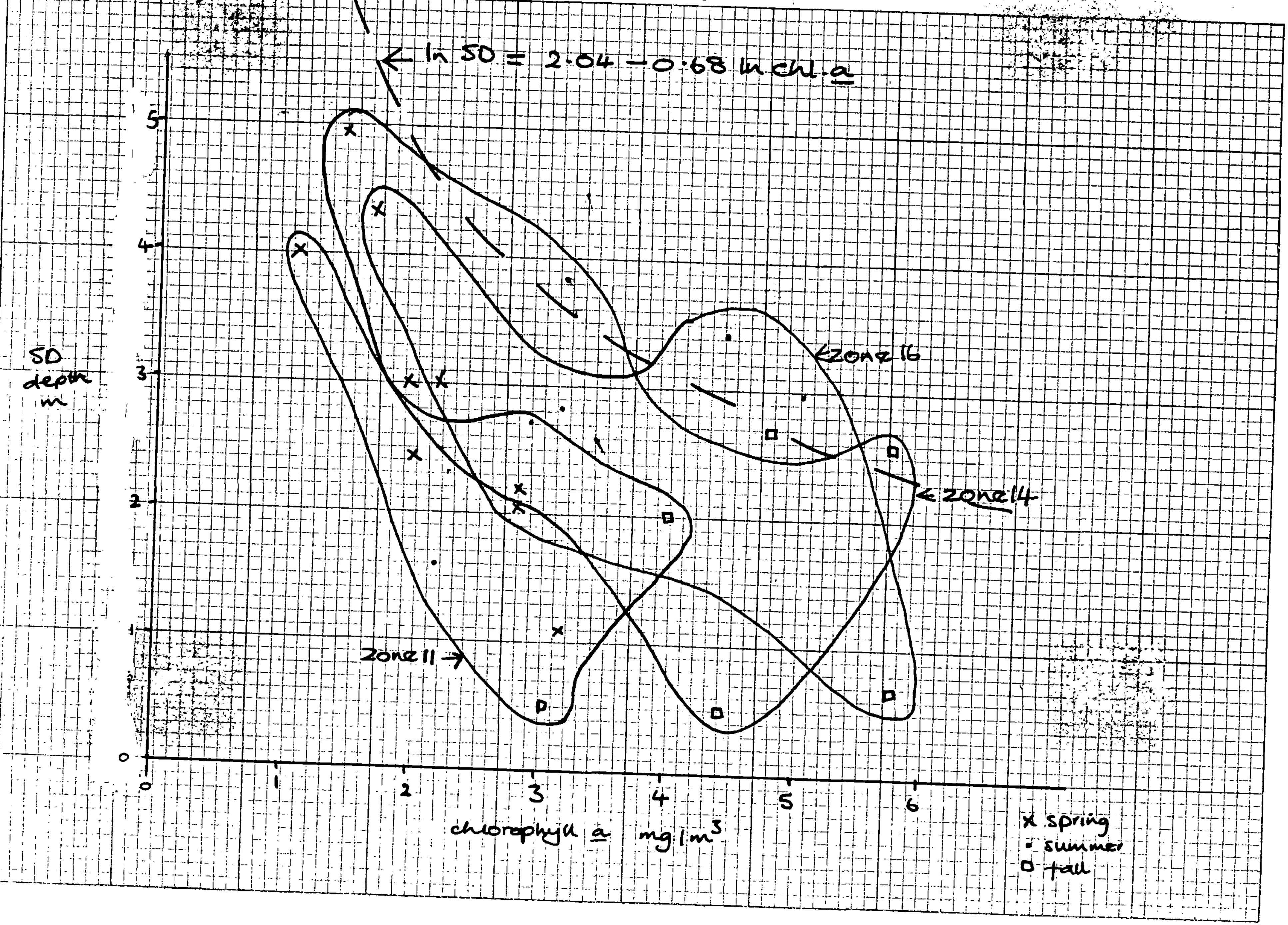


Figure 3

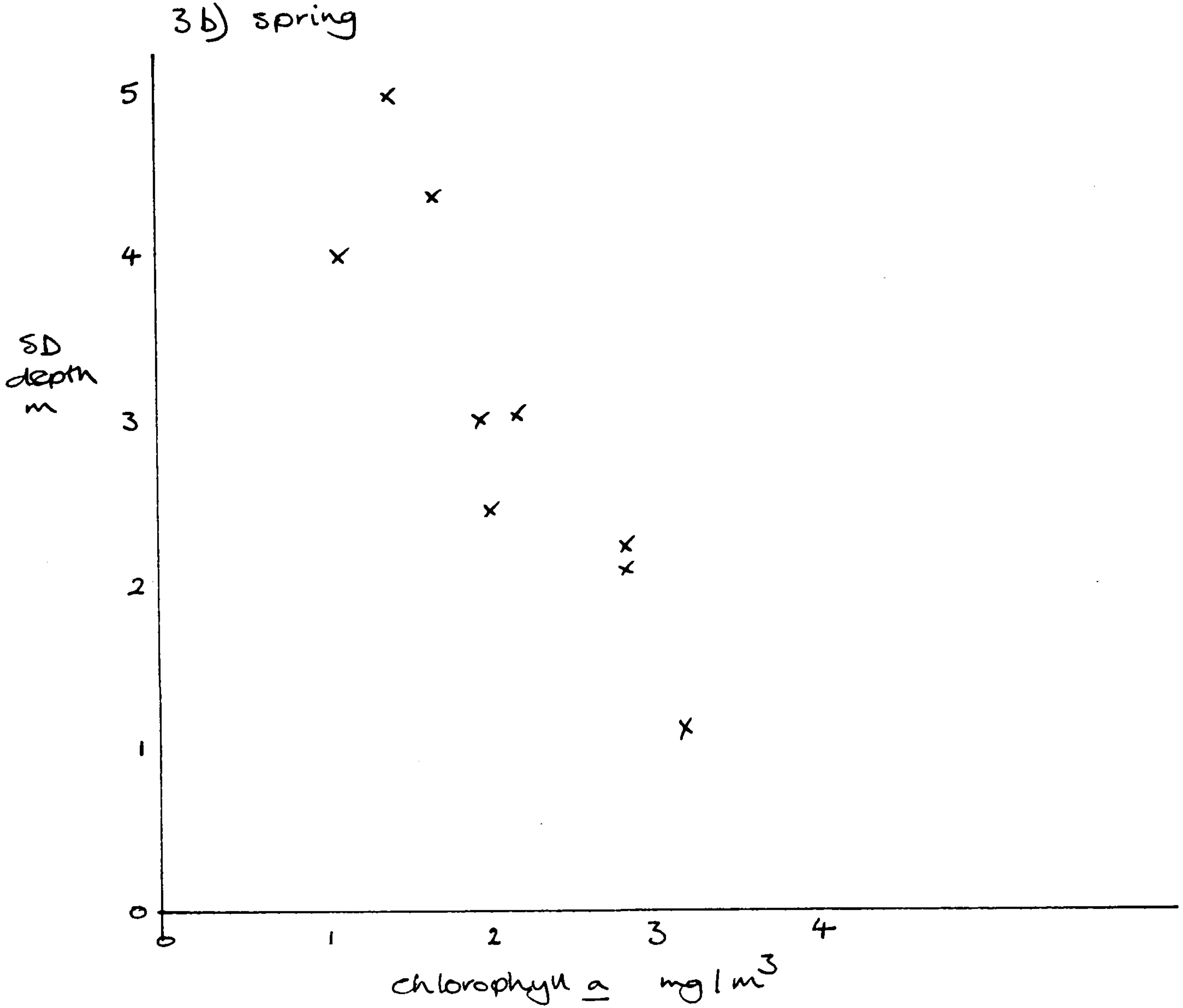


Figure 4 Plot of chlorophyll a concentration against lake level

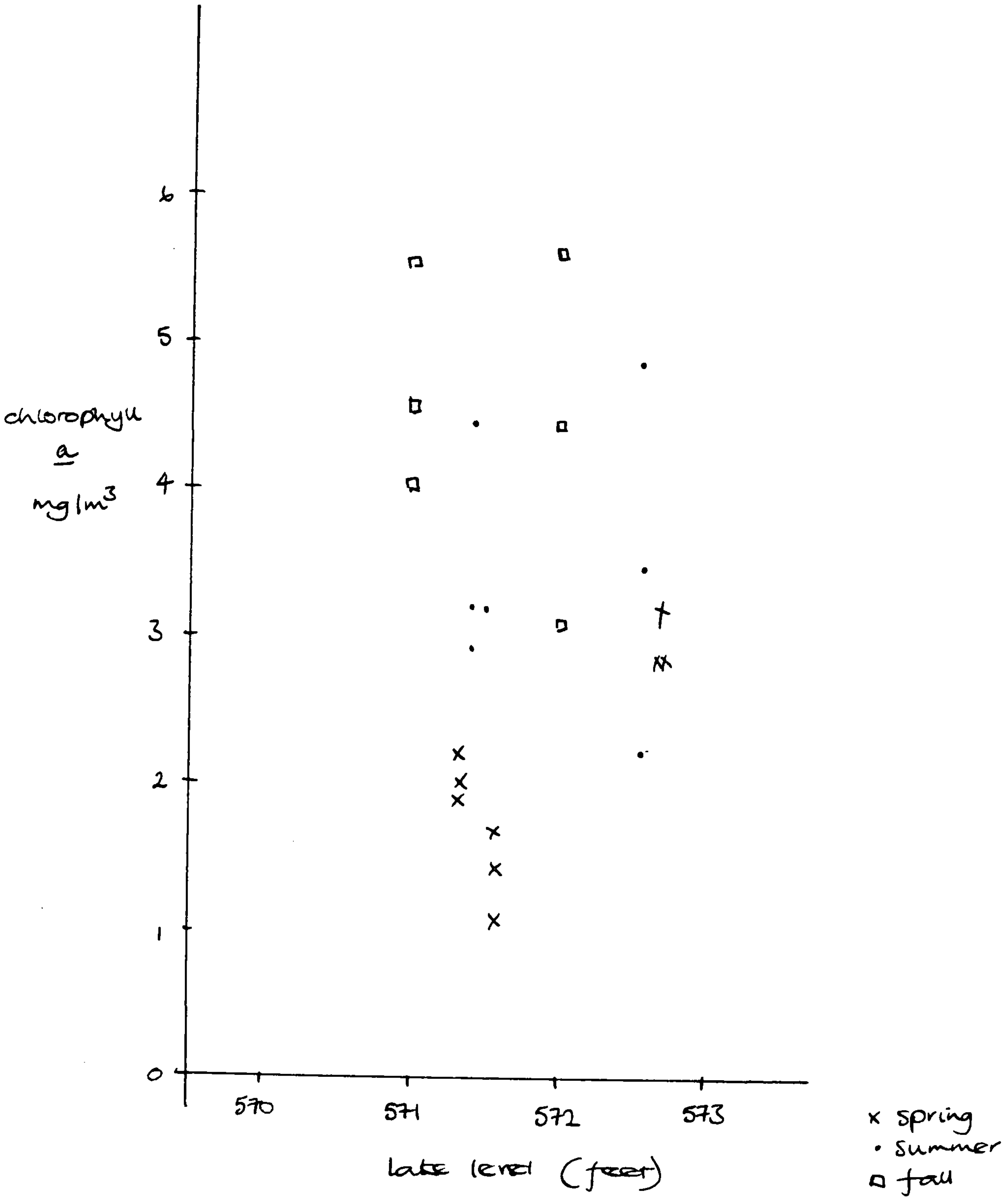


Figure 5 Plot of chlorophyll a concentration against total phosphorus concentration

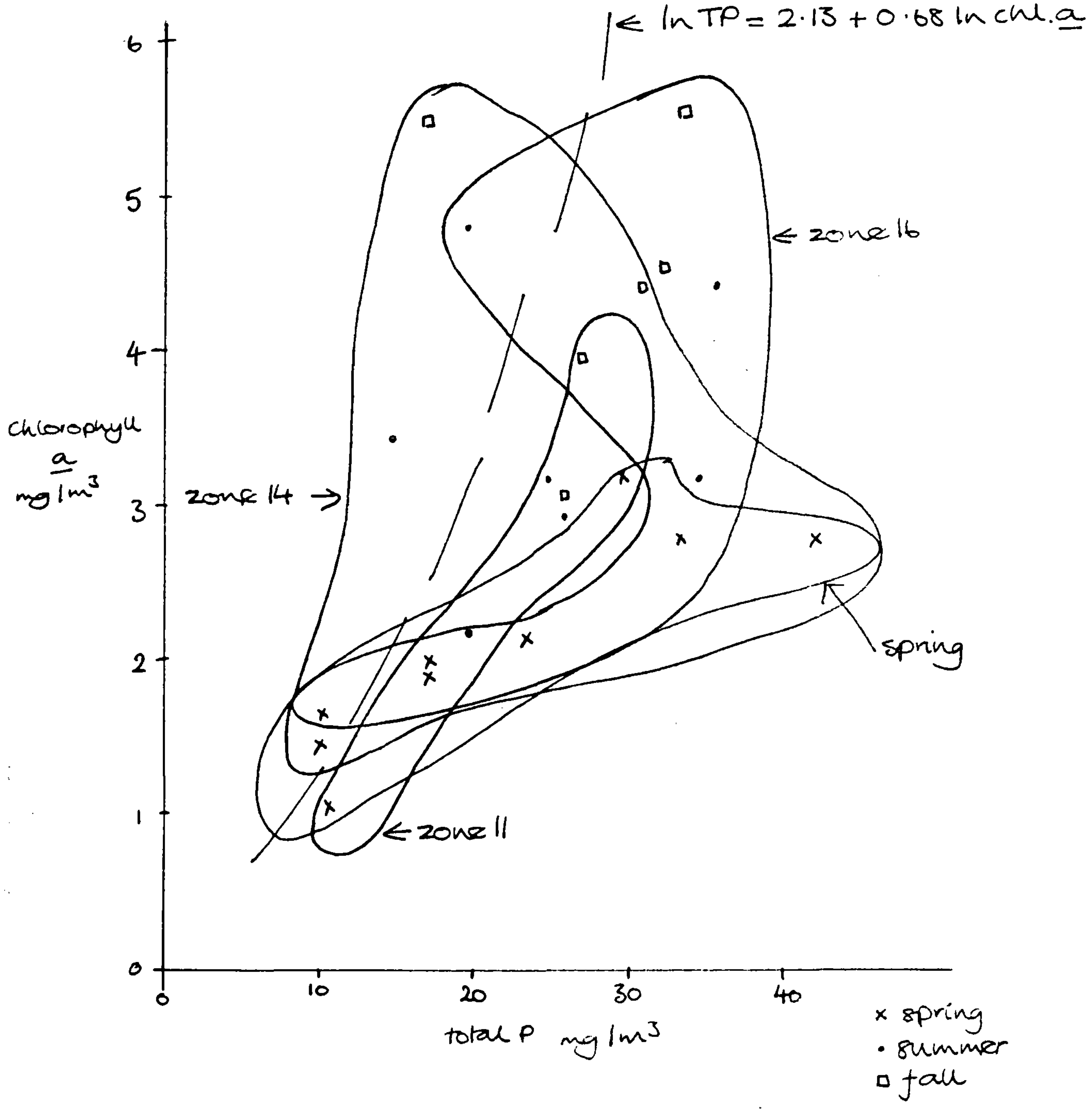


Figure 2: heavier erosion in zone 11 than in zones 14 and 16 causes higher turbidity and lower Secchi disc depths. This erosion does not appear to increase with rising lake level more in zone 11 than in the other zones. Algal biomass tends to be greater in the areas of low erosion and in the fall, but appears to be unrelated to lake level. (See Figure 4).

When the data for chlorophyll *a* and total phosphorus are plotted (Figure 5) only zone 11 data or spring values do not show very considerable spread, and most of the data have total phosphorus concentrations above those predicted by: $\ln TP - 2.13 + 0.68 \ln$ (chlorophyll *a*) which is a combination of Carlson's (1977) equations 5 and 6. In clear water lakes where phosphorus is limiting, most phosphorus will be taken up by algae. In turbid nearshore waters some of the phosphorus measured as total phosphorus may not be biologically available, and conditions may be less than ideal for phytoplankton growth.

This brief analysis shows that only non-biological turbidity appear to have been related to changing lake levels, and this particularly in the autumn when storms are most frequent. Much of the turbidity can be attributed to phytoplankton (measured as chlorophyll *a*) which shows some relationship with total phosphorus, but none with lake level. With these data no difference could be observed between zones. More extensive data analysis (were access to the original MOE data available) might reveal differences in turbidity changes in areas of different shoreline erosion. The trends in turbidity in the years 1974 - 1978, when water level fell, would perhaps provide verification of the relationship between turbidity and lake level.

TABLE 2

Mean Recorded Lake Erie Levels (Feet)

	Spring	Summer	Fall
1967-1969	571.31	571.41	570.65
1970-1971	571.52	571.49	570.99
1972-1973	572.70	572.60	571.99

TABLE 1

Surface Water Quality Mean Data

Quantity	1967 - 1969			1970 - 1971			1972 - 1973		
	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer	Fall
(a) <u>Region 11</u>									
Conductivity µmhos/cm	323	316	311	321	x	309	312	314	311
Total Nitrogen mg/m^3	235	233	307	296	x	349	476	355	326
Oxygen Saturation %	102	95	90	105	x	92	103	101	97
Total Phosphorus mg/m^3	17	26	20	11	x	27	29	19	26
Chloride mg/l	25	24	x	24	x	24	24	22	20
Total Coliform MF/100 ml	542	65	419	3	x	31	424	97	168
Chlorophyll a mg/m^3	2.0	2.9	x	1.1	x	4.0	3.2	2.2	3.1
Secchi Depth m	2.4	2.7	3.6	4.0	x	2.0	1.1	1.6	0.5
(b) <u>Region 16</u>									
Conductivity µmhos/cm	314	302	310	316	294	299	308	293	307
Total Nitrogen mg/m^3	340	410	322	252	476	373	426	353	335
Oxygen Saturation %	102	93	93	108	87	93	92	109	95
Total Phosphorus mg/m^3	23	36	30	10	34	32	33	19	33
Chloride mg/l	25	23	x	23	22	22	25	21	21
Total Coliform MF/100 ml	5	103	63	1	150	19	15	80	115
Chlorophyll a mg/m^3	2.2	4.4	x	1.7	3.2	4.6	2.8	4.8	5.6

TABLE 1 (Continued)

Surface Water Quality Mean Data

Quality	1967 - 1969			1970 - 1971			1972 - 1973		
	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer	Fall
Secchi Depth m	3.0	3.4	2.9	4.3	2.8	2.7	2.1	2.9	0.7
(c) <u>Region 14</u>									
Conductivity µmhos/cm	321	311	308	317	x	303	307	308	306
Total Nitrogen mg/m^3	297	393	321	272	x	345	412	320	331
Oxygen Saturation %	102	92	88	105	x	97	98	96	93
Total Phosphorus mg/m^3	17	24	29	10	x	17	42	14	31
Chloride mg/l	24	24	x	24	x	24	24	23	21
Total Coliform MF/100 ml	5	156	28	1	x	8	2	129	76
Chlorophyll *a* mg/m^3	1.9	3.2	x	1.4	x	5.5	2.8	3.4	4.4
Secchi Depth m	3.0	3.8	3.9	4.9	x	2.6	2.2	2.6	0.5

X represents absence of data

NB. An arithmetic mean is not a valid mean for total coliform. These data are included, however, for comparative purposes.

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TABLE 11A

Loadings of phosphorus to Lake Erie (mg P/yr x 109)

	BOC	Plan 1	Plan 3	Plan 5	Plan 6
J	17474	17474	17474	17474	17474
Available P in eroded material	347	312	260	208	174
Total available P	17821	17786	17734	17682	17648
Total P as a % of total P, BOC	100	99.8	99.5	99.2	99.0

Lake volume, water residence time, phosphorus retention coefficient

These quantities change by only a few percent between BOC and Plan 6. Differences between BOC and other Plans would be even smaller, and need not be quantified.

Chapter 5

It has been shown in Section 5.2 that though resuspension may be a very important factor governing turbidity in certain nearshore zones, changes in resuspension resulting from maximum lake level regulation would only be about 2%. It follows that the effects of lesser plans would probably not be significant.

Regulation would, by decreasing shoreline erosion, lead to an improvement in nearshore turbidity in areas near Bluff shorelines. An attempt to quantify this was based on Gregor and Ougley's (1978) analysis of MOT data. It was suggested (Section 5.4) that maximum regulation might lead to an increase in mean Secchi depth of about 0.9 m. The corresponding improvements likely to result from the lesser regulation plans are: 5 TCFs - 0.2m, 15 TCFs - 0.5m, 25 TCFs - 0.7m.

Chapter 6

Though it is recognized that hypolimnetic oxygen conditions in Lake Erie central basin may be affected adversely by regulation, calculations show the effect is likely to be small and unlikely to be significant when considered in relation to the large Chinatic changes which govern this system. The lesser regulation plans thus need not be reconsidered, as their ejects could be even smaller.

This report has focussed on the differences in certain aspects of water quality which would result from changes in long-term mean water levels where the maximum regulation of Lake Erie applied (Plan 6, 30 TCFs additional release when required). The Environmental Effects Subcommittee has requested that the more moderate regulation plans involving excess outflows of 25, 15 and 5 TCFs be considered (25 TCFs = Plan 5, 15 TCFs = Plan 3, 5 TCFs = Plan 1).

The report will be considered section by section and the probable effects of these regulation plans will be assessed.

Chapter 1

The predicted level changes are shown in Table 1A.

TABLE 1A

Lake	BOC	Plan 1	Plan 3	Plan 5	Plan 6
Erie		570.64	570.41	570.17	
		573.53	573.11	572.68	
		567.91	567.81	567.71	
	5.78	5.62	5.30	4.97	4.82
Ontario		244.73	244.72	244.73	
		248.54	248.60	248.65	
		241.24	241.02	240.97	
		7.30	7.58	7.08	

The differences in means are shown in Table 2A.

TABLE 2A

Changes in mean lake levels resulting from regulation.
(feet)

	Plan 1	Plan 3	Plan 5	Plan 6
Lake Erie (BOC 570.76)	-0.12	-0.35	-0.59	-0.71
Lake Ontario (with deviation BOC 244.72)	+0.01	0.00	+0.01	0.00

The analyses of frequency of occurence of lake levels has not been done for the intermediate Plans. It is expected that the observed effects of regulation in Lake Erie and St. Clair, reducing the frequency of high water levels (slightly increasing the frequency of low levels) and increasing the frequency of levels near the median would be seen, but to a lesser extent. Changes in Lake Ontario under any plan would be quite small.

Chapter 4

Erosion

Lake level has an important effect on shoreline erosion. As data pertaining to this relationship were not yet available, the assumption was made that maximum regulation (Plan 6) would bring about a 50% reduction in erosion. In the absence of other information, it will be assumed that the reductions in shoreline erosion in Lake Erie would be 10% (Plan 1), 25% (Plan 3) and 40% (Plan 5). The predicted increase of 10% in Lake Ontario, resulting from more frequent high water levels was an extreme estimate. It seems likely that with the lower flow regulation plans, changes in erosion in Lake Ontario would be too small to be observed against large and irregular seasonal and long-term fluctuations. Changes in total available phosphorus loading resulting from changes in erosion would be less than 10% (see Table 11A). The data in Table 16 shows that on an individual basin basis, the contribution of erosion to the phosphorus concentrations in Lake Erie would be insufficient for changes resulting from different regulation plans to be apparent.