NUTRIENT RESIDENCE TIMES IN RELATION TO THE TROPHIC CONDITION OF LAKES

By

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ABSTRACT

This thesis is concerned with defining systematic relationships between nutrient flow rates in aquatic ecosystems and their overall biological productivity. The most significant finding was that phosphorus residence time produced a consistent pattern relative to the trophic condition of freshwater lakes and reservoirs which allows both characterization of trophic state and more precise calculation of the concentration response to loadings as commonly applied in lake management.

Nutrient residence times were examined from the perspective of two data types. The data types included time series information on nine individual lake cases and single year cross-sectional information on 220 waterbodies of the OECD Programme on Eutrophication.

The nine case histories gave insight into the applicability of cross-sectionally derived models. These cases showed that sedimentation rates of phosphorus in a given lake varied tremendously from year to year and therefore models based on the assumption of a constant rate are in most instances insufficient. Case histories also showed that phosphorus relative residence times followed a remarkably consistent pattern of increase with an increase in trophic status regardless of the number or types of underlying mechanisms in control of nutrient flows. This increase is related to an acceleration of phosphorus recycling mechanisms rather than a decline in its gross deposition rate. The net decelleration of phosphorus flow rates creates a shift in the relative importance of elimination pathways, from deposition in the sediments to removal via flushing (i.e. $\sigma/\rho<1$), with increasing eutrophication. Lastly, case histories demonstrated that concentration ratios of lake/inflow gave reasonable estimates of nutrient relative residence times as calculated from budget information. Transposing this, the distinctly different dynamics according to trophic category reflected in the cross-sectional concentration ratio data may be interpreted as a functional pattern.

The cross-sectional data indicated that in the case of phosphorus, relative residence time was best described by a different multiple regression equation for each trophic category whereas there was no difference in nitrogen relative residence times according to trophic category. Practical application of this result is in refinement of the calculation of critical loads when the trophic status of a lake is known.

Nutrient limitation judged on the basis of most rapid flow rate implies that phosphorus limitation is far more common than nitrogen limitation, even in eutrophic waterbodies. The relative flow rates given by the ratio (τ_n/τ_p) is always greater than 1 in oligotrophic and mesotrophic waterbodies, and may be greater than 1 in eutrophic waterbodies. This ratio only drops below 1 in some eutrophic waterbodies. Therefore values less that 1 are not necessarily a consequence of eutrophication.

Phosphorus relative residence time was found to be a simple but highly integrative measure capable of characterizing trophic state and its temporal evolution.

PREFACE

This thesis is directly aligned with both the foremost problem and stimulus of limnological research over the past twenty years: eutrophication. The severe eutrophication problems of the 1960s led to the establisnment of the OECD's International Cooperative Programme on Eutrophication in 1973. The goal of this programme was to identify the causes and propose some solutions for eutrophication (ironically, a problem created by the political objective of the OECD Convention to achieve the highest sustainable economic growth). After a decade of international effort, the essential scientific results of the Eutrophication Programme were presented at the joint EPA-OECD conference "Restoration of Lakes and Inland Waters" (at Portland, Maine, September 1980) by the programme's principal scientific coordinator, director and authority, Richard A. Vollenweider. The summary document of the results presented at Portland was first given in the draft entitled the "Synthesis Report" (by R.A. Vollenweider and J.J. Kerekes, 1980) and this is presently the prime reference for diagnosis of nutrient-trophic relationships of Northern Temperate lakes. That meeting was my personal introduction to eutrophication research on a large-scale comparative basis.

Shortly after returning to Burlington, Ontario and the Canada Centre for Inland Waters, I was employed as a research assistant to R.A. Vollenweider to produce a follow-up document to the Synthesis Report. This was the OECD Canadian contribution which served as a test case for the relationships derived from the U.S. and Eurpoean data. It was published by Environment Canada as part of the National Water Research Institute's Scientific Series No. 131, in 1981. This report served to verify the relationships reported in the Synthesis Report, as well as highlight conditions responsible for modified responses.

The final scientific meeting to conclude the OECD Eutrophication Programme took place in August 1983 as a symposium of the XXII SIL Congress in Lyon, France. Although much had been gained for the practical diagnosis and management of lakes through this programme, much also remained to be resolved in the way of functional explanation and prediction of eutrophication phenomena. Recognizing the tremendous information potential of the data base of the OECD programme, R.A. Vollenweider suggested that I take this up for further analysis in a Ph.D. study. It was his idea to make use of this data in exploring the relationship of phosphorus residence time to trophic condition as a new and alternate approach to the present concentration based ideas and generalizations. In this way, the research presented here is a direct outgrowth of the OECD Programme on Eutrophication.

The background data for this thesis was generated through the four Regional Projects (i.e. Alpine Project, Nordic Project, U.S. Portion of the OECD Programme and Shallow Lakes and Reservoirs) in combination with that compiled for the Canadian contribution, this total representing approximately 250 waterbodies. In this respect, it differs from most theses in its employment of pre-existing data. However, it would have been impossible to develop such a data base without the extensive international cooperation of the many scientists involved (probably more than 300 limnologists) in the OECD programme. Further to this, and considering the range of individual lakes which have already been investigated, it was felt that the time was ripe for a more integrative approach of the type presented here. In Forscher's (1963) metaphor of the growth of a science as construction of a building, we are not no much in need of another "brick" (fact) as we are of some attention to the overall "construction" (conceptual organization) of our "buildings" (theories).

The philosophy behind the OECD programme, and that of R.A. Vollenweider in particular, has been to focus on the general properties of lake systems despite the fact that no two are exactly alike in their physiology. Following this approach, the first phase of the work presented here is an effort to identify consistent behavioral patterns of nutrient residence times from the information on individual lake studies. As a second phase, cross-sectional relationships are examined for their functional content by comparison with individual lake behaviour over time. Identification of the causes for departures from "average" behaviour provides the basis for understanding factors which may at times be prominent in controlling lake metabolism.

In essence, this work represents a step toward refinement of the prediction of trophic response of lakes to changes in their nutrient supplies.

ACKNOWLEDGEMENTS

I have much to be grateful for in the completion of this work, but foremost I am indebted for the generosity shown to me by Dr. Richard A. Vollenweider (Senior Scientist of the National Water Research Institute at the Canada Centre for Inland Waters) for the opportunity he provided me with to write this thesis. He alone was responsible for my introduction into the world of nutrient dynamics in lakes. It is a difficult field for the mixture of ecology, biology, chemistry, engineering and mathematics required to produce a cohesive, substantive picture for oneself and I greatly appreciated his guidance in emphasis of the most important aspects of these disciplines for practical application.

I am most thankful for the first hand experience I have had in learning something about Richard Vollenweider's very special approach to science. It is both analytic and synthetic without grinding into reductionism. The thought has never appealed to me of becoming the proverbial specialist who "learns more and more about less and less until everything is known about nothing"! Without the sense of a growing perspective I would likely have lost interest long ago.

To give further insight into Richard's ways of thinking, he brought me to the realization that one must never lose sight of the realities. At an early phase of this work I came to the sudden recognition that while attention is generally drawn to the regression lines we produce, it is in fact the deviations from it that hold the real information. With much of the emphasis in comparative science on condensing data into concise, quantitative formulae, it is all too easy to forget that although such formulations are useful summaries or references, they are also something of a mathematical fiction.

Finally, I would say that Richard taught me the art of scientific analysis; a process of drawing order out of chaos. He described one day that scientific problems were to be envisioned as multifacetted entities - I imagine a cut crystal ball - which must be rotated and examined from all sides for balanced evaluation and understanding. This type of mental triangulation, which I would identify as a trademark of Richard Vollenweider's way of thinking, is what has given permanence to his work despite the lack of data he has necessarily often faced in his position at the forefront of limnological problems.

I have indulged in describing these perspectives because they are not of the type that are taught in any text book; they are only imparted through a working situation. I hold this as the most valuable part of my experience.

In addition, several other people who served as committee members and advisors deserve special mention. Dr. Harry Shannon of the McMaster Biostatistics and Epidemiology Department is responsible for much of my understanding of statistics. His clearly organized presentations and sincere concern for understanding have made him an invaluable teacher.

Dr. Dave Rollo of the McMaster Biology Department was of exceptional help in providing me with a spirit of challenge for what might otherwise be taken as established. His fresh outlook, constructive criticism and enthusiasm have helped immensely as a source of inspiration.

Dr. Graham Harris, while also at the McMaster Biology Department, was responsible for my introduction to the fundamental importance of time and space scale considerations in ecology. To cast ecology in this light has given me some perspective on the implicit subjective elements involved in the technical exposé of natural systems, and with this awaraness, a better footing for balanced interpretation. His influence on my outlook became clear to me after he moved to Australia. Unknown to each other we simultaneously wrote papers of similar content despite our independent purposes and locations.

Dr. Joseph Kerekes contributed to this thesis in several ways. As co-author of the OECD Synthesis Report (Vollenweider and Kerekes, 1980) he was directly involved in compilation and preparation of the OECD data tape, which is part of the data used here. He further contributed the data for lakes of the Atlantic provinces that was used in both the OECD Canadian Contribution (Janus and Vollenweider, 1981) and subsequently this thesis. Finally, he was most helpful and generous with his time in discussion of my thesis work when it was only in its preliminary stages.

Sandra Horne, former secretary to R.A. Vollenweider, deserves special thanks for her enthusiastic typing of some early draft material and much appreciated encouragement at the very beginning of my writing.

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LIST OF SYMBOLS AND ABBREVIATIONS

Chl	chlorophyll
d	day
eu	eutrophic
kg	kilogram
l	litre
meso	mesotrophic
mg	milligram
oligo	oligotrophic
t	metric ton
UCC	Unusual Canadian Circumstances (a lake grouping)
SLR	Shallow Lakes and Reservoirs Project
$\bar{z}$	mean depth
z_{max}	maximum depth
β	(P_{ω}/P_{λ}); correction factor for the difference between lake and outflow concentrations
ρ	flushing rate (y-1)
σ	sedimentation rate (y-1)
τ	residence time
ζ	(z_{max}/z) ratio

SUBSCRIPTS:

j, i	inflow related
λ	lake related
n	nitrogen related
ω	outflow related
p	phosphorus related
s	sediment related
w	water related

PLOT SYMBOLS:

1	oliogotrophic
2	mesotrphic
3	eutrophic

1. INTRODUCTION

1.1 Overview of the Subject Areas Under Discussion

This research is an exploration of the residence times of nutrient elements in lakes taken up for the purpose of better understanding sedimentation, which is presently the least predictable aspect in the application of nutrient control for trophic management of lakes. Residence times describe flow rates of substances through systems or turnover times and are simply measured as a quantity divided by its replacement rate. Replacement rates are controlled by sediment - water interrelationships and flushing processes in lakes and, therefore, when residence times are calculated relative to flushing, they reflect the net result of sedimentation processes. The variety of mechanisms of physical, chemical and biological nature responsible for sedimentation, combined with the fact that they act independently or interactively, leads to the difficulty of predicting sedimentation rates. In addition, there is little information which identifies the most important controlling factors in a given lake and what their combined quantitative effects will be. Indeed, the observations show that each lake assimilates its nutrient input load in a different and temporally dynamic way.

The undefined nature of sedimentation presents problems for lake management since the latter is based on setting an upper limit for the load of the production limiting element (usually phosphorus in Northern temperate lakes) if a certain trophic status is to be maintained. However, the uncertainty associated with how much the lake will modify the input load (through sedimentation) and to what extent the remainder will be used in biological production means that the allowable limit for loading will vary with the lake, and possibly even from year to year in the same lake. Thus understanding the factors which control sedimentation, and how far they can be generalized, will be a step in the direction of more efficient and accurate predictions of the effects of nutrient enrichment or abatement.

In order to give some current perspective to the concept of residence times and its application to understanding nutrient cycling and trophic development of lakes, this introductory section will take up some historical review and descriptions of the main topics as follows.

First, a chronology of past approaches and problems of trophic definition will be described (cf. Section 1.2). This is followed by a section with particular emphasis on the history of the OECD Eutrophication Programme because of the advances made by this uncommonly consolidated, long-term scientific effort. The current status of "The Monitoring of Inland Waters; Eutrophication Control" (R.A. Vollenweider and J.J. Kerekes, 1982) as 'the Bible' for lake trophic management attests to the success of that programme and accounts for its prominence here. The advances made, present capabilities afforded by the OECD programme and remaining problems in predicting lake behaviour will be highlighted.

Second, the previous knowledge and uses of the residence time concept will be described (cf. Section 1.3). Residence time is a dynamic feature in contrast to concentration measurements, and represents a new and theoretically appealing approach to trophic characterization in view of the dynamic nature of trophic condition itself. Past studies using the concept of residence time are reviewed in order to demonstrate the scope of previous applications and the relatively unexplored ground of its relationship to the trophic condition of lakes.

Third, there is a section devoted to the description of the relationship between nutrient residence time and trophic condition (cf. Section 1.4). Previous studies are reviewed and these suggest that nutrient residence times differ with trophic condition in a systematic way. However, the present generalizations are based on cross-sectional data (from many different lakes). Such generalizations need to be demonstrated in individual lakes before they can be thought of as functional relationships and used for prediction. Thus the data analysis of this thesis is divided into two main parts (cf. Section 1.5. In the first part, time series analysis of nine case studies is used to compare residence time changes with trophic changes. In the second part, cross-sectional data is used to determine the best descriptive equations of nutrient relative residence times and how they differ with trophic categories.

1.2. Characterization of Trophic State

1.2.1. Chronological Review of Past Approaches and Problems

Trophic classification is a general conception which attempts to differentiate lakes on the basis of their overall productivity. Distinction on the basis of productivity evolved for a number of reasons. Foremost is the fact that variations in the productivity of plant and animal communities of lakes are of greatest interest with regard to human activities. Production levels within lakes determine their utility for water supply, fisheries, transportation routes and recreational facilities, as well as their aesthetic value. Secondly, the wide variations in the production of plant and animal communities are visually, perhaps, the most obvious differences among lakes and, therefore, biological production serves as a natural basis for classification. Thus classification is important as a means of identifying the general utility of waterbodies for different purposes, expressing in a concise way their relationships to one another and providing a basis for expectations regarding their features and reactions.

The current terminology "oligotrophic, mesotrophic and eutrophic", designating three basic categories of increasing productivity, originated from Weber's studies of German peat bogs (in 1907) and was adopted for lakes by Naumann around 1920 (Rodhe, 1969). The original meaning of eutrophic was 'well-nourished' and oligotrophic meant 'under-nourished', describing the sequence of nutrient conditions during the formation of a bog. Naumann applied these terms to describe the nutrient status of lake water specifically and, in his conception, a basin filled with eutrophic water resulted in a lake turbid with algal growth, while one filled with oligotrophic water remained transparent. With this he equated phytoplankton production to nutrient concentrations. The major underlying assumptions were that all lakes have similar exposure of nutrients in the euphotic zone and that they convert their nutrient potential into algal biomass with the same efficiency. Recognizing that this was not strictly true, Naumann suggested that "budgets" for light, temperature, detritus and various gases would have to be drawn up and their modifying effects taken into account. In an attempt to do this, Naumann's trophic system of 1932 consisted of more than 24 "pure" and "combined" lake types and included such categories as alkalitrophy, acidotrophy, argillotrophy and siderotrophy (Rhode, 1969) to account for the modified productivity of various lakes.

Contemporaneously (1925), Thienemann formulated a system to evaluate lake productivity based on oxygen conditions. The concept was that the oxygen reserve of the hypolimnion of a lake would be depleted in proportion to the requirements for decomposition of the organic matter produced. Oxygen depletion was inferred from the distributions of Chironomus species, a benthic larval insect form which survives low oxygen conditions (largely by virtue of hemoglobin in the blood). Thus, according to Thienemann, eutrophic lakes were characterized by algal blooms, clinograde oxygen curves, a euroxybiont Chironomus fauna, no stenotypic hypolimnetic fishes and were generally shallow and nutrient-rich (Hutchinson, 1969). The major assumptions of this system were that lakes form hypolimnia, which remain as isolated water masses over a period of time, representative of their relative productivities and that the ratio of epilimnion to hypolimnion volumes of different lakes were comparable.

With the development of analytical methods for water chemistry and the collection of new factual data, contradictions began to reveal the limitations of these first two classification schemes. Contrary to Naumann's system (which equated lake productivity to nutrient status), Pearsall (1932) found that blue-green algal blooms occurred in English lakes during periods of apparently severe nutrient deficiency, and Birge and Juday found no evidence of phosphorus changes during maintenance or increase of algal populations in Wisconsin lakes (Hutchinson, 1969). Similarly, contradictions to Thienemann's scheme (which equated lake productivity to oxygen depletion) were found. Ruttner's 1931 and 1952 studies revealed apparently oligotrophic tropical lakes of low plankton densities and high transparency, but marked oxygen depletion. Ruttner attributed this to temperature accelerated decomposition of sinking dead plankton (Findenegg, 1955). Hutchinson (1937) found that the Yaye Tso in Tibet, a shallow, oligotrophic lake at great altitude, had a stenoxybiont benthic fauna (indicative of oligotrophy), but developed a clinograde oxygen curve (indicative of eutrophy). Further, Findenegg (1955) reported oxygen depletion in apparently oligotrophic alpine lakes, but as a consequence of meromixis rather than eutrophic condition. Therefore, neither nutrient concentrations nor oxygen conditions were reliable as indicators of overall lake productivity.

In retrospect, a number of reasons for the breakdown of these initial proposals for lake classification can be identified. First and foremost was the fact that these systems were formulated in the absence of any quantitative data and, therefore, their basic assumptions were unfounded. Both Naumann and Thienemann had to infer chemical conditions from indicator organisms, i.e., phytoplankton and chironomids, respectively. Analytical chemistry later proved that these could not be strictly equated (as demonstrated by the studies referred to above). Hutchinson (1969) wrote "... the classification criteria for nutrient contents given by Naumann (1927) were either completely uncertain or wildly unrealistic, and, admittedly, were based on quite inadequate analyses". Furthermore, Naumann's expansion to 24 trophic types was inappropriate since these could not be placed in a sequence of increasing productivity; with this, much of the original intent of classification was lost.

A second aspect leading to the breakdown of Naumann's and Thienemann's systems was their overly restrictive assumptions regarding the uniformity of physical, chemical and biological processes in lakes. With few studies at their disposal, they could hardly anticipate the variation in such features as: seasonality of nutrient loading and subsequent temporal differences in algal production relative to stratification, efficiencies of nutrient-to-biomass conversions by the biota, oxygen production within the hypolimnion where extended euphotic zones existed, turbulence causing entrainment of oxygen from the epilimnion, etc. All contributed to distortion in the intended comparisons. The initial success of their systems was therefore highly dependent on the geographic and hydrologic similarities of their study lakes.

A third aspect leading to the breakdown of these early classification systems was the recognition that static measures such as concentrations were ambiguous in meaning. For example, low concentrations could be the result of either low initial supply (from internal and external sources), or abundant supply in combination with intense removal mechanisms (such as sedimentation and flushing). Static (instantaneous) measures would have to be replaced by rates - dynamic measures that reflected the balance between supply and loss over time.

One of the first schemes to incorporate rates was that proposed by Aberg and Rodhe (1942). They combined the idea of intensity of organic matter supply (as introduced by Strøm in 1931 who expressed this as areal hypolimnetic oxygen depletion rates) with Birge and Juday's distinction of sources, which could be either internal (autochthonous) or external (allochthonous). In this scheme, four trophic types could be distinguished according to organic supply rate and origin.

In a two-dimensional framework of increasing allotrophy versus increasing autotrophy, oligotrophic lakes reside at minimal levels of both. Amplification of the organic sources along a 1:1 line resulted in mixotrophy. If the increase was predominantly from external allochthonous sources, the classification was dystrophy or, if predominantly internal (autochthonous), the classification was eutrophy. The problem in practical application of this system was that no clear statement of the total primary productivity was possible since the methodology for its measurement had not been developed.

With the advent of radioisotopes after 1945, sensitive new techniques to determine the rates and pathways of various processes were developed. Radioactive carbon (^{14}C) was used in a technique to determine primary production rates and was introduced by Steeman Nielsen in 1952. Then, Hutchinson and Bowen (1947, 1950) and Hayes _et al._ (1952) were the first to add radioactive phosphorus to lakes. They showed that there was a rapid, exponential loss of phosphorus from lakewater to the mud and macrophytes which occurred within a few days. Equally significant, Hayes et al. (1952) showed that the phosphorus return from solids also proceeded exponentially, and that as more phosphorus was incorporated into the sediments, return became appreciable which tended to "hold up" the phosphorus content of the water. Further experimentation with radioactive phosphorus by Rigler (1956, 1964) revealed that its turnover time in the epilimnion was as brief as one minute. These experiments emphasized the rapid and very dynamic nature of nutrient cycling processes in lakes, and emphasized the inadequacy of single concentration measurements. Hutchinson (1969) concluded that a eutrophic system would be one where the "potential" nutrient concentration was high; what was important was "the total available supply in all forms and the rate at which it undergoes circulation".

It is precisely this aspect of circulation and ever-changing compartmentalization that has made a single measure of trophic condition so elusive. Although nutrients set the upper limits for biotic development, it remains unpredictable what percentage of the total potential will be used, and what phases or forms of the nutrient cycles will predominate. The nutrient potential does not always develop to the maximum biomass due to limitations set by such factors as biological efficiency, chemical availability (i.e., refactory nature of the compound) and physical distribution. Further, the efficiency of mixing has some bearing on the phase of the nutrient cycle which will predominate as a symptom of eutrophication. The symptoms of eutrophication are accumulations of either autotrophic or heterotrophic products and, therefore, represent the compartment in nutrient cycles where conversion or removal processes are slower than their formation processes. If the inorganic products (i.e., nutrients) from heterotrophic processes are not redistributed into the euphotic zone, the symptoms of eutrophication will take on the form of heterotrophic end products (either oxidized or reduced). If nutrients are efficiently distributed in the euphotic zone, the predominant symptom of eutrophication may be algal blooms. Therefore, the physical attributes of a lake determine to a large extent the distribution of substances and type of eutrophication symptoms which materialize from a given nutrient load. The fact that many different symptoms may appear from the same input is what makes trophic classification on the basis of a single entity somewhat untenable.

Recognizing the inadequacies of trophic classification on the basis of single parameters, limnologists began to formulate multivariate indices (cf. Table 1.1). The objective was to incorporate measurements of the severity of several symptoms into a single index which gave a relative rating of the degree of eutrophication of a lake. The advantages of multivariate indices over univariate ones was that they were less likely to lead to gross errors in classification. They could take into account the variety of symptoms eutrophication might show due to the different phases of nutrient cycles. This made multivariate indices more robust than their precedents based on single criteria.

The search for a generally applicable index of trophic status intensified after about 1960. Prior to this, only a few attempts at classification (as previously described) had been made (and their failure to simultaneously accommodate many different lake types largely dispelled the idea that any generalizations were possible). However, the widespread emergence of eutrophication around 1960 gave special impetus to this line of research and the variety of approaches to establishment of a trophic index are listed in Table 1.1.

These "index" studies were important for a number of reasons. First, it was of importance to establish the present status of lakes relative to one another in an objective way, and to define the geographic extent of the eutrophication problem. Secondly, an index was necessary to monitor the rate of deterioration, or rate of improvement following lake restoration measures. A third aspect was that these studies provided the first information on the ranges and correlations of factors associated with eutrophication and thus provided some basis for subsequent formulation of causal relationships.

Despite the information gained through these studies, a number of serious problems persisted. The attempts to gain stability and generality through a multivariate approach to

TABLE 1.1. INDICES: RECENT APPROACHES TO TROPHIC STATE QUANTIFICATION

Year	Authors	Index Name	Number of Variables to Formulate Index	Variables Used	Mathematical Approach of Derivation	Geographic Region Represented	Number of Lakes in Original
1968	Vollenweider, R.A.	(Categorical assignment)	1	Summer epilimnetic alkalinity decrease	Probability	Northern temperate (European alpine lakes)	41
1970	Lueschow et al.	(Trophic state index)	5	DO at bottom, ON, TIN, SD net plankton	Sum of numerical ranking for 5 variables	Northen temperate (Wisconsin)	12
1972	Shannon, E. and P. Brezonik	(Trophic state index)	7	PP, Chl a, TP, TON, SD, conductivity (Na+K)/(Ca+Mg)*	Principal components (BMDPX72 computer program)	Subtropical (north, central Florida)	55
1972	Michalski, M.F.P. and N. Conroy	(Average rank)	6	z, transparency Chl a, O_2 distribution, anaerobic (Fe/P) ratio, morpho-edaphic index$^+$	0 to 10 ranking averaged for 6 variables	Northern temperate (Ontario)	10
1974	U.S. EPA	Trophic Index System	6	TP, IN, SD, Chl a, DO, dissolved P	Sum of percentile ranking for 6 variables	Northern temperate to subtropical (U.S.A. lakes)	200
1974	Carlson, R.E. (cf 1977 publication)	T.S.I. (trophic state index)	1 of 3	SD (or by substitution TP or Chl a)	Linear transformation of Secchi depth (0 to 100 scale)	Northern temperate (U.S.A.)	147
1976	Piwoni, M.D. and G.F. Lee	(trophic state index)	10	Chl a, SD, OD as % lake volume, PO_4 P winter, PO_4 P summer, TP, winter, TP, summer TIN winter, TIN summer, ON 2 wk average for epilimnion	Sum of numerical ranking for 10 variables(as Lueschow et al., 1970)	Northern (temperate Wisconsin)	-

TABLE 1.1. cont'd.

Year	Authors	Index Name	Number of Variables to Formulate Index	Variables Used	Mathematical Approach of Derivation	Geographic Region Represented	Number of Lakes in Original
1978	Rast W. and G.F. Lee	(Trophic index system)	2	L_p, Q_s	Ranking by load in excess of Vollenweider's "permissible" load (as defined in L_p vs Q_s plot, 1975)	Northern temperate (U.S.A. waterbodies)	38
1978	Reckhow, K.	(Probability of oxic or anoxic conditions)	3	L_p, z, Q_s	Discriminant analysis (BMDP computer program)	Northern temperate (U.S.A. and Canada)	55
1978	Schroder, R. and H. Schroder	(trophogenic/ tropholytic) quotient	8	Chl a, TP, NH_4, temperature 0-10 m, temperature of hypolimnion insolation, z, A_s	Ratio of multiple regressions which describe Chl in trophogenic and tropholytic zones	Northern temperate (Germany)	14
1979	Walker, W.J.	I	3	Chl a, TP, SD	Average of modified versions of Carlson's T.S.I. for each variable	Northern temperate (Connecticut, Canada, other U.S.A. lakes)	30
1980	Forsberg, C. and S.-O. Ryding	(Categorical assignment)	1 of 4	TN, TP, Chl a, SD	Probability	Northern temperate (Swedish lakes)	30 (intensive sampling)
1980	Porcella, D.B., S.A. Peterson and D.P. Larsen	L.E.I. (lake evaluation index)	5	SD, TP, Chl a, DO, macrophyte coverage	Expanded version Carlson's T.S.I. (0 to 100 scale)	Northern temperate	209

TABLE 1.1. cont'd.

Year	Authors	Index Name	Number of Variables to Formulate Index	Variables Used	Mathematical Approach of Derivation	Geographic Region Represented	Number of Lakes in Original
1980	Vollenweider, R.A. and J.J. Kerekes	(Categorical assignment)	1 of 5	TP, TN, Chl, Chl maximum, SD	Probability	Northern temperate (OECD lakes)	120 (approx.)
1983	Canfield, D.E. *et al.*	--	2	TP in water column, P in macrophyte biomass	Sum of P components gives total potential P concentration; used e.g., in Carlson's, Forsberg's or Vollenweider's schemes above	Subtropical (Florida)	6

* Pearsall's cation ratio (1922)
\+ Ryder's (TDS/z) ratio (1965)

Key to abbreviations:

DO = dissolved oxygen
ON = organic nitrogen
TIN = total inorganic nitrogen
SD = Secchi depth
∑PP = areal primary production
Chl *a* = chlorophyll *a*
TP = total phosphorus
TON = total organic nitrogen
OD = oxygen depletion
L_p = phosphorus load
Q_s = hydraulic load
z = mean depth
A_s = lake surface area

indices made practical application more cumbersome since a greater number of measurements was required. Then, the presupposition was that each parameter would change monotonically over the trophic continuum and that an increase in trophic condition represented a simple amplification of the processes taking place at a lower status. In addition, some indices were formulated on the basis of restricted geographical regions (e.g., Florida lakes, Wisconsin lakes) and were not necessarily transferable. Perhaps the greatest weakness of all was the lack of concern for distinguishing dependent from independent variables or for the strong collinearity amongst the indicator variables (despite the straightforward statistical nature of index formulations). This later deficiency meant that indices were little more than statements of coincidence. Functional relationships remained undefined and the classification associations provided little guidance or leverage for lake management.

In historical perspective, the research on trophic classification and indices must be seen as only one specific topic of many concurrent studies related to eutrophication. The many international meetings dedicated to eutrophication (cf. Appendix 1.1) embodied hundreds of detailed studies of physical, chemical and biological processes affecting the productivity of lakes. Little was known about the relative importance of these details since the causal factors of eutrophication were still a matter of debate. More specifically, the discussion of the ASLO

(American Society of Limnology and Oceanography) Special Symposium entitled "Nutrients and Eutrophication: The Limiting Nutrient Controversy" (Likens, 1972) centered around the relative importance of carbon, nitrogen, phosphorus and micronutrients in the eutrophication process. It appeared that all these factors could control productivity at one time or another. The "piecemeal" nature (i.e., lack of comparability) of the evidence implicating one factor or another presented at these large congresses meant that little was resolved. A more consolidated effort was necessary.

The consistency of approach made possible through the OECD Programme on Eutrophication has been both unique and of paramount importance in the practical solution of eutrophication problems. It was only through this long-term effort under the unified philosophy of R.A. Vollenweider that some well defined statements on behavior of lakes could be made.

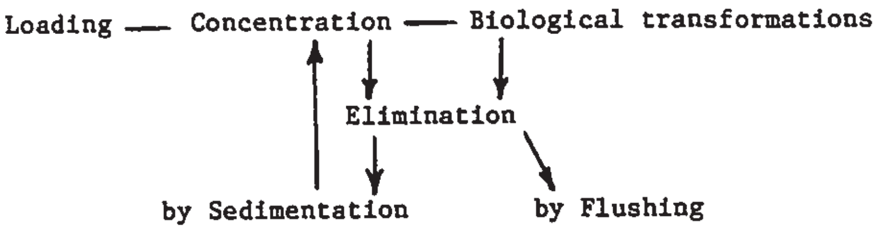
1.2.2 Recent Advances of the OECD Programme on Eutrophication

The OECD was formed in 1960 by 18 western European and North American nations with the express purpose of maintaining the highest economic growth possible. Ironically, the urban development, agricultural intensification and population growth implied by this credo were later identified, in a general sense, as the very causes of eutrophication problems which, subsequently, resulted in substantial economic losses. These losses (due to increased treatment costs for drinking water, deterioration of aesthetic properties and, therefore, depression of tourism, the loss of fisheries, hinderance of navigation, etc.) were severe enough to delineate the need for a solution to eutrophication problems as a major priority. With this, the OECD commissioned a long series of scientific investigations (which may be traced in Appendix 1.1) devoted to finding some practical solutions for eutrophication.

The first step in the scientific efforts of the OECD began with the appointment of R.A. Vollenweider in 1966 to produce a technical report collating all the pertinent facts on eutrophication. This culminated in the now well known classic entitled "Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication" (Vollenweider, 1968). The most significant points emerging from this report were (i) that nitrogen and phosphorus appeared to be the most important nutrients responsible for eutrophication; (ii) as a first approximation, the trophic level of a waterbody is endangered when phosphorus compounds exceed 10 $mg \cdot m^{-3}$ and inorganic nitrogen exceeds 200 to 300 $mg \cdot m^{-3}$; (iii) the major sources of these nutrients included municipal waste waters and agricultural runoff, which carried phosphate rich sewage, detergents and fertilizers; and (iv) since phosphorus sources were often highly localized "point" sources, much could be done to prevent further deterioration of water quality by immediate measures to control these sources.

Perhaps the greatest difficulty in establishing these points arose from the fact that the data from which they were derived were largely anecdotal. There were no standard guidelines for sampling or measurement methods and valid comparisons were difficult to extract. To overcome this difficulty the "Steering Group on Eutrophication Control" set up an "Agreed Monitoring Project on Eutrophication of Waters" and in 1973 established the "International Co-operative Program on Eutrophication". The 18 countries participating in the eutrophication program used the established guidelines to collect data on nearly 150 waterbodies between 1974 and 1976. The results of these efforts were published as four regional reports including: Alpine Lakes (Fricker, 1980), the Nordic Project (Ryding, 1980), Shallow Lakes and Reservoirs (Clasen, 1980), and the North American OECD Project (U.S. Portion) (Rast and Lee, 1978).

The data base provided by the four regional reports was subsequently summarized in the "Synthesis Report" (Vollenweider and Kerekes, 1980), now known under the published title "The Monitoring of Inland Waters; Eutrophication Control" (Vollenweider and Kerekes, 1982). A general philosophy behind this report was that some overall patterns of lake behavior existed (despite the prevalent attitude among limnologists that each lake would have to be studied on its own before predictions were possible). The basic conceptual framework underlying the report is summarized in the following diagram (Vollenweider, 1975):



In addition to a statistical analysis of the relative roles of nitrogen and phosphorus in controlling chlorophyll, the "Synthesis Report" gives simple regression results which quantify the relationships between (a) nutrient loadings and lake concentrations and (b) lake concentrations and trophic response characteristics (as depicted above). The major findings of the "Synthesis Report" may be summarized in the following points:

(1) Phosphorus is the element most often limiting biological growth in lakes and is therefore a key factor in eutrophication control.

(2) Lake concentrations of phosphorus are functionally related to loading and may be predicted (±50%) from it.

(3) Chlorophyll (a measure of trophic response) is related to phosphorus lake concentration and may be predicted (±50%) from it.

(4) Trophic state may be predicted from loadings or lake concentrations of phosphorus using a probabilistic scheme (constructed on the basis of past experience, cf. Figure 1).

The importance of the OECD regressions was that they provided the first quantitative relationships describing the general conditions to be expected in Northern Temperate Lakes. They could, therefore, be used as a diagnostic reference, or as a management tool to estimate loading levels necessary to maintain a desired chlorophyll (biomass) level.

As a follow-up to the "Synthesis Report", the "Canadian Contribution" (Janus and Vollenweider, 1981) was prepared as a test case, which essentially took the form of a residuals analysis. An independent set of Canadian data representing approximately 100 lakes was superimposed on the previously defined "OECD lines". In general, the basic trends of the OECD relationships were confirmed. In addition, a number of conditions creating deviations from the expected relationships were identified. This was of particular importance in highlighting situations where predictive use of these equations would require caution.

With completion of these seven major reports (as described above), the OECD's Programme on Eutrophication essentially drew to a close with a number of significant achievements. Phosphorus was identified as the prime factor of importance in setting the upper limit for the trophic development of lakes.

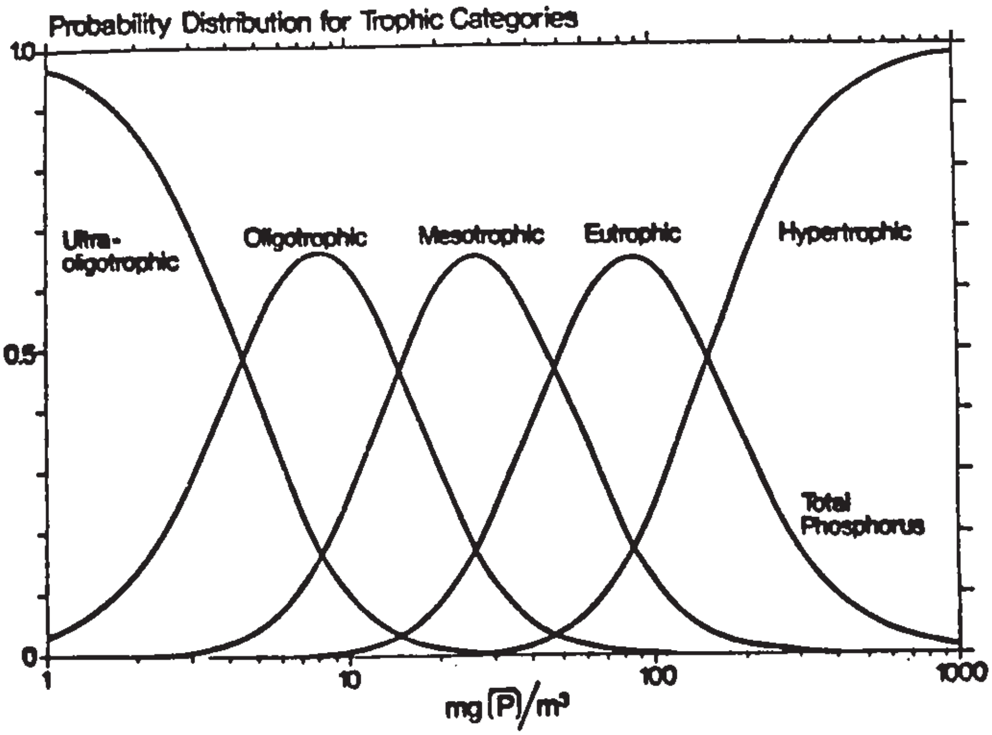


Figure 1.1 Vollenweider's (1968) probabilistic classification of lakes according to annual average lake phosphorus concentrations.

The view of lakes as open systems was firmly established. Input-output models based on mass balance provided the essential conceptual organization by which first approximations of lake concentrations from loadings could be made (Vollenweider, 1975, 1976). The range of values in nutrients and trophic indicators expected in each trophic category was established. Using this information, nutrient levels compatible with a chosen trophic status could be identified and nutrient loads necessary to achieve these levels could be calculated. The management of trophic condition was thus set in quantitative terms for the first time.

The ideas of Vollenweider (1968, 1969), which were subsequently developed in the OECD programme under his direction, had direct practical application from the very start. Most notably, as early as 1972, this work served as the basis of the "Water Quality Agreement between Canada and the U.S." for setting the target loads for preservation of the Laurentian Great Lakes. Further repercussions from the ability to set a definite target load included such technological changes as construction of treatment plants for removal of phosphorus from industrial and municipal wastewater, reformulation of phosphate detergents, and modification of agricultural practices, to name a few.

Despite the tremendous advances made by the OECD programme, present methods to predict lake behavior still remain as first approximations. In the first instance, a certain information gap has existed which has presented the problem that in the prediction of lake concentrations from loadings, sedimentation coefficients used in mass balance models have been estimated from statistical relationships in cross-sectional data (i.e., one year's data on many lakes). Hypotheses using such parameters as water residence time, mean lake concentrations, annual loadings or bottom surface area as the independent variable have been proposed by different workers. These have met with various successes in describing different lakes, but the functional content of such relationships remains to be verified by individual lake reactions. Only a few cases (i.e., lakes) exist where sedimentation has been measured as a temporal sequence, and those known are analysed here in the time series section on individual lakes to determine the extent to which the cross-sectional relationships are transferable.

As a second aspect of the problem of predicting lake behaviour, the relationship between nutrient concentration and trophic condition is only a probabilistic description at present. At a given lake concentration, there is at least a small probability that nearly any trophic condition will develop (cf. Figure 1.1). This uncertainty of trophic condition arises due to variations in the efficiency of conversion of nutrient potential into biomass. Further uncertainty arises from variation of the feedback mechanisms which complete nutrient cycles by conversion of biomass back to nutrients, which tends to mask the trophic condition - nutrient concentration relationship. Therefore, as an alternative to concentrations, nutrient dynamics in terms of residence times will be examined for their potential to portray trophic condition.

1.3. Characterization of Residence Time

The "residence time" of a substance may be described and expressed mathematically in some rather simple terms (as in the Section 1.3.1. below). However, it is in fact a complex concept which represents the aggregate effect of many processes acting simultaneously. These processes include all physical, chemical and biological reactions which shape the dynamics, and hence residence time, of the substance in question. Some insight into the variety of pathways and mechanisms which regulate substance dynamics has been gained in a number of studies since the late 1930s. These show that a great variety of regulating processes exists. Some details of these processes are set out in Section 1.3.2. below in order to present the current knowledge of factors which may modify residence time and its temporal evolution. One goal of the subsequent analysis in this thesis is evaluation of the relative importance of these processes.

1.3.1. Definition and Description

The residence time of a substance refers to the length of time that that substance remains within a well-defined pool. In the present context, it is descriptive of the exposure time of nutrient elements in the water column of lakes. (The water column, or more simply lakewater, is the defined pool and excludes nutrients stored in biota or deposited on the lake bed as sediments.) Residence time may be thought of variously as a fill-in, turnover or flow-through time. In operational terms, it may be defined as a quantity divided by its replacement rate:

$$\text{residence time [T]} = \frac{\text{quantity [M]}}{\text{replacement rate }[\mathrm{M \cdot T^{-1}}]} \qquad (1.1)$$

As a simple example, water residence time in lakes is calculated as lake volume (m^3) divided by water load ($m^3 \cdot y^{-1}$) which results in a measure of the time (y) required for renewal of the lake volume. It becomes evident from equation (1.1) above that residence time is determined by replacement rate, assuming the steady-state condition that the quantity of substance within the pool remains constant over time. Replacement rate may be measured as either the sum of the inflows or the sum of the outflows (which are equivalent by definition of steady-state). Technically speaking, the true replacement process in lakes is stochastic and therefore, total (100%) exchange of an element approaches asymptotically in time. However, if the units of the substance in question are considered interchangeable, replacement may be measured as a well defined rate.

Since "replacement" encompasses the full range of physical, chemical and biological mechanisms which regulate substance dynamics, alteration in the rates of any of these processes may alter substance residence time seasonally and yearly within a given lake system. Furthermore, residence time may vary from lake to lake due to differences in the types of processes in operation. Both time-series data and cross-sectional data must be used to evaluate these sources of variation in residence times.

Extending the residence time concept to compare the dynamics of two substances, a relative residence time may be calculated as the ratio of the residence times of two substances. A relative residence time gives a measure of the relative activity or flow-through rate of one substance to another. A most informative calculation is that of relative residence times using a nutrient substance relative to water. This essentially normalizes for hydraulic elimination and reflects the intensity of (primarily) the combined chemical and biological elimination components of replacement. (All subsequent references in this text to "relative residence time" assume the ratio of a substance to water, unless specified otherwise. Note that although referred to as a "time", the relative or ratio expression is dimensionless.)

On the basis of their reactivities, substances may be classified as "conservative" or "non-conservative" and this is reflected by their residence times. Conservative substances are defined as those which do not participate in any chemical or biological reactions. The flow-through rates of such substances are entirely dependent on physical transport by hydraulic flushing and, as such, have residence times equivalent to water. Therefore, their relative residence times are equal to 1. On the other hand, non-conservative substances are involved in chemical and biological reactions which enhance their replacement (elimination) rates. An increase in replacement rates beyond hydraulic flushing means that the residence times of non-conservative substances are less than water residence times. Therefore, the relative residence time ratios of non-conservative substances fall below 1. The magnitude of the decrease below 1 is indicative of the intensity of chemical and biological elimination.

1.3.2. Regulating Mechanisms and Pathways

As previously described, residence times are regulated by the combined effects of physical, chemical and biological elimination processes. Within each of these general categories, a number of studies have been made which identify some of the specific pathways and mechanisms important in the elimination of substances from lakes. A brief review of the studies on individual mechanisms and pathways is given below since these suggest factors which may be important in the explanation of residence times. The arrangement is chronological since the concept of residence times is just beginning to evolve, and although many important studies have direct bearing on this topic, they do not explicitly mention residence times. It is the intention here to refocus this background knowledge using "residence times" as an organizational theme.

The importance of oxygen as an indicator of the essential metabolic dichotomy of eutrophic versus oligotrophic lakes was recognized from the very beginning of trophic classification (cf. Section 1.2.1.), however, its role in the regulation of nutrient dynamics was not apparent until the classic studies of Mortimer. In the late 1930s, observations on lakes undergoing hypolimnetic oxygen depletion revealed that oxygen exhaustion was accompanied by reduction processes and that simultaneously there were large increases in the concentrations of dissolved nutrients which were <u>not</u> products of reduction. From this, Mortimer (1941) surmised that "oxidation-reduction conditions may exercise a profound influence on organic production, not only in determining the free energy of the environment, but also in affecting the rate of supply of nutrients". With this general notion in mind, he directed his studies more particularly towards analysis of the mechanisms by which redox conditions in the mud controlled the dynamics of dissolved nutrients.

In his extended publication of 1941 and 1942, Mortimer characterized lakes as reversible systems which may go through a cycle of stages driven by seasonal mixing. The stages he delineated were: Stage I, slow oxygen depletion and rise in both alkalinity and conductivity as stratification developed; Stage II, rapid fall in redox potential at the sediment surface, rapid rise in alkalinity, conductivity, Fe, Si, P, colour and turbidity, NO_3^- conversion to NO_2^-, all following extended stratification; Stage III, the processes of Stage II continued, but at a reduced rate up to the end of stratification; and finally at overturn there was a rapid reversal of all reduction changes. In regard to the particular mechanisms at work, the observations of Stage II indicated that adsorbed bases and Fe^{++} were liberated when colloidal Fe-precipitates were reduced. Conversely, when oxidized, the mud surface constituted an adsorbent barrier. These changes were reproduced in artificial mud-water systems subjected to aerobic and anaerobic conditions, and with this Mortimer demonstrated the profound influence of oxygen in the regulation of seasonal nutrient dynamics.

Finally, in a comparison of the seasonal cycles in lakes of different trophic condition, Mortimer was able to show that the extent of sediment reduction and nutrient flux was magnified with increasing trophic status. This relationship is discussed in the Section 1.4. which follows.

With the advent of radiotracers, one of the first direct demonstrations of the pathway of phosphorus in lakes was published in 1947 by Hutchinson and Bowen (Hayes, *et al.*, 1952). By addition of the tracer ^{32}P to a small eutrophic, stratified lake in Connecticut, they demonstrated that the epilimnion mixed, there was rapid uptake by littoral plants (1000-fold concentration and equilibration in one week), and there was a steady gain of the tracer by the hypolimnion. The hypolimnetic gain was attributed to sedimentation of dead plankton and faeces, and subsequent return from the mud.

Similar experiments were conducted by Hayes _et al._ in 1952. They also found rapid uptake of ^{32}P by plants and mud, but attributed the delayed loss in deep water to slower equilibration with the mud than live organisms (rather than return from mud). In addition, Hayes _et al._ were apparently the first to report phosphorus residence times of lakes; three Nova Scotia lakes were calculated to have phosphorus residence times of 5.4, 7.6 and 17 days. This paper was also important as the first to project a relationship between phosphorus residence time and eutrophication (which is further discussed in Section 1.4.).

In a follow-up paper, Hayes and Beckett (1956) showed that mineral flows were not restricted by thermal barriers. The rapid uptake and conversion of inorganic nutrients to organic particles by micro-organisms facilitated nutrient flows by sedimentation and migration phenomena. Furthermore, diffusion (as influenced by temperature) was suggested as an important mechanism governing the vertical flow of nutrients in addition to the flows created by turbulence.

A third paper by Hayes and Phillips (1958) reported "the remarkable ability of bacteria to hold phosphorus in the water" under both aerobic and anaerobic conditions. In over 100 artificial sediment-water systems, approximately 66% of added ^{32}P remained in the water after one week, but only 10% remained in systems where bacteria were killed with antibiotics. The suspension effect of bacteria was attributed to an accelerated return of phosphorus from the mud and/or bacterial ability to hold phosphorus from chemical or colloidal adsorption by the mud. They found these reactions uninfluenced by the productivity or redox state of their systems.

In the same year, Hepher (1958) found that most (usually more than 95%) of the phosphorus added to alkaline fishponds of high calcium content was precipitated as $Ca_3(PO_4)_2$. Furthermore, the fixation of phosphorus to the mud was greatest where $CaCO_3$ and total colloids were highest and least where there was accumulation of organic matter. In this environment, phosphorus fixation was enhanced where mud was mixed with pondwater by the activities of carp.

In a study of Lake Ontario by Chau _et al._ (1970), chlorophyll _a_ was found to be positively correlated with trace element concentrations. Although the original intent of this work was to find the role of trace elements in regulating primary productivity, the observations may also be interpreted in terms of the scavenging properties of organic particulates, now known to be important in regulating the chemical composition of waterbodies.

The 1971 review publication of Stumm and Leckie appears to be the second paper (after Hayes *et al.*, 1956) to explicitly mention phosphorus residence time. They point out that the productivity of a waterbody is dependent on its phosphorus reserve. The phosphorus reserve is not a simple function of supply and hydrographic conditions, but depends also on its relative residence time as influenced by the biota, mixing relationships, lake morphometry and sediment exchange or retention.

Stumm and Leckie (1971) further described specific mechanisms important in phosphorus dynamics. Emphasis was placed on the calcium-phosphate system, believed to be a major control mechanism of the distribution of phosphorus. Initially, the precipitation of calcite ($CaCO_3$), which is regulated by the partial pressure of CO_2, forms nuclei for epitaxial growth of apatite ($Ca(PO_4)_6(OH)_2$ (s); pH 6.8 to 8.3). The phosphate removal is proportional to the surface area of calcite. Fluoride enhances this reaction while magnesium inhibits it. At slightly lower pH (about 6) iron and aluminum phosphate complexes may form. Clays are also important scavengers for phosphate. Biological scavenging and deposition in the sediments by phytoplankton and bacteria is another important removal mechanism. Once these compounds reach the lake bottom, recycling is regulated by the phosphorus-binding capacity of lake muds. This is positively correlated with the mineral content of the sediment and is further dependent on the iron cycle.

In consideration of all these factors, the publication of Stumm and Leckie (1971) concluded that the productivity of lakes could not be managed by setting critical concentrations because the rate of biomass production by phytoplankton was primarily regulated by the rate of supply of phosphorus to the trophogenic zone (from both external and internal sources). According to them, "This rate is a composite function of the rates of (1) regeneration of nutrients from biota (biological turnover) and detritus, (2) supply of P to the lake, (3) exchange with the sediments, and (4) transport processes (sedimentation, upwelling, convection, diffusion)".

The first quantitative discussion of the relationship between phosphorus and nitrogen relative residence times and trophic condition is apparently that in an unpublished manuscript by R.A. Vollenweider (1974). The data on 14 lakes covering the full range of trophic types showed that nitrogen residence times ranged from less than 1 up to 30 years, while phosphorus residence times ranged from less than 1 to only 5 years. Phosphorus was eliminated from lakes rapidly (5 years) even where water residence time was as long as that of Lake Vattern at 57 years. In terms of relative residence times (i.e., correcting for water flow), the range for nitrogen was 0.25 to 0.95 and that of phosphorus was 0.09 to 0.82. Comparing the absolute residence times of nitrogen and phosphorus to water, Vollenweider (1974) found that while residence times of both elements were dominated by water, nitrogen seemed to be more strongly dependent on simple dilution than phosphorus. Further comparison of the flow velocity of nitrogen with phosphorus showed that despite the expected coupling of these elements through metabolic pathways, their flow velocities showed a pattern of uncoupling related to trophic conditions. (This relationship is taken up further in Section 1.4.) In concluding this manuscript, Vollenweider noted that the concept of limiting factors had evolved from concentrations to supply (to account for recycling and metabolic transformations), and finally to residence time (to account for both supply and elimination). Since the data were considered preliminary and the trophic relationships had not yet been demonstrated in the evolution of single lakes, this line of research was left open for further development.

The residence times of trace elements in the ocean were compared by Craig (1974). He reported "scavenging residence times" for the following elements: Cu = 1400 y, Sb = 3200 y, Sc = 2500 y, Ni = 3000 y and ^{210}Pb = 50 y. Chemical and biological agents were responsible for the removal of elements from surface waters to deep waters. He found his evidence for scavenging of Pb and Cu, but not Ni, consistent with the theory that clay minerals were the scavenging agent for Pb and Cu.

In concurrence with the ideas of Vollenweider on the uncoupling of nutrient flows, Banse (1974) suggested that the ratios of removal of carbon, nitrogen and phosphorus from the surface waters of the ocean should not be taken as the ratio in newly formed organics despite Redfield's (1934) longstanding claim to the contrary. Banse pointed out that dissolved and particulate organic pools generally exceeded the plankton and that small shifts in remineralization could lead to large changes in the concentrations of inorganic nutrients. Furthermore, none of the conversion rates in the cycling of elements between inorganics and seston were necessarily correlated.

Lerman (1974) used the previously established model of lakes as steady-state mixed reactors to compare the removal rates of 5 elements in 22 lakes of North America and Western Europe. The removal rates as a percentage of input loads were reported as: P, 25 to 50%; ^{137}Cs, 25 to 65%; ^{90}Sr, 1 to 4%; and Na and Cl, 0.5%. For elements of similar loading rates, higher removal rates resulted in lower concentrations.

P.W. Schindler (1975) used the observed residence times of nine elements in the sea to test a model describing trace metal removal. The existence of metal removal processes was clear from the fact that seawater is undersaturated with respect to metal hydroxides and carbonates, however the mechanism was not clear. Schindler proposed that the major mechanism was coprecipitation, including:

> "(i) uptake in the lattice of in situ formed solids (calcite, aragonite), (ii) incorporation into the organic debris, and (iii) adsorption at inorganic particulate matter (clay minerals, ferric oxide, manganese dioxide, in situ formed silica, etc.)."

The success of Schindler's model in predicting observed residence time implied that the main metal removal mechanism in seawater was adsorption and sedimentation by inorganic particulate matter, however, this model failed to predict the observed residence times of Ca and Pb. The unexplained removal of Ca was most likely precipitation of $CaCO_3$ (Schindler, 1975), but no explanation was offered in the case of Pb.

The ideas on residence times of nitrogen and phosphorus in lakes as related to eutrophication that had been set out in Vollenweider's 1974 manuscript were published formally in 1975. In this manuscript the observed relative residence times in 11 European and North American lakes were used to evaluate a mass balance model which employed a statistically estimated sedimentation coefficient based on mean depth. This suggested that the basic model was acceptable but refinements in estimating sedimentation were desirable. Secondly, the observed relative residence times for N and P were all less than 1, even in eutrophic lakes. (Values greater than 1 would be indicative of internal loading and/or meromixis.) As a third point, Vollenweider suggested that the most informative aspect of relative residence times was comparison of the ratio of two substances which were metabolically associated. This would give a measure of relative flow-through rates or degree of coupling of the two substances. In the case of N and P, Vollenweider (1975) presented the hypothesis that the relative residence time ratio (τ_n/τ_p) would decrease and approach 1 with increasing biological production as these nutrients they were incorporated into organic matter and sedimented out at proportional rates. Although this hypothesis remains to be confirmed, the data from 7 lakes showed that this ratio (τ_n/τ_p) indeed dropped with increasing degree of eutrophication, and in the most eutrophic lakes, the ratio was considerably below 1. Vollenweider's interpretation was that although "phosphorus is the initiating factor - the nitrogen metabolism becomes accelerated with increasing eutrophication, and this acceleration may likely be driven beyond the point of a simple nitrogen-phosphorus relationship, probably due to increasing denitrification." Finally, Vollenweider postulated that when the (τ_n/τ_p) ratio dropped below 1, nitrogen became the controlling factor and thus the (τ_n/τ_p) ratio could be used as a simple measurement to identify the limiting nutrient (cf. Figure 1.5, subsequently). The limiting nutrient would be defined as the one with the most rapid flow-through, or shortest relative residence time.

In a follow-up publication, Vollenweider (1976) used the relative residence time concept to refine estimates of critical loading levels of phosphorus. The statistical relationship of phosphorus relative residence time (τ_p/τ_w) to water residence time (τ_w) was used as a means of estimating a generalized sedimentation coefficient. This led to substantial improvement in demarcation of the boundary between eutrophic and oligotrophic lakes which was previously based on mean depth ($\bar{z}$) or hydraulic load ($\bar{z}/\tau_w$).

Sonzogni _et al._ (1976) used residence time of phosphorus to estimate recovery rates for lakes which had undergone restoration measures. They suggested that their model based on the reactivity of the element was more appropriate and realistic than recovery time estimated from hydraulic wash-out alone. Assuming a negative exponential approach from the initial phosphorus concentration to the new (steady-state) concentration following e.g., a loading reduction, they estimated that 50% and 95% of the expected recovery would take place after 0.69 τ_p and 3.00 τ_p, respectively (cf. Figure 1.2). Although few data were available to test this model, it appeared to be confirmed by the information available for Lakes Washington, Kegonsa and Waubesa. In conclusion, Sonzogni _et al._ (1976) suggested that this model had potential for assessing recovery rates following rehabilitation measures (provided the effects of such measures on sedimentation and flushing could be estimated).

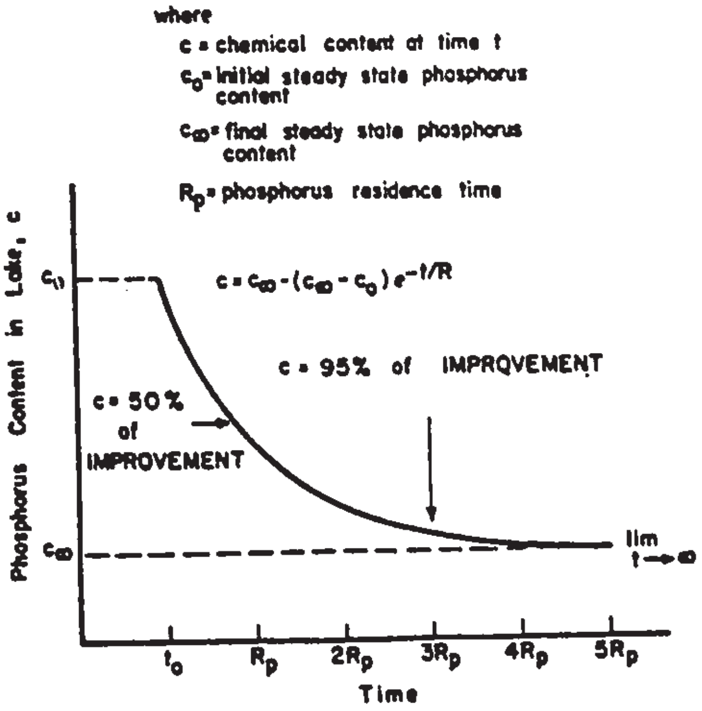


Figure 1.2 Rate of recovery of a lake following a step-change reduction of the phosphorus influx, from Sonzogni *et al*. (1976).

Cherry et al. (1978) found that the residence times of 15 elements in the sea were inversely related to their concentrations in zooplankton fecal pellets. Thus they suggested that the residence times of many elements were controlled by the mechanism of transport and deposition via fecal pellets.

Schwarzenback et al. (1979) used the residence times of two chlorinated hydrocarbons to infer mass transfer coefficients of their release into the atmosphere. The two compounds investigated were common pollutants of municipal and industrial sewage released into the Zurichsee. Since toth were volatile compounds resistant to chemical and biological degradation, transfer to the atmosphere appeared to be the most likely elimination mechanism. This was confirmed through mass balance calculations and concentration vs. depth profiles showing loss of these compounds from the epilimnion during stratified periods, with loss from the hypolimnion during mixing.

Balistrieri et al. (1981) noted that the low dissolved trace metal content of the ocean could not be explained by lack of supply and, therefore, efficient removal processes must exist. They found that the interactions of metals with organic compounds closely resembled those of metals with marine particulate matter. From this they deduced that the adsorption properties of particulates are controlled by organic coatings, which, therefore, control metal residence times.

Li's (1981) investigation of mechanisms regulating geochemical cycles in the ocean, in agreement with the work of Cherry et al. (1978), reported fecal pellets as the predominant transport mechanism of most elements in the sea. However, Mn, Co and Ni were found to be exceptions that appear to be controlled by direct incorporation into pelagic clays at the sediment-water interface.

Stumm and Morgan (1981) used residence times to explain the chemical composition of the ocean. They noted that the proportions of major ions in average river water and seawater differed, and therefore, removal processes exerted the predominant control on the chemical composition of the sea. These removal processes included (i) chemical equilibrium between sediments and seawater, and (ii) kinetic regulation by the interaction of supply rate with biological and mixing cycles. Oversaturation was the result of low reactivity and long residence time while undersaturation was the result of highly reactive substances with short residence times. Each removal process in which an element participated could be thought of as a fractional residence time. The overall observed residence time could be expressed as the sum of the fractional times as follows:

$$\frac{1}{\bar{\tau}} = \frac{1}{\tau_1} + \frac{1}{\tau_2} + \frac{1}{\tau_3} \ldots + \frac{1}{\tau_n} \qquad (1.2)$$

(Stumm and Morgan, 1981). Long fractional residence times represented weaker fluxes which contributed little to the overall flow-through rate of a substance. Phosphorus and silica, as biolimiting, reactive elements, were reported to have oceanic residence times of 2 x 10^5 and 6 x 10^5 years, respectively, in contrast to the unreactive element sodium with a residence time of 2 x 10^8 years. In applying these ideas, Stumm and Morgan (1981) noted that the explanation of residence times in lakes was more complicated than the sea because interactions with the sediments were greater, removal by flushing was an additional consideration and spatial proximity meant that time scales were shorter.

In a separate publication, Stumm _et al._ (1983) concerned with assessment of the impact of chemical pollution, suggested that chemodynamic concepts are needed to permit estimation of residence times (and therefore residual concentrations) in order to predict the relative risk presented by different pollutants.

The dependence of phosphorus relative residence time on different factors according to trophic condition was demonstrated in a statistical analysis of data on 135 OECD lakes by Janus and Vollenweider (1984). In oligotrophic lakes, relative residence times were dependent on variations in the magnitude of inflow concentrations; lake concentrations varied little (1.9 to 15.8 $mg \cdot m^{-3}$) due to stabilization of the input (4.7 to 121.2 $mg \cdot m^{-3}$) through sediment adsorption. On the other hand, relative residence times in eutrophic lakes were dependent on variation in lake concentrations (8.0 to 750.0 $mg \cdot m^{-3}$) indicating that sediment saturation and return mechanisms were greater in this group. The practical implication from this was that the impact of an increase in loading would be greatest in eutrophic lakes whereas their response to a decrease in loading would be least.

A number of papers describing various mechanisms important in the regulation of substance residence times in lakes were presented at a conference in Stans, Switzerland in 1983 (cf. Appendix 1.1). These studies (described below) were published collectively under the title "Chemical Processes in Lakes" (Stumm, ed., 1985) and represent some of the most recent studies on residence times and their regulating mechanisms.

The chapter by Sigg (1985) discusses the major role of biogenic particles in the binding and transport of metals to the sediments. The data from Lakes Zurich and Constance show that, although they receive much heavier metal loads than the oceans, ambient metal concentrations are about the same. The higher productivity and sedimentation within lakes provide an efficient scavenging mechanism. In addition, a second scavenging (or regeneration) cycle operates at the sediment surface: Mn^{++} and Fe^{++} released from sediments become oxidized in overlying waters to oxides which precipitate and deposit metals. In general, lakes retain more than 70% of their metal loads by these mechanisms. Further, the residence times of different metals were found to be inversely related to their partition coefficients (K_d = solid /dissolved) and directly related to residence times of particles (cf. Figure 1.3). Low primary production and low pH result in slow sedimentation of metals, increased concentrations and increased residence times. Therefore, although eutrophication often has negative consequences, it may also counteract metal pollution.

In the same volume, Morel and Hudson (1985) presented similar evidence for the importance of biota in regulating concentrations of both essential and toxic elements in the ocean. Isolation of the open ocean from allochthonous particulates and sediment interactions provided a simplified study system for this mechanism. Transport of elements by inorganic and humic materials was insufficient to explain residence times of metals and, therefore, biological particles were of major importance. Trace metals were found to be associated with biological particles and much of the uptake by algae was due to passive adsorption by high-affinity surface ligands. Similar to Sigg's findings in lakes, the residence times of elements in the sea were shown to be related to their partition coefficients (cf. Figure 1.4).

In the study by Stabel (1985) on mechanisms controlling the sedimentation sequence of elements in alpine lakes, he found that phytoplankton were more important in particle formation than allochthonous minerals. The annual succession of different algal

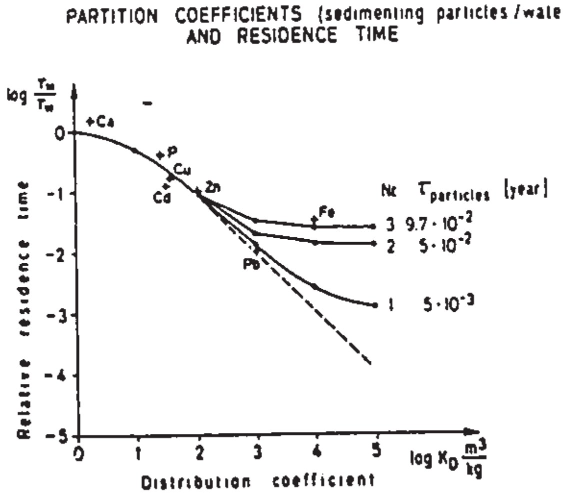


Figure 1.3 Relative residence time of elements in the lake as a function of the partition coefficients K_d. Drawn lines are calculated for the conditions of Lake Constance, with different particle residence times", from Sigg (1985).

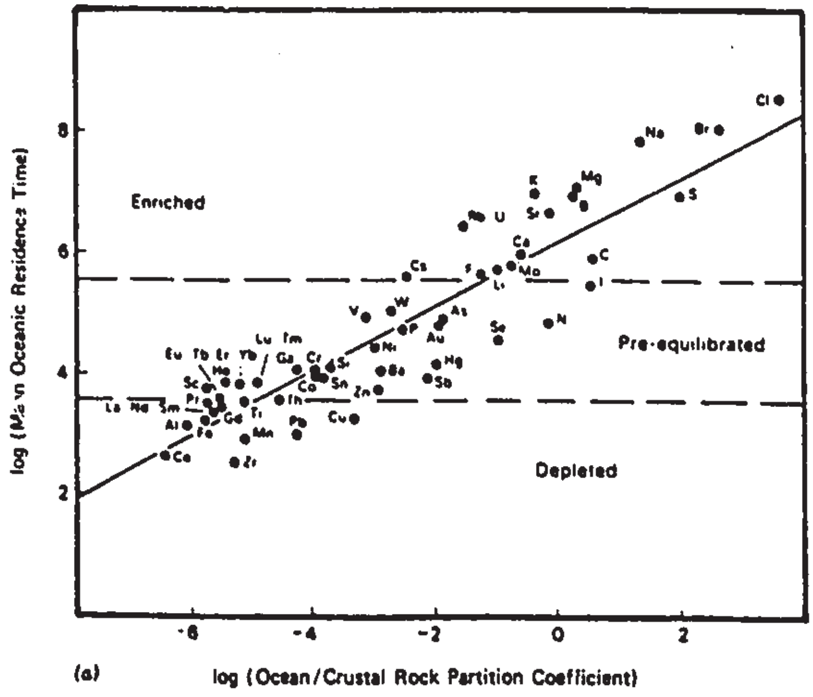


Figure 1.4 "General correlations between (a) mean oceanic residence time (in years) and ocean/crustal rock partition coefficient", from Morel and Hudson (1985).

species in Lake Constance (i.e., Bodensee) were further responsible for seasonal variations in the fluxes of organic matter, P, N and Si. Flagellates, blue-greens and dinoflagellates were found to remineralize within the euphotic zone, but diatoms transferred the bulk of particulate organic matter, Si and P, to the sediments. The sedimentation of Ca was not always related to conditions of supersaturation, but was at times controlled by algae; some species acted as precipitation nuclei while others did not. In relation to trophic conditions, the comparison of several lakes indicated that both the quantity of particulate organic matter and its turnover rate was greater in eutrophic than oligotrophic lakes. Stabel (1985) concluded that the quantity, quality and production rates of algae were important in determining the sedimentation of elements in lakes.

Baccini (1985) explored further the details of phosphorus exchange at the sediment-water interface. Phosphorus fluxes were found to vary greatly in different lakes due to differences in their trophic condition and chemical composition of sediments. Sediments could act as a source or sink for phosphorus and their capacity to buffer or assimilate an incoming load was dependent on trophic condition. Iron was known to be a master variable governing phosphorus flux, but its dynamics (as regulated by oxygen) could not explain all observations. Comparison of the chemical dynamics in three Swiss lakes (Zug, Alpnach and Kreutzrichter) showed that phosphorus release could be as great under oxic conditions as it was under anoxic conditions, and thus the earlier work of Mortimer required additional qualification. Baccini used Mn as a natural tracer for bioturbation and was able to demonstrate the effectiveness of this mechanism in contributing to phosphorus transfer from the sediments under oxic conditions. He concluded that the most important factors determining phosphorus return from the sediments were: (i) the thickness of the aerobic zone (indirectly proportional to the concentration of particulate organic carbon) in relation to bioturbation which could facilitate phosphorus transfer from the anaerobic zone into the hypolimnion, (ii) aerobic microbial decomposition which prevented phosphorus transfer to the dissolved phase, and (iii) the iron oxide barrier of the aerobic-anaerobic interface which could act as a sink for phosphorus, its capacity depending on the dissolved iron:phosphorus ratio of the interstitial water in the anaerobic zone.

As the previous studies indicate, there are many processes involved in regulating the cycling and recycling of elements and thus their residence times. The replacement rate of an element, which determines its residence time, involves physical, chemical and biological processes. With specific reference to phosphorus because of its importance as a limiting nutrient, these processes may be organized as in Table 1.2, given subsequently. Furthermore, the replacement rates which we observe are net values arising from the balance of transfers between all sources and sinks. Any or all of these transfer processes may be important in the instance of a particular lake and therefore, all such underlying mechanisms must be considered in the interpretation of residence times. Said in another way, it is important to recognize that each lake has a unique explanation for its elemental residence times. This does not preclude that some general patterns may exist. Thus the data here are explored to determine how far general terms using commonly measured limnological variables can be used to describe lakes despite their physiological differences. Generalized expressions are needed for both analytical reference standards (as per the OECD-Standard Regressions) and for management forecasts.

1.4 Nutrient Residence Times in Relation to Trophic Condition

1.4.1. Preliminary Qualitative Ideas

The publications of Stumm and Morgan (1981) and Morel and Hudson (1985) both acknowledge the unique opportunity to study the relationship of residence times to productivity in the open waters of the ocean. Offshore oceanic waters represent a simplified environment since they are free of allochthonous influences, sediment interactions and flushing effects. Thus residence times in the sea are determined nearly exclusively by the removal of elements as regulated by the in situ biological particles. Biogenic particles adsorb and transport elements to the sediments and, therefore, the removal efficiency is dependent on both the biological and chemical reactivity of the element as well as the number and sinking rate of particles (cf. Sigg, 1985). Considering this, it is not surprising that Sigg (1985) found the element removal capacity of lakes to far exceed that of the ocean due to their greater productivities and greater abundance of particles. Further, in the case of a biolimiting element such as phosphorus, removal from solution is enhanced by active uptake and luxury consumption by phytoplankton for growth and reproduction. Therefore, under the environmental conditions of the open ocean where the dominant removal mechanism is biogenic particles, one would expect a high inverse correlation between productivity and residence time.

The situation in lakes, however, is substantially more complex. The reduced spatial and temporal scales of lakes, as compared to the ocean, brings prominence to otherwise negligible removal phenomena. In the first instance, the role of particles from external (allochthonous) sources may take on much greater importance. In the second instance, the contact of water with sediments is far greater in lakes than the ocean and, therefore, sediment-water interactions may be highly influential. A third important factor contributing to the removal of elements in lakes is hydraulic flushing. Among lakes, both sediment - water interactions and hydraulic flushing efficiency are highly variable due to morphometric and mixing regime (stratification) differences.

Taken together, the influence of these factors, i.e., other than biogenic particles, precludes a simple 1:1 correspondence of nutrient residence times and productivity in lakes. Nonetheless, it remains the problem here to determine to what extent nutrient residence times imply the productivity levels (i.e., trophic condition) of lakes (or vice-versa) and what the relative importance of non-biological factors (as mentioned above) may be.

Some preliminary ideas regarding the association between nutrient residence times and trophic condition of lakes can be gleaned from the literature. Mortimer (1942) related differences in nutrient release from lake muds to trophic condition. He observed that the sediment surface of oligotrophic lakes remained oxidized and formed an adsorbent barrier for nutrients while the sediment surface of eutrophic lakes was reduced leaving nutrient reflux dependent on water movements. These observations led to a projection of sediment changes expected to occur over the course of trophic evolution. Assuming the tendency towards an increase in productivity (whether natural or accelerated by cultural development) to proceed, a point in time would be reached when the mud surface becomes reduced. This would be accompanied by accelerated oxygen depletion and release of ions (including plant nutrients) from the sediments, leading to an accelerated phase of productivity. The breakdown of the adsorbing influence of oxidized ferric compounds would lead to more complete utilization of plant nutrients. Still further reduction could lead to a sterile phase (with precipitation of iron as sulphide).

In summary, Mortimer proposed that lakes would pass through three phases over the course of trophic evolution. In phase I, a slow increase in productivity would take place. This would be followed by a rapid increase in phase II, due to the reflux of nutrients from the sediments. Phase III would be a highly reduced sterile condition of the mud. This would not depress productivity so long as external supplies of nutrients persisted. The rate of passage from one phase to the next would be dependent on geochemical and morphometric factors (Mortimer, 1942).

Reinterpretation of Mortimer's work in terms of nutrient residence times would lead one to expect first a decrease in residence times in accordance with the increased particulates associated with the increased productivity of phase I. With the reflux of nutrients from the sediments in phase II, depending on its rate relative to deposition, residence times would be expected to stabilize (if rates were equal) or even increase (if reflux were sufficient).

Hayes _et_ _al._ (1952) also related nutrient dynamics to trophic condition. In their observations on the depletion of phosphorus added to lakes, they found rapid uptake and concentration by the solids (plants, animals and mud) present in the lake. Turnover times for solids were found to be 5 to 10 times slower than those for water, so solids tended to store phosphorus at least in the early phases of uptake. Reasoning further from this, Hayes _et al._ supposed that if the equilibrating medium were primarily mud, the turnover rate of phosphorus would be directly proportional to the ratio of water volume to mud surface (at least for the unstratified period). Shallow lakes could be expected to have a more rapid phosphorus turnover than large, deep lakes. On the other hand, if the equilibrating medium were mainly live organisms, the rate of equilibration would be more rapid in eutrophic lakes, and more rapid in summer. This appeared to be supported by the 1930 data of Pearsall as listed below:

Lake	Percentage of Drainage System Cultivable	Inorganic Phosphorus in Surface Water ppb June, July and August Average
Wastwater	5.2	2.0
Ennerdale	5.4	2.6
Crummock	8.0	2.6
Derwentwater	10.0	1.8
Ullswater	16.6	1.4
Lowes Water	24.0	1.1
Bassenthwaite	29.4	0.9
Esthwaite	45.4	1.1

(from Hayes _et_ _al_., 1952)

Transposing the ideas of Hayes _et al._ to residence time of phosphorus, one would expect the water volume to mud surface ratio to be influential within the oligotrophic category, but standing crop of organisms to be most important in the eutrophic category of lakes. since the equilibration rate with living organisms is faster than with sediments, the residence times of phosphorus should be shortest in the most eutrophic environments.

The most extensive work attempting to explain the relationship of nutrient residence times to trophic condition is that of Vollenweider (1974, 1975). In comparing the residence times of phosphorus and nitrogen in 14 lakes of various trophic status, he found confirmation that, in general, the relative residence time of non-conservative substances was less than 1. Further, phosphorus was eliminated from the water column more rapidly than nitrogen. In comparing the two substances, Vollenweider found it surprising that their residence times showed little correlation ($r<0.10$) despite their metabolic coupling. However, plotting absolute residence times of phosphorus versus those of nitrogen revealed some interesting trends. As τ_n and τ_p declined, the ratio between the two (i.e., τ_n/τ_p) also declined from around 5 to less than 1, with the more eutrophic lakes grouped at low ratios. The interpretation of this was that, while the metabolism of both substances was speeded up in the course of eutrophication, the flow of nitrogen became faster than that of phosphorus. If the limiting nutrient is taken as that which flows through the system most rapidly, then the ratio of two residence times could be used as a simple measure to determine which nutrient was limiting (Vollenweider, 1975). In the case of nitrogen and phosphorus, nitrogen would be the limiting element when the ratio of their flows (i.e., residence times) dropped below 1. This concept is summarized in Figure 1.5, as depicted by Vollenweider (1974). The lack of data in 1974 has left this idea without verification up to now. The cross-sectional data will be used to evaluate this hypothetical scheme in Chapter 3.

In the investigation of eutrophic Prairie lakes, Allan and Williams (1978) found trophic status related to the availability of phosphorus from the sediments. In contrast to deep oligotrophic lakes where sediments played a dominant role as a sink for nutrient loads, the sediments of the Fishing Lakes and Prairie pothole lakes acted as a source. Phosphorus regeneration was favoured by winter anoxia under ice, the high organic and phosphorus content of the sediments and low iron:phosphorus ratios. In conclusion, Allan and Williams (1978) suggested that these lakes would respond only slowly to external loading reductions because the internal sediment source would become more significant in determining spring phosphorus concentrations and productivity. They predicted that the Fishing Lakes would be similar in response to Lake Norrviken (cf. case history in Section 2.9.) which showed only a gradual decline in sediment phosphorus regeneration following external load reduction.

In terms of relative residence time of phosphorus, the work of Allan and Williams (1978) leads to the expectation of a rise in values with increasing trophic state. Values for (τ_p/τ_w) greater than 1 would mark the point where internal

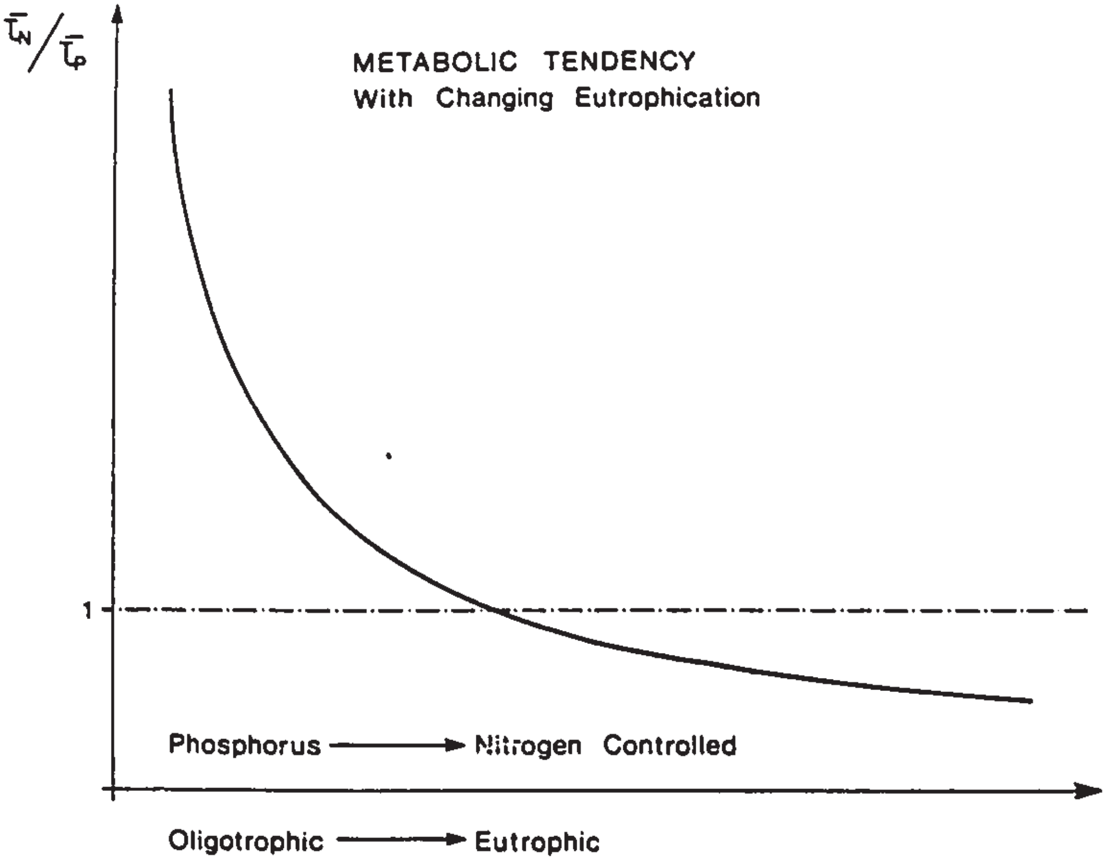


Figure 1.5 Metabolic tendency of ($\tau n/\tau p$) ratio with changing trophic state, from Vollenweider (1974).

sources exceeded external ones. This could occur in the situation of substantial external loading reduction.

In a study of sedimentation in natural and artificial Iowa lakes, Canfield *et al.* (1982) found *gross* sedimentation of phosphorus (as measured by sediment trap) highly correlated with chlorophyll *a* (r = 0.94). This suggested that trophic status (as measured by Chl *a*) strongly influenced sedimentation rates, with the highest rates occurring in the most productive lakes. However, *net* sedimentation rates calculated from nutrient budgets showed that sedimentation in artificial lakes was two orders of magnitude greater than in the natural lakes. This could be explained by the fact that sedimentation in the artificial lakes was most highly related to allochthonous inputs. The possible mechanisms proposed to explain this phenomenon were (i) a smaller proportion of natural lake loading composed of inorganic particulates and, therefore, a smaller proportion of the load prone to settling, (ii) a smaller concentration of inorganic sediments and, therefore, smaller removal capacity in natural lakes, and (iii) higher iron concentrations which promoted precipitation of phosphorus in artificial lakes. The work of Canfield *et al.* (1982) would thus imply that where relative residence times relate to *net* phosphorus balance, the influence of allochthonous inorganic materials may override the relationship with chlorophyll and trophic condition.

More recently, and on a much larger sample of lakes (i.e., 159), Janus and Vollenweider (1984) found phosphorus relative residence time to be dependent on different variables according to trophic condition. In oligotrophic lakes, (τ_p/τ_w) was dependent on variations of inflow concentrations since lake concentrations were buffered to a low, nearly constant value with little variation from 8 $mg \cdot m^{-3}$. On the other hand, (τ_p/τ_w) in eutrophic lakes was dependent on differences in lake concentrations which ranged widely (from a mean of 72 $mg \cdot m^{-3}$) signifying the loss of buffer capacity and/or increase of reflux from the sediments. In addition, the relative residence times of eutrophic lakes as a group were consistently higher than those of oligotrophic lakes receiving similar external loads. Relative residence times, therefore, measure the capacity of a lake to assimilate the input load and this is characteristically different according to trophic condition.

In summary of these preliminary expectations for phosphorus relative residence time behaviour, one would expect (τ_p/τ_w) to decrease with increasing trophic condition (cf. Table 1.2). A faster flow-through rate would be expected in more eutrophic environments due to the increased number of particles and thus increased removal efficiency. Furthermore, equilibration of phosphorus with organisms appears to be more rapid than with mud, so the organic productivity of the environment would play a determining role. However, this trend of increasing flow

TABLE 1.2. PROCESSES REGULATING THE RESIDENCE TIMES OF PHOSPHORUS (τ_p) IN LAKES

$$\tau_p = \frac{\text{lake content}}{\text{replacement rate}} ,$$

where: replacement rate = $\sum$ (physical + chemical + biological) rates.

Processes affecting replacement:

Function:	Physical	Chemical	Biological
Sinks: (+)*	-Hydraulic flushing -Sedimentation of refractive compounds -Diffusion to sediments -Mixing: -sediment deposition -oxygen transport	-Precipitation -Adsorption by Ca, Al, Fe, clay compounds -Oxidation of sediments (Fe required) -Flocculation	-Adsorption by particles -Plankton deposition -Macrophyte uptake -Plankton and fish migration -Bioturbation of adsorbent compounds
Sources: (-)*	-External loading (natural and cultural) -Diffusion from sediments -Mixing (sediment resuspension)	-Reduction of sediments	-Bioturbation of reduced elements -pH dependent release from colloids, humic substances -macrophyte release (? translocation pump from mud)

*In mass balance equations sinks are positive fluxes out of the defined pool out of the defined pool which increase "replacement rate" and thus decrease residence time; conversely source mechanisms increase residence time. Where steady-states exist, $\sum$ sources = $\sum$ sinks.

rates of phosphorus could be counteracted by reflux of the nutrient from reduced sediments. In addition, heavy loads of allochthonous particles including silt or other inorganic, adsorbent materials may control nutrient sedimentation and override any relationship of nutrient residence time to trophic condition.

Within the oligotrophic group of lakes, where chemical equilibration of phosphorus with mud may be the domimant process, lake depth may take on major importance. Shallow lakes may have shorter phosphorus residence times than deeper lakes because of their smaller lakewater volume to mud ratios.

These above hypothetical relationships have yet to be demonstrated.

1.4.2. Quantitative Expressions

Evaluation of the present condition of a lake, or prediction of some future state following natural or deliberate changes (in nutrient loads or basin characteristics) requires well-defined quantitative relationships. Such expressions have been developed in the past on the premise that "a quantifiable relation exists between the amount of nutrients reaching a lake and its trophic degree measurable with some kind of trophic state index" - now known as the nutrient loading concept (Vollenweider, 1976). Although simple enough as a theoretical statement, there is a great deal of uncertainty associated with the practical measurement of terms for a corresponding mathematical statement. To keep in mind the real situation, nutrient loads to lakes vary in total amount, concentration, relative composition, bioavailability, seasonality, etc. Translation of the load into biological production is then modified by such factors as species composition, water and sediment chemistry, temperature, morphometry, stratification and flushing, to name a few (cf. Figure 1.1 in Vollenweider and Kerekes, 1980). In addition, there remains the problem that no universally applicable scale to define trophic degree exists. In consideration of all these uncertainties, and in part only qualitative ideas, it cannot be a foregone conclusion that simple quantitative relationships between nutrient inputs and trophic outcome exist. Indeed, many early limnologists believed that no generalizations were possible and that each lake would have to be considered on its own.

Despite these complexities, Vollenweider developed an approach that tackled the quantitation problem in two parts. The first part of the problem was to relate trophic status to average nutritional conditions. To accomplish this, trophic categories - as defined by summer alkalinity change (i.e., a measure of primary productivity) - were related to nutrient concentrations on a probability basis (cf. Figure 1.1, given previously). This was later updated and expanded in 1980 using the OECD data base to relate trophic categories to both trophic indicators and nutrients (cf. Vollenweider and Kerekes, 1980) and is presently the most broadly based set of guidelines for identification of trophic status.

The second part of the problem was to relate nutrient concentrations in lakes to their nutrient loads. Treating this as a classical chemical engineering problem, Vollenweider (1975) developed an input-output model (based on solving a rate equation of mass balance) which predicted the steady-state concentration of phosphorus that would result from a certain nutrient load:

$$[P_\lambda] = \frac{L_p}{q_s} \left(\frac{\rho}{\rho + \sigma}\right) \qquad (1.3)$$

In the above equation, P_λ is the lake concentration of phosphorus ($mg \cdot m^{-3}$) at steady-state, L_p is the annual specific surface load of phosphorus ($mg \cdot m^{-3} \cdot y^{-1}$), q_s is the hydraulic load ($m \cdot y^{-1}$), ρ is the flushing rate (y^{-1}) and σ is the apparent net sedimentation rate (y^{-1}).

With these two components (i.e., probability relationships and the mass balance equation) taken together, the framework for lake management was established. A trophic category (or trophic indicator level) could be chosen and associated with a nutrient concentration. Subsequently, the loading necessary to attain that concentration could be estimated. The sequence could also be used in the reverse sense of estimating the trophic condition that would develop from a given nutrient load.

The practical application of this work for the estimation of critical loading levels (i.e., those which would lead to eutrophication) was taken up in detail in the publication "Advances in Defining Critical Loading Levels for Phosphorus in Lake Eutrophication" (Vollenweider, 1976). In brief review of how this system was developed, the initial estimates of critical loads (L_c) were based on the observation (for 20 lakes) that eutrophic lakes lay characteristically above oligotrophic lakes in a plot of loading versus mean depth (Vollenweider, 1968). Thus the initial line of demarcation was:

$$L_c\ (\mathrm{mg \cdot m^{-2} \cdot y^{-1}}) = (25 \text{ to } 50)\ \bar{z}^{\,0.6} \qquad (1.4)$$

(Vollenweider, 1968). However, this was acknowledged as no more than a rough estimate since $\bar{z}$ accounted only for a simplified dilution effect.

Further improvement from this initial line in the calculation of critical loads was made by use of the mixed reactor model which took into account sedimentation and flushing effects:

$$L_c = [P_\lambda]_c^{sp} \cdot \bar{z} \cdot (\rho + \sigma) \qquad (1.5)$$

(Vollenweider, 1976) where $[P_\lambda]_c^{sp}$ is the critical concentration of phosphorous at spring overturn and other symbols are as stated previously. For practical application of this equation, common limnological knowledge dictated that $[P_\lambda]_c^{sp}$ should be set at set at 10 $mg \cdot m^{-3}$ since lakes with concentrations above that were likely to have summer algal blooms (and were, therefore, to be considered eutrophic). The flushing rate (ρ) was measurable as Q/V (i.e., the ratio between the total annual hydraulic load and the lake volume). Sedimentation (σ) as used here represented the annual net result of all phosphorus fluxes to and from the sediments (due to any or all of the possible mechanisms regulating residence times reviewed earlier in this introduction). Since fluxes measured by sediment trap represent values closer to gross sedimentation, it would be inappropriate to use such values. Therefore, the most problematic aspect for application of this equation arose from the question of how to estimate the sedimentation coefficient.

Vollenweider (1976) suggested that there were several ways open for evaluation of the sedimentation coefficient. (1) One way, which maximizes use of the available data is the estimation of sedimentation from relative residence times. By theoretical definition, (τ_p/τ_w) reduces to the quantity (P_λ/P_j), which is the ratio of two measurable entities. In addition, by the mass balance model, this ratio represents $\rho + \sigma$ and, therefore, if ρ is known, σ may be estimated from (τ_p/τ_w) or (P_λ/P_j) (cf. Vollenweider, 1976). Further improvement of the simplified mixed-reactor model then is primarily dependent on finding expressions that accurately estimate (τ_p/τ_w).

Previously, Vollenweider (1976) found (τ_p/τ_w) inversely related to water residence time (τ_w) and used this statistical correlation ($r = -0.674$, $n = 21$) in his critical loading equation (cf. Equation 1.5, previously). Further modification of the form of the equation was made to account for the non-linear relation that (τ_p/τ_w) must approach unity as τ_w approaches zero. This approximation took the form:

$$(\tau_p/\tau_w) = \frac{1}{(1 + \tau_w{}^x)} \tag{1.6}$$

which could be inserted into the mass balance model and simplified to the current well-known version:

$$(\tau_p/\tau_w) = (P_\lambda/P_j) = \frac{1}{1 + \sqrt{\tau_w}} \tag{1.7}$$

(Vollenweider, 1976). At the time this method was formulated, little data existed, so the development of predictive expressions for (τ_p/τ_w) was left at a standstill. More recently, the availability of the OECD and other data has re-opened the possibilities. In view of the much larger data base available now ($n > 200$ in contrast to $n = 21$ in 1976), the relationship of (τ_p/τ_w) to τ_w will be re-evaluated to test its current validity.

In addition, the availability of data on a wider range of factors makes it possible to test some new simple and multiple regression relationships for their ability to explain (τ_p/τ_w), and thus σ. Any improvements in the precision of estimates for (τ_p/τ_w) may lead to revision of the currently used equations for critical loads. Thus the estimation of sedimentation rates from relative residence times is a major theme of the analysis presented here and a topic not yet explored in limnology.

(2) An alternative way to evaluate sedimentation coefficients is from whole-lake nutrient budgets of consecutive years. Where this type of data (i.e., time-series) is available, total sedimentation (S) may be calculated from a simple mass balance between the inflow quantity of a nutrient (I), its loss through the outflow (O) and change in lake content (G) as follows:

$$S = I - O - G \tag{1.8}$$

The sedimentation coefficient for the mixed-reactor model solution can then be obtained by conversion to the appropriate units. Total sediment (S) divided by lake surface area (A_s) gives a flux. The flux divided by the lake concentration gives an apparent sedimentation velocity (v_s), and sedimentation velocity divided by mean depth $(\bar{z})$ gives the sedimentation coefficient (σ). In equation form, this may be expressed as:

$$\sigma(y^{-1}) = \frac{S \qquad\qquad (mg \cdot y^{-1})}{A_S \cdot \bar{z} \cdot [P_\lambda] \quad (m^2 \cdot m \cdot mg \cdot m^{-3})} \tag{1.9}$$

1.5. Data Types and Their Relationship

Notably, the two methods of calculating sedimentation rates described above have been formulated on the basis of two essentially different types of data. These types of data are referred to in this paper as cross-sectional and time series data. Cross-sectional data is that derived from many lakes covering a wide geographic range, but representing only single years. In contrast, time-series data refers to that for an individual lake studied over many consecutive years. The distinction of these data types is retained throughout this work because of the essential differences in the processes they represent according to their inherent spacial and temporal scales.

The second method of calculating sedimentation via budgets is perhaps more accurate, than that based on the best statistical fit for the steady-state solution, on the grounds that the assumption of 'no change in lake content' may be eliminated. (The appropriate modifications to account for changes in lake content, and where possible flushing efficiency, in the estimate of (τ_p/τ_w) from the observed (P_λ/P_j) will be introduced later in Section 2.1.4 on the analysis of individual budgets.) Use of this method in the past has been hindered by the lack of data for such evaluation. Vollenweider (1976) had only one year's budget information on four Swiss lakes for the first calculations of sedimentation velocity. This information is supplemented in Chapter 2 here with nutrient budgets for a minimum of six years on each of nine lakes. This represents a substantial improvement in the amount of information available on apparent sedimentation velocities and, more particularly, gives some insight into the variability within a given lake.

Variability of the sedimentation coefficient within a single lake is an important, but essentially unknown feature up to now. Previously, one had to simply assume that sedimentation rates retained a relatively constant value, in accordance with the relatively constant values of the best "predictor" variables, i.e., $\bar{z}$ or τ_w. However, variability of this rate has major implications for a lake's trophic response, as well as its management. Changes in sedimentation rate - and therefore assimilation capacity (i.e., elimination by all routes including sedimentation, flushing, volatilization, etc.) - would imply that the effect of a constant load may vary. Consequently, the critical load for a given lake may also vary. It is therefore essential to know the magnitude of fluctuations in sedimentation rates for effective management or prediction. For this reason, attention is given to the documentation of sedimentation variability as observed in the time series data.

Furthermore, the time series data is of special importance in interpretation of the meaning of sedimentation coefficients. Since coefficients derived from time series data are devoid of variation due to geochemical or morphometric factors - these would be considered constant for most individual waterbodies - their interpretation must relate to temporal fluctuations of processes acting within the spacial limits of the drainage basin. In contrast, the variation of cross-sectionally derived coefficients may be explained in terms of the geochemical, hydrologic and morphometric variations which occur throughout the drainage basins of primarily northern Temperate lakes (as represented by the cross-sectional data here). Thus the time series and cross-sectional information should be seen to relate to somewhat different temporal and spacial scales and equations derived from each are not intrinsically transferable.

Although different, the information conveyed by the data bases (and methods of arriving at sedimentation coefficients) should be seen as complementary. Set in perspective to each other, the cross-sectional data delineates the realm within which the time series patterns occur, i.e., the cross-sectional patterns are more highly aggregated. Such equations would be useful in projecting the effects of major alterations to the basin morphometry or hydrology as, for example, in the case of dams or diversions. On the other hand where these factors are constant as in the case of a single lake, predictions based on them lose resolution, although the order of magnitude is still correct. To gain resolution for predictions or analysis of controlling factors in individual cases, time series data is essential. Predictive equations based on time series patterns (which fit within the limits set by the cross-sectional data) relate to the complex of processes effective in the individual basin. The factors which are "best predictors" of sedimentation may be quite different from lake to lake. For this reason, they may not be readily transferable between different situations. Cross-sectional patterns describe the global picture (with an all-encompassing uncertainty). More particularly, time series (with successive reduction in spacial and temporal scales and consequently elimnination of factors creating variability) provide partial and more detailed explanation of the global patterns. Thus in relation to one another, the two methods of deriving sedimentation coefficients should be seen as representative of different portions of a nested series of temporal and spacial scales. Further discussion and considerations on the complementarity of cross-sectional and time series data may be found in Janus (1984) and Vollenweider (1987).

The most important implication of the above is that different scalar levels implicit in data bases will have different descriptive models. In addition, the trends delineated in one framework are not necessarily adhered to in the context of another with different associated scales. For example, the global cross-sectional trend indicates that chlorophyll (as a measure of biological production) decreases with diminishing phosphorus concentrations, yet it is the experience in a number of individual cases that chlorophyll reduction did not occur in lakes managed for the reduction of phosphorus levels. This brings into question the effectiveness of management practices based on the variously derived equations which one might use. In other words, the transferability of equations is, at this point, not well defined. Where equations related to eutrophication are transferable and where they are not is a topic presently under investigation by a working group of the Instituut voor Milieu-en-Systeemanalyse (IMSA, cf. Verij and Sas, 1986). The question of transferability will also be taken up in the discussion of the research presented here.

2. THE TIME SERIES ANALYSIS; NINE CASE HISTORIES

2.1 Time Series Introduction

2.1.1 Overview and Scope

The time series data is one of the two major categories of data considered in this thesis. It is essentially different from the cross-sectional data in the temporal and spacial scales it represents and therefore differs in its major sources of variation but is nonetheless not independent of the cross-sectional findings. In particular, this data provides consecutive annual changes in lake content of nutrients and allows for elimination of the steady-state assumption required in the cross-sectional analysis. Through a correction for changes in lake content (cf. explanation in Section 2.1.4), relative residence times can be more clearly reconciled to gross sedimentation rates and overall lake dynamics. These corrected values give new insight into the processes that control sedimentation in various situations since it allows for more accurate correlation with controlling factors. The details of nine case studies are used as far as possible to develop such correlations. The refinement of predictions for these lakes is then a matter of incorporating the appropriate predictive relationships for sedimentation into their mass balance equations. Further description of the time series data and an outline of how it will be used are given below.

A final section of the chapter is devoted to a comparison of the qualitative and quantitative effects of processes which may determine the sedimentation characteristics of different lakes (as identified by the nine individual case studies). This gives a general perspective of the relative importance of such processes, their variability and consequently the limitations of general prediction models.

2.1.2 Description of Time Series Data

The data for this chapter were derived from journal articles and reports as listed in Table 2.1. It consists of nutrient budgets which span various time periods of 5 to 45 years for nine different lakes. These lakes are located throughout Europe and North America and are northern temperate lakes with the exception of Lake Okeechobee (a semi-tropical lake in southern Florida).

In terms of physical characteristics (c.f. Table 2.2), these nine lakes cover a wide range of conditions. Mean depths range from approximately 2 to 153 m and maximum depths range from 4 to 449 m. The basin shape, summarized in the term ξ (i.e., the ratio: $z_{max}/\bar{z}$), ranges from the approximate minimum of 1 for the flat, saucer-shaped basin of Okeechobee to 2.9 for the steep-walled basin of Mjøsa, a fjord lake. Surrounging factors,

TABLE 2.1. LIST OF LAKES WITH TIME SERIES DATA

Lake (long-term trophic tendency)	Time Span Investigation (number of years)	Location	Data Source
Bodensee-Obersees (oligotrophy)	1930 to 1975 (45)	Austrian, German, Swiss border	G. Wagner, 1976
Sempachersee (oligotrophy)	1954 to 1978 (24)	Switzerland	R. Gachter *et al.*, 1983
Washington (oligotrophy)	1950 to 1978 (28)	Washington, U.S.A.	W.T. Edmondson and J.T. Lehman, 1981
Léman (oligotrophy)	1964 to 1980 (17)	French, Swiss border	CIPEL, 1984
Mjøsa (oligotrophy)	1973 to 1980 (7)	Norway	H. Holtan, 1981
Baldeggersee (cultural eutrophy)	1975 to 1984 (9)	Switzerland	D.M. Imboden, 1985
Shagawa (cultural eutrophy)	1971 to 1976 (5)	Minnesota, U.S.A.	D.P. Larsen *et al.*, 1979 and K.W. Malueg *et al.*, 1975
Norrviken (natural eutrophy)	1962 to 1976 (15)	Norway	I. Ahlgren, 1978 and 1980
Okeechobee (natural eutrophy)	1973 to 1984 (11)	Florida, U.S.A.	A. Federico, K. Dickson, C. Kratzer and F. Davis, 1981

TABLE 2.2. MORPHOMETRIC FEATURES OF THE NINE LAKES WITH TIME-SERIES DATA AND MEANS FOR THE CROSS-SECTIONAL DATA

Variable:	$\bar{z}$	z_{max}	ζ*	A_S	A_D	Surrounding	V	τ_w
Units:	m	m		km^2	km^2	Factor+	km^3	y
A. Time-Series Data:								
Bodensee-Obersee	100	252	2.5	475	10000	21	47.6	4.4
Sempachersee	46	86	1.9	14	63	4	0.7	17.5
Washington	32.9	63	1.9	88	1588	18	2.9	2-3
Léman	153	310	2.0	582	7393	13	89.0	11.9
Mjφsa	153	449	2.9	365	16420	45	56.2	6.0
Baldeggersee	34	66	1.9	5	67	13	0.2	3.5-8
Shagawa	5.7	14	2.5	9	269	29	0.5	0.4-1.2
Norrviken	5.4	12	2.2	3	94	35	0.1	1.3
Okeechobee	2.1-3.1	4	1.3	1685	11914	7	2.9-5.6	1.9-6.8
B. Cross-Sectional Data:								
Arithmetic mean	23.8	59.6	-	2.6	1308	-	139	7.8
Geometric mean	11.7	31.2	-	2.4	5.5	-	19	1.0
n =	219	181	-	181	213	-	177	107

*$\zeta = (z_{max}/\bar{z})$

+ Surrounding factor = (A_D/A_S)

which express the ratio of drainage area to lake surface area, range from 4 to 45 times. Lake volumes range from small (0.1 km^3) to very large (89 km^3) and water residence times range from around 1 to 17 years. All these features create a diverse set of lakes that represent a very wide range of conditions in comparison with all lakes of the cross-sectional data (cf. Table 2.2, Section B).

In terms of trophic conditions, five of the nine lakes are considered oligotrophic but have in recent years shown signs of eutrophication. These include the Bodensee-Oberseee, the Sempachersee, Lake Washington, Lac Léman and Lake Mjosa. Two of the remaining lakes (the Baldeggersee and Shagawa Lake) have suffered long-term cultural (i.e. man-induced) eutrophication and two (Norrviken and Okeechobee) are considered naturally eutrophic with recent developments that have accentuated undesirable conditions. The trophic changes of these nine cases have developed as a consequence of changes in nutrient loads, which typically originate as both municipal sewage and agricultural runoff.

The time-series data set is somewhat smaller than the cross-sectional set, largely due to the fact that long-term studies are uncommon in comparison to single-year studies. Despite its smaller size, this compilation represents a substantial addition to the information on observed sedimentation rates. As noted earlier, the first estimates of sedimentation coefficients (based on statistical trends for 21 lakes) could only be verified in terms of four Swiss lakes, each with only one year of data on sedimentation. The data given in this analysis represents 161 years in total, and is therefore 40 times larger than that initially used (cf. Vollenweider, 1976) to verify the relationship of sedimentation and water residence time.

2.1.3 Objectives of Analysis

The increase over the last decade in availability of time-series data has opened up important new possibilities for verification of long-standing statistical relationships or formulation of new ones. In the first instance, the estimation of sedimentation coefficients from their statistical relation in cross-sectional data to water residence times (as introduced by Vollenweider, 1975) will be re-examined for functional content. Such generalized, cross-sectional relationships can only be considered functional (i.e., causal and therefore of use for prediction) if temporal series demonstrate these same trends. Therefore the time series data will be used to evaluate statistical methods of estimating sedimentation. Further to this, the time series data shows the degree of year to year variability in sedimentation coefficients in a single lake and gives some insight into the degree of error to be expected in the use of more generalized predictive equations derived from cross-sectional relationships. The underlying problem to overcome at this stage of research is that cross-sectional relationships are based on lake features which are highly variable in different lakes but relatively stable from year to year (such as $\bar{z}$ and τ_w) in a single lake. These stable features only provide "order of magnitude" estimates, but cannot, in most cases, resolve annual or seasonal variations.

Secondly, with respect to formulation of refinements or new relationships to estimate sedimentation, the time series data is indispensable. The temporal and spacial scales of the time-series data are such that they reflect intrabasin processes (in contrast to the cross-sectional data which reflects interbasin differences more prominently). These intrabasin relationships are the key to development of predictive equations for a given basin. Notably, such relationships are expected to vary from basin to basin in accordance with the variability of the complex of processes which regulate relative residence times and sedimentation. That is to say that each basin has a unique complex of regulating factors and the relative importance of the components of the complex may change yearly or even seasonally. The data will be analysed for relationships between residence times and regulating processes acting within each of the nine single basins treated in this chapter.

2.1.4 Calculation of (τ_p/τ_w) Under Changing Conditions

In more specific terms regarding calculations of relative residence times, the time-series data has special importance in that it allows for elimination of the steady-state assumption (i.e., that the annual change in lake content is zero). This can be accomplished by incorporating the observed changes in lake content into the basic mass balance statement. Accordingly, the change in lake content of a substance can be equated to the difference between inputs and outputs and, in terms of phosphorus, this can be stated mathematically as:

$$\frac{dP\lambda}{dt} = \frac{1}{\tau_w}(P_j) - \frac{1}{\tau_p}(P_\lambda) \tag{2.1}$$

where $(\frac{1}{\tau_p}) = (\frac{1}{\tau_w} + \frac{1}{\tau_s}) = (\rho + \sigma)$. This equation, which describes the sum of incoming and outgoing fluxes, assumes that the outflow concentration is equivalent to the mean lake concentration (cf. Vollenweider, 1975). Then by rearrangement of equation 2.1:

$$(\frac{\tau_p}{\tau_w} - \frac{dP\lambda}{dt} \cdot \frac{\tau_p}{P_j} \cdot \frac{\tau_w}{\tau_w}) = (\frac{P\lambda}{P_j}) \tag{2.2}$$

$$\frac{\tau_p}{\tau_w}(1 - \frac{dP\lambda}{dt} \cdot \frac{\tau_w}{P_j}) = (\frac{P\lambda}{P_j}) \tag{2.3}$$

$$(\frac{\tau_p}{\tau_w}) = \frac{(P\lambda/P_j)}{1 - \frac{dP\lambda}{dt} \cdot \frac{1}{(P_j/\tau_w)}} \tag{2.4}$$

and finally,

$$\left(\frac{\tau_p}{\tau_w}\right) = \frac{(P_\lambda/P_j)}{1 - \frac{dP_\lambda}{dt} \cdot \frac{1}{\text{load}}} \qquad (2.5)$$

By this equation, it can be seen that as a steady-state is approached (i.e., $dP_\lambda/dt \rightarrow 0$), the relative residence time (τ_p/τ_w) is more closely approximated by the ratio of measured values (P_λ/P_j). However, where the change in lake content is a known quantity other than zero, relative residence time may be calculated by Equation 2.5.

In addition to this correction, a second one can be made for flushing efficiency if lake and outflow concentrations are known and not equivalent. The correction factor β is simply the ratio of the outflow concentration (P_ω) to the mean lake concentration (P_λ):

$$\beta = \frac{P_\omega}{P_\lambda} \qquad (2.6)$$

In a mass balance equation, the outflow loss is then written: $\beta \cdot \rho \cdot P_\lambda$. This correction is used in the cases of the Sempachersee and Baldeggersee according to the available data. For the other seven lakes, the appropriate data is not available and it must be assumed that the outflow concentration can be reasonably well represented by the mean lake concentration.

2.2 Bodensee–Obersee

2.2.1 Description and Trophic History

The Bodensee is located at the border of Switzerland, Austria and Germany at 47°N, 9°E (cf. Figure 2.1). It is a fairly large, deep lake that was formed by glacial erosion, set in the northern foothills of the Alps at an altitude of 395 m a.s.l. The Rhine is its major inflow and outflow and the drainage area is estimated at 10,600 km^2. The lake is composed of two basins and it is the upper basin (Obersee) which is under discussion here. it is larger, deeper and more slowly flushed than the lower, downstream basin (Untersee). Mean and maximum depths of the Obersee are 100 and 252 m, respectively, surface area is 475 km^2 and the hydraulic load averages nearly 23 $m \cdot y^{-1}$. The water residence time for the Obersee is approximately 4.4 years (cf. Table 2.2; Fricker, 1980).

Eutrophication of the Bodensee has followed a simple consistant pattern which parallels the population growth in the basin. Untreated municipal waste has been the primary cause of progressive enrichment of the lake which was slow up until about 1950. After 1950, exponential increase of nutrient loading and lake concentrations led to a progressive deterioration of the lake's trophic condition. Phosphorus concentrations in the lake rose from 10 $mg \cdot m^{-3}$ to 80 $mg \cdot m^{-3}$ between 1930 and 1970. The annual average plankton density in the upper 10 m increased

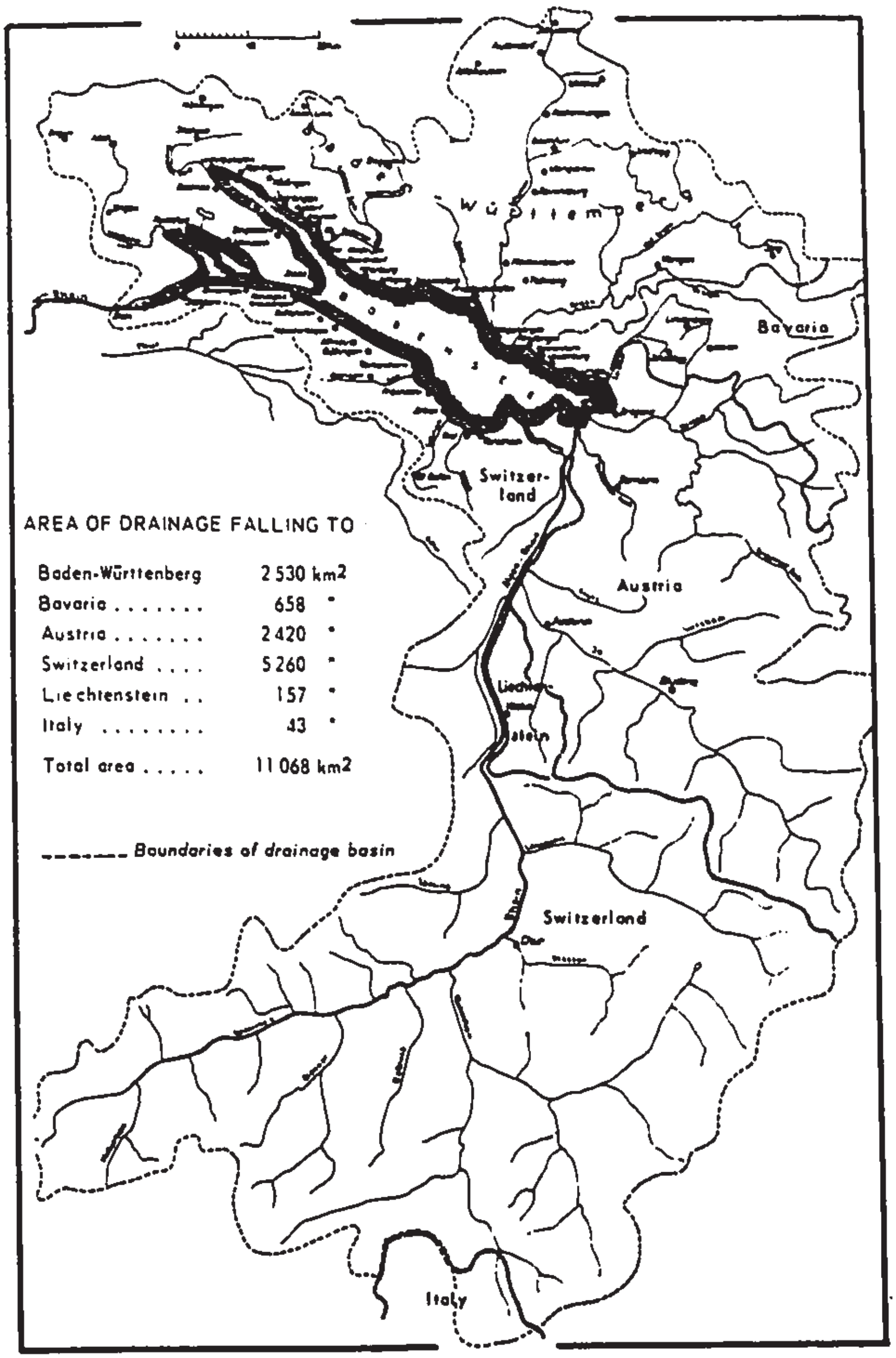


Figure 2.1 Map of the Bodensee, Germany, Switzerland, Austria, from Wagner (1976).

approximately 10-fold, from 200 to 2000 cells$\cdot$ml^{-1} over the same period of time, and oxygen minima dropped from 9.5 to 2.2 mg$\cdot$l^{-1}. Similar to the Baldeggersee, the whitefish population declined drastically and perch are now the dominant fish (Hartman and Numann, 1977). Macrophytes clog the river mouths, beaches and harbor entrances, and at present are removed mechanically. Treatment costs for drinking water are high because of the need for finer filtration, ozonization and chlorination. These increasing problems led the bordering countries of Switzerland, Germany and Austria to collectively embark on an improvement program. The goal was to treat 80% of all sewage to reduce nutrient loading to one-half of its 1975 level (2000 t$\cdot$y^{-1}) by the early 1980s. It is expected that this will result in a drop and stabilization of phosphorus lake concentrations at around 50 to 60 mg$\cdot$m^{-3}. (Indeed a recent publication shows that phosphorus lake concentrations had dropped below 70 mg$\cdot$m^{-3} by 1985; Bürgi _et al._, 1988.) Although this is not expected to restore oligotrophic conditions, it should alleviate some of the problems of drinking water treatment (Wagner, 1980).

2.2.2 Budget Analysis of the Bodensee-Obersee

The phosphorus budget for the Bodensee-Obersee covers the period 1930 to 1975 and was derived from the publication of Wagner (1976) (cf. Table 2.3). This 45-year period is the

Table 2.3 Bodensee-Obersee phosphorus balance; a 45 year time series (1930 - 74), adapted from Wagner (1976).

Year	Mean P Content of the Lake 10^3 kg (tons)	Total Load 10^3 kg · y^{-1}	Loss Via Outlet/ Drinking Water Consumption 10^3 kg · y^{-1}	Change in Lake Content 10^3 kg · y^{-1}	Net Sediment 10^3 kg . y^{-1}
1930	333	274	70	18	186
31	351	281	72	15	194
32	366	288	60	25	203
33	391	295	63	18	214
34	409	303	62	21	220
35	430	311	91	-6	226
36	424	319	83	9	227
37	433	326	84	12	230
38	445	338	69	29	240
39	474	343	102	-4	245
40	470	343	96	3	244
41	473	342	80	14	248
42	487	341	72	15	254
43	502	335	62	13	260
44	515	323	92	-27	258
45	488	311	85	-20	246
46	468	341	73	22	246
47	490	372	72	40	260
48	530	403	82	44	277
49	574	415	61	56	298
50	630	425	92	21	312
51	651	441	108	15	318
52	666	459	113	21	325
53	687	480	102	42	336
54	729	503	140	16	347
55	745	529	128	44	357
56	789	556	146	39	371
57	828	588	136	65	387
58	893	619	160	53	406
59	946	654	120/0.6	104	429
60	1050	693	191/0.7	49	452
61	1099	734	169/0.7	92	472
62	1191	782	149/1.0	131	501
63	1322	834	200/1.4	102	531
64	1424	893	188/1.6	145	558
65	1569	958	332/1.7	45	579
66	1614	1028	331/1.7	100	595
67	1714	1109	324/2.2	161	622
68	1875	1196	324/2.5	212	657
69	2087	1293	321/2.8	268	701
70	2355	1399	458/3.6	200	737
71	2555	1517	288/5.8	435	788
72	2990	1642	337/7.5	449	848
73	3439	1799	508/8.4	366	897
74	3805	1929	601/9.3	381	938
75	4186	--	--	--	--

longest consistent record for any lake and is depicted in Figure 2.2.

Phosphorus loading increased consistently over this period, at first linearly, and then exponentially after about 1960 from approximately 300 (metric) $t \cdot y^{-1}$ to more than 1900 $t \cdot y^{-1}$ (i.e., a 6-fold increase). At the same time, losses through the outlet increased from 70 to 610 $t \cdot y^{-1}$ (i.e., an 8-fold increase, proportionaly somewhat larger than the loading increase). The lake response was a rise in the lake content from 333 tons to 4186 tons (i.e., a 13-fold increase).

In terms of incremental changes, the increase in lake content per year rose from 18 to 381 metric $t.y^{-1}$, which is a 21-fold increase in rate. (The few negative values in Table 2.3 refer to years when the lake content went down relative to the previous year and this coincides with higher than usual losses through the outflow due to high flushing rates, cf. subsequent Table 2.5.)

Net sedimentation as calculated from the above fluxes (cf. equation 1.8) increased from 186 to 938 $t \cdot y^{-1}$ (i.e., only a 5-fold increase). Thus the rate of loss by sedimentation increased least while the change in lake content (as well as its rate of change) increased most and in a consistent positive direction since 1946. Furthermore, lake content increased parallel to the loading up until around 1955. After that, lake content rose faster than the loading.

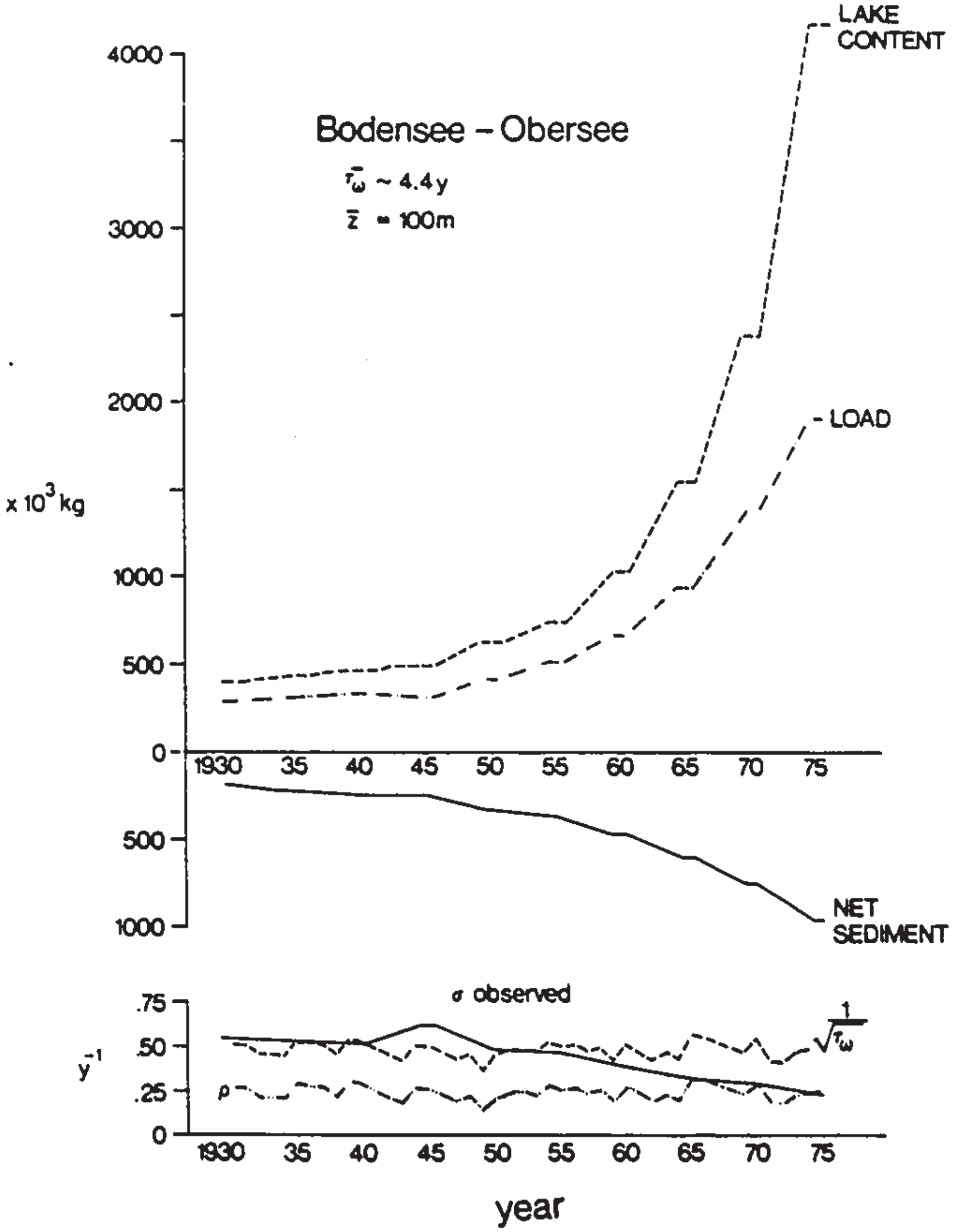


Figure 2.2 Bodensee-Obersee phosphorus loading, lake content and sedimentation (1930 - 45).

In terms of concentrations, the theoretical inflow (i.e., phosphorus load divided by hydraulic load) increased from 21 to a maximum of 222 $mg \cdot m^{-3}$ (1972), a 10-fold increase. At the same time, lake concentrations rose from 7 to a maximum of 80 $mg \cdot m^{-3}$ (1974), which similarly represents an 11-fold increase (cf. Table 2.4).

The relative residence time of phosphorus is given in Table 2.4 as both (P_λ/P_j), the ratio between the observed mean lake and inflow concentrations, and (τ_p/τ_w) with a correction for changes in lake content as given in Equation 2.5. These ratios are plotted in Figure 2.3. The ratio (P_λ/P_j) increased from 0.33 to a maximum of 0.48 (1970), which represents a 45% increase. Taking into account the known changes in lake content, the relative residence time (τ_p/τ_w) increased from 0.35 to a maximum of 0.57 (1970) which is higher (i.e., a 73% increase) than indicated by the ratio of observed concentrations. Overall, (τ_p/τ_w) shows a slight positive increasing trend, but remains well below a value of 1.

In terms of mass balance models, coefficients for sedimentation and flushing (calculated from the quantities given in the budget observations) are given in Table 2.5 and plotted in the lower panel of Figure 2.2. In addition, the sedimentation coefficient estimated as $1/\tau_w$ is plotted for comparison. The observed sedimentation coefficient drops consistently from 0.56 y^{-1} to 0.25 y^{-1}, i.e., to 45% of its initial value.

Table 2.4 Bodensee-Obersee phosphorus concentrations of the lake, theoretical inflow and their ratio.

Year	$[P_\lambda]$	$[P_j]$	observed (P_λ/P_j)	$(\frac{\Delta\ \text{lake}}{\text{load}})$	(τ_p/τ_w)
1930	7.00	21.24	.330	.07	.353
31	7.00	21.78	.321	.05	.339
32	8.00	28.24	.283	.09	.310
33	8.00	28.92	.277	.06	.295
34	9.00	31.89	.282	.07	.303
35	9.00	22.37	.402	.02	.395
36	9.00	24.92	.361	.03	.372
37	9.00	26.08	.345	.04	.358
38	9.00	34.49	.261	.09	.285
39	10.00	24.15	.414	.01	.409
40	10.00	25.41	.394	.01	.397
41	10.00	30.81	.325	.04	.338
42	10.00	35.52	.282	.04	.294
43	11.00	41.36	.266	.04	.277
44	11.00	26.26	.419	.08	.387
45	10.00	25.92	.386	.06	.363
46	10.00	33.11	.302	.06	.323
47	10.00	43.26	.231	.11	.259
48	11.00	39.90	.276	.11	.309
49	12.00	65.87	.182	.13	.211
50	13.00	45.21	.288	.05	.302
51	14.00	39.73	.352	.03	.365
52	14.00	42.50	.329	.05	.345
53	14.00	48.98	.286	.09	.313
54	15.00	38.99	.385	.03	.397
55	16.00	46.40	.345	.08	.376
56	17.00	44.84	.379	.07	.408
57	17.00	54.95	.309	.11	.348
58	19.00	53.36	.356	.09	.389
59	20.00	82.78	.242	.16	.287
60	22.00	56.34	.390	.07	.420
61	23.00	74.14	.310	.13	.355
62	25.00	96.54	.259	.17	.311
63	28.00	81.76	.342	.12	.390
64	30.00	108.90	.275	.16	.329
65	33.00	64.73	.510	.05	.535
66	34.00	74.49	.456	.10	.506
67	36.00	88.02	.409	.15	.478
68	39.00	103.10	.378	.18	.460
69	44.00	131.94	.333	.21	.421
70	49.00	100.65	.487	.14	.568
71	54.00	202.27	.267	.29	.374
72	63.00	221.89	.284	.27	.391
73	72.00	177.90	.405	.21	.510
74	80.00	178.61	.448	.20	.558

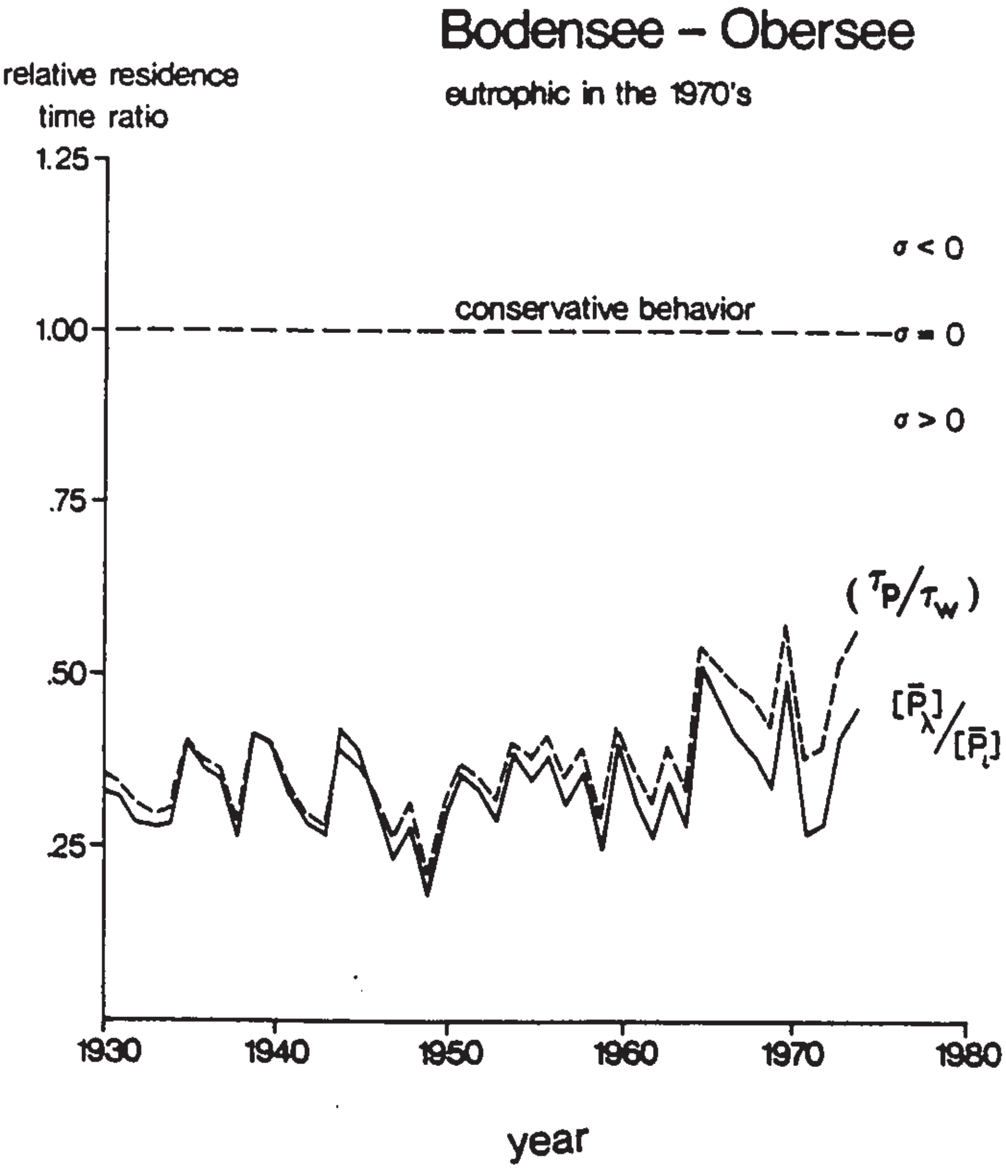


Figure 2.3 Bodensee-Obersee ($\tau p/\tau w$) from 1935 to 1974.

Table 2.5 Phosphorus elimination coefficients (sedimentation and flushing) and residence times in the Bodensee-Obersee.

year	σ y^{-1}	$\tau_s = (\frac{1}{\sigma})$ y	ρ y^{-1}	$\tau_w = (\frac{1}{\rho})$ y	$\tau_p = \frac{1}{(\sigma + \rho)}$ y	$(\tau_p/\tau_w) = \frac{\rho}{(\sigma + \rho)}$ -	$(\frac{\sigma}{\rho})$ -	v_s $m \cdot y^{-1}$
1930	.56	1.79	.27	3.70	1.20	.33	2.07	56.0
31	.55	1.82	.27	3.70	1.22	.33	2.04	55.0
32	.55	1.82	.21	4.76	1.32	.28	2.62	55.0
33	.55	1.82	.21	4.76	1.32	.28	2.62	55.0
34	.54	1.85	.20	5.00	1.35	.27	2.70	54.0
35	.53	1.89	.29	3.45	1.22	.35	1.83	53.0
36	.54	1.85	.27	3.70	1.23	.33	2.00	54.0
37	.53	1.89	.26	3.85	1.27	.33	2.04	53.0
38	.54	1.85	.21	4.76	1.33	.28	2.57	54.0
39	.52	1.92	.30	3.33	1.22	.37	1.73	52.0
40	.52	1.92	.28	3.57	1.25	.35	1.86	52.0
41	.52	1.92	.23	4.35	1.33	.31	2.26	52.0
42	.52	1.92	.20	5.00	1.39	.28	2.60	52.0
43	.52	1.92	.17	5.88	1.45	.25	3.06	52.0
44	.50	2.00	.26	3.85	1.32	.34	1.92	50.0
45	.50	2.00	.25	4.00	1.33	.33	2.00	50.0
46	.53	1.89	.22	4.55	1.33	.29	2.41	53.0
47	.53	1.89	.18	5.56	1.41	.25	2.94	53.0
48	.52	1.92	.21	4.76	1.37	.29	2.48	52.0
49	.52	1.92	.13	7.69	1.54	.20	4.00	52.0
50	.50	2.00	.20	5.00	1.43	.29	2.50	50.0
51	.49	2.04	.23	4.35	1.39	.32	2.13	49.0
52	.49	2.04	.23	4.35	1.39	.32	2.13	49.0
53	.49	2.04	.21	4.76	1.43	.30	2.33	49.0
54	.48	2.08	.27	3.70	1.33	.36	1.78	48.0
55	.48	2.08	.24	4.17	1.39	.33	2.00	48.0
56	.47	2.13	.26	3.85	1.37	.36	1.81	47.0
57	.47	2.13	.22	4.55	1.45	.32	2.14	47.0
58	.45	2.22	.24	4.17	1.45	.35	1.88	45.0
59	.45	2.22	.17	5.88	1.61	.27	2.65	45.0
60	.43	2.33	.26	3.85	1.45	.38	1.65	43.0
61	.43	2.33	.21	4.76	1.56	.33	2.05	43.0
62	.42	2.38	.17	5.88	1.69	.29	2.47	42.0
63	.40	2.50	.21	4.76	1.64	.34	1.90	40.0
64	.39	2.56	.17	5.88	1.79	.30	2.29	39.0
65	.37	2.70	.31	3.23	1.47	.46	1.19	37.0
66	.37	2.70	.29	3.45	1.52	.44	1.28	37.0
67	.36	2.78	.26	3.85	1.61	.42	1.38	36.0
68	.35	2.86	.24	4.17	1.69	.41	1.46	35.0
69	.34	2.94	.21	4.76	1.82	.38	1.62	34.0
70	.31	3.23	.29	3.45	1.67	.48	1.07	31.0
71	.31	3.23	.16	6.25	2.13	.34	1.94	31.0
72	.28	3.57	.16	6.25	2.27	.36	1.75	28.0
73	.26	3.85	.21	4.76	2.13	.45	1.24	26.0
74	.25	4.00	.23	4.35	2.08	.48	1.09	25.0

Calculated as apparent sedimentation velocities, these values drop from 56 $m \cdot y^{-1}$ to 25 $m \cdot y^{-1}$. In comparison to $1/\sqrt{\tau_w}$, observed sedimentation rates run approximately parallel, then drop below this estimate after about 1950. Flushing coefficients range from 0.13 y^{-1} to 0.31 y^{-1} with no particular trend. The combined coefficients result in approximations of absolute residence time (τ_p) ranging from 1.20 y to 2.27 y, or relative to water (τ_p/τ_w), of 0.20 to 0.48, both of which show an increasing trend over time.

The ratio of elimination coefficients (σ/ρ) shows a generally decreasing trend over time due to the decreasing trend in the value of σ. Overall, the ratio drops from 2 to approximately 1. Therefore the values of σ and ρ are approximately equivalent in the 1970s, following a period of diminishing dominance of sedimentation as the major component of elimination.

2.2.3 Assessment for the Bodensee-Obersee

The onset of eutrophication in the Bodensee-Obersee began in the 1960s. At this time the lake content began to rise disproportionately to the loading when the loading level was about 700 $t \cdot y^{-1}$ and phosphorus concentrations were about 20 $mg \cdot m^{-3}$. Therefore the maximum (critical) phosphorus load that the Bodensee can assimilate appears to be approximately 700 $t \cdot y^{-1}$.

The relative residence time of phosphorus remained substantially below 1 over the entire period indicating that the lake is essentially a strong sink for phosphorus despite eutrophic conditions. However, the increasing trend of (τ_p/τ_w) from 0.35 to 0.55, due to a 4-fold increase of the change in lake content per unit load, indicates that the sink capacity of the lake has diminished in time.

Maximum relative residence times (>0.53) (or equivalently, slowest flow rates of phosphorus through the system) occurred in 1965, 1970 and 1974. These coincided with relatively high flushing rates and relative minima of absolute residence times. Conversely, minimum relative residence times (<0.29) (or most rapid flows possibly indicating greatest biological limitation) occurred in 1938, 1943, 1947, 1949, with relative minima (<0.42) in 1962, 1964, 1969, 1971 and 1972 when flushing rates were minimal. Thus, net sedimentation of phosphorus is greatest in the Bodensee when water residence time is longest.

Comparing (τ_p/τ_w) with the concentration ratio (P_λ/P_j), shows that this latter is a fair estimate of the lake's dynamics. Discrepancies in the two measures are greatest in the later years of eutrophication and run parallel to the departure of σ from $(1/\sqrt{\tau_w})$. Whereas $(1/\sqrt{\tau_w})$ appears to be an excellent means of estimating the sedimentation coefficient for steady-state conditions (such as approximated in the years before serious eutrophication problems and when the changes in lake content per unit load were minimal), this estimate does not follow the real evolution of the observed sedimentation. As a consequence, lake concentrations predicted from the standard flushing-corrected inflow (cf. Vollenweider, 1975 and 1976; Vollenweider and Kerekes, 1982) for the years after 1960 would tend to be underestimated and lake conditions would be worse than expected. To summarize, the minor fluctuations in (τ_p/τ_w) (cf. Figure 2.3) reflect variations in water residence time, while the long-term trend of a slow rise reflects the drop in sedimentation efficiency.

This leads to the question of what controls sedimentation? The observed net sediment is plotted against the load and lake content in Figures 2.4 and 2.5, respectively. The pattern is very regular in both cases. The correlation coefficient r of net sediment and loading is 0.99 ($p < 0.001$; $n = 45$) and that for sediment and lake content is 0.98 ($p < 0.001$; $n = 45$). Therefore sedimentation could be estimated from a regression equation for either relationship with approximately the same accuracy.

More interestingly, the relationship of sediment to lake content suggests a saturation phenomenon. With increasing lake content, the departure of this relationship from linearity begins at a lake content of about 1000 tons, a net sedimentation level of about 450 tons and a lake concentration of 20 $mg \cdot m^{-3}$. This is also at the point of the (earlier) proposed maximum load of about 700 $t \cdot y^{-1}$. After 1960, sedimentation progressively levels off to a maximum sedimentation rate of approximately 1000 $t \cdot y^{-1}$. The diminishing sedimentation could therefore be attributed to

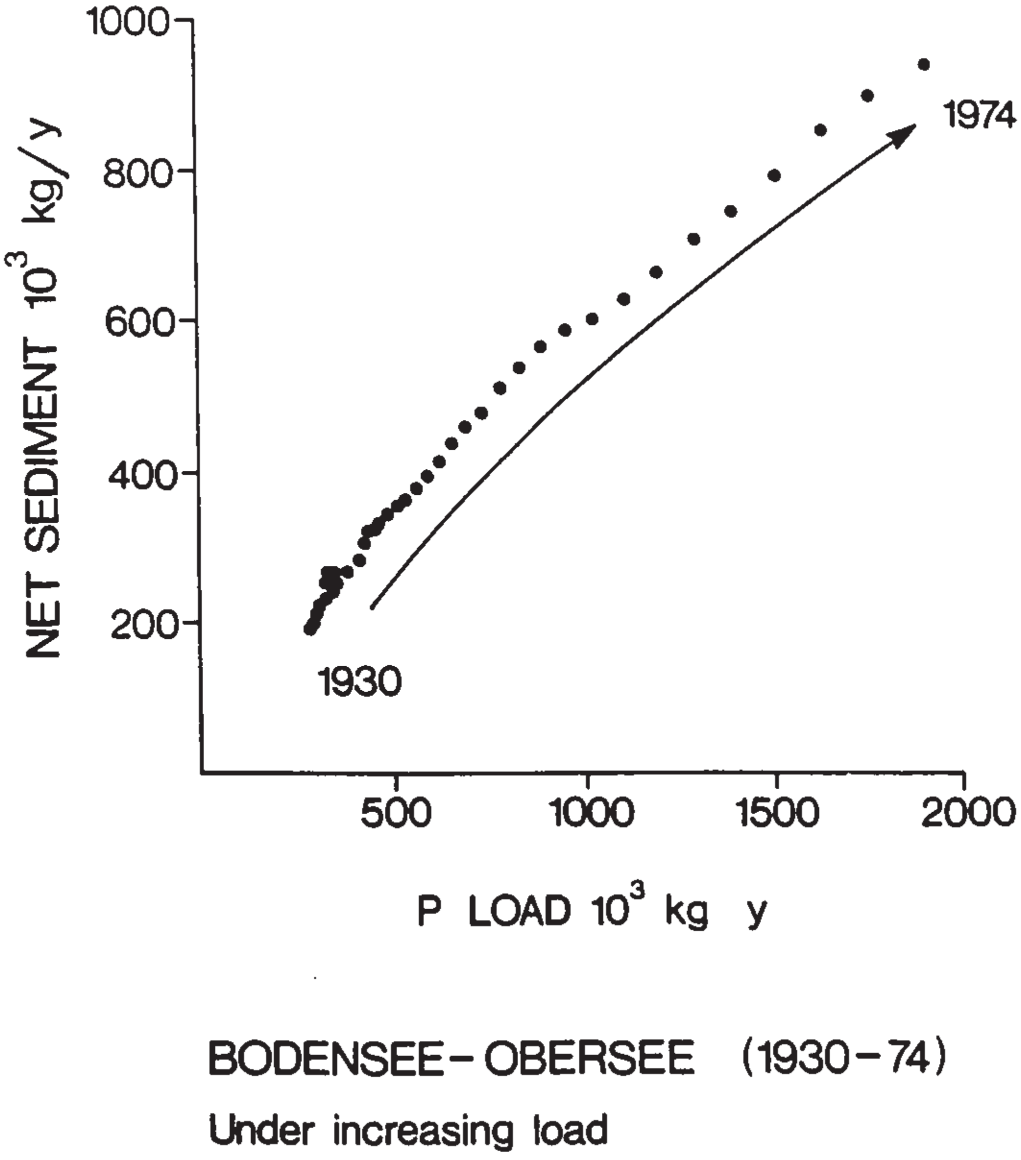


Figure 2.4 Bodensee-Obersee phosphorus sediment vs load.

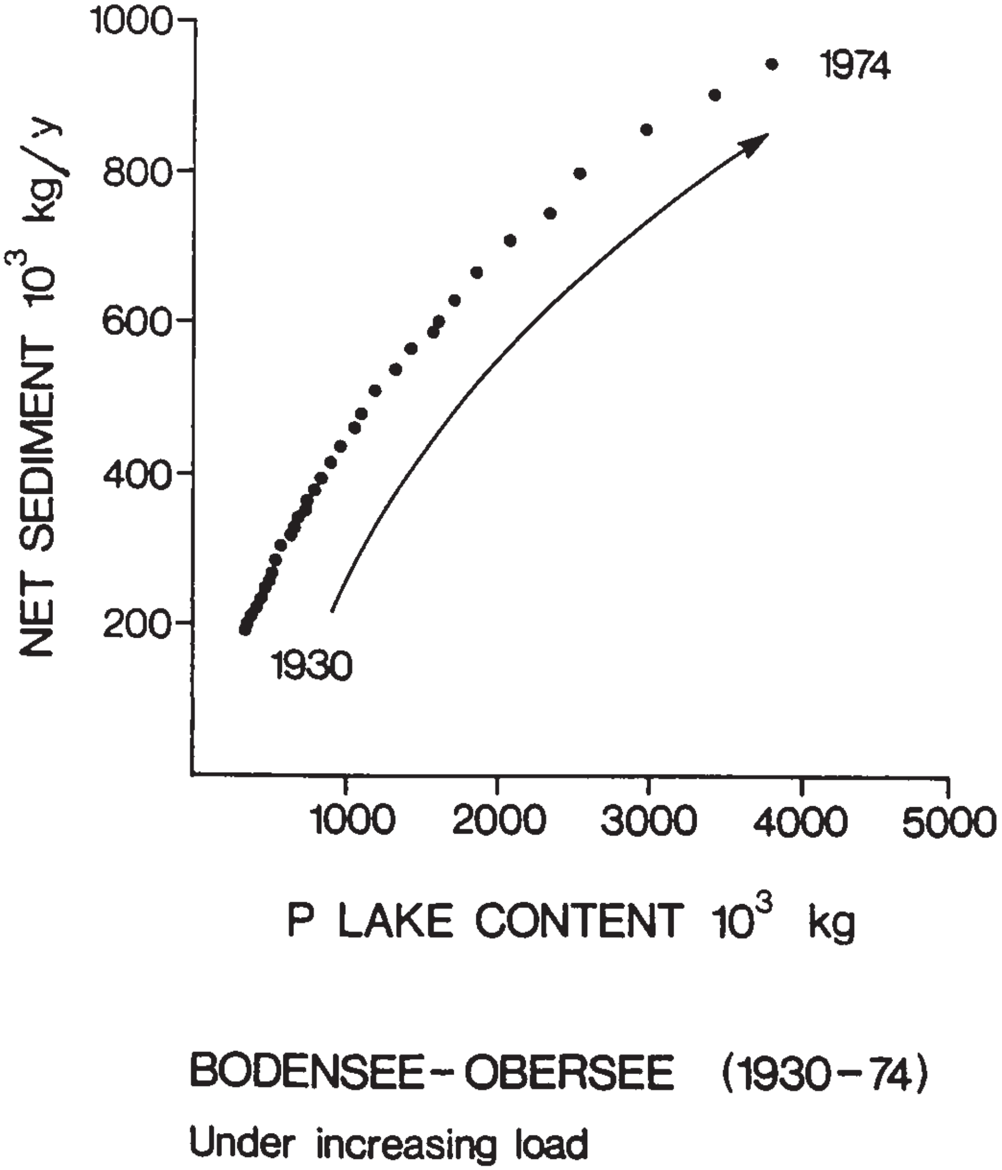


Figure 2.5 Bodensee-Obersee phosphorus sediment vs lake content.

saturation of the absorptive capacity of the bottom sediments which takes place slowly and steadily beyond the loading of about 700 $t \cdot y^{-1}$.

An additional mechanism which may contribute to the slow rise in relative residence time is a progressive change in phytoplankton species composition with eutrophication. Stabel (1985) found that in the Bodensee, flagellates, blue-greens and dinoflagellates were nearly completely remineralized in the euphotic zone while diatoms transferred the bulk of phosphorus (as well as silica and particulate organic matter) to the lake bottom. Since the former are more likely to predominate under eutrophic conditions, their remineralization may be at least partial explanation for longer phosphorus relative residence times.

In summary, (τ_p/τ_w) in the Bodensee has become longer (maximum = 0.56) with increasing eutrophication, and longer than expected from the concentration ratio (P_λ/P_j), (maximum = 0.48). Over the period of the study, apparent sedimentation velocity of phosphorus dropped from 56 $m \cdot y^{-1}$ to 25 $m \cdot y^{-1}$ and the sedimentation coefficient decreased from 0.56 to 0.25 y^{-1}. This has shifted the control of phosphorus elimination in the lake from a predominance of sedimentation $(\sigma/\rho = 2.07)$ to a condition of near equivalence of sedimentation and flushing mechanisms $(\sigma/\rho = 1.09)$ in removal. The regularity and exponential pattern of sedimentation changes appears to be a saturation phenomenon and may be due to progressive saturation and reduction of bottom sediments as Mortimer (1941, 1942) described for English lakes. Nonetheless, the relative residence time remains substantially below 1 and the lake is a sink for phosphorus. If an exponential model for the rate of recovery after loading reduction is correct, one would expect a 95% recovery to the new steady-state condition in 3 τ_p or 6.24 years for the Bodensee. However, recovery could be faster if τ_p decreases to its former values of around 1.3 as loading decreases and sedimentation efficiency recovers.

2.3 Sempachersee

2.3.1 Description and Trophic History

The Sempachersee is a relatively small, deep lake of glacial origin (not unlike the Baldeggersee discussed later), which lies along the northern border of the Alps in Switzerland (cf. Figure 2.6). The lake is located at approximately 47°N, 8°E, at an altitude of 504 m and is seldom ice-covered. The drainage basin is nearly 63 km^2 and the surface area of the lake is 14.4 km^2 with a resultant surrounding factor of 4.4. The mean and maximum depths of the lake are 46 and 87 m, respectively. The volume is 624 x 10^6 m^3, and with a hydraulic load of 2.79 $m \cdot y^{-1}$, the water residence time averages 16.5 y (Stadelmann and Fricker, 1980).

The history given by Stadelmann and Fricker (1980) states that the first scientific records on the condition of the lake

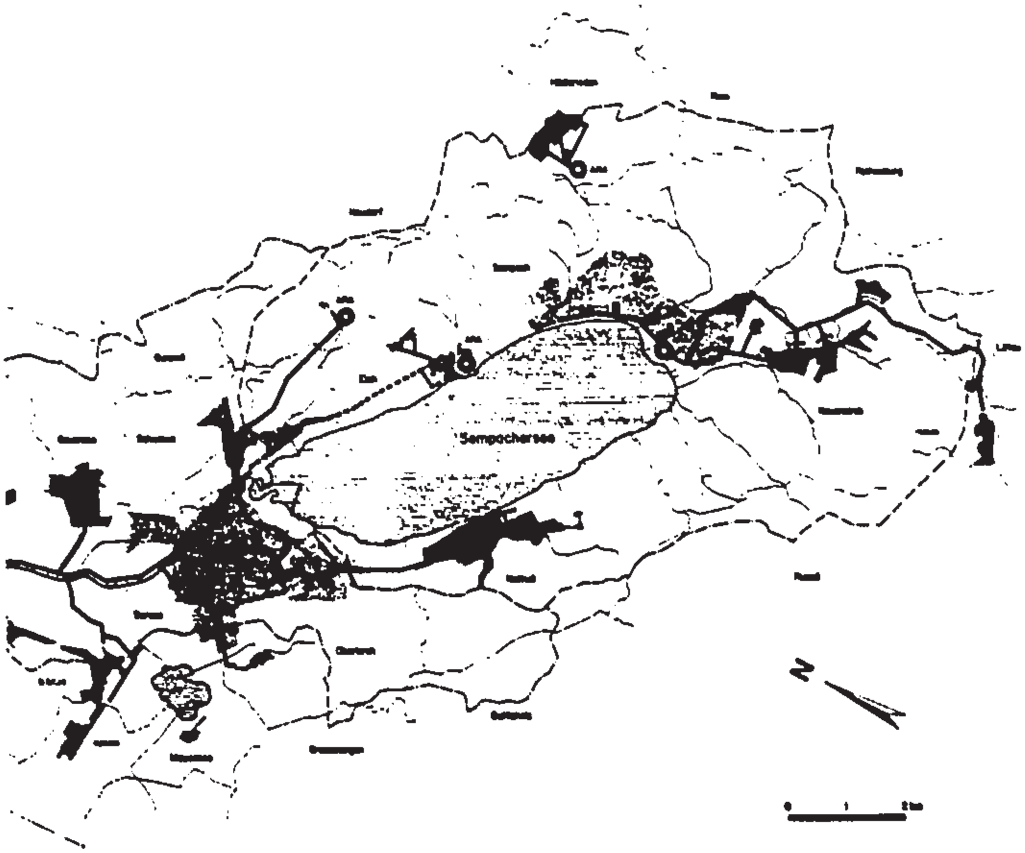


Figure 2.6 Map of the Sempachersee, Switzerland, from Stadelmann (1972).

began in 1910, when Secchi summer minima of 2.3 m were reported. In 1938 oxygen measurements showed that little depletion took place and oxygen levels were at 6 $\mathrm{mg \cdot l^{-1}}$ after stratification. This began to change in the 1950s when low levels of oxygen in the deepest regions of the lake were found. Despite this condition and a gradual but continuously increasing external load, the phosphorus concentration in the lake remained stable at about 10 $\mathrm{mg \cdot m^{-3}}$. Nitrate levels at that time were approximately 300 $\mathrm{mg \cdot m^{-3}}$. Then in the mid-1960s the lake began a rapid evolution away from its original oligotrophic condition. In the early 1970s Secchi minima fell to 1.3 m and occurred in spring rather than late summer. Oxygen levels fell to 0.2 $\mathrm{mg \cdot l^{-1}}$ in the deep water and a pronounced metalimnetic minimum developed. In the 8-year period from 1965 to 1972, the average phosphorus concentration in the lake rose from 10 to 75 $\mathrm{mg \cdot m^{-3}}$, then remained stable at that level for about three years. Nitrate levels had doubled since 1960 and were approximately 600 $\mathrm{mg \cdot m^{-3}}$. After 1975 the phosphorus concentration began to rise again.

The gradually increasing nutrient load to the lake was a result of population growth after WW II and intensification of the agricultural activities in the basin. In 1977 phosphorus loading was estimated at 15 $\mathrm{t \cdot y^{-1}}$ with 50% of that originating from the dairy industry and other agriculture. Presently, five sewage treatment plants are in operation serving 60% of the population and these have reduced the municipal contribution from

7 $t \cdot y^{-1}$ to about 3 $t \cdot y^{-1}$. However, the loading tolerance of the lake roughly estimated from the mean depth and water residence time is 4 $t \cdot y^{-1}$. Clearly further reductions in loading will be necessary to prevent the lake from stabilizing at a highly eutrophic condition, but how this will be accomplished is not yet resolved (Stadelmann and Fricker, 1980).

2.3.2 Budget Analysis of the Sempachersee

The phosphorus budget for the Sempachersee covers the period 1954 to 1978 (cf. Table 2.6) and was derived from the publication by Gachter *et al.* (1983). This 25-year period is the second longest record for the lakes discussed here and is depicted in Figure 2.7.

Phosphorus loading to the Sempachersee increased linearly from 3.4 to 15.2 metric $t \cdot y^{-1}$ (i.e., a 4.5-fold increase) over a 24-year period. Losses via the outlet (estimated from the relationship that: outlet losses = 0.042·lake content) also increased steadily from 0.36 to 2.82 $t \cdot y^{-1}$, an increase of 7.8 times. The lake response to these inputs and outputs was a steady exponential rise from 8.6 tons to 67.25 tons, with only a brief stabilization between 1973 and 1976. In terms of incremental changes, the increases in lake content followed a general rising pattern from gains of 0.2 up to 10.0 metric $t \cdot y^{-1}$, but also decreased by small amounts of 3.0 and 1.5 tons in the years

Table 2.6 Sempachersee phosphorus balance; a 25 year time series (1954 - 78), adapted from Gachter _et al_. (1983).

Year	Mean P Content of the Lake kg	Total Load $kg \cdot y^{-1}$	Loss Via Outlet* $kg \cdot y^{-1}$	Change in Lake Content $kg \cdot y^{-1}$	Net Sediment $kg \cdot y^{-1}$
1954	8600	3400	360	200	2840
55	9100	3800	332	800	2618
56	9800	4200	412	600	3168
57	10350	4700	433	500	3767
58	11050	5100	464	900	3736
59	11750	5600	493	500	4607
60	12500	6100	525	1000	4575
61	13500	6600	567	1000	5033
62	14500	7000	609	1000	5391
63	15500	7500	651	1000	5849
64	16600	8000	697	1200	6103
65	17850	8400	748	1300	6352
66	19100	8700	802	1200	6698
67	20850	9300	874	2300	6126
68	23000	9900	966	2000	6934
69	26000	10600	1090	4000	5510
70	30000	11000	1260	4000	5740
71	35500	11600	1490	5000	5110
72	42000	12100	1760	10000	340
73	50250	12900	2108	6500	4292
74	52500	13300	2180	-3000	14120
75	49750	14000	2090	-1500	13410
76	52000	14600	2180	6000	6420
77	59750	15200	2509	9500	3191
78	67250	15200	2824	5500	6876

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*$P_\omega = 0.042\ P_\lambda$

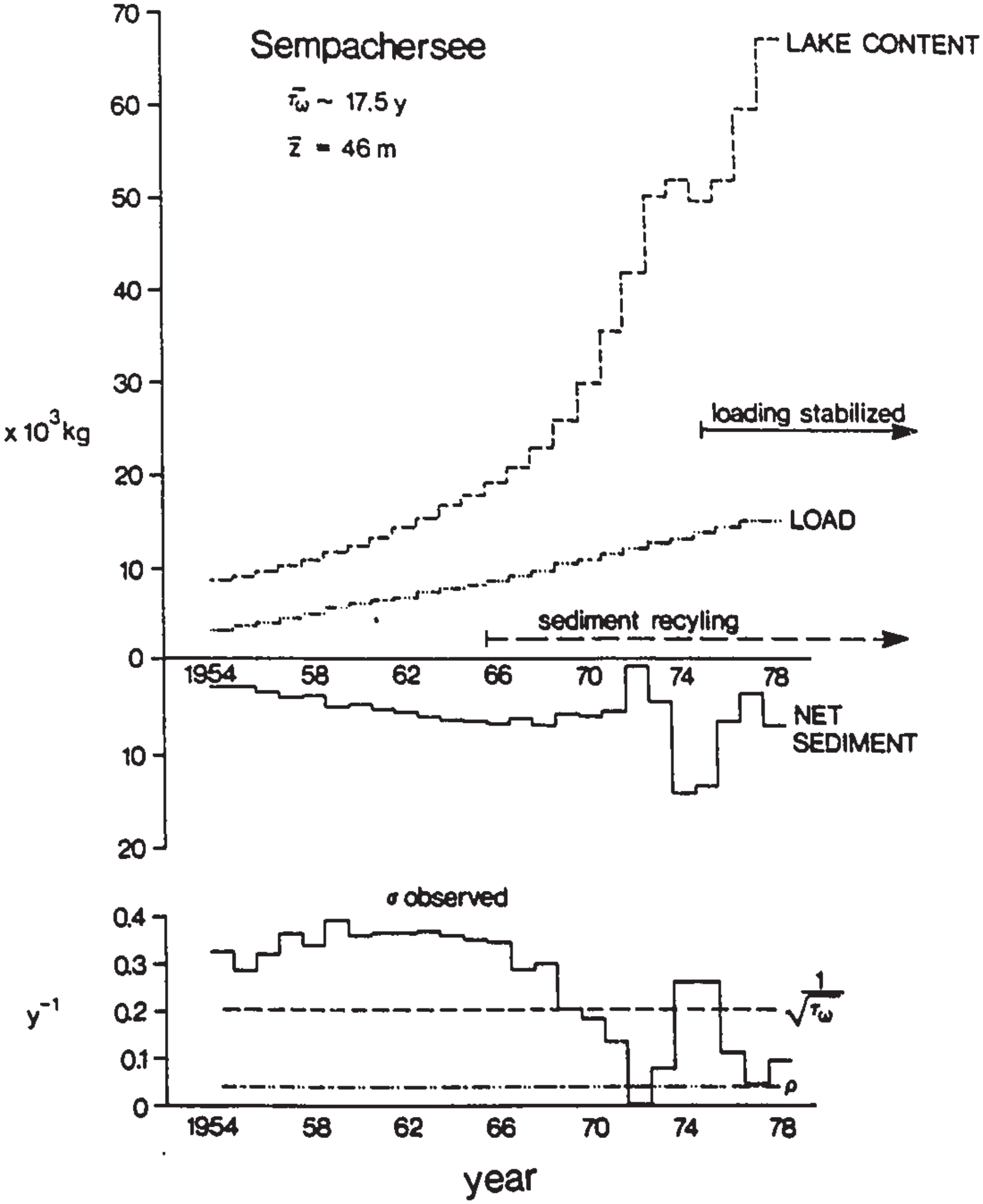


Figure 2.7 Sempachersee phosphorus loading, lake content and sedimentation (1930 - 45).

1974 and 1975, respectively (i.e., during the period when lake content stabilized).

Net sedimentation as calculated from these fluxes increased steadily up until 1968. After that, sedimentation was highly irregular with minimum values of 0.34 and 3.19 $t \cdot y^{-1}$ in 1972 and 1977, respectively, and maximum values of 14.1 and 13.4 $t \cdot y^{-1}$ consecutively in 1974 and 1975 during the brief stabilization of the lake content.

Lake content and loading increased parallel to one another until about 1960 and after that the rise in lake content rose disproportionately to the loading, concurrent with the first signs of eutrophication beginning around 1960.

In terms of concentration, the mean inflow concentration rose steadily from 89.4 to 399.8 $mg \cdot m^{-3}$ (4.7-fold) over the 25-year period (cf. Table 2.7). At the same time, the lake concentration also followed a consistent rise from 13.0 to 101.6 $mg \cdot m^{-3}$ (a 7.8-fold increase).

The relative residence time of phosphorus is given in Table 2.7 as both the ratio of observed lake and inflow concentrations (P_λ/P_j) and (τ_p/τ_w) which includes the correction for changes in lake content (cf. Equation 2.5). These ratios are plotted in Figure 2.8. The ratio (P_λ/P_j) increased slowly and consistently from 0.15 to 0.25 over the study period with little variation. In contrast, (τ_p/τ_w) showed very dynamic temporary maxima of 1.15 and 0.60 in 1972 and 1977.

Table 2.7 Sempachersee phosphorus concentrations of the lake, theoretical inflow and their ratio.

Year	$[P_\lambda]$	$[P_J]$	observed (P_λ/P_J)	$(\frac{\Delta \text{ lake}}{\text{load}})$	(τ_p/τ_w)
1954	12.99	89.44	.145	.06	.154
55	13.75	99.96	.138	.21	.174
56	14.80	110.48	.134	.14	.156
57	15.63	123.63	.126	.11	.142
58	16.69	134.15	.124	.18	.151
59	17.75	147.31	.120	.09	.132
60	18.88	160.46	.118	.16	.141
61	20.39	173.61	.117	.15	.138
62	21.90	184.13	.119	.14	.139
63	23.41	197.29	.119	.13	.137
64	25.08	210.44	.119	.15	.140
65	26.96	220.96	.122	.15	.144
66	28.85	228.85	.126	.14	.146
67	31.50	244.63	.129	.25	.171
68	34.74	260.42	.133	.20	.167
69	39.27	278.83	.141	.38	.226
70	45.32	289.35	.157	.36	.246
71	53.63	305.13	.176	.43	.309
72	63.44	318.29	.199	.83	1.149
73	75.91	339.33	.224	.50	.451
74	78.55	349.85	.225	-.23	.183
75	75.15	368.27	.204	-.11	.184
76	78.55	384.05	.205	.41	.347
77	90.26	399.83	.226	.63	.602
78	101.59	399.83	.254	.36	.398

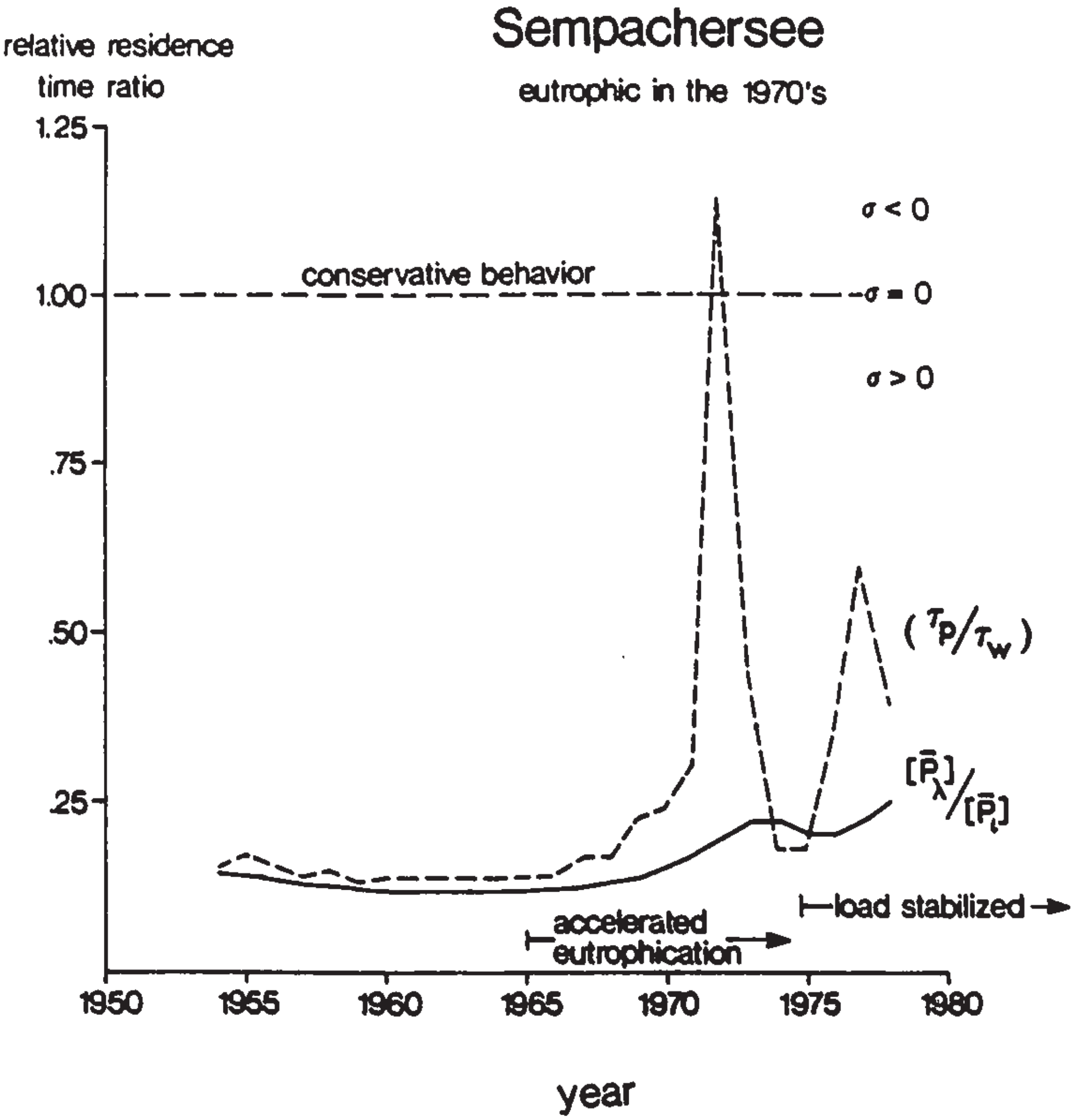


Figure 2.8 Sempachersee (Tp/Tw) from 1935 to 1974.

The maximum discrepancy in the two measures occurs in 1972 and 1977 when the most dynamic increases in lake content took place. Significantly, (τ_p/τ_w) exceeded the value of 1 when σ dropped below ρ, despite the fact that the net sedimentation is never negative in this series.

In terms of mass balance coefficients, sedimentation and flushing rates as calculated from the budget quantities are listed in Table 2.8 and plotted in the lower panel of Figure 2.8. In addition, the sedimentation rate as estimated from $1/\sqrt{\tau_w}$ is plotted in the same figure. The observed sedimentation rate remained high at an average of 0.35 y^{-1} from 1954 to 1966, then dropped rapidly to 0.01 y^{-1} by 1972. Sedimentation rate increased enough in 1974 and 1975 (i.e., to 0.27 y^{-1}) to stabilize the lake content, but dropped again in the remaining three years of the record (i.e., until 1978). Calculated as apparent sedimentation velocities, values ranged from a high of 18.0 $m \cdot y^{-1}$ in 1959 to a low of 0.4 $m \cdot y^{-1}$ in 1972. Comparing the observed sedimentation rate to that estimated by $1/\sqrt{\tau_w}$ shows that the estimate is in general too low, but is much too high in 1972 and from 1976 on. (Notably, the estimate of sedimentation rate from water residence time is constant because yearly measurements were not made and an average value had to be used. This has the consequence that flushing elimination differences from year to year are transferred into the estimate of net sedimentation and contribute to the error of sedimentation rate

Table 2.8 Phosphorus elimination coefficients (sedimentation and flushing) and residence times in the Sempachersee.

year	σ y^{-1}	$\tau_s = (\frac{1}{\sigma})$ y	$\beta\rho$* y^{-1}	$\tau_w = (\frac{1}{\beta\rho})$ y	$\tau_p = \frac{1}{(\sigma + \beta\rho)}$ y	$(\tau_p/\tau_w) = \frac{\beta\rho}{(\sigma + \beta\rho)}$ -	$(\frac{\sigma}{\beta\rho})$ -	v_s† $m \cdot y^{-1}$
1954	.33	3.03	.042	23.8	2.69	.11	7.86	15.2
55	.29	3.45	.042	23.8	3.01	.13	6.90	13.2
56	.33	3.03	.042	23.8	2.69	.11	7.86	15.0
57	.36	2.78	.042	23.8	2.49	.10	8.57	16.7
58	.34	2.94	.042	23.8	2.62	.11	8.10	15.6
59	.39	2.56	.042	23.8	2.31	.10	9.29	18.0
60	.36	2.78	.042	23.8	2.49	.10	8.57	16.8
61	.37	2.70	.042	23.8	2.43	.10	8.81	17.2
62	.37	2.70	.042	23.8	2.43	.10	8.81	17.1
63	.38	2.63	.042	23.8	2.37	.10	9.05	17.4
64	.37	2.70	.042	23.8	2.43	.10	8.81	16.9
65	.36	2.78	.042	23.8	2.49	.10	8.57	16.4
66	.35	2.86	.042	23.8	2.55	.11	8.33	16.1
67	.29	3.45	.042	23.8	3.01	.13	6.90	13.5
68	.30	3.33	.042	23.8	2.92	.12	7.14	13.9
69	.21	4.76	.042	23.8	3.97	.17	5.00	9.8
70	.19	5.26	.042	23.8	4.31	.18	4.52	8.8
71	.14	7.14	.042	23.8	5.49	.23	3.33	6.6
72	.01	100.00	.042	23.8	19.23	.81	.24	.4
73	.09	11.11	.042	23.8	7.58	.32	2.14	3.9
74	.27	3.70	.042	23.8	3.21	.13	6.43	12.5
75	.27	3.70	.042	23.8	3.21	.13	6.43	12.4
76	.12	8.33	.042	23.8	6.17	.26	2.86	5.7
77	.05	20.00	.042	23.8	10.87	.46	1.19	2.5
78	.10	10.00	.042	23.8	7.04	.30	2.38	4.7

*β factor = $\frac{\text{outlet export of p}}{\text{lake content of p}}$; used to correct efficiency of ρ; ρ = .057 y^{-1} and τ_w = 17.5 y.

†$v_s = \sigma \cdot \bar{z}$ where $\bar{z}$ = 46 m.

estimates. However, flushing rate is so minimal compared to sedimentation rate that fluctuations in water residence time should create only negligible error in the sedimentation estimates.)

The combined coefficients result in absolute residence time estimates (τ_p) of approximately 2 to 3 years up until 1969. After that the residence time increases to about 7 years with maxima of 19.2 y in 1972 and 1977, respectively.

As mentioned earlier, the ratio of sedimentation to flushing is generally high at 6 to 9 up until 1969. After that, the ratio drops to values of 2 and less. The minimum ratio of 0.24 occurred in 1972 when sedimentation losses (0.34 tons) fell far below elimination by flushing (1.76 tons). Therefore sedimentation is the dominant elimination pathway in the Sempachersee but this is gradually changing as phosphorus residence times increase and this element tends to behave more conservatively.

2.3.3 Assessment for the Sempachersee

Eutrophication of the Sempachersee became apparent in the mid-1960s when Secchi depths decreased to about 1.3 m and oxygen levels fell to 0.2 $mg \cdot l^{-1}$ in the hypolimnion. At this time lake concentrations of phosphorus began to exceed 25 $mg \cdot m^{-3}$ and the lake content rose disproportionately to the load. Thus it appears that the maximum load that the Sempachersee can assimilate is about 8 $t \cdot y^{-1}$ after which the lake's basic trophic character begins to change. This maximum load is twice that estimated by Stadelmann and Fricker (1980), who based their estimate on the average effects of mean depth and water residence time on loading. However, since elimination is dominated by sedimentation in the Sempachersee and water residence time gives a very low estimate of the observed sedimentation, the model they have used to estimate the tolerable load is uncalibrated for this particular situation. The lake is more efficient than average in sedimentation of phosphorus and this may have to do with its particular morphometry and stratification relative to flushing. The underestimation of sedimentation by water residence time (cf. Figure 2.7) has led Stadelmann and Fricker to most likely an underestimate of the assimilation capacity and tolerable load for the lake. Thus if 50% of the load can be eliminated by sewage diversion and changes in agricultural practices, the lake may recover without lake-internal restoration measures, however, recovery time may be excessively long (cf. discussion below).

The relative residence time of phosphorus reached a maximum value greater than 1 in 1972. Net sedimentation was only 340 $kg \cdot y^{-1}$ and σ approached 0. The most likely explanation for such low net sedimentation is internal loading resulting from oxygen depletion (oxygen was recorded at 0.2 $mg \cdot l^{-1}$ in the early 1970s), sediment reduction and phosphorus release as described in the classical studies of Mortimer (1941, 1942). The subsequent recovery of sedimentation in 1974 and 1975 cannot be explained for lack of information on primary productivity, stratification and oxygen distribution, etc.

Notably, the concentration ratio (P_λ/P_j) is exceptionally bad in portraying the dynamic events of this lake system. In the particular case of the Sempachersee, this has to do with the disparity of volumes in the annual water load as compared to the lake volume. With a water residence time of 23 years and flushing rate of only 0.042 y^{-1}, even large increases in inflow concentration may be small in terms of total loading increases. Further to this, even small changes in lake concentration may represent tremendous fluxes in terms of total substance. Thus an increase of 13.2 $mg \cdot m^{-3}$ in the inflow (from 1971 to 1972) represented an increase in the total load of only 0.5 tons, while a comparable increase of 9.8 $mg \cdot m^{-3}$ in the lake represented an increase of 6.5 tons in the lake content (i.e., a value equivalent to half the total external load in that year). This leads to the conclusion that the concentration ratio (of lake to inflow) may be a poor representation of the dynamics of a waterbody if water residence time is long (i.e., 23 years, as compared to the geometric mean for all OECD and Canadian lakes of 1.3 y).

Given these various points then, it remains a question of whether or not total net sediment can be estimated from the loading or lake content; the appropriate plots are given in Figures 2.9 and 2.10, respectively. At first sight the overall

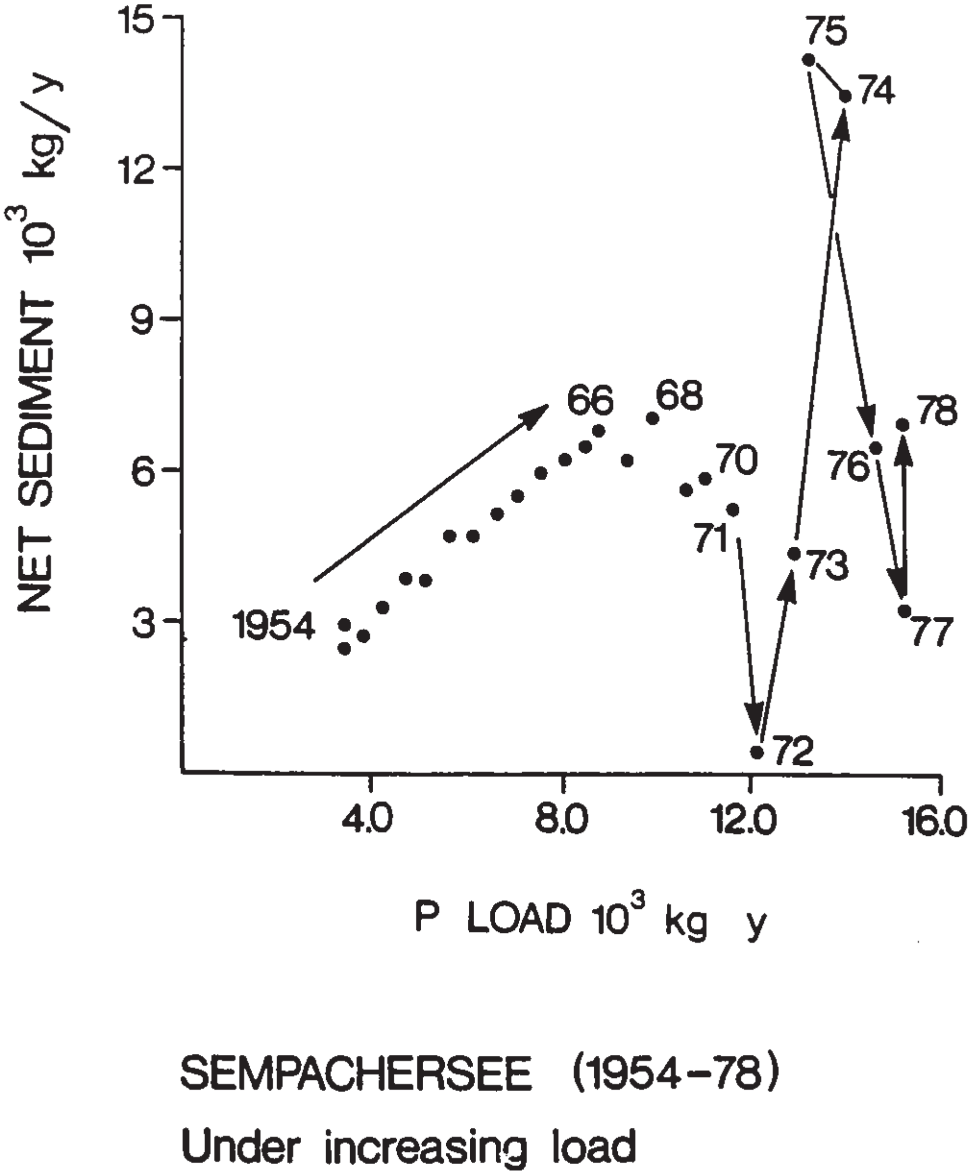


Figure 2.9 Sempachersee phosphorus sediment vs load.

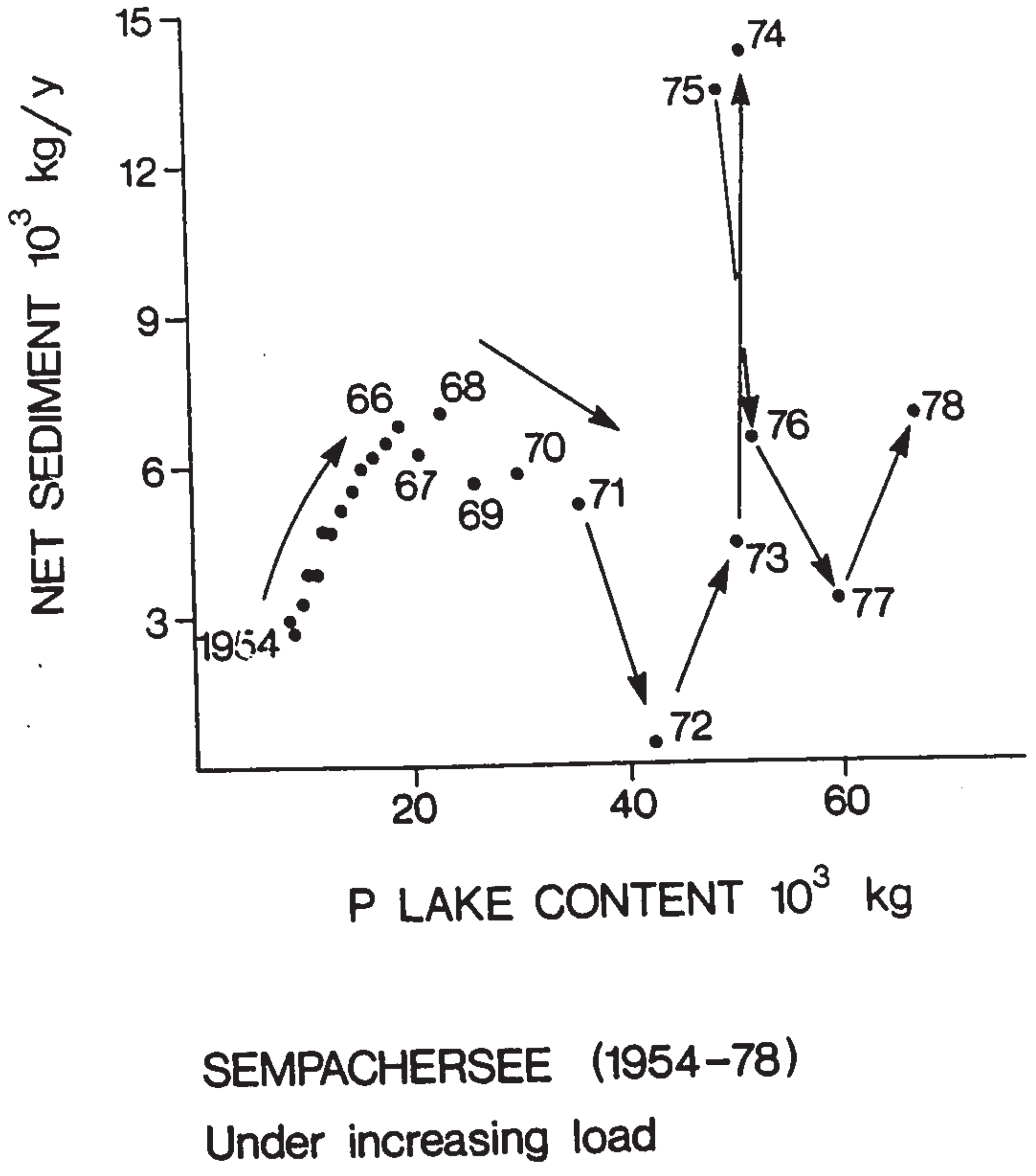


Figure 2.10 Sempachersee phosphorus sediment vs lake content.

correlation is low in either case. However, if only the period up to 1966 is considered, the same relationship as found in the Bodensee appears. Either the load or lake content could be used to estimate the net sediment so long as τ_p is less than about 3 y or (τ_p/τ_w) is less than 0.12. Subsequent to this, it may be hypothesized that the absorbtive capacity of the sediment became saturated in 1966 and sedimentation was threafter erratic and dependent on other mechanisms. Without further data it is not possible to explain conclusively the subsequent maxima (in 1974 and 1975) and minima (1972 and 1977) in sedimentation, however, the minima are contemporaneous with increasing oxygen depletion as mentioned earlier.

If the last five years of the record are taken to calculate an average τ_p for the lake, then it can be projected that the 95% response time (i.e., $3 \cdot \tau_p$) for the Sempachersee to attain a new steady-state with a load reduction is 18.3 years. This has yet to be confirmed by data subsequent to 1978.

Further observations on the history and condition of the Sempachersee lead one to a somewhat pessimistic view for recovery of the lake in that it may require lake-internal measures to break the recycling of sediment phosphorus. Sediment absorption of phosphorus - and with it lake resilience - was lost in 1966. Even if the load could be reduced to 8 $t \cdot y^{-1}$, the desorption, washout and then recovery of absorptive capacity may be so slow that the apparent recovery would be negligible. On the other hand, the high sedimentation in 1974 and 1975 demonstrates that other mechanisms may enhance recovery.

2.4 Lake Washington

2.4.1 Description and Trophic History

Lake Washington is a large, deep lake located in the northwest corner of the continental United States at 47°N, 122°W on the Pacific coast in the state of Washington. The lake was formed about 13,500 years ago with the retreat of the last glacier. The basin left behind was a long, narrow gouge (approximately 21 x 3 km; cf. Figure 2.11) in a glacial flood plain of clay and rock, an inorganic layer estimated to be 60 m thick at the lake bottom. As described by Edmondson (1977), the mean depth of Lake Washington is 32.9 m and the maximum is 62.5 m. The sides of the basin are steep with the result that the littoral area is minimal. Surface area of the lake is 87.6 km^2 and the volume is 2885.3×10^6 m^3. Rainfall in the region is 866 mm annually which arrives predominantly during the fall and winter months. The catchment area is approximately 1588 km^2 and the mean inflow volume between 1942 and 1972 was estimated at 1211×10^6 $m^3 \cdot y^{-1}$, which translates to a hydraulic load of 13.8 $m \cdot y^{-1}$. The major portion (86%) of the inflow enters the lake via the two main tributaries, the Cedar and Sammamish Rivers. The average water residence time in recent years is about 2.4 years, ranging from a maximum in 1944 of 6.2 years to a

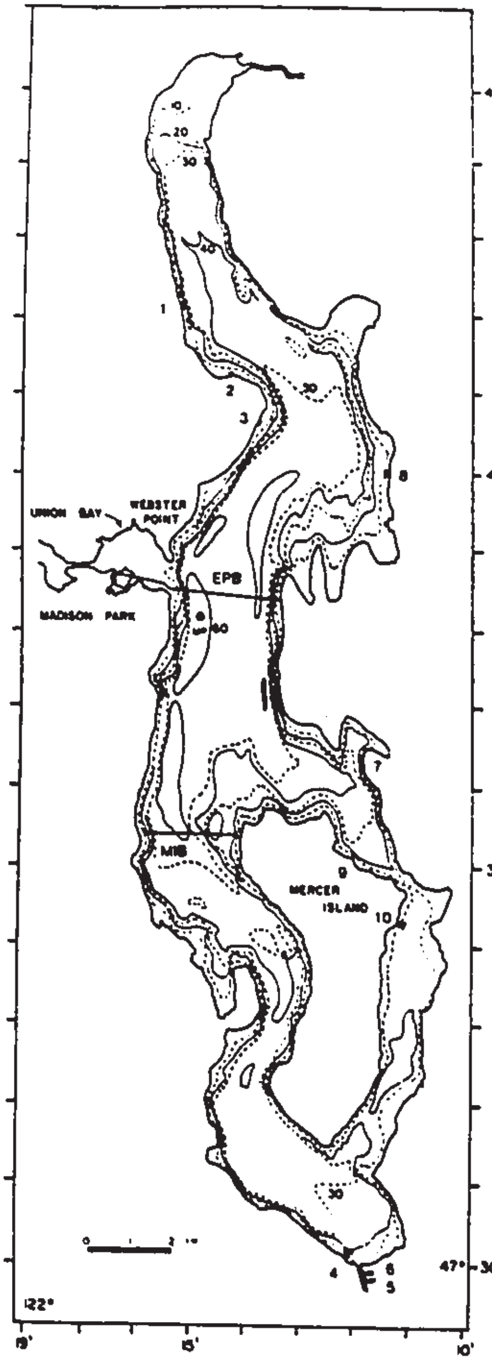


Figure 2.11 Map of Lake Washington, State of Washington, from Edmondson and Lehman (1981).

minimum in 1950 of 1.7 years. The lake never freezes and is considered monomictic with free circulation during the winter isothermal period. The stratification period is from mid-May to November and the epilimnion is typically about 10 m thick.

According to Williams (1985), studies of the lake bottom and sediments have revealed a number of major events in Lake Washington's past. Approximately 1100 years ago three large tracts of forest slid into the lake with many of the trees left standing upright. In more recent times, the first pioneers arrived at Lake Washington in the 1850s and at that time Isaac Ebey christened it "Lake Geneva" because of the natural beauty of the lake and clarity of its water. The sediments show that around 1980 the deposition rate increased seven times the former rate due to the large scale logging and land clearing operations of the settlers. In 1916 the Lake Washington Ship Canal was opened to create a link with the Pacific Ocean. This caused the lake level to drop nearly 3 m and is evident as a band of heavy silt in the lake sediments. At the same time that the new outlet to the ocean was created, the Cedar River was diverted to become a new inlet to the lake. This not only changed the direction of flow through the lake, but also approximately doubled its flushing rate. These major alterations destroyed the pink and chum salmon runs of the Cedar River, however, the new conditions were satisfactory for sockeye salmon which now have an established run between Lake Washington and the Pacific of about 500,000 fish each year.

The history of the eutrophication of Lake Washington is the familiar story of progressive nutrient enrichment which has increased parallel to the population growth, in this case, of the city of Seattle and the surrounding region. In 1955 the first Oscillatoria rubescens bloom occurred making it obvious that the lake was over-enriched. At that time the lake received 24,000 $m^3 \cdot d^{-1}$ of secondary effluent from ten treatment plants serving a population of about 68,000 inhabitants. Edmondson (1970) estimated that this source alone constituted about 56% of the phosphorus and 12% of the nitrogen input to the lake. The lake reached its worst appearance in 1963 when the summer Secchi transparency dropped to less than 1 m from the 1950 level of nearly 4 m. Then in 1963, sewage diversion projects began and by 1968 virtually all treatment plant effluents had been diverted from the lake. With this, the total phosphorus load dropped from a maximum of 204 x 10^3 $kg \cdot y^{-1}$ (in 1964) to a low of 43 x 10^3 $kg \cdot y^{-1}$ (Edmondson and Lehman, 1981).

The nutrient concentrations in the lake and the biological response to the loading reductions were almost immediate. The phosphorus concentration in the lake dropped from a maximum of nearly 70 $mg \cdot m^{-3}$) to less than half that value (i.e., 30 $mg \cdot m^{-3}$) by the end of 1968 when the diversion was complete. The late summer blue-green algal blooms that had begun in 1955 disappeared and water clarity improved to a 4 m Secchi depth as it was prior to the heavy phosphorus loading in the 1960s. Throughout this period the spring diatom blooms of Lake Washington remained a constant feature and the blue-green blooms were merely superimposed on this regime. Edmondson and Lehman (1981) estimated that the lake reached equilibrium with its new lower loading (40 to 60 metric $t \cdot y^{-1}$) by 1977. Then suddenly water clarity improved far beyond expectation and Secchi depths reached more than 12 m. The explanation for this may be linked to some other biological events in the lake. When water clarity improved, milfoil could grow at deeper depths and its realm expanded accordingly. This shifted a portion of the available nutrients into a biomass compartment of slower turnover rate than the phytoplankton. Secondly, longfin smelt appeared in the lake around 1960 consuming the Neomysis predator which held the Daphnia population at a low level. An explosion of the Daphnia population followed in the 1970s which resulted in thorough filtration of the lakewater and improved water clarity. Presently the State Game Department is stocking Lake Washington with 250,000 rainbow trout each year to provide a sport fishery. However, a major food of the trout is Daphnia and it is unknown how the introduction of the trout will affect water clarity.

2.4.2 Budget Analysis of Lake Washington

The phosphorus budget for Lake Washington covers the 17-year period of 1962 to 1978 and was derived from the publication by Edmondson and Lehman (1981) (cf. Table 2.9). These values are plotted in Figure 2.12.

In contrast to the previous two cases (i.e., the Bodensee and the Sempachersee), the study of Lake Washington covers a period of reduction of the phosphorus load. The load declined rapidly after 1964 from a maximum of 204 metric $t \cdot y^{-1}$ to an average of around 50 $t \cdot y^{-1}$ after 1966 (excluding the years of heavy silt loads; 1972 and 1975) as the result of the sewage diversion projects which began in 1963.

Losses through the outlet generally declined over the period from a pre-diversion (i.e., prior to 1968) average of 63.2 $t \cdot y^{-1}$ to a post-diversion average of 24.0 $t \cdot y^{-1}$. Changes in the lake content closely reflect the changes in loading, except in 1972 and 1975 when the loading increases were due to silt washed into the lake from higher than normal hydraulic loads. (Notably, flushing rates were highest (0.59 y^{-1}) in 1972 and 1975; cf. Table 2.11, given subsequently). The pre-diversion lake content averaged 163.3 tons while the post diversion average was 52.5 tons. Thus, loading decreased 4-fold, losses through the outlet decreased 2.6-fold and the lake content decreased 3.1-fold.

Table 2.9 Lake Washington phosphorus balance; a 16 year time series (1962 - 78), adapted from Edmondson and Lehman (1981).

Year	Mean P Content of the Lake 10^3 kg (tons)	Total Load 10^3 kg · y^{-1}	Loss Via Outlet 10^3 kg · y^{-1}	Change in Lake Content 10^3 kg · y^{-1}	Net Sediment 10^3 kg · y^{-1}	Corrected Net Sediment[§] 10^3 kg · y^{-1}
1962	169.3	148.5	51.4	33.5	63.6	71.0
63[*]	202.8	156.5	68.8	-6.6	94.3	79.2
64[*]	196.2	204.2	92.7	-3.8	115.3	122.3
65[*]	192.4	142.8	66.7	-17.3	93.4	80.4
66[*]	175.1	124.8	65.8	-47.6	106.6	79.9
67[*]	127.5	54.3	50.9	-42.4	45.8	42.4
68[*]	85.1	59.1	46.2	-23.4	36.3	45.5
69	61.7	48.2	26.5	0.6	21.1	35.4
70	62.3	59.0	25.3	-11.5	45.2	39.8
71	50.8	53.8	29.0	-4.3	29.1	31.4
72[†]	46.5	103.4	30.0	7.7	65.7	75.5
73[‡]	54.2	42.9	18.8	1.8	22.3	20.9
74	56.0	58.5	29.6	-10.4	39.3	29.4
75[†]	45.6	99.3	29.9	-4.1	73.5	76.8
76	41.5	42.9	15.7	7.8	19.4	28.9
77	49.3	60.3	16.8	7.3	36.2	38.2
78	56.6	48.6	18.9			27.8

[*] period of sewage diversion

[†] heavy silt load due to high water flow (and landslides in 1972)

[‡] minimal water flow

[§] net sedimentation resulting when the particulate portion of fluvial inputs is subtracted from the total load; R.A. Vollenweider, 1981, unpubl. manuscript.

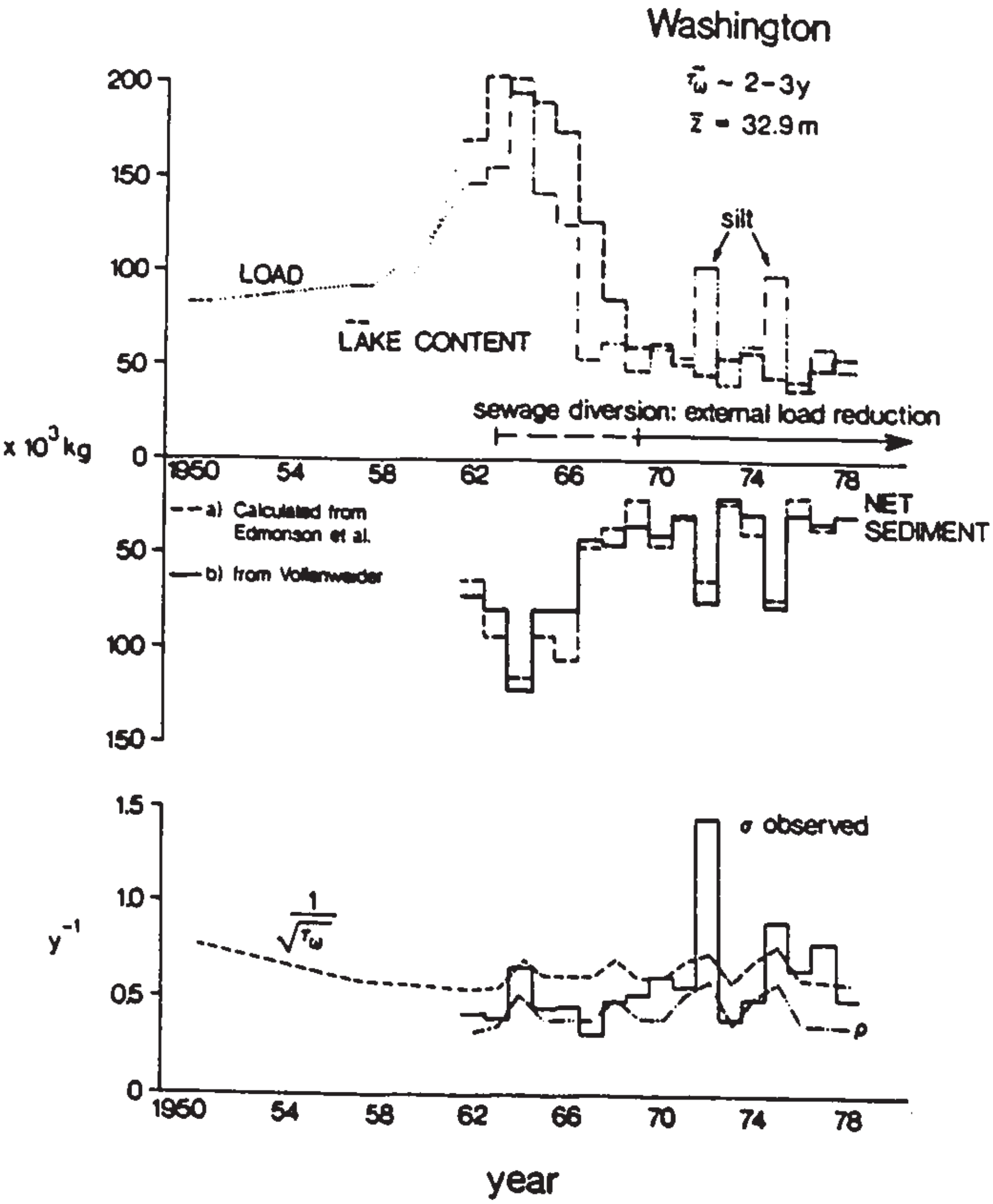


Figure 2.12 Lake Washington phosphorus loading, lake content and sedimentation (1954 - 78).

The net sediment as calculated from the above fluxes generally declined from a maximum of around 120 $t \cdot y^{-1}$ to an average of around 30 $t \cdot y^{-1}$ after the late 1960s and completion of the sewage diversion. The exceptions to this were the years 1972 and 1975 when sedimentation was high due to the silt influxes. Note that a "corrected net sediment" as calculated by Vollenweider (1981, unpubl.) is also given in Table 2.9 and is plotted in Figure 2.12. This corrected value results from subtracting out the particulate portion of fluvial inputs from the total load. The reason for this is to simply discount that portion of the load which settles out rapidly and does not essentially contribute to the lake content. (This is indeed borne out by the stable lake content values in 1972 and 1975; cf. Figure 2.12.) The essential pattern of sedimentation remains the same regardless of which set of values is used.

In terms of concentrations, inflow values decreased from a maximum of 161.8 $mg \cdot m^{-3}$ in 1962 to 111.6 $mg \cdot m^{-3}$ in 1966, then sharply dropped to a plateau averaging 47.3 $mg \cdot m^{-3}$ from 1967 on (cf. Table 2.10), reflecting the sewage diversions that took place. The lake response showed only a slight lag of about one year; lake concentrations ranged from 59 to a maximum of 70 $mg \cdot m^{-3}$ (in 1963 when algal blooms in the lake were reported to be worst) and then dropped off to a plateau of 18 $mg \cdot m^{-3}$ after 1969 (after which the blooms disappeared). In the transition phase around 1967, the lake concentration had not yet dropped

Table 2.10 Lake Washington phosphorus concentrations of the lake, theoretical inflow and their ratio.

Year	$[P_\lambda]$*	$[P_J]$†	$(P_\lambda/P_J)_{\text{observed}}$
1950	-	51.5	-
1957	25.6	94.4	.27
1962	58.7	161.8	.36
63‡	70.3	155.0	.45
64‡	68.0	136.4	.50
65‡	66.7	141.4	.47
66‡	60.7	111.6	.54
67‡	44.2	49.1	.90
68‡	29.5	40.8	.72
69	21.4	42.7	.50
70	21.6	52.4	.41
71	17.6	35.7	.49
72	16.1	61.3	.26
73	18.8	40.7	.46
74	19.4	39.6	.49
75	15.8	58.2	.27
76	14.4	40.6	.35
77	17.1	58.5	.29
78	19.6	47.8	.41

*from Edmondson and Lehman, 1981.

†recalculated from Edmondson and Lehman, 1981: $[P_J] = \dfrac{\text{total P load kg} \cdot y^{-1}}{\text{water load m}^3 \cdot y^{-1}}$

‡period of loading reduction

in proportion to the loading change and at this point of disequilibrium, the lake and inflow concentrations were nearly the same at 44 and 49 $mg \cdot m^{-3}$, respectively.

The relative residence time of phosphorus as estimated by the ratio of mean lake and inflow concentrations (P_λ/P_j) and as corrected for changes in lake content (τ_p/τ_w) are given in Table 2.10 and plotted in Figure 2.13. These two measures basically fluctuate together between 0.25 and 0.50 over the entire period, except for 1967 when only the concentration ratio reaches a maximum of nearly 0.90. Therefore, the concentration ratio would indicate a tremendous slowdown in phosphorus flows whereas (τ_p/τ_w) would indicate that removal was as efficient as ever. Relative minima occur in 1972 and 1975 when the silt loads were high. Overall, the positioning of the relative residence times is below 0.50.

The phosphorus budget values calculated in terms of mass balance coefficients are given in Table 2.11 and are plotted in the lower panel of Figure 2.12 (given previously). The sedimentation coefficient as estimated by $1\sqrt{\tau_w}$ is also plotted in Figure 2.12 for comparison. Sedimentation coefficients do not appear to follow any particular trend over the study period; they fluctuate around a mean of 0.53 excluding the years 1972 and 1975 when values were maximal at 1.47 and 0.92, respectively, due to heavy silt influxes. Other years, with relatively high sedimentation coefficients are 1963 (when the lake was in its most

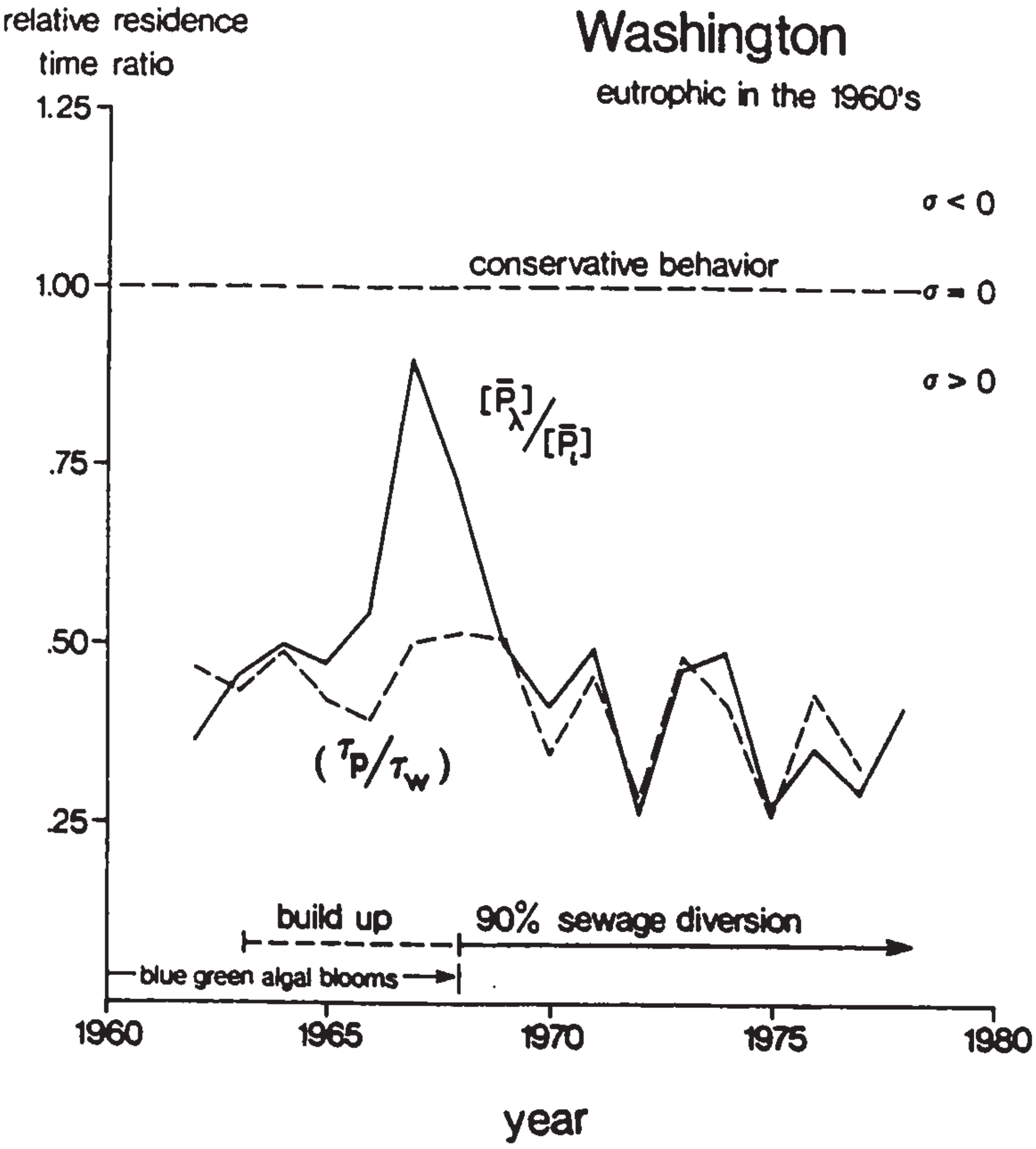


Figure 2.13 Lake Washington ($\tau p/\tau w$) from 1962 to 1979.

Table 2.11 Phosphorus elimination coefficients (sedimentation and flushing) and residence times in Lake Washington.

year	$\sigma^{\dagger}$ y^{-1}	$\tau_s = (\frac{1}{\sigma})$ y	ρ y^{-1}	$\tau_w = (\frac{1}{\rho})$ y	$\tau_p = \frac{1}{(\sigma + \rho)}$ y	$(\tau_p/\tau_w) = \frac{\rho}{(\sigma + \rho)}$ -	$(\frac{\sigma}{\rho})$ -	$v_s^{\ddagger}$
1962	.44	2.27	.32	3.13	1.32	.42	1.38	14.5
63	.40	2.50	.35	2.86	1.33	.47	1.14	13.2
64	.68	1.47	.52	1.92	.83	.43	1.31	22.4
65	.46	2.17	.38	2.63	1.19	.45	1.21	15.1
66	.47	2.13	.39	2.56	1.16	.45	1.21	15.5
67	.32	3.13	.38	2.63	1.43	.54	.84	10.5
68	.49	2.04	.50	2.00	1.01	.51	.98	16.1
69	.52	1.92	.39	2.56	1.10	.43	1.33	17.1
70	.62	1.61	.39	2.56	.99	.39	1.59	20.4
71	.56	1.79	.52	1.92	.93	.48	1.08	18.4
72*	1.47	0.68	.59	1.69	.49	.29	2.49	48.4
73	.41	2.44	.37	2.70	1.28	.47	1.11	13.5
74	.51	1.96	.51	1.96	.98	.50	1.00	16.8
75*	.92	1.09	.59	1.69	.66	.39	1.56	30.3
76	.67	1.49	.37	2.70	.96	.36	1.81	22.0
77	.81	1.23	.36	2.78	.85	.31	2.25	26.7
78	.52	1.92	.35	2.86	1.15	.40	1.49	17.1
								range: 10.5 to 48.4

*heavy silt load

† $\sigma = \frac{\text{net sediment kg}}{\text{lake content kg}}$

‡ $v_s = \sigma \cdot \bar{z}$ where $\bar{z} = 32.9$ m eutrophic state) and 1977 (when loading was at a relative high). In terms of sedimentation velocities (cf. Table 2.11), the values range from 13.2 to 26.7 $m \cdot y^{-1}$, except when they were substantially faster in 1972 and 1975 and velocities reached 48.4 and 30.3 $m \cdot y^{-1}$, respectively. Coefficients estimated as $1\sqrt{\tau_w}$ were generally higher than those observed, except in 1972, 1975 and 1977 when observed values were at relative maxima.

Flushing coefficients showed no particular trend and ranged from 0.32 to 0.59 y^{-1}. The maximum rates occurred in 1972 and 1975 coincident with the heavy silt loads.

The combined coefficients result in approximations of absolute residence times (τ_p) ranging from 1.43 y (in 1967) to 0.49 y (in 1975) (cf. Table 2.11). Values greater than 1 year are most frequent during the eutrophic phase of the lake whereas values tend to be a little less than 1 year after loading reductions.

Relative residence times of phosphorus (τ_p/τ_w) ranged from 0.33 to 0.51 over the study period, except in 1972 and 1975 when they dropped to 0.28 and 0.26, respectively (cf. Table 2.10). No particular trend over time is apparent (cf. Figure 2.13).

The ratio of elimination coefficients (σ/ρ) ranges from 0.84 (in 1967) to 1.81 (in 1976), excepting 1972 and 1976 when the ratio increased to 2.49 and 2.25, respectively. In general, values tend to be slightly over 1 indicating that sedimentation is only slightly more important than flushing as an elimination mechanism.

2.4.3 Assessment for Lake Washington

The eutrophic phase of Lake Washington during the 1950s and 1960s lasted until sewage diversions decreased the lake's phosphorus concentrations to around or below 20 $mg \cdot m^{-3}$. This occurred in 1969 immediately following the completion of the diversions in 1968. Thus the response of the lake was immediate despite the fact that, judging from the record of algal blooms, loading had been high for more than 10 years (i.e., at least since 1955). The original oligotrophic character of the lake and its resilience had been retained.

In Lake Washington, loading levels of more than approximately 100 tons per year (or around 100 $mg \cdot m^{-3}$ promote the symptoms of eutrophy or at least algal blooms. Therefore 100 $t \cdot y^{-1}$ would have to be set as an approximate critical load for the lake.

The relative residence time of phosphorus remained at or below approximately 0.50 over the study period indicating that the lake is a relatively strong sink for phosphorus. This property of the lake persisted even through the period of high loading and high biological productivity indicating that the latter did not essentially alter the absorptive capacity of the bottom sediments. Minimum relative residence times occurred when silt loads were heavy implicating silt particles as a mechanism by which phosphorus is removed from the water column, much in the way alum or lime are commonly used as phosphate flocculants in lake restoration programmes.

The maximum relative residence time as estimated by the mean concentration ratio ($P\lambda/P_j$) sharply peaked to 0.90 in 1967 due to the severe reduction in total loading. In that year, the lake concentration did not fall in accordance with the load reduction. However, lake concentrations dropped from 44.2 to 29.5 in 1968 and further decreased to the post-diversion plateau of approximately 20 $mg \cdot m^{-3}$ in 1969. Therefore the lag in lake response was only one to two years. According to Sonzogni _et al._ (1976), 95% recovery to a new steady-state after a new loading is established should take $3 \cdot \tau_p$, or a little more than three years for Lake Washington. The observations seem to show that the lake responded more rapidly than this expectation. In addition, if the lake attained equilibrium to its loading in about 1969 or 1970, this is substantially sooner than the estimate made by Edmondson and Lehman (1981) that equilibrium would only be reached in 1977.

According to the concentration ratio ($P\lambda/P_j$), relative residence time of phosphorus was maximal in 1967, almost to the point of appearing conservative (i.e., $P\lambda = P_j$). However, the measured values show that more than 40 tons of phosphorus sedimented out that year and the sedimentation coefficient of

0.32 was only somewhat less than previous or subsequent years. Therefore the concentration ratio as a measure of lake dynamics can be particularly misleading if the lake is not at steady-state. However, the concentration ratio is an excellent approximation of lake dynamics in the other years of the study.

With regard to standard predictions for Lake Washington, $1/\sqrt{\tau_W}$ tends to be higher than the observed sedimentation rate. Therefore, the general model proposed by Vollenweider (1975) tends to underestimate the lake concentration for a given loading, except in years of heavy silt loads when sedimentation is much higher than expected from this estimate. In addition, sedimentation was higher than usual in 1964 and 1977 when silt loads were normal. This appears to be the consequence of a higher flushing rate and perhaps import of allochthonous flocculants in 1964. In 1977 the lake content increased (from the previous year) by only about 8 tons despite a loading increase of about 17 tons. The high sedimentation rate ($\sigma = 0.81$) must be explained by some lake-internal mechanism (such as algal uptake and deposition or possibly export by migrating salmon stocks) since flushing rates, and therefore nutrient export by this pathway, were not unusual.

In summary, the ratio (σ/ρ) tends to be slightly greater than 1 indicating that sedimentation mechanisms are only slightly more important than mechanical elimination by flushing in the regulation of Lake Washington's phosphorus dynamics. When elimination by sedimentation does dominate, it appears to be related to the type of load (silt) or biological uptake and removal.

With regard to the possibility of finding a simple expression to estimate sedimentation, total net sediment was plotted against both total load and lake content in Figures 2.14 and 2.15, respectively. A second version of these two plots is given in Figures 2.16 and 2.17 where net sediment has been "corrected" for the particulate phosphorus carried by the inflow. (The rationale for this was that phosphorus carried by particles may be refractory and may settle rapidly, thereby contributing little to the lake content.) The correlation of net sediment with load is high, and somewhat better in the corrected version ($r = 0.92$ and 0.94, respectively). The correlation of sediment with lake content is lower than in the case of load and lower in the corrected version ($r = 0.81$ and 0.72, respectively). However, the poor correlation of sediment with lake content is due to the years when there were heavy silt loads (1972 and 1975) and the early-diversion, non-equilibrium year 1964 (a year of exceptionally high sedimentation when lake content decreased despite a loading increase). If these three years are excluded, the correlation coefficient for sediment vs lake content is 0.96, i.e., slightly higher than that for the relationship with loading. Therefore it appears that, with discretion, either relationship could be used to estimate sedimentation.

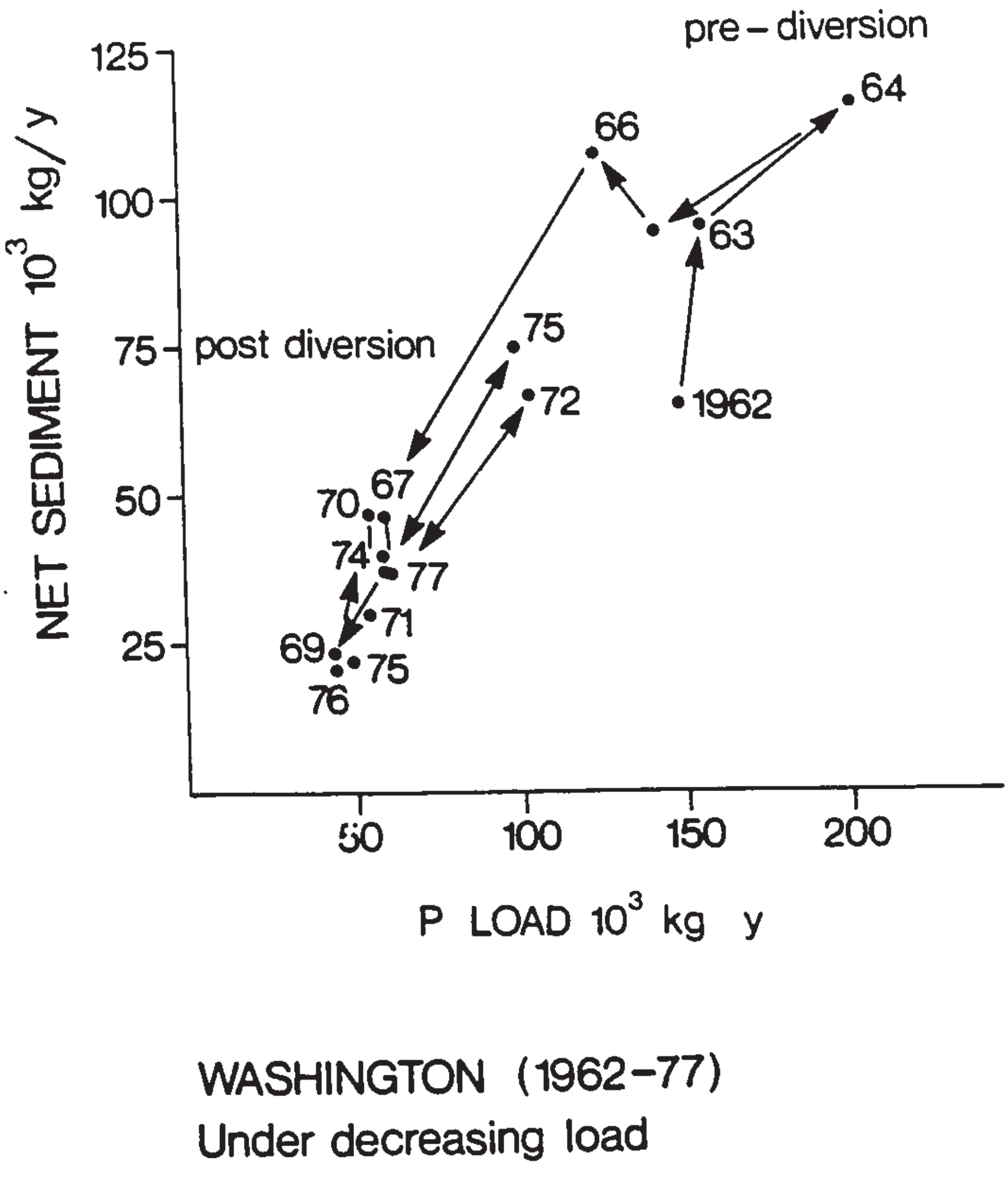


Figure 2.14 Lake Washington phosphorus net sediment vs load.

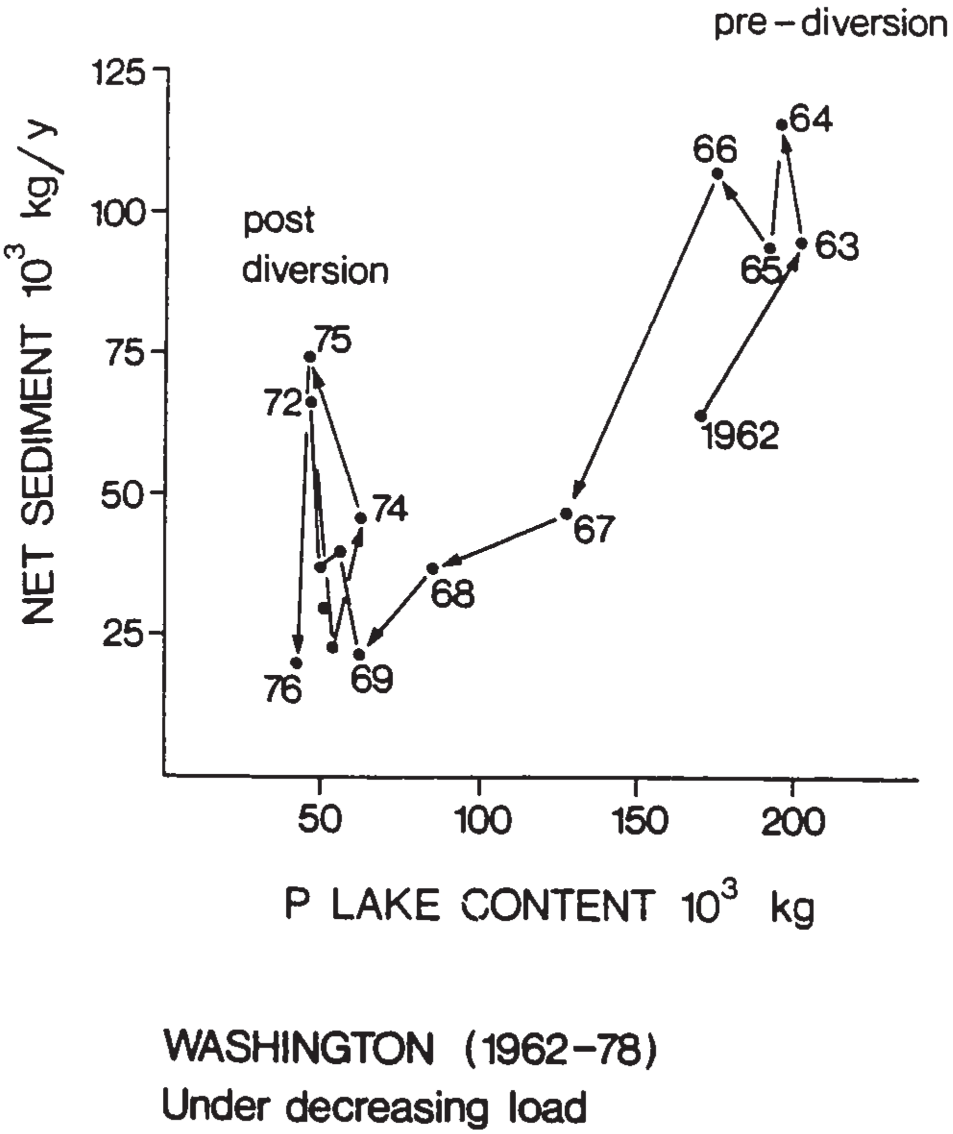


Figure 2.15 Lake Washington phosphorus net sediment vs lake content.

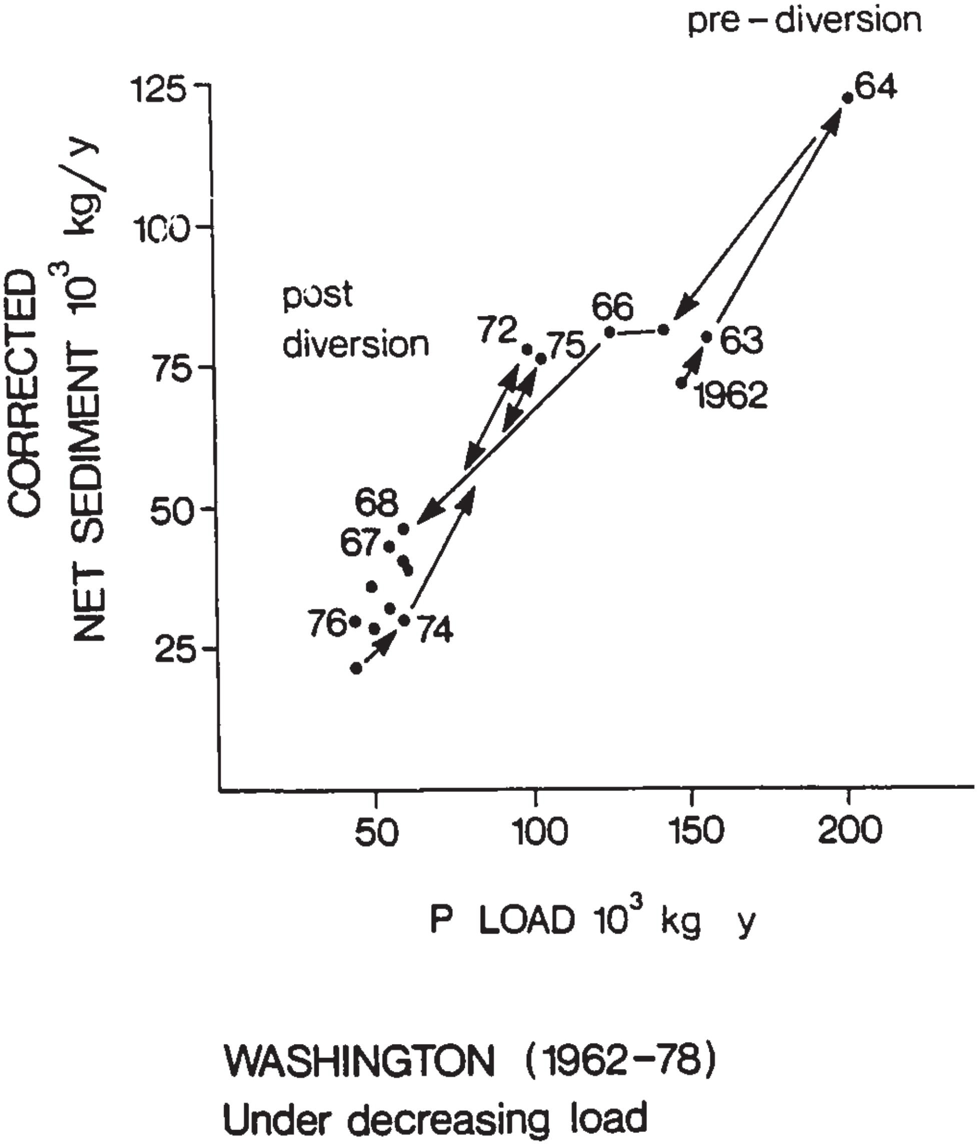


Figure 2.16 Lake Washington phosphorus corrected net sediment vs load.

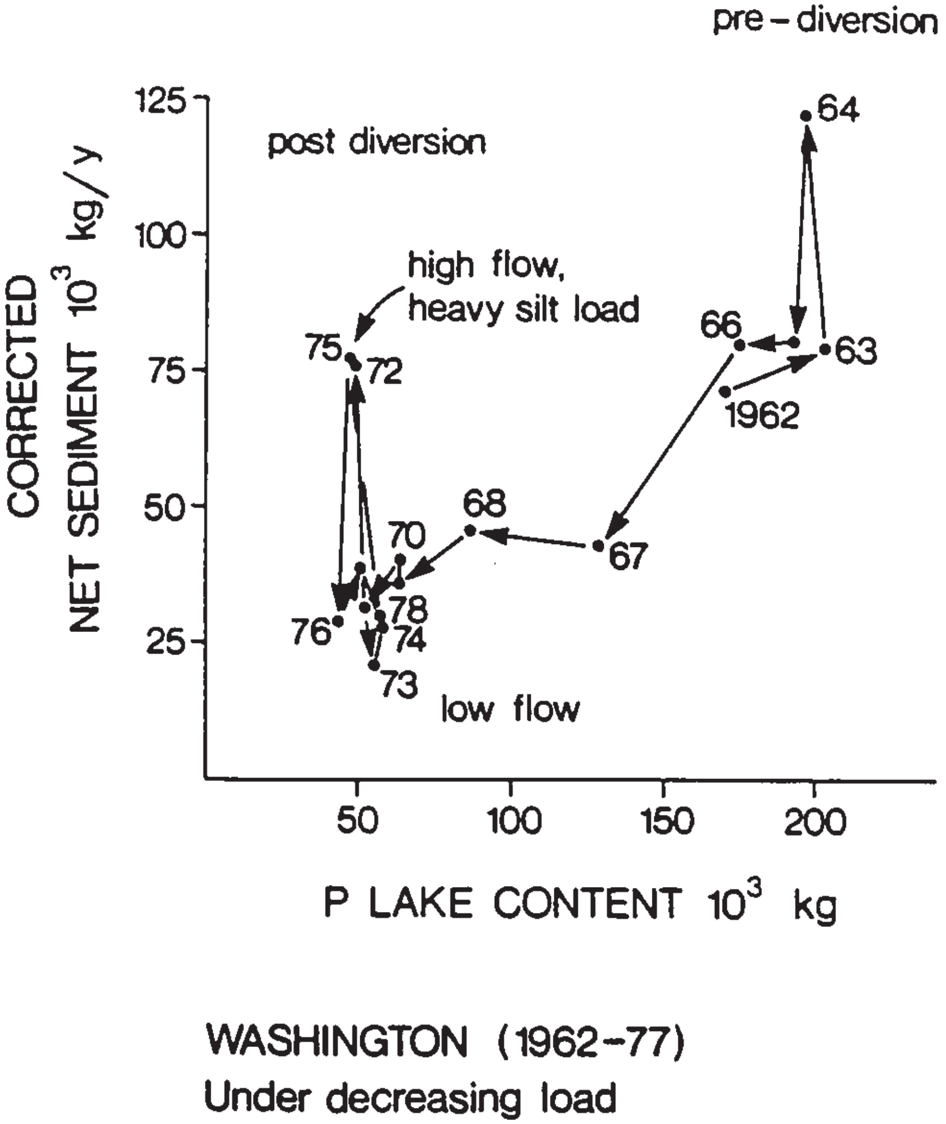


Figure 2.17 Lake Washington phosphorus corrected net sediment vs lake content.

2.5 Lac Léman

2.5.1 Description and Trophic History

Lac Léman lies within the northern pre-alpine region between France and Switzerland at approximately 46°N, 6°E and at an altitude of 372 m a.s.l. It is the largest of all the great alpine lakes of Europe with a surface area of 582.4 km^2, drainage area of 7,975 km^2 and volume of 89 km^3. The lake is a crescent-shaped enlargement of the Rhône River (which is the lake's major inflow and outflow) and it consists of two basins; the Grand Lac and Petit Lac (cf. Figure 2.18). (According to the account of Fricker (1980), the Grand Lac accounts for 96% of the lake's volume and has a mean and maximum depth of 153 m and 310 m, respectively. The shallower Petit Lac, situated at the outlet, has a mean depth of 41 m and maximum depth of 76 m. The mean water residence time for the lake as a whole is approximately 11.4 y. Léman is monomictic with a turnover period from January to March. There is no ice-cover during the winter and the lake does not normally mix below a depth of 150 to 200 m. Only during exceptionally cold winters does it mix to the bottom (310 m).

The trophic evolution of Léman is one of the most completely documented cases available since the importance (both aesthetic and economic) of this lake have made it the focus of many physical, chemical and biological studies. Foremost among these studies was "Le Léman, Monographie Limnologique", published 1892 to 1904 by François A. Forel, who is considered the founder

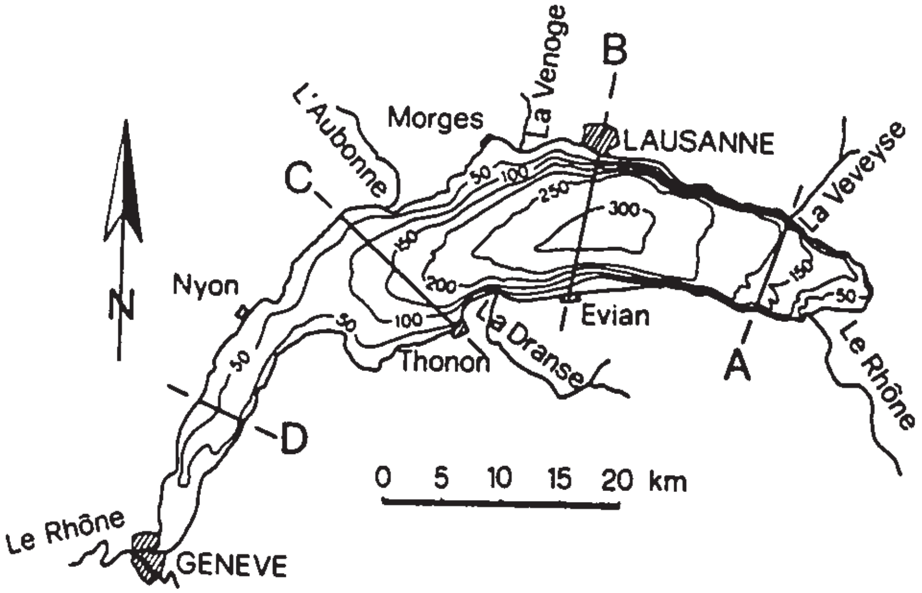


Figure 2.18 Bathymetric map of Lac Léman, from Zahner (1984).

of modern limnology. In the early 1900s the "Lake of Geneva" was classically oligotrophic (and indeed set such a standard of unspoiled beauty that several large oligotrophic lakes in North America, including Tahoe and Washington, were called Lake Geneva by the first European settlers). Whitefish, lake trout and pike were abundant at the turn of the century.

However, with the surge in population growth, urbanization and intensification of agriculture after WWII, the signs of eutrophication began to appear. According to Fricker (1980), nutrient levels in the lake increased and phosphorus concentrations rose from 11 $mg \cdot m^{-3}$ before 1950 to a high of 90 $mg \cdot m^{-3}$ in 1976. Over this same period of time Secchi disk readings decreased from more than 7 m to about 6 m. Blooms of the blue-green alga Oscillatoria rubescens occurred in the autumn of 1966 and again in 1978. Average chlorophyll readings for 1976, which probably represent the peak of eutrophication, were 7.3 $mg \cdot m^{-3}$. Typical oxygen profiles evolved to an oversaturation of the surface waters due to rapid algal growth, and hypolimnetic oxygen levels became low (particularly during the two periods 1968 to 1969 and 1973 to 1979 when winters were not sufficiently cold to produce complete mixing; cf. Figure 2.19, Monod et al., 1984). In addition, the lake developed metalimnetic oxygen minima at the end of summer. The fishery of Léman has been highly variable in both quantity and quality over the past 30 years due to eutrophication, over-fishing and introduction of

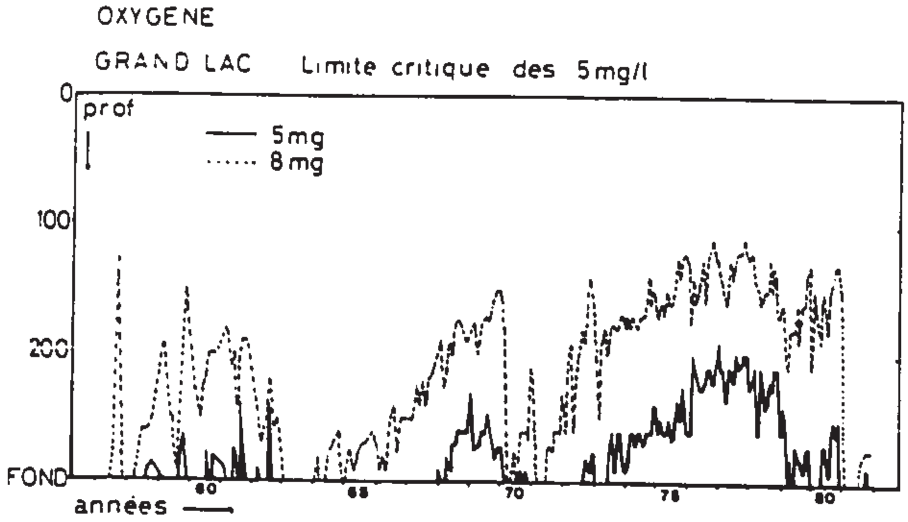


Figure 2.19 Oxygen conditions in Lac Léman (1957 - 81), from Monod et al. (1984).

new species, however, little is known about the relative importance of these factors in creating the population fluctuations of the various species.

Léman is presently subjected to the pressures of more than 2 million inhabitants in its basin. In order to combat these pressures French and Swiss limnologists formed the "Association pour la Sauvegarde du Léman", a group instrumental in providing recommendations on nutrient limitation. Approximately 132 treatment plants for phosphorus removal have been in operation since the late 1970s, but most of these point sources have only 40 to 70% of the initial phosphorus removed and their effluent concentrations are often 1000 $mg \cdot m^{-3}$. Despite the efforts to minimize nutrient loading to the lake, they may be insufficient since there has been no obvious improvement in the trophic condition of the lake with the operation of these treatment plants. In the 1980s, Lac Léman is considered mesotrophic with occasional symptoms of eutrophy (CIPEL, 1984).

2.5.2 Budget Analysis for Lac Léman

The phosphorus budget for Lac Léman covers an 18-year period from 1964 to 1981 (cf. Table 2.12). This is also the maximum phase of eutrophication in the known history of the lake. The budget values are plotted in Figure 2.20.

The total load to Lac Léman ranged from a minimum of 0.44 to a maximum of 1.77 metric $t \cdot y^{-1}$ in 1964 and 1970,

Table 2.12 Lac Léman phosphorus balance; an 18 year time series (1964 - 81), adapted from Burkard (1984).

Year	Mean P Content of the Lake 10^3 kg	Total Load 10^3 kg · y^{-1}	Loss Via Outlet 10^3 kg · y^{-1}	Change in Lake Content 10^3 kg · y^{-1}	Net Sediment 10^3 kg · y^{-1}
1964	5509	438	257	-270	451
65	5239	681	253	-1301	1729
66	5938	1385	178	-1464	2674
67	2474	1116	185	1384	-453
68	3858	874	248	583	43
69	4441	748	278	5153	-4683
70	9594	1771	397	-3617	4991
71	5977	1229	275	425	529
72	6402	1080	252	971	-143
73	7373	1109	383	-299	1025
74	7074	911	444	496	-29
75	7570	1350	520	585	245
76	8155	842	293	-82	631
77	8073	737	446	-222	513
78	7851	1207	428	166	613
79	8017	1252	625	-563	1190
80	7454	1204	632	-184	756
81	7270	1098	627	-390	861

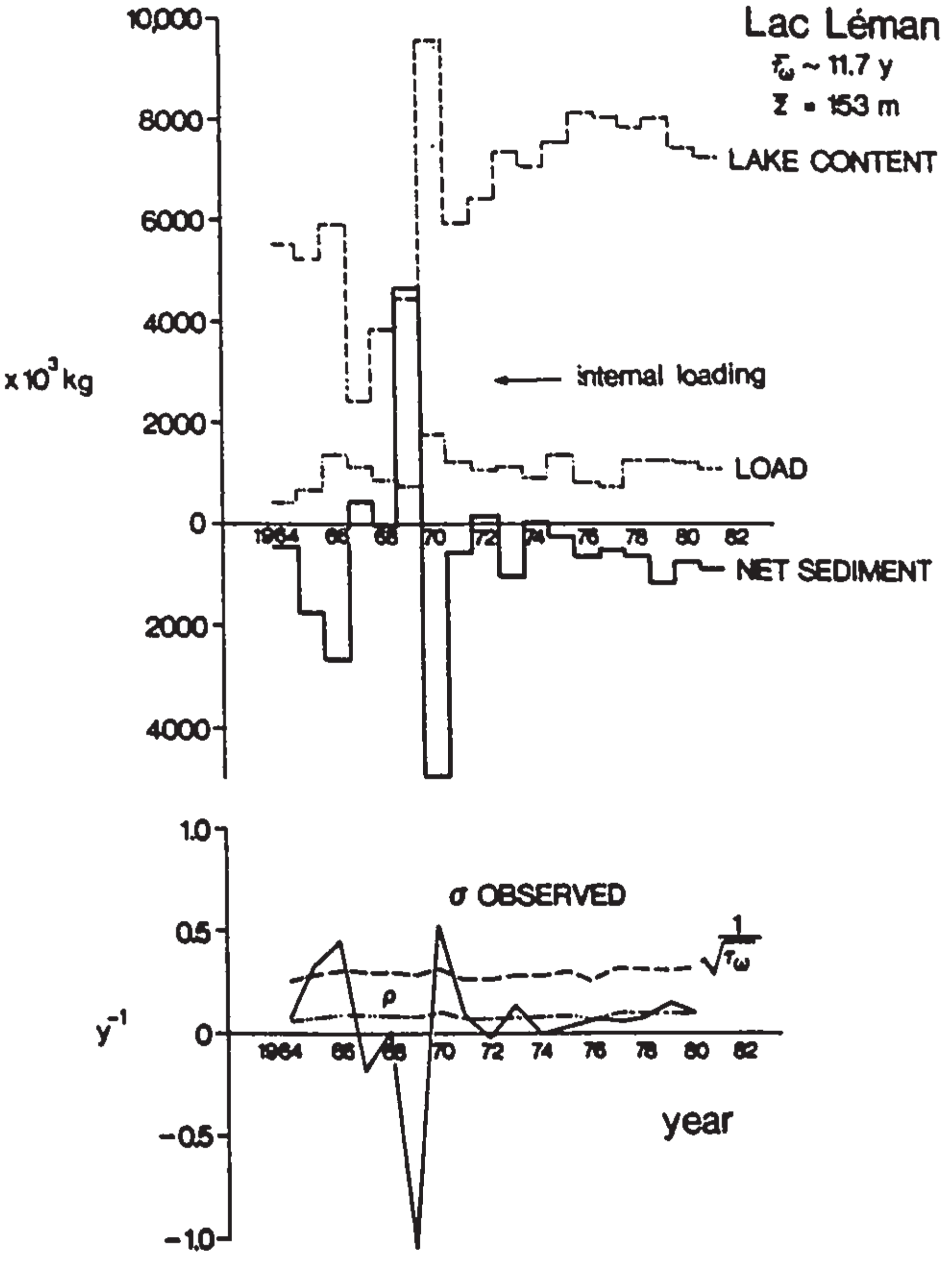


Figure 2.20 Lac Léman phosphorus loading, lake content and sedimentation (1964 - 81).

respectively. There is no particular trend in time for the loading and its variability is not related to the relatively small annual changes in flushing rates (or therefore hydraulic load). On the other hand, losses via the outlet followed a general increasing trend over time and ranged from a minimum of 0.18 $t \cdot y^{-1}$ to a maximum of 0.63 $t \cdot y^{-1}$.

Lake content also generally increased over time from about 4 tons in the 1960s to a level of about 8 tons which persisted throughout the 1970s. The exceptions to this general trend were the years 1967 when lake content was at a minimum of 2.47 tons and 1970 when a maximum of 9.60 tons occurred.

Net sediment given in Table 2.12 was calculated from these fluxes. Maximum net sediment values occurred in 1966 and 1970 while minima and negative values occurred in 1967, 1969, and 1972. (Negative values indicate that sediments became a source rather than sink for phosphorus.) In general, the pattern is erratic with a slight trend towards increasing sedimentation after 1974.

Notably, the lake content rose disproportionately to the loading from 1966 to 1976. After that, the lake content began to decrease somewhat while the loading was stable (at about 1.20 $t \cdot y^{-1}$).

In terms of concentrations (cf. Table 2.13), the inflow is irregular with minimum values of 73 and 78 $mg \cdot m^{-3}$ in 1964 and 1977. Maximum inflow concentrations of 195, 193 and 176 $mg \cdot m^{-3}$

Table 2.13 Lac Léman phosphorus concentrations of the lake, theoretical inflow and their ratio.

Year	$[P_\lambda]$	$[P_j]$	observed (P_λ/P_j)	$(\frac{\Delta\ \text{lake}}{\text{load}})$	$({}^{\tau}p/{}^{\tau}w)$
1964	62.0	72.7	.853	-.616	1.469
65	59.0	91.0	.648	-1.910	2.558
66	44.0	161.2	.273	-1.057	1.330
67	28.0	140.6	.199	1.240	-1.041
68	43.0	108.2	.397	.667	-.270
69	50.0	102.6	.488	6.889	-6.401
70	108.0	195.4	.553	-2.042	2.595
71	67.0	192.6	.348	.346	.002
72	72.0	175.8	.409	.899	-.490
73	83.0	152.0	.546	.270	.816
74	80.0	129.1	.620	.544	.076
75	85.0	164.1	.518	.433	.085
76	92.0	141.9	.648	-.097	.745
77	91.0	77.9	1.168	-.301	1.469
78	88.0	136.1	.646	.138	.508
79	90.0	146.5	.614	-.450	1.064
80	84.0	130.9	.642	-.153	.795
81	--	142.6	--	-.355	--

occurred consecutively in 1970 to 1972, respectively. Lake concentrations rose from about 40 to 70 $mg \cdot m^{-3}$ from 1964 to 1972, then stabilized at 80 to 92 $mg \cdot m^{-3}$ for the remainder of the record. The exceptions to this pattern occurred in 1967 and 1980 when the lake concentration reached a minimum of 28 $mg \cdot m^{-3}$ and a maximum of 108 $mg \cdot m^{-3}$, respectively.

Phosphorus relative residence time as estimated by the concentration ratio (P_λ/P_j) and corrected for changes in lake content as (τ_p/τ_w) (cf. Equation 2.5) are given in Table 2.13 and plotted in Figure 2.21. The concentration ratio generally fluctuates in the range 0.3 to 0.6 with the exception of maximum values of 0.85 and 1.17 in 1964 and 1977, respectively and a minimum of 0.20 in 1967. There seems to be a general increase over time. On the other hand, (τ_p/τ_w) shows much greater fluctuations than is evident from the concentration ratio. Three maximum values exceeding 1 occurred in 1968, 1972 and 1974 and two extreme minima below 0 occurred in 1967 and 1969.

In terms of mass balance models, the coefficients for sedimentation and flushing are given in Table 2.14 and are plotted in the lower panel of Figure 2.20. For comparison, sedimentation as estimated by $1/\sqrt{\tau_w}$ is also plotted. The observed sedimentation rate peaked in 1966 and 1970 at values somewhat above the estimates from water residence time. (Notably these two peaks are the only two years when the estimate would give a reasonable approximation of the observed sedimentation; otherwise

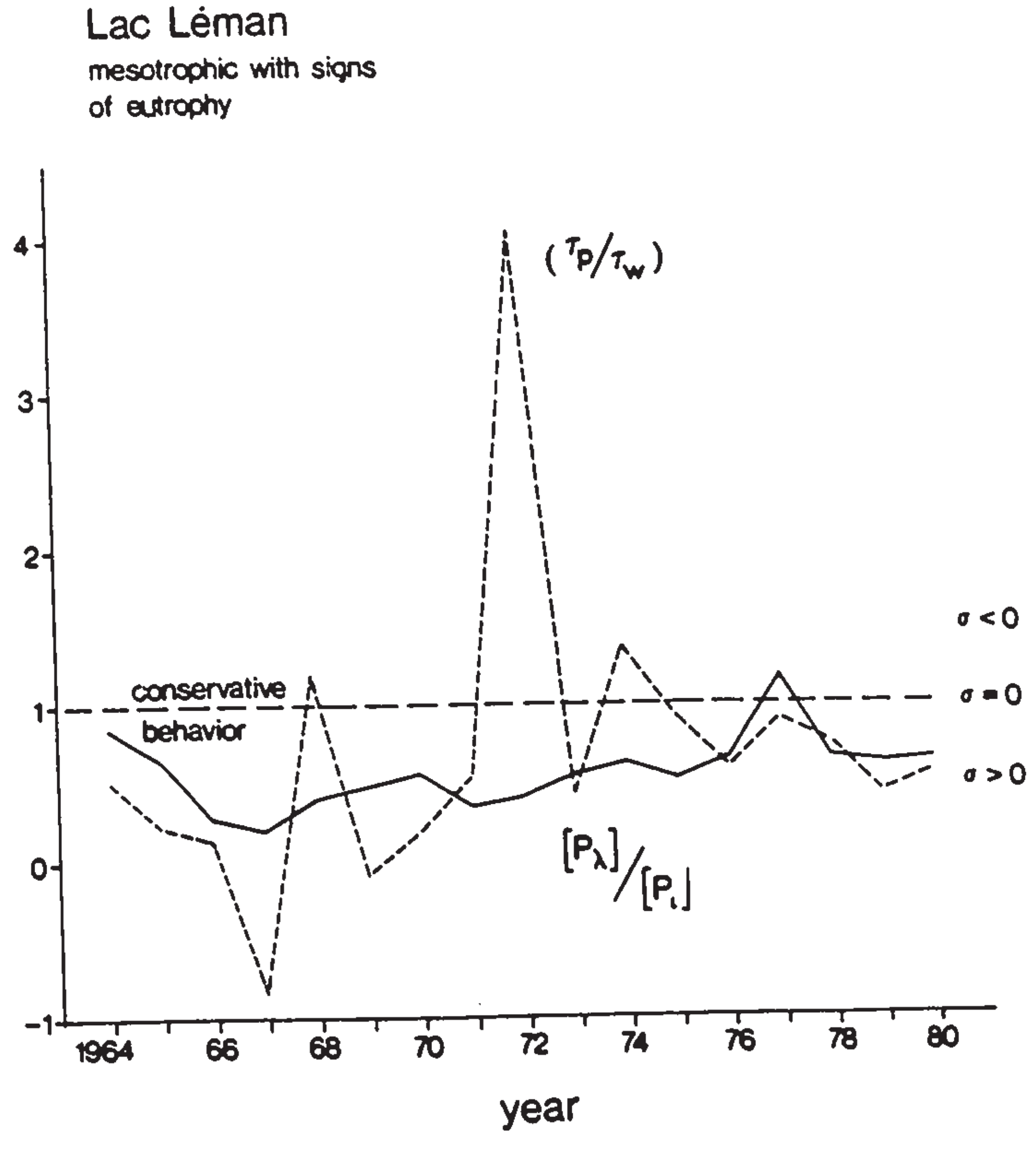


Figure 2.21 Lac Léman (τp/τw) from 1964 to 1981.

Table 2.14 Phosphorus elimination coefficients (sedimentation and flushing) and residence times in Lac Léman.

year	σ y^{-1}	$\tau_s = (\frac{1}{\sigma})$ y	ρ y^{-1}	$\tau_w = (\frac{1}{\rho})$ y	$\tau_p = \frac{1}{(\sigma + \rho)}$ y	$(\tau_p/\tau_w) = \frac{\rho}{(\sigma + \rho)}$ -	$(\frac{\sigma}{\rho})$ -	v_s $m \cdot y^{-1}$
1964	.08	12.20	.07	14.71	6.67	.45	1.21	12.5
65	.33	3.03	.09	11.76	2.41	.20	3.88	50.5
66	.45	2.22	.10	10.31	1.83	.18	4.64	68.9
67	-.18	-5.46	.09	11.24	-10.64	-.95	-2.06	-28.0
68	.01	90.91	.09	10.99	9.80	.89	.12	1.7
69	-1.05	- .95	.08	12.20	-1.03	-.08	-12.85	-161.3
70	.52	1.92	.10	9.80	1.61	.16	5.10	79.6
71	.09	11.24	.07	14.08	6.25	.44	1.25	13.6
72	-.02	-45.45	.07	14.49	21.28	1.47	-.32	-3.4
73	.14	7.19	.08	12.20	4.52	.37	1.70	21.3
74	-.004	-250.00	.08	12.66	13.33	1.05	-.05	-.6
75	.03	31.25	.09	10.75	8.00	.74	.34	4.9
76	.08	12.99	.07	14.93	6.94	.47	1.15	11.8
77	.06	15.63	.10	9.80	6.02	.61	.63	9.8
78	.08	12.82	.10	10.00	5.62	.56	.78	11.9
79	.15	6.76	.10	10.53	4.12	.39	1.56	22.6
80	.10	9.90	.10	9.62	4.88	.51	.97	15.5

range:
-161.3 to
79.6

this estimate is much too high.) In 1967 and 1969 sedimentation coefficients were negative values, indicating internal loading took place. From 1972 on, sedimentation remained low and close to flushing rates, both at about 0.08 y^{-1}.

Sedimentation rates calculated as apparent settling velocities, v_s (cf. Table 2.14), ranged widely from an extreme minimum of -161.3 $m \cdot y^{-1}$ in 1969 to a maximum of 79.6 $m \cdot y^{-1}$ in the following year.

Flushing rates showed no particular trend and remained within a narrow range of 0.07 to 0.10 over the entire period. Corresponding water residence times were 9.6 to 14.9 years.

These combined coefficients gives estimates of absolute residence times ranging from -10.6 to 21.3 years in 1967 and 1972, respectively (cf. Table 2.14). (Negative residence times result from negative sedimentation coefficients - which at the same time exceed flushing losses - and indicate internal loading.)

The ratio of elimination coefficients (σ/ρ) ranges from -12.9 in 1969 to a maximum of 5.1 in 1970. In the majority of instances, sedimentation effects dominate over flushing effects i.e., $(\sigma/\rho)>1$.

2.5.3 Assessment for Lac Léman

The first obvious signs of the eutrophication of Lac Léman began in the mid-1960s when blooms of *Oscillatoria* rubescens appeared. The mean lake concentration of phosphorus was around 50 $mg \cdot m^{-3}$ and in subsequent years (1967 and 1969) organic loading to the hypolimnion was sufficient to create low oxygen conditions and sediment release of phosphorus (cf. Figure 2.20).

The loading in 1964 was 438 $t \cdot y^{-1}$ and this appears to be in excess of a permissible loading. Loading increased to a maximum of 1771 $t \cdot y^{-1}$ in 1970 (i.e., an increase from 1964 of about 1300 tons) and this resulted in an increase in lake content from around 5500 tons in 1964 to 9500 tons in 1970 (i.e., an increase of about 4000 tons). The lake concentration varied between 28 and 108 $mg \cdot m^{-3}$ over the same period. As in the previous cases of eutrophication, the lake content increased disproportionately to the loading increase. The particular combination of features of Lac Léman renders it extremely sensitive to changes in its external load. With a long water residence time, low sedimentation rate ($\rho \approx 0.10$) and incomplete mixing, the lake tends to accumulate whatever nutrient load it receives within the water column.

The relative residence time of phosphorus (τ_p/τ_w) is in general above 0.50 reflecting the chronically low sedimentation rate in the lake. Values of (τ_p/τ_w) exceeding 1 occurred in 1968, 1972 and 1974. These were years of incomplete mixing as judged from hypolimnetic oxygen which fell below 5 $mg \cdot l^{-1}$. Sedimentation was minimal in these years. At the other extreme, sedimentation was at a maximum in 1966 and 1970 when winters were sufficiently cold to produce deep mixing (oxygen at the bottom of the lake was 8 $mg \cdot l^{-1}$; cf. Monod et al., 1984).

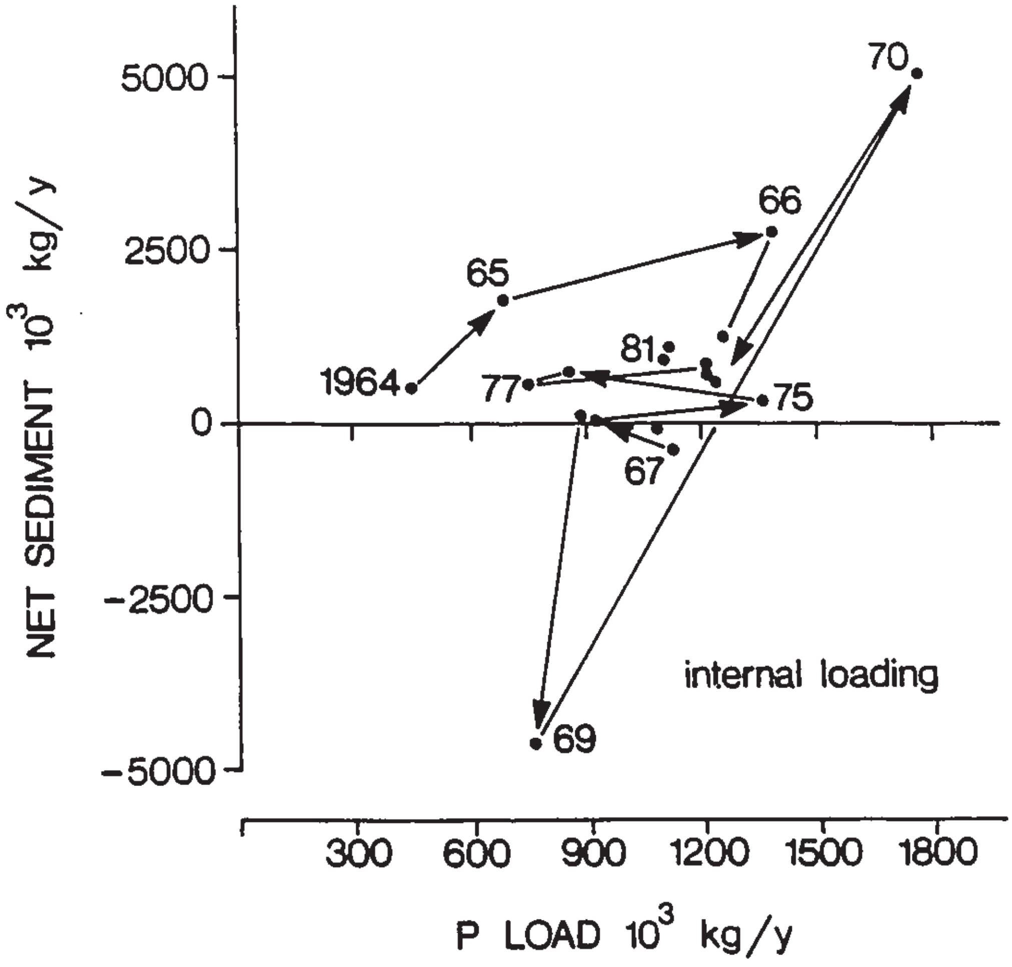
Regarding long-term trends, the minimum (τ_p/τ_w) in the 1970s are higher than those in the 1960s. Thus, there seems to be a tendency towards more conservative behavior in more recent times; the ratio (σ/ρ) has decreased to around 1 or less. Taking these effects together, Lac Léman seems to have a slowly declining capacity to eliminate phosphorus, but overall, nutrient fluxes in the lake are highly variable and short-term mixing events have the capacity to modify the sedimentation characteristics (and trophic response) from one extreme to the other. Sedimentation of phosphorus and the trophic response of Lac Léman thus appears to be predominantly under the control of the climate and its influence on mixing.

The concentration ratio (P_λ/P_j) shows a relatively steady increase from about 1967 on and only poorly reflects the dynamics of (τ_p/τ_w). The concentration ratio would imply that the lake was a sink for phosphorus in all years except 1977 when (P_λ/P_j) was greater than 1. However this was due to a drop in loading rather than increase in lake content and reflects the disequilibrium between lake content and load (i.e., a washout situation) and not internal loading. In 1967 and 1969 when internal loading did occur (cf. Figure 2.20), (P_λ/P_j) overestimated (τ_p/τ_w) and therefore underestimated nutrient flow rates. On the other hand, the concentration ratio underestimated (τ_p/τ_w), and therefore overestimated flow rates, in 1968, 1972 and 1974 when net sedimentation rates were near zero. In summary, (P_λ/P_j) underestimates flow rates under conditions of internal loading or at disequilibria between lake and inflow concentration, whereas this ratio overestimates phosphorus flow rates when sedimentation is near zero.

With regard to the estimation of sedimentation from $(1/\sqrt{\tau_w})$, the observed coefficient is in general much lower than expected. Therefore observed lake concentrations would tend to be high relative to predictions from the steady-state model using the sedimentation rate estimated in this way.

The relationship of net sediment to either load (cf. Figure 2.22) or lake content (cf. Figure 2.23) is poor, with respective correlation coefficients of 0.55 and 0.53. Both relationships appear to be independent even if the two extreme points of net sediment (caused by internal loading in 1969 and deep mixing in 1970) were excluded. Therefore, neither lake content nor load is particularly good as an estimator of sedimentation.

In summary, (τ_p/τ_w) in Lac Léman is highly variable and the only trend over time seems to be a general rise in the minima, i.e. progressively slower flow rates. This general rise is reflected by (P_λ/P_j), however this concentration ratio is particularly poor in reflecting the known budget dynamics. Sedimentation velocities in Léman can be very high - on the order of



Lac Léman (1964 - 81)
Under increasing load

Figure 2.22 Lac Léman phosphorus net sediment vs load.

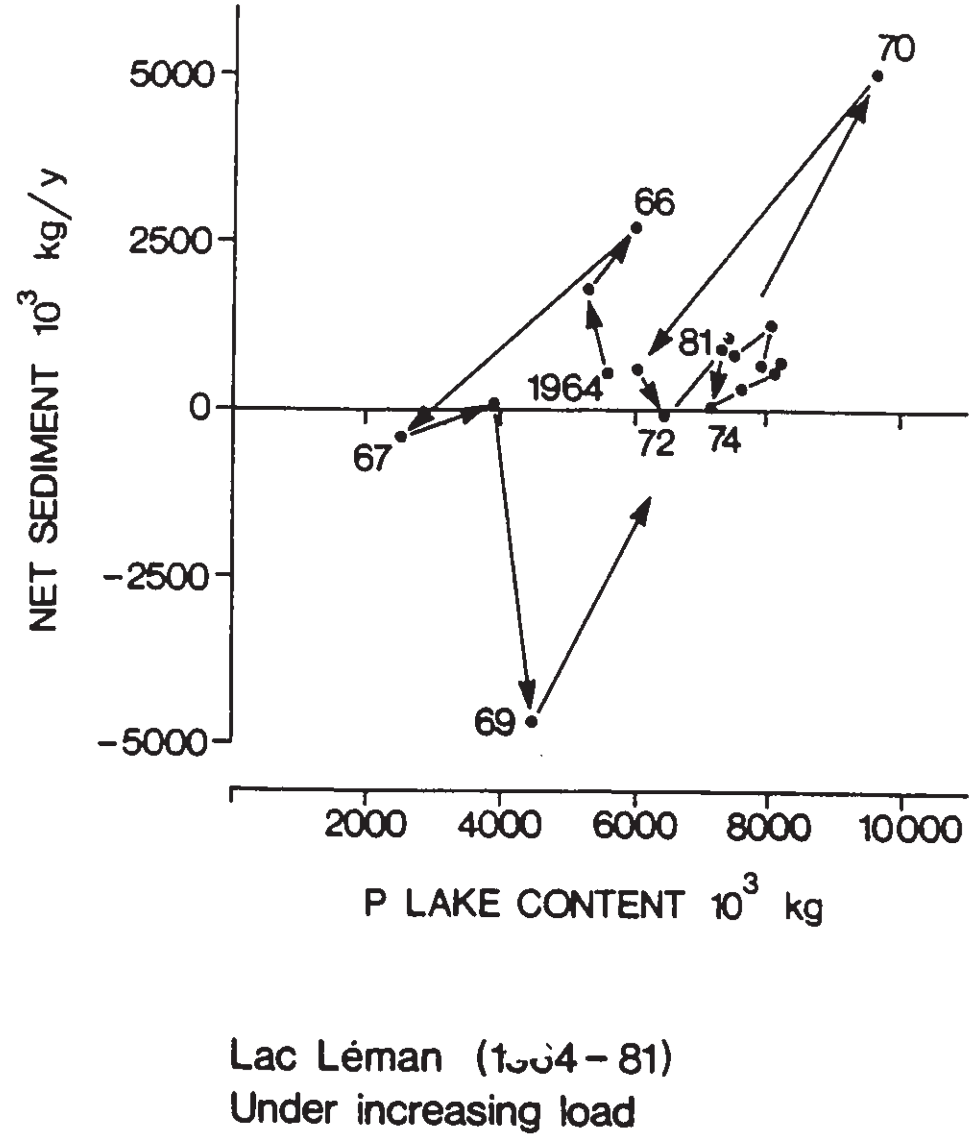


Figure 2.23 Lac Léman phosphorus net sediment vs lake content.

70 $m \cdot y^{-1}$ - in years of deep mixing and recharge of hypolimnetic oxygen. Since the relationships of net sediment with load, lake content and water residence time are nebulous, it may well be that the best predictor of sedimentation in Léman will be one related to mixing phenomena. This seems logical in view of the polymictic character of the lake in combination with its long water residence time. The long absolute residence time of about five years for Léman means that external loading reduction for the purpose of lake restoration may take about 15 years for a new, lower lake concentration to be established. However, even this may be an overly optimistic estimate of recovery time because of the incomplete mixing of the lake which most likely decreases the flushing efficiency.

2.6 Lake Mjøsa

2.6.1 Description and Trophic History

Lake Mjøsa is the largest lake in Norway and the fourth deepest in Europe (z_{max} = 449 m and $\bar{z}$ = 153 m). It is a typical, long, narrow fjord lake (approximately 117 km long by 10 km wide; cf. Figure 2.24) located at 60°N and, due to its large volume, only remains ice-covered for about 60 days. The sides of the lake basin are steep, so littoral area and macrophytes are at a minimum. The main uses of the lake have been for drinking water, sport fishing and swimming. The drainage basin (16,420 km^2) is mountainous and the bedrock is predominantly granite, but some

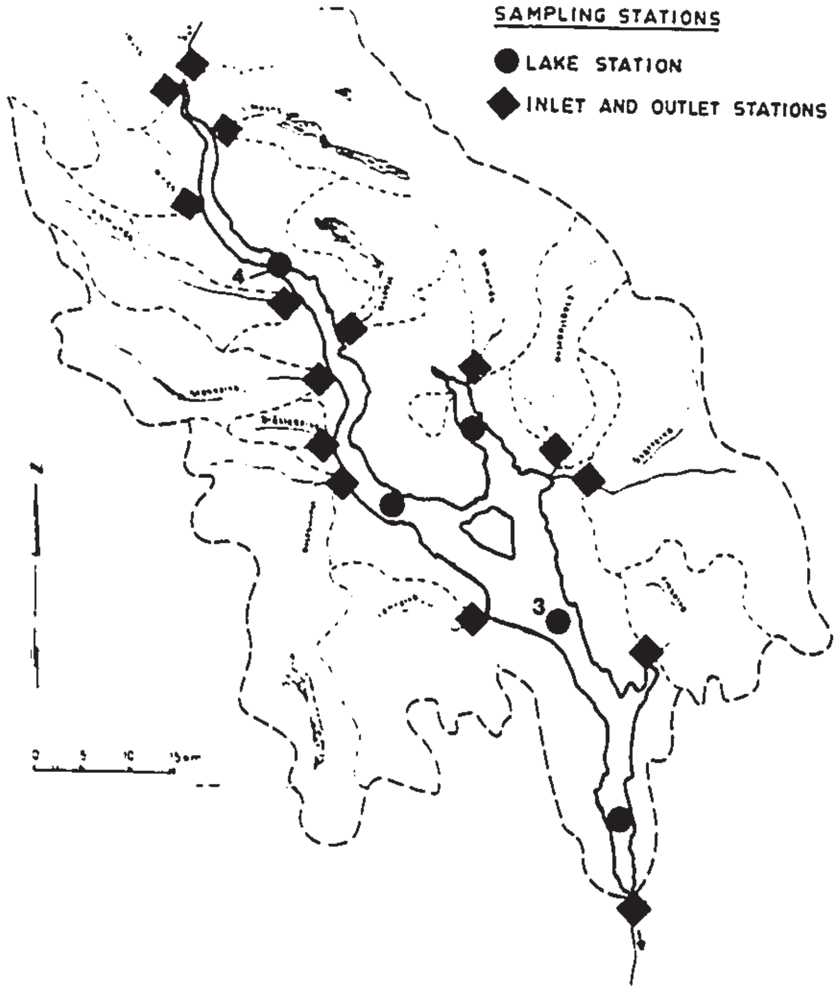


Figure 2.24 Map of Lake Mjøsa, Norway, from S.-O. Ryding (1980).

calcareous regions exist. Fourteen major inlet streams surround the lake and 90% of the region they drain is covered by natural forest and lakes. The 6% of the basin used for agricultural purposes is considered some of the best farmland in Norway.

In the 20 to 30 years following WWII, Mjφsa changed from a definitely oligotrophic waterbody with phytoplankton dominated by diatoms to a mesotrophic condition with blue-green algal blooms in late summer. Although changes in the lake were obvious in the 1960s, they were not documented until the 1970s when the Norwegian Institute for Water Research began scientific investigations to provide the necessary information to instate eutrophication control. In 1972 the total phosphorus loading to the lake was estimated at 460 tons. Four major sources were identified as follows:

(i) untreated sewage from three cities (Lillehammer, Gjovik and Hamar) and other smaller municipalities with a total population of approximately 200,000;

(ii) runoff from the intensive agricultural area;

(iii) wood pulp, metallurgical and food industries (including dairies, slaughterhouses, canneries and breweries); and

(iv) natural loading from the watershed.

Each of these sources was estimated to contribute approximately 100 $t \cdot y^{-1}$ of phosphorus, and an extra 60 $t \cdot y^{-1}$ was estimated to arrive from diffuse sources (cf. Ryding, 1980).

In 1973 the Norwegian Parliament allocated grants for improvement and construction of sewer systems and 42 new treatment plants. The goal was to reduce the phosphorus load from 460 to 175 $t \cdot y^{-1}$ in order to restore oligotrophic conditions. However, before these measures could become fully effective, the lake reached its worst condition, and in 1976 a heavy bloom of <u>Oscillatoria</u> <u>bornetti</u> <u>f.</u> <u>tennis</u> ruined the drinking water supply for the 200,000 inhabitants of the basin. (This algae produces geosmin, an organic product causing taste and odor problems in drinking water supplies). The algal bloom was the stimulus for the "Mjøsa Campaign", which was a resolution to reach the lower loading target by 1980. At the time of the bloom it was estimated that 40% of the total phosphorus load for the year entered the lake during summer stratification resulting in a condition conducive to blooms. Epilimnetic concentrations of phosphorus in 1976 were about 18 $mg \cdot m^{-3}$.

At the present, all the projected treatment plants are in service, operating at a rate of 90% reduction of phosphorus in the effluent. The contribution from municipal sewage has gone from nearly 100 $t \cdot y^{-1}$ to approximately 25 $t \cdot y^{-1}$ and in 1980 phosphorus concentrations in the lake were down to 10 $mg \cdot m^{-3}$ or lower. The cyanophyceae have been an insignificant component of the phytoplankton since the campaign and the lake has resumed its oligotrophic character (Holtan, 1981).

2.6.2 Budget Analysis of Lake Mjøsa

The available phosphorus budget for Lake Mjøsa covers a seven-year period of loading reduction from 1973 to 1980 (cf. Table 2.15; Holtan, 1981). Through the efforts of the Mjøsa Campaign loading was reduced from more than 300 metric $t \cdot y^{-1}$ to around 225 metric $t \cdot y^{-1}$. Losses through the outlet varied little from approximately 85 $t \cdot y^{-1}$, except for the 1979 maximum when this amounted to 112 $t \cdot y^{-1}$. The lake content of phosphorus ranged from a maximum of approximately 580 tons in 1976 to a minimum of approximately 480 tons in 1980. Variations in the lake content reflect loading changes (cf. Figure 2.25). Furthermore, the variations in net sedimentation calculated from the above fluxes directly reflect both the changes in lake content and loading; sedimentation is minimal in 1976 and 1977 when both lake content and loadings are low.

In terms of concentrations, the inflow decreased steadily from an average of 36 $mg \cdot m^{-3}$ in 1976 to 20 $mg \cdot m^{-3}$ in 1980. The lake concentration decreased slightly from 10.3 to 8.6 $mg \cdot m^{-3}$ over the same period. Notably, the epilimnetic concentration in 1976 of about 18 $mg \cdot m^{-3}$ was substantially above the lakewide mean of 10 $mg \cdot m^{-3}$.

Relative residence times as calculated by the concentration ratio (P_λ/P_j) and corrected for the changes in lake content (cf. Equation 2.5) are given in Table 2.16. Both rise for two to three consecutive years over the period of loading

Table 2.15 Lake Mjøsa phosphorus balance; an 8 year time series (1973 - 80), adapted from Holtan (1981).

Year	Mean P Content of the Lake⁺ 10^3 kg	Total Load 10^3 kg · y^{-1}	Loss Via Outlet⁺ 10^3 kg · y^{-1}	Change in Lake Content 10^3 kg · y^{-1}	Net Sediment 10^3 kg · y^{-1}
1973 74 75	494. 2⁺⁺	317	84⁺⁺	85.1	147.9
76	579.3	308	87.6	-16.9	237.3
77	562.4	230	88.0	0	142.0
78	562.4	219	87.4	11.3	120.3
79	573.7	252	112.3	-90.0	229.7
80	483.7	225*	83.0		

*Estimated value

⁺Calculated from mean lake concentrations; assumed $[P_\omega] = [P_\lambda]$

⁺⁺Estimated from OECD data

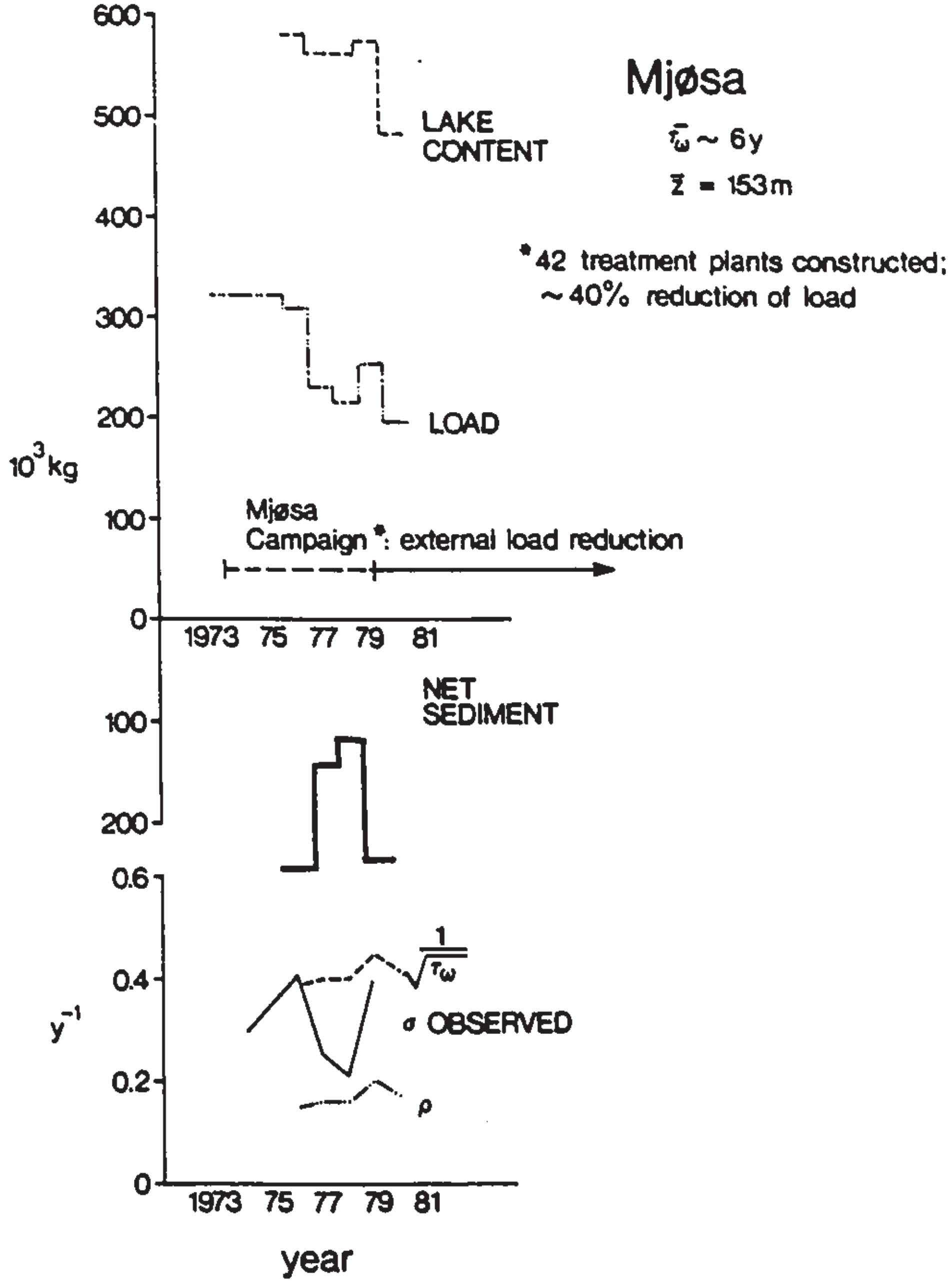


Figure 2.25 Lake Mjøsa phosphorus loading, lake content and sedimentation (1937 - 80).

Table 2.16 Lake Mjøsa phosphorus concentrations of the lake, theoretical inflow and their ratio.

Year	$[P_\lambda]$	$[P_j]$	observed (P_λ/P_j)	$(\frac{\Delta \text{ lake}}{\text{load}})$	$(\tau p/\tau w)$
1973 74 75	—	—	—	.268	—
76	10.3	36.2	.285	.055	.270
77	10.0	26.1	.383	.000	.383
78	10.0	25.0	.400	.052	.422
79	10.2	22.9	.445	.357	.328
80	8.6	20.1	.428	—	—

reduction, then subsequently decrease (cf. Figure 2.26). The minimum relative residence time (τ_p/τ_w) is 0.27 and coincides with both the year of maximum net sedimentation and worst algal bloom problems. Overall, the relative residence time of phosphorus remains between 0.25 and 0.45.

In terms of coefficients calculated for a mass balance model (cf. Table 2.17), σ ranged from a minimum of 0.21 in 1978 to a maximum of 0.41 in 1976. This translates to an apparent sedimentation velocity of 32 to 63 $m \cdot y^{-1}$. With an average water residence time of about six years, flushing coefficients averaged 0.17 y^{-1}. The ratio (σ/ρ) ranged from 1.3 to 2.67, thus sedimentation processes influence the nutrient dynamics of Mjøsa to a greater extent than flushing.

Sedimentation rate is over estimated by ($1/\sqrt{\tau_w}$) (cf. the lower panel of Figure 2.25), so consequently estimates of lake concentration using the standard flushing corrected inflow (cf. Vollenweider, 1975) are too low in comparison to observed values. Further to this, total net sediment is not significantly correlated to either load or lake content (cf. Figures 2.27 to 2.28), so neither could be used as a means of estimating sedimentation. However, all three of these factors (net sediment, load and lake content) vary together qualitatively, therefore lack of significance may be due to the low availability of data ($n = 5$).

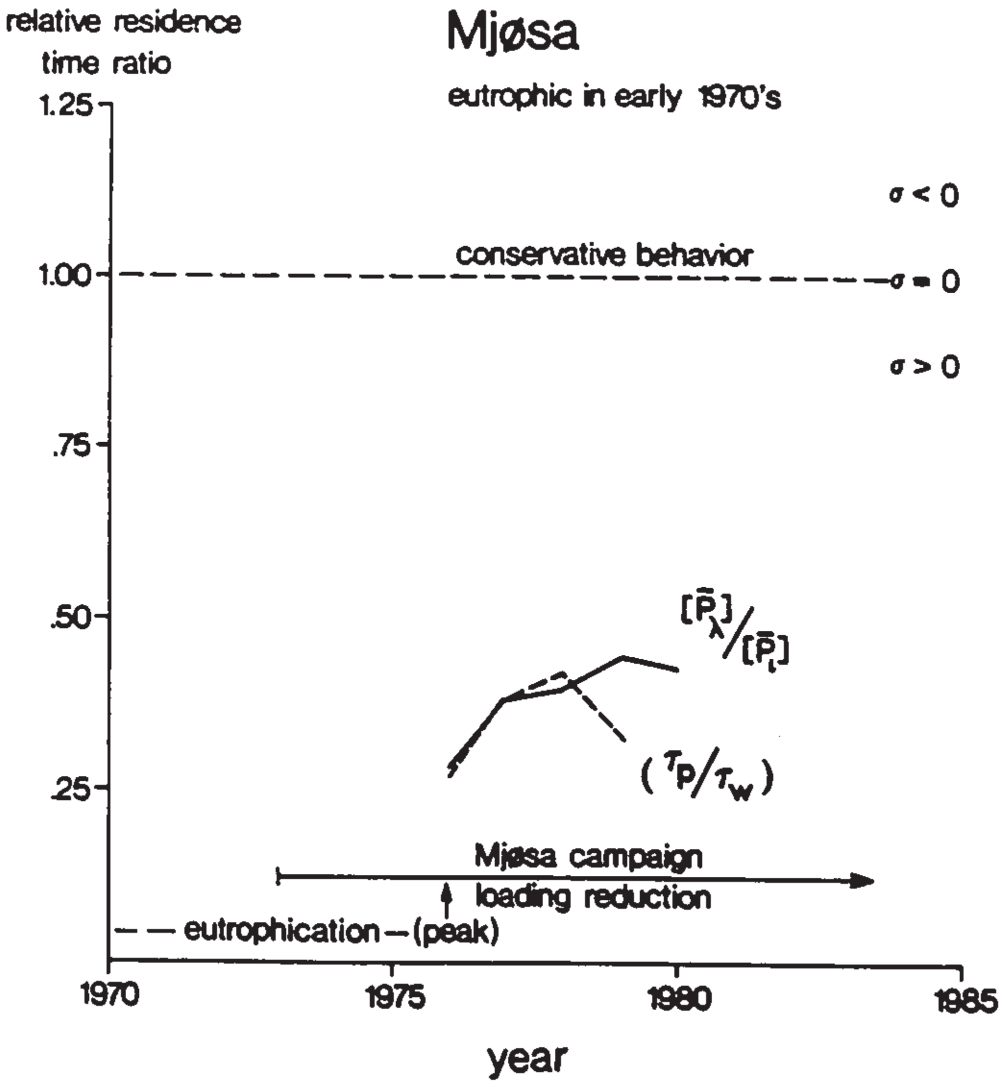


Figure 2.26 Lake Mjøsa ($\tau p/\tau w$) from 1973 to 1980.

Table 2.17 Phosphorus elimination coefficients (sedimentation and flushing) and residence times in Lake Mjøsa.

year	σ y^{-1}	$\tau_s = (\frac{1}{\sigma})$ y	ρ y^{-1}	$\tau_w = (\frac{1}{\rho})$ y	$\tau_p = \frac{1}{(\sigma + \rho)}$ y	$(\tau_p/\tau_w) = \frac{\rho}{(\sigma + \rho)}$ -	$(\frac{\sigma}{\rho})$ -	v_s* $m \cdot y^{-1}$
1973 74 75	.30	3.3	-	-	-	-	-	45.9
76	.41	2.4	.15	6.7	1.79	.27	2.73	62.7
77	.25	4.0	.16	6.3	2.44	.39	1.56	38.3
78	.21	4.8	.16	6.3	2.70	.43	1.31	32.1
79	.40	2.5	.20	5.0	1.67	.33	2.00	61.2
80	-	-	.17	5.9	-	-	-	-

range:
32.1 to 62.7

*$v_s = \sigma \cdot \bar{z}$ where $\bar{z} = 153$ m

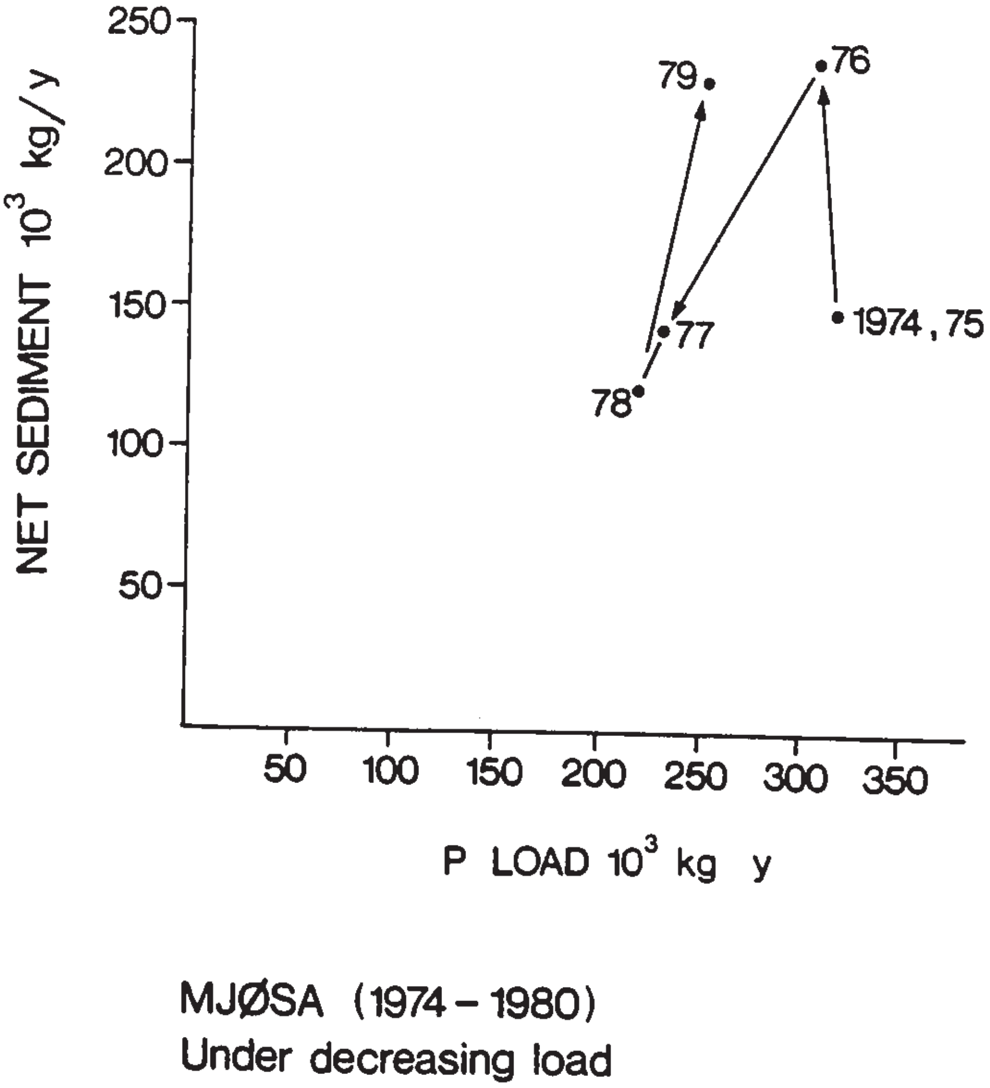


Figure 2.27 Lake Mjøsa phosphorus net sediment vs load.

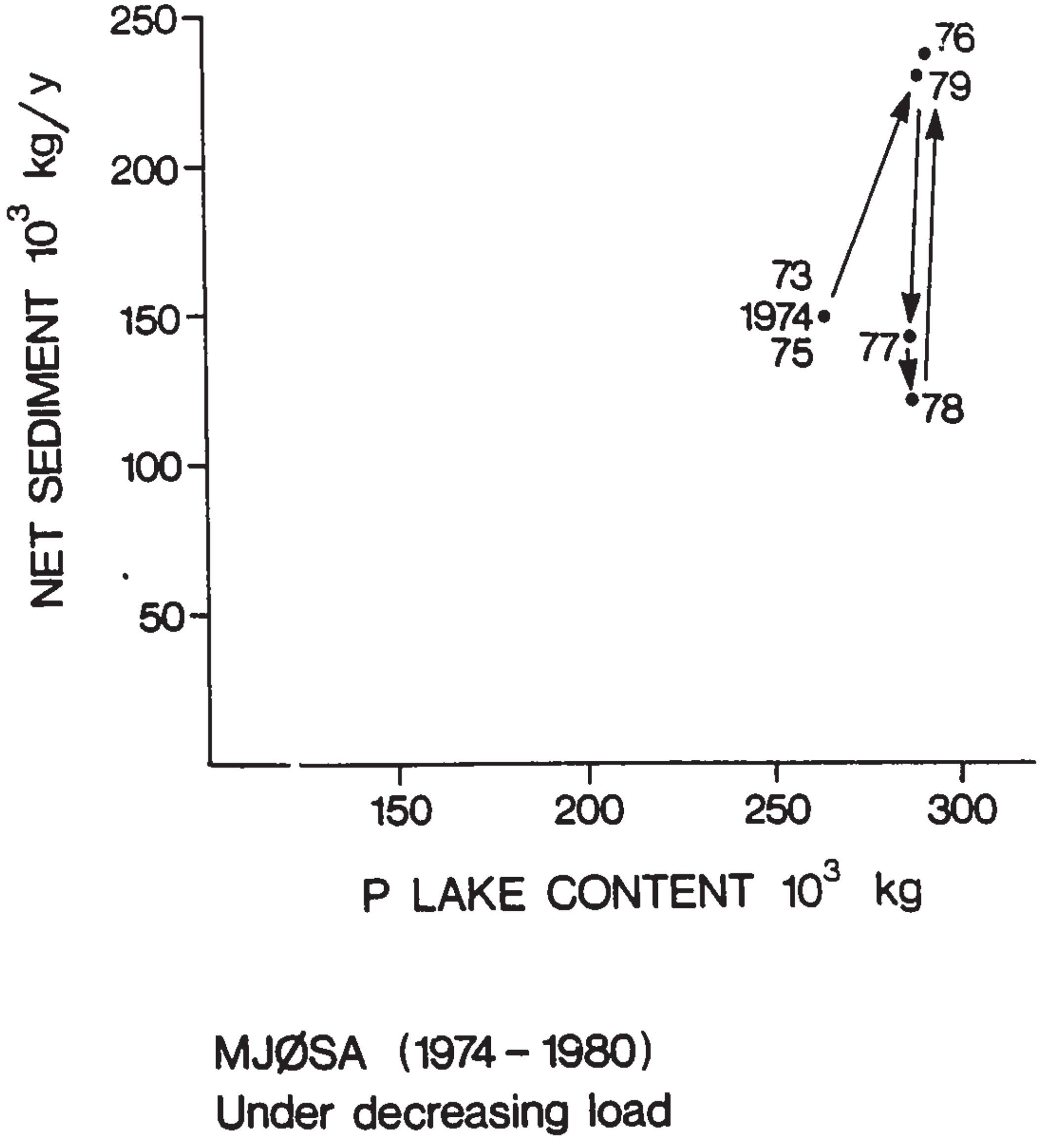


Figure 2.28 Lake Mjøsa phosphorus net sediment vs lake content.

2.6.3 Assessment for Mjøsa

As previously stated, the most eutrophic phase of Lake Mjøsa evolved over the 1960s and 1970s and peaked in 1976 with a severe Oscillatoria bloom. Epilimnetic phosphorus concentrations at that time were approximately 18 $mg{\cdot}m^{-3}$ and phosphorus loading was approximately 300 $t{\cdot}y^{-1}$. Therefore this loading is in excess of a critical level despite the fact that the lakewide mean concentration was only about 10 $mg{\cdot}m^{-3}$. The occurrence of a bloom at this relatively low average phosphorus concentration in a large, deep, naturally oligotrophic lake such as Mjøsa can only be explained by the relationship between loading and stratification. As Holtan (1981) pointed out, 40% of that year's load arrived during the summer when the lake was stratified. this localization of nutrients in the epilimnion during maximum temperatures and insolation obviously provided the conditions for the 1976 Oscillatoria bloom. In consideration of this, it seems that the critical loading for Mjøsa must be calculated on the basis of its stratification characteristics and loading seasonality.

Overall, the relative residence time of phosphorus in Mjosa is quite low (0.25 to 0.50) which reflects the moderately strong nature of the sedimentation processes ($\bar{\sigma}$ = 0.31 and v_s = 48 $m{\cdot}y^{-1}$). The high apparent sedimentation velocity is an indication of the predominant downward flux of phosphorus. The deep "v" shape of the basin (ζ = 2.93; z_{max} = 449 m) and relatively small sediment surface per stratum undoubtedly contribute to this. The ratio (σ/ρ) averages around 1.8 indicating that processes within the lake are more important in determining the phosphorus dynamics than is the physical flushing process. Considering these characterisics, it is not surprising that Mjφsa responded immediately to loading reductions. With an absolute residence time of phosphorus at about two years, the estimated recovery time (i.e., $3 \cdot \tau_p$) would be six years according to Sonzogni et al. (1976) (cf. Figure 1.2). The more rapid than predicted response rate of Mjφsa indicates that this hypothetical model may be more appropriate for lakes dependent on sediment desorption and wash-out for recovery.

2.7 Baldeggersee

2.7.1 Description and Trophic History

The Baldeggersee is a relatively small, deep lake of the Swiss Alps located at 47°N latitude, 463 m above sea level (cf. Figure 2.29). The surface area of the drainage basin is estimated at 69 km^2 and the lake's surface area at 5.2 km^2 with a resultant ratio of approximately 14:1. The mean depth of the lake is 34 m, the maximum is 66 m, and the volume is approximately 176 x 10^6 m^3. The hydraulic load to the lake averages 8.5 $m \cdot y^{-1}$ and the theoretical water residence time ranges from 3.5 to 8 years, depending on the year's hydraulic load. The lake is meromictic, and does not thoroughly mix due to the fact that

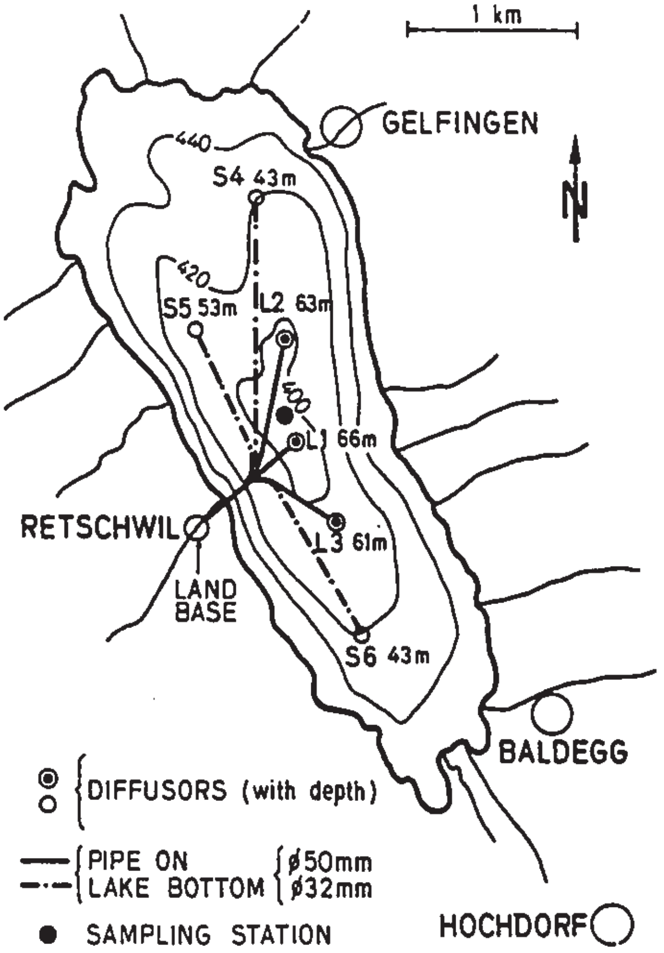


Figure 2.29 Map of the Baldeggersee, Switzerland, from Imboden (1985).

it is well sheltered from the wind by the surrounding mountains. (Considering this, the elimination of nutrient and other substances from the lake is most likely less efficient than indicated simply by the water residence time.)

The Baldeggersee has a long history of eutrophication which reached its peak in about 1975 (cf. Stadelmann, 1980). Originally, in the early 14th century before the present day population and agricultural pressures came to bear, the lake was known for its abundant whitefish. However, by 1884 cultivation of the eggs was necessary to sustain the fishery. At this time, the blue-green alga Oscillatoria rubescens became a dominant feature of the phytoplankton. Around the turn of the century Secchi minima were approximately 3 m and nitrogen and phosphorus concentrations were less than 400 $mg \cdot m^{-3}$and 100 $mg \cdot m^{-3}$, respectively. In 1921 it was discovered that the deepest 16 m of the hypolimnion were anaerobic and the reduction product H_2S was present. By 1940 the whitefish population collapsed completely and in 1958 it was observed that the thickness of the anaerobic zone had grown to 46 m, leaving only the upper 20 m of the lake oxygenated. Secchi minima were then down to 0.6 m. Although the population growth around the lake after WWII had stabilzed by 1958, nutrient loadings and lake concentrations continued to increase, despite the fact that 70% of the population was connected to sewers and treatment plants. Intensive production of dairy and pork products was largely responsible for this trend.

The lake reached its peak nutrient levels in 1975 when maximum nitrogen and phosphorus concentrations were 1800 $mg \cdot m^{-3}$ and 500 $mg \cdot m^{-3}$, respectively. From 1958 to 1974 phosphorus loadings had increased from 9.4 to 11.3 metric tons per year and phosphorus retention by the sediments had dropped from approximately 80% to 40%. The chemical oxygen demand of the hypolimnion was high due to dissolved ammonia, methane and sulfides (Imboden, 1985).

At the end of the 1970s, concentrations began to decline by virtue of increased and improved sewage treatment and improved agricultural facilities and practices. Serious study of alternatives for restoration were also underway and it was decided that lake-internal measures were necessary to alter the trophic state of the Baldeggersee. It became evident that external reductions alone would not be sufficient to substantially change nutrient levels. In 1982 the "Tanytarsus" system to enhance winter mixing and allow summer hypolimnetic aeration was installed. (As alternate restoration measures, phosphorus precipitation was avoided due to high cost and with only temporary effect and hypolimnetic drainage was avoided since the downstream lake which would receive the drainage was already highly eutrophic.) To date, the Tanytarsus system has been able to double the rate of total phosphorus assimilation from 3.1 $t \cdot y^{-1}$ to 7.3 $t \cdot y^{-1}$, mainly by prevention of internal loading in the autumn (Imboden, 1985).

2.7.2 Budget Analysis of the Baldeggersee

The phosphorus budget for the Baldegersee only consists of three years of sampling which represent a time span of ten years (1975 to 1984; cf. Table 2.18). The nutrient values are taken from a study by Imboden (1985) which began at the peak of the lake's eutrophication and reflect the effects of both loading reduction and later, hypolimnetic aeration. The total reduction in external load over this period was 3.2 metric $t \cdot y^{-1}$ from the maximum in 1975 of 11.3 $t \cdot y^{-1}$. Losses through the outlet were estimated at 5 to 10 $t \cdot y^{-1}$ and changes in lake content ranged from zero in 1975 to a decrease of 7.3 $t \cdot y^{-1}$ in 1984 (when the Tanytarsus system was in operation). Based on these fluxes, net sedimentation was estimated at 3 to 4 $t \cdot y^{-1}$, and later 9 $t \cdot y^{-1}$ when the hypolimnion was aerated (cf. Figure 2.30).

The concentration of phosphorus (cf. Table 2.19) as an average inflow, dropped from 494 $mg \cdot m^{-3}$ (in 1975) to less than half this value (i.e., 184 $mg \cdot m^{-3}$ in 1984). The average lake concentration responded similarly and dropped from 415 $mg \cdot m^{-3}$ (in 1975) to 216 $mg \cdot m^{-3}$ (in 1984).

The relative residence time of phosphorus, both corrected for lake content and as a concentration ratio, increased with the loading reduction, then decreased with hypolimnetic aeration (cf. Table 2.19 and Figure 2.31). Notably the concentration ratio is substantially greater than 1 (from about 1976 on) and

Table 2.18 Baldeggersee phosphorus balance; a 10 year time series (1975 - 84), adapted from Imboden (1985).

Year	Mean P Content of the Lake 10^3 kg	Total Load 10^3 kg · y-1	Loss Via Outlet 10^3 kg · y^{-1}	Change in Lake Content 10^3 kg · y^{-1}	Net Sediment 10^3 kg · y^{-1}
1975/76	73	11.3	6.8	0	4.5
81	56	10.3	10.0	-3.1	3.4
84	38	7.1 (±0.5)	5.3	-(7.3 ± 0.5)	(9.0 ± 0.5)

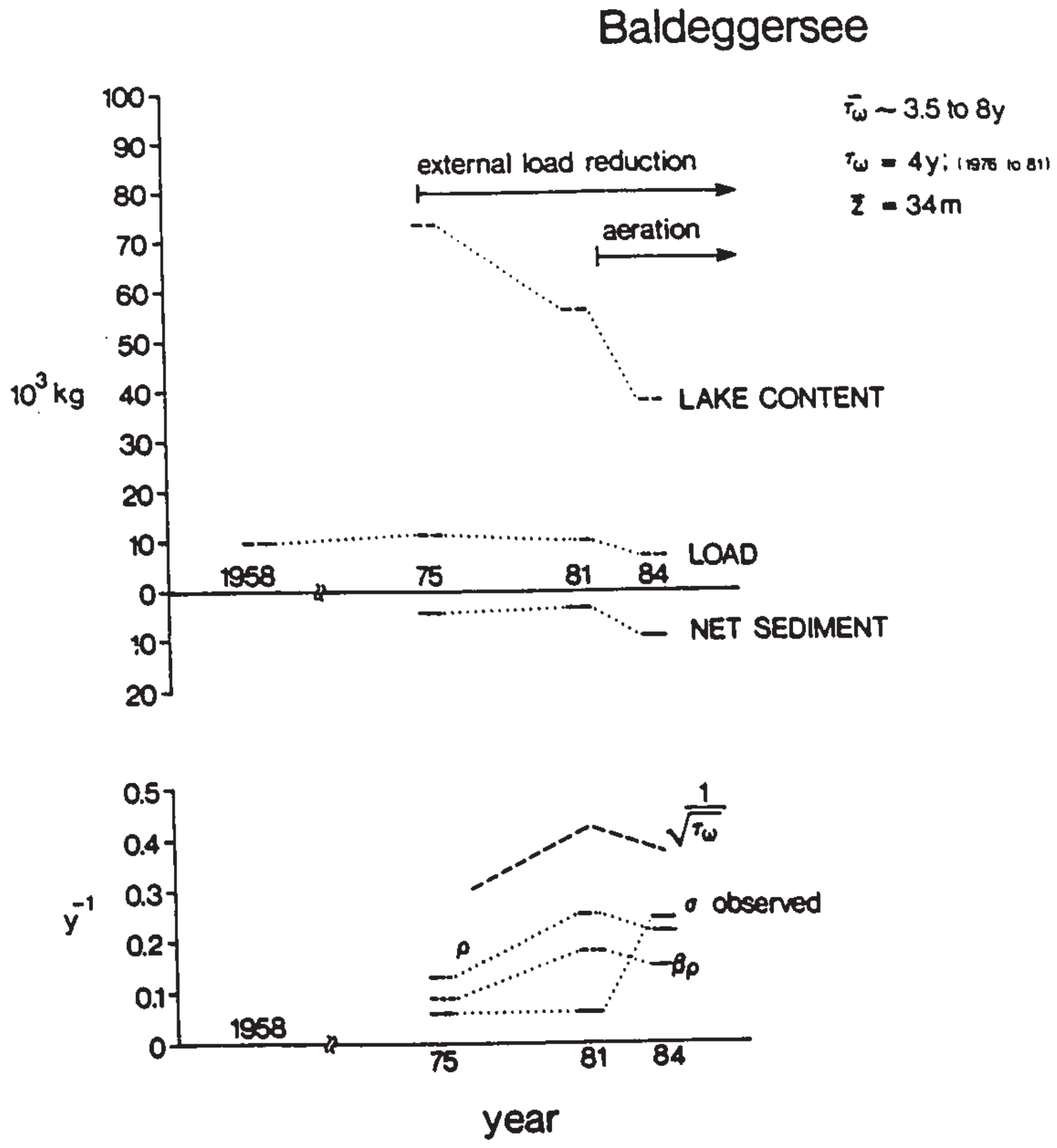


Figure 2.30 Baldeggersee phosphorus loading, lake content and sedimentation (1975 - 84).

Table 2.19 Baldeggersee concentrations of the lake, theoretical inflow and their ratio.

Year	$[P_\lambda]$	$[P_j]$	observed (P_λ/P_j)	$(\frac{\Delta \text{ lake}}{\text{load}})$	$({}^{\tau}p/{}^{\tau}w)$
1975 76	414.8	493.5	.841	0.00	.841
81	318.2	234.1	1.359	.301	1.045
84	215.9	183.5	1.177	1.028	.580

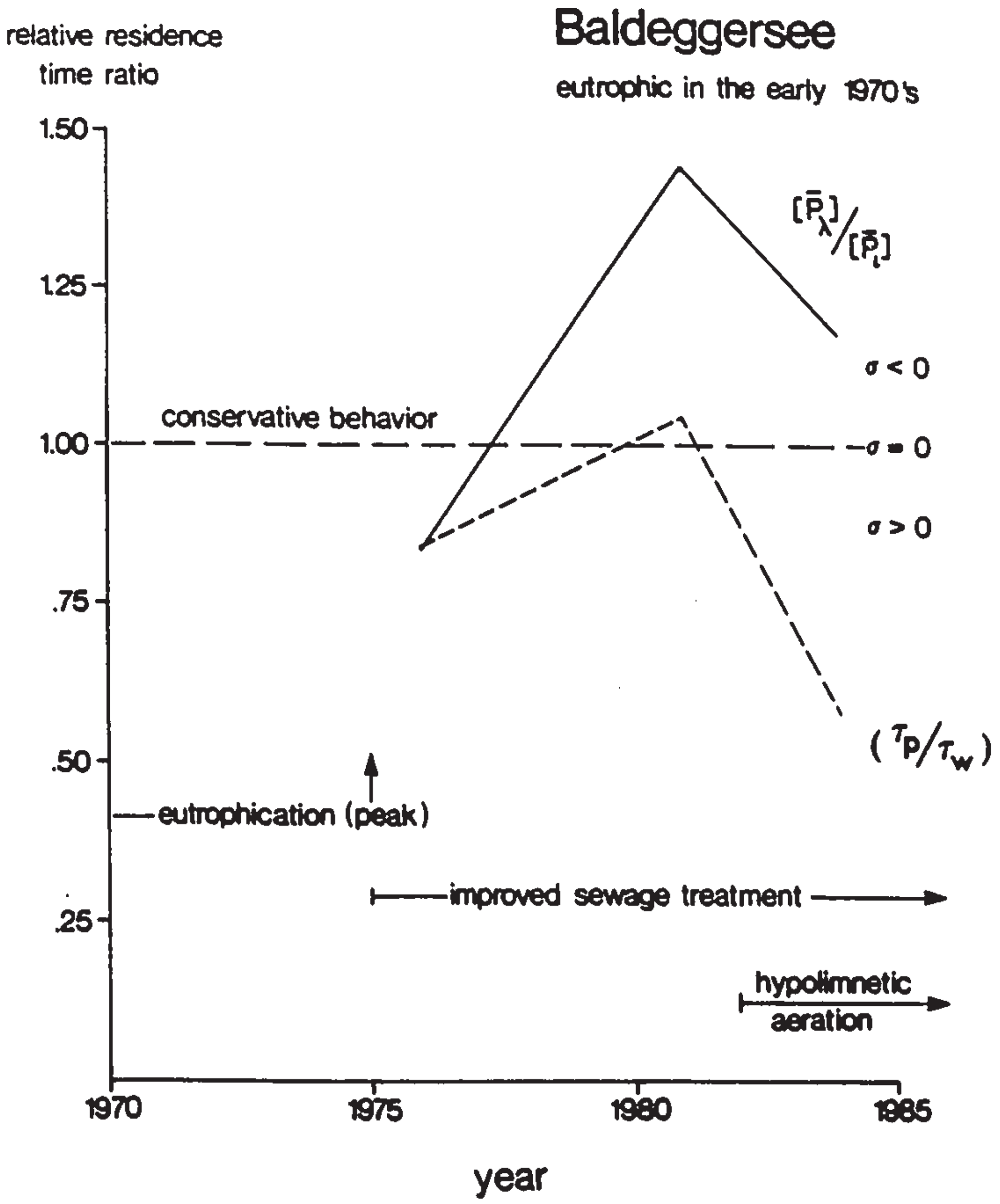


Figure 2.31 Baldeggersee (τp/τw) from 1975 to 1984.

indicates much slower flow rates of phosphorus than the value (τ_p/τ_w) which is corrected for the change in lake content.

In terms of mass balance coefficients as calculated from the budget information (cf. Table 2.20), this sedimentation coefficient is rather low and ranges from 0.06 to 0.24 y^{-1}. The apparent sedimentation velocity is only 2 to 8 $m \cdot y^{-1}$. The flushing coefficient corrected for the lower outflow than lake concentration (cf. Equation 2.6) ranges from 0.09 to 0.18 y^{-1}. The absolute residence time of phosphorus as calculated from these coefficients ranges from 6.7 to 2.6 y and consistently decreased over the period of observation. The ratio $(\sigma/\beta\rho)$ increased from a minimal value of 0.33 during the "wash-out" phase of the lake to 1.7 when restoration measures were in full effect. Therefore, a substantial shift in the route of elimination took place and sedimentation processes within the lake became more important than flushing losses.

The estimation of the sedimentation coefficient from $(1/\sqrt{\tau_w})$ gives a value of about 0.40 y^{-1}, which is much higher than the observed rate of 0.24 y^{-1} (at the most). Therefore the standard flushing corrected inflow (cf. Vollenweider, 1975) which employs this estimate of σ substantially underestimates the average concentration (cf. Figure 2.30, given previously). Too few data exist to evaluate 'load' or 'lake content' as estimators of total net sediment ($n = 3$; cf. Figures 2.32 and 2.33).

Table 2.20 Phosphorus elimination coefficients (sedimentation and flushing) and residence times in the Baldeggersee.

year	σ y^{-1}	$\tau_s = (\frac{1}{\sigma})$ y	$\beta\rho$* y^{-1}	$\tau_w = (\frac{1}{\beta\rho})$ y	$\tau_p = \frac{1}{(\sigma + \beta\rho)}$ y	$(\tau_p/\tau_w) = \frac{\beta\rho}{(\sigma + \beta\rho)}$ -	$(\frac{\sigma}{\beta\rho})$ -	v_s† $m \cdot y^{-1}$
1975 76	.06	16.7	.09	11.11	6.67	.60	.67	2.0
81	.06	16.7	.18	5.56	4.17	.75	.33	2.0
84	.24	4.2	.14	7.14	2.63	.37	1.71	8.2

* β factor = $\frac{\text{outlet export of p}}{\text{lake content of p}}$; used to correct efficiency of ρ

† $v_s = \sigma \cdot \bar{z}$ where $\bar{z} = 34$ m

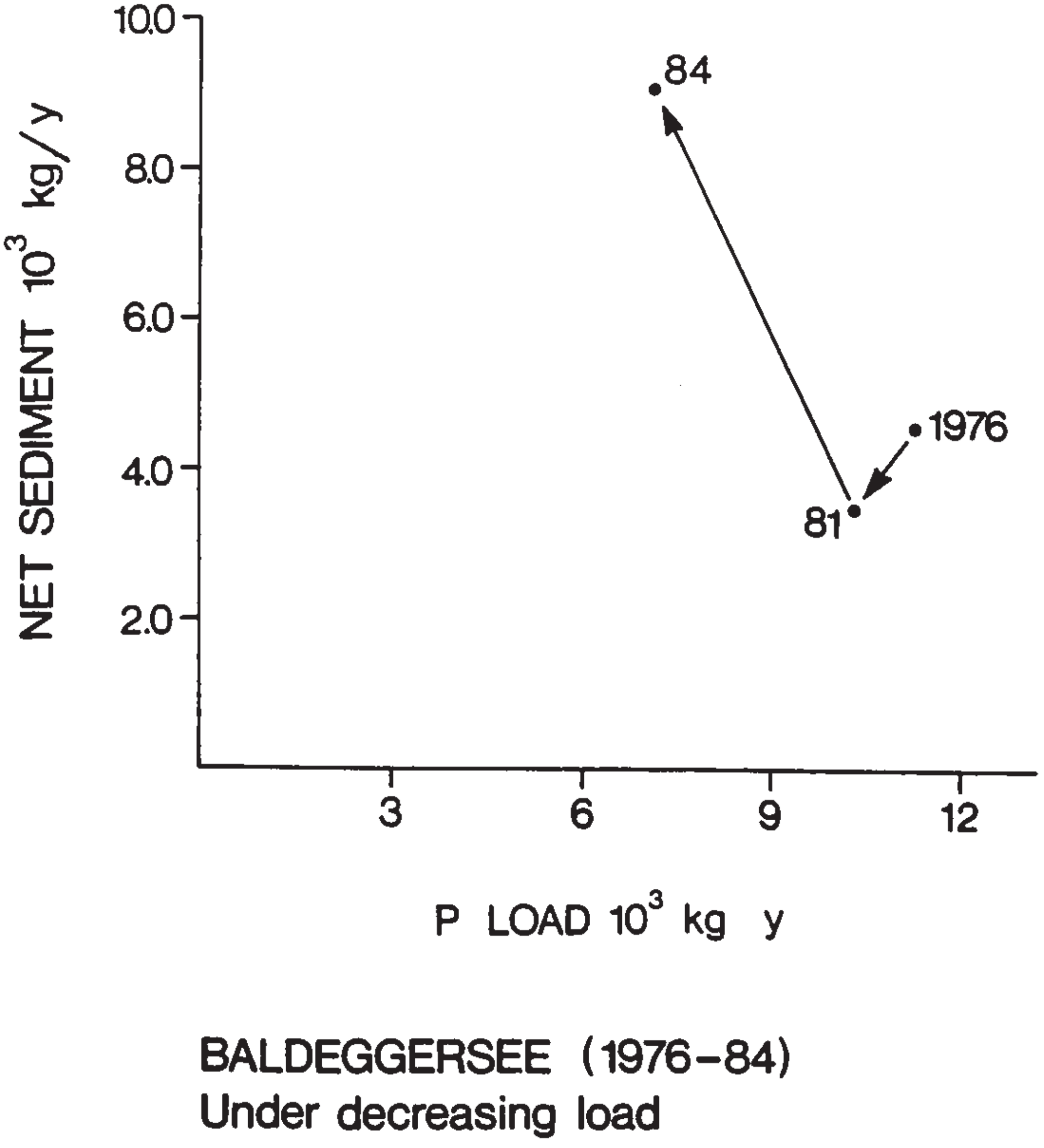


Figure 2.32 Baldeggersee phosphorus net sediment vs load.

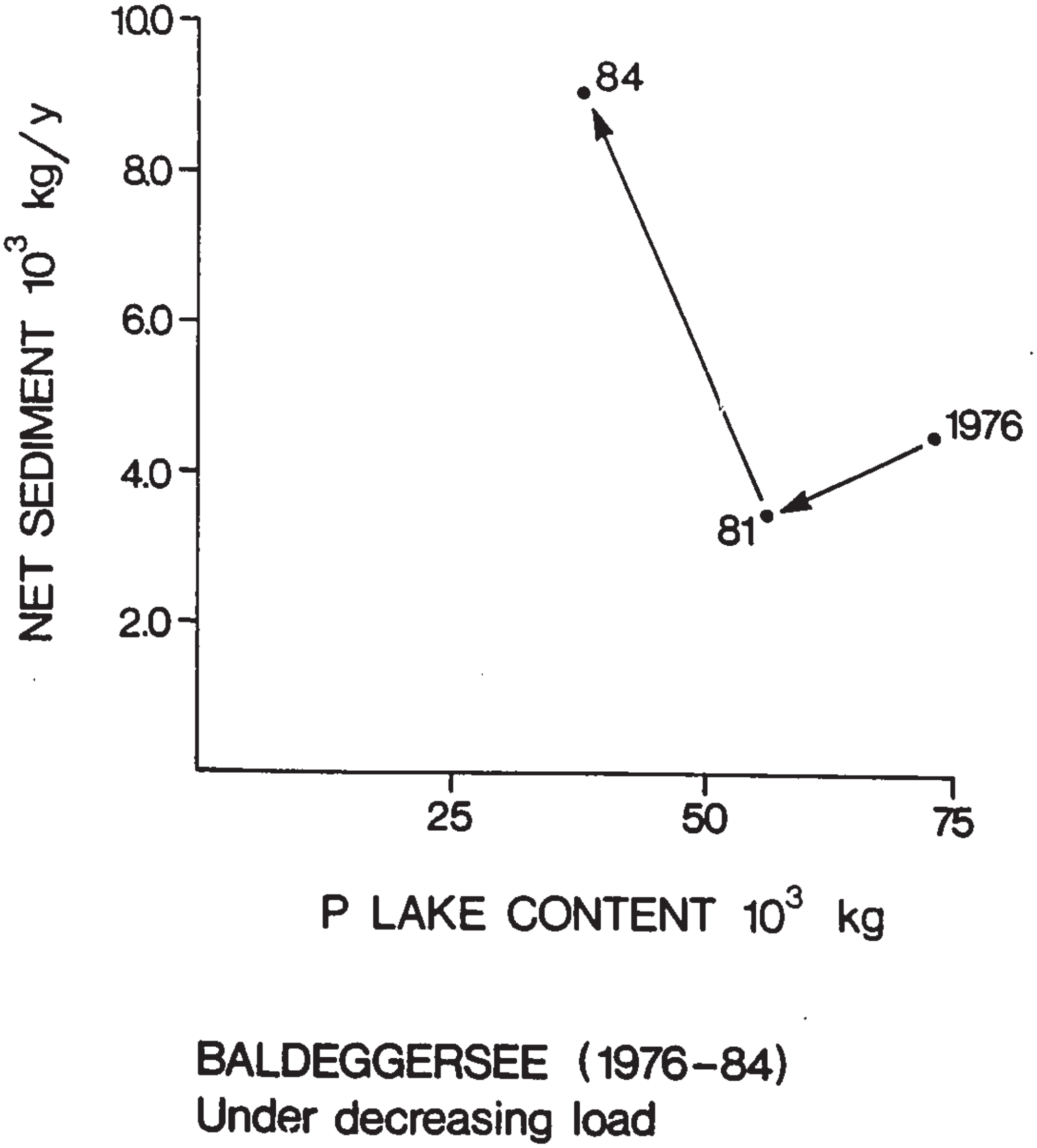


Figure 2.33 Baldeggersee phosphorus net sediment vs lake content.

2.7.3 Assessment for the Baldeggersee

The Baldeggersee was eutrophic for a half century or more before scientific records of the lake were made. The annual average concentrations of phosphorus in the lake (494 $mg{\cdot}m^{-3}$ in 1975) are among the highest reported in any of the northern temperate lakes. Under such enriched conditions, it is not surprising that the whitefish population collapsed, that algal blooms are common and that only the upper regions of the lake remain oxygenated.

The relative residence time of phosphorus is rather high and ranged from about 0.5 to 1.0. This indicates that the flow rates of phosphorus are quite slow and even approximate the behaviour of a conservative substance. Considering these high values, phosphorus may not (at the present) be the limiting element in the Baldeggersee. (Indeed, it is the common experience that blue-green algal blooms develop by virtue of the competitive advantage they have as nitrogen-fixers.) The drop in relative residence time in 1984 accompanied a two-fold increase in the total net sediment and appears to be a direct result of the Tanytarsus aeration system. This system is a step in the right direction for rehabilitation of the lake; it reduced the relative residence time to 0.58. However, at an average inflow concentration of 184 $mg{\cdot}m^{-3}$ this still implies an average lake concentration of 107 $mg{\cdot}m^{-3}$, a level typical of highly eutrophic waterbodies. In addition, absolute residence time in 1984 was

2.6 years which gives an estimate of 7.8 years ($3 \cdot \tau_p$) to reach equilibrium with any future loading reductions. If the sedimentation rate does not increase above the 1984 level of 0.24 y^{-1} and loading is not reduced below 7 $t \cdot y^{-1}$, it is highly unlikely that the Baldeggersee will change trophic condition. The main problems in rehabilitating this lake stem from its low sedimentation rate and inefficient flushing.

2.8 Shagawa Lake

2.8.1 Description and Trophic History

Shagawa Lake is a relatively small lake of glacial origin set in the forested lake region of Minnesota known as the Boundary Waters Canoe Area. Surface area of the lake is 9.2 km^2, altitude 407 m a.s.l. and mean and maximum depths are 5.7 m and 14 m, respectively. The volume of the lake is approximately 52.4 x 10^6 m^3 and water residence time ranges from 0.42 to 1.23 years. The drainage area for the lake is 109 km^2 and the hydraulic load is approximately 8.6 $m \cdot y^{-1}$. The basin of the lake has rather steep sides which drop sharply to 6 to 8 m, a flat bottom and a somewhat irregular shoreline. The lake has one major inflow, the Burntside River which drains from oligotrophic Burntside Lake located 10 km upstream. The one major outflow is the Shagawa River, which eventually drains into Fall Lake (Malueg *et al.*, 1975; cf. Figure 2.34). Conductivity of these lakes is low (~60 $\mu mhos \cdot cm^{-1}$) and they are surrounded by dense forest.

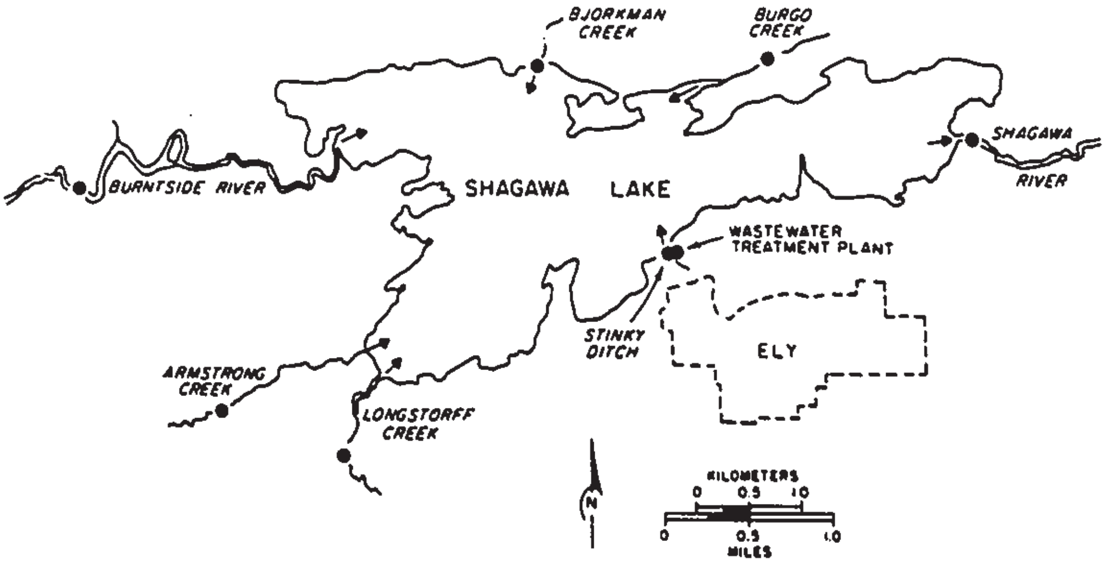


Figure 2.34 Map of Shagawa Lake, Minnesota, from Malueg _et al._ (1975).

Ice-cover lasts about five months and typically these lakes mix in the sping and fall. Additional complete mixing events are known to occur with storms and windy weather.

The town of Ely is the only settlement in the region. It began in the 1890s as a mining and logging town with a local dairy industry. In contrast to the other lakes of the rgion, blue-green algal blooms were apparent in Shagawa since the early 1900s, soon after Ely was established. Untreated sewage was dumped directly into the lake and in the 1930s bacterial levels were too high to allow its use as drinking water (Larsen and Malueg, 1976). In the late 1960s, nutrient budgets were constructed for Shagawa Lake to determine the role that the municipal secondary sewage from Ely played in the trophic condition of the lake. (Only primary sewage treatment existed prior to 1955.) The municipal treatment plant effluent was responsible for 80% of the phosphorus and 24% of the nitrogen loads. Furthermore, bioassay work showed that the phosphorus in the secondary sewage effluent was responsible for stimulation of algal growth.

In 1973 advanced wastewater treatment began and 99% of the phosphorus content of the treatment plant effluent was eliminated. By that time all the previous industries had disappeared and the livelihood of Ely was tourism. The total external phosphorus loading to the lake dropped from a maximum of 7370 kg in 1970 to 890 kg in 1986 and phosphorus concentrations in the lake declined from 50 to 20 $mg \cdot m^{-3}$ (Larsen *et al.*, 1979). A residence time model (based on sedimentation proportional to lake content) predicted that concentrations close to 12 $mg \cdot m^{-3}$ (rather than the observed 20 $mg \cdot m^{-3}$) would be reached within 1.5 years. The response lag of the lake was atributed to phosphorus feedback from the sediments since oxygen depletion in the bottom waters was known to be a regular feature of the lake in June through September. Over this same period, phosphorus and iron concentrations of bottom waters typically increased implying that phosphorus is released from iron oxides when the redox potential is low. The modelling efforts of Larsen et al. (1979) not only indicate that sedimentation varies throughout the year, but deposition rates in the winter are most likely close to zero. In the case of Shagawa Lake, it appears that internal mechanisms have strongly delayed a response to nutrient reduction.

2.8.2 Budget Analysis for Shagawa Lake

The phosphorus budget or Shagawa Lake spans the period 1971 to 1976 and covers a period three years prior to and three years during loading reduction, which began in 1983 (cf. Table 2.21 and Figure 2.35). The pertinent data were extracted from two sources: Malueg et al., 1975 and Larsen et al., 1979. Therefore the data is not strictly consistent, but rather an indication of the major fluxes.

The loading decrease from 1971 to 1976 followed an exponential drop from 6.8 to 0.9 metric $t \cdot y^{-1}$ (cf. Table 2.21).

Table 2.21 Shagawa Lake phosphorus balance; a 6 year time series prior to wastewater treatment (1966 - 72), adapted from Malueg <u>et al</u>. (1975) and 4 years after tertiary treatment (1973 - 76) adapted from Larsen <u>et al</u>. (1979).

Year	Mean P Content of the Lake* kg	Total Load $kg \cdot y^{-1}$	Loss Via Outlet $kg \cdot y^{-1}$	Change in Lake Content++ $kg \cdot y^{-1}$	Net Sinks $kg \cdot y^{-1}$
1966					
1967		6040	2930		
1968		6880	6200		
1969		6780	5490		
1970		7370	6140		
1971	2486	6840	4680	+ 300	1809
1972	2837	6240	3140	+ 620	2480
1973+	2554	2140	4310	- 1250	- 920
1974	1647	1490	2180	+ 50	- 740
1975	1537	1020	1670	- 280	- 370
1976	1547	890	930	+ 110	- 150

*Calculated from $[P_\lambda] \cdot V$; V assumed constant at 52.44×10^6 m^3

+tertiary waste water treatment effective

++ change in lake content at year's end, as given by Larsen et al., 1979

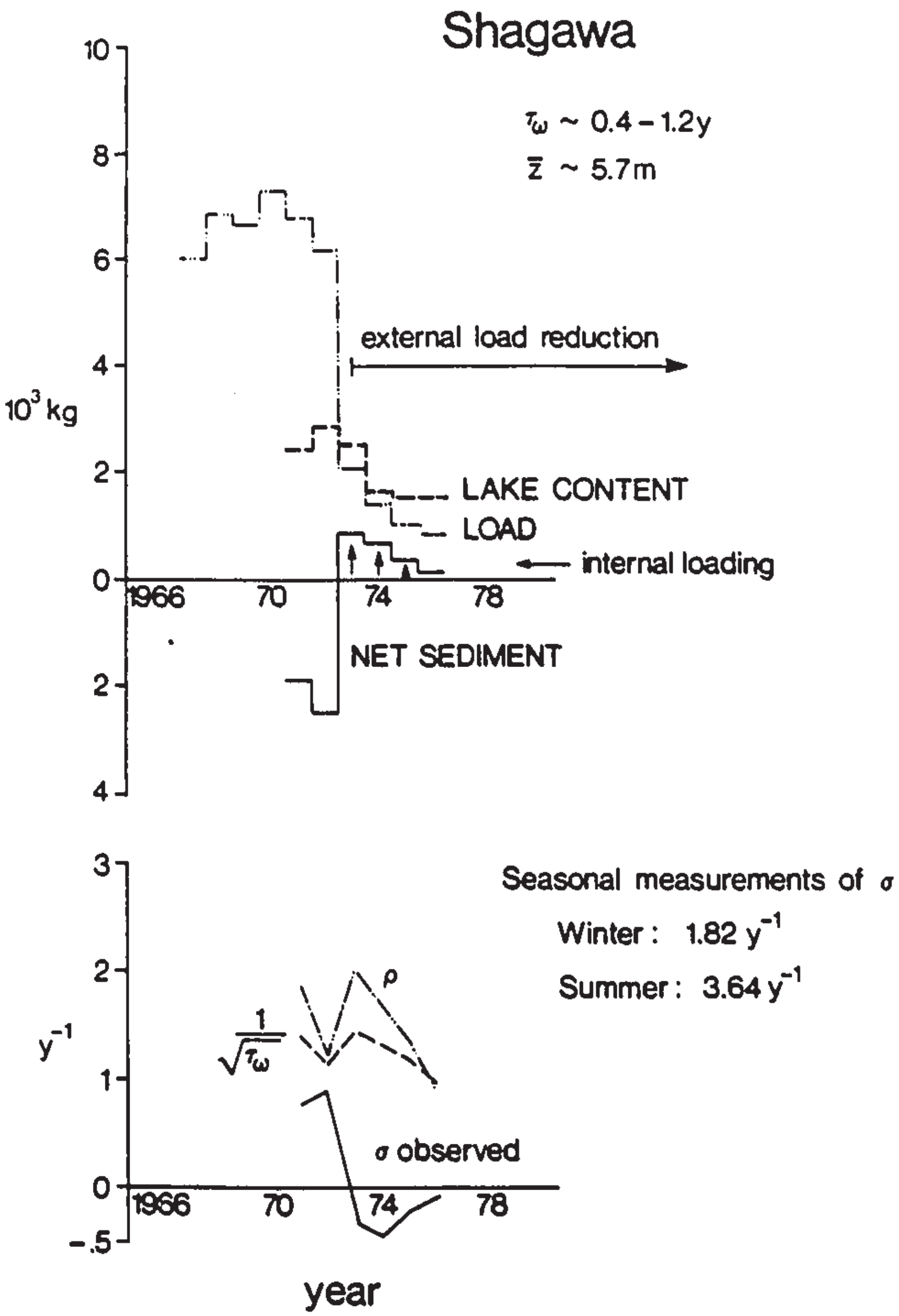


Figure 2.35 Shagawa Lake phosphorus loading, lake content and sedimentation (1971 - 76).

Losses through the outlet also generally declined from 4.7 $t \cdot y^{-1}$ in 1971 to 0.9 $t \cdot y^{-1}$ in 1976. Changes in the lake content as reported by Larsen *et al.* (1979) alternated between a gain of 0.6 tons in 1972 and a loss of 1.3 tons in 1973 when the sewage treatment began.

Total net sediment as calculated from these fluxes ranged from a deposition of 2.5 $t \cdot y^{-1}$ in 1972 to a reflux from the sediments of 0.9 $t \cdot y^{-1}$ in 1973. This reflux (or internal loading) continued through 1976, but decreased to about 0.2 $t \cdot y^{-1}$ at the end of the record.

The inflow *concentration* of phophorus dropped from 100 $mg \cdot m^{-3}$ in 1972 to approximately 20 $mg \cdot m^{-3}$ in the remaining years (cf. Table 2.22). (The sharp decrease between 1972 and 1973 was the direct result of the tertiary sewage treatment.) Over the same period, average lake concentations decreased from a maximum of 54 $mg \cdot m^{-3}$ to about 30 $mg \cdot m^{-3}$ by 1974, i.e., only one year after the loading decrease.

The *relative residence time* of phophorus generally increased with the loading reduction (cf. Table 2.22 and Figure 2.36). The minimum value of (τ_p/τ_w) at 0.6 in 1972 increased to a maximum of 1.8 in 1974. The relative residence time as estimated by the concentration ratio (P_λ/P_j) showed the same general pattern but with the maximum value of 2.4 in the first year of the loading reduction (i.e., 1973). Notably, both

Table 2.22 Shagawa Lake phosphorus concentrations of the lake, theoretical inflow and their ratio.

Year	$[P_\lambda]$	$[P_j]$	observed (P_λ/P_j)	$\left(\frac{\Delta \text{ lake}}{\text{load}}\right)$	(τ_p/τ_w)
1971	47.4	71.0	0.668	0.044	0.698
72	54.1	100.0	0.541	0.099	0.601
73	48.7	20.6	2.364	-0.584	1.492
74	31.4	17.8	1.764	0.034	1.825
75	29.3	15.3	1.915	-0.275	1.503
76	29.5	20.7	1.425	0.124	1.626

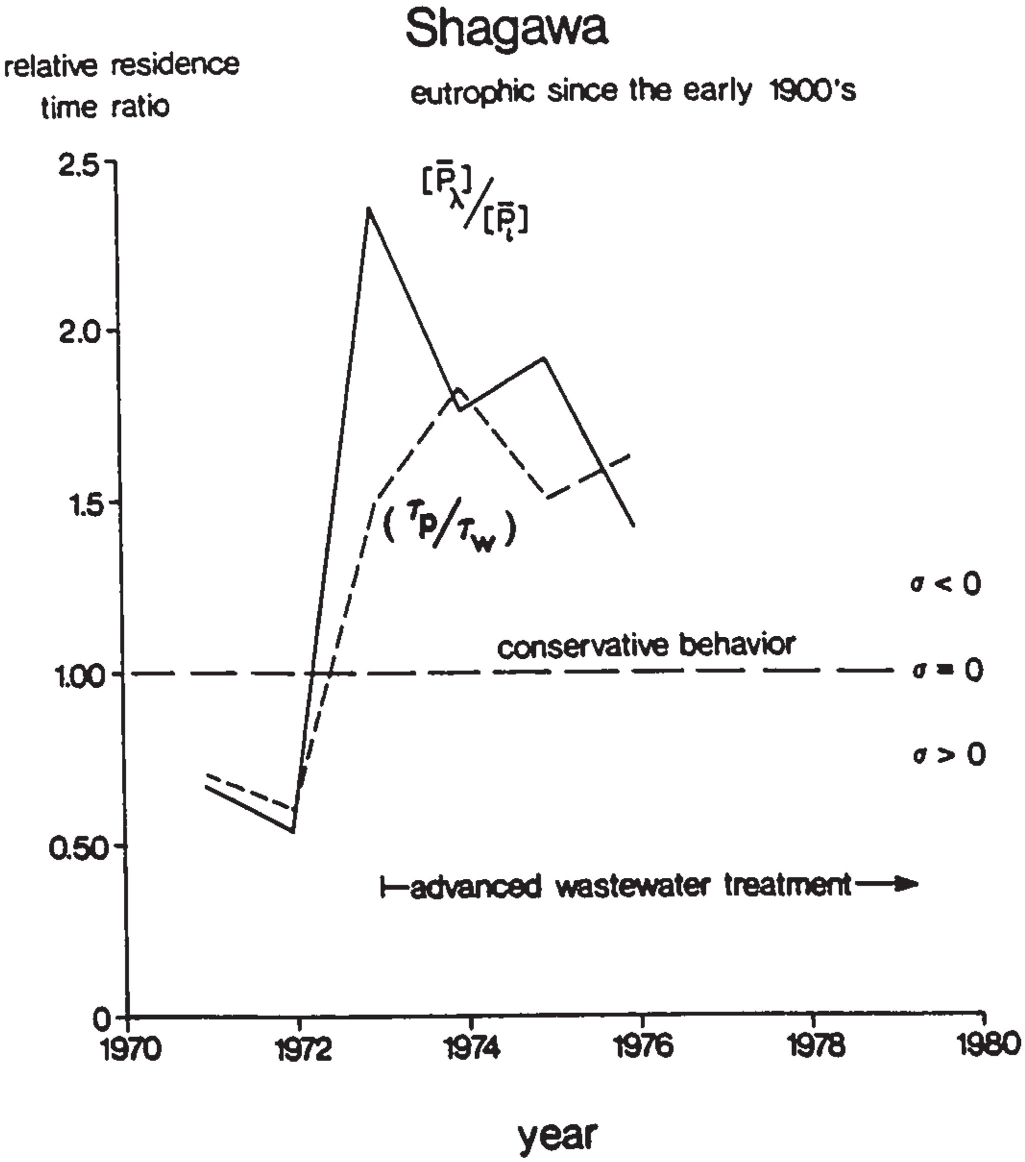


Figure 2.36 Shagawa Lake (τp/τw) from 1971 to 1976.

measures are substantially above 1 over the entire period of wastewater treatment.

Table 2.23 lists the mass balance coefficients that can be calculated from the budget data. The flushing coeficients range from 0.82 y^{-1} (in 1976) to 1.99 y^{-1} (in 1973). The sedimentation coefficients range from 0.87 y^{-1} (in 1972) to -0.45 y^{-1} (in 1974). All the years of wastewater treatment have negative coefficients indicating that the sediments became a phosphorus source which exceeded deposition. Calculated as apparent sedimentation velocity, values decreased from an already slow rate of 5 $m \cdot y^{-1}$ in 1972 to -2.5 $m \cdot y^{-1}$ in 1974 (with the negative sign indicating the flux from the sediments into the water column as opposed to a positive sign indicating deposition).

The ratio (σ/ρ) is always less than 1 indicating that the bulk of phosphorus is transported by the physical water flow out of the lake; water residence times are fairly short and range from 0.5 to 1.2 years. Absolute phosphorus residence times, which increase from 0.39 y to 1.39 y over the period of the budget, vary directly as the water residence times.

The estimation of sedimentation rate from the expression ($1/\sqrt{\tau_w}$) is much higher (i.e., 1 to 2 y^{-1}) than the observed rate (-.05 to 1.0 y^{-1}). Therefore, estimation of sedimentation by this expression would lead to underestimates of lake concentrations.

Table 2.23 Phosphorus elimination coefficients (sedimentation and flushing) and residence times in Shagawa Lake.

year	σ y^{-1}	$\tau_s = (\frac{1}{\sigma})$ y	ρ y^{-1}	$\tau_w = (\frac{1}{\rho})$ y	$\tau_p = \frac{1}{(\sigma + \rho)}$ y	$(\tau_p/\tau_w) = \frac{\rho}{(\sigma + \rho)}$ -	$(\frac{\sigma}{\rho})$ -	v_s†
1971	.75	1.3	1.84	.54	.39	.71	.41	4.3
72	.87	1.2	1.20	.83	.48	.58	.73	5.0
73*	-.36	- 2.8	1.99	.50	.61	1.22	-.18	-2.1
74*	-.45	- 2.2	1.61	.62	.86	1.39	-.28	-2.5
75*	-.24	- 4.2	1.28	.78	.96	1.23	-.19	-1.4
76*	-.10	-10.0	0.82	1.22	1.39	1.14	-.12	-0.6

*wastewater treatment effective

†$v_s = \sigma \cdot \bar{z}$ where $\bar{z} = 5.7$ m

The correlation of total net sediment with load is apparently significant ($r = 0.919$, $p < 0.01$). However, the data only consists of six years and the high correlation is due to the wide separation of 'before' (1971 and 1972) and 'after' (1973 to 1976) sewage treatment years (cf. Figure 2.37). The correlation of total net sediment with lake content is not signficant (cf. Figure 2.38). Therefore, neither load nor lake content would be satisfactory estimators of sedimentation.

2.8.3 Assessment for Shagawa Lake

Similar to the Baldeggersee, Shagawa Lake suffered more than half a century of cultural enrichment before restoration measures were attempted. With average lake concentrations of more than 50 $mg \cdot m^{-3}$, it is not surprising that the lake has commmonly produced algal blooms. In spite of the loading reductions, the mean lake concentration in 1976 was still typical of eutrophic environments at 30 $mg \cdot m^{-3}$. However, the mean inflow concentration was only about 20 $mg \cdot m^{-3}$ and the lake was still in a phase of 'washout'.

Overall, the absolute residence time of phosphorus in Shagawa Lake (i.e., 3 to 15 months) is controlled primarily by flushing. Sedimentation processes are secondary in their influence on phosphorus elimination ($\sigma/\rho < 1$).

Despite the highly eutrophic nature of Shagawa Lake, relative residence times of phosphorus were less than 1 before

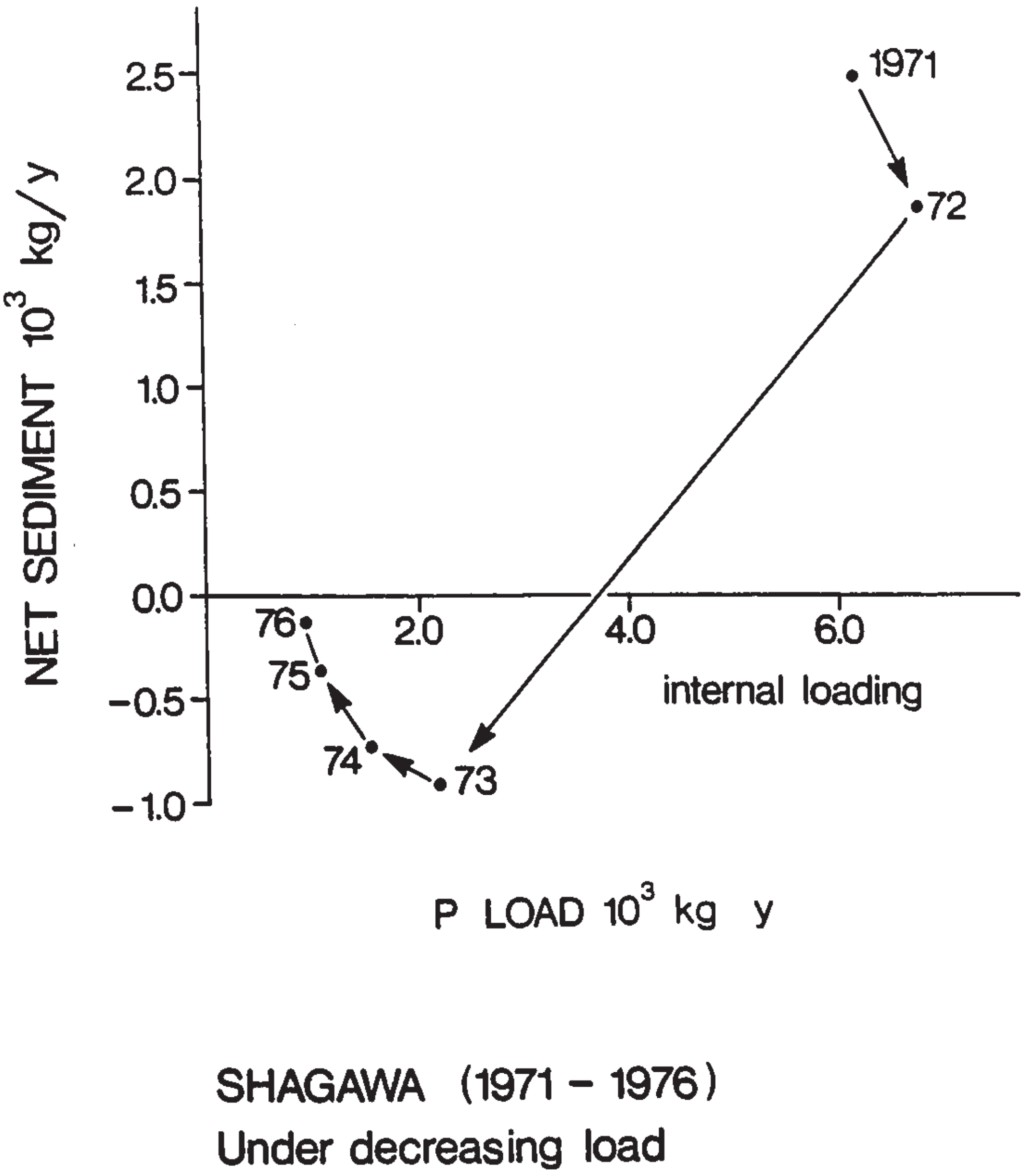
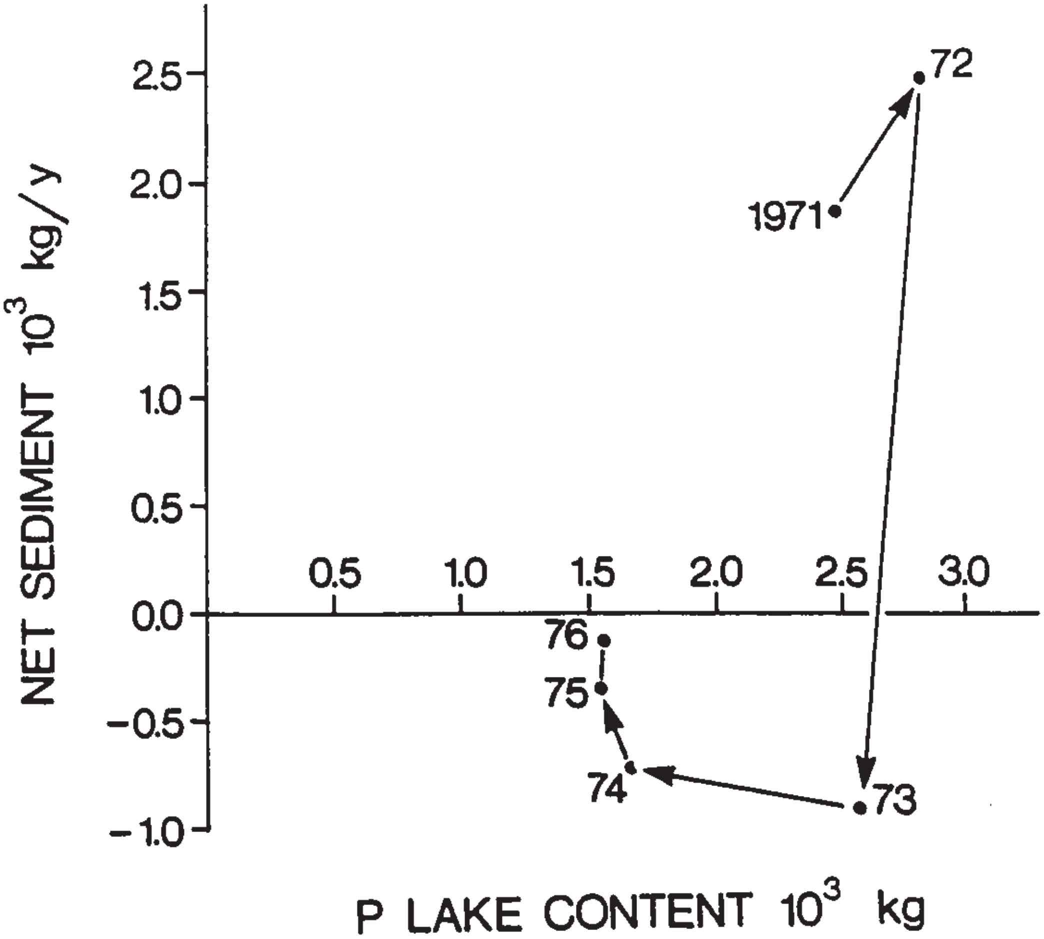


Figure 2.37 Shagawa Lake phosphorus net sediment vs load.



SHAGAWA (1971 – 1976)
Under decreasing load

Figure 2.38 Shagawa Lake phosphorus net sediment vs lake content.

sewage treatment, and the lake was a net sink for phosphorus. It was only when inflow concentrations dropped below the lake concentration that sedimentation became negative, i.e., sediments became a phosphorus source. Since the lake had been eutrophic for many years prior to this 'internal loading', it does not appear to be the consequence of a biological alteration of the sediment redox potential. In addition, the consistent decrease in the amount of phosphorus flowing from the sediments into the water column (from 1973 to 1976) was directly parallel to the consistent decrease in flushing rate. In opposition to this, one would expect that the decrease in inflow concentration and lake concentration over this period would promote the desorption of nutrients and perhaps increase the internal loading. However, in the case of Shagawa Lake, the physical flow of water is obviously a more important determinant of the quantity desorbed and during the washout period, flushing rate seems to be the factor controlling sedimentation.

With regard to the recovery of Shagawa Lake, the prospect for re-establishment of a new, lower trophic condition seems likely. If the lower loading of 20 $mg{\cdot}m^{-3}$ is maintained and the former relative residence time of approximately 0.6 is regained after the washout period, then the new mean lake concentration should be around 12 $mg{\cdot}m^{-3}$, a level typical of mesotrophic and oligotrophic environments.

2.9 Norrviken

2.9.1 Description and Trophic History

Lake Norrviken is a small, shallow lake located in central Sweden, at nearly 60°N latitude. Ice-cover is usually five months long and lasts from the beginning of December until the end of April. The lake is narrow and irregular in shape (cf. Figure 2.39) and has an intermediate position in a chain of four shallow eutrophic lakes (studied by Ahlgren, 1980). The upstream lake which supplies the major inflow to Norrviken is Lake Vallentunasjön and the outflow from Norrviken empties into Lake Edssjön. The connecting streams are approximately 3 km long and the drainage basins for Vallentunasjön (the upstream lake) and Norrviken are 50.7 and 94 km^2, respectively. The surface area of Norrviken is 2.67 km^2, the mean depth is 5.4 m and the volume is 14.3×10^6 m^3. Although the water residence time averages 0.83 years in the long-term, it remained at approximately 1.25 years from 1970 to 1976 due to low precipitation.

It has been estimated that the natural background phosphorus loading to Norrviken is sufficient to place it in the mesotrophic or eutrophic category according to Vollenweider's 1976 criterion (Ahlgren, 1978). Therefore, the municipal and industrial nutrient loads of more recent times have simply compounded the problems of a naturally eutrophic system. The major 'cultural' source of nutrients to Norrviken has been a yeast factory. Blue-green algal blooms and winter oxygen depletion

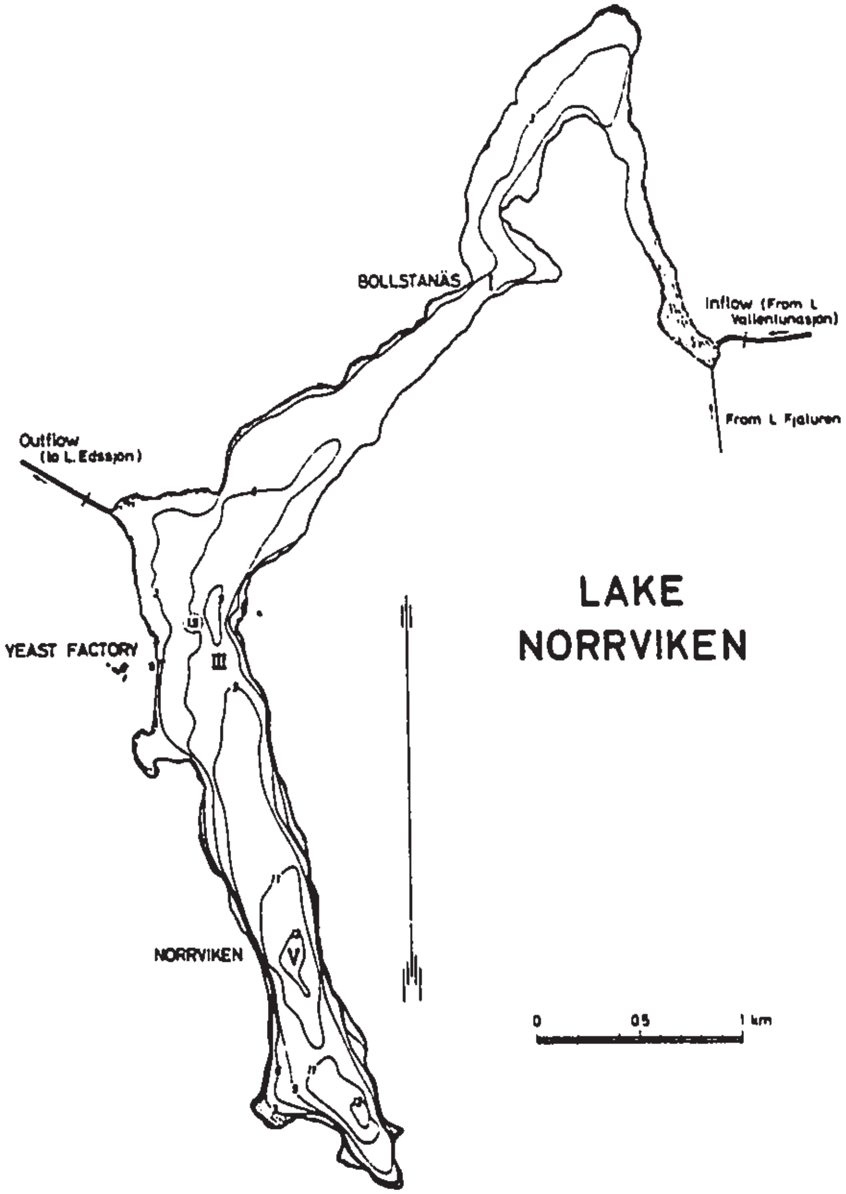


Figure 2.39 Map of Lake Norrviken, Sweden, from Ahlgren (1970).

(lasting through spring) have been consistent features of the lake since at least the 1940s. The regular treatment of these blooms with copper sulphate began in 1947. At first, *Microcystis* was the dominant genus and the copper treatments were highly successful in suppressing blooms (cf. Ahlgren, 1970). However, *Aphanizomenon flos-aquae* and *Oscillatoria agardhii* eventually replaced *Microcystis* species and the treatments diminished in effectiveness. In 1962 the copper treatments were abandoned altogether. Finally in 1969, all sewage was diverted from the lake, and as a result of the "Norrviken Project", detailed information was gathered to follow the course of the lake's recovery. That information is most complete for the years 1970 to 1976 covering the period immediately after diversion and forms the basis for the analysis given here.

2.9.2 Budget Analysis of Lake Norrviken

The *phosphorus budget* for Lake Norrviken consists of data for the years 1970 to 1976 and records the reaction of the lake immediately following the sewage diversion which began in 1969 (cf. Table 2.24 and Figure 2.40). Only partial data exists for 1962, seven years prior to diversion, but this at least demonstrates that loading was reduced to less than 20% of the pre-diversion level by 1971. The loading in 1962 was 10.9 metric $t \cdot y^{-1}$ which was reduced to 5.7 metric $t \cdot y^{-1}$ the first year after diversion (1970). After another sharp decline in the loading in

Table 2.24 Lake Norrviken phosphorus balance; a 15 year time series (1962 - 76), adapted from Ahlgren (1978 and 1980).

Year	Mean P Content of the Lake 10^3 kg*	Total Load 10^3 kg · y^{-1}	Loss Via Outlet 10^3 kg · y^{-1}	Change in Lake Content 10^3 kg · y^{-1}	Net Sediment 10^3 kg · y^{-1}
1962†	-	10.94	5.56	0.00	5.37
1970	3.72	5.67	6.02	-1.30	2.57
71	3.15	1.13	2.51	-0.30	-1.08
72	2.96	1.22	2.73	-1.73	0.22
73	2.66	1.22	1.13	-0.46	0.54
74	2.26	2.03	2.54	-0.86	0.35
75	1.40	1.30	1.08	(+)0.11	0.11
76	1.32	0.24	0.35	-0.11	0.00

*calculated from (lake volume x average concentration)

†before sewage diversion which commenced in 1969

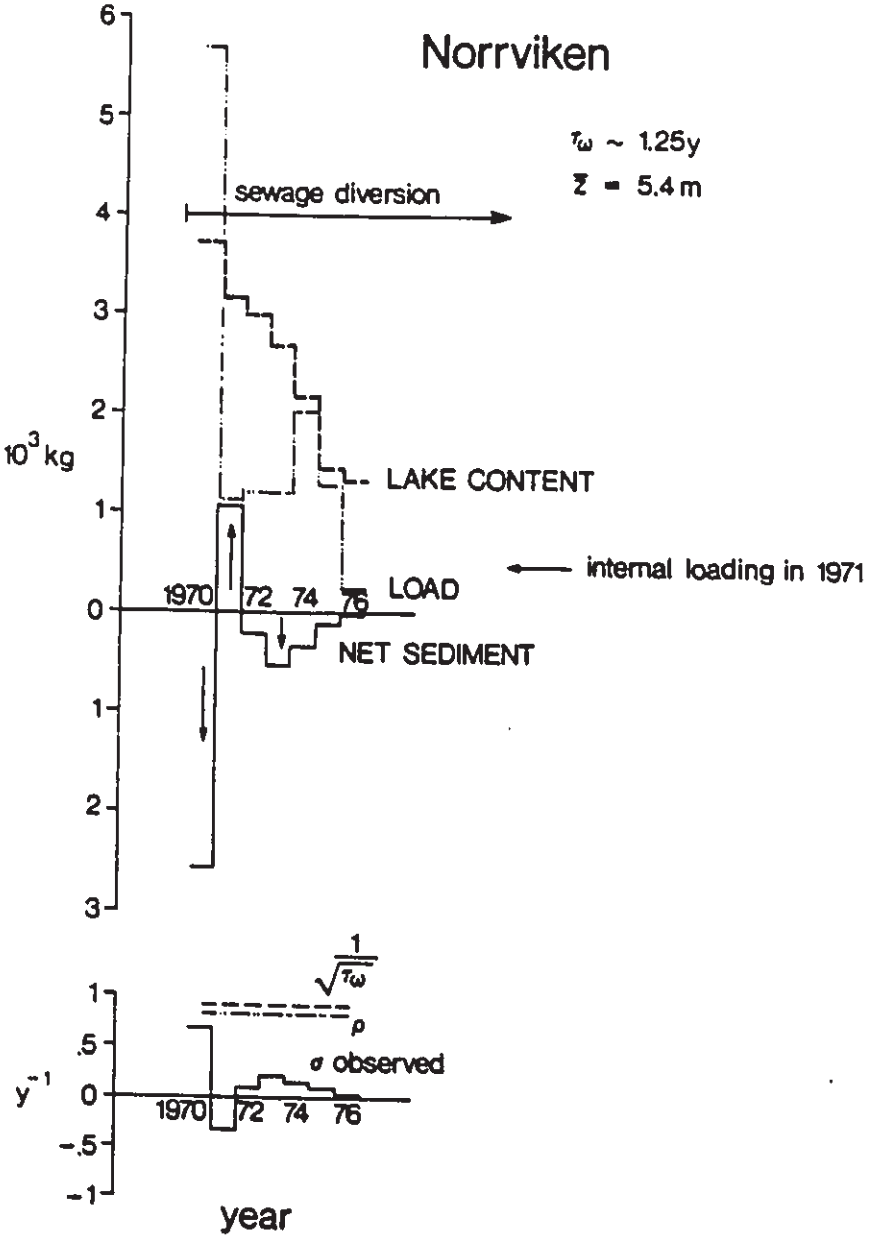


Figure 2.40 Lake Norrviken phosphorus loading, lake content and sedimentation (1970 - 76).

1971, a plateau of 1 to 2 $t \cdot y^{-1}$ was maintained (for four years) until 1976 when another sharp decline to 0.2 $t \cdot y^{-1}$ occurred. Losses via the outlet ranged from 6.0 $t \cdot y^{-1}$ (in 1970) to 0.4 $t \cdot y^{-1}$ (in 1976) and followed a general decline which ran parallel to the loading reduction. The lake content showed a general decline from 1978 to 1976 with the maximum decrease in 1972, when losses via the outflow were at a maximum.

The net sediment was estimated at 5.4 $t \cdot y^{-1}$ before diversion which dropped to half that value (2.6 $t \cdot y^{-1}$) in 1970, the first year after sewage diversion. After that, sedimentation generally declined to very low values of zero in 1975 and 1976.

In terms of concentrations (cf. Table 2.25), the annual mean inflow dropped from about 500 $mg \cdot m^{-3}$ in 1970 to a plateau averaging 120 $mg \cdot m^{-3}$ in the subsequent five years. In 1976 a second substantial drop to 21 $mg \cdot m^{-3}$ occurred. The lake concentrations over the same period steadily declined from 260 to 92 $mg \cdot m^{-3}$

The relative residence time of phosphorus as estimated by the concentration ratio (P_λ/P_j) or corrected for the change in lake content (τ_p/τ_w) (cf. Table 2.25 and Figure 2.41) both depict the same basic dynamcis. Values near and above 1 are common. These indicate that the slowest flows through the system occurred in 1971 and 1976 while the most rapid flows occurred in 1970 and 1974.

Table 2.25 Lake Norrviken phosphorus concentrations of the lake, theoretical inflow and their ratio.

Year	$[P_\lambda]$	$[P_j]$	observed (P_λ/P_j)	$(\frac{\Delta \text{ lake}}{\text{load}})$	$({}^{\tau}p/{}^{\tau}w)$
1970	260.0	496.0	0.524	-0.229	0.426
71	220.0	99.0	2.222	-0.265	1.756
72	207.0	107.0	1.935	-1.418	0.800
73	186.0	107.0	1.738	-0.377	1.262
74	158.0	177.0	0.893	-0.424	0.627
75	98.0	114.0	0.860	0.085	0.939
76	92.0	21.0	4.381	0.458	3.004

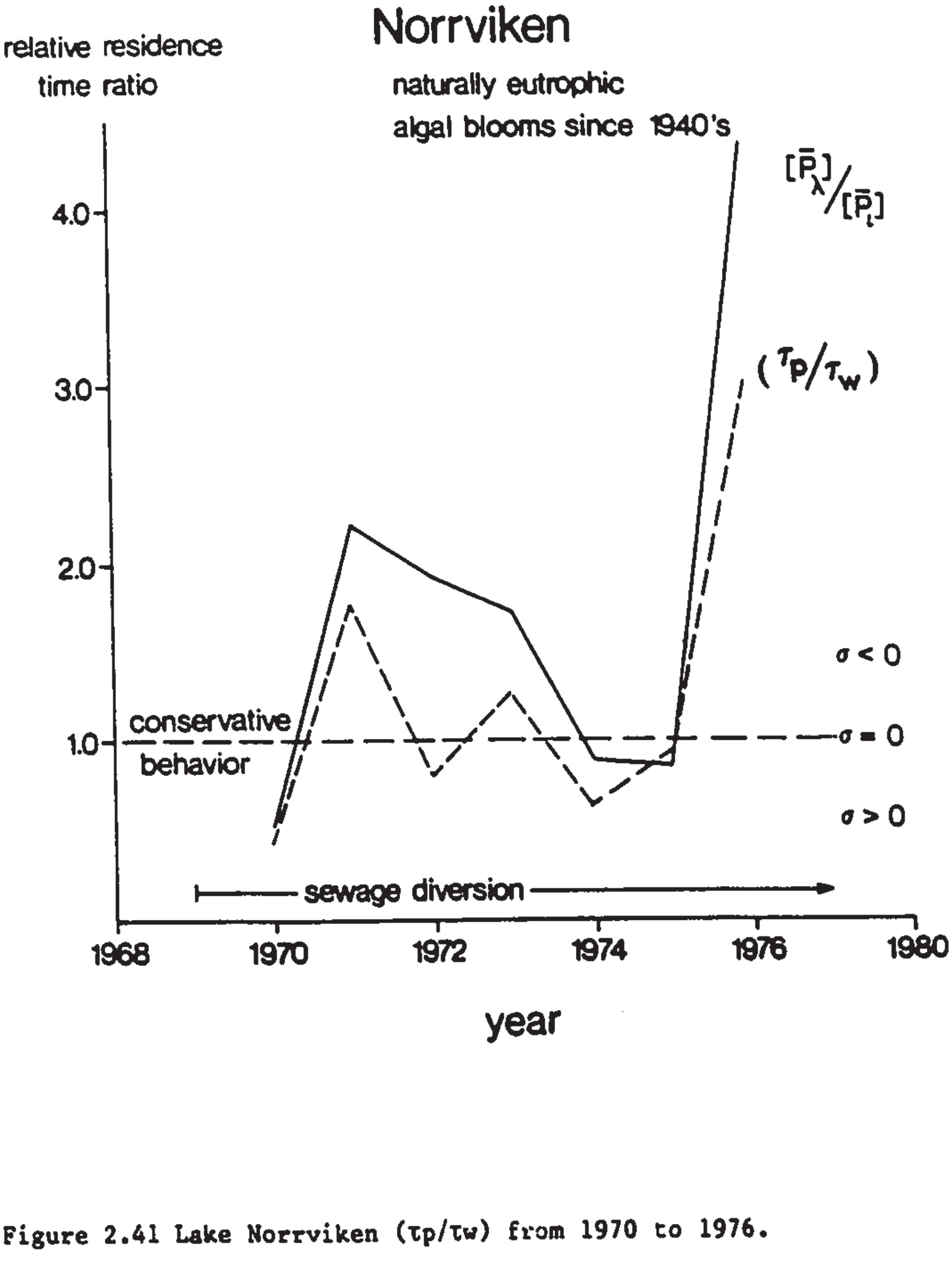


Figure 2.41 Lake Norrviken ($\tau p/\tau w$) from 1970 to 1976.

The budget figures calculated as mass balance coefficients (cf. Table 2.26 have only a single value for water residence time (τ_w) and flushing rate (ρ); for lack of other information, this value was assumed to apply for all years. The sedimentation coefficient was highest in 1970 at 0.69 y^{-1}, became negative (−0.34 y^{-1}) the following year, then hovered around 0.05 y^{-1} for the remaining five years of the record. In terms of apparent sedimentation velocities, none exceeded 4 $m \cdot y^{-1}$ and most were less than 1 $m \cdot y^{-1}$. These coefficients combined give estimates for absolute phosphorus residence times ranging from 0.7 to 2.2 years. These values are in general just below water residence times.

The ratio of the coefficients (σ/ρ) is always less than 1, so flushing is the predominant mechanism of phosphorus elimination. In addition, flushing may be more important than indicated by this ratio since a constant flushing rate had to be assumed and differences in its elimination capacity are automatically transferred to the difference value of sedimentation.

The estimation of sedimentation rate from ($1/\sqrt{\tau_w}$) gives a value near 1 (cf. the lower panel of Figure 2.40) which is much higher than the observed rate. Therefore, the observed concentrations are higher than those predicted from a flushing corrected inflow.

The correlation of total net sediment with load is evidently significant ($r = 0.87$; $n = 7$), but this correlation

Table 2.26 Phosphorus elimination coefficients (sedimentation and flushing) and residence times in Lake Norrviken.

year	σ y^{-1}	$\tau_s = (\frac{1}{\sigma})$ y	ρ* y^{-1}	$\tau_w = (\frac{1}{\rho})$ y	$\tau_p = \frac{1}{(\sigma + \rho)}$ y	$(\tau_p/\tau_w) = \frac{\rho}{(\sigma + \rho)}$ -	$(\frac{\sigma}{\rho})$ -	v_s†
1970	.69	1.5	0.80	1.25	.67	.54	.86	3.7
71	-.34	-2.9	0.80	1.25	2.17	1.74	-.43	-1.8
72	.07	14.3	0.80	1.25	1.15	.92	.88	0.4
73	.20	5.0	0.80	1.25	1.00	.80	.25	1.1
74	.15	6.7	0.80	1.25	1.05	.84	.19	0.8
75	.08	12.5	0.80	1.25	1.14	.91	.10	0.4
76	<.00	>100	0.80	1.25	1.25	1.00	<.00	0.0

*1970 to 1976 was a period of low precipitation; more usually $\bar{\rho}$ is 1.2 y^{-1} and $\overline{\tau_w}$ is .83 y.

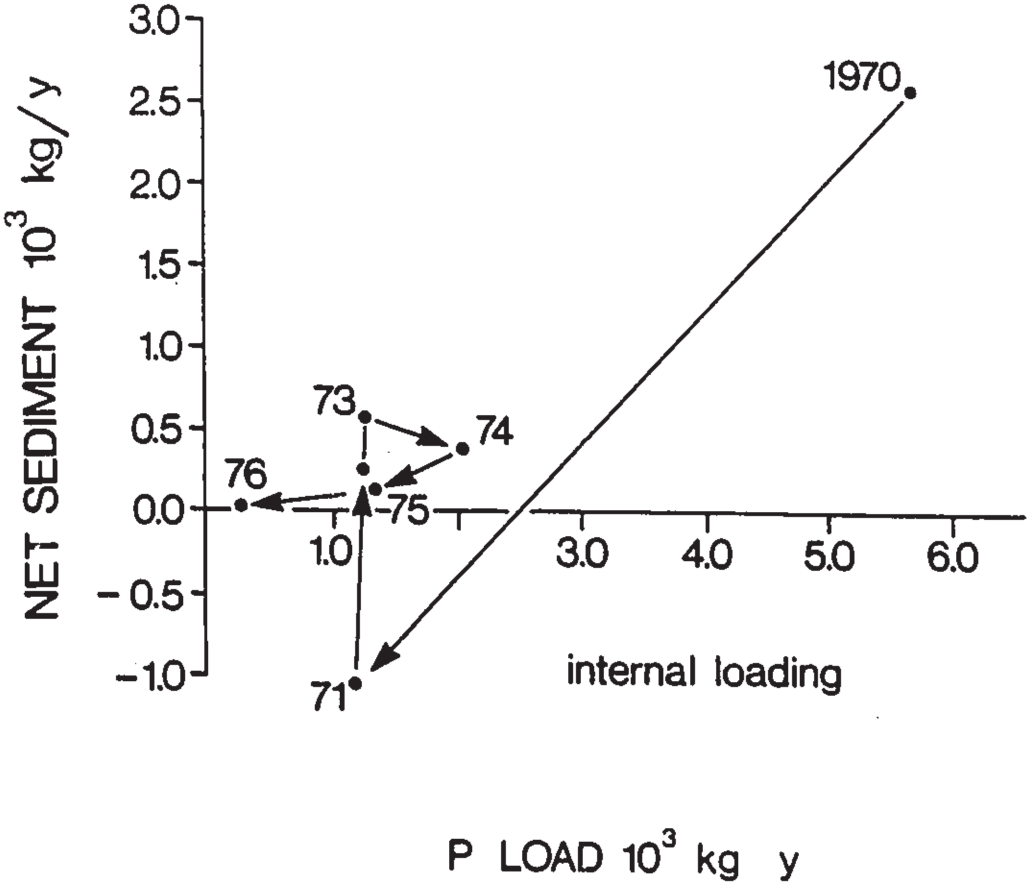
†$v_s = \sigma \cdot \bar{z}$ where $\bar{z}$ is 5.4 m

depends almost exclusively on the wide separation of the 1970 point from the remaining years (cf. Figure 2.42.) If the year 1970 is excluded, neither lake content (cf. Figure 2.43) nor load is significantly correlated with net sediment, so neither would serve in estimating sedimentation.

2.9.3 Assessment for Lake Norrviken

Similar to the previous two cases of the Baldeggersee and Shagawa Lake, Lake Norrviken suffered cultural eutrophication for at least three decades before loading reduction took place. As far as can be surmized from the records, the average phosphorus concentrations in the lake were greater than 200 $mg \cdot m^{-3}$ up to 1972. At such high concentrations, it is not surprising that algal blooms and oxygen depletion have been typical conditions of the lake. Even seven years after sewage diversion the mean lake concentation was more than 90 $mg \cdot m^{-3}$ - a concentration typical of highly eutrophic environments.

The relative residence time of phosphorus in Lake Norrviken has commonly been near or above 1 over the recorded period. Since the lake concentration has been consistently decreasing, this is a consequence of the loading decrease and disequilibrium between the lake and the load. The minimum relative residence time recorded for the lake was in 1970 when (τ_p/τ_w) was 0.43. If the sedimentation rate $(\sigma = 0.69)$ associated with this year can be recovered and the inflow



NORRVIKEN (1970-76)
Under decreasing load

Figure 2.42 Shagawa Lake phosphorus net sediment vs load.

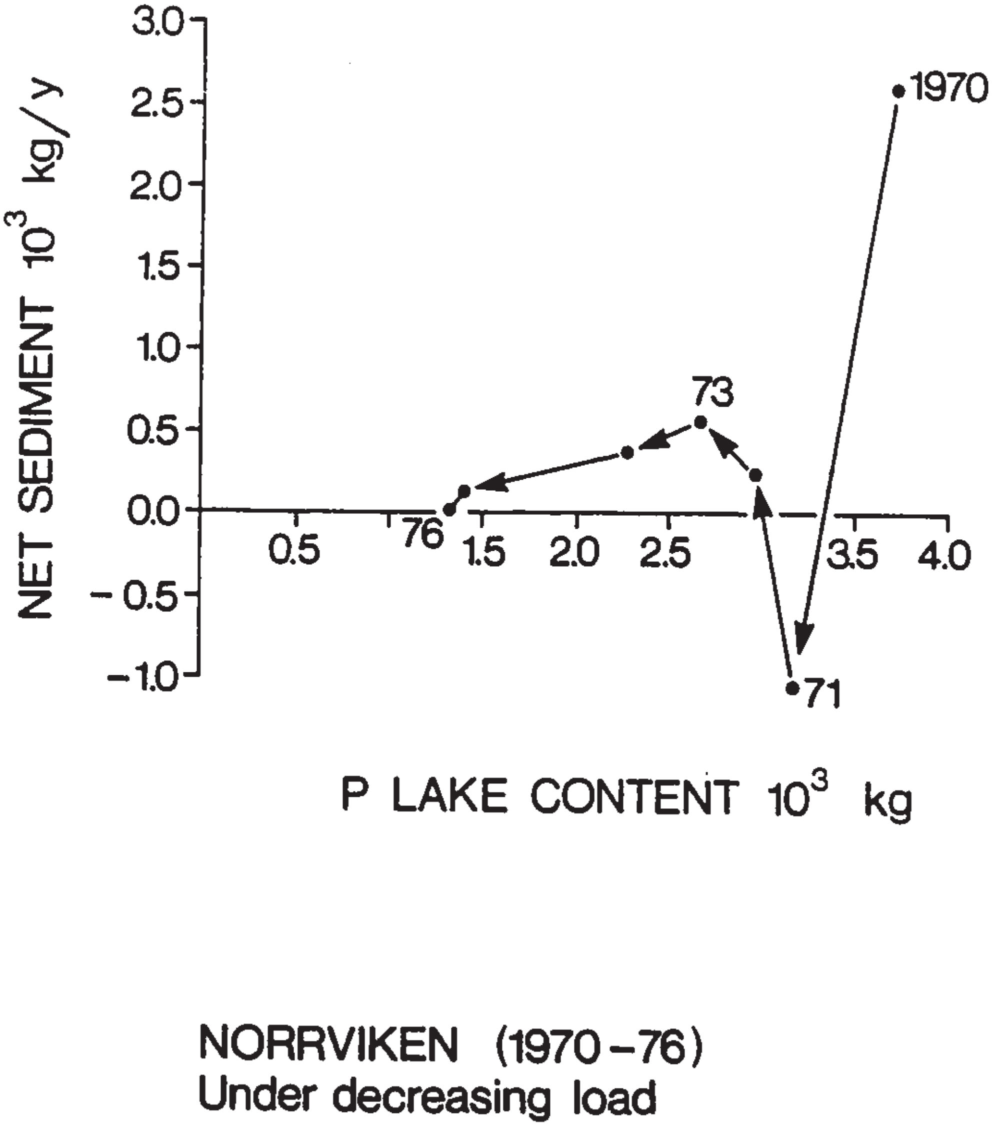


Figure 2.43 Shagawa Lake phosphorus net sediment vs lake content.

concentration can be maintained at the 1976 level of 21 $mg \cdot m^{-3}$, it is estimated that the lake concentration may decrease to about 9 $mg \cdot m^{-3}$. If this lake concentration could be sustained, it would likely change the trophic condition of the lake to at least a mesotrophic condition.

With regard to recovery rate of the lake, a new mean lake concentration would be established in about 3 τ_p or 3.75 years even if phosphorus remained nearly conservative in behaviour (as in 1976).

2.10 Lake Okeechobee

2.10.1 Description and Trophic History

Lake Okeechobee is the second largest lake in surface area totally within U.S. borders (and is only exceeded by Lake Michigan). It is located at 26°N in central southern Florida, has a surface area of 1705 km^2 and volume of 4.5 km^3. This lake differs from the other lakes discussed in a number of respects. First, it is located farther south than any of the other case studies, in a semi-tropical zone, so ice-cover is unknown and water temperatures are consistently warmer than those of the other lakes. Second, the lake basin was originally a depression in the ocean floor (not of glacial origin) which became an isolated lake with a mean depth of only 2 to 3 m when the sea level decreased. Its present altitude is approximately 5 m above sea level. It does not maintain stratification for any extended period of time and sediment resuspension is common, especially during the drier, windier winter months. The lake remains fully oxygenated at about 8 $mg \cdot l^{-1}$ O_2 throughout the year.

The natural state of the lake is considered to be moderately eutrophic. Twenty percent of the surface area is covered by macrophytes which provide excellent fish habitat and Okeechobee is famous for its bass fishing. The lake also supports a large commercial fishing industry.

Other important functions of the lake are as a drinking water supply for three million people and as a flood control structure. Hurricanes in 1926 and 1928 were responsible for extensive flooding and loss of over 2,100 lives. To protect against similar catastrophes, the Corps of Engineers was given the task of constructing a levee surrounding the entire lake. This structure, known as the Hoover Dike, was completed in 1937, and after being raised in the early 1960s, now stands 8 m above the original lake level. All the inflow and outflow channels of Okeechobee (cf. Figure 2.44) are equipped with control structures and at present the lake level is maintained at approximately 5.3 m. There are 15 major inflows surrounding the northern half of the lake, most of which are man-made canals that were constructed in the early 1900s to improve the drainage of approximately 4,600 km^2 of land surface. There are three major outflows around the southern end of the lake which are channelled

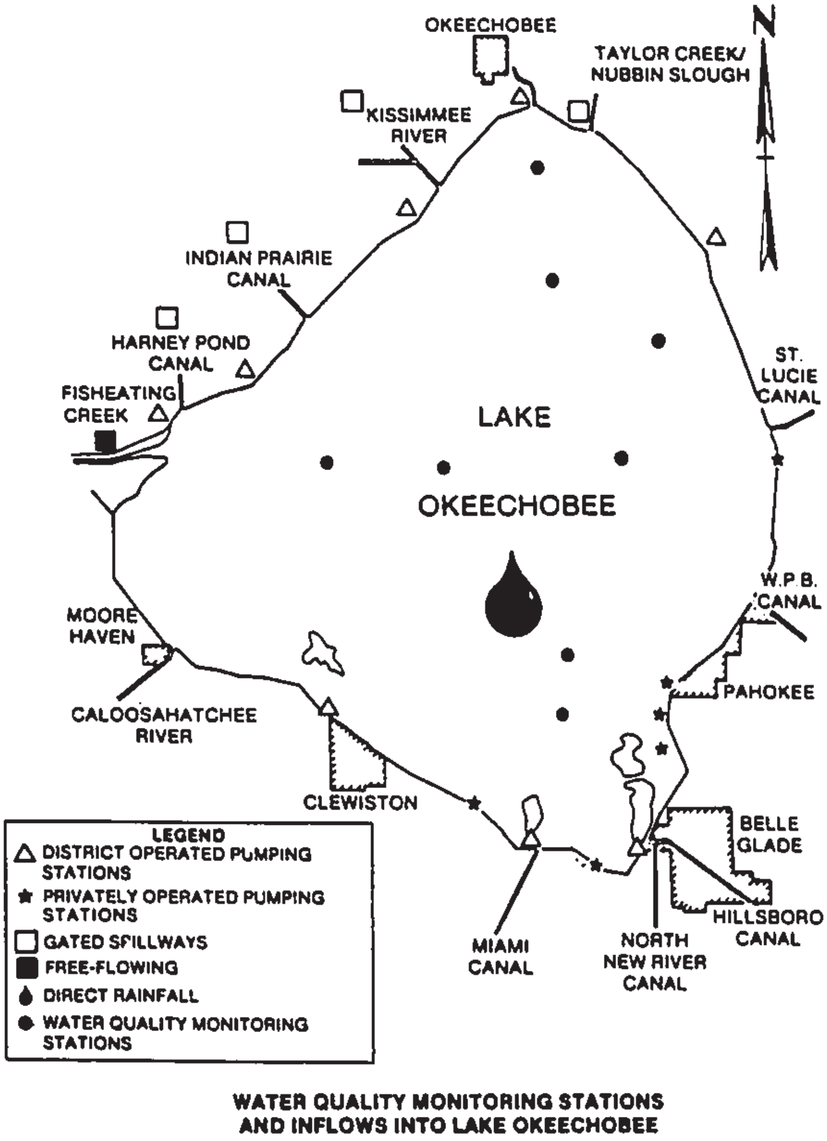


Figure 2.44 Map of Lake Okeechobee, Florida, from South Florida Water Management District (1985).

to irrigate the sugar cane and vegetable crops of the Everglades Agricultural Area.

The major nutrient sources to Okeechobee are drainage from intensive cattle farming via Taylor Creek/Nubbin Slough in the north and drainage from the Everglades Agricultural Area in the south which was formerly backpumped into the lake to conserve water. The quality of these inputs differs and while the cattle drainage tends to be relatively high in phosphorus, the agricultural drainage tends to be relatively high in nitrogen.

At the present time, there is great apprehension about the eutrophication of Okeechobee, largely due to the recent hypereutrophication of nearby Lake Apopka, a lake similar in many respects to Okeechobee.

To review the story of Apopka, the lake received municipal sewage effluent, cattle farm runoff and the discharge from a citrus processing plant beginning in the 1920s. These nutrients were assimilated by macrophytes and the water remained extremely clear. In 1947 a hurricane uprooted much of the macrophyte coverage and the first algal blooms appeared. The macrophytes have never been re-established, algal blooms are common, and the unconsolidated sediment is frequently resuspended (the mean depth of the lake is only 1.5 m). Unfortunately, some management practices, intended to "stabilize" the lake (i.e., force it back to its original condition as an excellent bass fishing ground) probably made matters worse. Water hyacinths were sprayed with herbicides, "rough" fish (shad, gar and catfish) were selectively poisoned and all was left to rot in the lake. By 1960, the lake was abandoned as a fishery resource and it presently remains in its degraded condition with only blue-green algal blooms, rough fish and water hyacinths to offer. Apopka is now well known, particularly among the sport fishermen, as a prime example of destructive eutrophication.

At the present time (1986), concerns of the long-term residents and fishermen have prompted the South Florida Water Management District (SFWMD) to attempt a more clearly defined evaluation of the present state of Lake Okeechobee and its proximity to a collapse such as the one which occured in Apopka. Interviews with Okeechobee fishing guides consistently reported that the vegetation of the lake has been in a rapid state of increase and species change. The former pepper and needle grass beds which provided good fish habitat in the past have been overtaken by a slimy periphytic layer which they fear is destroying the bass spawning grounds. Most of those interviewed blamed the perceived deterioration on the nutrient enrichment from backpumping practices of the Everglades Agricultural Area at the south end of the lake. Only one of the eleven men interviewed recognized that the nutrient contribution from municipal sewage and cattle ranching which entered via the Taylor Creek/Nubbin Slough inflow was a major problem. The South Florida Water Management District (SFWMD) is therefore presently faced with the task of defining the remedial measures necessary to protect this resource.

Assignment of a tropic state for Okeechobee is difficult because based on average phosphorus concentrations the lake should be rated highly eutrophic, but based on average chlorophyll levels the lake is only moderately eutrophic. Therefore, simplistic identification of the lake's tropic condition, and perhaps more importantly any trend thereof, is not possible. Fortunately, the SFWMD has been constructing nutrient and water budgets for Okeechobee since 1973, and that data forms the basis of the analysis given here.

2.10.2 Budget Analysis of Lake Okeechobee

The phosphorus budget for Lake Okeechobee covers a period of 12 years (1973 to 1984) and relates to a period of high variation in both annual phosphorus loading (cf. Table 2.27 and Figure 2.45) and water levels. Although no time trend exists, both maximum and minimum loading values have become more extreme since 1980. The minimum load recorded was 215 metric $t \cdot y^{-1}$ in 1980 and the maximum was 1,137 metric $t \cdot y^{-1}$ in 1982, coincident with first a drought and then high water levels, respectively. Losses through the outlet ranged from 37 $t \cdot y^{-1}$ (in 1976) to 294 $t \cdot y^{-1}$ (in 1982, coincident with the maximum load). The change in lake content ranged from a decrease of 163 tons in 1980 to an increase of 307 tons in 1982.

Table 2.27 Lake Okeechobee phosphorus balance; a 12 year time series (1973 - 84), adapted from Federico *et al.* (1981) and SFWMD, pers. commun. (1985).

Year	Mean P Content of the Lake[+] 10^3 kg	Total Load 10^3 kg · y^{-1}	Loss Via Outlet 10^3 kg · y^{-1}	Change in Lake Content 10^3 kg · y^{-1}	Net Sediment 10^3 kg · y^{-1}
1973	204	538.3	57.1	-3.1	484.3
74	212	632.0	183.1	6.6	442.3
75	228	363.4	57.8	-6.6	312.2
76	234	522.4	36.7	40.1	445.6
77	263	508.3	46.7	32.6	429.0
78	366	676.7	158.3	30.4	488.0
79	537	800.2	155.2	22.3	622.7
80	390	214.8	92.5	-163.4	285.7
81	206	414.2	60.1	-43.7	397.8
82	470	1,136.9	294.1	306.8	536.0
83	519	366.0	220.4	-63.0	208.6
84	443	508.6	222.6	157.5	443.5

[*] Data from A. Federico and F. Davis, South Florida Water Management District, personal communication 1986 and Federico *et al.*, 1981

[+] mean P content = mean concentration x lake volume

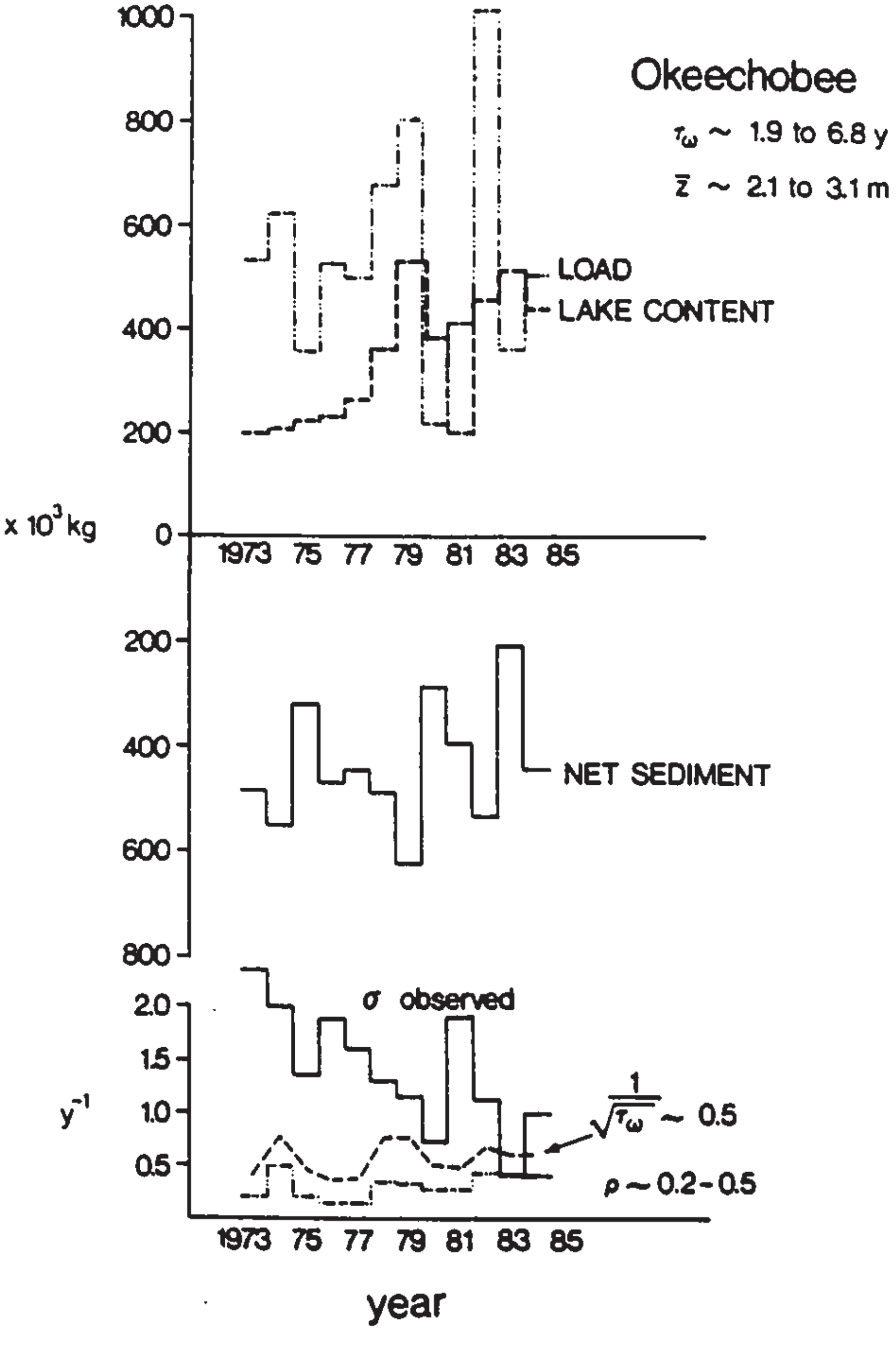


Figure 2.45 Lake Okeechobee phosphorus loading, lake content and sedimentation (1973 - 84).

Based on these fluxes, the net sediment was estimated to range from 209 tons (in 1983) to 623 tons (in 1979). The net flux of phosphorus was consistently toward the lake bottom. In addition, values were always of the order of several hundred tons and in general ran parallel to loading figures, but at a slightly lower level.

In terms of *concentrations*, the mean inflow value varied from a minimum of 134 $\mathrm{mg \cdot m^{-3}}$ in 1983 to a maximum of 332 in 1981 without any particular time trend. On the other hand, the lake concentrations showed a much more consistent pattern of increase. The 1984 value of 98 $\mathrm{mg \cdot m^{-3}}$ is approximately twice the 1973 value of 49 $\mathrm{mg \cdot m^{-3}}$.

The *relative residence times* of phosphorus as given by both the observed concentration ratios $(P\lambda/P_j)$ and corrected for changes in lake content (τ_p/τ_w) ranged from about 0.2 to 0.7 and both increased over the known 12-year period (cf. Table 2.28 and Figure 2.46). (The change in lake content per unit load also showed a general increase from about 0.01 to 0.31.) The minimum (τ_p/τ_w) values, which indicate most rapid flow rates, occurred in 1980 to 1981 during a drought period. The maximum value, indicating the slowest flow rate, occurred in 1982 when the lake received its maximum load and water levels were high. The greatest discrepancy in the two estimates of relative residence time occurred in a drought year (1980) when flows were probably substantially faster than indicated by the

Table 2.28 Lake Okeechobee phosphorus concentrations of the lake, theoretical inflow and their ratio.

Year	$[P_\lambda]$	$[P_j]$*	observed (P_λ/P_j)	$(\frac{\Delta \text{ lake}}{\text{load}})$	(τ_p/τ_w)
1973	49	186	.263	.006	.262
74	49	161	.304	.010	.308
75	58	149	.389	.018	.382
76	55	176	.313	.077	.338
77	63	226	.279	.064	.298
78	67	181	.370	.045	.388
79	97	224	.433	.028	.445
80	84	209	.402	.761	.228
81	70	332	.211	.106	.191
82	91	188	.484	.270	.663
83	93	134	.694	.172	.592
84	98	252	.389	.310	.563

*flow weighted mean inflow

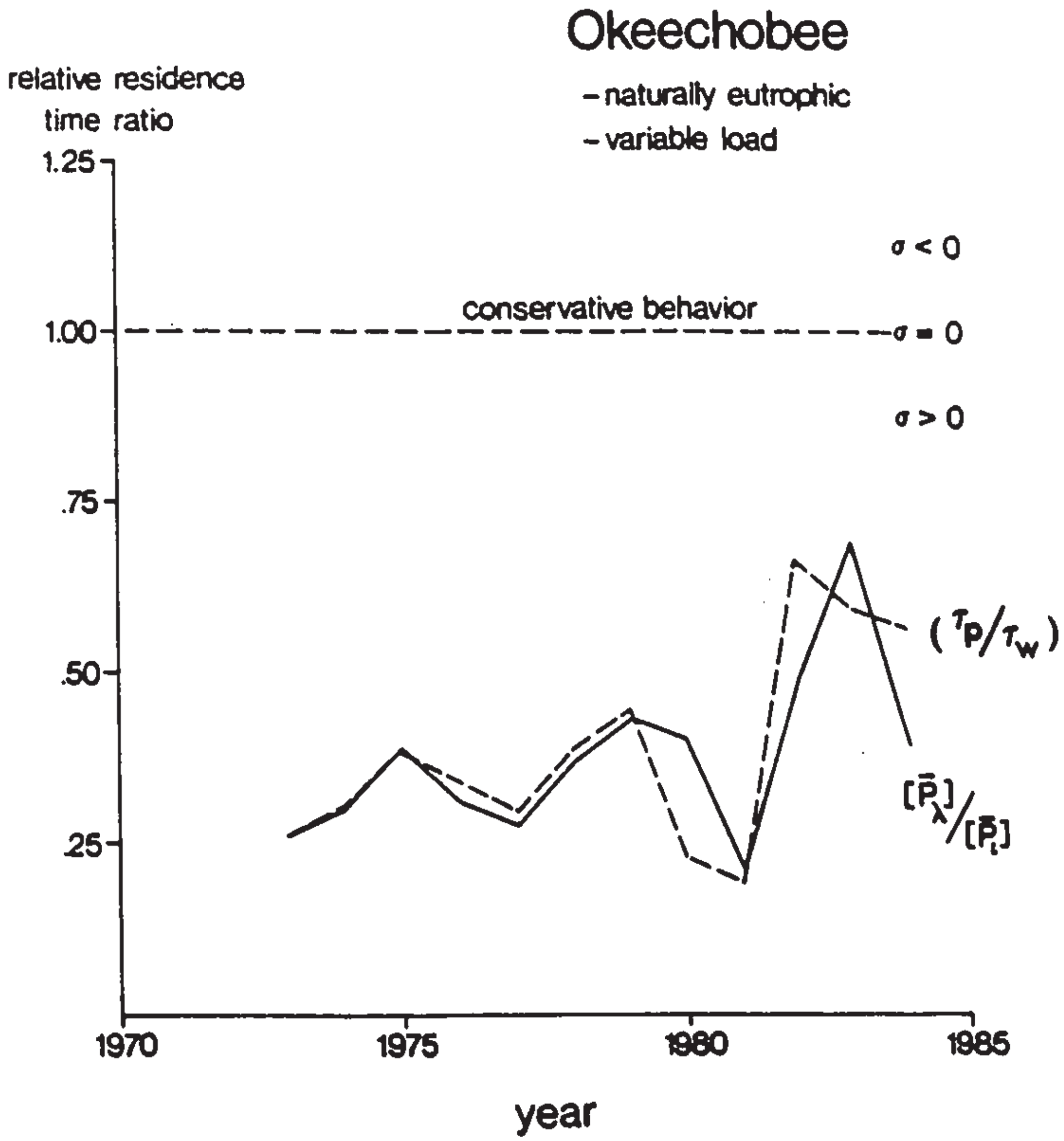


Figure 2.46 Lake Okeechobee (τp/τw) from 1973 to 1984.

concentration ratio: (P_λ/P_j) was 0.40 when (τ_p/τ_w) was 0.23.

A calculation of mass balance coefficients from the budget values is given in Table 2.29. The flushing rate ranges from 0.15 to 0.54 y^{-1} with the associated water residence times of 6.8 and 1.9 years, respectively. There is a tendency towards higher flushing rates at the end of the 12-year period with lowest values in the drought years 1975-76 and 1980-81. The sedimentation coefficient ranges from 0.4 (in 1983) to 2.4 (in 1973) and most frequently assumes values greater than 1; it was only in 1980 and 1983 that values less than 1 occurred. Recalculated as apparent sedimentation velocities, values ranged from a minimum of 1.2 $m \cdot y^{-1}$ (in 1983) to a maximum of 5.8 $m \cdot y^{-1}$ (in 1973). Together, these values give an estimate of absolute phosphorus residence times ranging from a minimum of 0.38 y (in 1974) to a maximum of 1.28 y (in 1983). This is substantially less than the water residence time as can be seen from the low relative residence times given previously.

The ratios of the coefficients (σ/ρ) are very high in the 1970s, with a maximum value of 12.7 in 1976, but these taper off in the 1980s to a minimum of 1.1 in 1983. Therefore the sedimentation processes within the lake appear to be losing prominence as a phosphorus elimination pathway.

The estimation of sedimentation rates from $(1/\sqrt{\tau_w})$ averages about 0.5 y^{-1} and is much lower than the observed rates

Table 2.29 Phosphorus elimination coefficients (sedimentation and flushing) and residence times in Lake Okeechobee.

year	σ y^{-1}	$\tau_s = (\frac{1}{\sigma})$ y	ρ y^{-1}	$\tau_w = (\frac{1}{\rho})$ y	$\tau_p = \frac{1}{(\sigma + \rho)}$ y	$(\tau_p/\tau_w) = \frac{\rho}{(\sigma + \rho)}$ -	$(\frac{\sigma}{\rho})$ -	$\bar{z}$ m	v_s $m \cdot y^{-1}$
1973	2.37	.42	.22	4.6	.39	.08	10.8	2.46	5.8
74	2.09	.48	.54	1.9	.38	.21	3.9	2.54	5.3
75	1.37	.73	.21	4.7	.63	.13	6.5	2.40	3.3
76	1.90	.53	.15	6.8	.49	.07	12.7	2.48	4.7
77	1.63	.61	.16	6.2	.56	.09	10.2	2.47	4.0
78	1.33	.75	.35	2.9	.60	.21	3.8	2.99	4.0
79	1.16	.86	.34	3.0	.67	.23	3.4	3.03	3.5
80	0.73	1.37	.26	3.8	1.01	.26	2.8	2.63	1.9
81	1.93	.52	.28	3.5	.45	.13	6.9	2.12	4.1
82	1.14	.88	.46	2.2	.63	.29	2.5	3.02	3.4
83	0.40	2.50	.38	2.6	1.28	.49	1.1	3.09	1.2
84	1.00*	1.00	.41	2.5	.71	.29	2.4	3.09	3.1

range:
1.2 to 5.8

*estimate

which are generally greater than 1. The exception to this was in 1983 when the observed rate fell to the minimum of 0.40 y^{-1}, a rate lower than $(1/\sqrt{\tau_w})$ which was equal to 0.62 y^{-1}. This resulted in an observed value that exceeded the predicted lake concentration (cf. Figure 2.47). At the other extreme, observed sedimentation rates were exceptionally high in 1973-74 and 1981, so observed values fell below predicted values.

With regard to the possible prediction of sedimentation from loading, the correlation coefficient r of their observed values is 0.78 ($n = 12$, $p = 0.003$) (cf. Figure 2.48). Notably, in years of high flushing such as 1982 and 1983, the total net sediment tends to be lower than in other years. Otherwise, there is a general positive correspondence between the total net sediment and loading.

Alternatively, the relationship of sediments to lake content is not significant if all years are taken together (cf. Figure 2.49). However, an inverse relationship shows up for the years 1975, 1980 and 1983 in contrast to all other years which indicate a positive correspondence (as in the case with loading). Therefore, there is a dichotomy in the relationship of sediment to lake content, and the inverse relationship is most likely related to the high water levels which distinguish the three deviating years.

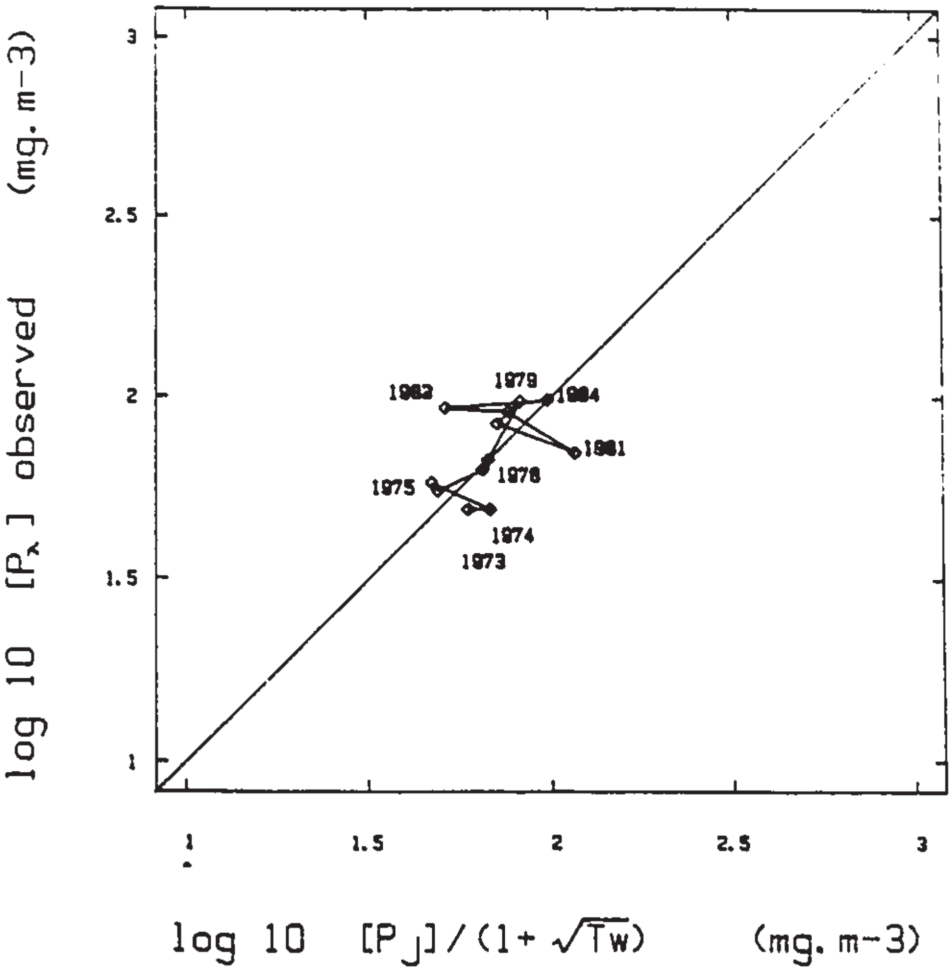
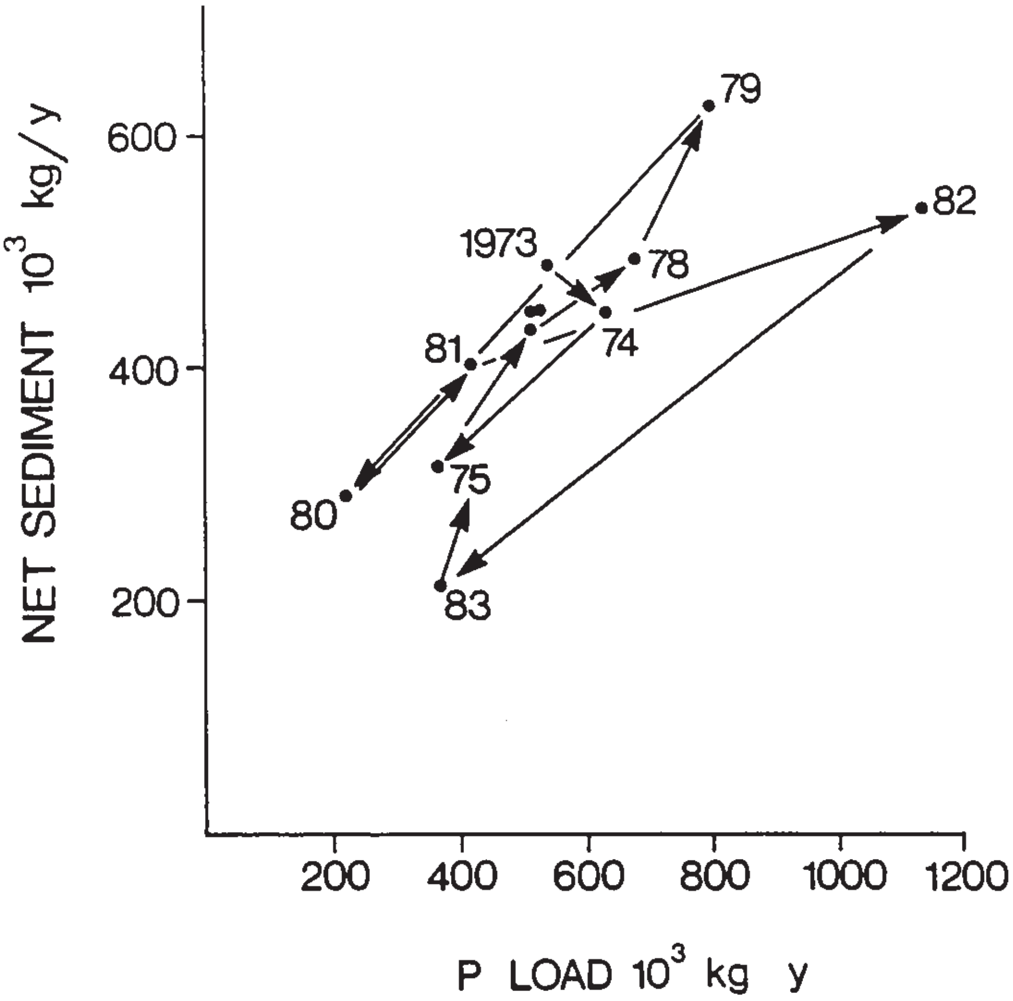


Figure 2.47 Lake Okeechobee observed vs predicted phosphorus concentrations.



OKEECHOBEE (1973-84)

Under variable load

Figure 2.48 Lake Okeechobee phosphorus net sediment vs load.

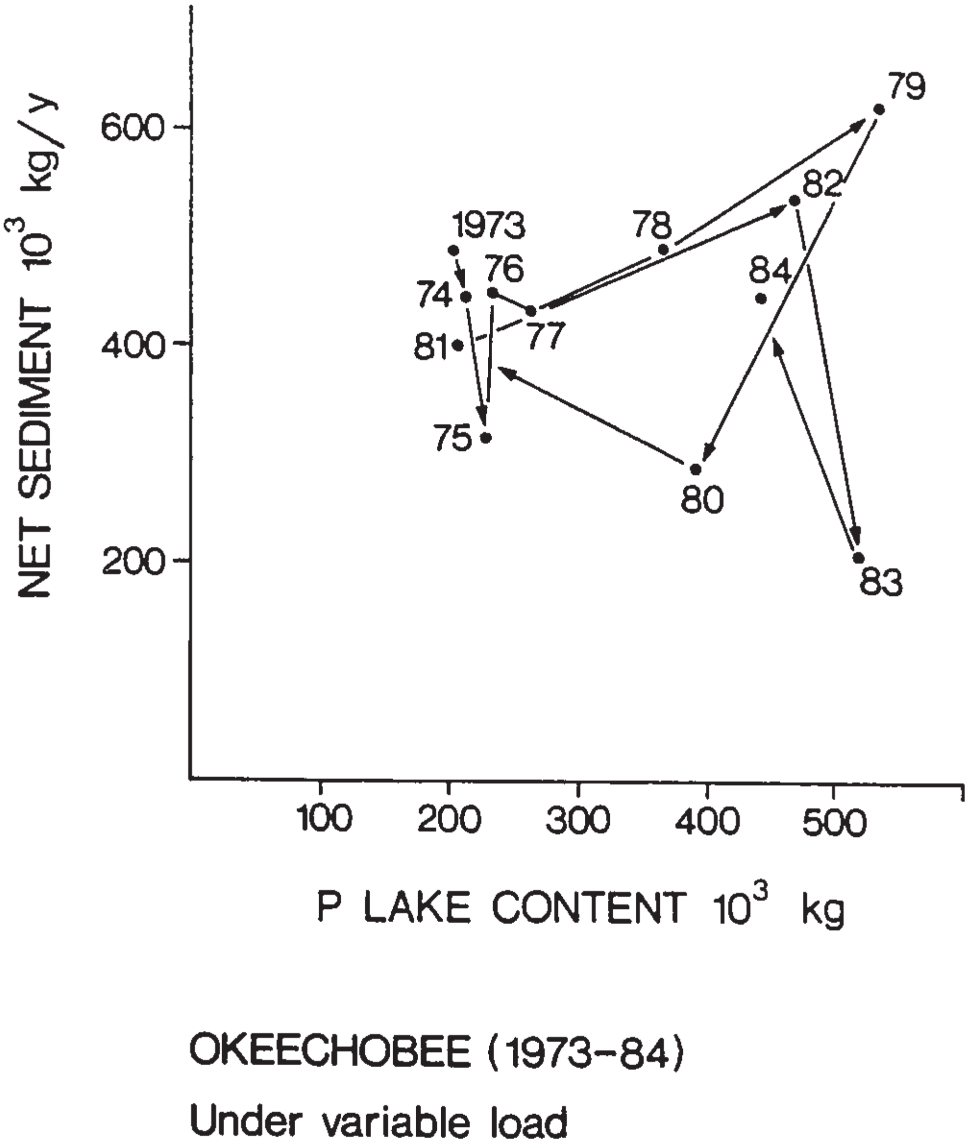


Figure 2.49 Lake Okeechobee phosphorus net sediment vs lake content.

2.10.3 Assessment for Lake Okeechobee

The assessment for Lake Okeechobee is organized with respect to a controversy that has developed in recent years regarding the trophic evolution of the lake and the efficacy of controlling external nutrient loads. On the one hand, Okeechobee is considered naturally eutrophic by virtue of the abundant macrophytes and fish, and has been so throughout its existence. This has been used as an arguemnt to dispel the idea that the lake is presently going through any trophic change. On the other hand, fishermen who have observed the lake daily have claimed that significant qualitative changes, particularly in periphyton growth, are a recent sign of deterioration. Furthermore, the appearance and increasing frequency of blue-green algal blooms (Anabaena) tend to support this view, that the lake is indeed changing in trophic character. Unfortunately, the establishment of real trends in trophic evolution are difficult due to high natural variability in the parameters used to measure trophic status and the anecdotal type of record of biological changes which exists.

To describe the problem further, the lack of correspondence between lake concentrations of phosphorus and loadings has shed some doubt that the former can be controlled through limitation of the latter. It appears that the phosphorus content of the lake is controlled more by the natural variation in water levels than loading and there is a limit to the practical control of either. Therefore, the costs of external nutrient load reduction need justification in terms of expected benefits.

In consideration of the data in terms of these problems, there are a number of important trends and relationships to be distinguished despite - or perhaps by virtue of - the heterogeneous (in the statistical sense) nature of the data. Although the phosphorus loading to the lake has fluctuated quite dramatically over the 12-year record, the lake concentration has shown a steady increase from about 50 $\text{mg} \cdot \text{m}^{-3}$ to nearly 100 $\text{mg} \cdot \text{m}^{-3}$. The qualitative changes which have run parallel to this are the massive growths of periphyton and appearance of algal blooms. Therefore it is logical to establish the period just prior to this as an upper limit for nutrient conentrations which are compatible with an acceptable water quality. This means that desirable lake concentrations are about 50 to 60 $\text{mg} \cdot \text{m}^{-3}$, as in the early 1970s when loading levels were about 500 $\text{t} \cdot \text{y}^{-1}$ and this could be used as a critical loading reference.

Presuming that the external load can be regulated to no more than 500 $\text{t} \cdot \text{y}^{-1}$, what are the prospects for the lake? This, of course, depends upon the sedimentation properties of the lake as a whole. As previously mentioned, the budget shows that Okeechobee has always been a net sink for phosphorus throughout the years for which data exists. However, the sedimentation coefficient shows a decreasing trend over the record with few exceptions. The consistency of this trend implies the possible alteration of the absorptive capacity of the sediments. Further to this, although an overall trend in (τ_p/τ_w) is not so evident, there is a progressive increase in the (τ_p/τ_w) maxima over time which reflects the trend of decreasing sedimentation rates. Therefore a process similar to that which has taken place in both the Bodensee and Sempachersee may be taking place in Okeechobee.

Parallel to this, it is also obvious that water levels play a determining role for the annual net sedimentation. Sedimentation is minimal when water levels are high and maximal when water levels are low. It has been estimated that the lake's surface area increased by 40% in 1973 when water levels were highest and the low net sedimentation appears to be related to the flooding of both lowlands around the perimeter of the lake and two islands which were formerly under cultivation. This is not unlike the "trophic upsurge" reported for newly flooded reservoirs. Alternatively, sedimentation is at a maximum in years of drought such as 1981; in that year the mean depth was only 2.2 m.

Since lake levels were increasing over the same period when sedimentation coefficients were decreasing, the sediment saturation hypothesis cannot be unequivocally demonstrated. The relative roles of 'saturation' versus 'water level' will only become apparent if lake levels are stabilized sometime in the future.

Despite the fact that the sedimentation rate in Okeechobee has decreased, it is still exceptionally high (at values near 1.0 y^{-1}) in contrast to what is usually observed in lakes considered to be eutrophic. The features of the lake which contribute to this are its shallow basin, turbulence and turbidity. These features allow consistent oxygenation of the lakewater and bottom sediments as well as resuspension of clay which may absorb and remove phosphorus from the water column. In addition, the turbidity most likely imposes light limitation on algal growth. Therefore, Lake Okeechobee seems to have an exceptional natural ability to minimize the biological cycling of the external phosphorus loading it receives. The previous suggestion that an upper loading limit for the lake be set at around 500 $t \cdot y^{-1}$ is, of course, conditional on the return and maintenance of a sedimentation rate closer to 2 than 1, as was the case in the early 1970s. Since the lake still showed this capability in 1981, it would most likely resume sedimentaton rates similar to those of the 1970s if the water level were stabilized at a lower mean stage level.

2.11 Summary for the Nine Case Histories

The nine case histories are summarized below in the context of answers to three main questions which originated with the surge of modelling efforts in the 1960s to combat eutrophication. These modelling efforts were, more specifically, attempts to predict average phosphorus concentrations, and ultimately trophic conditions, from a knowledge of external phosphorus loading to the lakes. Sedimentation rates and their variability have been the least understood aspect of lake behaviour and therefore the weak link in such prediction models. The preceding budget analyses are important because they give an unprecedented view of measured net sedimentation, free of any hypotheses. Thus sedimentation can now be more accurately characterized, in terms of its variability and patterns of change related to trophic evolution, than was previously possible. Furthermore, the analyses also indicate which generalizations may be useful for prediction and which are not. The questions and their answers presented below give perspective to some previous hypotheses to explain sedimentation and indicate some directions for future research.

2.11.1 How Variable is Sedimentation in Individual Lakes?

Since the mid-1960s, several hypotheses to explain the general pattern of sedimentation in cross-sectional data have been proposed. These hypotheses included those of (i) Piontelli and Tonolli (1964) who suggested that sedimentation was a fixed proportion of the input mass, (ii) Vollenweider (1969) who proposed that sedimentation was a function of the lake content, and (iii) Chapra (1975) who proposed that sedimentation was a function of the bottom surface area. The time series data can be used to either reject or verify the functional content of these ideas.

In consideration of the first two hypotheses above (i.e., i and ii), the plots in the nine preceding sections on individual lakes illustrate the relationships of total net sediment of phosphorus with both load and lake content. The correlation coefficients (r) for these relationships are compared in Table 2.30. The results show that correlation coefficients for the two hypotheses are strikingly comparable and neither load nor lake content seems to out-perform the other as a predictor of total net sediment.

The second and third hypotheses (i.e., ii and iii above) imply constant apparent settling velocities (v_s) (Chapra and Reckhow, 1983). However, Table 2.31 of the following section shows that v_s may be highly variable in a given lake. Values range from -161 $m \cdot y^{-1}$ (the negative sign indicates internal loading) to 69 $m \cdot y^{-1}$ and both of these extremes occur in a single lake, Lac Léman. Therefore, the hypothesis of a constant v_s for lakes should be discarded.

In conclusion, simple hypotheses to describe the annual variability of sedimentation in single lakes may be adequate for some lakes which are controlled by a single dominant factor, such as seems to be the case for the Bodensee, but in the majority of cases more complex models are necessary. Nearly all the case studies examined showed high variability in sedimentation and do

TABLE 2.30. CORRELATION COEFFICIENTS (r) FOR PHOSPHORUS NET SEDIMENT WITH ANNUAL LOADS AND MEAN LAKE CONTENT IN FIVE INDIVIDUAL LAKES

Lake	Correlation coefficient (r) for net sediment and:		Number of Years
	Lake content	Load	
Bodensee-Obersee	0.99	0.98	45
Sempachersee	0.38	0.44	25
Washington	0.72 (0.96)*	0.95	16
Léman	0.53	0.55	18
Okeechobee	NS (0.73)**	0.78	12

* r if heavy silt years and non-equilibrium year due to diversion excluded.

** r if two years (1980 and 1983) of low water load excluded.

not appear to be dependent on a single controlling factor. Therefore, accurate description of a lake's response by a simple model seems to be more the exception than the rule. The ultimate refinement of predictions of temporal changes in a given case can only be achieved through a thorough budget analysis to identify the most important controlling factors coupled with development of a model of adequate complexity to reflect the action of the predominant factors.

2.11.2 Are There General Patterns of Relative Residence Times and Sedimentation Rates Under Changing Trophic Conditions?

Over the course of eutrophication in single lakes, this research shows that there are systematic changes in sedimentation and relative residence times of phosphorus. Values typical of the pre-enrichment (natural) and post enrichment situations are listed in Table 2.31. These values are the means of subjectively chosen years thought to be representative of contrasting phases of the lakes as described by the original researchers. The table represents different degrees of trophic evolution and should therefore be interpreted more as a qualitative indication of tendencies, rather than an absolute representation of the full spectrum of values possible for each lake.

In comparison of the post-enrichment values of phosphorus relative residence times with pre-enrichment values, it can be seen that there is a consistent tendency of (τ_p/τ_w) to rise

TABLE 2.31. THE EFFECTS OF ENRICHMENT ON PARAMETERS RELATED TO RELATIVE RESIDENCE TIMES OF PHOSPHORUS IN NINE LAKES. (Values have been chosen to represent low(L) and high(H) loading periods.

Parameter:	(τ_p/τ_w)		τ_p (y)		τ_w (y)	σ (y^{-1})		v_s ($m \cdot y^{-1}$)		(σ/ρ)	
Loading phase:	L	H	L	H	(Mean)	L	H	L	H	L	H
Bodensee-Obsersee	0.32	0.56	1.3	2.1	4.4	0.55	0.28	55	28	2.5	1.5
Sempachersee	0.16	0.40	2.7	7.0	17.5	0.34	0.14	15	6	8.0	3.0
Washington	0.35	0.44	0.9	1.3	2.5	0.75	0.50	25	16	1.5	1.2
Léman*+	-	(4)	-	(21)	11.9	-	(0.10)	(-161 to 69)		-	(5)
Mjøsa++	-	0.27	-	1.8	6.0	-	0.41	-	63	-	2.7
Baldeggersee+	0.58	0.84	2.6	6.7	5.8	0.24	0.06	8	2	1.7	0.7
Shagawa*+	(1.6)	0.70	(1.4)	0.4	0.8	(-0.10)	0.75	(0.60)	4	(-0.1)	0.6
Norrviken*+	-	(3)	-	(2)	1.3	-	(0.7)	-	(4)	-	(0.8)
Okeechobee	0.28	0.58	0.4	0.7	4.4	2.4	1.2	6	3	10.0	2.0

Note: "low" loading phase is eutrophic for Shagawa, Norrviken and Okeechobee.

* Highly variable values in Léman and Norrviken; parentheses indicate phase of non-equilibrium in Shagawa.

\+ Pre-enrichment conditions unknown quantitatively.

++ Transition state from higher to lower loading; temporal trends incomplete therefore greater differences are expected in the future.

with increasing eutrophication. The absolute residence times of phosphorus show the same tendency and this general decrease in the flow rates of phosphorus is reflected as decreases in both net sedimentation rates (σ) and apparent sedimentation velocities (v_s). The only apparent exception to this is the case of Shagawa Lake where the relative residence time has increased with loading reduction. However, this is most likely a temporary phase caused by the extremely sharp reduction in loading such that the record represents a period of disequilibrium between lake content and loading. Under such conditions the lake is in a phase of washout and lake concentrations are artificially high relative to loadings; this creates a temporarily high (P_λ/P_j) ratio.

In addition to the slower net flow rates of phosphorus through systems undergoing eutrophication, there is also a general decline in the importance of sedimentation as an elimination mechanism relative to flushing. This is apparent in the general decline of the ratio (σ/ρ) as lakes go from lower to higher enrichment conditions. Lake internal mechanisms of elimination (i.e., σ) dominate during the more oligotrophic phases. However, flushing (ρ) becomes progressively more important as an elimination pathway in eutrophic phases concurrent with the apparently more conservative behaviour of phosphorus (i.e., as (τ_p/τ_w) approaches 1).

In summary, the eutrophication of lakes is reflected by a progressive decline in the net flow of phosphorus to sediments. This can be documented quantitatively as an increase in the phosphorus relative residence time, as well as decreases in sedimentation rates and apparent sedimentation velocities. In addition, the decline in the ratio (σ/ρ) indicates that over the course of eutrophication, the loss of net sedimentation capacity results in a shift from deposition to flushing as the predominant pathway of elimination.

2.11.3 Can the Concentration Ratio (P_λ/P_j) be used as a Representation of Relative Residence Time (τ_p/τ_w) Dynamics?

As previously discussed, Vollenweider (1976) used the relative residence time in 21 lakes to estimate sedimentation coefficients when the budgeting data on sedimentaiton was almost non-existent. However, with the compilation of information in this chapter it is now possible to evaluate to some degree how well the concentration ratio portrays the real nutrient dynamics of phosphorus as estimated by the budgets.

Differences in the two estimates result from the variability of the factor "Change in lake content per unit load" (cf. equation 2.5), which may vary due to either changes in sedimentation rates, flushing efficiencies and/or loading variations. Therefore, the concentration ratio has the capacity to either over or underestimate the dynamics of interest. A list of the physical circumstances which cause over and underestimates of (τ_p/τ_w) by a straightforward use of the concentration ratio is given in Table 2.32.

In summary, (P_λ/P_j) is a good approximation of (τ_p/τ_w) if a waterbody is close to equilibrium (i.e., the change in lake content per unit load is zero). This ratio is suitable as a comparative measure in more broadly based cross-sectional data, but may not reflect the dynamics of an individual year in a given lake. The interpretation of (P_λ/P_j) variation is best done in the context of budget information.

TABLE 2.32. A LIST OF CONDITIONS WHICH CAUSE (P_λ/P_j) TO MISREPRESENT (τ_p/τ_w).

I. Underestimation of (τ_p/τ_w) by $(P_\lambda//P_j)$ (i.e., net flow rates of materials are slower than expected from the concentration ratio):

Case:	Condition:
a) Bodensee	- decline in sedimentation rate due to saturation; P_λ increases disproportionately to P_j
b) Sempachersee	- same as above; (P_λ/P_j) also misleading due to disparity of volumes represented by P_j (small volume, large concentration changes) and P_λ (Large volume, small concentration changes)
c) Léman	- oxygen depletion causing internal loading
d) Okeechobee	- perimeter of lake flooded leading to trophic upsurge and essential underestimate of load

II Overestimation of (τ_p/τ_w) by $(P_\lambda//P_j)$ (i.e., net flow rates of materials are faster than expected from the concentration ratio):

Case:	Condition:
a) Washington	- sharp loading reduction causing lake concentration unequilibrated to new load; (short-lived effect)
b) Léman	- deep mixing and oxygenation of the hypolimnion; high sedimentation rate
c) Mjøsa	- same as Washington above; (short-lived effect)
d) Baldeggersee	- same as Washington above; also hypolimnetic aeration creating increase in sedimentation rate
e) Shagawa	- same as Washington above
f) Norrviken	- same as Washington above
g) Okeechobee	- drought leading to low loading, low water levels and high sedimentation rates

Note: The "Change in lake content per unit of load" exceeded the value of 1 in Lac Léman due to extremely high internal loading. In such a case (τ_p/τ_w) is calculated to be a negative and the model is undefined.

3. THE CROSS-SECTIONAL ANALYSIS (220 LAKES)

3.1 Introduction to the Cross-Sectional Analysis

This section is devoted to a statistical analysis of phosphorus and nitrogen relative residence times of 220 northern temperate lakes and reservoirs. It is primarily a search for the best multivariate expression for nutrient residence times and an understanding of what controls them. Correct anticipation of a waterbody's nutrient residence time or equivalently its net sedimentation rate, will allow better prediction of nutrient concentrations from loadings. Nutrient concentration predictions from loadings are at the heart of present-day management methods for setting maximum allowable loads to prevent eutrophication.

A major difference between this section and that which analyses the reactions of single lakes is that the observed variations of data on many different lakes reflect intra-basin differences in morphometry, hydrology and geochemistry in addition to differences of temporal biological and chemical change. The morphometry, hydrology and geochemistry of a single lake are relatively constant features of a given lake or an annual scale. Therefore the cross-sectional relationships reflect geographically related differences of lakes, but cannot be expected to track the temporal changes within a given lake over short (<1 year) time scales.

In the original development of Vollenweider's mass balance model (cf. Vollenweider, 1968, 1975 and 1976) it was assumed as a working hypothesis that each lake could be characterized by its own unique, but constant sedimentation coefficient (σ). Chapter 2 of this thesis shows that there is marked year to year variability of σ in the nine individual case studies. This voids the ability of a general equation with a constant sedimentation rate to predict year to year changes in lake concentrations, given loadings. However, the cross-sectional models are still of unique importance despite this limitation.

First, they are important as diagnostic standards which can be used as a rapid means of testing the validity and consistency of data for a lake. Second, such equations are important as predictive tools for lakes were no information on their nutrient budgets or dynamics exists. Third, these relationships can provide insight into the effects of morphometric, hydrologic and geologic variations on nutrient processing, which cannot be derived from single lake studies. It is conceivable that these factors should be considered in the design criteria of, for example, creation of a new reservoir to the extent that the depth, water flow rates and location can be chosen prior to construction. Furthermore, such relationships may suggest alterations to improve water quality of existing lakes or reservoirs. They may also contribute to funcional understanding via analysis of the residuals as pursued in the Canadian test case of the OECD "Standard Regressions" (cf. Janus and Vollenweider, 1981).

A previous publication by Janus and Vollenweider (1984) showed that different trophic categories maintained characteristically different phosphorus relative residence times for a given phosphorus load. The analysis here specifically examines for differences due to both trophic groups and classification as a shallow lake or reservoir (SLR) versus natural lakes. This will determine what lake groupings require their own unique predictive equations. Furthermore, the data will be examind to see if different lake groups also require different explanatory variables.

In summary, the cross-sectional models provide additional important information which the study of single lakes cannot provide.

The most important restriction of what follows is that most of the lakes in the data base are dimictic northern temperate lakes which have an ice-cover in winter and stratify into an epilimnion/hypolimnion system during the summer. Therefore, the derived equations may not describe lakes which are shallow, tropical, turbid or meromictic (etc.).

3.2 Data Description and Methodology

3.2.1 Origin of the Data

The cross-sectional information is derived directly from the four regional OECD projects in combination with the data from the Canadian Contribution. These waterbodies are listed in Appendix 2. In total, 48 variables measured in 275 waterbodies (i.e., approximately 13,000 data entries) were selected for analysis. A magnetic tape containing the data from the four initial OECD projects had been prepared for the calculations contained in the Synthesis Report and a copy of this tape was obtained from its authors (cf. Vollenweider and Kerekes, 1980). This data was then transferred and stored as SPSS systems files on disc in the Cyber 171 computing unit at CCIW, Burlington for further caculations. The Canadian data (for 146 waterbodies) was derived from the OECD Canadian Contribution data supplement (Janus and Vollenweider, 1981) and was added to the Synthesis Report data in the same format.

The total data set was also entered onto magnetic cassette tapes for calculations and plots done with an Hewlett-Packard (HP) 9825B desktop computer and (HP) 9862A calculator plotter located at CCIW. The statistical packages used with the data in these two forms were SPSS Version 9 and the Hewlett-Packard Statistical Library, respectively. The documentation for this software is readily available as standard manuals (Nie *et al.*, 1975 and HP Part No. 09825-15001) and will not be repeated here. Some of the final plots were done using an IBM AT, Hewlett-Packard plotter and "Statgraphics" software located at the South Florida Water Management District.

3.2.2 Geographic Representation

The grouping of lakes by geographic region was suggested from the outset of the OECD Programme on Eutrophication by the Planning Group of the Water Management Sector. This approach was taken because of the importance geographic, ecological, and morphometric features might have in the development of eutrophication, yet the impossibliity of quantifying all possible sources of variation. The original regional grouping was retained here (cf. Figure 3.1) both as an aid to data organization and a means of remaining sensitive to the geographic context of individual lakes.

The most general statement which may be made about the lakes considered here is that they are nearly all within the northern temperate zone (i.e., 22°30' to 66°30' north latitude). Only two Australian reservoirs (Mount Bold and Prospect) lie south of this belt, however, their latitude of approximately 35° south places them symetrically from the equator and thus in the southern temperate zone. The majority of lakes in fact lies in a more restricted belt between approximately 45° and 60° north latitude, which means that most stratify, have a winter ice-cover for about five months and undergo rapid flushing during the

File Name (Abbreviation)	n of waterbodies*
THE FOUR ORIGINAL OECD PROJECTS:	
Nordic	15
Alpine	38
USA	27
Shallow Lakes and Reservoirs (SLR)	36
European and Japanese (EURO)+	8
THE CANADIAN TEST CASE:	
Atlantic	18
Quebec	17
Ontario Shield	40
Laurentian Great Lakes	7
Experimental Lakes Area (ELA)	7
Prairie	3
British Columbia Interior	4
Unusual Canadian Circumstances (UCC)+	51
Total	271

* The term waterbody usually refers to an entire lake, but may also represent distinct basins, bays or a different year of data.

\+ These subdivisions were formed to distinguish water-bodies which could not be considered homogeneous with those of the parent file.

Figure 3.1 The regional organization of the cross-sectional data files.

spring snow melt. In this sense, the Florida lake Weir at about 28°N differs most from the majority of lakes since it never freezes or stratifies for long periods and may be considered subtropical.

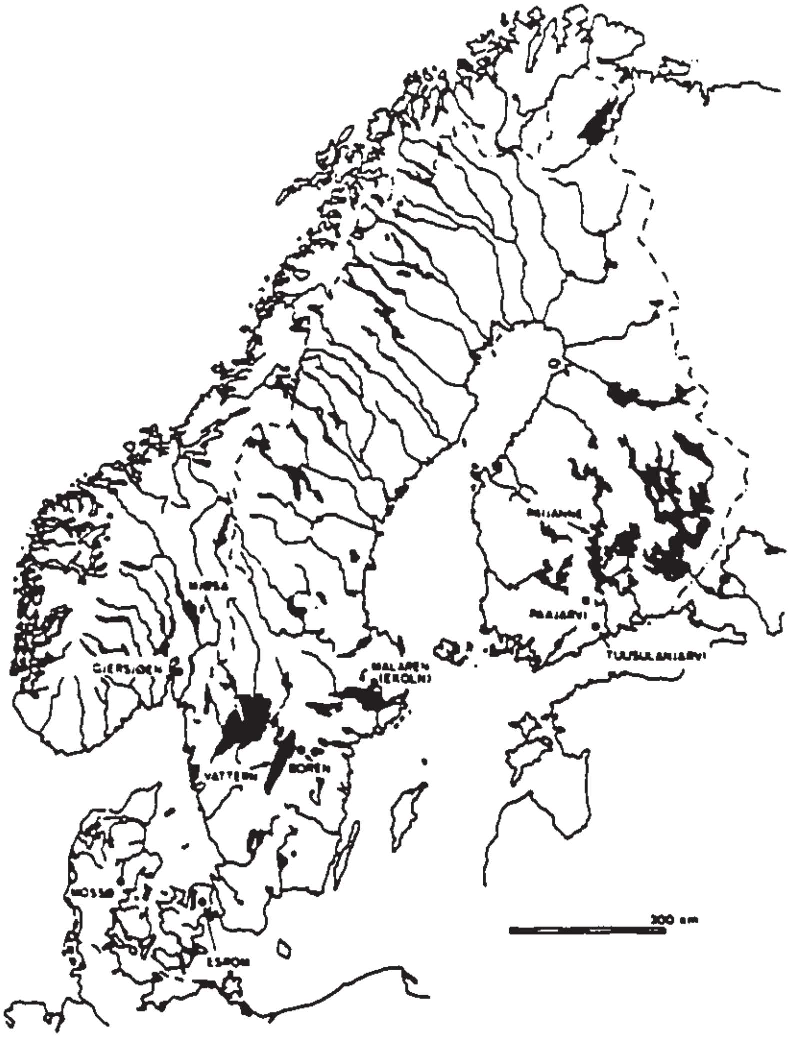
A second general feature of the majority of lakes is their glacial origin and formation at the end of the last ice age. Exceptions to this are a few small lakes in France which occupy the craters of inactive volcanoes, the deep graben basin of Lake Tahoe in California and the artificial basins of the Shallow Lakes and Reservoirs project.

Beyond this, it is difficult to generalize about the array of lakes and their settings, so a brief description of each region and its most distinctive features follows.

3.2.2.1 Description of the OECD Regions

The Nordic Lakes:

The 15 lakes of the Nordic Project (cf. Figure 3.2) lie between 56° and 60° north latitude and do not exceed an altitude of 125 m above sea level. The basins are typically composed of granite, gneiss, and/or clay and sand of glacial moraines and the shorelines are exceptionally complex and dendritic. They each have a large number of major inflows (4 to 13) distributed around the lake and may have more than one outflow such that drainage patterns are all but a simple inflow located opposite a single outflow. Ice cover lasts about 150 days on the smaller lakes but



LAKES OF THE NORDIC PROJECT:

DENMARK
Esrom
Mossø

FINLAND
Pääjärvi
Päijänne
Tuusulanjärvi

NORWAY
Gjersjøen
Mjøsa

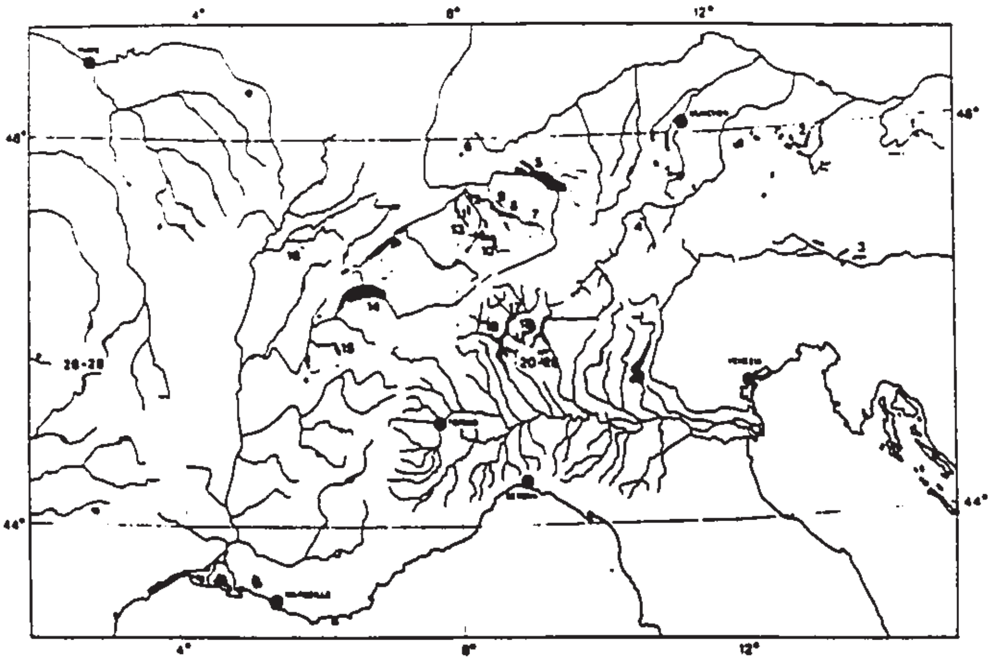
SWEDEN
Ekoln
Vättern
Boren

Figure 3.2 The Nordic Project of the OECD Programme on Eutrophication, from Ryding et al. (1980).

only about 60 days on the larger lakes (i.e., with volumes more than 50 km^3; as for Mjøsa and Vättern). The surrounding forest is a Boreal type with peat bogs, which contribute a high humic load, to Päijänne and Pääjärvi in particular, resulting in low transparency (2 to 4 m). The transparency of Tuusulanjarvi is low for a different reason; with a mean depth of only about 3 m the clay of the bottom is frequently resuspended. Eight of the fifteen lakes (50%) are considered eutrophic which is largely due to the municipal sewage and agricultural wastes released to them. Pulp and paper mill effluents are also discharged in Mosso, Päijänne, Mjøsa and Vättern.

The Alpine Lakes:

The Alpine lakes lie between 45° and 47° north latitude in central Europe, with a maximum altitude of approximately 1200 m above sea level for Lac Pavin, France (cf. Figure 3.3). This group contains both the large, deep lakes which lie in the crystalline rock valleys to the north and south (Insurbrian lakes) of the Alps, as well as the smaller lakes which occupy a limestone region in Italy (The Brianza lakes) and the craters of extinct volcanoes in France. The great depths (i.e., maxima of more than 200 m as in the Vierwaldstattersee, Bodensee-Obersee, Lugano, Léman and Maggiore) and shelter of the mountainous terrain results in complex stratification patterns which attest to the incomplete mixing not infrequently observed in these lakes.



LAKES OF THE ALPINE PROJECT:

AUSTRIA
1 Lunzer Untersee
2 Attersee
3 Ossiacher See
4 Piburger See

GERMANY
5 Bodensee Obersee = Lake of Constance
6 Feldsee

SWITZERLAND
7 Walensee
8 Zürichsee = Lake of Zurich
    Obersee
    Untersee
9 Greifensee
10 Vierwaldstättersee = Lake of Lucerne
    Urnersee
    Gersauersee
    Kreuztrichter
11 Baldeggersee
12 Hallwilersee
13 Sempachersee

FRANCE
14 Lac Léman = Lake of Geneva
15 Lac d'Annecy
16 Lac de Nantua
26 Lac de Tazenat
27 Lac de Pavin
28 Lad d'Aydat

ITALY
17 Lago Maggiore = Lago Verbano
18 Lago Ceresio = Lake of Lugano
    Bay of: Ponte Tresa
        Capolago
        Melide
        Gandria
        Lugano
        Agno
        Morcote
        Figino
19 Lago de Mergozzo
Laghi di Brianza:
20 Lago di Oggiono
21 Lago di Pusiano
22 Lago di Montorfano
23 Lago di Annone
24 Lago del Segrino
25 Lago d'Alserio

Figure 3.3 The Alpine Project of the OECD Programme on Eutrophication, from Fricker (1980).

Ice cover for these lakes ranges from a maximum of approximately 100 days for the smaller lakes in the mountains, to seldom for the large lakes. Precipitation averages 1100 mm annually for the region as a whole, but the higher average rainfall (1800 mm) in the region of Lago Maggiore may arrive as torrential rains which substantially alter lake levels and account for the relatively high flushing rates of some lakes despite their large volumes. Although the Mediterranean influence produces a particular oasis of vegetation (including palms) around the Insurbrian lakes, the remainder of the 'Alpine' region is mostly mixed deciduous forest and meadows.

The lakes of this region are affected to a greater extent than any of the others by maximum population densities and all the attendant municipal, agricultural and industrial loading pressures. A sign of this infuence is that even the atmospheric portion of nutrient loads is significant. Indeed, 21 of the 39 waterbodies (i.e., 54%) are considered eutrophic. The economic and aesthetic importance of the Alpine Region lakes and their deterioration through eutrophication has been the prime impetus for the establishment of the OECD Programme on Eutrophication.

The U.S.A. Lakes:

Most of the lakes in the U.S.A. project lie within the belt of northern states which form the boundary with Canada i.e., at about 46° to 48° north latitude (cf. Figure 3.4). The

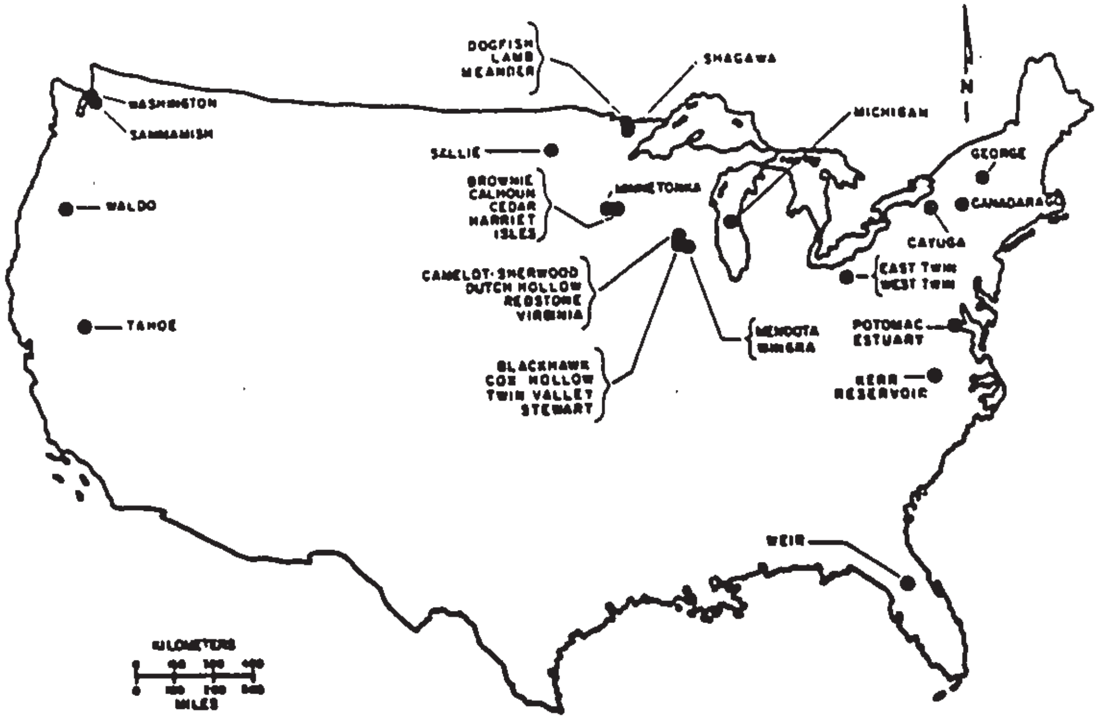


Figure 3.4 The USA Project of the OECD Programme on Eutrophication, from Rast and Lee (1978).

southernmost exception to this is Weir Lake in Florida (29°N) and the Potomac Estuary at the Virginia-Maryland border (38°N). Lake Tahoe located in the Sierra Nevada Mountains of California has the maximum elevation of 1900 m above sea level, while the Minnesota lakes lie at about 400 m and the southern, coastal waterbodies lie close to sea level. Although most of the lakes are of glacial origin, and these range in size from small kettle lakes in Minnesota to the inland 'sea' of Lake Michigan (the largest lake within the U.S.), other types of basins are also included. Lake Tahoe is of tectonic origin and lies in a graben fault, the reaches of the Potomac are enlarged sections of a large slow flowing river that forms an estuary of the Atlantic, and Weir Lake in Florida is a seepage depression in sand with no surface inflow or outflow. In general, the lakes of this project have shallow basins and more than 50% have mean depths of less than 10 m. The most notable exceptions to this are Lake Tahoe with a mean depth of 313 m and Michigan with a mean depth of 84 m.

Due to the varied geology, the lakes vary widely in hardness with soft water lakes in sandy or crystalline granitic basins and hardwater lakes in the limestone areas of Minnesota. The conductivity of lakes in this project is relatively high (most exceed 200 μmhos$\cdot$cm^{-1}) and those in Minnesota are commonly 400 μmhos$\cdot$cm^{-1}. Ice cover ranges from 180 days in the small northern lakes to no freeze-up (or predictable stratification) for Weir which is considered semi-tropical. Precipitation averages 1000 $mm \cdot y^{-1}$ in the north and 1300 $mm \cdot y^{-1}$ in Florida, however evaporation is only about 60% of this in the north while it is of the same order of magnitude as the precipitation in the south. The forest type surrounding most lakes, where it exists, is mixed deciduous-coniferous. Transparency is generally low and all have Secchi depths of less than 4 m with three exceptions. The most transparent waterbody is Tahoe with an average Secchi depth of 28 m and the least transparent is the Potomac with an average of 0.6 m. The U.S.A. project contains a comparison of phosphorus loadings (a) estimated by individual investigators, and (b) estimated from standard export coefficients. Five of the twenty comparisons had export estimated loads more than twice that reported by their principal investigators. The figures given by the individual researchers familiar with the situation were chosen for use here. Eighteen of the twenty-nine waterbodies (62%) are considered eutrophic.

Most of the data reported in the U.S.A. project was derived from previously completed individual investigations which was then organized for a composite analysis in the respective OECD regional report. Therefore, the sampling programmes and methodologies are more variable than those of the Nordic and Alpine projects.

The Shallow Lakes and Reservoirs:

The 34 waterbodies of this group have no regional connection. They are located in seven countries ranging from the German reservoirs at 56°N to the Australian reservoirs at 35°S, but most are located in the Federal Republic of Germany, the Netherlands and the U.S.A.

The basins of this group can be divided into three categories: natural, semi-artificial and completely artificial. The natural basins that were chosen for this project are either shallow (i.e., do not stratify) or have unusual hydrology (i.e., either extremely rapid flushing or no inflows or outflows). The semi-artificial reservoirs are those which have been created by impoundment of natural river valleys with the distinguishing features that they are elongate, the deepest point is located at the outlet, and the ouflow water may be regulated in quantity and location such that hypolimnetic rather than surface water is released. The completely artificial basins consist of small, geometrically simple enclosures formed by the walls of dykes raised above the natural ground level. No inflow or outflow exists, water must be pumped in and they are circulated artificially. Four of these waterbodies in the Netherlands (i.e., Petrusplat, Honderd en Dertig, Braakman II and Braakman III) are lined to 7 m, or completely as in Braakman II and III, by an asphalt bituminous pavement. Since the reservoirs are subject to maximum use during dry periods, they have greater fluctuations in water level than natural lakes (and for this reason some are devoid of macrophytes). The change of water level makes it difficult to define such entities as volume, mean depth and water residence time. None of these lakes or impoundments forms a winter ice cover for more than a month.

The main function of most of these impoundments is for drinking water storage, but many are also used for boating and fishing. The exceptions to this are the so called "real estate lakes" in Minnesota; small, highly flushed lakes created to enhance property value through improved aesthetics and recreational facilities. Of the 34 waterbodies included in this project, 25 are considered eutrophic (i.e., 74%). Some of the data was already present at the start of the Shallow Lakes and Reservoirs Project and where incomplete, data was collected to fill the gaps and may therefore refer to different years. In addition, sampling frequency and methods varied within the project (cf. Clasen, 1980).

European and Japanese Waterbodies (EURO):

This file of nine waterbodies was formed as an organizational convenience. It includes lakes which were originally treated in the SLR project, yet were considered to fall within the realm of natural conditions here, hence their reclassification. Although Loch Leven, the southern basin of Biwa and both basins of Kasumigaura tend to be shallow (all with mean depths of approximately 4 m), the sediments are not artificial as in some cases of the SLR project, and the inflows and outflows are surface feature as in most natural lakes.

3.2.2.2 Canadian Regions

The number of cases (96) in the Canadian project is nearly equivalent to that of all the OECD regional projects combined. These waterbodies span the entire North American continent and lie in all of the different major geographic regions including the eastern maritimes, Precambrian Shield, prairies and interior valleys of the western mountains. The data has been grouped into seven regions according to this geographic variation (cf. Figure 3.5). The data for the Canadian lakes file (CANADA) was drawn directly from the OECD Canadian Contribution (Janus and Vollenweider, 1981) and its origin was both published data (from journal articles and reports) and personal communication with individual investigators. No standard methods for data collection or calculation were followed and at times, mean values refer only to a limited seasonal period (summer) rather than the entire annual cycle. A detailed description of all seven regions and the data for each lake is published in the OECD Canadian Contribution (Janus and Vollenweider, 1981; NWRI Scientific Series Report 131 and Data Supplement 131-S). Only a brief description of each region is given below.

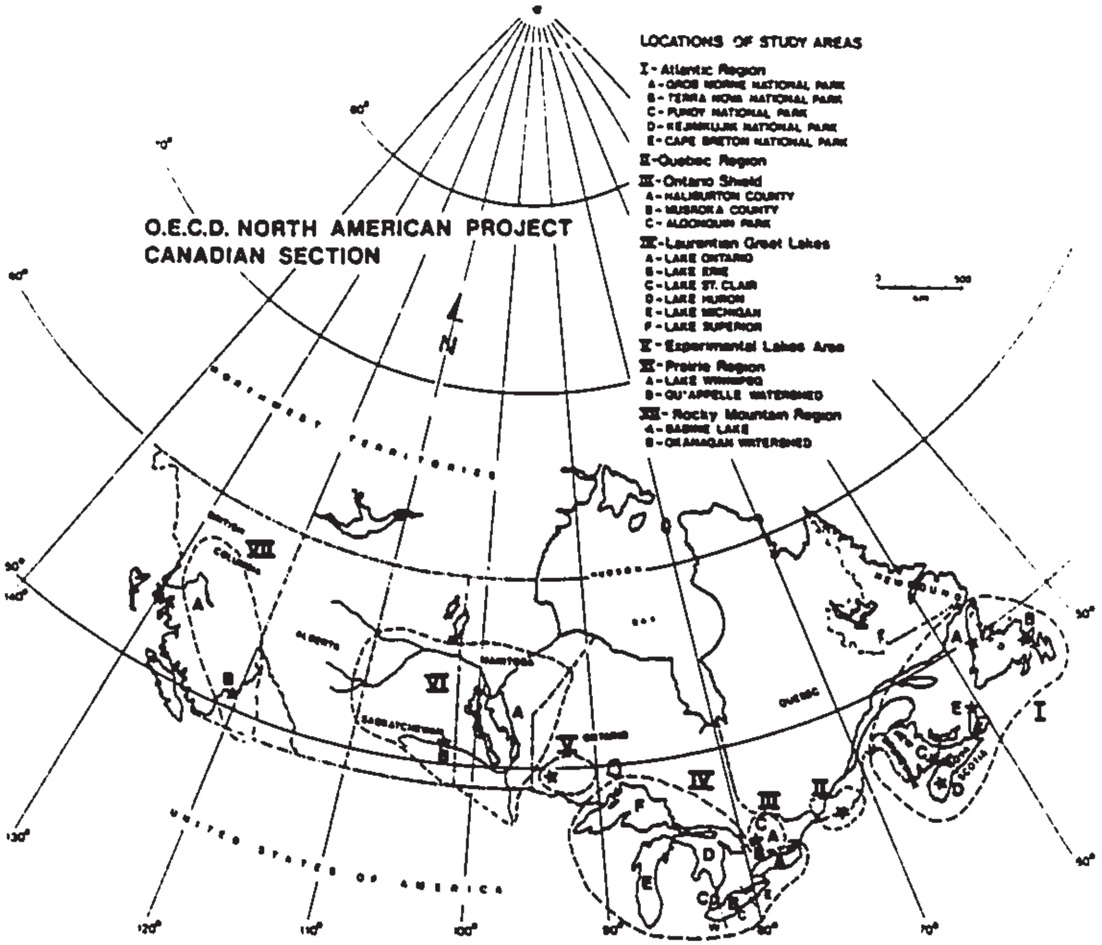


Figure 3.5 The Canadian Project of the OECD Programme on Eutrophication, from Janus and Vollenweider (1981).

The Atlantic Region:

The lakes of this eastern-most North American region centre around 46°N and are located in five national parks. The data is drawn from the ongoing studies of J. Kerekes (Canadian Wildlife Service) and a substantial collection of background reports and related publications. The maritime climate is rainy and overcast, with little sunshine; annual mean precipitation is approximately 1500 mm. Since precipitation exceeds evaporation (by approximately 800 mm annually), podzolization is a dominant soil process which leads to 'hardpan' formation and poor drainage. This, in combination with the impervious bedrock of the Shield, means that there is little water storage capacity of the soil and the small lakes of this region tend to be highly flushed. The southern air currents from the ocean tend to moderate the climate, so this region undergoes the least temperature change over the annual cycle. (Average temperatures in January and June are -7.5°C and 9°C, respectively.) Frequent winter rains tend to wash away the snow, and ice cover on the lakes is infrequent. These lakes are soft water lakes and are at the lowest end of the range for hardness found in Canadian waters ($<100\ mg \cdot l^{-1}\ CaCO_3$). Boreal forest surrounds these lakes and several are "brownwater" lakes due to the humic stain washed in from bogs.

Québec Lakes:

All of the 17 Québec waterbodies lie along the 45th parallel. Most of the data is drawn from the thesis of P. Potvin (1976) which examines ten lakes of the St. François River and four of the Yamaska River Basin. The remaining three waterbodies are the north, central and south basins of Memphremagog studied by R. Peters (1979). The climate is humid continental and precipitation averages 1000 $mm \cdot y^{-1}$. Ice cover of the lakes lasts about four months. The sedimentary and metamorphic bedrock is overlain by a grey-brown podzol and the forest is a mixed deciduous-coniferous type. The soil is only of medium quality, but the region is important agriculturally as part of the hay and dairy belt due to the abundance of water. Since most of the Québec lakes are recreational lakes, a major source of nutrients is cottages in addition to farms.

Ontario Shield Lakes:

The lakes of this group lie southeast of Georgian Bay in Muskoka and Haliburton counties and Algonquin Park, all at approximately 45°N. This area is considered a 'vacationland' since the rocky, rugged Shield landscape provides a scenic beauty that is difficult to use for other purposes. The granitic basins are of very irregular shape and these lakes often have numerous small islands. Precipitation for the region is 800 to 1000 mm annually and the portion of this which enters the lakes as runoff is soft water of low conductivity due to the crystalline bedrock. The ice cover for these lakes usually lasts four to five months and they undergo rapid flushing in the spring at snowmelt. The forest is mixed spruce and hardwood and the poor drainage promotes bog formation. Subsequently, the lakes tend to be brown-water lakes from humic runoff. Cottage development around the lakes has become the major source of nutrients. The appearance of blue-green algal blooms in some of these naturally pristine lakes brought the eutrophication problem to the attention of the provincial Ministry of the Environment. The data used here is derived from the studies of these lakes under the direction of P.J. Dillion.

The Laurentian Great Lakes:

The most remarkable aspect of the Great Lakes is, as their name implies, their vast size. It is the largest single lake system in the world and contains 10% of the world's supply of freshwater (approximately 22,600 km^3), with more than half of that in Superior alone. The lakes are located between 40° and 50°N and span the entire province of Ontario at the U.S. border, a distance of approximately 1200 km. The system flows from west to east and empties into the Atlantic via the St. Lawrence River. The water residence times of these lakes range from 185 years for Superior to 2.6 years for Erie. Precipitation for the region averages 800 mm annually, but slightly less (600 mm) for the two northern lakes Superior and Huron. The temperature for the northern lakes is also somewhat cooler and average January and June air temperatures are -12°C and 12.5°C, as contrasted with -7°C and 15°C for the more southern lakes. It is rare for any of the lakes to freeze and this only happens in the most severe winters. In addition to having the largest volume and coolest temperature, Superior varies from the other lakes in its geology. It lies directly on the Precambrian Shield and is not influenced by the Ordovician sediments as are the other lakes. The forest also reflects this, and Superior is surrounded by boreal spruce forest while the drainage area of the lower lakes is covered by a mixed deciduous-coniferous forest. The climate and soil of the southern lakes makes the region a more easily inhabitable one and most of the major population centres are distributed around Erie, Ontario and Michigan. Of all the Canadian regions, the Great Lakes Region has the maximum population density of approximately 24 inhabitants km^{-2}. (The other regions have less than half this population density.) The large size, localized population centres, thermal bar and natural currents in the lakes tend to emphasize 'onshore' versus 'offshore' differences. The heterogeneity of such large lakes makes representative sampling difficult and the problem of adequately characterizing a vast area by a single value is at its maximum here. The data available on the Great Lakes is largely the result of a cooperative effort between the United States and

Canada because of the importance and common 'ownership' of the lakes. A great deal of literature on the Great Lakes is available.

The Experimental Lakes Area (ELA):

The Experimental Lakes are small Shield lakes located in northwestern Ontario (49°N) in a natural lake district. The climate is cool with January and June mean air temperatures of -15°C and 11°C, respectively. Ice cover on the lakes lasts five to six months. The total annual precipitation is about 700 mm, evaporation is nearly 500 mm and runoff is estimated to be around 200 mm. The conductivity of these lakes is very low ($<$30 μmhos$\cdot$cm^{-1}) due to the insoluble crystalline bedrock, and transparency is greater (i.e., 4 to 6 m Secchi depths) than is typical for Shield lakes since there is little bog influence. The area is uniformly covered by boreal forest that periodically burns in forest fires as a natural part of the ecology of the region. There is little human influence on these lakes and the atmospheric portion of nutrient loads is significant. The lakes of the ELA were originally chosen as a testing ground for monitoring the effects of artificial nutrient enrichments. The lakes which were subjected to such enrichments are grouped in the file: "Unusal Canadian Circumstances" (UCC). The data used here is derived from studies of these lakes under the direction of D.W. Schindler.

The Prairie Lakes:

The lakes of the prairie included here are located at approximately 50°N near the Saskatchewan-Manitoba border. The climate of the region is dry, continental and, for lack of moderating geographic features, is the region subject to maximum annual temperature variation. Average January and June air temperatures are -15°C and 12.5°C, respectively. The Qu'Appelle chain of six lakes was formed by an enormous flow of glacial meltwater which carved the present lake basins from the sand, silt and clay of the prairie plain. This penetrated deep enough to cut into the aquifer such that the "Fishing Lakes" (as the Qu'Appelle lakes are also known) are spring fed. Lake Winnipeg, on the other hand, lies on the border of the prairie and Precambrian Shield and is a remnant of Lake Agassiz. The lakes do not usually stratify, or if they do, it may be under ice cover which lasts approximately five and one-half months.

The high clay content of the soils turns it into a waterlogged 'gumbo' when wet and drainage is very poor. Annual precipitation is only about 400 mm whereas evaporation is estimated to be 700 mm. In this situation, sodium and other salts tend to deposit at the soil surface. Water hardness of the prairie lakes is the highest of all lakes in Canada. Hydraulic loads of the lakes are highly variable and flushing ranges from one month to three years. Drainage from the prairies is turbid and transparency of the lakes is low at least in part for this reason.

The prairie lakes are used for irrigation, fishing and recreation. Agricultural and municipal nutrient loads to the lakes are among the highest in Canada, which makes these naturally eutrophic situations worse. Blue-green algal blooms are a common feature of the Qu'Appelle system. This chain of lakes and Lake Winnipeg, used in the analysis here, are large highly flushed waterbodies and therefore differ greatly from the typical small pothole lakes of the prairies.

British Columbia Interior Valley Lakes:

The lakes of British Columbia are located at approximately 50°N within the interior valleys of the west coast mountain ranges. These include five lakes in the chain of Okanagan Valley lakes as well as Babine, Kamloops and Kootenay. Average air temperatures for January and June are -7.5°C to 12.5°C, respectively. The valleys of these lakes tend to be warmer and drier than the windward sides of the mountains due to a rain-shadow effect. Rainfall increases drastically with height, so the peaks may have the vegetation of a high rain forest while the leeward slopes and valleys have the xerophytes of a steppe landscape. Average annual precipitation ranges from 275 mm in the south, to 440 mm in the north of the Okanagan Valley, while that for the Babine Lake watershed is 600 mm. Evaporation is considerable and has been estimated to be equivalent to 33% of the outflow in the Okanagan chain. Ice cover for the Okanagan lakes generally only lasts for three months and is rarely present on the largest of the chain, Okanagan Lake. Ice cover on Babine may last approximately four and one-half months, but Kamloops and Kootenay rarely freeze over. The lakes of the Okanagan chain have irregular hydraulic loads from year to year and among the lakes, average water residence times range from 0.4 to 52 years. The major portion of the inflow arrives in the spring. The Okanagan Valley is a major fruit growing region in Canada, with some cattle and a rapidly increasing human population; these are the major factors responsible for nutrient loads to these lakes.

Babine Lake is unusual in its high humic content and has been classified as dystrophic or polytrophic. Kamloops is highly flushed (in 18 to 340 days) by cold water from the mountains which sinks as it enters the lake. Not only does this create an unusual flow pattern for this river-run lake, but the inflow carries a high apatite load which may be misleading in phosphorus-trophic response relationships since little of the apatite-phosphorus is biologically available. Kootenay is unusual in that all inflows and outflows are controlled by dam structures, primarily for flood control, and in 1975 phosphorus loading to Kootenay from a fertilizer plant was reduced by 90%. Unusual lakes such as Babine, Kootenay and Kamploops are grouped in the subfile Unusual Canadian Circumstances (UCC) as described below.

Unusual Canadian Circumstances:

This file contains data on lakes which, for various reasons, would not be expected to comply with the statistical standard relationships of the OECD programme, are sequential data on individual years or represent alternate methodologies. The lakes and reason for inclusion in this group are listed in Appendix 3. Identification of these situations is important in keeping the heterogeneity of the data to a minimum, and as such, this group was omitted in the calculation of correlations and descriptive regressions.

3.2.3 Temporal and Spacial Representation Within Lakes

The set of variables collated for each lake and used in this analysis are listed in Appendix 4. They are basic physical, chemical and biological features thought to be most important in determining the trophic response of lakes as stated in the OECD Agreed Monitoring Programme (cf. OECD, 1973).

The technical group responsible for this Agreed Programme established that the values of interest were annual means and set the recommendations for a minimum sampling programme whereby the more dynamic variables were to be measured at least once every four weeks, while more stable features only required measurement once every three months. However, due to the complexity of some lakes more intensive sampling programmes were necessary to adequately characterize annual mean values and those details may be found in the individual regional reports. In addition, some intercalibration of analytical methods performed at different laboratories was accomplished in both the Nordic and the Alpine projects. Error due to methodology is therefore expected to be at a minimum for these two projects.

The basic data used for the cross-sectional analysis are listed in Appendices 5.1 through 5.6 as a series of six tables. Each table has three lake groups consisting of natural waterbodies, shallow lakes and reservoirs and unusual Canadian circumstances. Each lake group is further subdivided by trophic category and some basic statistics are listed for each group and category.

3.2.4 Regression Methodology

Regressions were run for phosphorus and nitrogen residence times using a progression of from one to four explanatory variables. A preconceived order of entry of these variables was used to reflect a logical and realistic sequence of events. Loadings were considered a necessary prerequisite for nutrient residence times and were always used as the primary explanatory variable. Second, the physical parameters mean depth and water residence time were added for the two- and three-variable multiple regressions. Last, the biological variables were added to equations to determine if these could improve explanation, and therefore prediction, of nutrient residence times. The order of variable entry for multiple regressions was hierarchical, i.e., chosen to reflect an intrinsic, causal relationship between the variables.

The regression coefficients and statistics of the following section were generated by the software package "Statgraphics". This package uses the Graham-Schmidt algorithm to estimate model coefficients. The forward stepwise multiple regression procedure was used to produce tables of (i) regression coefficients and t statistics (which gives the marginal contribution of each variable as if it were the last to enter the equation), (ii) an analysis of variance (ANOVA) for the full regression, and (iii) conditional sums of squares to obtain F values for variables in the order as they were added to the regression equation.

The partial F tests listed in the tables are formed according to the formula:

$$F = \frac{\text{incremental SS due to variable(s) added}/p}{\text{SS residual}/(N-k-1)}$$

where p is the number of variables added in that step, N is the total number of cases and k is the number of variables in the full model. This hierarchical F value tests the increment in the "explained" sum of squares at each step (and is in contrast to the "standard" regression F test which examines the significance of variables as if each were added last).

Two categorical groupings were incorporated into the multiple regressions by use of dummy variables (cf. Kleinbaum and Kupper, 1978; Nie _et_ _al_., 1975). The categorical distinctions for trophic category were defined by the dummy variables:

$Z1 = 1$ for mesotrophic lakes; 0 otherwise

$Z2 = 1$ for eutrophic lakes, 0 otherwise

The oligotrophic lakes formed the reference category. Therefore, in the case of one independent variable the full model evaluated can be written as:

$$\hat{y} = \beta_o + \beta_1 X + \beta_2 Z_1 + \beta_3 Z_1 X + \beta_4 Z_2 + \beta_5 Z_2 X + E$$

Equations for each trophic group specialize as follows:

Oligotrophic lakes: $\hat{y} = \beta_o + \beta_1 X + E$

Mesotrophic lakes: $\hat{y} = (\beta_o + \beta_2) + (\beta_1 + \beta_3)X + E$

Eutrophic lakes: $\hat{y} = (\beta_o + \beta_4) + (\beta_1 + \beta_5)X + E$

Similarly, a single dummy variable was used to distinguish the shallow lakes and reservoirs (SLR) from the natural lakes group.

The null hypothesis for coefficients is that the variables or groups make no significant contribution to the prediction of the dependent variable. Large F values lead to rejection of the null hypothesis and the conclusion that the added factor is important for the explanation of the dependent variable. Best equations were chosen on the basis of an adjusted r^2. This coefficient of determination (r^2) is adjusted for the number of independent variables in the model and, unlike the unadjusted r^2, it may decrease in value as insignificant variables are added to the equation due to the increased degrees of freedom.

3.3 Results for the Cross-Sectional Data

3.3.1 Distributions

Arithmetic (untransformed) and geometric ($\log_{10}$ transformed) distribution statistics are compared in Table 3.1. The $\log_{10}$ transformation reduces skewness of the distributions in every case and reduces kurtosis in all but five cases. This improvement in symetry (equalization of variance) is required by the subsequent regression analyses of this paper. In addition, arithmetic means are often twice the value of the geometric means and these former tend to overestimate the value of maximum frequency. Therefore the $\log_{10}$ transformation will be used for all subsequent calculations and graphic displays.

TABLE 3.1. ARITHMETIC AND GEOMETRIC DISTRIBUTION STATISTICS FOR ALL LAKES (NATURAL LAKES AND SLR).

				MEAN		KURTOSIS		SKEWNESS		
Variable*	Units	Min	Max	Arith.	Geom.	Arith.	Geom.	Arith.	Geom.	n
AREA	km^2	0.1	82,367	1308	5.5	64.3	1.0	7.8	1.2	213
VOL	$10^6\ m^3$	0.2	12,190,300	111,803	65.6	135.0	0.8	11.1	0.9	212
MAXZ	m	2.0	501	59.5	31.4	9.53	-0.2	2.9	0.2	181
MEANZ	m	0.7	313	23.8	11.7	18.7	0.1	3.1	0.4	219
AREAD	km^2	0.2	952,796	9854	105.2	157.6	-0.5	12.3	0.3	179
TWL	y	0.005	700	7.3	1.0	166.9	1.1	12.5	0.2	207
RWL	y^{-1}	0.001	63.7	3.7	1.0	24.2	1.1	4.6	-0.3	206
QSL	$m \cdot y^{-1}$	0.45	407.4	36.7	10.6	28.9	-0.5	4.7	0.1	207
LPL	$g \cdot m^{-2} \cdot y^{-1}$	0.02	84.9	3.3	0.8	46.5	-0.01	6.4	0.2	187
ANP	$mg \cdot m^{-3}$	1.9	750	58.2	24.2	17.5	-0.8	3.5	0.5	209
SPMXP	$mg \cdot m^{-3}$	3.0	429.5	86.7	41.2	2.11	-1.1	1.6	1.0	39
LTN	$g \cdot m^{-2} \cdot y^{-1}$	0.33	1710	63.3	19.9	57.1	1.4	7.1	-0.01	91
ANTN	$mg \cdot m^{-3}$	263.6	6095	1794	1245	0.23	-1.3	1.0	0.05	58
SPMXTN	$mg \cdot m^{-3}$	302	8299	2413	1489	0.19	-1.3	1.2	0.1	34
ANEUP	$mg \cdot m^{-3}$	3.8	373	74.3	40.1	2.7	-1.0	1.7	-0.01	77
ANEUTN	$mg \cdot m^{-3}$	247.7	6095	1721	1199	0.9	-1.2	1.2	0.05	57
ANEUCHL	$mg \cdot m^{-3}$	0.3	89.9	10.9	5.4	9.6	-0.5	2.8	0.2	153
SPEUCHL	$mg \cdot m^{-3}$	1.3	105	14.4	7.9	10.4	0.1	3.1	0.4	37
MXEUCHL	$mg \cdot m^{-3}$	2.0	275	43.7	22.2	5.9	-0.7	2.3	0.04	73
MNEUCHL	$mg \cdot m^{-3}$	0.01	19.4	2.3	1.2	9.9	2.4	2.9	-0.3	72
ANEUALG	$mg \cdot m^{-3}$	0.8	7.7	2.7	2.1	0.9	0.2	1.1	-0.7	30
ANEUALGA	$mg \cdot m^{-2}$	3.7	54.7	22.1	19.6	1.8	1.9	0.8	-1.1	34

cont'd.

TABLE 3.1. cont'd

Variable*	Units	Min	Max	MEAN		KURTOSIS		SKEWNESS		n
				Arith.	Geom.	Arith.	Geom.	Arith.	Geom.	
ANSEC	m	0.8	28.3	4.3	3.6	23.4	-0.3	3.3	-0.2	178
HYPOAREA	m^2	0.6	534.6	47.0	6.9	11.7	0.2	3.5	-0.2	31
HYPOVOL	m^3	0.5	39,265	4507	215.8	7.2	-0.7	2.9	-0.3	20
YPRAR	$mg\ C \cdot m^{-2} \cdot y^{-1}$	5.6	1168.8	265.8	161.8	3.0	0.4	1.6	-0.8	82
O2DM3	$g\ O_2 \cdot m^{-3} \cdot y^{-1}$	0.03	10.5	3.2	1.8	0.6	3.4	1.3	-1.2	24
O2DM2	$g\ O_2 \cdot m^{-2} \cdot y^{-1}$	0.10	787.0	130.6	52.2	7.1	1.8	2.2	-1.3	49
O2DM3MD	$g\ O_2 \cdot m^{-3} \cdot y^{-1}$	0.01	2.1	0.6	0.4	1.9	4.0	1.5	-1.3	24
O2DM2MD	$g\ O_2 \cdot m^{-2} \cdot y^{-1}$	0.6	131.2	24.6	13.7	6.3	0.1	2.2	-0.9	53
PJ	$mg \cdot m^{-3}$	4.7	4898	175.5	67.0	98.7	-0.6	8.9	0.3	278
PO	$mg \cdot m^{-3}$	3.8	1503	102.4	42.0	34.5	-0.3	5.3	0.5	66
TP	y	0.006	24.5	1.36	0.46	28.2	0.3	4.9	0.1	181
TPR	–	0.03	1.85	1.51	0.39	1.7	0.9	1.3	-0.7	172
SP	y^{-1}	0.01	31.5	2.72	1.09	17.1	0.3	3.8	-0.2	165
VSP	$m \cdot y^{-1}$	0.09	143.0	24.5	12.5	4.2	1.3	2.1	-0.8	165
ACHLPR	–	0.02	0.9	0.26	0.19	1.6	0.8	1.2	-0.9	188
SCHLERP	–	0.03	1.36	0.36	0.25	1.1	-1.1	1.0	-0.4	60
TNJ	$mg \cdot m^{-3}$	192.3	19,906.7	2786	1749.9	13.9	-0.8	3.0	-0.1	83
TNO	$mg \cdot m^{-3}$	250.0	8912.5	1672	1132.4	6.1	-0.7	2.2	0.4	48
TN	y	0.02	10.5	1.13	0.54	17.0	0.2	3.7	0.1	46
TNR	–	0.15	1.06	0.61	0.55	-0.8	0.3	0.02	-0.9	46
TNTPR	–	0.20	3.69	0.91	0.73	6.7	0.5	2.5	0.4	46
NPLR	–	1.02	146.2	18.9	13.4	17.7	1.3	3.8	-0.01	91
NPDR	–	3.55	219.3	38.4	26.9	9.9	0.6	2.8	-0.1	48
NPR	–	3.12	202.3	36.0	25.1	7.7	0.8	2.6	0.1	57
SN	y^{-1}	1003	17.7	1.43	0.56	29.9	2.3	5.1	-0.9	43
VSN	$m \cdot y^{-1}$	0.3	67.4	12.6	9.2	14.0	4.2	3.1	-1.2	43

* cf. Appendix 4 for variable definitions.

Further points of justification for the transformation include (1) ease of comparison with previous work in this field (cf. Heyman, Forsberg and Ryding, 1984; Vollenweider and Kerekes, 1982) and (2) portrayal of variable effects as multiplicative which is more logical than an additive model for this situation. This becomes more clear by consideration of the units of the variable combinations used in the multiple regressions. (Note that a linear model applied to $\log_{10}$ transformed values is in fact a multiplicative model, for example [$\log_{10}Y = \log_{10}A + B\log_{10}X$] translates to [$Y = 10^{A}X^{B}$].)

Histograms for $\log_{10}$ values of all variables are presented in Appendix 6. Each variable is categorized in two ways, based on the premise that lakes of different categories may have rather different ways of processing nutrients, and therefore, different nutrient residence times. (A subsequent section on regressions will test the null hypothesis that these lake groups are the same.) In the first breakdown, ranges and frequencies of shallow lakes and reservoirs (SLR, i.e., waterbodies which do not stratify) are compared with those of natural lakes in the upper panel of each page. As a second breakdown, all waterbodies are classified according to trophic category (as designated by the original investigator; cf. Appendix 2). These are shown as three-dimensional histograms on the lower panel of each page. The two panels are directly comparable in that they both depict the same lakes; the lower panel may be thought of as a regrouping and projection of the sample of lakes shown in the upper panel.

In reference to the upper panels, there are 184 lakes in the "natural lake" category which are distributed quite equitably among the trophic categories. The numbers of lakes in oligotrophic, mesotrophic and eutrophic categories are 73, 45 and 66, respectively. In contrast to this, there are 36 lakes in the SLR group with the trophic distribution of 6 oligotrophic, 3 mesotrophic and 27 eutrophic lakes. Therefore, the SLR group is primarily composed of eutrophic waterbodies.

An overview comparison of the first breakdown shows that among the morphometric and hydrologic features of the lakes (cf. Appendicies 6.1 to 6.8), the main difference of the SLR group is that hydraulic loads tend to be higher than natural lakes and therefore these waterbodies in general have shorter water residence times and higher flushing rates.

With reference to nutrients, the SLR group also tends to have higher phosphorus and nitrogen loads and inflow, outflow and lake concentrations (cf. Appendices 6.9 through 6.20) than the population sample of natural lakes. While the (N/P) loading ratio is lower, the (N/P) ratio of both the lake and outflow tend to be higher in the SLR group than the natural lakes group (cf. Appendices 6.21 through 6.23).

In terms of biological response, chlorophyll concentrations are generally higher and Secchi depths are shallower in the

SLR group than those in natural lakes (cf. Appendices 6.24, 6.26 and 6.30).

Finally, absolute residence time of phosphorus and nitrogen tend to be shorter than the natural lakes, while relative residence times tend to be longer than those in natural lakes. Both phosphorus and nitrogen sedimentation coefficients and apparent sedimentation velocities tend to be higher in the SLR group relative to natural lakes (cf. Appendices 6.40 through 6.47).

In review of this same sequence of plots (i.e., Appendix 6), but with the focus on trophic breakdown as depicted in the lower panels, the histograms show that drainage basin areas, lake surface areas and lake volumes tend to be higher in the eutrophic category. However, mean and maximum depths are somewhat lower in eutrophic lakes. Hydraulic loads are generally higher and therefore it's not surprising that water residence times are shorter and flushing rates higher than the oligotrophic lake means for the same parameters (cf. Appendices 6.1 through 6.8).

In terms of nutrients, phosphorus and nitrogen loads, lake concentrations and outflow concentrations are distinctly higher in the eutrophic than the oligotrophic group. Nitrogen to phosphorus ratios of loading, lake concentrations and outflow concentrations all tend to be lower in eutrophic lakes (cf. Appendices 6.9 through 6.23).

In terms of biological response variables (cf. Appendices 6.24 through 6.33), the measures of chlorophyll and algal biomass were higher and Secchi depths were more shallow in eutrophic lakes than oligotrophic lakes. Primary production rates and chlorophyll to phosphorus ratios (as measures of biological activity and efficiency, respectively) tend to be higher in eutrophic lakes.

Among the measures related to hypolimnetic oxygen depletion (cf. Appendices 6.34 through 6.37), the best distinction of trophic groups shows up as higher monthly volumetric oxygen depletion rates in the eutrophic lakes.

The figures which refer to phosphorus and nitrogen residence times and sedimentation are given in Appendices 6.40 through 6.48. Absolute residence times of phosphorus and nitrogen in eutrophic lakes tend to be shorter, while relative to water both tend to be longer, than the same values for oligotrophic lakes. Phosphorus sedimentation coefficients and apparent settling velocities are higher in eutrophic lakes than oligotrophic lakes, whereas the comparable measures for nitrogen appear to be about the same regardless of trophic group. The nitrogen to phosphorus residence time ratios take on lower values in the eutrophic than in the oligotrophic lakes.

3.3.2 Correlations

Pearson correlation coefficients (r) selected from a complete (50 x 49 variable) matrix are listed in Tables 3.2 and 3.3 which refer to phosphorus and nitrogen, respectively. These two tables refer to all correlation coefficients selected on the basis of significance at or above the 95% level ($p < 0.05$) for phosphorus and nitrogen absolute residence times, relative residence times and sedimentation coefficients.

A series of scatterplots for all significant valriable combinations for absolute and relative residence times listed in the two tables was produced. In these plots, each point was identified by trophic category and outlying points were identified by lake name. The most significant of these mentioned below are shown in Appendix 7. This series of "working" plots was used to define the variables for which trophic distinction would play a role in the strength of regression relationships, and where lake groups or individuals reacted differently from the general population sample. These tables and plots were used to guide variable selection for the multiple regressions which follow, therefore this information has been incorporated into the final analysis.

Table 3.2 gives the significant ($p < 0.01$) correlation coefficients for phosphorus. The highest positive correlation coefficients (r) for absolute phosphorus residence time are with water residence time ($r = 0.89$), nitrogen residence time

TABLE 3.2. SELECTED PEARSON CORRELATION COEFFICIENTS ($p < 0.01$) FOR VARIABLES RELATED TO PHOSPHORUS RESIDENCE TIMES AND NET SEDIMENTATION RATES (log 10 values; n of cases in parenthesis; all water bodies included)

Variable*	(τ_p/τ_w)	(τ_p)	(σ_p)
TP	-0.223 (172)	1 (181)	-0.818 (165)
TPRR	1 (172)	-0.223 (172)	
TN	-0.302 (46)*	0.852 (46)	-0.616 (43)
TNR	0.504 (46)	-0.310 (46)*	
TNTPR	-0.693 (46)	-0.295 (46)*	0.389 (43)
SP		-0.818 (165)	1 (185)
AREA	-0.207 (170)	0.328 (179)	-0.264 (163)
VOL	-0.231 (169)	0.465 (178)	-0.338 (162)
MAX2	-0.178 (139)	0.648 (147)	-0.462 (134)
MEAN2	-0.242 (171)	0.666 (180)	-0.453 (164)
AREAD			
TW	-0.627 (171)	0.898 (172)	-0.574 (164)
RW	0.631 (171)	-0.893 (171)	0.574 (164)
QS	0.595 (172)	-0.605 (172)	0.347 (165)
LP	0.161 (172)	-0.457 (181)	0.512 (165)
ANP	0.190 (172)		0.208 (165)
SPMXP			
LTN	0.321 (83)	-0.553 (91)	0.461 (77)
ANTN			0.491 (45)
SPMXTN		-0.389 (34)	0.502 (33)
ANEUP			
ANEUTN			0.545 (44)
ANEUCHL		-0.325 (124)	0.386 (110)
SPEUCHL	0.382 (25)		
MXEUCHL		-0.261 (63)	0.307 (52)
MNEUCHL		-0.476 (62)	0.465 (51)
ANEUALG			0.656 (16)
ANEUALGA			0.511 (19)
ANSEC		0.444 (148)	-0.362 (136)

* $p < 0.05$; all others $p < 0.01$.

cont'd.

TABLE 3.2. cont'd.

Variable*	(τ_p/τ_w)		(τ_p)		(σ_p)	
HYPOAREA						
HYPOVOL						
YPAR	0.342	(67)				
O2DM3			-0.443	(22)		
O2DM2						
O2DM3MO						
O2DM2MO						
PJ	0.402	(72)			0.259	(165)
PO						
TP						
VSP	-0.369	(165)	-0.338	(165)	0.670	(165)
ACHLPR	-0.170	(154)	-0.233	(163)		
SCHLERP			-0.513	(58)	0.459	(45)
TNJ					0.272	(77)
TNO			-0.379	(48)	0.536	(43)
NPLR	0.229	(83)			-0.238	(77)
NPOR						
NPR	-0.405	(4)	-0.264	(56)	0.325	(45)

* $p < 0.05$; all others $p < 0.01$.

(r = 0.67) and maximum depth (r = 0.65). Two other relationships which deserve mention are absolute residence time with areal phosphorus loading (r = 0.46) and annual mean Secchi depth (r = 0.44). The scatterplots show that these two correlations would improve if trophic groups were taken into account. The maximum inverse correlations are with flushing rate (r = -0.89), net phosphorus sedimentation rate (r = -0.82) and hydraulic load (r = 0.61). These correlations are depicted in Appendices 7.1 through 7.9.

Phosphorus relative residence time has highest positive correlations with flushing rate (r = 0.63), hydraulic load (r = 0.60) and nitrogen relative residence time (r = 0.51). The maximum inverse correlations are with the nitrogen:phosphorus relative residence time ratio (r = -0.69) and water residence time (r = -0.63). Four other phosphorus relative residence time relationships should also be mentioned. The scatterplots show that correlations with phosphorus inflow concentration (r = 0.40), areal phosphorus load (r = 0.16), annual mean lake concentration (r = 0.19) and annual areal primary production (r = 0.34) would all improve with trophic category distinction. These relationships are depicted in Appendices 7.10 through 7.18.

Net phosphorus sedimentation rates are most highly correlated with apparent phosphorus sedimentation velocity (r = 0.67), annual mean euphotic algal biomass (r = 0.66) and flushing rate (r = 0.57). Highest inverse correlations are with absolute phosphorus residence time (r = -0.82), absolute nitrogen residence time (r = -0.62) and water residence time (r = -0.57).

Table 3.3 gives the significant correlation coefficients for nitrogen. The highest positive correlation coefficients (r) for absolute nitrogen residence time are with water residence time (r = 0.93), absolute phosphorus residence time (r = 0.85), mean depth (r = 0.73) and maximum depth (r = 0.70). Maximum inverse correlations are with flushing rate (r = -0.92), net phosphorus sedimentation rate (r = -0.62), total nitrogen load (r = -0.55), and hydraulic load (r = -0.48). These relationships are depicted in Appendices 7.19 through 7.26.

Nitrogen relative residence time has highest positive correlations with hydraulic load (r = 0.81), flushing rate (r = 0.54) and phosphorus relative residence time (r = 0.50). Highest inverse correlations are with annual mean euphotic algal biomass concentration (r = -0.72), annual mean euphotic algal biomass per unit surface area (r = -0.59) and water residence time (r = -0.53). Correlations with the inflow concentration and total nitrogen load are relatively low. These relationships are depicted in Appendices 7.27 through 7.34.

Net nitrogen sedimentation rates have highest positive correlations with net phosphorus sedimentation rates (r = 0.62) and flushing rates (r = 0.60). Other high positive correlations are with monthly and annual volumetric hypolimnetic oxygen depletion where r = 0.76 and r = 0.67, respectively; however, these

TABLE 3.3. SELECTED PEARSON CORRELATION COEFFICIENTS ($p < 0.01$) FOR VARIABLES RELATED TO NITROGEN RESIDENCE TIMES AND NET SEDIMENTATION RATES (log 10 values; n of cases in parenthesis; all water bodies included)

Variable	TNR	TN	SN	TNTPR
TP	-0.310 (46)*	0.852 (46)	-0.663 (43)	-0.295 (46)
TPRR	0.504 (46)	-0.302 (46)*		-0.693 (46)
TN			-0.811 (43)	
TNR			-0.296 (43)*	
TNTPR				1 (46)
SP		-0.616 (43)	0.619 (40)	0.389 (43)
AREA			-0.303 (43)*	
VOL		0.467 (46)	-0.537 (43)	
MAX2		0.702 (46)	-0.803 (43)	
MEAN2		0.732 (46)	-0.835 (43)	
AREAD				
TW	-0.530 (46)	0.934 (46)	-0.607 (43)	
RW	0.543 (46)	-0.918 (46)	0.604 (43)	
QS	0.809 (46)	-0.476 (46)		
LP	-0.310 (46)*	-0.418 (46)		
ANP				
SPMXP				
LTN	-0.390 (46)	-0.550 (46)	0.307 (43)*	
ANTN				
SPMXTN				
ANEUP				
ANEUTN		-0.292 (45)*		
ANEUCHL			0.368 (38)*	
SPEUCHL				-0.606 (21)
MXEUCHL				
MNEUCHL		-0.319 (39)*	0.509 (36)*	
ANEUALG	-0.724 (8)*			
ANEUALGA	-0.589 (11)*			
ANSEC		0.594 (32)	-0.633 (29)	

* $p < 0.05$; all others $p < 0.01$.

cont'd.

TABLE 3.3. cont'd.

Variable	TNR	TN	SN	TNTPR
		0.852 (46)	-0.663 (43)	-0.295 (46)
HYPOAREA		0.595 (12)*	-0.644 (10)*	
HYPOVOL		0.610 (11)*	-0.664 (9)*	
YPAR				
O2DM3			0.671 (9)*	-0.746 (11)
O2DM2				
O2DM3MO			0.757 (9)*	-0.660 (11)
O2DM2MO				
PJ	-0.456 (46)			
PO	-0.360 (44)			
TP				
VSP				0.711 (43)
ACHLPR				
SCHLERP				
TNJ	-0.498 (46)		0.359 (43)	
TNO		-0.312 (45)	0.386 (42)	
NPLR				
NPOR	0.350 (44)			0.386 (44)
NPR	0.305 (46)			0.616 (46)

* $p < 0.05$; all others $p < 0.01$.

are based on only nine (9) data pairs ($0.01 > p > 0.05$). Highest inverse correlations are with mean depth ($r = -0.83$), absolute nitrogen residence time ($r = -0.81$), maximum depth ($r = -0.80$), absolute phosphorus residence time ($r = -0.66$), annual mean Secchi depth ($r = -0.63$) and water residence time ($r = -0.61$).

The nitrogen:phosphorus relative residence time ratio is positively correlated with net phosphorus sedimentation rate ($r = 0.71$) and N/P lake concentration ratio ($r = 0.62$). Maximum inverse correlations are with volumetric hypolimnetic oxygen depletion rates ($r = -0.75$) and phosphorus relative residence time ($r = 0.69$).

3.3.3 Regression Results for Phosphorus Residence Times in Relation to Loadings and Physical Attributes

Table 3.4 gives r^2 values for 36 simple regression equations for phosphorus absolute residence time. Six different independent variables with six lake groupings are given.

In the relationships for all waterbodies, τ_p is best correlated with τ_w ($r^2 = 0.81$) (cf. Figs. 3.6 and 3.7). The next best relationships, with $\bar{z}$ and q_s, are not as strong.

Distinction of shallow lakes and reservoirs (SLR) and natural lakes does not lead to any consistent improvement in these relationships.

Table 3.4 Percentage of variation (r^2) explained for phosphorus absolute residence time (τp) according to waterbody groupings.

$f(x)$	Natural Waterbodies		SLR†		All Waterbodies		All Waterbodies by Trophic Category					
							Oligotrophic		Mesotrophic		Eutrophic	
A. 1-Variable Models:												
P_j	.03	(142)	.13	(30)	.02	(172)	.24	(57)	.05	(40)	.08	(78)
L_p	.13	(151)	.49	(30)	.21	(181)	.41	(57)	.06	(40)	.30	(84)
P_λ	.003	(151)	.06	(30)	.004	(181)	.09	(57)	.01	(40)	.01	(84)
τ_ω	.83	(141)	.60	(30)	.81	(172)	.90	(57)	.65	(39)	.80	(76)
z	.46	(150)	.12	(30)	.44	(180)	.42	(57)	.47	(39)	.50	(84)
Q_s	.38	(142)	.21	(30)	.37	(172)	.54	(57)	.14	(40)	.40	(75)

• Given in Decimal Format (.50 = 50 Percent)

† Shallow Lakes and Reservoirs (Unstratified Waterbodies)

Note: Correlation Coefficients (R^2) are for Simple Linear Regressions of Log_{10} Transformed Data; N of Cases in Parentheses

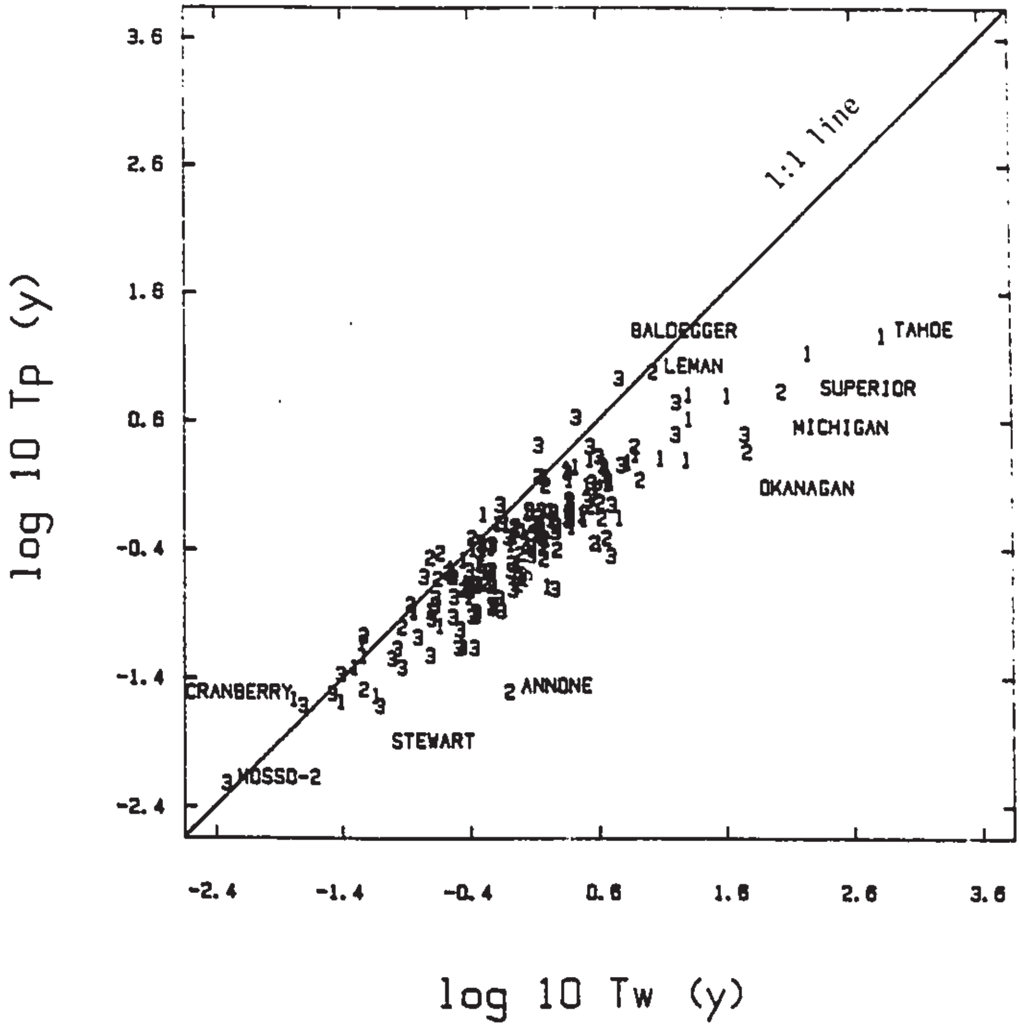


Figure 3.6 τp vs τw with trophic groups defined. (1 oligo., 2 meso., 3 eu.).

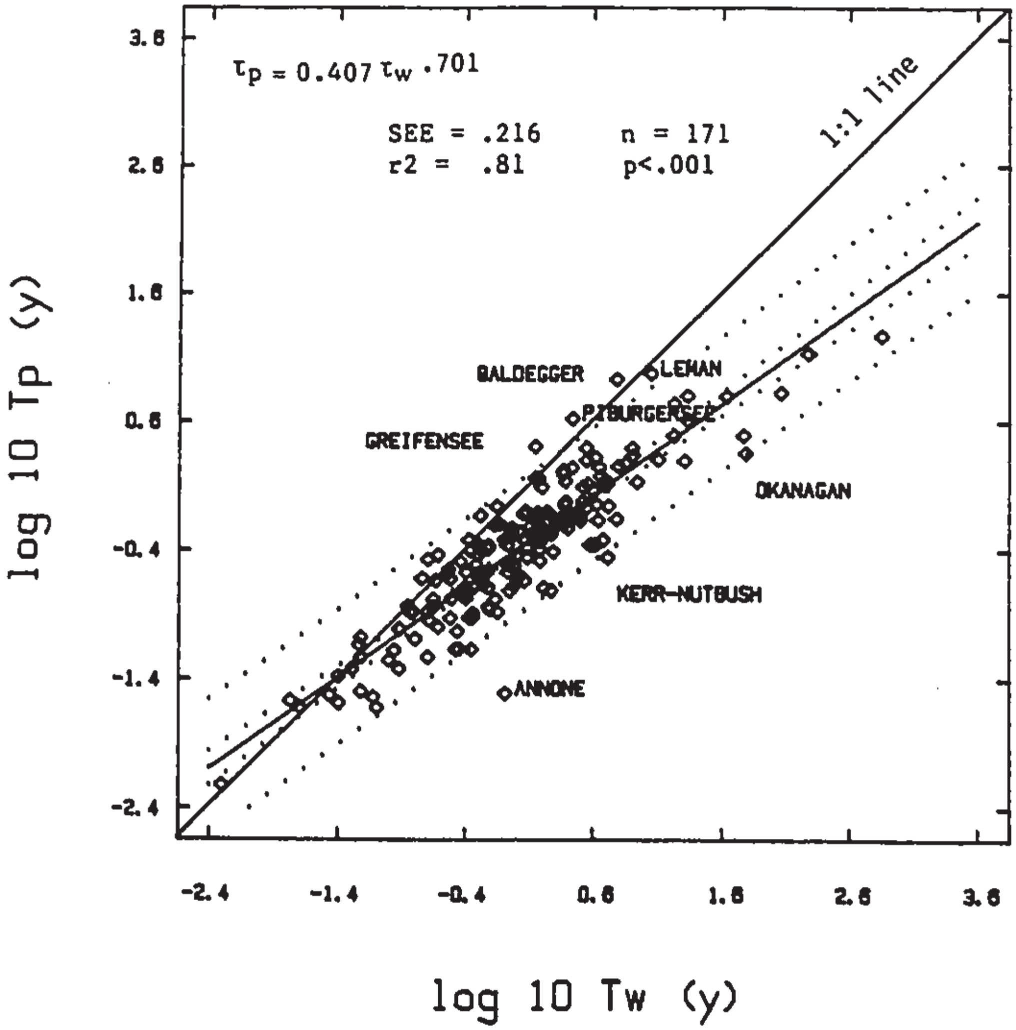


Figure 3.7 τp vs τw for all waterbodies.

In contrast, distinction of trophic categories leads to equal or better r^2 in at least two of the three categories in the cases of τ_w, $\bar{z}$ and q_s as independent variables.

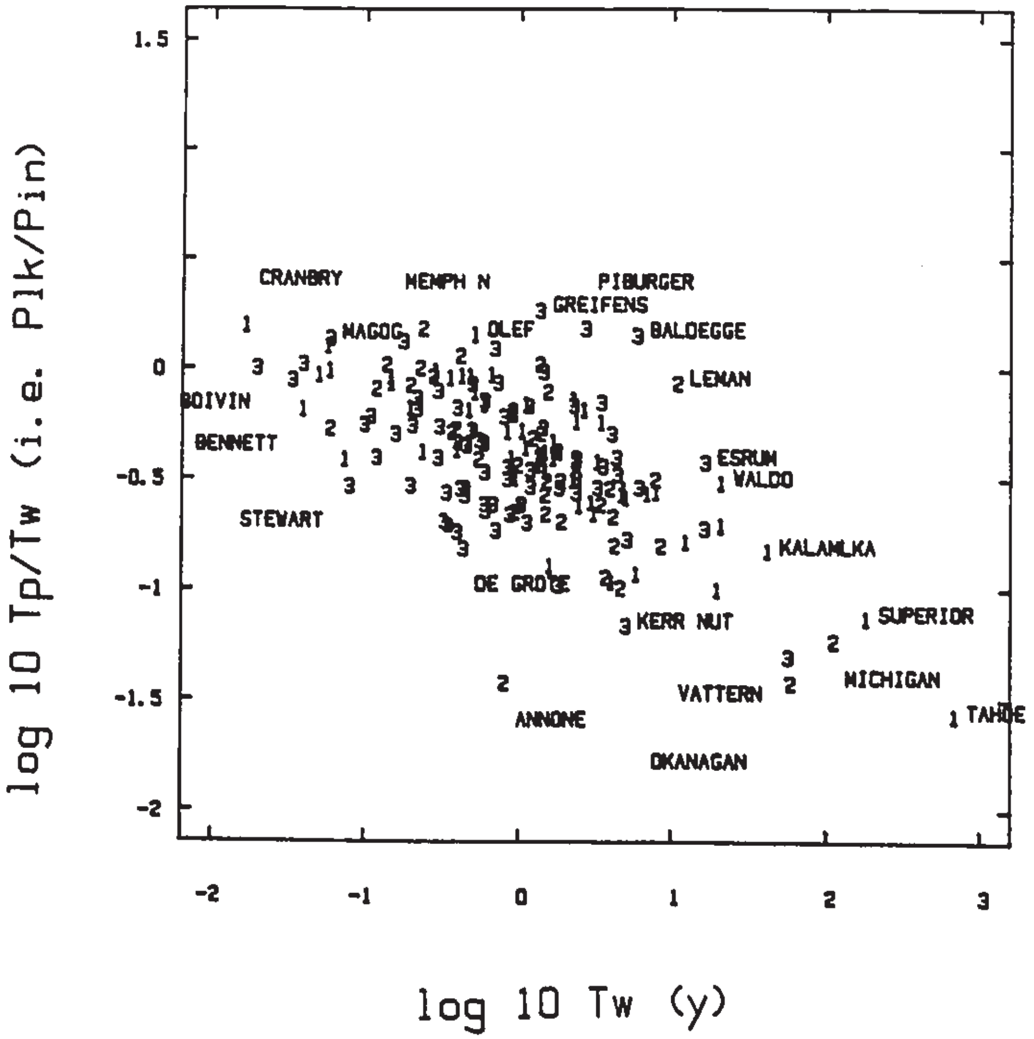
The same 36 regressions were run for phosphorus relative residence time (P_λ/P_j) with an additional 12 regressions for the two-variable models and an additional 6 regressions for the three-variable model. The r^2 values for these 52 regressions are given in Table 3.5.

The best single variable relationship for all waterbodies taken together is that with τ_w (cf. Figure 3.8) as the independent variable ($r^2 = 0.39$). The correlation with q_s is the second best ($r^2 = 0.36$).

Separation of natural lakes and the SLR group resulted in higher r^2 values in the natural lakes but lower r^2 values in the SLR group for the τ_w and q_s regressions.

The separation of lakes into trophic groups resulted in substantial increases of r^2 values in the oligotrophic and mesotrophic groups, but deterioration to a lower r^2 in the eutrophic category for the τ_w and q_s regressions. Notably, the highest r^2 for any group was that for the relationship with P_j in the oligotrophic watebodies (cf. Figure 3.9).

The two-variable models give higher r^2 values than one-variable models for all lake groups (cf. Table 3.5, B). The two formulations (P_j,τ_w) and (L_p,q_s) perform about equally well and vary with group parallel to one another. These



$$(\tau p/\tau w) = 0.402\,\tau_w^{-.288}$$

SEE = .262 n = 171

r^2 = .39 p<.001

Figure 3.8 (τp/τw) vs τw for all waterbodies

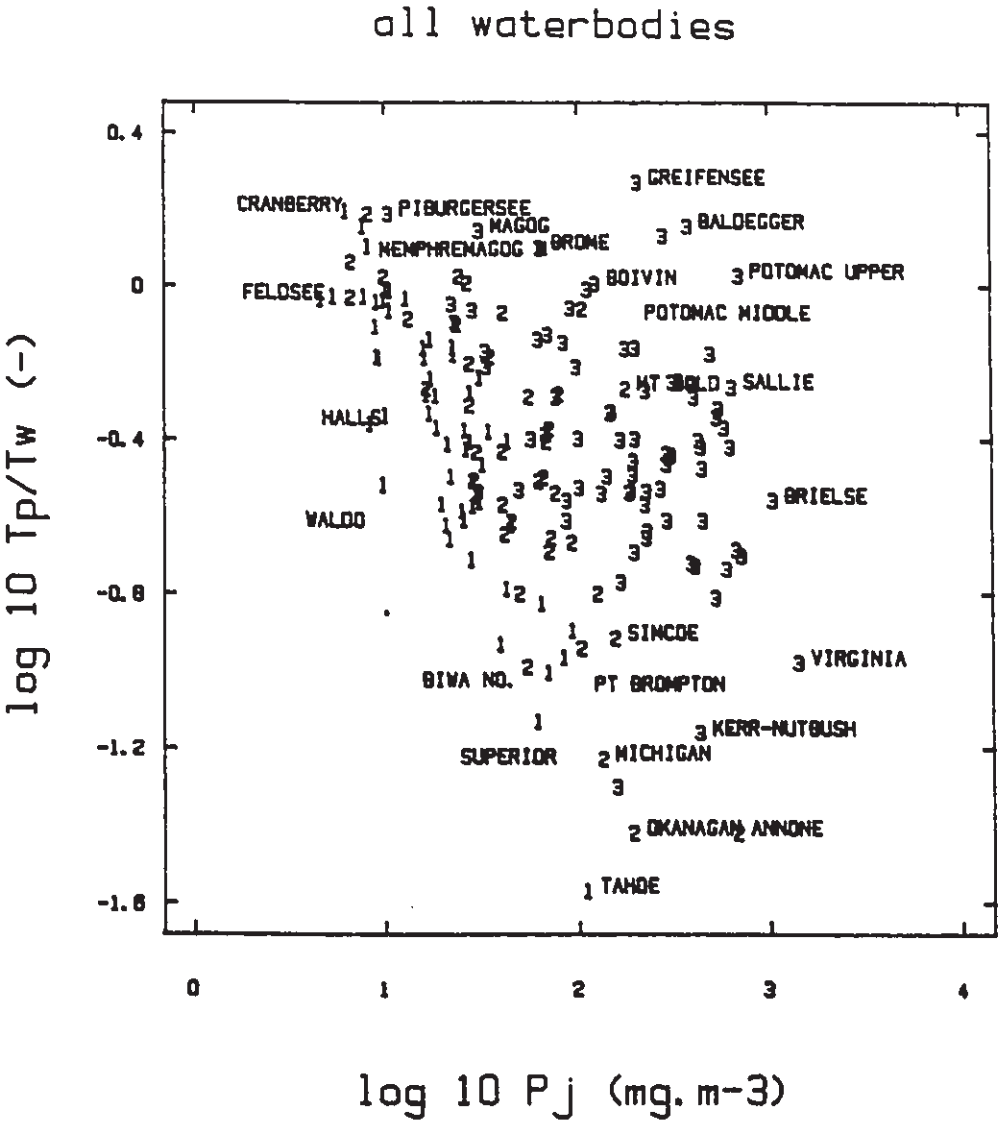


Figure 3.9 (τp/τw) vs Pj for all waterbodies with trophic groups defined.

Table 3.5 Percentage of variation (r^2) explained for phosphorus relative residence time ($\tau p/\tau w$) according to waterbody groupings.

$f(x)$	Natural Waterbodies		SLR†		All Waterbodies*		All Waterbodies by Trophic Category					
							Oligotrophic		Mesotrophic		Eutrophic	
A. 1-Variable Models:												
P_j	.13	(142)	.38	(30)	.16	(172)	.73	(57)	.58	(40)	.17	(75)
L_ρ	.08	(142)	.06	(30)	.03	(172)	.14	(57)	.05	(40)	.003	(75)
P_λ	.09	(142)	.04	(30)	.04	(172)	.16	(87)	.07	(40)	.08	(75)
τ_ω	.48	(141)	.10	(30)	.39	(171)	.68	(57)	.46	(39)	.14	(75)
z	.10	(141)	.10	(30)	.06	(171)	.23	(57)	.004	(39)	.008	(75)
Qs	.40	(142)	.21	(30)	.36	(172)	.50	(57)	.54	(40)	.17	(75)
B. 2-Variable Models:												
(P_j, τ_ω)	.50	(141)	.42	(30)	.48	(171)	.84	(57)	.64	(39)	.25	(75)
(L_ρ, Qs)	.42	(142)	.41	(30)	.41	(172)	.76	(57)	.72	(40)	.24	(75)
C. 3-Variable Model:												
$(P_j\, \tau_\omega, z)$	.52	(141)	.41	(30)	.49	(171)	.83	(57)	.72	(39)	.25	(75)

* Given in Decimal Format (.50 = 50 Percent)

† Shallow Lakes and Reservoirs (Unstratified Waterbodies)

Note: Correlation Coefficients (R^2) are for Simple or Multiple Linear Regressions of Log_{10} Transformed Data; N of Cases in Parentheses two-variable models are especially good in the explanation of variation in oligotrophic and mesotrophic groups, but in both cases are less descriptive of the eutrophic lakes.

The three-variable model gives results very similar to the two-variable models with the advantage of matching the highest r^2 value of either of the two-variable models for any given lake group (cf. Table 3.5, C). Therefore, the three-variable model has all the best attributes of the two-variable models combined into one. Observed versus predicted values for the three-variable model are plotted for each trophic category separately in Figures 3.10, 3.11 and 3.12. The r^2 is highest for oligotrophic waterbodies ($r^2 = 0.83$) and lowest for eutrophic lakes ($r^2 = 0.25$).

3.3.4 Regression Results for Nitrogen Residence Times in Relation to Loading and Physical Attributes

Table 3.6 gives the r^2 values for 36 simple regressions which describe nitrogen absolute residence times. As in the case for phosphorus, τ_n is most highly correlated with τ_w, if all waterbodies are taken together (cf. Figures 3.13 and 3.14. The second best correlation is with mean depth ($\bar{z}$). The relationship with q_s is somethat weaker than either of the relationships with τ_w or $\bar{z}$.

The division of lakes into SLR and natural waterbodies results in lower r^2 values for both the τ_w and $\bar{z}$ relationships indicating that no improvement is gained by this grouping.

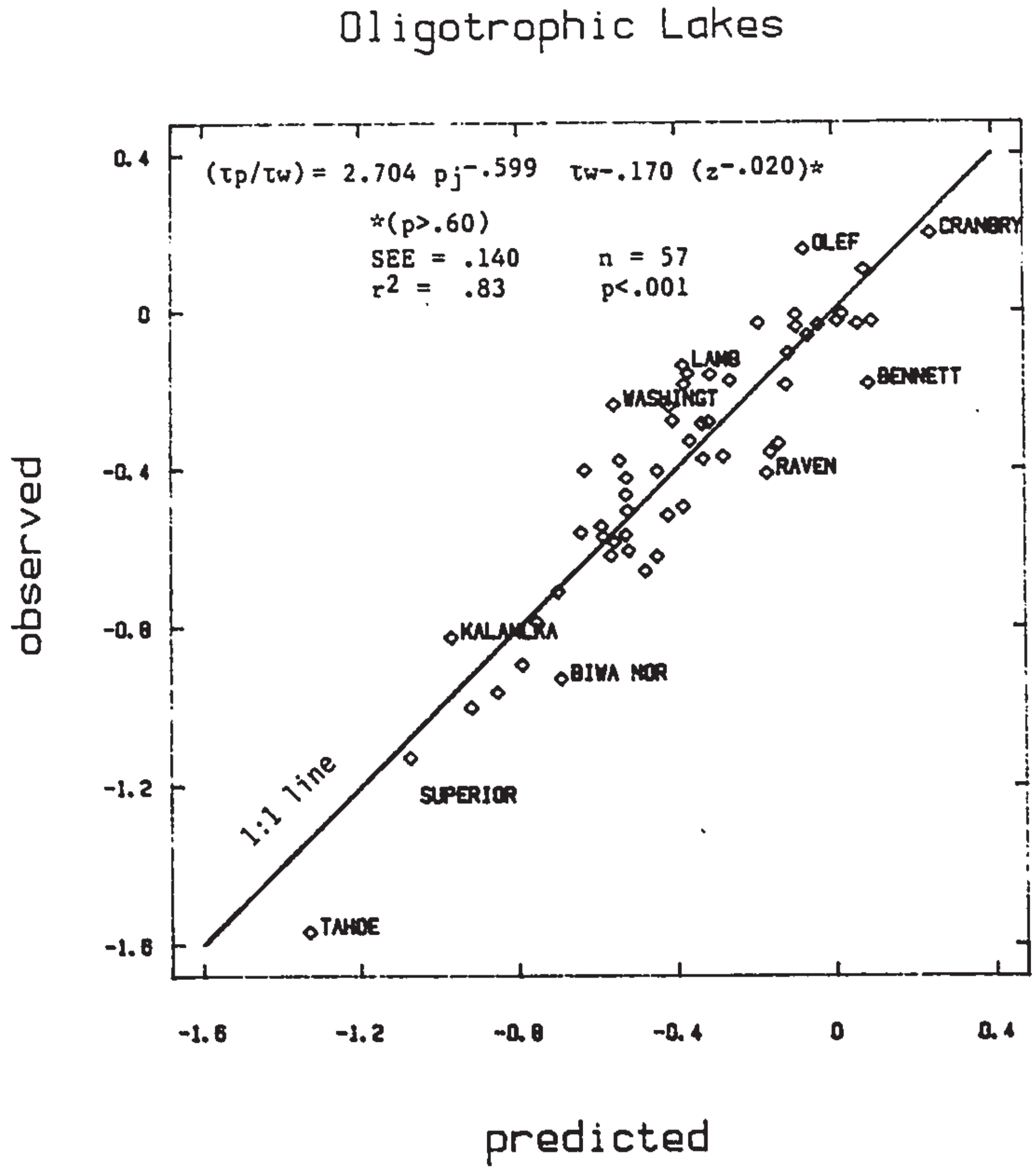


Figure 3.10 $(\tau p/\tau w) = f(Pj, \tau w, z)$: oligotrophic lakes.

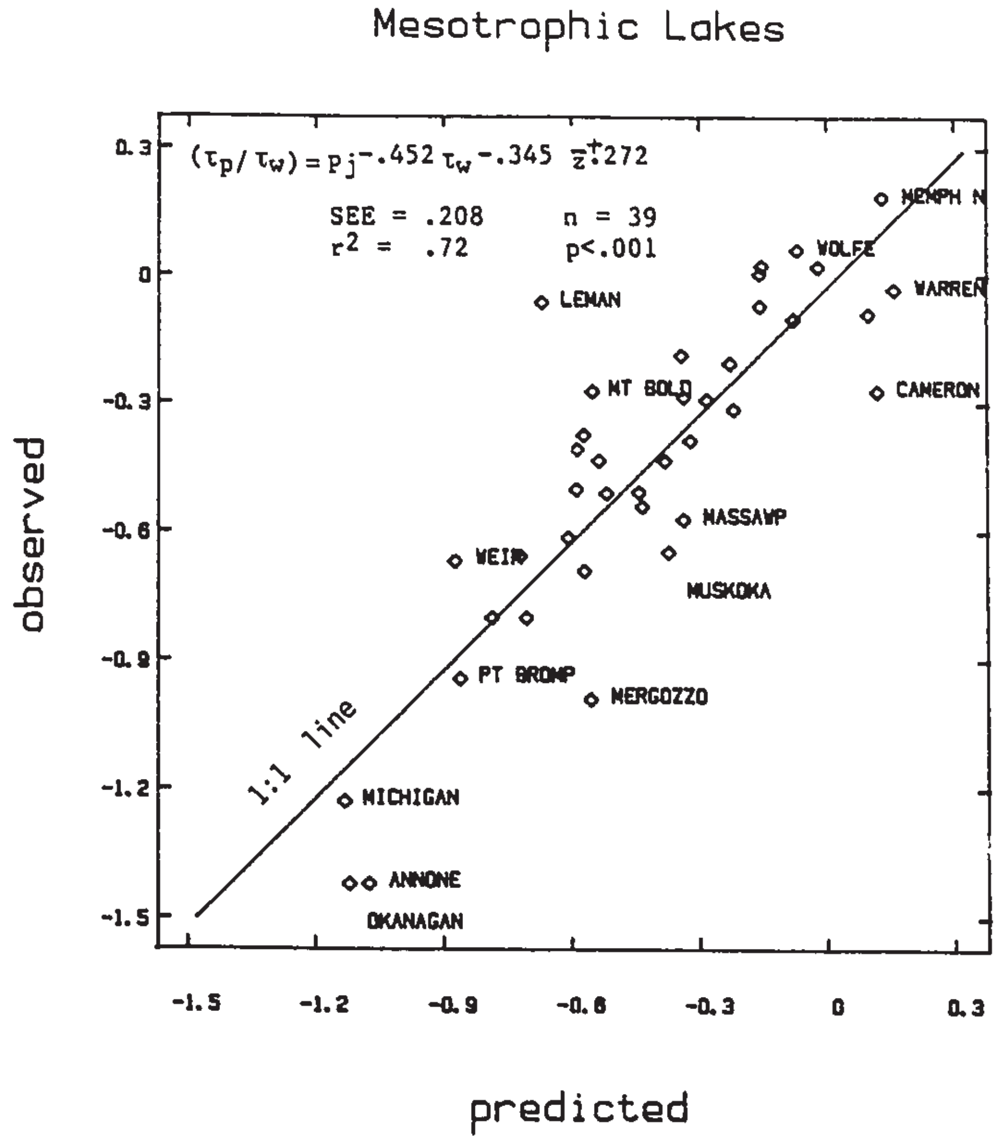
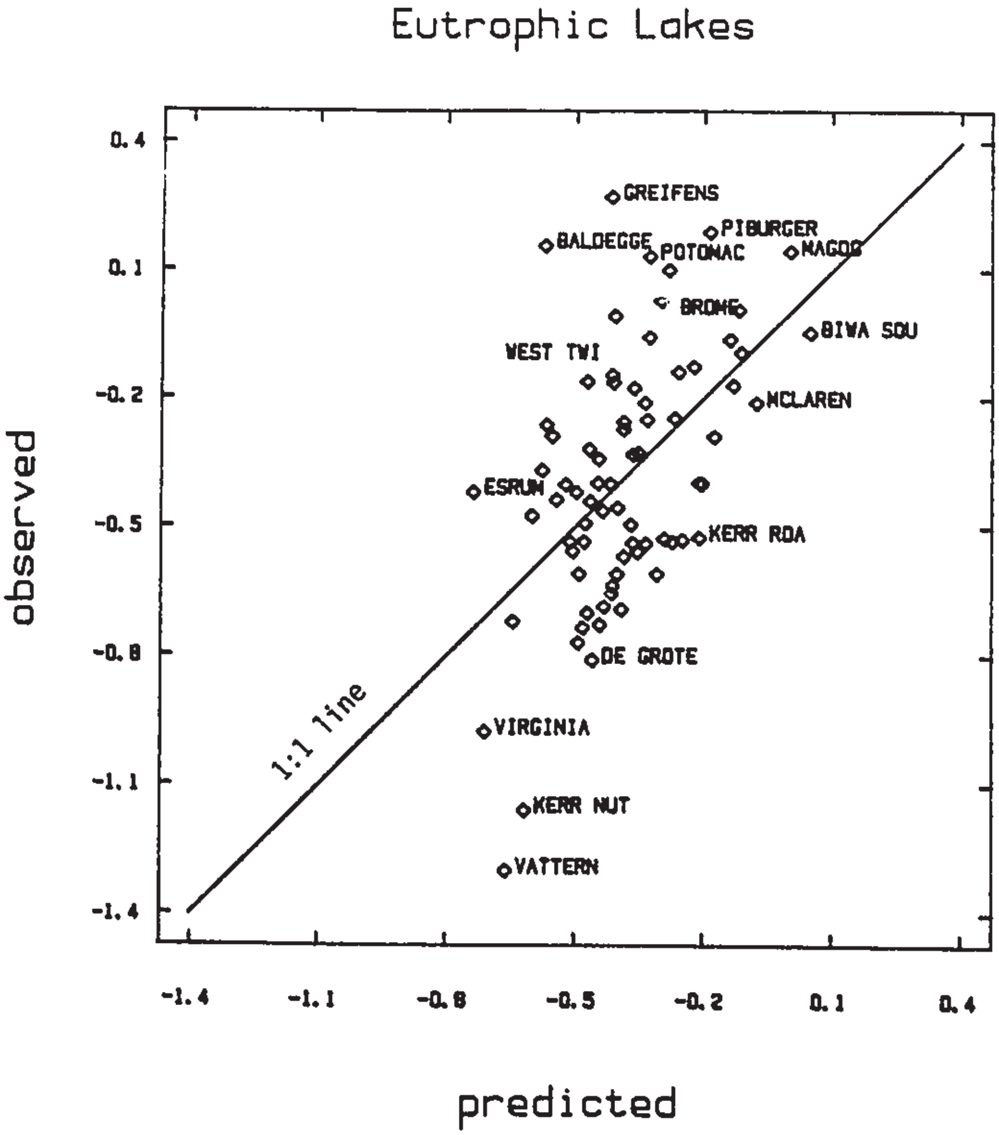


Figure 3.11 $(\tau p/\tau w) = f(Pj, \tau w, \bar{z})$: mesotrophic lakes.



$(\tau_p/\tau_w) = (1.1)^* P_j^{-.229}\ \tau_w^{-.184}\ (\bar{z}^{.077})^*$

*(NS)

SEE = .260 n = 75

r^2 = .25 p<.001

Figure 3.12 $(\tau p/\tau w) = f(Pj,\tau w, \bar{z})$: eutrophic lakes.

Table 3.6 Percentage of variation (r^2) explained for nitrogen absolute residence time (τn) according to waterbody groupings.

$f(x)$	Natural Waterbodies	SLR†	All Waterbodies	All Waterbodies by Trophic Category: Oligotrophic	All Waterbodies by Trophic Category: Mesotrophic	All Waterbodies by Trophic Category: Eutrophic
A. 1-Variable Models:						
N_j	.05 (58)	.11 (25)	.007 (46)	.001 (10)	.002 (7)	.01 (29)
L_N	.29 (66)	.58 (25)	.30 (46)	.30 (10)	.08 (7)	.34 (29)
N_λ	.04 (39)	.32 (15)	.05 (46)	.07 (10)	.006 (7)	.06 (29)
τ_ω	.23 (59)	.20 (25)	.87 (46)	.94 (10)	.82 (7)	.89 (29)
$\bar{z}$	.04 (66)	.08 (25)	.54 (46)	.31 (10)	.84 (7)	.63 (29)
Q_s	.26 (58)	.31 (25)	.23 (46)	.28 (10)	.008 (7)	.32 (29)

* Given in Decimal Format (.50 = 50 Percent)

† Shallow Lakes and Reservoirs (Unstratified Waterbodies)

Note: Correlation Coefficients (R^2) are for Simple Linear Regressions of Log_{10} Transformed Data; N of Cases in Parentheses.

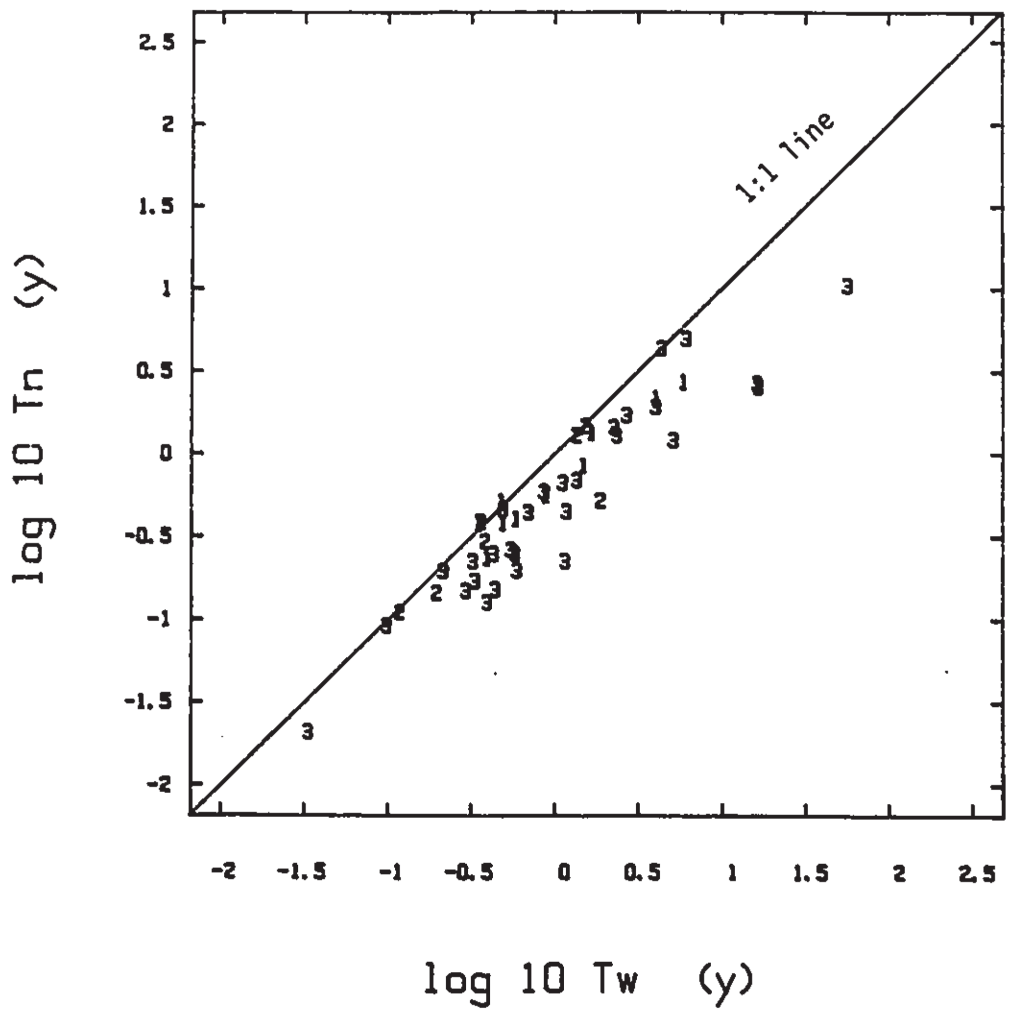


Figure 3.13 τn vs τw with trophic groups defined.

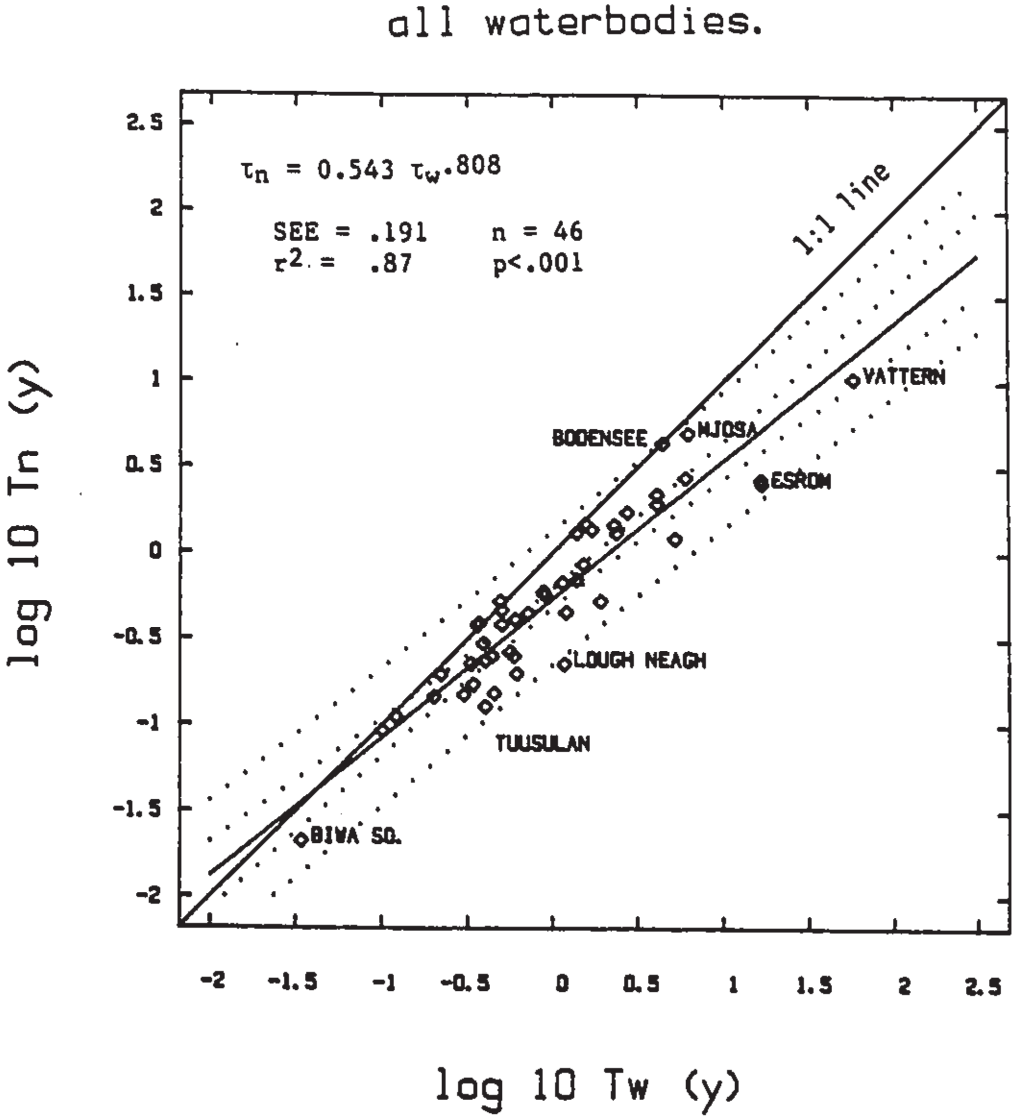


Figure 3.14 τn vs τw for all waterbodies.

Division of lakes into trophic groups results in improvement in r^2 (above that for all waterbodies together) in two out of three trophic categories. Most notable is the consistently high r^2 (0.80) for τ_n versus τ_w in each trophic group.

The same 36 regressions were run for <u>nitrogen relative residence time</u> with an additional 12 regressions for the two-variable models and 6 regressions for the three-variable model. The r^2 values for the these 52 regressions are given in Table 3.7.

When all waterbodies are taken together the best relationship is (τ_n/τ_w) with q_s (r^2 = 0.66); the relationship with T_w is substantially weaker (r^2 = 0.28).

The separation into SLR and natural waterbodies gives about the same r^2 values for q_s and τ_w as when all waterbodies are combined.

The classification of waterbodies into trophic groups results in equivalent or better r^2 values, than all waterbodies taken together, in two out of three trophic categories for the q_s and T_w relationships.

The <u>two-variable</u> models have the best r^2 value for all waterbodies together in the (L_N, q_s) formulation (cf. Table 3.7, B).

Separation of SLR and natural waterbodies results in improvement of r^2 for both two-variable models, however, the

Table 3.7 Percentage of variation (r^2) explained for nitrogen relative residence time (τ_n/τ_w) according to waterbody groupings.

							All Waterbodies by Trophic Category					
$f(x)$	Natural Waterbodies		SLR†		All Waterbodies		Oligotrophic		Mesotrophic		Eutrophic	
A. 1-Variable Models:												
N_j	.57	(31)	.25	(15)	.25	(46)	.18	(10)	.59	(7)	.07	(29)
L_N	.13	(31)	.03	(14)	.15	(46)	.13	(10)	.09	(7)	.29	(29)
N_λ	.05	(31)	.08	(15)	.0001	(46)	.03	(10)	.05	(7)	.11	(29)
τ_ω	.22	(31)	.32	(15)	.28	(46)	.50	(10)	.17	(7)	.28	(29)
$\bar{z}$	.11	(31)	.19	(15)	.05	(46)	.002	(10)	.05	(7)	.01	(29)
Q_s	.66	(31)	.60	(15)	.66	(46)	.59	(10)	.84	(7)	.62	(29)
B. 2-Variable Models:												
N_j, τ_ω	.58	(31)	.53	(15)	.46	(46)	.60	(10)	.42	(7)	.30	(29)
L_N, Q_s	.70	(31)	.72	(15)	.67	(46)	.56	(10)	.78	(7)	.63	(29)
C. 3-Variable Models:												
$N_j\, \tau_\omega, \bar{z}$	.71	(31)	.71	(15)	.66	(46)	.61	(19)	.57	(7)	.61	(29)

* Given in Decimal Format (.50 = 50 Percent)

† Shallow Lakes and Reservoirs (Unstratified Waterbodies)

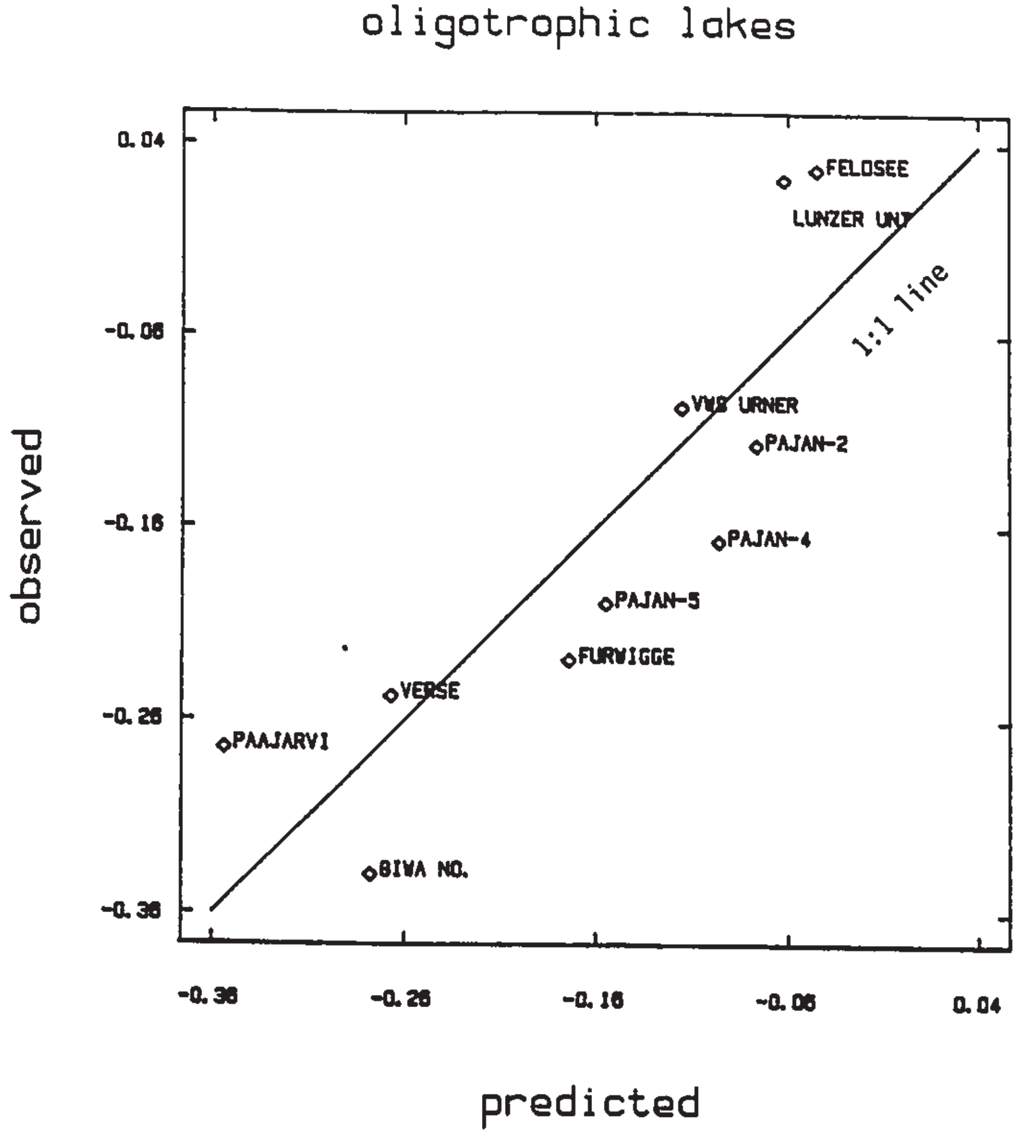
Note: Correlation of Coefficients (R^2) are for Simple or Multiple Linear Regressions of Log_{10} Transformed Data; N of Cases in Parentheses.

(L_N, q_s) combination retains its higher explanatory power than the (N_j, τ_w) model.

With trophic groupings in the two-variable models, the best r^2 value for oligotrophic waterbodies is given by the (N_j, τ_w) combination, while the best r^2 values for mesotrophic and eutrophic lakes is obtained with the (L_N, q_s) combination as independent variables.

The three-variable model does not lead to any substantial gains in r^2 values over the best two-variable model (i.e., L_N, q_s) in any category. However, the three-variable model does confer the advantage of giving the better of the two-variable model results, except for mesotrophic lakes where best prediction is obtained with the (L_N, q_s) combination as independent variables. The three-variable model results are plotted for each trophic category in Figures 3.15, 3.16 and 3.17.

A last question pertaining to the three-variable models for both phosphorus and nitrogen is whether or not they behave the same way in each of the three trophic categories. Table 3.8 shows the appropriate statistics to test the hypotheses for whether or not these relationships are parallel or coincident. The partial F tests for (τ_p/τ_w) show that the equations are not parallel (or coincident, necessarily). Therefore three separate equations should be retained to describe (τ_p/τ_w) in the three different groups. On the other hand, the partial F tests



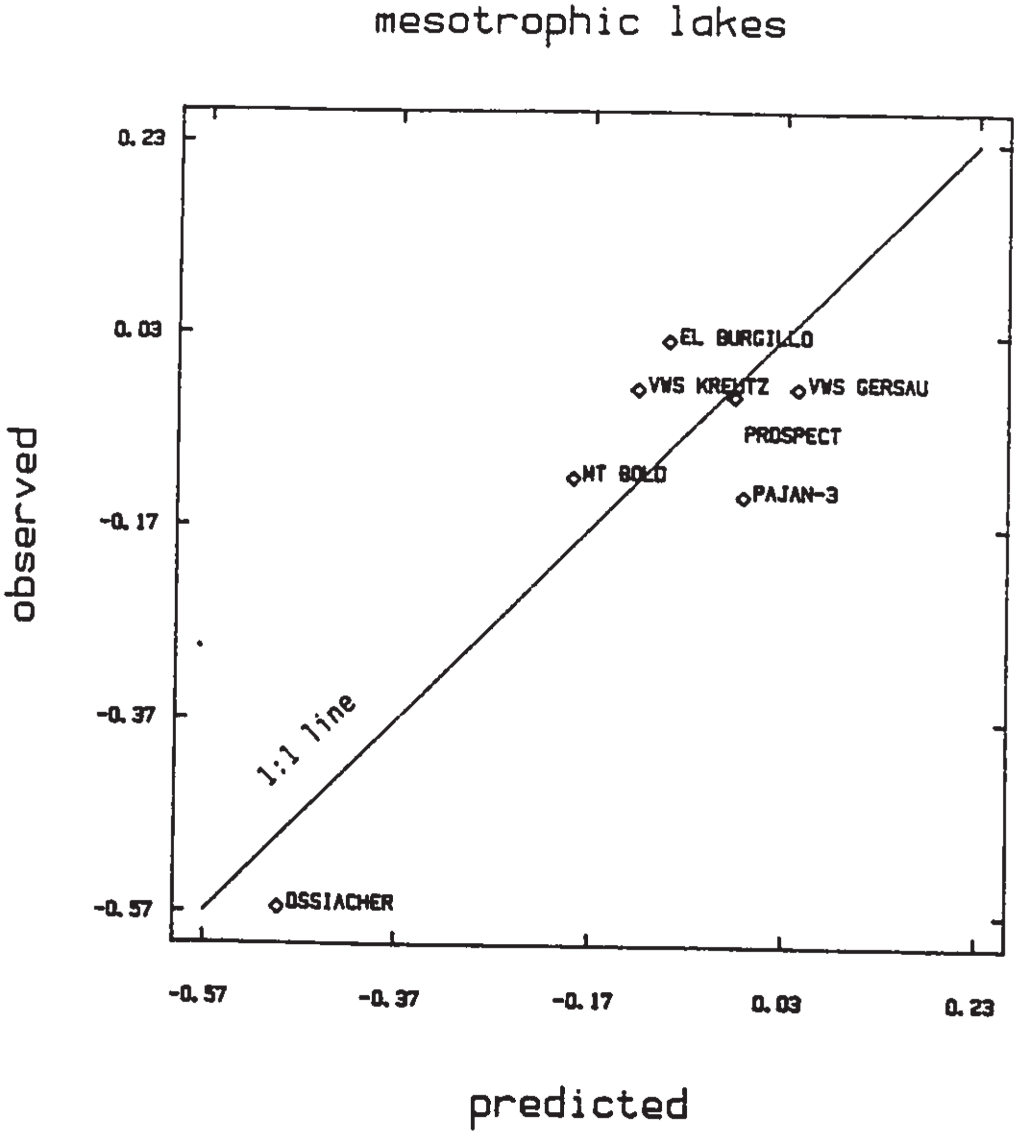
$(\tau_n/\tau_w) = (1.169)*(N_j^{-.123})*, \ \tau_w^{-.224} \ (\bar{z}^{.101})*$

*(p>0.20 for coefficient)

SEE = .076 n = 10

r^2 = .61 p = .03 (full model)

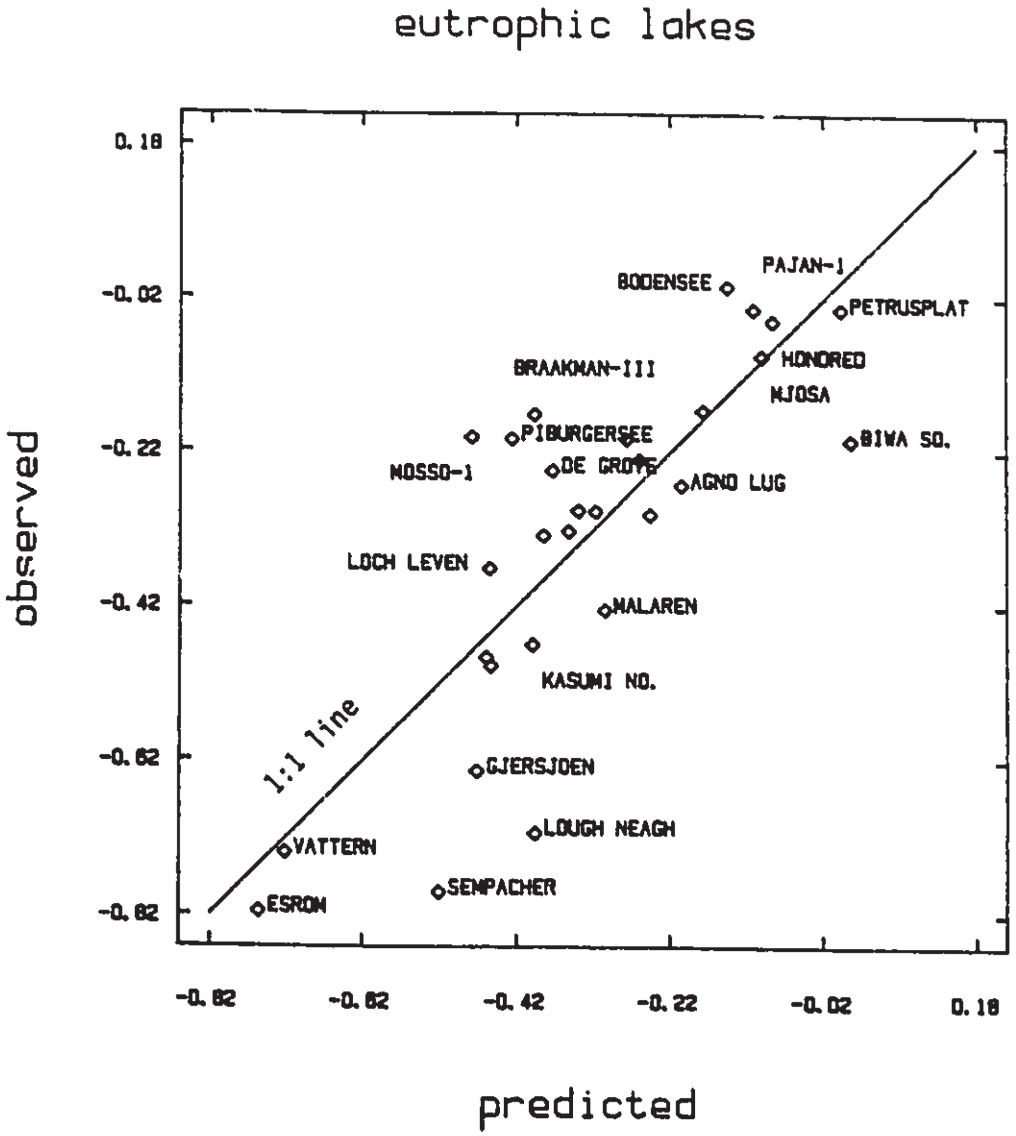
Figure 3.15 $(\tau n/\tau w) = f(Nj, \tau w, \bar{z})$: oligotrophic lakes.



$(\tau_n/\tau_w) = (0.030)*(N_j^{.113})*(\tau_w^{-.638})(\bar{z}^{.630})$

*(p>>.20:others ≈.20)
SEE = .132 n = 7
r^2 = .57 p = .16

Figure 3.16 $(\tau n/\tau w) = f(Nj, \tau w, \bar{z})$: mesotrophic lakes.



$$(\tau_n/\tau_w) = 0.272\ (N_j{}^{-.060})^*(\tau_w{}^{-.343})(\bar{z}^{.410})$$

$^*(p>.40)$
SEE = .145 n = 29
r^2 = .61 $p<.001$

Figure 3.17 $(\tau n/\tau w) = f(Nj,\ \tau w,\ \bar{z})$: eutrophic lakes.

TABLE 3.8. PARTIAL F TESTS FOR PARALLEL AND COINCIDENT TROPHIC CATEGORY RELATIONSHIPS FOR THREE-VARIABLE MODELS DESCRIBING NUTRIENT RELATIVE RESIDENCE TIMES.

Component	Model					
	$(\tau_p/\tau_w) = f(P_j, \tau_w, \bar{z})$			$(\tau_n/\tau_w) = f(N_j/\tau_w, \bar{z})$		
		r^2	df†		r^2	df†
a) SS full model*	11.846	0.59	11	1.626	0.64	11
b) SS model with same slope for all trophic groups	10.845	0.55	5	1.556	0.66	5
c) SS model with same slope and intercept for all trophic groups	9.571	0.49	3	1.532	0.66	3
d) MSE full model	0.046	-	159	0.018	-	34
PARTIAL F:						
i) Ho: parallel $\frac{(a-b)/8df^{\dagger}}{d}$	3.63**	-	6,159	0.486	-	6,34
ii) Ho: coincident $\frac{(a-c)/8df^{\dagger}}{d}$	(6.182**)	-	8,159	0.653	-	8,34

* The full model includes 11 coefficients for the three-variable models with trophic groups distinguished by dummy variables.

** Highly significant ($p < 0.001$).

† Degrees of freedom.

for (τ_n/τ_w) nitrogen show that all three trophic groups can all be treated with a single equation.

3.3.5 The Problem of Colinearity of the Physical Attributes, τ_w and z:

The high correlation with of τ_w with $\bar{z}$ ($r^2 = 0.30$ to 0.40, depending on lake grouping, cf. Table 3.9) is a pervasive underlying feature of all the cross-sectional modelling literature. This colinearity confounds the assignment of functional roles to either $\bar{z}$ or τ_w. Therefore, this section is devoted to answering two questions with regard to this relationship which may shed some light on their relative roles in determining nutrient residence times. First, this relationshp will be tested for its consistency between trophic groups and second, both τ_w and $\bar{z}$ will be tested for the significance of their additions to two- and three-variable models describing phosphorus and nitrogen relative residence times.

A scatterplot of τ_w versus $\bar{z}$ with trophic categories defined is given in Figure 3.18. The first question is whether or not this relationship is to be considered the same in all three trophic categories. Table 3.10 gives the results of tests for parallel and coincident lines for the three trophic groups using the dummy variable technique to distinguish trophic groups. The null hypothesis was accepted for both tests and therefore the relationship τ_w and $\bar{z}$ can be considered equivalent in all three

TABLE 3.9. CORRELATION COEFFICIENTS (r^2) OF τ_w AND $\bar{z}$ FOR DIFFERENT GROUPINGS OF LAKES.

Lake Group	r^2	n
Natural waterbodies	0.40**	172
Shallow lakes and reservoirs	0.004	35
All waterbodies together	0.35**	207
Oligotrophic	0.40**	78
Mesotrophic	0.37**	46
Eutrophic	0.29**	83

** $p < 0.001$.

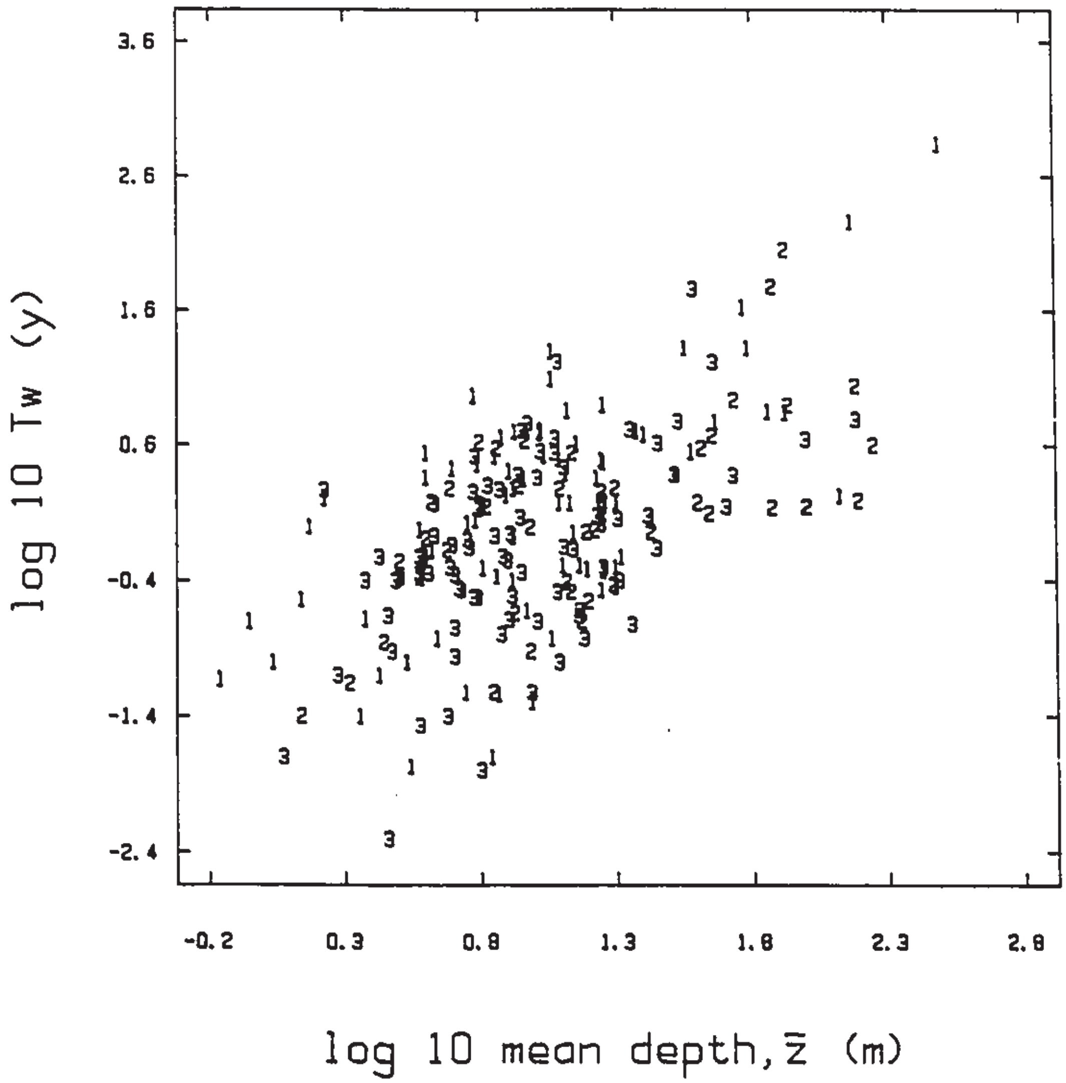


Figure 3.18 Water residence time vs mean depth with trophic groups defined.

TABLE 3.10. TEST OF HYPOTHESIS THAT THE MEAN DEPTH VERSUS WATER RESIDENCE TIME RELATIONSHIP IS THE SAME FOR ALL TROPHIC CATEGORIES.

Full model:

$$\hat{y} = \beta_0 + \beta_1 X + \beta_2 Z_1 + \beta_3 Z_2 + \beta_4 Z_1 X + \beta_5 Z_2 X + E$$

where $y = \tau_w$

$X = \bar{Z}$

Z_1 = mesotrophic increment

Z_2 = eutrophic increment

1) Test for parallel lines:

$H_0 : \beta_4 = \beta_5 = 0$

tested by $F(Z_1X, Z_2X \mid Z_1, Z_2, X)$

$$F = \frac{(44.296 - 43.688)/204}{73.615/201}$$

F = 0.008 NS; H_0 accepted; lines are parallel

2) Test for coincidence:

$H_0 : \beta_2 = \beta_3 = \beta_4 = \beta_5 = 0$

tested by $F(Z_1, Z_2, Z_1X, Z_2X \mid X)$

$$F = \frac{(44.296 - 41.559)/202}{73.615/202}$$

F = 0.037 NS; H_0 accepted; lines are coincident trophic categories. The regression line with 95% confidence and prediction limits is shown in Figure 3.19.

The second question pertains to the significance of adding either τ_w or $\bar{z}$ to the two- and three-variable models given in the previous section. To investigate this, the partial F tests for τ_w and $\bar{z}$ added after other variables have been accounted for are listed for phosphorus and nitrogen in Tables 3.11, 3.12, 3.13 and 3.14.

The consideration of phosphorus relationships shows that the addition of τ_w to models (cf. Table 3.11) is highly significant for all lake groupings both before and after the inclusion of $\bar{z}$. Therefore, water residence time plays an important explanatory role independent of its relationship with mean depth.

The exchange of position of $\bar{z}$ and τ_w in this same sequence is given in Table 3.12 in order to examine the significance of $\bar{z}$. When all lakes are taken together, mean depth is significant at least at the 95% level both with and without water residence time accounted for. However, with trophic breakdown, $\bar{z}$ is only significant in the oligotrophic category before τ_w is added to the model and in the mesotrophic category after τ_w has been accounted for. Therefore, mean depth has most explanatory power in the mesotrophic category (provided the effects of τ_w have been considered).

In consideration of the nitrogen relationships, Table 3.13 shows that water residence time is significant at least at

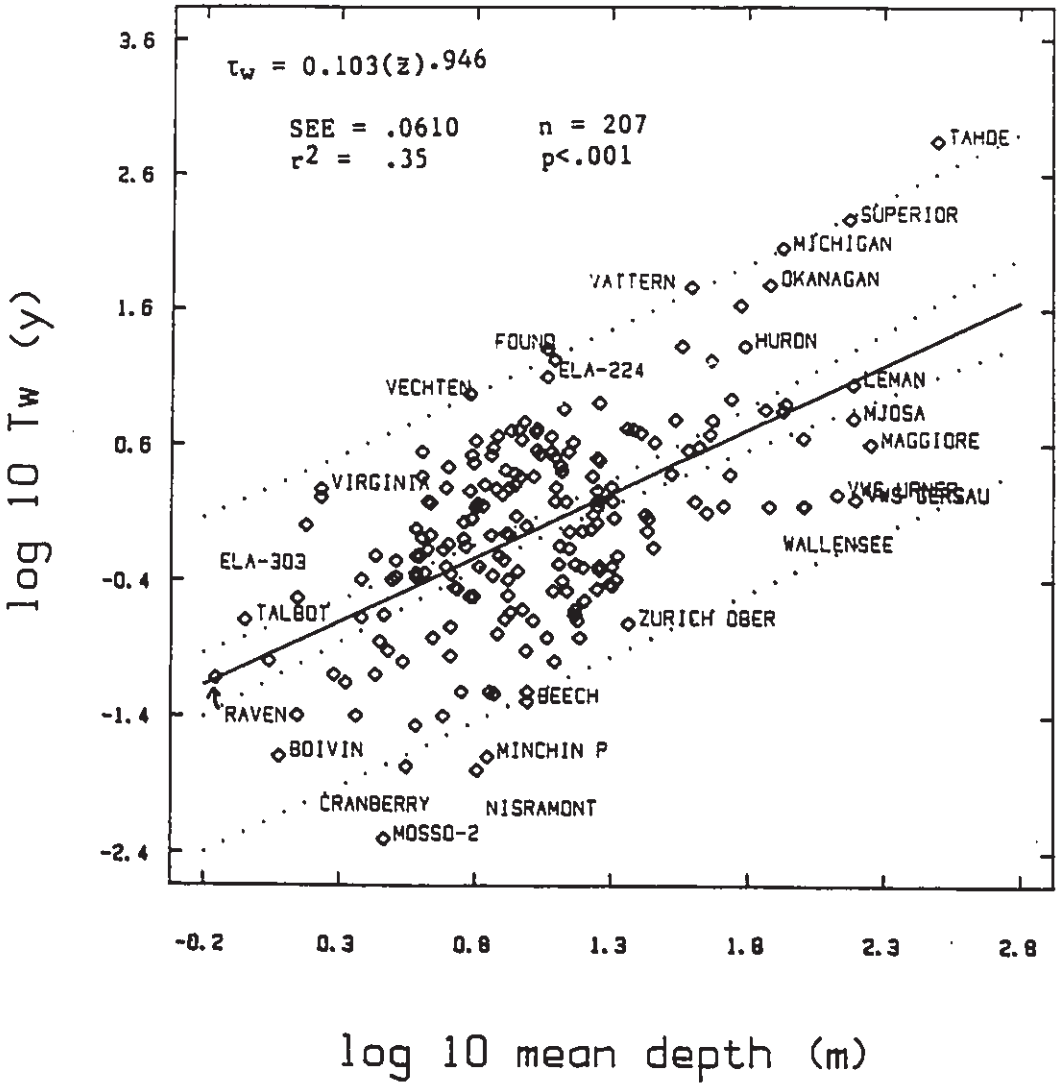


Figure 3.19 Water residence time (τw) vs mean depth ($\bar{z}$) in 207 waterbodies.

Table 3.11. Partial F tests for the significance of water residence time (τ_w) in models to explain phosphorus relative residence time (P_λ/P_j), including trophic breakdown.

Model Component	Partial F	r^2 for Full Model	n
A. All Trophic Groups:			
P_j	(32.92**)	.16	171
$\tau_w \mid P_j$	105.68**	.48	171
$\tau_w \mid P_j, \bar{z}$	89.48**	.49	171
B. Oligotrophic:			
P_j	(150.22**)	.73	57
$\tau_w \mid P_j$	38.26**	.84	57
$\tau_w \mid P_j, \bar{z}$	20.46**	.83	57
C. Mesotrophic:			
P_j	(52.75**)	.57	40
$\tau_w \mid P_j$	9.39**	.64	39
$\tau_w \mid P_j, \bar{z}$	22.58**	.72	39
D. Eutrophic:			
P_j	(14.76**)	.16	75
$\tau_w \mid P_j$	9.97**	.25	75
$\tau_w \mid P_j, \bar{z}$	8.61**	.24	75

** $p < .001$

Table 3.12. Partial F tests for the significance of mean depth ($\bar{z}$) in models to explain phosphorus relative residence time (P_λ/P_j), including trophic breakdown.

Model Component	Partial F	r^2 for Full Model	n
A. All Trophic Groups:			
P_j	(32.92**)	.16	171
$\bar{z} \mid P_j$	15.37**	.22	171
$\bar{z} \mid P_j, \tau_w$	4.84*	.49	171
B. Oligotrophic:			
P_j	(150.22**)	.73	57
$\bar{z} \mid P_j$	12.77**	.78	57
$\bar{z} \mid P_j, \tau_w$	0.17	.83	57
C. Mesotrophic:			
P_j	(52.75**)	.57	40
$\bar{z} \mid P_j$	0.59	.55	39
$\bar{z} \mid P_j, \tau_w$	11.41**	.72	39
D. Eutrophic:			
P_j	(14.76**)	.16	75
$\bar{z} \mid P_j$	1.73	.17	75
$\bar{z} \mid P_j, \tau_w$	0.61	.25	75

** $p < .001$
* $p < .05$

Table 3.13. Partial F tests for the significance of water residence time (τ_w) in models to explain nitrogen relative residence time (N_λ/N_j), including trophic breakdown.

Model Component	Partial F	r^2 for Full Model	n
A. All Trophic Groups:			
N_j	(14.57**)	.23	46
$\tau_w \mid N_j$	19.06**	.46	46
$\tau_w \mid N_j, \bar{z}$	58.00**	.66	46
B. Oligotrophic:			
N_j	(2.97)	.18	10
$\tau_w \mid N_j$	9.60*	.60	10
$\tau_w \mid N_j, \bar{z}$	10.32*	.61	10
C. Mesotrophic:			
N_j	(7.31*)	.51	7
$\tau_w \mid N_j$	.20	.42	7
$\tau_w \mid N_j, \bar{z}$	2.62	.57	7
D. Eutrophic			
N_j	(2.12)	.04	29
$\tau_w \mid N_j$	11.22*	.30	29
$\tau_w \mid N_j, \bar{z}$	41.03**	.61	29

** $p < .001$
* $p < .05$

Table 3.14. Partial F tests for the significance of mean depth ($\bar{z}$) in models to explain nitrogen relative residence time (N_λ/N_j), including trophic breakdown.

Model Component	Partial F	r^2 for Full Model	n
A. All Trophic Groups:			
N_j	(14.57**)	.23	46
$\bar{z} \mid N_j$	.09	.22	46
$\bar{z} \mid N_j, \tau_w$	27.72**	.66	46
B. Oligotrophic:			
N_j	(2.97)	.18	10
$\bar{z} \mid N_j$	0.23	.09	10
$\bar{z} \mid N_j, \tau_w$	1.17	.61	10
C. Mesotrophic:			
N_j	(7.31*)	.51	7
$\bar{z} \mid N_j$	<.001	.39	7
$\bar{z} \mid N_j, \tau_w$	2.35	.57	7
D. Eutrophic:			
N_j	(2.12)	.04	29
$\bar{z} \mid N_j$	0.06	.004	29
$\bar{z} \mid N_j, \tau_w$	21.23**	.61	29

** $p < .001$
* $p < .05$

the 95% level with or without the inclusion of $\bar{z}$ effects with the exception of the mesotrophic category. In this group, τ_w does not add to the explanation of (N_λ/N_j).

Table 3.14 shows the analogous test sequence for the significance of $\bar{z}$. This table shows that $\bar{z}$ is only signifcant in the cases of all trophic groups together and eutrophic waterbodies after the effects of τ_w have been adjusted for. Therefore, the effects of $\bar{z}$ are more subtle than those of τ_w, and only appear in the eutrophic group after τ_w has been taken into account.

In summary of the analyses on the relative contributions of τ_w and $\bar{z}$, it appears that τ_w is uniformly important as an explanatory variable for nutrient relative residence times. The role of mean depth is variable. While it is most significant for phosphorus in the oligotrophic and mesotrophic groups, it is most significant for nitrogen in the eutrophic group. This variability would suggest that $\bar{z}$ should be retained in all models to simulaneously retain both the highest percent explanation of variation and comparability of equations from group to group.

3.3.6 Significance of Biological Attributes in Relation to Phosphorus Relative Residence Time

Four biological variables (i.e., annual mean euphotic chlorophyll, annual areal primary production, annual mean euphotic algal biomass and annual areal hypolimnetic oxygen depletion) were tested individually for their ability to improve the percent explanation of (τ_p/τ_w) over and above the three-variable model described previously (i.e., $\tau_p/\tau_w = f(P_j, \tau_w, \bar{z})$. The three-variable model was presupposed to be the physical basis which might be further influenced by biological events. Following this line of reasoning, partial F statistics were calculated for each biological variable, given that P_j, τ_w and $\bar{z}$ were already entered into the model. The test statistic was formed by the ratio:

$$\text{partial F} = \frac{(\text{SS}_4 \text{ variables} - \text{SS}_3 \text{ variables})/\text{df}}{\text{MSE}_4 \text{ variables}}$$

where "3 variables" refers to the physical effects and "4 variables" refers to physical plus biological effects.

Twenty-four partial F values (for each of the six waterbody groupings and four biological variables) are given in Table 3.15. Correlation coefficients (r^2) for models both before and after addition of each biolgoical variable are also given for comparison.

Of the four variables tested, a comparison of groups shows that chlorophyll has the highest incidence of significance with greatest effect in All, Natural and Eutrophic waterbody groups. In these groups, r^2 values increased by approximately 0.10 by addition of chlorophyll to the models.

Annual areal primary production is significant for all waterbodies together and natural waterbodies.

TABLE 3.15. PARTIAL F TESTS FOR THE SIGNIFICANCE OF BIOLOGICAL VARIABLES ADDED TO A THREE-VARIABLE PHYSICAL MODEL FOR (τ_p/τ_w).

Biological variable	Data Group	Partial F	r^2 for 3 variables	r^2 for 4 variables	n
A. Annual mean euphotic chlorophyll (ANEUCHL)	All	26.89**	0.48	0.58	115
	Oligo-	3.04†	0.84	0.85	33
	Meso-	0.00	0.61	0.67	22
	Eu-	8.72*	0.26	0.35	60
	Natural	22.07**	0.48	0.59	87
	SLR	2.29	0.39	0.42	28
B. Annual area primary production (YPRAR)	All	13.25**	0.35	0.45	69
	Oligo-	1.65	0.90	0.91	18
	Meso-	0.24	0.65	0.64	20
	Eu-	2.83	0.08	0.14	29
	Natural	10.26*	0.35	0.45	59
	SLR	0.05	0.28	0.05	8
C. Annual mean euphotic algal biomass (ANEUALG)	All	7.99††	0.00	0.39	14
	Oligo-$^{(a)}$	-	-	-	-
	Meso-	0.16	0.76	0.58	6
	Eu-	0.07	0.11	0.00	8
	Natural	4.69	0.00	0.18	13
	SLR$^{(a)}$	-	-	-	-
D. Annual areal hypolimnetic oxygen depletion (O2DM2)	All	1.15	0.07	0.08	34
	Oligo-	0.27	0.80	0.78	12
	Meso-	1.04	0.07	0.06	9
	En-	3.50	0.00	0.14	13
	Natural	0.85	0.00	0.00	11
	SLR$^{(a)}$	-	-	-	-

† $p<0.10$
†† $p<0.05$
* $p<0.01$
** $p<0.001$
(a) Insufficient data to evaluate model.

Annual mean euphotic algal biomass was only significant at the 95% level for all waterbodies and areal hypolimnetic oxygen depletion was insignificant in all groups. However, data on these two biological variables is relatively rare.

In summary, the annual mean chlorophyll level, usually considered an index of algal biomass, appears to be the most effective variable in supplementing the explanation of the variability of (τ_p/τ_w).

3.3.7 Significance of Biological Attributes in Relation to Nitrogen Relative Residence Time

A series of partial F statistics was calculated for (τ_n/τ_w) parallel to the series for (τ_p/τ_w) in the previous section.

However, annual euphotic algal biomass had to be dropped from the biological variables due to too few observations. Therefore, only annual mean euphotic chlorophyll, annual areal primary production and areal hypolimnetic oxygen depletion could be tested. The partial F tests for these three variables are given in Table 3.16.

None of the biological variables tested contributes to the explanation of (τ_n/τ_w). In fact, the addition of these variables tends to decrease r^2 values due to te increased degrees of freedom associated with the model. Therefore, the addition of these biological variables to multiple regression models which explain (τ_n/τ_w) is not recommended.

TABLE 3.16. PARTIAL F TESTS FOR THE SIGNIFICANCE OF BIOLOGICAL VARIABLES ADDED TO A THREE-VARIABLE PHYSICAL MODEL FOR (τ_n/τ_w).

Biological variable	Data Group	Partial F	r^2 for 3 variables	r^2 for 4 variables	n
A. Annual mean euphotic chlorophyll (ANEUCHL)	All	0.28	0.61	0.60	40
	Oligo-	0.00	0.59	0.48	9
	Meso-(a)	-	-	-	-
	Eu-	1.91	0.54	0.56	26
	Natural	0.31	0.65	0.64	26
	SLR	1.74	0.78	0.73	14
B. Annual area primary production (YPRAR)	All	1.84	0.35	0.63	21
	Oligo-(a)	-	0.90	-	-
	Meso-(a)	-	0.65	-	-
	Eu-	0.35	0.08	0.35	13
	Natural	0.61	0.35	0.40	12
	SLR(a)	-	0.28	-	-
C. Annual mean euphotic algal biomass (ANEUALG)	All	0.00	0.00	0.78	25
	Oligo-	0.05	-	0.54	10
	Meso-(a)	-	0.76	-	-
	Eu-	1.14	0.11	0.85	10
	Natural	0.09	0.00	0.79	19
	SLR(a)	-	-	-	-

(a) Insufficient data to evaluate model.

3.3.8 Phosphorus and Nitrogen Residence Time Interrelationships

The regression relationships referred to in this section are listed in Table 3.17. This table shows that a high positive correlation ($r^2 = 0.73$) exists between the absolute residence time of nitrogen (τ_n) and phosphorus (τ_p) (cf. Figure 3.20). If trophic categories are distinguished (cf. Figure 3.21), it is notable that only eutrophic and two mesotrophic lakes are found below the 1:1 line. Therefore, only the more eutrophic waterbodies dislay phosphorus residence times which exceed those of nitrogen. In oligotrophic waterbodies nitrogen residence times exceed those of phosphorus.

A plot of nitrogen relative residence time (τ_n/τ_w) versus phosphorus relative residence time (τ_p/τ_w) has a highly significant regession line, but low r^2 (0.25; cf. Figure 3.22). Therefore, the sedimentation rates of nitrogen and phosphorus are only loosely associated with one another.

If trophic categories are distinguished (cf. Figure 3.23), it is notable that similar to absolute residence times, only eutrophic and two mesotrophic waterbodies fall below the 1:1 line. Therefore, the flow-through rate of nitrogen exceeds that of phosphorus only in eutrophic systems, whereas phosphorus may exceed nitrogen flow rates in all trophic conditions and this is more generally the rule as demonstrated by the majority of waterbodies which lie above the 1:1 line. In addition, there appears

TABLE 3.17. REGRESSION EQUATIONS WHICH DESCRIBE PHOSPHORUS AND NITROGEN RESIDENCE TIME INTERRELATIONSHIPS

	Equation	p	SEE	r^2	n
1)	$\tau_n = 1.131\ \tau_p^{0.841}$	0.000	0.281	0.73	46
2)	$\tau_p = 2.454\ \tau_w^{0.710}$	0.000	0.261	0.81	171
3)	$\tau_n = 0.543\ \tau_p^{0.807}$	0.000	0.191	0.87	46
4)	$(\tau_n/\tau_w) = 0.754\ (\tau_p/\tau_w)^{-0.633}$	0.000	0.195	0.25	46
5)	$(\tau_n/\tau_w) = 0.726\ (\tau_p/\tau_w)^{-0.633}$	0.000	0.212	0.48	46
6)	$(\tau_n/\tau_w) = 1.131\ \tau_p^{-0.160}$	0.046	0.281	0.09	46
7)	$(\tau_n/\tau_w) = 1.550\ \tau_n^{0.288}$	0.141	0.287	0.05	46
8)	$(\tau_n/\tau_w) = 1.415\ \tau_n^{0.136}$	0.097	0.285	0.06	46
9)	$(\tau_n/\tau_w) = 1.302\ \tau_w^{0.063}$	0.035	0.291	0.02	46

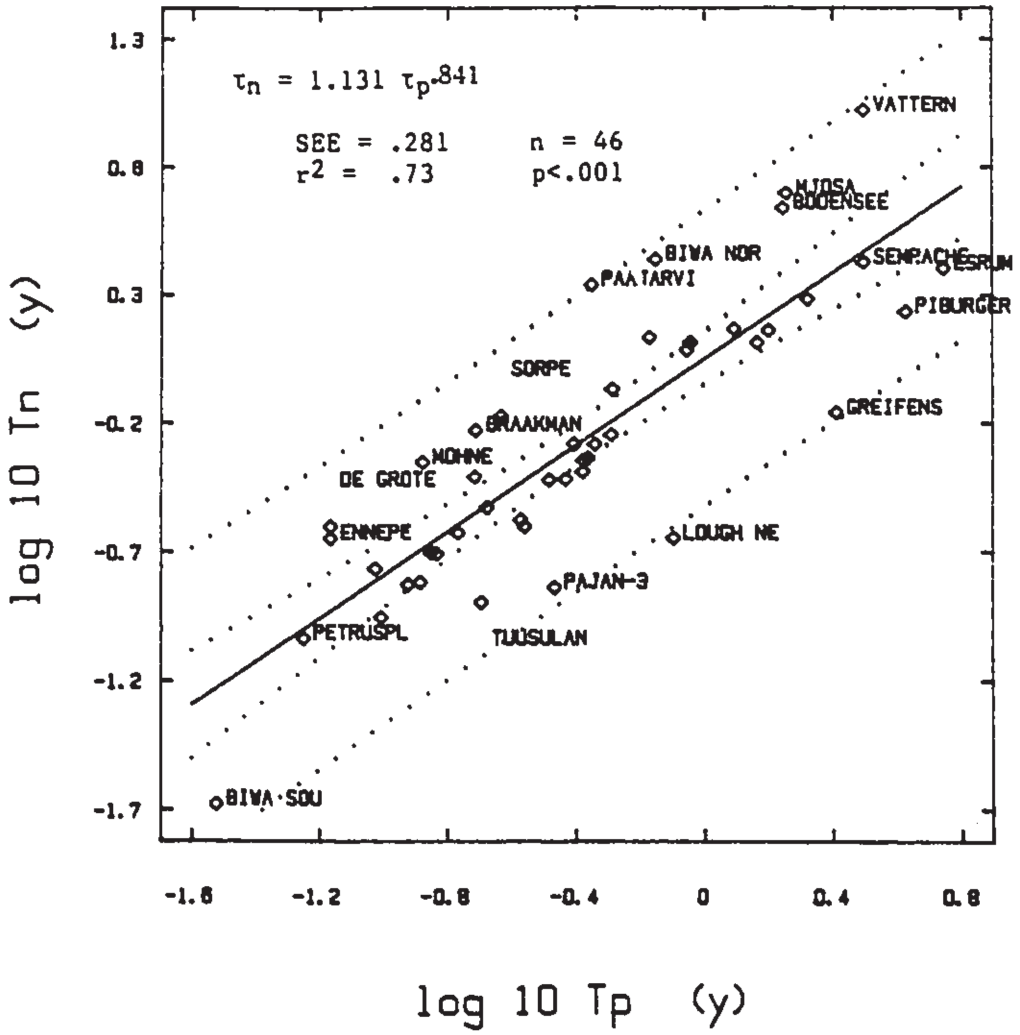


Figure 3.20 τ_n vs τ_p in all waterbodies.

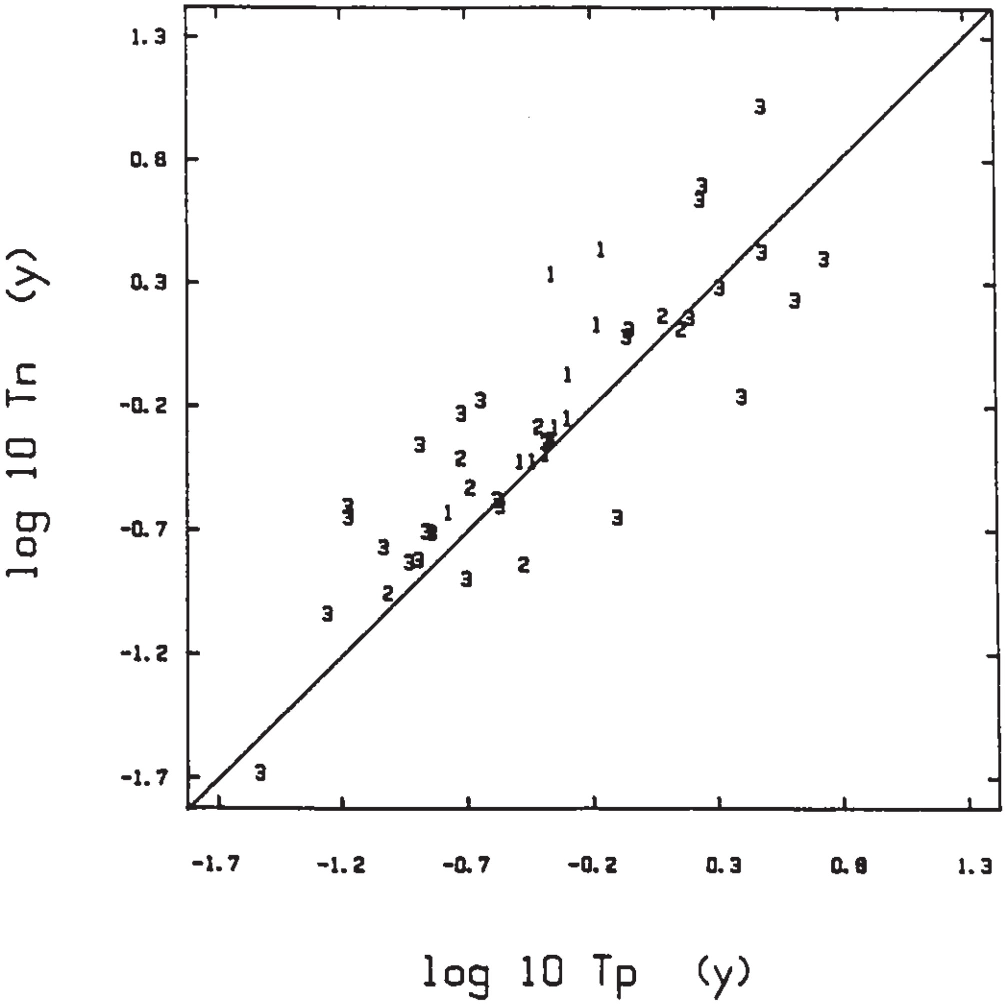
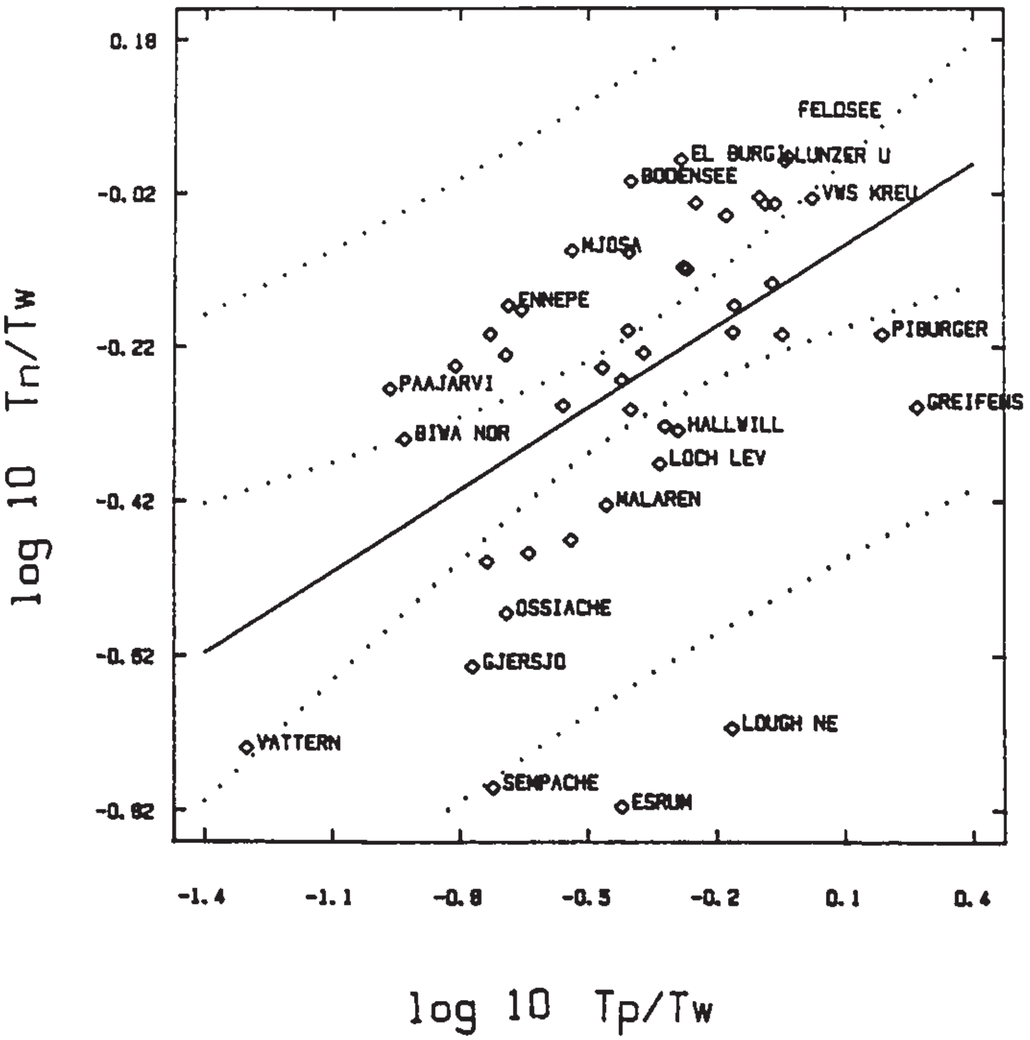


Figure 3.21 τn vs τp with trophic groups defined.



$$(\tau_n/\tau_w) = 0.754(\tau_p/\tau_w)^{.353}$$

SEE = .195 n=46
r^2 = .25 $p<.001$

Figure 3.22 ($\tau n/\tau w$) vs ($\tau p/\tau w$) for all waterbodies.

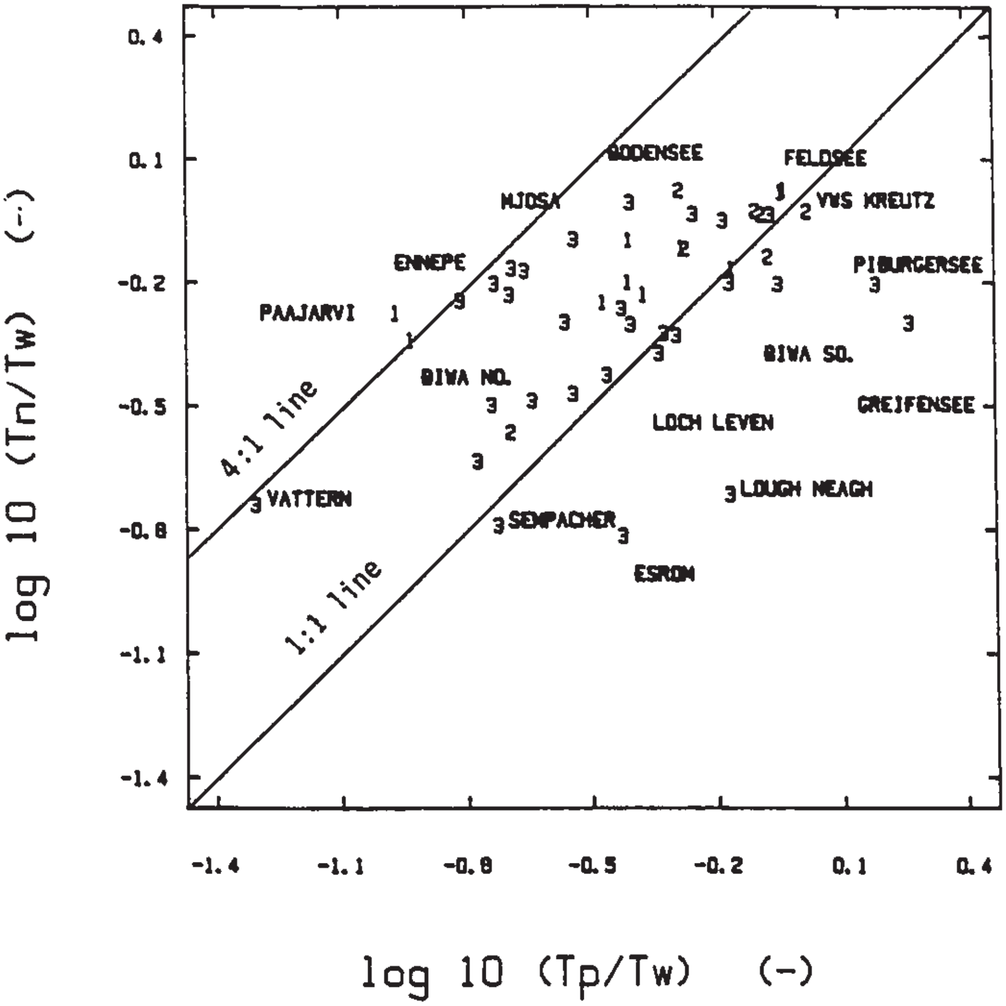


Figure 3.23 (τn/τw) vs (τp/τw) with trophic groups defined.

to be an upper limit of (τ_n/τ_p) at about 4:1 (cf. Figure 3.23. This implies that phosphorus flow rates are never less than about 25% of the nitrogen flow rates.

Four regressions for (τ_n/τ_p) versus (τ_p/τ_w), τ_p, (τ_n/τ_w) and τ_n show that the best relationship is with (τ_p/τ_w), however these relationships are all weak and r^2 values are all less than 0.10 (cf. Table 3.17 given previously).

3.4. Discussion of the Cross-Sectional Results

The data used for this analysis collectively represent a substantial proportion of the world's freshwater supply. The total water surface area represented by the data is 21% of the world's total, which is reported as 1.3 x 10E6 km^2, excluding the Caspian and Aral Seas (R.A. Vollenweider, personal communication). The freshwater volume represented is 19% of the world's total which is reported as 125 x 10E3 km3 (Pearse, *et al*.,1985). Therefore, the results are thought to be truly indicative of the general situation in waterbodies, particularly of the Northern Temperate Zone since most of the data originate there.

A wide variety of geologic, hydrologic, morphometric and biological conditions are represented by the data as described previously in Section 3.2. These conditions include the tiny dyked pump storage reservoirs with artificial bottoms to the vast natural Laurentian Great Lakes which border Canada and the United States. Although this diversity results in high variability of the data, it also serves to delimit the full realm of possibile conditions to be found in freshwaters. The wide representation of conditions means that the results given here are unlikely to change essentially with the addition of new cases. The observed relationships may therefore be thought of as reference standards by which new situations may be evaluated in the same way that the OECD "Standard Regressions" have been used (cf. Vollenweider and Kerekes, 1980).

The analyses of the cross-sectional data were done using a log 10 transformation of all data in order to equalize variance as required for the regression procedures and to maintain comparability with previous work. In addition, this resulted in multiplicative models which were thought to be more descriptive of reality than additive models.

Several data groupings were used to identify where waterbodies could be considered homogeneous populations and where they behaved differently. The two breakdowns used were i) shallow lakes and reservoirs (SLR) vs natural waterbodies and ii) the three trophic groups.

The shallow lakes and reservoirs (SLR) group was composed of 75% (i.e. 27/36) eutrophic waterbodies and therefore this group reflected the characteristics of eutrophic environments. The SLR group had higher loads of both water and nutrients and higher chlorophyll levels than the natural lakes group. Perhaps the most interesting observation in regard to this grouping was the fact that while the N / P loading ratio was lower, the mean lake and outflow ratios were higher than those of natural lakes. This is consistent with the observation by Chapra (1981) that elongate, incompletely mixed reservoirs are more efficient sinks for phosphorus than most natural lakes. The data here showed that both the phosphorus sedimentation rates and apparent settling velocities are higher in the SLR group than in the natural lakes group. The more efficient sedimentation of phosphorus could explain the progressive increase from inflow to outflow in the N/P concentration ratios of these basins.

The trophic grouping of waterbodies revealed that the eutrophic group included lakes of large dimensions and high nurient levels. Drainage areas, lake surface areas and volumes were highest in this group, however mean depths tended to be shallow. These results were largely expected since these features have commonly been associated with eutrophic lakes throughout the limnological literature. For example, Rawson (1955) used mean depth as a predictor of lake biomass and Vollenweider (1968) found that trophic condition could be estimated from a plot of areal phosphorus load vs mean depth. Hydraulic loads and nutrient concentrations of the inflow, lake and outflow all tended to be higher in the eutrophic group than in the other trophic groups. This was reflected as higher levels in the chlorophyll and biomass measurements, as well as the monthly hypolimnetic oxygen depletion. The N/P concentration ratios of the inflow, lake and outflow were all lower than those of the other trophic groups, therefore there is a general trend of phosphorus overenrichment relative to nitrogen in eutrophic waterbodies. Absolute residence times of both phosphorus and nitrogen were shorter in the eutrophic group as would be expected from the generally high hydraulic loads of these environments, but relative residence times of phosphorus were generally longest in the eutrophic group. This implies that phosphorus recycling mechanisms become more important with increasing eutrophication. (Further discussion of this topic is taken up later.)

Multivariate relationships (i.e. stepwise multiple regressions) were developed to arrive at the best expressions to describe relative residence times. In order to develop these equations, all correlations with $p < 0.05$ of the available explanatory variables with nitrogen and phosphorus absolute and relative residence times were considered provided correlation coefficients (r) were above 0.30. It was found that absolute residence times of nitrogen and phosphorus were best explained by water residence times for all waterbody groupings, and therefore physical transport was found to be the dominant factor which determines absolute nutrient residence times.

Calculation of nutrient residence times relative to water provides a measure which corrects for the variation of water residence times among different lakes and therefore provides a comparative measure which relates to the chemical and biological differences of waterbodies. With this in mind, the multiple regressions were formulated in two steps. First, the physical and hydrologic variables were used in conjunction with nutrient loads to describe relative residence times. These "physical and morphometric" models were considered to be the basis upon which biological and chemical effects could act to create the observed variations in relative residence times. Consequently, biological factors added to these models were tested for their ability to improve the explaination of relative residence times.

In the case of phosphorus, absolute phosphorus residence time (τ_p) is best explained by water residence time (τ_w). A plot of τ_p vs τ_w shows that this relationship lies below the 1:1 line, particularly in the upper range of τ_w. The lakes which lie in this upper range (i.e. τ_w > 10 y) are large, deep oligotrophic and mesotrophic lakes including Tahoe, Superior and Michigan. These lakes are particularly efficient in phosphorus sedimentation and this indicates that there is an interaction between mean depth and τ_w. Depth has the effect of isolating the sediments from the most turbulent regions of the water column thus minimizing recycling and resuspension. The effect of depth seems to be particularly apparent when τw is greater than 10 years. Lake Annone also lies in a low position on the plot of τ_p vs τ_w but this is most likely due to the industrial effluent it recieved which tended to precipitate phosphorus and reduce its concentration. In contrast, lakes such as the Baldeggersee, known to undergo internal loading (cf. Imboden, 1985) may lie slightly above the 1:1 line due to the reflux of nutrients from the sediments.

The "physical" model series for the relative residence time of phoshorus (τ_p/τ_w) had highest r^2 values by the inclusion of all three of the variables (i.e. Pj, τ_w and $\bar{z}$) in the model, combined with trophic categorization of the waterbodies. The r^2 values were highest in the oligotrophic group (i.e. 0.83) and lowest in the eutrophic group (i.e. 0.25). The variability of the eutrophic group seems to indicate that there are more processes at work acting to modify the cycling of phosphorus in this group than in the more consistent pattern of the oligotrophic group. Therefore, biological variables were added to the models in an attempt to explain a greater proportion of the variation.

The addition of biological variables to the models for (τ_p/τ_w) showed that chlorophyll was the most effective; annual primary production,annual euphotic algal biomass and areal hypolimnetic oxygen depletion rates did not improve the models, however this may be due in part to the scarcity of data for these variables. The positive coefficients for chlorophyll in the regression equations imply that the chlorophyll measurements on an annual time scale reflect the recycling of phosphorus rather than deposition by uptake and sedimentation of algal cells as one would observe at shorter time scales. It is generally known that biomass decomposition in the sediments of lakes depletes the oxygen and this may result in the release of phosphorus (cf. Mortimer, 1946 and 1947). Annual chlorophyll levels therefore appear to reflect this reflux of phosphorus as well as being instrumental in creating it.

In the case of nitrogen, absolute nitrogen residence time (τ_n) was best explained by water residence time (τ_w), similar to the case for phosphorus. The correlations were high for nitrogen ($r^2 > 0.80$) in all trophic groups which implies that there are not as varied an array of influences or interactions for the nitrogen cycle as for the phosphorus cycle in waterbodies, that is to say that 80% of the variation in τn can be explained by physical transport by water alone. The nitrogen relationship (τ_n vs τ_w) lies closer to the 1:1 line than does the phosphorus relationship (τ_p vs τ_w). In the upper range of τ_w, the eutrophic lakes tend to lie below the regression line, thus the eutrophic condition appears to promote the elimination of nitrogen from the system rather than cause its stagnation or recirculation as in the case of phosphorus. This may occur via uptake by phytoplankton and macrophytes and through denitrification under anoxic conditions.

Models for the relative residence time of nitrogen ($\tau n/\tau w$) showed that the inclusion of all three variables (i.e. Nj, τ_w and $\overline{z}$) in the "physical" model series were best in order to retain the highest r^2 values in all trophic categories. The r^2 values are much more equitable between trophic groups than in the case of phosphorus and are approximately 0.60 in all three groups for the three variable model. It also appears that $\overline{z}$ has has greater significance for the nitrogen models than for the phosphorus models, particularly in the eutrophic group. The coefficient for $\overline{z}$ is positive (at about 0.40 in the eutrophic group) and this may indicate that isolation of the sediments by virtue of increased depth results in a lower probability of denitrification and therefore longer (τ_n/τ_w). In any case it appears that all three variables should be retained in the model. In addition, unlike phosphorus, all three trophic groups may be described by one equation; there was no significant difference in the equations for trophic groups treated separately.

The addition of biological variables to improve the explaination of (τ_n/τ_w) was unsucessful, so a single three variable model based on loadings, hydrology and morphometry (i.e. Ln, τ_w and $\bar{z}$) was the best that could be formulated with the available data.

With regard to the problem of collinearity of the independent variables τ_w and $\bar{z}$, it was shown that the relationship between these two variables was essentially the same for all three trophic groups. In addition, a series of significance tests showed that τ_w was universally important as an explanatory factor for relative residence times of both phosphorus and nitrogen, however the effect of $\bar{z}$ was variable. For phosphorus, $\bar{z}$ was only significant in the oligotrophic and mesotrophic groups in the explanation of (τ_p/τ_w) after τw was included in the model. For nitrogen, $\bar{z}$ was only significant in the eutrophic group in explanation of (τ_n/τ_w) after τw was included in the model. The variation in the effect of mean depth suggested that this parameter should be included in all models in order to attain the highest r^2 values and to retain comparability of equations for the different trophic groups.

In summary, (τ_p/τ_w) can best be described with a different four-variable multiple regression equation for each trophic group. On the other hand, nitrogen can best be described with a single three-variable equation for all trophic groups together. These equations are listed in Table 3.18.

Practical application of this result is in the refinement of estimations of critical loading levels as proposed by Vollenweider (1976). The equations for relative residence times of phosphorus as listed for the three trophic categories may be inserted into the following expression:

$$L_{crit.} = [P]_{crit.} \ \bar{z} \ . \ (1/(f(x).\rho))$$

where $[P]_{crit.}$ is the critical concentration of phosphorus above which signs of eutrophication appear (usually taken as 20 mg.m-3 for phosphorus); $\bar{z}$ is mean depth; $f(x)$ is the multiple regression equation for the appropriate trophic group as listed in Table 3.18; and ρ is the flushing rate. The nitrogen equation should be used for waterbodies with (τ_n/τ_p) less than 1 which are presumably cases of nitrogen limitation. This is to be considered an update of the expressions given by Vollenweider (1976) with the main difference here that there is now a specialized equation for each trophic category when phosphorus is considered limiting.

Table 3.18. Best regression equations for $(\tau p/\tau w)$ and $(\tau n/\tau w)$.

	SEE	r^2	n
A. Phosphorus:			
1) Oligotrophic:			
$(\tau p/\tau w) = 3.654Pj^{-.731}\ \tau w^{-.141}\ z^{-.028}\ Chl^{.028}$	.147	.85	33
2) Mesotrophic:			
$(\tau p/\tau w) = 1.145Pj^{-.478}\ \tau w^{-.271}\ z^{.269}\ Chl^{.001}$	.248	.59	22
3) Eutrophic:			
$(\tau p/\tau w) = 0.554Pj^{-.332}\ \tau w^{-.224}\ z^{.213}\ Chl^{.318}$	.239	.35	60
B. Nitrogen:			
All trophic groups:			
$(\tau n/\tau w) = 0.401Nj^{-.085}\ \tau w^{-.314}\ z^{.337}$	.129	.66	46

The differences found for the different trophic categories shows that some refinement of predictions by the cross-sectional models is possible. This was mainly achieved through grouping of waterbodies on the basis of the trophic group. Further groupings on the basis of common features (such as alkalinity, euphotic/tropholytic volume, etc.) may bring about further refinements, however the cross-sectionally derived models have certain limitations. The cross-sectional data embodies more sources of variation than that for a single lake since it includes all the physical, chemical and biological differences of lakes. Cross-sectional models may therefore reflect hydrologic or morphometric differences and such equations will not necessarily track temporal changes in a given lake. The most important predictor variables of a cross-sectional data set may be relatively constant features in a single lake and therefore cannot be expected to follow single lake dynamics closely; however, they will describe the correct order of magnitude. Therefore, the equations specialized for trophic condition may be better predictors of (τ_p/τ_w) as long as the original trophic condition is maintained, but will fail to a greater degree if the lake shifts to a different trophic condition. Lastly, the equations above should not be applied in the case of meromictic, tropical or highly turbid lakes since these conditions lie outside the realm of the data used for derivation of the equations.

The interdependence of τn and τp and their joint behaviour in relation to trophic conditions are two final points of discussion for the cross-sectional data. The increased availability of data and its elaboration here allows for some comparisons with earlier work by Vollenweider (1974) which gives some new insight into some early hypotheses. The remainder of this section is devoted to these topics.

The dependencies of phosphorus and nitrogen residence times were first explored by Vollenweider (1974). He reported the correlation coefficients (r) of τ_n with τ_w as 0.95 and of τ_p with τ_w as 0.76 using data on 14 lakes. From this he proposed the hypothesis that the stronger relation of τ_n with τ_w indicated the greater dependence of nitrogen (in contrast to phosphorus) on physical transport by water and a more conservative nature than phosphorus. In comparison, the data here for 172 waterbodies produces correlations for τ_n with τ_w of 0.93 and that for τ_p with τ_w of 0.90. Therefore with more data, the differences are not so pronounced and it would be difficult to defend this hypothesis of different dependencies on the sole basis of the cross-sectional correlations.

The interrelationship of phosphorus and nitrogen relative residence times do not appear to be very strong for annual mean values (i.e. on an annual time scale). The correlation of (τ_n/τ_w) with (τ_p/τ_w) shows that there is only a weak association between the two ($r^2 = 0.25$, $n = 46$). Therefore it appears that these nutrients are controlled by different agglomerations of processes to a greater extent than they are by the common process of metabolic uptake by plants. Some of the disparity in flow rates of the two nutrients appears to be related to oxygen conditions. The data here show that (τ_n/τ_p) is negatively correlated with volumetric hypolimnetic oxygen depletion. Further to this, τ_n is positively correlated to mean and maximum depth. These relationships imply that denitrification and sediment release of phosphorus, which both occur under anoxic conditions, create opposite effects in the flows of the two nutrients, and these are at least partial explanation of the weak association between the two.

A second hypothesis put forth by Vollenweider (1974) was that of a decreasing (τ_n/τ_p) ratio with increasing eutrophication (cf.Figure 1.5) As observed in the results, only the eutrophic waterbodies fall below the 1:1 line whereas any trophic group may be found above the 1:1 line in a plot of τ_n vs τ_p. The same pattern is observed in the plots of (τ_n/τ_w) vs (τ_p/τ_w). It appears that the flow-through rate of nitrogen only accelerates to a rate faster than that for phosphorus under eutrophic conditions. The explanation for this may be denitrification, but this may only be stated as a hypothesis for lack of further data. Notably, denitrification does not necessarily occur under eutrophic conditions, so $(\tau n/\tau p)$ may also assume values >1 despite eutrophic conditions.

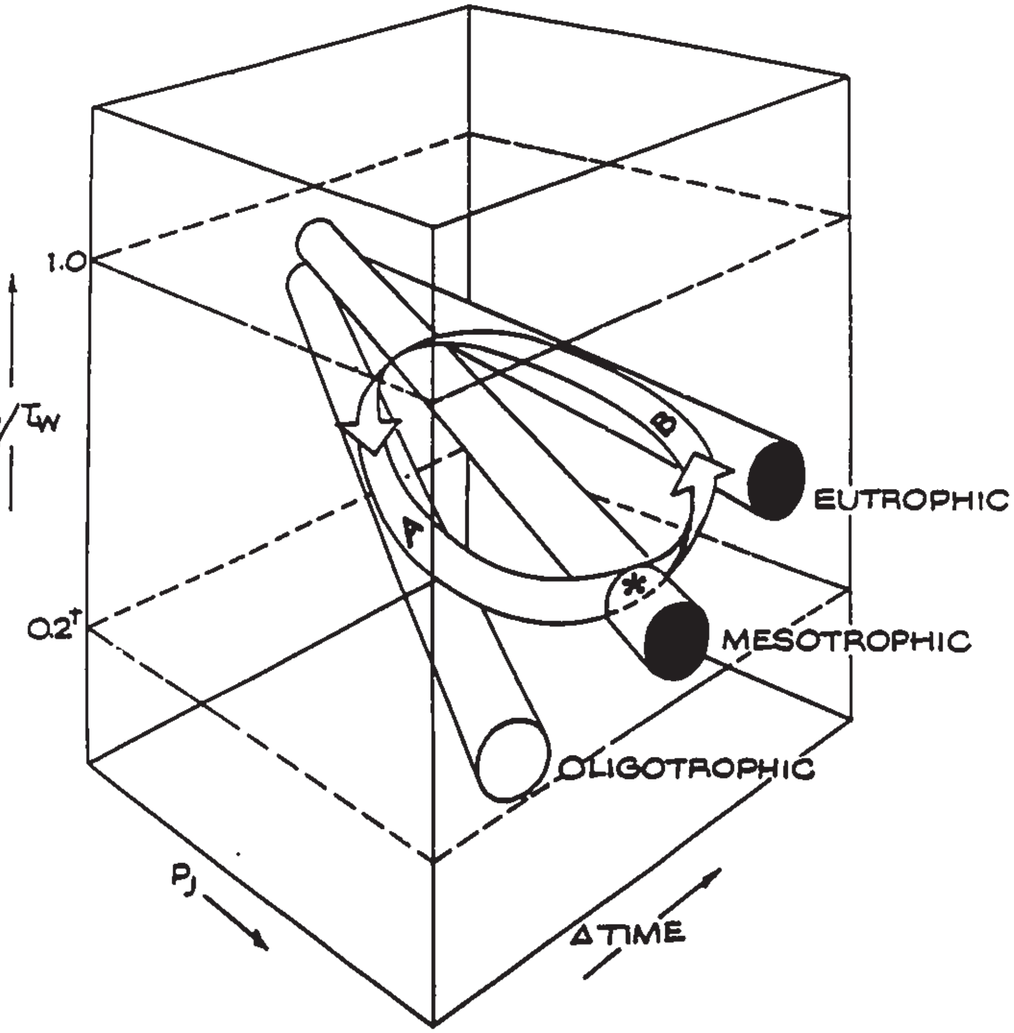
On the other end of the spectrum, nitrogen flow-through is always slower than phosphorus, i.e. $(\tau_n/\tau_w) > (\tau_p/\tau_w)$, and (τ_n/τ_p) is greater than 1 in oligotrophic waters. As a lower limit, (τ_p/τ_w) never drops below 1/4 of the (τ_n/τ_w) values, which is to say that phosphorus sedimentation never accelerates to values of more than about four times that of nitrogen. Furthermore, the best independent variable to explain (τ_n/τ_p) is (τ_p/τ_w). Therefore it appears that the (τ_n/τ_p) decrease with eutrophication is primarily the result of the variation in phosphorus sedimentation rates. As a last point, (τ_n/τ_p) is correlated with the N/P lake concentration ratio which implies that the concentration ratio may be used as a preliminary evaluation of the dynamic relationship between nitrogen and phosphorus.

In summary, (τ_p/τ_w) tends to increase with eutrophication due to internal recycling processes. This contributes to the observed decrease of (τ_n/τ_p) with increased trophic condition. At the same time, denitrification may occur which would also contribute to a decrease in the (τ_n/τ_p) ratio. These two processes may work independently or in conjunction and it is therefore not surprising that eutrophic waterbodies show a decrease of the (τ_n/τ_p) ratio to different extents, and for this reason the pattern is not highly uniform.

3.5 Interrelationships of the Time Series and Cross-Sectional Data

The final consideration of this work is the question of whether or not the cross-sectional patterns of nutrient residence times portray functional patterns. This can only be answered by an examination of how well the time series patterns depict the same trends, that is, how well the cross-sectional patterns can be verified by the time series patterns.

The behaviour of phosphorus relative residence time relative to inflow concentration in individual lakes is depicted in Chapter 2. In most cases the lakes have undergone increasing phosphorus loads and there is a distinct tendency for (τ_p/τ_w) to rise. In the case of decreasing load (eg. Shagawa and the Baldeggersee), there is a pattern of increase to a maximum and then decrease. This traces the same pattern as seen in the cross-sectional plot. The equations to describe (τ_p/τ_w) in the three different trophic categories were given earlier in Table 3.18. Although these cannot be represented graphically because of the number of dimensions, the basic relationships can be depicted by a simplified three dimensional version as in Figure 3.24. This figure shows that during a phase of increased



A - increasing loading phase
B - decreasing loading phase
* - transition point for critical load
\+ - observed lower limit

Figure 3.24 The cycle of relative residence time under changing loading conditions.

loading, the relative residence time (τ_p/τ_w) of the limiting nutrient will first decrease, then increase as the critical load is surpassed and the waterbody changes to a eutrophic condition. If loading is reduced, relative residence time will first increase during a phase of washout, then decrease as the waterbody changes to an oligotrophic phase. Unfortunately, little is known in regard to the time for these changes to take place. The best that can be done at present is to chart (τ_p/τ_w) for its point of change in direction under increasing or decreasing load as a mark of impending change of trophic condition.

Further to this, eutrophication may be distinguished as two types: resilient and permanent. The resilient type is caused by short term phenomena which do not change the basic nature of nutrient processing. Examples would be the cases of the algal increases in Lake Mjøsa and Lake Washington which are essentially oligotrophic lakes. These lakes responded immediately to phosphorus loading reductions and returned to their original oligotrophic conditions. Lac Léman is another example of this resilient type. The trophic expression of Léman is largely dependent on how cold the winter becomes or how much spring runoff there is. Deep mixing or a heavy silt load via runoff may cause an essentially oligotrophic lake to show symptoms of eutrophication. On the other hand, a more permanent type of eutrophication is exhibited by the Bodensee (Lake Constance) where the effects of heavy loading over many years has essentially changed the nutrient processing within the lake. Under this condition, loading reduction may be slow to produce a result since the reduction must be sufficient to create a washout phase that would allow desorption of phosphorus from the sediments and eventually change the sediment absorbtion capacity. Notably, the Sonzogni (1976) τp model for recovery time seems to describe sediment controlled lakes like the Bodensee best.

In conclusion, it appears that phosphorus plays a more significant role in the process of eutrophication than does nitrogen. Changes in phosphorus relative residence time appear to reflect the nutrient processing rates of waterbodies in a consistent way that follows changes in trophic status. This has allowed the formulation of new equations that may be used to estimate critical nutrient loads taking into account the trophic status of the waterbody in question. This method provides a more refined version of the critical loading equations proposed by Vollenweider (1976) more than a decade ago. Despite these refinements, as discussed previously, the cross-sectional information does not give sufficient resolution to describe short term changes. Only studies on the complex of processes important for a particular lake will lead to better understanding of its trophic expression; these will be the studies of the future.

4.0 CONCLUSIONS

The relationship of nutrient residence times to the trophic conditions of freshwater lakes and reservoirs was characterized using the vantagepoints of two types of data. The two data types consisted of time series information on individual lakes for nine different cases and cross-sectional information on 220 waterbodies of the OECD programme.

Nine case histories (i.e. the time series data) were used to answer three questions designed to give insight into the applicability of the cross-sectional models. Such models are used to predict phosphorus concentrations from loadings or conversely, loadings required to produce a desired mean lake concentration as is the usual concern in lake management. The scarcity of time series data for nutrient budgets has precluded answers to these questions up to now.

The first question answered was whether or not individual lakes had relatively constant sedimentation rates from one year to the next. The individual analyses showed that sedimentation in individual lakes could vary tremendously from year to year (as particularly demonstrated by Lac Léman). Furthermore, these variations were caused by different controlling factors in different years, thus simple models based on single controlling factors (such as τ_w, lake content, load, bottom surface area, etc.) can only be successful to the extent that the dominant control factors retain the same hierarchy of influence. It is only through budget analyses that the particular interplay of factors can be understood. From there it is a matter of developing a model of adequate complexity and flexability to reflect the functional roles of major factors to attain accurate predictions.

The second question was whether or not there are general patterns of sedimentation with changing trophic condition. The case histories showed that indeed, the relative residence times of phosphorus typically increased with increasing eutrophication. This decelleration of net sedimentation rate of phosphorus is due to accelleration of recycling mechanisms rather than a decrease in the overall gross deposition rate. In addition, the decrease in phosphorus net sedimentation leads to a shift in the relative importance of elimination pathways. As lake internal processes begin to dominate the phosphorus dynamics of a lake, sedimentation becomes less important relative to flushing as a mechanism of nutrient elimination.

The third question was whether or not the concentration ratio ($P\lambda/Pj$) may be used to portray the dynamics of relative residence times (τ_p/τ_w). These two measures are identical at steady state (i.e. when there is no change in the lake content per unit load). Therefore, as long as a waterbody is at a dynamic equilibrium with its loading, the concentration ratio will be a good indication of the nutrient residence times or flow rates. In general, the time series data showed that the concentration ratio was a good indicator of lake dynamics. However, discrepancies did occur during times of rapid change in loadings. Therefore, the interpretation of $(P\lambda/Pj)$ is best done in the context of budget informatiom. The fact that $(P\lambda/Pj)$ is reasonably close to (τ_p/τ_w) implies that the cross-sectional data represents steady state conditions for the most part and gives a reasonable delineation of the sedimentation characteristics of the different trophic groups.

The cross-sectional data analyzed in the second part of this thesis were used to decide whether or not the three trophic categories had significantly different nutrient residence time characteristics and whether biological variables could be used to improve their prediction. Statistical analyses showed that phosphorus relative residence time was best described by different equations for each different trophic category whereas for nitrogen, all trophic groups were statistically the same. The best models (cf. Table 3.18) for phosphorus included Pj, τ_w, $\bar{z}$, and Chl as the independent variables. In the case of nitrogen, Chl was insignificant and therefore omitted from the (τ_n/τ_w) models. These equations may be used to improve estimates of sedimentation for waterbodies of a known trophic group. In practical terms, this means that the loading target to achieve a desired lake concentration may be calculated with greater accuracy. However, these improvements do not escape the limitations of other cross-sectionally based models; it is only through understanding of the functional relationships that models can be tailored to a particular case.

Finally, the time series data was used to verify the functional content of the cross-sectional pattern of increasing (τ_p/τ_w), or equivalently decreasing sedimentation rate, with increasing eutrophication. It is remarkable that this pattern is highly consistent regardless of the various combinations and permutations of mechanisms (as revealed by the nine case studies) which create it. Changes in the (τ_n/τ_w) pattern with trophic category are not so distinct, therefore the drop in (τ_n/τ_w) with increasing eutrophication in the cross-sectional relationship seems to be predominantly dependent on changes in the cycling rates of phosphorus rather than those of nitrogen. Considering this, phosphorus appears to be more dynamic than nitrogen with respect to eutrophication, and changes in phosphorus relative residence times may be used to characterize the trophic condition of lakes.

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APPENDICES

Appendix 1. Chronology of the major meetings concerned with eutrophication.

date	location	meeting	resultant publication/action
1960 (Dec)	Paris, France	OECD, Canada, U.S.	OECD established under a Convention between North America and European nations
1966 (Feb. 16-17)	Paris, France	Water Management Research Group, OECD	Vollenweider, R.A.,1968. Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to phosphorus and nitrogen as factors in eutrophication, OECD Tech. Rpt. DAS/CSI/68. 27, 159 pp.
1967 (June 11-15)	Madison, Wisconsin	International Symposium on Eutrophication	National Academy of Sciences 1969. Eutrophication: Causes, Consequences, Correctives. Washington, D.C. National Academy of Sciences. 661 pp.
1968 (May)	Uppsala, Sweden	Symposium on Large Lakes and Impoundments	OECD. 1970. Eutrophication in Large Lakes and Impoundments. Paris. 560 pp.
1971 (Feb. 11-12)	Hickory Corners Michigan	ASLO Special Symposium: Nutrients and Eutrophication: The Limiting - Nutrient Controversy	Likens, G.E. (ed.) 1972. Nutrients and Eutrophication: The Limiting Nutrient Controversy Special Symposium, Amer. Soc. Limnol. Oceanogr., 1, 328 pp.
1971	Paris, France	OECD - Water Management Sector Group (established the Steering Group on Eutrophication Control)	OECD. 1973. Summary report of the agreed monitoring project on eutrophication of waters. Environment Directorate, OECD Paris, 22 pp.

Appendix 1 cont.

date	location	meeting	resultant publication/action
1973	Paris, France	OECD - Water Management Sector Group	18 member countries established the: International Co-operative Programme on Eutrophication
1976 (Sept. 6-10)	Amsterdam, the Netherlands	Joint International Symposium of SIL and UNESCO	Golterman, H.L. (ed.). 1976. Interaction between sediments and fresh water. W. Junk, The Hague. Wageningen. 473 pp. Golterman, H.L., P.G. Sly and R.L. Thomas, 1983. Study of the relationship between water quality and sediment transport. UNESCO/ France. 231 pp.
1976 (Sept. 20-25)	Karl-Marx-Stadt, G.D.R.	EUTROSYM '76 UNEP, FAO,WHO IIASA	Proceedings of the International Symposium on Eutrophication and Rehabilitation of Surface Waters (published as 5 volumes in report form)
1978 (Oct 3-4)	Rome, Italy	Convegno sulla Eutrofizzazione in Italia	Consiglio Nazionale delle Ricerche 1979. Atti del Convegno sulla Eutrofizzazione in Italia. Roma 1978. CNR.AC/2/45-70. 472 pp.
1980 (Sept. 8-12)	Portland, Maine	International Symposium on Inland Waters and Lake Restoration (EPA, OECD)	EPA. 1980. Restoration of Lakes and Inland Waters US-EPA 440/5-81-010. 552 pp.
1981 (Oct. 7-9)	Vienna, Austria	Specialized Conference on Eutrophication and Water Supply	Gomella, C. and J.-P. Mounier (eds.) 1983 Special issue: Eutrophication and Water Supply Water Supply I(1) 280 pp.
1981 (Oct. 12-15)	Luxenburg, Austria	International Workshop on the Control of Eutrophication (UNESCO, IIASA OECD)	Rast, W. and J. Kerekes (eds.) 1981. Proceedings: International Workshop on the Control of Eutrophication. UNESCO. IIASA. 107 pp.

Appendix 1 cont.

date	location	meeting	resultant publication/action
1983 (Aug. 31-Sept. 3)	Geneva, Switzerland	Colloquium at Geneva of the Association for the Safeguard of Lac Léman	CIPEL (Commission Internationale pour la protection des eaux du Léman Contre la pollution). 1984. Le Léman: 1957-1982. Secretariat de la Commission Internationale. CH-1000, Lausanne. 650 pp.
1983 (Sept. 13-14)	Stans, Switzerland	International Workshop on Chemical Processes in Lakes	Stumm, W. (ed.) 1984. Chemical Processes in Lakes. John Wiley & Sons. New York. 435 pp.
1984 (Aug. 27-31)	Otsu, Japan	LECS '84 (Shiga Prefecture, NIRA UNEP, UNU, OECD, and several governmental agencies of Japan)	LECS '84. 1984. Shiga Conference '84 on Conservation and Management of World Lake Environment. Proceedings. Shiga Prefecture, 520 Japan. 473 pp.
1985 (Apr. 15-17)	Rome, Italy	Lakes Pollution and Recovery	EWPCA (European Water Pollution Control Association). 1985. Lakes Pollution and Recovery. Proceedings - Pre Prints. ANDIS. 353 pp.
1986 (Apr.)	Zurich, Switzerland	IMSA (Institut voor Milieu-en System analyse)	Vermij, S. and H. Sas (eds.) 1986. First Intermediary Report of the Project: Eutrophication Management in International Perspective Unpubl. Rpt. 40 pp. (+ figures)

Appendix 2. List of Lakes by Project.

1. Nordic Project (15 lakes):

Lake name and	year(s) of investigation	Country	Subjectively assigned Trophic State
Esrøm	1974, 75, 76	Denmark	eutrophic
Mossø I	1974, 75, 76	Denmark	eutrophic
Mossø II	1974, 75, 76	Denmark	eutrophic
Päijänne I	1974, 75, 76	Finland	eutrophic
Päijänne II	1974, 75, 76	Finland	oligotrophic
Päijänne III	1974, 75, 76	Finland	mesotrophic
Päijänne IV	1974, 75, 76	Finland	oligotrophic
Päijänne V	1974, 75, 76	Finland	oligotrophic
Pääjärvi	1974, 75, 76	Finland	oligotrophic
Tuusulanjarvi	1974, 75, 76	Finland	eutrophic
Gjersjøen	1974, 75, 76	Norway	eutrophic
Mjøsa	1974, 75, 76	Norway	mesotrophic
Boren	1974, 75, 76	Sweden	eutrophic
Ekoln	1974, 75, 76	Sweden	eutrophic
Vättern	1974, 75, 76	Sweden	oligotrophic

A2 cont. List of Lakes by Project

2. Alpine Project (38 lakes):

Lake name and	year(s) of investigation	Country	Subjectively assigned Trophic State
Lunzer Untersee	1975, 76	Austria	oligotrophic
Feldsee	1974, 75	Federal Republic of Germany	oligotrophic
Bodensee-Obersee	1971, 72	Federal Republic of Germany	mesotrophic
Lago di Mergozzo	1975	Italy	(oligo-)mesotrophic
Lago di Lugano:			
Ponte-Tresa-Bassin	1975(?)	Italy	eutrophic
Capolago-Bassin	1975(?)	Italy	eutrophic
Melide-Bassin	1975(?)	Italy	eutrophic
Gondria-Bassin	1975(?)	Italy	eutrophic
Lugano-Bassin	1975(?)	Italy	eutrophic
Agno-Bassin	1975(?)	Italy	eutrophic
Morcote-Bassin	1975(?)	Italy	eutrophic
Figino-Bassin	1975(?)	Italy	eutrophic
Ossiacher	1974, 75, 76	Austria	mesotrophic
Attersee	1975, 76	Austria	oligotrophic
Greifensee	1975, 76	Switzerland	eutrophic
Walensee	1973, 74, 75, and 76	Switzerland	mesotrophic
Baldeggersee	1974	Switzerland	eutrophic

A2 cont. List of Lakes by Project

2. Alpine Project con't

Lake name and	year(s) of investigation	Country	Subjectively assigned Trophic State
Hallwilersee	1973	Switzerland	eutrophic
Sempachersee	1975, 76	Switzerland	eutrophic
Vierwaldstattersee Kreuztrichter	1973, 74, 75, and 76	Switzerland	mesotrophic
Vierwaldstattersee Gersau-Bassin	1973, 74, 75, and 76	Switzerland	mesotrophic
Vierwaldstattersee Urnersee	1973, 74, 75 and 76	Switzerland	mesotrophic
Lago Maggiore	1972, 73	Italy	(meso-) eutrophic
Walensee WVZ	1976	Switzerland	(oligo-) mesotrophic
Zurichsee-Untersee	1976	Switzerland	(meso-) eutrophic
Zurichsee-Obersee	1976	Switzerland	eutrophic
Lac Léman	1976	France	mesotrophic
Lago di Oggiono	1973	Italy	eutrophic
Lago di Pusiano	1973	Italy	eutrophic
Lago di Montorfano	1973	Italy	(meso-) oligotrophic
Lago di Annone	1973	Italy	mesotrophic
Lago del Segrino	1973	Italy	eutrophic
Lago d'Alserio	1973	Italy	eutrophic
Lac d'Annecy	1973(?)	France	mesotrophic

A2 cont. List of Lakes by Project

2. Alpine Project con't

Lake name	year(s) of investigation	Country	Subjectively assigned Trophic State
Lac Nantua	1973(?)	France	eutrophic
Lac Tazenat	1973, 74, 75 and 76	France	oligotrophic
Lac Pavin	1973, 74, 75	France	(oligo-) mesotrophic
Lac Aydat	1975, 76	France	eutrophic

A2 cont. List of Lakes by Project

3. Euro (8 lakes). (This grouping was formed as a "catchall" subfile to accomodate lakes which did not belong in the SLR, shallow lakes and reserviors, grouping.)

Lake name and	year(s) of investigation	Country	Subjectively assigned Trophic State
Lough Neagh	1974	Ireland	eutrophic
Lough Leven	1974	Scotland	eutrophic
Lough Leane	1973, 74	Ireland	mesotrophic
Lough Ennell	1975, 76	Ireland	eutrophic
Biwa South	1974, 75, 76	Japan	eutrophic
Biwa North	1974, 75, 76	Japan	oligotrophic
Kasumigaura West	1974, 75, 76	Japan	eutrophic
Kasumigaura North	1974, 75, 76	Japan	eutrophic

A2 cont. List of Lakes by Project

4. U.S.A. (27 lakes).

Lake name	year(s) of investigation	State	Subjectively assigned Trophic State
Brownie	(*)	Minnesota	eutrophic
Calhoun	(*)	Minnesota	eutrophic
Canadarango	1968, 69	New York	eutrophic
Cayuga	1972, 73	New York	mesotrophic
Cedar	(*)	Minnesota	eutrophic
Dogfish	1971, 72	Minnesota	oligotrophic
George	(*)	New York	(oligo-) mesotrophic
Harriet	(*)	Minnesota	eutrophic
Lamb	1971, 72	Minnesota	oligotrophic
Meander	1971, 72	Minnesota	oligotrophic
Mendota	1965, 66	Wisconsin	eutrophic
Lower Minnetonka	1969	Minnesota	eutrophic
Potomac (upper reach)	(*)	Virginia/ Maryland	ultra-eutrophic
Potomac (lower reach)	(*)	Virginia/ Maryland	ultra-eutrophic
Potomac (lower reach)	(*)	Virgina/ Maryland	ultra-eutrophic

[*] Unless otherwise indicated, lakes were studies during the first half of the 1970s.

A2 cont. List of Lakes by Project

4. U.S.A. Project con't

Lake name and	year(s) of investigation	State	Subjectively assigned Trophic State
Sallie	(*)	Minnesota	eutrophic
Sammamish	(*)	Washinton	mesotrophic
Shagawa	(*)	Minnesota	eutrophic
Tahoe	(*)	California	oligotrophic
East Twin	1972, 73, 74	Ohio	eutrophic
West Twin	1972, 73, 74	Ohio	eutrophic
Waldo	(*)	Oregon	oligotrophic
Washington	1957	Washington	eutrophic
Washington	1964	Washington	eutrophic
Washington	1971	Washington	mesotrophic
Weir	(*)	Florida	mesotrophic
Wingra	(*)	Wisconsin	eutrophic

A2 cont. List of Lakes by Project

5. Canada (96 lakes)

Lake name	year(s) of investigation	Region: Province (area)	Subjectively assigned Trophic State
		Atlantic Region I	
Western Brook Pond	1972, 73	Newfoundland (Gros Morne National Park)	oligotrophic
Bluehill North	1969, 70	Newfoundland (Gros Morne National Park)	oligotrophic
Bluehill South	1969, 70	Newfoundland (Gros Morne National Park)	oligotrophic
Michin Pond	1969- 70	Newfoundland (Gros Morne National Park)	oligotrophic
Yuddle North Pond	1969, 70	Newfoundland (Gros Morne National Park)	oligotrophic
Pinehill Pond	1969, 70	Newfoundland (Gros Morne National Park)	oligotrophic
Bennett	1974, 75	New Brunswick (Fundy National Park)	oligotrophic
McLaren	1974, 75	New Brunswick (Fundy National Park)	eutrophic
Wolfe	1974, 75	New Brunswick (Fundy National Park)	mesotrophic
Grafton	1971, 72	Nova Scotia (Kejimkujik National Park)	mesotrophic
Kejimkujik	1971, 72	Nova Scotia (Kejimkujik National Park)	oligotrophic
Mountain	1971, 72	Nova Scotia (Kejimkujik National Park)	oligotrophic

A2 cont. List of Lakes by Project

5. Canada con't

Lake name and	year(s) of investigation	Region: Province (area)	Subjectively assigned Trophic State
Pebbleloggitch	1971, 72	Nova Scotia (Kejimkujik National Park)	oligotrophic
Little Kempton	1971, 72	Nova Scotia (Kejimkujik National Park)	mesotrophic
Freshwater	1975, 76	Nova Scotia (Cape Breton Highlands National Park)	oligotrophic
McDougall's	1975, 76	Nova Scotia (Cape Breton Highlands National Park)	oligotrophic
Presqu'ile	1975, 76	Nova Scotia (Cape Breton Highlands National Park)	mesotrophic
Warren	1975, 76	Nova Scotia (Cape Breton Highlands National Park)	mesotrophic
		<u>Quebec Region II</u>	
Memphremagog (north)	1974, 75	Quebec	mesotrophic
Memphremagog (central)	1974, 75	Quebec	mesotrophic
Memphremagog (south)	1974, 75	Quebec	mesotrophic
Aylmer	1974	Quebec (St. Francois River Basin)	mesotrophic
Bowker	1974	Quebec (St. Francois River Basin)	oligotrophic

A2 cont. List of Lakes by Project

5. Canada con't

Lake name and	year(s) of investigation	Region: Province (area)	Subjectively assigned Trophic State
Brompton	1974	Quebec (St. Francois River Basin)	mesotrophic
Lovering	1974	Quebec (St. Francois River Basin)	mesotrophic
Magog	1980	Quebec (St. Francois River Basin)	eutrophic
Massawippi	1980	Quebec (St. Francois River Basin)	mesotrophic
Montjoie	1974	Quebec (St. Francois River Basin)	oligotrophic
Petit Brompton	1980	Quebec (St. Francois River Basin)	mesotrophic
St. François	1974	Quebec (St. Francois River Basin)	mesotrophic
Stuckely	1980	Quebec (St. Francois River Basin)	oligotrophic
Boivin	1975	Quebec (Yamaska River Basin)	eutrophic
Brome	1975	Quebec (Yamaska River Basin)	eutrophic
Roxton	1974	Quebec (Yamaska River Basin)	mesotrophic
Waterloo	1975	Quebec (Yamaska River Basin)	eutrophic

A2 cont. List of Lakes by Project

5. Canada con't

Lake name and	year(s) of investigation	Region: Province (area)	Subjectively assigned Trophic State
		Ontario Shield Region III	
Beech	1971, 72	Ontario (Haliburton County)	oligotrophic
Bob	1971, 72	Ontario (Haliburton Country)	oligotrophic
Cameron	1971, 72	Ontario (Haliburton Country)	mesotrophic
Cranberry	1971, 72	Ontario (Haliburton Country)	oligotrophic
Eagle-Moose	1971, 72	Ontario (Haliburton Country)	oligotrophic
Four Mile	1971, 72	Ontario (Haliburton Country)	mesotrophic
Halls	1971, 72	Ontario (Haliburton Country)	oligotrophic
Maple	1971, 72	Ontario (Haliburton Country)	oligotrophic
Oblong-Haliburton	1972	Ontario (Haliburton Country)	oligotrophic
Pine	1971, 72	Ontario (Haliburton Country)	oligotrophic
Raven	1971, 72	Ontario (Haliburton Country)	oligotrophic
Talbot	1972	Ontario (Haliburton Country)	oligotrophic

A2 cont. List of Lakes by Project

5. Canada con't

Lake name	year(s) of investigation	Region: Province (area)	Subjectively assinged Trophic State
Twelve Mile-Boshkung	1971, 72	Ontario (Haliburton Country)	oligotrophic
Dudley Bay	1969, 70	Ontario (Muskoka Country)	mesotrophic
Jerry	1973, 74	Ontario (Muskoka Country)	oligotrophic
Harp	1973, 74	Ontario (Muskoka Country)	mesotrophic
Little Joseph	1969, 70	Ontario (Muskoka Country)	oligotrophic
Muskoka (south)	1969, 70	Ontario (Muskoka Country)	mesotrophic
Rosseau	1969, 70	Ontario (Muskoka Country)	oligotrophic
Simcoe	1969	Ontario (Muskoka Country)	mesotrophic
Skeleton Bay	1969, 70	Ontario (Muskoka Country)	oligotrophic
Brewer	1973	Ontario (Algonquin Park)	oligotrophic
Clarke	1973	Ontario (Algonquin Park)	oligotrophic
Costello	1970	Ontario (Algonquin Park)	oligotrophic
Found	1973	Ontario (Algonquin Park)	oligotrophic

A2 cont. List of Lakes by Project

5. Canada con't

Lake name and	year(s) of investigation	Region: Province (area)	Subjectively assigned Trophic State
Kearney	1973	Ontario (Algonquin Park)	oligotrophic
Little McCauley	1973	Ontario (Algonquin Park)	oligotrophic
Bigwind	1976, 77, 78, and 79	Ontario (Haliburton-Muskoka)	oligotrophic
Blue Chalk	1976, 77, 78, and 79	Ontario (Haliburton-Muskoka)	oligotrophic
Buck	1976, 77, 78, and 79	Ontario (Haliburton-Muskoka)	oligotrophic
Chub	1976, 77, 78, and 79	Ontario (Haliburton-Muskoka)	mesotrophic
Crosson	1976, 77, 78, and 79	Ontario (Haliburton-Muskoka)	oligotrophic
Dickie	1976, 77, 78, and 79	Ontario (Haliburton-Muskoka)	mesotrophic
Gullfeather	1976, 77, 78, and 79	Ontario (Haliburton-Muskoka)	mesotrophic
Harp	1976, 77, 78, and 79	Ontario (Haliburton-Muskoka)	oligotrophic
Jerry	1976, 77, 78, and 79	Ontario (Haliburton-Muskoka)	oligotrophic
Little Clear	1976, 77, 78, and 79	Ontario (Haliburton-Muskoka)	oligotrophic
Red Chalk	1976, 77, 78, and 79	Ontario (Haliburton-Muskoka)	oligotrophic

A2 cont. List of Lakes by Project

5. Canada con't

Lake name and	year(s) of investigation	Region: Province (area)	Subjectively assigned Trophic State
Solitaire	1976, 77, 78, and 79	Ontario (Haliburton-Muskoka)	oligotrophic
Walker	1976, 77, 78, and 79	Ontario (Haliburton-Muskoka)	oligotrophic
		Laurentian, Great Lakes Region IV	
Superior	1967, 68, 69, 70, 71, 72, 73, 74, 75	Ontario/USA border	oligotrophic
Michigan	1967, 68, 69, 70, 71, 72, 73, 74, 75	Ontario/USA border	mesotrophic
Huron	1967, 68, 69, 70, 71, 72, 73, 74, 75	Ontario/USA border	oligotrophic
Erie (Western Basin)	1967, 68, 69, 70, 71, 72, 73, 74, 75	Ontario/USA border	eutrophic
Erie (Central Basin)	1967, 68, 69, 70, 71, 72, 73, 74, 75	Ontario/USA border	mesotrophic
Erie (Eastern Basin)	1967, 68, 69, 70, 71, 72, 73, 74, 75	Ontario/USA border	mesotrophic
Ontario	1967, 68, 69, 70, 71, 72, 73, 74, 75	Ontario/USA border	mesotrophic

A2 cont. List of Lakes by Project

5. Canada con't

Lake name and	year(s) of investigation	Region: Province (area)	Subjectively assigned Trophic State
		Experimental Lakes Area Region V	
114	1974	Ontario (northwest)	oligotrophic
120	1974	Ontario (northwest)	oligotrophic
223	1974	Ontario (northwest)	oligotrophic
224	1974	Ontario (northwest)	oligotrophic
239	1969, 70, 71, 72, 73, 74	Ontario (northwest)	oligotrophic
240	1969, 70, 71, 72	Ontario (northwest)	oligotrophic
303	1970, 71	Ontario (northwest)	oligotrophic
		Prairie Lakes Region VI	
Winnipeg	1968, 69, 70	Manitoba	eutrophic
Crooked	1970, 71, 72, 73, 74, 75, 76, 77	Manitoba (QuAppelle River Lakes)	eutrophic
Round	1970, 71, 72, 73, 74, 75, 76, 77	Manitoba (QuAppelle River Lakes)	eutrophic

A2 cont. List of Lakes by Project

5. Canada con't

Lake name and	year(s) of investigation	Region: Province (area)	Subjectively assigned Trophic State
		British Columbia Region VII	
Kalamalka	1974, 75, 76 and 77	British Columbia (Okanagan Valley)	oligotrophic
Okanagan	1971	British Columbia (Okanagan Valley)	mesotrophic
Skaha	1971	British Columbia (Okanagan Valley)	eutrophic
Osooyoos (north)	1971	British Columbia (Okanagan Valley)	eutrophic

A2 cont. List of Lakes by Project

6. Shallow Lakes and Reservoirs (SLR). (36 waterbodies):

Lake name and	year(s) of investigation	Country	Subjectively assigned Trophic State
Wanbachtalsperre	1974, 75, 76	Federal Republic of Germany	eutrophic
Oleftalsperre	1975, 76	Federal Republic of Germany	oligotrophic
Sorpetalsperre	1974	Federal Republic of Germany	eutrophic
Mohnetalsperre	1973	Federal Republic of Germany	eutrophic
Versetalsperre	1976	Federal Republic of Germany	oligotrophic
Sosetalsperre	1974, 75, 76	Federal Republic of Germany	oligotrophic
Ennepetalsperre	1974, 75	Federal Republic of Germany	eutrophic
Furwiggetalsperre	1976	Federal Republic of Germany	oligotrophic
De Grote Rug	1974, 75, 76	Netherlands	eutrophic
Brielse Meer	1974, 75	Netherlands	eutrophic
Petrusplaat	1974, 75, 76	Netherlands	eutrophic
Honderd en Dertig Reservoir	1974, 75, 76	Netherlands	eutrophic
Braakman II Reservoir	1974, 75, 76	Netherlands	eutrophic
Braakman III Reservoir	1974, 75, 76	Netherlands	eutrophic

A2 cont. List of Lakes by Project

6. Shallow Lakes and Reservoirs con't

Lake name	year(s) of investigation	Country	Subjectively assigned Tropic State
Tjeukemeer	1975	Netherlands	eutrophic
Queen Elizabeth II	1969	England	eutrophic
Farmoor Reservoir	1971, 72, 73	England	eutrophic
Grafham Water	1969, 73	England	eutrophic
Mt. Bold	1973, 75, 76	Australia	mesotrophic
Prospect	1975, 76	Australia	mesotrophic
El Burgillo	1974, 75, 76	Spain	mesotrophic
Barrage de Nisramont	1974, 75, 76	Belgium	eutrophic
Eupen	1974, 75, 76	Belgium	oligotrophic
Blackhawk	*	U.S.A.	eutrophic
Camelot Sherwood	*	U.S.A.	eutrophic
Cox Hollow	*	U.S.A.	eutrophic
Dutch Hollow	*	U.S.A.	eutrophic
Isles	*	U.S.A.	eutrophic
Kerr Roanoke	*	U.S.A.	eutrophic
Redstone	*	U.S.A.	eutrophic
Stewart	*	U.S.A.	eutrophic
Twin Valley	*	U.S.A.	eutrophic

*Cases were collated from single year means which refer to the period of 1970 to 1975; different variables may refer to different years.

A2 cont. List of Lakes by Project

6. Shallow Lakes and Reservoirs con't

Lake name and	year(s) of investigation	Country	Subjectively assigned Trophic State
Virginia	*	U.S.A.	eutrophic
Vechten	1974	Netherlands	oligotrophic
Piburgersee	1974, 75, 76	Austria	eutrophic

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*Cases were collated from single year means which refer to the period of 1970 to 1975; different variables may refer to different years.

A2 cont. List of Lakes by Project

7. Unusual Canadian Circumstances, UCC (51 cases):

Lake name and	year(s) of investigation	Region: Province (area)	Subjectively assigned Trophic State
Pink's	1972, 73	Québec, Gatineau Park	eutrophic
Aylmer	1974	Québec, St. François River Basin	mesotrophic
Bowker	1974	Québec, St. François River Basin	oligotrophic
Brompton	1974	Québec, St. François River Basin	mesotrophic
Lovering	1974	Québec, St. François River Basin	mesotrophic
Magog	1974	Québec, St. François River Basin	eutrophic
Massawpi	1974	Québec, St. François River Basin	mesotrophic
Montjoie	1974	Québec, St. François River Basin	oligotrophic
Petit Brompton	1974	Québec, St. François River Basin	mesotrophic
St. Francois	1974	Québec, St. François River Basin	mesotrophic
Stuckely	1974	Québec, St. François River Basin	oligotrophic
Boivin	1974	Québec, Yamaska River Basin	eutrophic
Brome	1974	Québec, Yamaska River Basin	eutrophic

A2 cont. List of Lakes by Project

7. Unusual Canadian Circumstances, con't

Lake name and	year(s) of investigation	Region: Province (area)	Subjectively assigned Trophic State
Roxton	1974	Québec, Yamaska River Basin	mesotrophic
Waterloo	1974	Québec, Yamaska River Basin	eutrophic
Little Otter	1971	Ontario, Muskoka County	eutrophic
226 NE	1973	Ontario, ELA	mesotrophic
226 NE	1974	Ontario, ELA	mesotrophic
226 SW	1973	Ontario, ELA	mesotrophic
226 SW	1974	Ontario, ELA	mesotrophic
227	1969	Ontario, ELA	mesotrophic
227	1970	Ontario, ELA	eutrophic
227	1971	Ontario, ELA	eutrophic
227	1972	Ontario, ELA	eutrophic
227	1973	Ontario, ELA	eutrophic
227	1974	Ontario, ELA	eutrophic
261	1973	Ontario, ELA	mesotrophic
261	1974	Ontario, ELA	mesotrophic
302 N	1972	Ontario, ELA	mesotrophic
302 N	1973	Ontario, ELA	mesotrophic
302 N	1974	Ontario, ELA	mesotrophic
304	1971	Ontario, ELA	eutrophic

A2 cont. List of Lakes by Project

7. Unusual Canadian Circumstances, con't

Lake name and	year(s) of investigation	Region: Province (area)	Subjectively assigned Trophic State
304	1972	Ontario, ELA	eutrophic
304	1973	Ontario, ELA	eutrophic
304	1974	Ontario, ELA	mesotrophic
Pasqua	1960, 61, 62, 63, 64, 65, 66, 67	Manitoba, Qu'Appelle River Lakes	eutrophic
Echo	1960, 61, 62, 63, 64, 65, 66, 67	Manitoba, Qu'Appelle River Lakes	eutrophic
Mission	1960, 61, 62, 63, 64, 65, 66, 67	Manitoba, Qu'Appelle River Lakes	eutrophic
Katepwa	1960, 61, 62 63, 64, 65, 66, 67	Manitoba, Qu'Appelle River Lakes	eutrophic
Babine	1972, 73	British Columbia Interior Mountains	mesotrophic
Kamloops	1974, 75	British Columbia Interior Mountains	oligotrophic
Kootenay	1976	British Columbia Interior Mountains	mesotrophic
Kootenay	1977	British Columbia Interior Mountains	mesotrophic
Wood	1972	British Columbia, Okanagan Valley	eutrophic
Okanagan	1977	British Columbia Okanagan Valley	mesotrophic

A2 cont. List of Lakes by Project

7. Unusual Canadian Circumstances, con't

Lake name and	year(s) of investigation	Region: Province (area)	Subjectively assigned Trophic State
Okanagan	1978	British Columbia Okanagan Valley	mesotrophic
Skaha	1977	British Columbia Okanagan Valley	eutrophic
Skaha	1978	British Columbia Okanagan Valley	eutrophic
Osooyoos	1977	British Columbia Okanagan Valley	eutrophic
Osoyoos	1978	British Columbia Okanagan Valley	eutrophic
Gravenhurst Bay	1969, 70, 71	Ontario, Muskoka County	eutrophic

Appendix 3. Explanation of Unusual Canadian Circumstances, UCC (51 cases).

Lake Name	Year(s) of Investigation	Unusual Aspect
Pink's	1972, 73	meromictic
Aylmer	1974	This block of Quebec lakes is reported with INRS Eau loading figures estimated from a detailed census taken in each drainage basin. The same block of lakes is also reported in the Canadian Lakes file, but loading figures there are based on estimates from land use.
Bowker	1974	
Brompton	1974	
Lovering	1974	
Magog	1974	
Massawpi	1974	
Montjoie	1974	
Petit Brompton	1974	
St. Francois	1974	
Stuckely	1974	
Boivin	1974	
Brome	1974	

A3. UCC cont.

Lake Name	Year(s) of Investigation	Unusual Aspect
Roxton	1974	(cont. from above)
Waterloo	1974	
Little Otter	1971	- phosphate descaling agent from an auto industry dumped into the lake
226 NE	1973	- experimental enrichment with N and P
226 NE	1974	
226 SW	1973	- experimental whole-lake enrichment with N and C (as sucrose)
226 SW	1974	
227	1969	
227	1970	
227	1971	- experimental whole-lake enrichment with N and P
227	1972	
227	1973	
227	1974	
261	1973	- experimental whole-lake enrichment with P
261	1974	

A3. UCC cont.

Lake Name	Year(s) of Investigation	Unusual Aspect
302 N	1972	- experimental enrichment of the hypolimnion with N, P and C (as sucrose)
302 N	1973	
302 N	1974	
304	1971	- experimental whole-lake enrichment with N, P and C (as sucrose)
304	1972	
304	1973	- experimental whole-lake enrichment with N and C (as sucrose); note previous years included P enrichment which is discontinued here
304	1974	
Pasqua	1960, 61, 62, 63, 64, 65, 66, 67	- phosphorus and chlorophyll concentrations are reported as geometric means due to non-normal frequency distributions; high year to year variability of hydraulic loads and carry-over from one lake to the next in the chain may complicate the nutrient - response relationships
Echo	1960, 61, 62, 63, 64, 65, 66, 67	
Mission	1960, 61, 62, 63, 64, 65, 66, 67	
Katepwa	1960, 61, 62, 63, 64, 65, 66, 67	

A3. UCC cont.

Lake Name	Year(s) of Investigation	Unusual Aspect
Babine	1972, 73	- the Canadian Contribution identifies that loading is underestimated; salmon migration constitutes a considerable phosphorus load to the lake at spawning; chlorophyll is reported as a geometric mean
Kamloops	1974, 75	- phosphorus is reported as total, however a large fraction is apatite which is biologically unavailable
Kootenay	1976	- drastic reduction in P loading occurred in 1970 when the Cominco fertilizer plant began effluent control; 90% reduction of its previous loading was achieved by 1975
Kootenay	1977	
Wood	1972	- lake concentrations of P are higher than expected from loading; internal loading may be significant

A3. UCC cont.

Lake Name	Year(s) of Investigation	Unusual Aspect
Okanagan	1977	- period of phosphorus loading reduction; in 1972 Pentiction began tertiary sewage treatment and in 1977 Vernon began use of effluents for spray irrigation rather than direct release to Okanagan Lake
Okanagan	1978	
Skaha	1977	
Skaha	1978	
Osooyoos	1977	
Osooyoos	1978	
Gravenhurst Bay	1969, 70, 71	- heavy enrichment from sewage effluent; (reductions began in 1972)

Appendix 4. Variables used for the Cross-Sectional Analysis.

Variable abbreviation	Symbol in text	Variable description	Units
LAKE	-	a consecutive number lable	—
NAME	-	name of the lake	—
TROPH	-	trophic category: 1 = oligotrophic 2 = mesotrophic 3 = eutrophic	—
PROJ	-	Project number: 1 = Nordic 2 = Alpine 3 = Euro 4 = USA 5 = Canada 6 = unusual Canadian circumstances (UCC) 7 = shallow lakes and reservoirs (SLR)	—
AREA	A_o	lake surface area	km^2
VOL	V	lake volume	$x10^6\ m^3$
MAXZ	z_{max}	maximum depth	m
MEANZ	$\bar{z}$	mean depth	m
AREAD	A_D	drainage basin area excluding lake surface	km^2
TW	τ_w	water residence time	y
RW	ρ	flushing rates	y^{-1}
QS	q_s	hydraulic load	$m.y^{-1}$

Appendix 4. cont.

Variable abbreviation	Symbol in text	Variable description	Units
LP	L_p	total phosphorus loading	$g.m^{-2}.y^{-1}$
ANP	$P\lambda$	annual mean phosphorus concentration for whole lake	$mg.\ m^{-3}$
SPMXP	$P\lambda^{sp}$	phosphorus concentration at spring overturn	$mg.\ m^{-3}$
ANEUP	$P\lambda^{eu}$	annual average phosphorus concentration of the euphotic zone	$mg.m^{-3}$
LTN	L_n	total nitrogen loading	$g.m^{-2}.y^{-1}$
ANTN	$N\lambda$	annual mean nitrogen concentration for whole lake	$mg.m^{-3}$
SPMXTN	N^{sp}	nitrogen concentration at spring overturn	$mg.m^{-3}$
ANEUTN	N_{λ}^{eu}	annual average total nitrogen concentration of the euphotic zone	mg.m-3
ANEUCHL	Chl	annual mean chlorophyll concentration of the euphotic zone	$mg.m^{-3}$
SPEUCHL	$Chl^{s,eu}$	spring chlorophyll concentration of the euphotic zone	$mg.m^{-3}$
MXEUCHL	Chl^{max}	maximum chlorophyll concentration of the euphotic zone	$mg.m^{-3}$
MNEUCHL	Chl^{min}	minimum chlorophyll concentration of the euphotic zone	$mg.m^{-3}$
ANEUALG	Alg	annual mean algal biomass concentration of the euphotic zone	$g.m^{-3}$

Appendix 4. cont

Variable abbreviation	Symbol in text	Variable description	Units
ANEUALG	—	annual average volumetric algal biomass	$g.m^{-3}$
ANEUALGA	Alg_s	annual mean areal algal biomass of the euphotic zone	$g.m^{-2}$
YPRAR	ΣPP	annual total areal primary production	$g.C.m^{-2}.y^{-1}$
O2DM3	HOD	volumetric hypolimnetic oxygen depletion rate	$gO_2.m^{-3}.y^{-1}$
O2DM2	AHOD	areal hypolimnetic oxygen depletion rate	$gO_2.m^{-2}.y^{-1}$
O2DM3MO	monthly HOD	monthly hypolimnetic oxygen depletion rate	$gO_2.m^{-3}.mo^{-1}$
O2DM2MO	monthly AHOD	monthly areal hypolimnetic oxygen depletion rate	$gO_2.m^{-2}.mo^{-1}$
HYPOAREA	—	surface area of hypolimnion	m^2
HYPOVOL	—	volume of hypolimnion	m^3
ANSEC	SD	annual mean Secchi disc depth	m
PJ	P_J	annual mean phosphorus inflow concentration	$mg.m^{-3}$
PO	P_ω	annual mean phosphorus outflow concentration	$mg.m^{-3}$
TP	τ_p	absolute phosphorus residence time	y
TPR	τ_p / τ_w	phosphorus relative residence time	—

Appendix 4. cont.

Variable abbreviation	Symbol in text	Variable description	Units
SP	σ_p	phosphorus sedimentation coefficient	y^{-1}
VSP	v_{sp}	apparent phosphorus settling velocity	$m.y^{-1}$
ACHLPR	Chl/P	annual mean chlorophyll to phosphorus ratio	—
SCHLEPR	Chl^s/P^{eu}	summer chlorophyll to euphotic phosphorus ratio	—
TNJ	N_J	mean total nitrogen inflow concentration	$mg.m^{-3}$
TNO	$N\omega$	mean total nitrogen outflow concentration	$mg.m^{-3}$
TN	τ_n	absolute nitrogen residence time	y
TNR	τ_n/τ_w	nitrogen relative residence time	—
TNTPR	τ_n/τ_p	ratio of nitrogen to phosphorus residence time	—
NPLR	Ln/Lp	nitrogen to phosphorus loading ratio	—
NPOR	$N\omega/P\omega$	nitrogen to phosphorus outflow ratio	—
NPR	N/P	nitrogen to phosphorus mean lake concentration ratio	—
SN	σ_n	nitrogen sedimentation coefficient	y^{-1}
VSN	v_{sn}	apparent nitrogen sedimentation velocity	$m.y^{-1}$

APPENDIX 5 Page:

Appendix 5 cont.

A5.1.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR GEOLOGIC AND MORPHOMETRIC VARIABLES IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	SURFACE AREA KM2	VOLUME OF LAKE 10E6 M3	MAXIMUM DEPTH M	MEAN DEPTH M	DRAINAGE AREA KM2	WATER RESIDENCE TIME Y	FLUSHING RATE Y-1	HYDRAULIC LOAD M.Y-1
OLIGOTROPHIC										
	110	PAJAN-2	156.0	3320.000	64.0	20.3	-0	.50	1.43	28.8
	112	PAJAN-4	143.0	3003.000	73.0	21.0	-0	.60	1.67	35.0
	113	PAJAN-5	542.0	8148.000	63.0	14.0	-0	.90	.77	10.8
	114	PAAJARVI	13.4	192.960	87.0	14.4	244.3	4.13	.24	3.5
	201	LUNZER U	.7	14.000	33.7	20.0	27.5	.30	2.70	55.5
	202	FELDSEE	.1	1.570	32.0	15.7	1.5	.49	2.04	32.0
	214	ATTERSEE	46.5	3923.720	170.6	84.2	463.5	7.00	.15	12.0
	222	VWS UPNE	26.3	3564.400	200.0	133.0	924.0	1.70	.54	73.2
	236	TAZEHAT	.3	12.300	53.0	41.0	-0	-0	-0	-0
	306	BIWA NOR	619.0	28783.500	104.0	46.5	3160.0	5.99	.17	7.3
	406	DOGFISH	.3	1.260	9.5	4.0	.9	3.53	.28	1.1
	407	GEORGE	114.0	2052.000	58.0	13.0	492.0	8.00	.13	2.3
	409	LAMB	.4	1.600	5.5	4.0	2.0	2.30	.43	1.7
	410	MEANDER	.4	2.000	7.0	5.0	1.7	2.70	.37	1.8
	420	TAHOE	495.0	156187.00	501.0	313.0	1310.0	700.00	1.40E-003	.4
	423	VALOC	27.0	972.000	127.0	30.0	79.0	21.00	.05	1.7
	426	WASHINGT	87.6	2890.800	62.5	33.0	1590.0	2.40	.42	13.9
	501	VSPOCK P	22.8	1655.280	163.0	72.0	-0	7.14	.14	10.2
	502	BLHILL N	.2	.540	10.5	2.7	5.1	.08	12.50	33.8
	503	BLHILL S	-0	10.283	22.5	9.2	4.1	2.27	.44	4.1
	504	MINCHP P	.1	.700	14.5	7.0	15.7	.02	50.00	350.0
	505	YUDDLE N	.1	.240	11.5	2.4	.6	.21	4.76	11.4
	506	PINEHL P	2.0E-002	.022	5.5	1.1	-0	.10	10.00	11.0
	507	BENNETT	.3	.674	11.1	2.3	-0	.04	25.00	57.5
	511	KEJIM	24.4	107.360	19.2	4.4	659.0	.15	6.67	29.3
	512	MOUNTAIN	1.4	5.883	14.3	4.2	-0	.67	1.49	6.3
	513	PFBRLECH	.3	.420	2.5	1.4	-0	.29	3.45	4.8
	515	FRESHWTG	.4	2.600	-0	3.5	-0	.50	2.00	13.0
	516	MC DOUG	.1	.340	-0	3.4	-0	.10	10.00	34.0
	523	BOWKER	2.3	55.200	59.0	24.0	9.2	5.10	.20	4.7
	528	MONTJOIE	3.3	26.070	22.2	7.9	10.6	1.70	.59	4.7
	531	STUKLEY	3.9	51.090	36.5	13.1	14.9	2.50	.40	5.2
	536	BEECH	1.4	13.720	32.0	9.3	519.0	.07	14.61	192.0
	537	ROP	2.3	41.400	65.0	18.0	29.0	3.00	.33	6.0
	539	CRANBRY	.7	2.450	9.0	3.5	264.0	.02	56.52	203.4
	540	EAGL-MJD	5.2	66.560	40.0	12.3	251.0	.52	1.92	24.0
	542	HALLS	5.3	144.160	76.0	27.2	270.0	1.12	.89	24.3
	543	MAPLE	3.3	38.280	35.0	11.6	502.0	.15	6.67	77.3
	544	OBL-HALI	11.0	194.700	55.0	17.7	143.0	3.13	.32	5.7
	545	PINE	1.1	8.140	19.0	7.4	300.0	.05	17.24	127.6
	546	RAVEN	1.1	.803	3.3	.7	45.0	.08	13.33	9.7
	547	TALBOT	1.1	.935	12.0	.9	14.0	.20	5.00	4.3
	548	IZMI-BOS	11.7	211.770	75.0	18.1	933.0	.49	2.03	37.7
	550	JERRY	.6	8.160	35.0	13.5	7.3	1.50	.67	9.1
	552	LTL JOS	2.3	39.160	38.7	17.0	36.9	2.30	.43	7.4
	554	ROSSEAU	58.4	1489.200	90.2	25.5	649.0	4.60	.21	5.3
	556	SKELIN B	1.6	15.040	20.1	9.4	206.6	.24	4.17	39.2
	557	BREWER	.4	2.280	11.0	5.7	4.3	1.05	.94	5.4
	558	CLARKE	.2	1.120	11.0	5.5	33.3	.06	16.67	93.3
	559	COSTELLO	.3	2.520	15.0	8.4	11.5	.85	1.18	9.9
	560	FOUND	.1	1.160	29.0	11.6	.2	20.00	.05	.6
	561	KEARNEY	.3	2.190	15.0	7.3	11.5	.43	2.33	17.0
	562	L MC CAU	.2	.760	7.0	3.8	2.4	.95	1.05	4.0
	563	BIGWIND	1.1	11.660	32.0	10.5	5.1	5.17	.19	2.1
	564	BL CHALK	.5	4.250	23.0	8.5	1.8	5.00	.20	1.7
	565	BUCK	.4	4.360	30.0	10.9	2.9	3.35	.30	3.3
	567	CROSSCN	.6	5.040	25.0	8.4	5.5	1.90	.53	4.4
	570	HARP	.7	8.680	40.0	12.4	5.3	3.19	.31	3.9
	571	JERRY	.5	6.260	35.0	12.4	9.1	1.51	.66	8.2
	572	L CLEAR	.1	.810	25.0	8.1	.6	2.57	.39	3.2

A5.1.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR GEOLOGIC AND MORPHOMETRIC VARIABLES IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	SURFACE AREA KM2	VOLUME OF LAKE 10E6 M3	MAXIMUM DEPTH M	MEAN DEPTH M	DRAINAGE AREA KM2	WATER RESIDENCE TIME Y	FLUSHING RATE Y-1	HYDRAULIC LOAD M.Y-1
OLIGOTROPHIC	(CONT.)									
	573	RD CHAL	4.4	167.200	16.7	38.0	4.0	3.59	.28	10.0
	574	SOLITR	1.2	15.960	31.0	13.3	5.0	7.26	.14	1.8
	575	WALKER	.7	4.340	17.0	6.2	3.3	2.08	.48	2.2
	576	SUPERIOR	82367.0	12190396	406.0	148.0	138586.0	185.00	.01	.9
	578	HURON	59570.0	3633770.0	225.0	61.0	128863.0	21.00	.05	2.9
	583	114	.1	.170	5.0	1.7	.5	1.51	.66	1.1
	584	120	.1	.750	14.0	7.6	.6	4.57	.22	1.7
	585	223	.2	1.440	19.4	7.2	1.3	3.30	.30	2.2
	586	224	.3	3.400	27.4	11.5	.4	12.50	.08	.9
	587	239	.5	5.250	30.4	10.5	3.4	4.40	.20	2.1
	588	240	.4	2.440	13.1	6.1	1.2	1.12	.89	5.5
	589	303	.1	.150	2.5	1.0	.5	1.00	1.00	1.0
	593	KALAMLKA	26.0	1534.000	141.0	59.0	192.0	42.40	.02	1.4
# OF LAKES		73	72	73	71	73	62	72	72	72
MEAN			2006.524	219770.05	55.114	22.763	4531.533	15.7347	4.1637	23.923
ST DEV			11393.941	1482815.3	83.137	43.343	23301.383	84.7507	9.4603	54.360
MINIMUM			2.0E-002	.022	2.5	.7	.2	.02	1.40E-003	.4
MAXIMUM			82367.0	12190396	501.0	313.0	138586.0	700.00	58.02	330.0

A5.1.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR GEOLOGIC AND MORPHOMETRIC VARIABLES IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	SURFACE AREA KM2	VOLUME OF LAKE 10E6 M3	MAXIMUM DEPTH M	MEAN DEPTH M	DRAINAGE AREA KM2	WATER RESIDENCE TIME Y	FLUSHING RATE Y-1	HYDRAULIC LOAD M.Y-1
MESOTROPHIC										
	111	PAJAN-3	45.0	675.000	53.0	15.0	-0	.20	2.50	37.5
	204	MERGOZZO	1.8	81.720	73.0	45.4	-0	4.70	.21	9.7
	213	OSSIACHE	10.9	214.920	52.0	19.9	170.0	1.92	.52	10.4
	216	WALLENSE	24.2	2444.200	145.0	101.0	1061.0	1.40	.71	72.1
	220	VWS KPEU	57.0	4275.000	152.0	75.0	340.0	1.39	.72	54.3
	221	VWS GERS	25.4	3962.400	214.0	155.0	567.0	1.55	.64	100.0
	223	MAGGIORE	212.5	37612.500	370.0	177.0	6599.0	4.00	.25	44.3
	224	WALLENSE	24.2	2420.000	145.0	100.0	-0	1.40	.71	71.4
	227	LEMAN	582.4	88932.460	309.7	152.7	7975.3	11.00	.09	13.3
	230	MONTORFA	.5	2.075	6.9	4.2	1.7	1.51	.66	2.7
	231	ANNONE	1.7	6.800	10.1	4.0	14.5	.81	1.23	4.9
	234	D ANNECY	27.0	1120.500	64.7	41.5	278.0	3.63	.25	10.9
	237	PAVIN	.4	20.960	93.0	52.4	-0	-0	-0	-0
	303	LOUGH LE	20.2	276.740	54.0	13.7	647.5	.33	3.03	41.5
	404	CAYUGA	172.6	9374.000	-0	54.5	2030.0	8.60	.12	5.3
	418	SAMMAPIS	19.8	350.460	-0	17.7	273.0	1.80	.55	9.6
	427	WEIR	24.0	151.200	-0	6.3	45.0	4.20	.24	1.5
	509	WOLFE	.2	.765	9.1	3.9	-0	.42	2.39	9.1
	510	GRAFTON	2.7	7.560	10.0	2.9	-0	.14	7.14	20.0
	514	LTL KEMP	2.5E-002	-0	-0	1.4	-0	.04	25.00	35.0
	517	PRESCUL	4.4E-002	-0	-0	2.1	-0	.07	14.29	30.0
	518	WARREN	.9	14.310	31.0	15.9	31.5	.28	3.57	56.8
	519	MEMPH N	20.4	299.880	-0	14.7	-0	.24	4.17	61.3
	520	MEMPH C	23.6	1045.480	-0	44.3	-0	1.25	.80	35.4
	522	AYLMER	29.5	250.750	35.2	8.5	477.8	.23	4.35	37.0
	524	BROMPTON	11.9	148.750	42.3	12.5	97.1	1.90	.53	6.5
	525	LOVERING	4.6	44.620	23.9	9.7	36.1	.99	1.01	9.3
	527	MASSAWP	17.9	719.580	35.7	40.2	536.5	1.75	.57	23.3
	529	PT BROMP	.7	5.110	19.5	7.3	1.5	3.75	.27	1.9
	530	ST FRAN	47.1	734.760	40.1	15.6	1157.0	.91	1.10	17.1
	534	ROXTON	1.8	5.760	5.5	3.2	15.5	.55	1.82	5.8
	538	CAMERON	12.7	90.170	16.0	7.1	3250.0	.05	16.67	119.3
	541	4-MI	7.7	71.610	22.0	9.3	45.0	4.30	.23	2.2
	549	DUDLEY B	3.5	23.450	19.2	6.7	43.3	1.40	.71	4.8
	551	HARP	.6	11.120	35.0	13.9	-0	3.50	.29	4.0
	553	MUSKOKA	130.0	2184.000	57.0	16.8	3835.0	.94	1.06	17.8
	555	SIMCOE	725.0	-0	-0	-0	-0	-0	-0	1.2
	566	CHUB	.3	2.640	27.0	8.8	3.2	1.99	.50	4.4
	568	DICKIE	.9	4.410	12.0	4.9	5.4	1.90	.53	2.6
	569	GULFEATH	.7	3.360	13.0	4.8	10.5	.67	1.49	7.2
	577	MICHIGAN	58016.0	4873344.0	281.0	84.0	117403.0	113.00	.01	.7
	580	CB ERIE	15390.0	273942.00	26.0	17.8	48057.0	1.53	.65	11.6
	581	EB ERIE	6150.0	166050.00	64.0	27.0	19208.0	.91	1.10	29.7
	582	ONTARIO	19009.0	1634774.0	244.0	86.0	75272.0	7.90	.13	10.9
	594	OKANAGAN	344.4	25933.320	242.0	75.3	6063.6	60.00	.02	1.3
N OF LAKES		45	45	42	37	44	33	43	43	44
MEAN			2248.917	169800.77	84.589	35.925	5958.075	6.0233	2.3940	24.107
ST DEV			9263.036	785908.93	96.011	44.558	24786.026	19.0387	4.6782	27.466
MINIMUM			2.5E-002	.766	5.5	1.4	1.7	.04	.01	.7
MAXIMUM			58016.0	4873344.0	370.0	177.0	117408.0	113.00	25.00	118.3

A5.1.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR GEOLOGIC AND MORPHOMETRIC VARIABLES IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABRR)	SURFACE AREA KM2	VOLUME OF LAKE 10E6 M3	MAXIMUM DEPTH M	MEAN DEPTH M	DRAINAGE AREA KM2	WATER RESIDENCE TIME Y	FLUSHING RATE Y-1	HYDRAULIC LOAD M.Y-1
EUTROPHIC										
	101	ESRUP	17.3	212.790	22.0	12.3	84.0	16.60	.07	.6
	102	MOSSO 1	13.1	134.930	22.0	10.3	-0	2.30	.43	4.5
	103	MOSSO 2	.4	1.160	3.7	2.9	-0	.01	-0	-0
	104	GJERSJO	2.7	61.250	64.0	22.7	84.0	5.20	.19	4.4
	105	MJOSA	365.0	55945.000	449.0	153.0	16420.0	6.20	.16	24.7
	106	BOPEN	28.0	168.000	14.0	6.0	6437.0	.30	3.33	20.0
	107	MALAREN	20.2	345.420	35.0	17.1	22603.0	1.20	.83	14.3
	108	VATTERN	1912.0	74568.000	119.0	39.0	6359.0	57.67	.02	.6
	109	PAJAN-1	142.0	2556.000	104.0	18.0	26490.0	.50	2.00	36.0
	115	TUUSULAN	6.0	18.600	10.0	3.1	92.0	.43	.91	2.8
	203	BODENSEE	475.0	47547.500	252.0	100.1	10600.0	4.41	.23	22.7
	205	PONTE LU	1.0	30.000	55.0	30.0	-0	-0	-0	-0
	206	CAPOLAGO	2.6	109.980	76.0	42.3	-0	-0	-0	-0
	207	MELIDE L	6.2	456.940	92.0	73.7	-0	-0	-0	-0
	208	GONDRIA	17.2	3629.260	322.0	211.0	-0	-0	-0	-0
	209	LUGANO L	10.7	1610.350	250.0	150.5	-0	-0	-0	-0
	210	AGNO LUG	2.0	107.800	37.0	53.9	-0	2.33	.42	22.3
	211	MARCOTE	3.0	109.200	75.0	36.4	-0	-0	-0	-0
	212	FIGINO L	6.1	326.250	105.5	52.5	-0	-0	-0	-0
	215	GREIFENS	8.5	150.450	32.6	17.7	150.0	1.33	.72	12.5
	217	BALDEGGE	5.3	180.200	56.0	34.0	-0	6.00	.17	5.7
	218	HALLWILL	5.9	212.180	48.0	29.6	-0	4.10	.24	5.0
	219	SEMPACHE	14.4	662.460	87.0	46.0	62.6	16.50	.06	2.8
	224	ZURICH U	65.1	3320.100	136.0	51.0	1740.1	1.40	.71	35.4
	226	ZURICH C	20.3	466.900	48.0	23.0	1564.3	.19	5.20	121.1
	228	OGGIONO	3.8	23.940	11.3	6.3	12.7	1.35	.74	4.6
	229	PUSIANO	4.9	68.600	24.3	14.0	90.6	.68	1.47	20.6
	232	SEGRINO	.4	1.268	8.6	3.2	3.4	.42	2.38	7.6
	233	D ALSERI	1.2	6.408	8.1	5.3	15.4	.35	2.85	15.3
	235	MANTUA	1.4	39.760	42.8	28.4	50.3	.69	1.45	41.2
	236	AYDAT	.5	3.000	15.5	6.0	-0	-0	-0	-0
	301	LOUGH NE	383.0	3408.700	34.0	8.9	4453.3	1.17	.85	7.5
	302	LOCH LEV	13.3	51.870	23.5	3.9	145.0	.59	1.69	6.6
	304	LOUGH EN	11.8	88.500	30.0	7.5	195.3	1.87	.53	4.0
	305	BIWA SOU	53.0	201.400	7.0	3.8	683.0	.03	29.41	111.8
	307	KASUMI W	171.0	666.900	6.0	3.9	1597.0	.61	1.64	6.4
	308	KASUMI N	34.0	139.400	7.0	4.1	394.0	.45	2.22	9.1
	401	BROWNIE	.1	.680	-0	6.8	.5	2.00	.50	3.4
	402	CALHOUN	1.7	18.020	-0	10.6	7.6	3.60	.28	2.9
	403	CANADARA	7.6	58.520	-0	7.7	182.0	.60	1.67	12.8
	405	CEDAR	.7	4.270	-0	6.1	1.6	3.30	.30	1.8
	408	HARRIET	1.4	12.320	-0	8.8	4.8	2.40	.42	3.7
	411	MENDOTA	39.4	472.800	-0	12.0	636.0	4.50	.22	2.7
	412	LOWER MI	26.2	217.460	-0	8.3	371.0	-0	-0	-0
	413	LOWER MI	26.2	217.460	-0	8.3	371.0	-0	-0	-0
	414	POTOMAC	57.0	273.600	-0	4.8	2253.4	.04	25.00	120.0
	415	POTOMAC	210.0	1071.000	-0	5.1	8295.4	.18	5.56	28.3
	416	POTOMAC	695.0	5004.000	-0	7.2	27451.2	.85	1.18	8.5
	417	SALLIE	5.3	33.920	-0	6.4	1540.0	1.45	.69	4.4
	419	SHAGAWA	9.2	52.440	-0	5.7	269.0	.80	1.25	7.1
	421	EAST TWI	.3	1.500	-0	5.0	33.3	.73	1.37	6.8
	422	WEST TWI	.3	1.290	-0	4.3	33.3	1.47	.68	2.9
	424	WASHINGT	87.6	2890.800	-0	33.0	1590.0	2.40	.42	13.8
	425	WASHINGT	87.6	2890.800	-0	33.0	1590.0	2.40	.42	13.8
	428	WINGRA	1.4	3.360	-0	2.4	14.0	.40	2.50	6.0
	508	MCLAREN	6.7E-003	.036	12.5	5.1	-0	.11	9.09	46.4
	521	MEMPH S	56.1	347.920	-0	6.2	-0	.30	3.33	20.7
	526	MAGOG	10.8	105.340	19.1	9.8	154.6	.09	10.87	103.3
	532	BOIVIN	1.6	1.920	6.9	1.2	172.2	.02	50.00	58.0
	533	BROME	14.5	84.160	12.3	5.8	135.7	.70	1.43	8.3

A5.1.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR GEOLOGIC AND MORPHOMETRIC VARIABLES IN NATURAL LAKES.

TROPHIC GROUP	LAKE #	LAKE NAME (ABBR)	SURFACE AREA KM2	VOLUME OF LAKE 10E6 M3	MAXIMUM DEPTH M	MEAN DEPTH M	DRAINAGE AREA KM2	WATER RESIDENCE TIME Y	FLUSHING RATE Y-1	HYDRAULIC LOAD M.Y-1
EUTROPHIC	(CONT.)									
	535	WATERLOO	1.5	4.350	4.9	2.9	31.6	.22	4.55	13.2
	579	WB ERIE	3630.0	27968.000	14.0	7.6	11492.3	.15	5.25	47.5
	590	WINNIPEG	23750.0	285000.00	36.0	12.0	953000.0	3.50	.29	3.4
	591	CROOKED	14.8	122.840	11.0	8.3	14400.0	.31	3.27	27.1
	592	ROUND	11.0	85.100	9.0	8.1	15300.0	.21	4.08	37.3
	595	SKAHA	20.1	532.650	55.8	26.5	822.3	1.23	.83	22.1
	596	OSOYCOS	9.9	204.930	63.4	20.7	1269.0	.40	2.50	51.3
N OF LAKES		67	67	67	48	67	62	57	56	56
MEAN			447.455	7838.9584	63.319	24.165	21958.060	2.9595	3.6652	23.465
ST DEV			2929.629	36705.316	87.935	37.552	131823.65	8.0414	8.3403	33.295
MINIMUM			6.7E-003	.036	3.7	1.2	.5	.01	.02	.6
MAXIMUM			23750.0	285000.00	449.0	211.0	953000.0	57.67	56.00	163.3
TOTAL N OF LAKES		185	184	182	156	184	147	172	171	172
MEAN			1512.667	130220.09	64.631	26.431	11690.027	9.1015	3.5031	24.463
ST DEV			8900.874	1012019.8	89.001	41.752	83638.459	55.9151	8.3553	42.226
MINIMUM			6.7E-003	.022	2.5	.7	.2	.01	1.40E-003	.4
MAXIMUM			82367.0	12190396	501.0	313.0	953000.0	700.00	58.82	350.0

A5.1.2 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR GEOLOGIC AND MORPHOMETRIC VARIABLES IN SHALLOW LAKES AND RESERVOIRS.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	SURFACE AREA KM2	VOLUME OF LAKE 10E6 M3	MAXIMUM DEPTH M	MEAN DEPTH M	DRAINAGE AREA KM2	WATER RESIDENCE TIME Y	FLUSHING RATE Y-1	HYDRAULIC LOAD M.Y-1
OLIGOTROPHIC										
	602	OLEF	.7	10.290	40.5	14.7	45.5	.52	1.92	23.3
	605	VERSE	1.7	22.110	47.5	20.1	24.1	1.51	.66	13.3
	606	SOSE	1.0	18.000	43.3	18.0	50.0	.47	2.13	38.3
	608	FURWIEGE	.1	.830	25.0	8.3	4.7	.40	2.30	20.8
	623	EUPEN	.9	15.930	52.3	17.7	-0	.34	2.94	52.1
	635	VECHTEN	4.7E-002	.023	12.3	6.0	-0	9.33	.11	.6
N OF LAKES		6	6	6	6	6	4	6	6	6
MEAN			.741	11.19717	36.355	14.133	31.525	2.0953	1.7103	25.255
ST DEV			.617	9.17531	15.369	5.723	21.632	3.5710	1.0474	15.253
MINIMUM			4.7E-002	.023	12.3	6.0	4.7	.34	.11	.6
MAXIMUM			1.7	22.110	52.3	20.1	50.0	9.33	2.94	52.1

A5.1.2 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR GEOLOGIC AND MORPHOMETRIC VARIABLES IN SHALLOW LAKES AND RESERVOIRS.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	SURFACE AREA KM2	VOLUME OF LAKE 10E6 M3	MAXIMUM DEPTH M	MEAN DEPTH M	DRAINAGE AREA KM2	WATER RESIDENCE TIME Y	FLUSHING RATE Y-1	HYDRAULIC LOAD M.Y-1
MESOTROPHIC										
	619	MT BOLD	2.3	30.360	41.4	13.2	388.0	.39	2.56	33.8
	620	PROSPECT	5.2	50.440	23.3	9.7	10693.0	.12	8.33	80.8
	621	EL BURGI	5.4	106.380	56.4	19.7	1050.0	.37	2.70	53.2
N OF LAKES		3	3	3	3	3	3	3	3	3
MEAN			4.300	62.39333	43.700	14.200	4043.667	.2933	4.5334	55.974
ST DEV			1.735	39.39444	21.642	5.074	5767.757	.1504	3.2516	23.012
MINIMUM			2.3	30.360	23.3	9.7	388.0	.12	2.56	33.8
MAXIMUM			5.4	106.380	66.4	19.7	10693.0	.39	8.33	80.8

A5.1.2 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR GEOLOGIC AND MORPHOMETRIC VARIABLES IN SHALLOW LAKES AND RESERVOIRS.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	SURFACE AREA KM2	VOLUME OF LAKE 10E6 M3	MAXIMUM DEPTH M	MEAN DEPTH M	DRAINAGE AREA KM2	WATER RESIDENCE TIME Y	FLUSHING RATE Y-1	HYDRAULIC LOAD M.Y-1
EUTROPHIC										
	601	WANBACH	2.1	28.160	42.7	17.6	69.3	1.04	.95	16.9
	603	SORPE	3.2	65.280	57.0	20.4	99.5	1.14	.88	17.9
	604	MOHNE	10.4	134.160	33.7	12.9	432.0	.71	1.41	18.2
	607	ENNEPE	1.0	12.200	35.5	12.2	48.0	.33	3.03	37.0
	609	DE GROTE	.6	3.060	5.4	5.1	.6	.44	2.27	11.6
	610	BRIELSE	4.3	23.220	15.4	5.4	70.0	.34	2.94	15.9
	611	PETRUSPL	1.0	12.400	15.0	12.4	1.1	.10	10.00	124.0
	612	HONDRED	2.2	32.340	30.0	14.7	2.2	.22	4.55	66.8
	613	BRAAKMAN	.2	1.600	10.5	8.0	100.0	.55	1.79	14.3
	614	BRAAKMAN	.2	1.640	10.5	8.2	-0	.88	1.14	9.3
	615	TJEUKEME	20.0	36.000	2.0	1.8	21.0	-0	-0	-0
	616	QUEEN EL	1.3	19.890	17.2	15.3	9869.0	.15	6.67	102.0
	617	FARMOOR	.5	4.500	11.0	9.0	1563.0	.46	2.17	19.6
	618	GRAFHAM	6.1	57.950	21.0	9.5	15.3	5.88	.17	1.6
	622	NISRAPON	.5	3.200	13.0	6.4	740.0	.02	63.69	407.6
	624	BLACKHAW	.9	4.410	-0	4.9	35.3	.50	2.00	9.8
	625	CAMELOT	2.8	8.400	-0	3.0	90.6	.12	8.33	25.0
	626	COX HOLL	.4	1.520	-0	3.9	16.1	.60	1.67	6.5
	627	DUTCH HO	.8	2.400	-0	3.0	12.5	1.80	.56	1.7
	628	ISLES	.4	1.060	-0	2.7	2.8	.60	1.67	4.5
	629	KERR ROA	125.0	1287.500	-0	10.3	14395.7	.20	5.00	51.5
	630	KERR AUT	50.4	413.280	-0	8.1	5803.5	5.10	.20	1.6
	631	REDSTONE	2.5	10.750	-0	4.3	76.7	.85	1.18	5.1
	632	STEWART	2.5E-002	-0	-0	1.9	2.1	.08	12.50	23.8
	633	TWIN VAL	.6	2.280	-0	3.8	31.1	.45	2.22	8.4
	634	VIRGINIA	.2	.340	-0	1.7	6.5	1.85	.54	.9
	636	PIBURGER	.1	1.300	24.7	13.0	2.7	2.74	.37	4.7
N OF LAKES		27	27	26	15	27	25	26	26	25
MEAN			8.806	83.41707	21.537	8.274	1288.750	1.0414	5.3034	38.563
ST DEV			25.325	259.05930	14.925	5.134	3454.607	1.4459	12.3192	81.236
MINIMUM			2.5E-002	.340	2.0	1.7	.6	.02	.17	.9
MAXIMUM			125.0	1287.500	57.0	20.4	14395.7	5.88	63.69	407.6
TOTAL										
N OF LAKES		36	36	35	25	36	33	35	35	35
MEAN			7.086	69.23494	27.873	9.744	1386.842	1.1577	4.6214	37.922
ST DEV			22.057	224.06003	17.431	5.695	3507.445	1.9092	10.6671	73.043
MINIMUM			2.5E-002	.023	2.0	1.7	.5	.02	.11	.6
MAXIMUM			125.0	1287.500	65.4	20.4	14395.7	9.33	63.69	407.6

A5.1.3 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR GEOLOGIC AND MORPHOMETRIC VARIABLES IN UNUSUAL CANADIAN CIRCUMSTANCES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	SURFACE AREA KM2	VOLUME OF LAKE 10E6 M3	MAXIMUM DEPTH M	MEAN DEPTH M	DRAINAGE AREA KM2	WATER RESIDENCE TIME Y	FLUSHING RATE Y-1	HYDRAULIC LOAD M.Y-1
OLIGOTROPHIC										
	703	BOWKER	2.3	55.200	59.0	24.0	8.2	5.10	.20	4.7
	708	MONTJOIE	3.3	26.070	22.2	7.9	10.6	4.70	.59	4.6
	711	STUKELY	3.9	51.090	32.2	13.1	14.9	2.32	.43	5.2
	717	226N '73	4.8E-002	.243	15.4	3.0	.2	4.23	.24	-0
	718	226N '74	4.8E-002	.243	15.4	3.0	.2	3.93	.25	-0
	719	226S '73	4.7E-002	.269	13.0	5.7	.3	4.23	.24	1.3
	720	226S '74	4.7E-002	.263	13.0	5.7	.3	3.93	.25	1.4
	721	227 '69	5.0E-002	.220	10.0	4.4	.5	-0	-0	-0
	722	227 '70	5.0E-002	.220	10.0	4.4	.5	1.43	.70	3.1
	723	227 '71	5.0E-002	.220	10.0	4.4	.5	2.17	.45	2.0
	724	227 '72	5.0E-002	.220	10.0	4.4	.5	2.53	.33	1.7
	725	227 '73	5.0E-002	.220	10.0	4.4	.5	2.63	.36	1.7
	726	227 '74	5.0E-002	.220	10.0	4.4	.5	2.91	.34	1.5
	727	261 '73	.1	.161	9.6	2.9	.4	-0	-0	-0
	728	261 '74	.1	.161	9.6	2.9	.4	.77	1.30	3.8
	729	302N '72	.1	.730	13.3	5.7	.4	6.47	.15	.9
	730	302N '73	.1	.730	13.3	5.7	.4	3.32	.26	1.5
	731	302N '74	.1	.730	13.3	5.7	.4	-0	-0	-0
	732	304 '71	3.6E-002	.116	6.7	3.2	.3	-0	-0	-0
	733	304 '72	3.6E-002	.116	6.7	3.2	.3	-0	-0	-0
	734	304 '73	3.6E-002	.116	6.7	3.2	.3	-0	-0	-0
	735	304 '74	3.6E-002	.116	6.7	3.2	.3	-0	-0	-0
	741	KAMLOOPS	52.1	3699.100	143.0	71.0	39100.0	.15	6.23	443.7
N OF LAKES		23	23	23	23	23	23	15	16	14
MEAN			2.727	166.81643	19.765	8.674	1701.773	3.04553	.7742	34.087
ST DEV			10.818	770.17242	29.142	14.313	8152.587	1.64330	1.46609	117.918
MINIMUM			3.6E-002	.116	6.7	2.9	.6	.15	.15	.9
MAXIMUM			52.1	3699.100	143.0	71.0	39100.0	6.47	6.25	443.7

A5.1.3 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR GEOLOGIC AND MORPHOMETRIC VARIABLES IN UNUSUAL CANADIAN CIRCUMSTANCES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	SURFACE AREA KM2	VOLUME OF LAKE 10E6 M3	MAXIMUM DEPTH M	MEAN DEPTH M	DRAINAGE AREA KM2	WATER RESIDENCE TIME Y	FLUSHING RATE Y-1	HYDRAULIC LOAD M.Y-1
MESOTROPHIC										
	702	AYLMER	29.5	250.750	36.2	8.5	477.8	.23	4.35	37.0
	704	BROMPTON	11.9	148.750	42.3	12.5	97.1	1.90	.53	6.6
	705	LOVERING	4.6	44.620	24.9	9.7	38.1	.99	1.01	9.5
	707	MASSAWPI	17.9	719.560	85.7	40.2	535.5	1.50	.67	26.8
	709	PT BROMP	.7	5.110	19.5	7.3	1.8	3.70	.27	1.9
	710	ST FRAN	47.1	734.760	40.1	15.6	1157.0	.91	1.10	17.1
	714	ROXTON	1.8	5.760	5.5	3.2	15.6	.55	1.82	5.8
	740	BABINE	490.7	27037.570	230.0	55.1	10000.0	12.73	.08	4.3
	742	KOOTN'76	389.0	36566.000	154.0	94.0	45670.0	1.80	.56	52.2
	743	KOOTN'77	339.0	36566.000	154.0	94.0	45670.0	1.80	.56	52.2
	745	OKANG'77	344.4	25933.320	242.0	75.3	6060.6	142.40	.01	.5
	746	OKANG'78	344.4	25933.320	242.0	75.3	6060.6	44.10	.02	1.7
N OF LAKES		12	12	12	12	12	12	12	12	12
MEAN			172.583	12828.755	106.350	40.592	9652.433	17.7200	.9125	18.005
ST DEV			196.979	15887.263	92.347	35.965	17132.459	41.1099	1.2005	19.402
MINIMUM			.7	5.110	5.5	3.2	1.8	.23	.01	.5
MAXIMUM			490.7	36566.000	242.0	94.0	45670.0	142.40	4.35	52.2

A5.1.3 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR GEOLOGIC AND MORPHOMETRIC VARIABLES IN UNUSUAL CANADIAN CIRCUMSTANCES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	SURFACE AREA KM2	VOLUME OF LAKE 10E6 M3	MAXIMUM DEPTH M	MEAN DEPTH M	DRAINAGE AREA KM2	WATER RESIDENCE TIME Y	FLUSHING RATE Y-1	HYDRAULIC LOAD M.Y-1
EUTROPHIC										
	701	PINK	.1	1.240	20.0	12.4	2.0	1.12	.39	11.1
	706	MAGOG	10.8	105.840	19.1	9.8	164.2	.05	16.57	163.3
	712	BOIVIN	1.6	1.920	5.7	1.2	172.2	.02	50.00	60.0
	713	BROME	14.5	84.100	12.8	5.8	185.7	.70	1.43	8.3
	715	WATERLOO	1.5	4.350	4.9	2.9	31.5	.22	4.55	13.2
	716	LT OTTER	.7	1.850	5.0	2.7	10.6	.10	10.00	27.0
	736	PASQUA	19.9	115.420	15.5	5.8	128000.0	.35	2.86	16.5
	737	ECHO	12.5	113.750	22.0	9.1	11600.0	.34	2.94	26.8
	738	MISSION	7.6	66.120	17.0	8.7	11800.0	.19	5.26	45.9
	739	KATEPWA	16.1	227.010	23.0	14.1	12000.0	.65	1.54	24.7
	744	WOOD	9.3	195.300	34.0	21.0	55.0	14.00	.07	1.5
	747	SKAHA'77	20.1	532.650	55.8	26.5	828.0	1.20	.83	22.1
	748	SKAHA'78	20.1	532.650	55.8	26.5	828.8	1.20	.93	22.1
	749	OSOOY'77	9.9	204.930	63.4	20.7	1259.0	.40	2.50	51.8
	750	OSOOY'78	9.9	204.930	63.4	20.7	1269.0	.40	2.50	51.8
	751	GRAVNH 8	4.1	31.160	15.8	7.6	38.9	1.60	.56	4.2
N OF LAKES		16	16	16	16	16	16	16	16	16
MEAN			9.919	151.45375	27.337	12.219	10515.922	1.4219	6.4642	34.192
ST DEV			6.998	168.12589	20.528	8.418	31661.875	3.3921	12.3663	38.792
MINIMUM			.1	1.240	4.9	1.2	2.0	.02	.07	1.5
MAXIMUM			20.1	532.650	63.4	26.5	128000.0	14.00	50.00	163.3
TOTAL										
N OF LAKES		51	51	51	51	51	51	44	44	42
MEAN			44.950	3141.2858	42.514	17.367	6337.880	6.4573	2.8811	29.532
ST DEV			117.153	9233.2258	60.714	23.917	20314.319	22.0943	7.8736	71.518
MINIMUM			3.6E-002	.116	4.9	1.2	.2	.02	.01	.5
MAXIMUM			490.7	36566.000	242.0	94.0	128000.0	142.40	50.00	443.7

A5.2.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR NUTRIENT LOADINGS AND CONCENTRATIONS IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	PHOSPHORUS LOADING G M-2 Y-1	PHOSPHORUS MEAN BASIN CONC. MG M-3	PHOSPHORUS SPRING-MIX CONC. MG M-3	NITROGEN LOADING G M-2 Y-1	NITROGEN MEAN BASIN CONC. MG M-3	NITROGEN SPRING-MIX CONC. MG M-3	ANNUAL EUPHOTIC PHOSPHORUS MG M-3	ANNUAL EUPHOTIC NITROGEN MG M-3
OLIECTROPHIC										
	110	PAJAN-2	.800	14.70	18.60	17.600	470.00	458.70	15.80	461.50
	112	PAJAN-4	.800	15.80	15.20	23.200	450.70	430.30	14.40	450.80
	113	PAJAN-5	.300	10.90	10.60	7.300	427.70	443.30	13.70	432.90
	114	PAAJARVI	.300	9.20	11.30	6.300	952.80	1043.30	10.50	994.50
	201	LUNZER U	.510	8.35	-0	47.670	890.00	-0	7.93	885.00
	202	FELDSEE	.150	4.33	-0	9.220	306.00	-0	3.20	306.00
	214	ATTERSEE	.240	5.38	-0	3.600	-0	-0	6.43	-0
	222	VWS URNE	3.420	17.20	-0	51.000	520.00	-0	17.10	437.00
	236	TAZENAT	-0	-0	-0	-0	-0	-0	7.30	-0
	306	BIWA NOR	.310	4.67	7.33	4.470	263.33	302.00	7.67	241.00
	406	DOGFISH	.020	10.00	-0	-0	-0	-0	-0	-0
	407	GEORGE	.070	8.50	-0	1.800	-0	-0	-0	-0
	409	LAMB	.030	12.50	-0	-0	-0	-0	-0	-0
	410	MEANDER	.030	10.50	-0	-0	-0	-0	-0	-0
	420	TAHOE	.050	3.00	-0	.520	-0	-0	-0	-0
	423	WALDO	.020	3.00	-0	.330	-0	-0	-0	-0
	426	WASHINGT	.430	18.00	-0	4.400	-0	-0	-0	-0
	501	WOPCOK P	-0	1.90	-0	-0	-0	-0	-0	-0
	502	BLHILL N	-0	2.90	-0	-0	-0	-0	-0	-0
	503	BLHILL S	-0	3.70	-0	-0	-0	-0	-0	-0
	504	MINCHM P	-0	7.00	-0	-0	-0	-0	-0	-0
	505	YUDDLE N	-0	7.70	-0	-0	-0	-0	-0	-0
	506	PINEHL P	-0	9.60	-0	-0	-0	-0	-0	-0
	507	BENNETT	.520	6.00	-0	-0	-0	-0	-0	-0
	511	KEJIM	.300	9.20	-0	-0	-0	-0	-0	-0
	512	MOUNTAIN	.030	5.10	-0	-0	-0	-0	-0	-0
	513	PEBBLGCH	.050	10.50	-0	-0	-0	-0	-0	-0
	515	FRESHWTR	-0	7.50	-0	-0	-0	-0	-0	-0
	516	MC DL	-0	5.90	-0	-0	-0	-0	-0	-0
	523	BOWKER	.120	6.60	-0	-0	-0	-0	-0	-0
	528	MONTJOIE	.080	8.00	-0	-0	-0	-0	-0	-0
	531	STUKLEY	.110	5.00	-0	-0	-0	-0	-0	-0
	536	BEECH	1.520	7.40	-0	-0	-0	-0	-0	-0
	537	BOB	.160	6.40	-0	-0	-0	-0	-0	-0
	539	CRANBRY	1.300	9.90	-0	-0	-0	-0	-0	-0
	540	EAGL-MGC	.220	7.10	-0	-0	-0	-0	-0	-0
	542	HALLS	.210	3.70	-0	-0	-0	-0	-0	-0
	543	MAPLE	.830	9.30	-0	-0	-0	-0	-0	-0
	544	DBL-HALI	.120	4.80	-0	-0	-0	-0	-0	-0
	545	PINE	1.050	10.50	-0	-0	-0	-0	-0	-0
	546	RAVEN	.210	8.30	-0	-0	-0	-0	-0	-0
	547	TALBOT	.100	15.30	-0	-0	-0	-0	-0	-0
	548	12MI-BOS	.350	6.10	-0	-0	-0	-0	-0	-0
	550	JERRY	.320	14.50	-0	-0	-0	-0	-0	-0
	552	LTL JOS	.210	8.80	-0	-0	-0	-0	-0	-0
	554	ROSSEAU	.150	7.70	-0	-0	-0	-0	-0	-0
	556	SKELTN B	1.030	11.00	-0	-0	-0	-0	-0	-0
	557	BREWER	.090	8.60	-0	-0	-0	-0	-0	-0
	558	CLARKE	.950	10.00	-0	-0	-0	-0	-0	-0
	559	COSTELLO	.180	9.60	-0	-0	-0	-0	-0	-0
	560	FOUND	.040	7.00	-0	-0	-0	-0	-0	-0
	561	KEARNEY	.220	12.10	-0	-0	-0	-0	-0	-0
	562	L MC CAU	.090	7.10	-0	-0	-0	-0	-0	-0
	563	BIGWIND	-0	6.80	-0	-0	-0	-0	-0	-0
	564	BL CHALK	-0	5.60	-0	-0	-0	-0	-0	-0
	565	BUCK	-0	6.30	-0	-0	-0	-0	-0	-0
	567	CROSSON	-0	9.15	-0	-0	-0	-0	-0	-0
	570	HARP	-0	6.85	-0	-0	-0	-0	-0	-0
	571	JERRY	-0	7.00	-0	-0	-0	-0	-0	-0
	572	L CLEAR	-0	7.40	-0	-0	-0	-0	-0	-0

A5.2.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR NUTRIENT LOADINGS AND CONCENTRATIONS IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	PHOSPHORUS LOADING G M-2 Y-1	PHOSPHORUS MEAN BASIN CONC. MG M-3	PHOSPHORUS SPRING-MIX CONC. MG M-3	NITROGEN LOADING G M-2 Y-1	NITROGEN MEAN BASIN CONC. MG M-3	NITROGEN SPRING-MIX CONC. MG M-3	ANNUAL EUPHOTIC PHOSPHORUS MG M-3	ANNUAL EUPHOTIC NITROGEN MG M-3
OLIGOTROPHIC	(CONT.)									
	573	RD CHAL	-0	4.80	-0	-0	-0	-0	-0	-0
	574	SOLITR	-0	5.70	-0	-0	-0	-0	-0	-0
	575	WALKER	-0	6.60	-0	-0	-0	-0	-0	-0
	576	SUPERIOR	.050	4.60	-0	-0	-0	-0	-0	-0
	578	HURON	.050	5.50	-0	-0	-0	-0	-0	-0
	583	114	.100	12.00	-0	-0	-0	-0	-0	-0
	584	120	-0	7.00	-0	-0	-0	-0	-0	-0
	585	223	.060	10.00	-0	-0	-0	-0	-0	-0
	586	224	.040	7.00	-0	-0	-0	-0	-0	-0
	587	239	.060	8.50	-0	-0	-0	-0	-0	-0
	588	240	.090	11.00	-0	-0	-0	-0	-0	-0
	589	303	.070	11.00	-0	-0	-0	-0	-0	-0
	593	KALAMLKA	.090	9.70	-0	-0	-0	-0	-0	-0
N OF LAKES		73	53	72	5	13	8	5	10	8
MEAN			.35283	8.1996	12.6060	13.55623	535.0063	535.5200	10.1930	527.0162
ST DEV			.55462	3.3605	4.3653	17.08599	233.3173	290.6240	4.3726	267.4824
MINIMUM			.020	1.90	7.33	.330	263.33	302.00	3.80	248.00
MAXIMUM			3.420	18.00	13.60	51.000	952.80	1043.30	17.10	994.90

A5.2.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR NUTRIENT LOADINGS AND CONCENTRATIONS IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	PHOSPHORUS LOADING G M-2 Y-1	PHOSPHORUS MEAN BASIN CONC. MG M-3	PHOSPHORUS SPRING-MIX CONC. MG M-3	NITROGEN LOADING G M-2 Y-1	NITROGEN MEAN BASIN CONC. MG M-3	NITROGEN SPRING-MIX CONC. MG M-3	ANNUAL EUPHOTIC PHOSPHORUS MG M-3	ANNUAL EUPHOTIC NITROGEN MG M-3
MESOTROPHIC										
	111	PAJAN-3	1.950	35.00	33.80	28.100	544.50	538.30	29.80	478.00
	204	MERGOZZO	.530	5.60	-0	-0	680.00	-0	6.00	694.60
	213	OSSIACHE	.740	14.50	-0	33.440	878.00	-0	14.90	999.00
	216	VALLENSE	4.900	27.80	-0	-0	-0	-0	23.40	-0
	220	VWS KREU	1.330	25.80	-0	30.680	530.00	-0	21.20	464.00
	221	VWS GERS	2.370	18.70	-0	54.860	517.00	-0	16.50	473.00
	223	MAGGIORF	3.390	22.00	-0	-0	-0	-0	-0	-0
	224	VALLENSE	4.000	28.60	-0	-0	-0	-0	18.50	-0
	227	LEMAN	1.480	92.00	-0	-0	583.00	-0	69.00	518.00
	230	MONTORFA	.200	16.00	-0	.810	-0	-0	16.20	-0
	231	ANNONE	3.400	26.00	-0	13.500	-0	-0	27.00	-0
	234	D ANNECY	.390	-0	-0	-0	-0	-0	-0	-0
	237	PAVIN	-0	28.20	-0	-0	-0	-0	31.80	-0
	303	LOUGH LE	1.000	-0	-0	-0	-0	-0	-0	-0
	404	CAYUGA	.800	20.00	-0	14.300	-0	-0	-0	-0
	418	SAMMAMIS	.700	30.00	-0	13.000	-0	-0	30.00	-0
	427	WEIR	.140	20.00	-0	2.600	-0	-0	20.00	-0
	509	WOLFE	.050	7.70	-0	-0	-0	-0	-0	-0
	510	GRAFTON	.200	10.50	-0	-0	-0	-0	-0	-0
	514	LTL KEPP	-0	27.90	-0	-0	-0	-0	-0	-0
	517	PRESQUL	-0	13.90	-0	-0	-0	-0	-0	-0
	518	WARREN	.380	6.20	-0	-0	-0	-0	-0	-0
	519	MEMPH N	.510	12.70	-0	-0	-0	-0	-0	-0
	520	MEMPH C	.980	13.40	-0	-0	-0	-0	-0	-0
	522	AYLMER	1.000	27.30	-0	-0	-0	-0	-0	-0
	524	BROMPTON	.190	9.00	-0	-0	-0	-0	-0	-0
	525	LOVERING	.300	11.00	-0	-0	-0	-0	-0	-0
	527	MASSAWP	1.130	11.00	-0	-0	-0	-0	-0	-0
	529	PT BROMP	.200	12.00	-0	-0	-0	-0	-0	-0
	530	ST FRAN	.630	22.70	-0	-0	-0	-0	-0	-0
	534	ROXTON	.400	27.00	-0	-0	-0	-0	-0	-0
	538	CAMERON	1.960	8.90	-0	-0	-0	-0	-0	-0
	541	4-MI	.110	7.90	-0	-0	-0	-0	-0	-0
	549	DUDLEY B	.200	15.00	-0	-0	-0	-0	-0	-0
	551	HARP	.180	11.00	-0	-0	-0	-0	-0	-0
	553	MUSKOKA	.750	9.40	-0	-0	-0	-0	-0	-0
	555	SIMCOE	.190	19.00	-0	-0	-0	-0	-0	-0
	566	CHUB	-0	9.30	-0	-0	-0	-0	-0	-0
	568	DICKIE	-0	12.70	-0	-0	-0	-0	-0	-0
	569	GULFEATH	-0	13.00	-0	-0	-0	-0	-0	-0
	577	MICHIGAN	.100	8.00	-0	-0	-0	-0	-0	-0
	580	CB ERIE	.730	19.40	-0	-0	-0	-0	-0	-0
	581	EB ERIE	.820	17.20	-0	-0	-0	-0	-0	-0
	582	ONTARIO	.730	21.00	-0	-0	-0	-0	-0	-0
	594	OKANAGAN	.250	7.40	-0	-0	-0	-0	-0	-0
N OF LAKES		45	39	43	1	9	6	1	13	6
MEAN			.99641	18.6442	33.8000	21.25444	622.0833	538.3000	24.9462	604.4333
ST DEV			1.14857	13.8561	M	17.16144	138.5030	M	15.0864	211.6630
MINIMUM			.060	5.50	33.80	.810	517.00	538.30	6.00	464.00
MAXIMUM			4.900	92.00	33.80	54.860	878.00	538.30	69.00	999.00

A5.2.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR NUTRIENT LOADINGS AND CONCENTRATIONS IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	PHOSPHORUS LOADING G M-2 Y-1	PHOSPHORUS MEAN BASIN CONC. MG M-3	PHOSPHORUS SPRING-MIX CONC. MG M-3	NITROGEN LOADING G M-2 Y-1	NITROGEN MEAN BASIN CONC. MG M-3	NITROGEN SPRING-MIX CONC. MG M-3	ANNUAL EUPHOTIC PHOSPHORUS MG M-3	ANNUAL EUPHOTIC NITROGEN MG M-3
EUTRCPHIC										
	101	ESRUM	.530	238.00	247.50	4.100	742.30	1006.50	252.30	773.30
	102	MOSSO 1	.900	137.60	152.50	12.600	1766.70	2275.00	135.30	1781.30
	103	MOSSO 2	80.000	163.30	168.30	1710.000	2550.00	4875.00	155.30	2633.30
	104	GJERSJO	.730	28.20	20.40	20.000	1365.00	1213.30	23.30	959.90
	105	MJOSA	.750	8.90	12.50	12.100	393.30	441.50	6.40	371.40
	106	BOREN	1.150	22.80	23.30	21.100	525.00	560.00	22.30	494.30
	107	MALAREN	2.800	68.30	81.80	69.030	1815.00	2325.00	67.20	1600.00
	108	VATTERN	.100	8.00	9.00	1.800	523.00	543.00	3.50	513.00
	109	PAJAN-1	1.030	24.60	27.20	20.400	522.90	512.70	25.40	503.40
	115	TUUSULAN	1.700	110.30	116.00	18.200	2350.00	2826.70	103.70	2033.00
	203	BODENSEE	4.540	79.50	-0	24.120	1049.00	-0	55.90	857.00
	205	PONTE LU	2.840	193.00	-0	18.470	3658.00	-0	149.00	2755.00
	206	CAPOLAGO	5.000	178.00	-0	55.400	3577.00	-0	135.00	3041.00
	207	MELIDE L	.800	181.00	-0	7.820	3719.00	-0	135.00	2655.00
	208	GONOFIA	1.450	170.00	-0	18.590	3220.00	-0	139.00	2695.00
	209	LUGANO L	3.880	163.00	-0	28.080	2538.00	-0	151.00	2144.00
	210	AGNO LUG	10.010	167.00	-0	121.330	2916.00	-0	137.00	2263.00
	211	MAFCOTE	3.930	174.00	-0	33.660	3547.00	-0	132.00	2314.00
	212	FIGINO L	1.340	174.20	-0	13.250	3335.00	-0	135.00	3349.00
	213	GREIFENS	2.676	386.00	-0	57.650	2259.00	-0	232.00	2131.00
	217	BALDEGGE	2.160	543.00	-0	23.680	-0	-0	373.00	-0
	218	HALLWILL	2.040	207.00	-0	16.170	1506.00	-0	67.00	1155.00
	219	SEMPACHE	1.090	73.90	-0	14.480	542.00	-0	50.00	740.00
	225	ZURICH U	-0	99.30	-0	-0	-0	-0	47.20	-0
	226	ZURICH C	-0	38.40	-0	-0	-0	-0	24.50	-0
	228	OGGIONO	2.000	170.30	-0	7.900	-0	-0	-0	-0
	229	PUSIANO	6.000	71.00	-0	23.600	-0	-0	55.00	-0
	232	SEGRINO	1.000	38.00	-0	4.100	-0	-0	33.00	-0
	233	D ALSERI	11.000	143.00	-0	44.300	-0	-0	137.00	-0
	235	MANTUA	2.700	-0	-0	-0	-0	-0	-0	-0
	238	AYDAT	-0	52.60	-0	-0	694.00	-0	64.10	607.00
	301	LOUGH NE	1.350	121.00	-0	15.800	400.00	-0	121.00	400.00
	302	LOCH LEV	.970	68.00	91.00	23.700	1520.00	2520.00	58.00	1523.00
	304	LOUGH EN	.920	66.50	60.00	-0	-0	-0	34.00	-0
	305	BIWA SOU	2.500	20.00	17.66	53.700	299.97	317.67	23.00	300.00
	307	KASUMI W	1.490	53.03	38.16	22.300	1134.33	1131.67	54.73	1253.40
	308	KASUMI K	1.690	53.40	19.67	25.000	928.33	790.00	50.53	962.00
	401	BROWNIE	1.180	-0	-0	-0	-0	-0	-0	-0
	402	CALHOUN	.860	106.00	-0	-0	-0	-0	-0	-0
	403	CANADARA	.800	45.00	-0	18.000	-0	-0	-0	-0
	405	CEDAR	.350	55.00	-0	-0	-0	-0	-0	-0
	408	HARRIET	.710	62.00	-0	-0	-0	-0	-0	-0
	411	MENDOTA	1.200	150.00	-0	13.000	-0	-0	-0	-0
	412	LOWER MI	.506	60.00	-0	-0	-0	-0	-0	-0
	413	LOWER MI	.200	50.00	-0	-0	-0	-0	-0	-0
	414	POTOMAC	85.000	750.00	-0	288.000	-0	-0	-0	-0
	415	POTOMAC	8.000	380.00	-0	32.000	-0	-0	-0	-0
	416	POTOMAC	1.200	45.00	-0	25.000	-0	-0	-0	-0
	417	SALLIE	2.830	350.00	-0	2.900	-0	-0	-0	-0
	419	SHAGAWA	.700	60.00	-0	7.800	-0	-0	-0	-0
	421	EAST TWI	.630	80.00	-0	25.350	-0	-0	-0	-0
	422	WEST TWI	.330	110.00	-0	15.500	-0	-0	-0	-0
	424	WASHINGT	1.200	24.00	-0	7.800	-0	-0	-0	-0
	425	WASHINGT	2.300	66.00	-0	4.600	-0	-0	-0	-0
	428	WINGRA	.900	70.00	-0	5.140	-0	-0	-0	-0
	508	MCLAREN	1.560	20.60	-0	-0	-0	-0	-0	-0
	521	MEMPH S	.480	18.60	-0	-0	-0	-0	-0	-0
	526	MAGOG	5.000	43.00	-0	-0	-0	-0	-0	-0
	532	BOIVIN	6.200	125.00	-0	-0	-0	-0	-0	-0
	533	BROME	.530	80.00	-0	-0	-0	-0	-0	-0

AS.2.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR NUTRIENT LOADINGS AND CONCENTRATIONS IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	PHOSPHORUS LOADING G M-2 Y-1	PHOSPHORUS MEAN BASIN CONC. MG M-3	PHOSPHORUS SPRING-MIX CONC. MG M-3	NITROGEN LOADING G M-2 Y-1	NITROGEN MEAN BASIN CONC. MG M-3	NITROGEN SPRING-MIX CONC. MG M-3	ANNUAL EUPHOTIC PHOSPHORUS MG M-3	ANNUAL EUPHOTIC NITROGEN MG M-3
EUTROPHIC	(CONT.)									
	535	WATERLOO	.910	52.00	-0	-0	-0	-0	-0	-0
	579	WB ERIE	3.660	39.30	-0	-0	-0	-0	-0	-0
	590	WINNIPEG	.290	60.00	-0	-0	-0	-0	-0	-0
	591	CROOKED	10.880	221.00	-0	-0	-0	-0	-0	-0
	592	ROUND	12.380	175.00	-0	-0	-0	-0	-0	-0
	595	SKAHA	1.090	14.50	-0	-0	-0	-0	-0	-0
	596	OSOYOOS	1.720	22.30	-0	-0	-0	-0	-0	-0
N OF LAKES		67	64	65	15	44	28	14	35	28
MEAN			4.94797	120.4312	72.3327	68.01162	1753.4302	1324.5743	93.0960	1530.4700
ST DEV			14.31362	127.9030	70.9539	257.30000	1172.0913	1293.0070	78.3224	939.8893
MINIMUM			.100	8.00	9.00	1.800	299.67	317.67	8.40	300.00
MAXIMUM			85.000	750.00	247.50	1710.000	3719.00	4875.00	373.00	3349.00
TOTAL										
N OF LAKES		185	156	180	81	66	42	20	58	42
MEAN			2.39891	51.2226	56.2771	50.91030	1359.7252	1227.9970	66.9016	1211.0443
ST DEV			9.39732	92.9379	64.9843	210.91499	1111.8333	1173.7667	72.7806	903.8229
MINIMUM			.020	1.90	7.33	.330	263.33	302.00	3.80	243.00
MAXIMUM			85.000	750.00	247.50	1710.000	3719.00	4875.00	373.00	3349.00

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A5.2.2   DATA LISTING BY TROPHIC CATEGORY WITH
         BASIC STATISTICS FOR NUTRIENT LOADINGS
         AND CONCENTRATIONS IN SHALLOW LAKES
         AND RESERVOIRS.

TROPHIC            LAKE   LAKE NAME PHOSPHORUS PHOSPHORUS PHOSPHORUS  NITROGEN    NITROGEN    NITROGEN     ANNUAL      ANNUAL
 GROUP                      (ABBR)  LOADING    MEAN BASIN SPRING-MIX  LOADING   MEAN BASIN  SPRING-MIX   EUPHOTIC    EUPHOTIC
                                               CONC.        CONC.                  CONC.       CONC.    PHOSPHORUS   NITROGEN
                                    G M-2 Y-1   MG M-3     MG M-3    G M-2 Y-1    MG M-3      MG M-3      MG M-3      MG M-3
OLIGOTROPHIC

                    602 OLEF            .220      11.15       6.00        -0          -0          -0       10.10          -0
                    605 VERSE           .430      11.00      13.00    38.420     1630.00     1680.00       12.00     1630.00
                    606 SOSE            .390       4.67       3.00        -0          -0          -0        4.33          -0
                    608 FUFWIGGE        .390       6.00       9.00    57.000     1620.00     1650.00        8.00     1620.00
                    623 EUPEN             -0         -0         -0        -0          -0          -0          -0          -0
                    635 VECHTEN           -0         -0         -0        -0          -0          -0          -0          -0

N OF LAKES                       6         4          4          4         2           2           2           4           2
  MEAN                              .35750     8.7650     7.7500  47.71000   1625.0000   1665.0000      8.6075   1625.0000
 ST DEV                             .09359     3.0563     4.2720  13.13804      7.0711     21.2132      3.2365      7.0711
MINIMUM                               .220       4.57       3.00    38.420     1620.00     1650.00        4.33     1620.00
MAXIMUM                               .430      11.15      13.00    57.000     1630.00     1680.00       12.00     1630.00
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A5.2.2 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR NUTRIENT LOADINGS AND CONCENTRATIONS IN SHALLOW LAKES AND RESERVOIRS.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	PHOSPHORUS LOADING G M-2 Y-1	PHOSPHORUS MEAN BASIN CONC. MG M-3	PHOSPHORUS SPRING-MIX CONC. MG M-3	NITROGEN LOADING G M-2 Y-1	NITROGEN MEAN BASIN CONC. MG M-3	NITROGEN SPRING-MIX CONC. MG M-3	ANNUAL EUPHOTIC PHOSPHORUS MG M-3	ANNUAL EUPHOTIC NITROGEN MG M-3
MESOTROPHIC										
	619	MT BOLD	6.050	95.67	146.00	61.800	1386.67	2040.00	98.67	1416.67
	620	PROSPECT	1.080	10.90	13.50	31.600	361.00	501.00	10.94	-0
	621	EL BURGI	4.260	41.50	40.67	58.300	1154.00	1288.00	35.50	990.67
N OF LAKES		3	3	3	3	3	3	3	3	2
MEAN			3.79667	49.3567	66.7233	50.56667	967.2233	1276.3333	43.7033	1203.6700
ST DEV			2.51719	42.9277	69.9867	16.51658	537.7396	769.5063	45.1202	301.2275
MINIMUM			1.080	10.90	13.50	31.600	361.00	501.00	10.94	990.67
MAXIMUM			6.050	95.67	146.00	61.800	1386.67	2040.00	98.67	1416.67

A5.2.2 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR NUTRIENT LOADINGS AND CONCENTRATIONS IN SHALLOW LAKES AND RESERVOIRS.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	PHOSPHORUS LOADING G M-2 Y-1	PHOSPHORUS MEAN BASIN CONC. MG M-3	PHOSPHORUS SPRING-MIX CONC. MG M-3	NITROGEN LOADING G M-2 Y-1	NITROGEN MEAN BASIN CONC. MG M-3	NITROGEN SPRING-MIX CONC. MG M-3	ANNUAL EUPHOTIC PHOSPHORUS MG M-3	ANNUAL EUPHOTIC NITROGEN MG M-3
EUTROPHIC										
	601	WANPACH	1.480	21.33	13.00	-0	-0	-0	21.00	-0
	603	SOPPE	3.540	40.00	48.00	68.000	2230.00	2580.00	42.00	2190.00
	604	MOHNE	7.480	76.50	91.50	87.160	3000.00	3500.00	76.00	3040.00
	607	ENNEPE	25.010	139.00	206.00	202.000	3721.50	6750.00	138.00	4525.00
	609	DE GROTE	6.090	81.00	109.33	61.700	3023.33	4166.67	91.00	3023.33
	610	BRIELSE	16.700	290.00	430.00	148.000	4700.00	7000.00	295.00	4700.00
	611	PETRUSPL	41.900	190.00	240.00	684.000	5100.00	5400.00	190.00	5100.00
	612	HONORED	33.330	330.00	310.00	400.000	5333.33	5700.00	330.00	5333.33
	613	BRAAKMAN	7.810	260.00	246.66	184.000	6100.00	8300.00	253.00	6100.00
	614	BRAAKMAN	2.120	50.00	33.33	59.600	4300.00	6833.33	50.00	4300.00
	615	TJEUKEME	-0	-0	-0	-0	-0	-0	-0	-0
	616	QUEEN EL	-0	-0	-0	-0	-0	-0	-0	-0
	617	FARMOOR	10.450	241.67	237.00	-0	-0	-0	-0	-0
	618	GRAFHAM	8.030	-0	-0	-0	2864.00	-0	-0	2910.00
	622	WISRAMON	33.670	-0	-0	-0	-0	-0	-0	-0
	624	BLACKHAW	2.220	120.00	-0	23.400	-0	-0	120.00	-0
	625	CAMELOT	2.510	40.00	-0	34.600	-0	-0	-0	-0
	626	COX HOLL	1.850	100.00	-0	19.160	-0	-0	-0	-0
	627	DUTCH HC	.980	250.00	-0	10.400	-0	-0	-0	-0
	628	ISLES	2.030	110.00	-0	-0	-0	-0	-0	-0
	629	KERR RGA	5.200	30.00	-0	36.200	-0	-0	-0	-0
	630	KERR NUT	.700	30.00	-0	2.400	-0	-0	-0	-0
	631	REDSTONE	1.560	111.00	-0	16.100	-0	-0	-0	-0
	632	STEWART	6.430	80.00	-0	73.600	-0	-0	-0	-0
	633	TWIN VAL	1.890	60.00	-0	17.400	-0	-0	-0	-0
	634	VIRGINIA	1.310	150.00	-0	18.300	-0	-0	-0	-0
	636	PIBURGER	.050	16.20	-0	3.270	431.00	-0	10.60	353.00
N OF LAKES		27	25	23	11	20	11	9	12	11
MEAN			8.97350	122.4652	179.0745	107.56150	3709.3782	5591.1111	134.5333	3779.5145
ST DEV			11.78766	93.8881	130.1406	165.83714	1619.9167	1850.4606	111.1481	1654.0537
MINIMUM			.050	16.20	18.00	2.400	431.00	2580.00	10.60	353.00
MAXIMUM			41.900	330.00	430.00	684.000	6100.00	8300.00	330.00	6100.00
TOTAL										
N OF LAKES		36	32	30	18	25	16	14	19	15
MEAN			7.41125	99.9863	122.2772	95.93400	2934.6709	4105.6429	97.0600	3148.3000
ST DEV			10.84601	92.9004	127.5163	149.55263	1797.4406	2347.5046	105.1550	1773.5462
MINIMUM			.050	4.67	3.00	2.400	361.00	501.00	4.33	353.00
MAXIMUM			41.900	330.00	430.00	684.000	6100.00	8300.00	330.00	6100.00

A5.2.3 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR NUTRIENT LOADINGS AND CONCENTRATIONS IN UNUSUAL CANADIAN CIRCUMSTANCES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	PHOSPHORUS LOADING G M-2 Y-1	PHOSPHORUS MEAN BASIN CONC. MG M-3	PHOSPHORUS SPRING-MIX CONC. MG M-3	NITROGEN LOADING G M-2 Y-1	NITROGEN MEAN BASIN CONC. MG M-3	NITROGEN SPRING-MIX CONC. MG M-3	ANNUAL EUPHOTIC PHOSPHORUS MG M-3	ANNUAL EUPHOTIC NITROGEN MG M-3
OLIGOTROPHIC										
	703	BOWKER	.120	6.60	-0	-0	-0	-0	-0	-0
	708	MONTJOIE	.140	8.00	-0	-0	-0	-0	-0	-0
	711	STUKELY	.170	8.30	-0	-0	-0	-0	-0	-0
	717	226N '73	.640	11.00	-0	4070.000	-0	-0	-0	-0
	718	226N '74	.640	11.00	-0	4070.000	-0	-0	-0	-0
	719	226S '73	.090	11.00	-0	4540.000	-0	-0	-0	-0
	720	226S '74	.090	10.00	-0	4540.000	-0	-0	-0	-0
	721	227 '69	.410	6.00	-0	6100.000	-0	-0	-0	-0
	722	227 '70	.580	14.00	-0	7900.000	-0	-0	-0	-0
	723	227 '71	.590	22.00	-0	7790.000	-0	-0	-0	-0
	724	227 '72	.530	20.00	-0	7350.000	-0	-0	-0	-0
	725	227 '73	.590	28.00	-0	7220.000	-0	-0	-0	-0
	726	227 '74	.590	32.00	-0	7220.000	-0	-0	-0	-0
	727	261 '73	.310	13.00	-0	1070.000	-0	-0	-0	-0
	728	261 '74	.310	18.00	-0	1080.000	-0	-0	-0	-0
	729	302N '72	.580	17.00	-0	3720.000	-0	-0	-0	-0
	730	302N '73	.570	15.00	-0	3540.000	-0	-0	-0	-0
	731	302N '74	.570	19.00	-0	3540.000	-0	-0	-0	-0
	732	304 '71	-0	9.00	-0	-0	-0	-0	-0	-0
	733	304 '72	-0	24.00	-0	-0	-0	-0	-0	-0
	734	304 '73	-0	24.00	-0	-0	-0	-0	-0	-0
	735	304 '74	-0	19.00	-0	-0	-0	-0	-0	-0
	741	KAMLOOPS	17.000	9.00	-0	-0	-0	-0	-0	-0
N OF LAKES		23	19	23	0	15	0	0	0	0
MEAN			1.29053	15.4304	M	4916.66667	M	M	M	M
ST DEV			3.80980	7.1674	M	2260.61201	M	M	M	M
MINIMUM			.090	6.00	M	1070.000	M	M	M	M
MAXIMUM			17.000	32.00	M	7900.000	M	M	M	M

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A5.2.3     DATA LISTING BY TROPHIC CATEGORY WITH
           BASIC STATISTICS FOR NUTRIENT LOADINGS
           AND CONCENTRATIONS IN UNUSUAL
           CANADIAN CIRCUMSTANCES.

TROPHIC                  LAKE   LAKE NAME PHOSPHORUS PHOSPHORUS PHOSPHORUS  NITROGEN    NITROGEN   NITROGEN    ANNUAL     ANNUAL
 GROUP                             (ABBR) LOADING    MEAN BASIN SPRING-MIX  LOADING   MEAN BASIN SPRING-MIX  EUPHOTIC   EUPHOTIC
                                                     CONC.        CONC.                 CONC.      CONC.    PHOSPHORUS  NITROGEN
                                          G M-2 Y-1   MG M-3     MG M-3     G M-2 Y-1   MG M-3     MG M-3     MG M-3     MG M-3

MESOTROPHIC

                          702  AYLMER        1.720      27.30        -0         -0         -0         -0         -0         -0
                          704  BROMPTON       .320       8.80        -0         -0         -0         -0         -0         -0
                          705  LOVERING       .320      11.00        -0         -0         -0         -0         -0         -0
                          707  MASSAWPI      1.700      13.30        -0         -0         -0         -0         -0         -0
                          709  PT BROMP       .130      13.30        -0         -0         -0         -0         -0         -0
                          710  ST FRAN       1.130      22.70        -0         -0         -0         -0         -0         -0
                          714  ROXTON         .650      27.00        -0         -0         -0         -0         -0         -0
                          740  BABINE         .050       5.95        -0         -0         -0         -0         -0         -0
                          742  KOOTN'76      1.200      22.40        -0         -0         -0         -0         -0         -0
                          743  KOOTN'77       .740      18.80        -0         -0         -0         -0         -0         -0
                          745  OKANG'77       .250       8.50        -0         -0         -0         -0         -0         -0
                          746  OKANG'78       .250       6.30        -0         -0         -0         -0         -0         -0

N OF LAKES                           12         12         12         0          0          0          0          0          0
  MEAN                                      .70500    15.4456         M          M          M          M          M          M
 ST DEV                                     .59698     7.8709         M          M          M          M          M          M
MINIMUM                                       .050       5.95         M          M          M          M          M          M
MAXIMUM                                      1.720      27.30         M          M          M          M          M          M
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A5.2.3 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR NUTRIENT LOADINGS AND CONCENTRATIONS IN UNUSUAL CANADIAN CIRCUMSTANCES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	PHOSPHORUS LOADING G M-2 Y-1	PHOSPHORUS MEAN BASIN CONC. MG M-3	PHOSPHORUS SPRING-MIX CONC. MG M-3	NITROGEN LOADING G M-2 Y-1	NITROGEN MEAN BASIN CONC. MG M-3	NITROGEN SPRING-MIX CONC. MG M-3	ANNUAL EUPHOTIC PHOSPHORUS MG M-3	ANNUAL EUPHOTIC NITROGEN MG M-3
EUTROPHIC										
	701	PINK	.850	30.00	-0	-0	-0	-0	-0	-0
	706	MAGOG	4.620	17.60	-0	-0	-0	-0	-0	-0
	712	BOIVIN	7.230	125.00	-0	-0	-0	-0	-0	-0
	713	BROME	.510	80.00	-0	-0	-0	-0	-0	-0
	715	WATERLOO	1.700	52.00	-0	-0	-0	-0	-0	-0
	716	LT OTTER	.440	110.00	-0	-0	-0	-0	-0	-0
	736	PASQUA	6.460	553.00	-0	-0	-0	-0	-0	-0
	737	ECHO	10.760	449.00	-0	-0	-0	-0	-0	-0
	738	MISSION	18.510	479.00	-0	-0	-0	-0	-0	-0
	739	KATEPWA	8.510	489.00	-0	-0	-0	-0	-0	-0
	744	WOOD	.160	92.60	-0	-0	-0	-0	-0	-0
	747	SKAHA'77	1.090	11.00	-0	-0	-0	-0	-0	-0
	748	SKAHA'78	1.090	18.00	-0	-0	-0	-0	-0	-0
	749	OSOOY'77	1.720	21.00	-0	-0	-0	-0	-0	-0
	750	OSOOY'78	1.720	23.50	-0	-0	-0	-0	-0	-0
	751	GRAVNH 8	8.160	44.00	-0	8162.000	-0	-0	-0	-0
N OF LAKES	15		16	16	0	1	0	0	0	0
MEAN			4.59563	162.1688	M	8162.00000	M	M	M	M
ST DEV			5.08082	200.6616	M	M	M	M	M	M
MINIMUM			.160	11.00	M	8162.000	M	M	M	M
MAXIMUM			18.510	553.00	M	8162.000	M	M	M	M
TOTAL										
N OF LAKES	51		47	51	0	16	0	0	0	0
MEAN			2.26517	61.4696	M	5119.50000	M	M	M	M
ST DEV			4.13511	129.8774	M	2329.79341	M	M	M	M
MINIMUM			.050	5.75	M	1070.000	M	M	M	M
MAXIMUM			18.510	553.00	M	8162.000	M	M	M	M

A5.3.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR ALGAL BIOMASS AND CHLOROPHYLL IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	ANNUAL EUPHOTIC CHLOROPHYLL MG M-3	SPRING EUPHOTIC CHLOROPHYLL MG M-3	MAXIMUM EUPHOTIC CHLOROPHYLL MG M-3	MINIMUM EUPHOTIC CHLOROPHYLL MG M-3	EUPHOTIC ALGAL BIOMASS (PER VOLUME) G M-3	EUPHOTIC ALGAL BIOMASS (PER SURFACE) G M-2	ANNUAL SECCHI DEPTH M
OLIGOTROPHIC									
	110	PAJAN-2	2.10	4.60	8.50	.40	-0	-0	-0
	112	PAJAN-4	2.40	5.80	10.60	.60	-0	-0	-0
	113	PAJAN-5	1.40	2.10	4.00	.20	-0	-0	-0
	114	PAAJARVI	1.80	2.20	4.90	.40	-0	-0	-0
	201	LUNZER U	1.84	3.34	5.90	.63	.420	7.400	9.0
	202	FELDSEE	2.26	1.97	3.90	.45	.330	3.650	5.4
	214	ATTERSEE	1.33	5.26	2.40	.85	.400	9.700	8.5
	222	VWS URNE	-0	-0	-0	-0	-0	14.700	7.4
	236	TAZENAT	3.50	2.94	6.40	1.34	1.850	21.400	5.6
	306	BIWA NOR	1.99	-0	4.13	1.01	-0	-0	7.5
	406	DOGFISH	3.00	-0	-0	-0	-0	-0	-0
	407	GEORGE	-0	-0	-0	-0	-0	-0	8.5
	409	LAMB	4.00	-0	-0	-0	-0	-0	-0
	410	MEANDER	2.00	-0	-0	-0	-0	-0	-0
	420	TAHOE	.30	-0	-0	-0	-0	-0	23.3
	423	WALDO	.30	-0	-0	-0	-0	-0	-0
	426	WASHINGT	6.00	-0	-0	-0	-0	-0	3.5
	501	WBROOK P	.55	-0	-0	-0	-0	-0	3.9
	502	BLHILL N	1.30	-0	-0	-0	-0	-0	4.7
	503	BLHILL S	1.10	-0	-0	-0	-0	-0	5.5
	504	MINCHY P	-0	-0	-0	-0	-0	-0	4.2
	505	YUDDLE N	.90	-0	-0	-0	-0	-0	4.2
	506	PINEHL P	1.40	-0	-0	-0	-0	-0	4.3
	507	BENNETT	1.30	-0	-0	-0	-0	-0	4.4
	511	KEJIM	1.20	-0	-0	-0	-0	-0	1.8
	512	MOUNTAIN	1.00	-0	-0	-0	-0	-0	11.7
	513	PEBBLGCH	1.60	-0	-0	-0	-0	-0	1.6
	515	FRESHWTR	2.50	-0	-0	-0	-0	-0	-0
	516	MC DOUG	1.10	-0	-0	-0	-0	-0	-0
	523	BOWKER	-0	-0	-0	-0	-0	-0	4.6
	528	MONTJOIE	-0	-0	-0	-0	-0	-0	3.1
	531	STUKLEY	-0	-0	-0	-0	-0	-0	3.2
	536	BEECH	-0	-0	-0	-0	-0	-0	4.5
	537	BOB	-0	-0	-0	-0	-0	-0	5.9
	539	CRANBRY	-0	-0	-0	-0	-0	-0	5.4
	540	EAGL-MOO	-0	-0	-0	-0	-0	-0	6.1
	542	HALLS	-0	-0	-0	-0	-0	-0	8.7
	543	MAPLE	-0	-0	-0	-0	-0	-0	5.2
	544	OBL-HALI	-0	-0	-0	-0	-0	-0	3.2
	545	PINE	-0	-0	-0	-0	-0	-0	5.5
	546	RAVEN	-0	-0	-0	-0	-0	-0	-0
	547	TALBOT	-0	-0	-0	-0	-0	-0	-0
	548	12MI-BOS	-0	-0	-0	-0	-0	-0	6.3
	550	JERRY	-0	-0	-0	-0	-0	-0	4.3
	552	LTL JOS	2.48	-0	-0	-0	-0	-0	6.0
	554	ROSSEAU	1.70	-0	-0	-0	-0	-0	6.2
	556	SKELTN B	1.48	-0	-0	-0	-0	-0	5.2
	557	BREWER	-0	-0	-0	-0	-0	-0	4.1
	558	CLARKE	-0	-0	-0	-0	-0	-0	3.1
	559	COSTELLO	-0	-0	-0	-0	-0	-0	3.8
	560	FOUND	-0	-0	-0	-0	-0	-0	9.4
	561	KEARNEY	-0	-0	-0	-0	-0	-0	3.4
	562	L MC CAU	-0	-0	-0	-0	-0	-0	4.8
	563	BIGWIND	2.15	-0	-0	-0	-0	-0	5.0
	564	BL CHALK	1.73	-0	-0	-0	-0	-0	6.9
	565	BUCK	2.10	-0	-0	-0	-0	-0	6.1
	567	CROSSON	2.08	-0	-0	-0	-0	-0	3.7
	570	HARP	2.53	-0	-0	-0	-0	-0	3.9
	571	JERRY	2.83	-0	-0	-0	-0	-0	4.0
	572	L CLEAR	2.00	-0	-0	-0	-0	-0	5.2

A5.3.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR ALGAL BIOMASS AND CHLOROPHYLL IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	ANNUAL EUPHOTIC CHLOROPHYLL MG M-3	SPRING EUPHOTIC CHLOROPHYLL MG M-3	MAXIMUM EUPHOTIC CHLOROPHYLL MG M-3	MINIMUM EUPHOTIC CHLOROPHYLL MG M-3	EUPHOTIC ALGAL BIOMASS (PER VOLUME) G M-3	EUPHOTIC ALGAL BIOMASS (PER SURFACE) G M-2	ANNUAL SECCHI DEPTH M
OLIGOTROPHIC	(CONT.)								
	573	RO CHAL	1.88	-0	-0	-0	-0	-0	6.1
	574	SOLITR	1.70	-0	-0	-0	-0	-0	7.7
	575	WALKER	2.00	-0	-0	-0	-0	-0	5.5
	576	SUPERIOR	.70	-0	-0	-0	-0	-0	8.4
	578	HURON	-0	-0	-0	-0	-0	-0	5.2
	583	114	11.00	-0	-0	-0	-0	-0	2.5
	584	120	2.00	-0	-0	-0	-0	-0	-0
	585	223	3.50	-0	-0	-0	-0	-0	5.0
	586	224	2.00	-0	-0	-0	-0	-0	7.0
	587	239	1.50	-0	-0	-0	-0	-0	4.8
	588	240	2.50	-0	-0	-0	-0	-0	4.2
	589	303	2.00	-0	-0	-0	-0	-0	-0
	593	KALAMLKA	1.30	-0	-0	-0	-0	-0	9.0
N OF LAKES		73	48	8	9	9	4	5	59
MEAN			2.1110	3.5263	5.6367	.6333	.75000	11.17000	6.033
ST DEV			1.5346	1.5062	2.5610	.3564	.73435	6.76300	3.014
MINIMUM			.30	1.97	2.40	.20	.330	3.650	1.0
MAXIMUM			11.00	5.80	10.60	1.34	1.850	21.400	28.3

A5.3.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR ALGAL BIOMASS AND CHLOROPHYLL IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	ANNUAL EUPHOTIC CHLOROPHYLL MG M-3	SPRING EUPHOTIC CHLOROPHYLL MG M-3	MAXIMUM EUPHOTIC CHLOROPHYLL MG M-3	MINIMUM EUPHOTIC CHLOROPHYLL MG M-3	EUPHOTIC ALGAL BIOMASS (PER VOLUME) G M-3	EUPHOTIC ALGAL BIOMASS (PER SURFACE) G M-2	ANNUAL SECCHI DEPTH M
*MESOTROPHIC									
	111	PAJAN-3	3.50	9.20	11.70	.40	-0	-0	-0
	204	MERGOZZO	3.20	3.30	7.20	.30	1.300	25.400	3.1
	213	OSSIACHE	3.30	6.22	20.00	.25	1.540	15.100	4.6
	216	VALLENSE	-0	-0	-0	-0	-0	30.100	6.5
	220	VWS KREU	-0	-0	-0	-0	-0	23.100	5.7
	221	VWS GERS	-0	-0	-0	-0	-0	20.300	7.9
	223	MAGGIORE	4.20	-0	8.70	1.20	1.210	15.900	6.5
	224	VALLENSE	-0	-0	-0	-0	1.900	25.600	7.6
	227	LEMAN	7.30	9.40	24.80	.56	-0	-0	7.1
	230	MONTORFA	9.70	-0	20.40	2.20	2.100	12.600	7.1
	231	ANNONE	16.90	-0	49.50	4.80	3.580	21.900	2.2
	234	D ANNECY	2.20	2.80	-0	-0	-0	-0	-0
	237	PAVIN	4.08	1.81	15.10	1.14	.470	7.800	8.9
	303	LOUGH LE	5.15	-0	20.00	1.00	-0	-0	2.7
	404	CAYUGA	5.50	-0	-0	-0	-0	-0	2.3
	418	SAMMAMIS	5.00	-0	-0	-0	-0	-0	3.3
	427	WEIR	6.00	-0	-0	-0	-0	-0	1.9
	509	WOLFE	3.60	-0	-0	-0	-0	-0	5.3
	510	GRAFTON	1.80	-0	-0	-0	-0	-0	5.4
	514	LTL KEMP	-0	-0	-0	-0	-0	-0	-0
	517	PRESOUL	3.30	-0	-0	-0	-0	-0	-0
	518	WARREN	.70	-0	-0	-0	-0	-0	4.1
	519	MEMPH N	5.20	-0	-0	-0	-0	-0	4.9
	520	MEMPH C	3.40	-0	-0	-0	-0	-0	4.8
	522	AYLMER	-0	-0	-0	-0	-0	-0	1.2
	524	BROMPTON	-0	-0	-0	-0	-0	-0	2.3
	525	LOVERING	-0	-0	-0	-0	-0	-0	2.1
	527	MASSAWP	-0	-0	-0	-0	-0	-0	2.1
	529	PT BROMP	-0	-0	-0	-0	-0	-0	2.3
	530	ST FRAN	-0	-0	-0	-0	-0	-0	1.3
	534	ROXTON	-0	-0	-0	-0	-0	-0	1.7
	538	CAMERON	-0	-0	-0	-0	-0	-0	4.5
	541	4-MI	-0	-0	-0	-0	-0	-0	5.5
	549	DUDLEY B	1.49	-0	-0	-0	-0	-0	5.0
	551	HARP	2.00	-0	-0	-0	-0	-0	4.4
	553	MUSKOKA	1.88	-0	-0	-0	-0	-0	4.4
	555	SMCOE	-0	-0	-0	-0	-0	-0	-0
	566	CHUB	3.10	-0	-0	-0	-0	-0	3.3
	568	DICKIE	5.38	-0	-0	-0	-0	-0	2.8
	569	GULFEATH	4.09	-0	-0	-0	-0	-0	2.5
	577	MICHIGAN	-0	-0	-0	-0	-0	-0	5.9
	580	CB ERIE	-0	-0	-0	-0	-0	-0	4.7
	581	EB ERIE	-0	-0	-0	-0	-0	-0	5.0
	582	ONTARIC	5.40	-0	-0	-0	-0	-0	2.6
	594	OKANAGAN	-0	-0	-0	-0	-0	-0	6.7
# OF LAKES		45	26	6	9	9	7	10	40
MEAN			4.4754	5.4550	19.7111	1.3722	1.72857	20.13000	4.461
ST DEV			3.1267	3.3212	12.6349	1.4075	.97188	6.98956	2.118
MINIMUM			.70	1.81	7.20	.25	.470	7.800	1.2
MAXIMUM			16.90	9.40	49.50	4.80	3.580	30.100	8.9

A5.3.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR ALGAL BIOMASS AND CHLOROPHYLL IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	ANNUAL EUPHOTIC CHLOROPHYLL MG M-3	SPRING EUPHOTIC CHLOROPHYLL MG M-3	MAXIMUM EUPHOTIC CHLOROPHYLL MG M-3	MINIMUM EUPHOTIC CHLOROPHYLL MG M-3	EUPHOTIC ALGAL BIOMASS (PER VOLUME) G M-3	EUPHOTIC ALGAL BIOMASS (PER SURFACE) G M-2	ANNUAL SECCHI DEPTH M
EUTROPHIC									
	101	ESRUM	5.93	62.00	20.60	2.00	-0	-0	-0
	102	MOSSO 1	51.50	70.00	197.70	4.00	-0	-0	-0
	103	MOSSO 2	77.50	105.00	223.30	4.50	-0	-0	-0
	104	GJERSJO	16.70	14.00	48.70	.50	-0	-0	-0
	105	MJOSA	2.50	1.50	9.60	1.00	-0	-0	-0
	106	ROFEN	5.00	4.20	4.50	1.50	-0	-0	-0
	107	MALAREN	9.40	11.50	36.50	1.00	-0	-0	-0
	108	VATTERN	.70	1.30	2.00	.20	-0	-0	-0
	109	PAJAN-1	2.80	4.70	12.30	.30	-0	-0	-0
	115	TUUSULAN	29.30	-0	97.30	1.30	-0	-0	-0
	203	BODENSEE	6.45	14.68	36.10	.19	.970	10.600	7.0
	205	PONTE LL	5.29	5.74	12.50	.50	2.100	17.500	6.0
	206	CAPOLAGO	6.67	9.66	13.60	.46	2.220	20.500	4.5
	207	MELIDE L	5.59	9.83	13.50	.37	1.860	15.500	4.8
	208	GONGRIA	5.86	10.01	13.30	.44	1.950	19.400	5.6
	209	LUGANO L	8.96	18.77	35.10	.55	2.990	33.700	5.2
	210	AGNO LUG	8.56	12.37	16.20	.50	2.050	22.200	4.0
	211	MARCOTE	5.76	10.19	14.60	.55	1.920	16.500	4.5
	212	FIGINO L	6.50	11.04	14.30	.01	2.170	18.600	4.5
	215	GREIFENS	16.80	23.70	62.30	7.50	5.610	30.400	3.3
	217	BALDEGGE	-0	-0	-0	-0	-0	-0	5.6
	218	HALLWILL	-0	-0	-0	-0	-0	-0	6.9
	219	SEMPACHE	13.40	11.16	72.30	1.22	2.480	36.300	4.2
	225	ZURICH U	-0	-0	-0	-0	4.030	54.700	4.9
	226	ZURICH O	-0	-0	-0	-0	1.900	26.700	4.8
	228	OGGIONO	32.10	-0	121.70	4.90	3.550	21.100	2.5
	229	PUSIANO	22.30	-0	126.90	1.40	3.330	27.300	2.5
	232	SEGRINO	24.60	-0	43.50	8.20	5.510	36.900	2.1
	233	D ALSERI	75.80	-0	222.50	14.40	7.680	34.200	1.3
	235	MANTUA	-0	-0	-0	-0	-0	-0	-0
	238	AYDAT	21.89	27.46	56.40	11.40	7.270	30.400	1.7
	301	LOUGH NE	21.40	-0	54.00	2.60	-0	-0	1.7
	302	LOCH LEV	39.00	-0	-0	-0	-0	-0	1.4
	304	LOUGH EN	25.30	-0	41.90	7.55	-0	-0	1.4
	305	BIWA SOU	4.70	-0	9.80	1.95	-0	-0	2.5
	307	KASUMI W	30.00	-0	96.73	7.93	-0	-0	1.3
	308	KASUMI N	25.80	-0	59.93	9.77	-0	-0	1.2
	401	BROWNIE	-0	-0	-0	-0	-0	-0	1.5
	402	CALHOUN	-0	-0	-0	-0	-0	-0	2.1
	403	CANADARA	10.00	-0	-0	-0	-0	-0	-0
	405	CEDAR	20.00	-0	-0	-0	-0	-0	1.6
	408	HARRIET	-0	-0	-0	-0	-0	-0	2.4
	411	MENDOTA	10.00	-0	-0	-0	-0	-0	3.0
	412	LOWER MI	21.00	-0	-0	-0	-0	-0	-0
	413	LOWER MI	12.00	-0	-0	-0	-0	-0	-0
	414	POTOMAC	90.00	-0	-0	-0	-0	-0	-0
	415	POTOMAC	65.00	-0	-0	-0	-0	-0	-0
	416	POTOMAC	15.00	-0	-0	-0	-0	-0	-0
	417	SALLIE	-0	-0	-0	-0	-0	-0	-0
	419	SHAGAWA	15.00	13.00	-0	-0	-0	-0	-0
	421	EAST TWI	29.20	-0	-0	-0	-0	-0	2.0
	422	WEST TWI	27.50	-0	-0	-0	-0	-0	2.3
	424	WASHINGT	12.00	-0	-0	-0	-0	-0	2.2
	425	WASHINGT	20.00	-0	-0	-0	-0	-0	1.2
	428	WINGRA	-0	-0	-0	-0	-0	-0	1.3
	508	MCLAREN	9.40	-0	-0	-0	-0	-0	1.7
	521	MEMPH S	5.60	-0	-0	-0	-0	-0	3.2
	526	MAGOG	-0	-0	-0	-0	-0	-0	1.7
	532	BOIVIN	-0	-0	-0	-0	-0	-0	.9
	533	BROME	-0	-0	-0	-0	-0	-0	2.1

A5.3.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR ALGAL BIOMASS AND CHLOROPHYLL IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	ANNUAL EUPHOTIC CHLOROPHYLL MG M-3	SPRING EUPHOTIC CHLOROPHYLL MG M-3	MAXIMUM EUPHOTIC CHLOROPHYLL MG M-3	MINIMUM EUPHOTIC CHLOROPHYLL MG M-3	EUPHOTIC ALGAL BIOMASS (PER VOLUME) G M-3	EUPHOTIC ALGAL BIOMASS (PER SURFACE) G M-2	ANNUAL SECCHI DEPTH M
EUTROPHIC	(CONT.)								
	535	WATERLOO	-0	-0	-0	-0	-0	-0	1.0
	579	WB ERIE	-0	-0	-0	-0	-0	-0	-0
	590	WINNIPEG	-0	-0	-0	-0	-0	-0	1.0
	591	CROOKED	15.30	-0	-0	-0	-0	-0	-0
	592	ROUND	9.30	-0	-0	-0	-0	-0	-0
	595	SKAHA	4.15	-0	-0	-0	-0	-0	3.3
	596	OSOYOOS	-0	-0	-0	-0	-0	-0	2.7
N OF LAKES		67	50	22	31	31	13	18	55
MEAN			20.1535	20.7277	57.4010	3.3401	3.52278	26.32222	2.649
ST DEV			20.0913	25.4798	61.3153	4.4111	1.98457	10.48212	1.640
MINIMUM			.70	1.30	2.00	.01	.970	10.600	.4
MAXIMUM			90.00	105.00	223.30	19.40	7.630	54.700	7.0
TOTAL									
N OF LAKES		185	124	36	43	49	29	33	144
MEAN			9.3820	14.3597	40.9766	2.4890	2.70724	22.15515	4.617
ST DEV			15.3769	21.3386	53.5761	3.7219	1.96614	10.39309	3.015
MINIMUM			.30	1.30	2.00	.01	.330	3.650	.9
MAXIMUM			90.00	105.00	223.30	19.40	7.680	54.700	23.3

A5.3.2 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR ALGAL BIOMASS AND CHLOROPHYLL IN SHALLOW LAKES AND RESERVOIRS.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	ANNUAL EUPHOTIC CHLOROPHYLL MG M-3	SPRING EUPHOTIC CHLOROPHYLL MG M-3	MAXIMUM EUPHOTIC CHLOROPHYLL MG M-3	MINIMUM EUPHOTIC CHLOROPHYLL MG M-3	EUPHOTIC ALGAL BIOMASS (PER VOLUME) G M-3	EUPHOTIC ALGAL BIOMASS (PER SURFACE) G M-2	ANNUAL SECCHI DEPTH M
OLIGOTROPHIC									
	602	OLEF	3.65	-0	8.65	1.20	-0	-0	5.9
	605	VERSE	2.90	-0	4.00	1.00	-0	-0	8.2
	606	SOSE	1.05	-0	2.05	.35	-0	-0	6.6
	608	FURWIGGE	2.40	-0	6.40	-0	-0	-0	11.5
	623	EUPEN	1.40	-0	3.42	.50	-0	-0	3.5
	635	VECHTEN	4.50	-0	6.70	1.40	-0	-0	-0
N OF LAKES		6	6	0	6	5	0	0	5
MEAN			2.6500	M	5.2033	.8900	M	M	7.140
ST DEV			1.3162	M	2.4545	.4506	M	M	2.968
MINIMUM			1.05	M	2.05	.35	M	M	3.5
MAXIMUM			4.50	M	8.65	1.40	M	M	11.5

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A5.3.2  DATA LISTING BY TROPHIC CATEGORY WITH
        BASIC STATISTICS FOR ALGAL BIOMASS AND
        CHLOROPHYLL IN SHALLOW LAKES
        AND RESERVOIRS.

TROPHIC              LAKE  LAKE NAME   ANNUAL       SPRING       MAXIMUM      MINIMUM      EUPHOTIC         EUPHOTIC         ANNUAL
 GROUP                      (ABBR)    EUPHOTIC     EUPHOTIC     EUPHOTIC     EUPHOTIC    ALGAL BIOMASS    ALGAL BIOMASS    SECCHI
                                     CHLOROPHYLL  CHLOROPHYLL  CHLOROPHYLL  CHLOROPHYLL  (PER VOLUME)    (PER SURFACE)    DEPTH
                                       MG M-3       MG M-3       MG M-3       MG M-3        G M-3            G M-2          M
MESOTROPHIC

                      619 MT BOLD           3.33          -0        16.97          .90           -0               -0         1.2
                      620 PROSPECT          3.10          -0         5.92         1.13           -0               -0         2.7
                      621 EL BURGI         11.00          -0        20.67         2.70           -0               -0         2.3

N OF LAKES                      3              3           0            3            3            0                0           3
  MEAN                                    5.8100           M      14.5200       1.5767            M                M       2.056
 ST DEV                                   4.4961           M       7.6741        .9796            M                M        .771
MINIMUM                                     3.10           M         5.92          .90            M                M         1.2
MAXIMUM                                    11.00           M        20.67         2.70            M                M         2.7
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A5.3.2 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR ALGAL BIOMASS AND CHLOROPHYLL IN SHALLOW LAKES AND RESERVOIRS.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	ANNUAL EUPHOTIC CHLOROPHYLL MG M-3	SPRING EUPHOTIC CHLOROPHYLL MG M-3	MAXIMUM EUPHOTIC CHLOROPHYLL MG M-3	MINIMUM EUPHOTIC CHLOROPHYLL MG M-3	EUPHOTIC ALGAL BIOMASS (PER VOLUME) G M-3	EUPHOTIC ALGAL BIOMASS (PER SURFACE) G M-2	ANNUAL SECCHI DEPTH M
EUTROPHIC									
	601	WANBACH	5.26	-0	13.43	.80	-0	-0	4.0
	603	SORPE	8.60	-0	24.00	2.00	-0	-0	4.0
	604	MOHNE	15.90	-0	39.75	7.50	-0	-0	2.6
	607	ENNEPE	-0	-0	-0	-0	-0	-0	3.4
	609	DE GROTE	17.43	-0	70.80	2.20	-0	-0	1.3
	610	BRIELSE	24.65	-0	92.00	.95	-0	-0	1.3
	611	PETRUSPL	5.00	-0	41.33	1.00	-0	-0	3.3
	612	HONDRED	5.67	-0	36.33	1.00	-0	-0	3.2
	613	BRAAKMAN	50.00	-0	275.33	2.67	-0	-0	1.9
	614	BRAAKMAN	27.00	-0	123.67	2.67	-0	-0	3.2
	615	TJEUKEME	50.00	-0	100.00	10.00	-0	-0	-0
	616	QUEEN EL	2.00	-0	47.50	.50	-0	-0	3.0
	617	FARMOOR	19.23	-0	56.87	2.03	-0	-0	3.8
	618	GRAFHAM	9.95	-0	39.50	1.00	-0	-0	4.2
	622	WISRAPEN	19.20	-0	99.23	.80	-0	-0	2.4
	624	BLACKHAW	14.00	-0	-0	-0	-0	-0	3.6
	625	CAMELOT	5.30	-0	-0	-0	-0	-0	2.0
	626	COY HOLL	25.50	-0	-0	-0	-0	-0	1.5
	627	DUTCH HO	33.40	-0	-0	-0	-0	-0	.8
	628	ISLES	-0	-0	-0	-0	-0	-0	1.0
	629	KEEP RCA	13.20	-0	-0	-0	-0	-0	1.4
	630	KEEP NUT	21.20	-0	-0	-0	-0	-0	1.2
	631	REDSTONE	12.60	-0	-0	-0	-0	-0	1.6
	632	STEWART	12.30	-0	-0	-0	-0	-0	1.4
	633	TWIN VAL	19.00	-0	-0	-0	-0	-0	1.5
	634	VIRGINIA	29.00	-0	-0	-0	-0	-0	1.2
	636	PIEURGEE	10.10	15.95	40.80	.93	2.750	20.700	7.6
N OF LAKES		27	25	1	15	15	1	1	26
MEAN			18.2716	15.9500	73.6360	2.4033	2.75000	20.70000	2.547
ST DEV			12.6021	M	64.1655	2.7141	M	M	1.496
MINIMUM			2.00	15.95	13.43	.50	2.750	20.700	.8
MAXIMUM			50.00	15.95	275.33	10.00	2.750	20.700	7.6
TOTAL									
N OF LAKES		36	34	1	24	23	1	1	34
MEAN			14.4153	15.9500	49.1383	1.9665	2.75000	20.70000	3.187
ST DEV			12.6552	M	59.6978	2.2850	M	M	2.370
MINIMUM			1.05	15.95	2.05	.35	2.750	20.700	.8
MAXIMUM			50.00	15.95	275.33	10.00	2.750	20.700	11.5

A5.3.3 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR ALGAL BIOMASS AND CHLOROPHYLL IN UNUSUAL CANADIAN CIRCUMSTANCES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	ANNUAL EUPHOTIC CHLOROPHYLL MG M-3	SPRING EUPHOTIC CHLOROPHYLL MG M-3	MAXIMUM EUPHOTIC CHLOROPHYLL MG M-3	MINIMUM EUPHOTIC CHLOROPHYLL MG M-3	EUPHOTIC ALGAL BIOMASS (PER VOLUME) G M-3	EUPHOTIC ALGAL BIOMASS (PER SURFACE) G M-2	ANNUAL SECCHI DEPTH M
OLIGOTROPHIC									
	703	BOWKER	1.80	-0	-0	-0	-0	-0	4.6
	708	MONTJOIE	1.30	-0	-0	-0	-0	-0	3.1
	711	STUKELY	3.20	-0	-0	-0	-0	-0	3.2
	717	226N '73	7.00	-0	-0	-0	-0	-0	-0
	718	226N '74	11.00	-0	-0	-0	-0	-0	-0
	719	226S '73	6.00	-0	-0	-0	-0	-0	4.2
	720	226S '74	7.00	-0	-0	-0	-0	-0	-0
	721	227 '69	11.00	-0	-0	-0	-0	-0	2.6
	722	227 '70	19.00	-0	-0	-0	-0	-0	-0
	723	227 '71	20.00	-0	-0	-0	-0	-0	-0
	724	227 '72	34.00	-0	-0	-0	-0	-0	-0
	725	227 '73	44.00	-0	-0	-0	-0	-0	-0
	726	227 '74	34.00	-0	-0	-0	-0	-0	-0
	727	261 '73	6.00	-0	-0	-0	-0	-0	-0
	728	261 '74	10.00	-0	-0	-0	-0	-0	-0
	729	302N '72	7.00	-0	-0	-0	-0	-0	-0
	730	302N '73	8.00	-0	-0	-0	-0	-0	-0
	731	302N '74	11.00	-0	-0	-0	-0	-0	-0
	732	304 '71	21.00	-0	-0	-0	-0	-0	-0
	733	304 '72	30.00	-0	-0	-0	-0	-0	3.0
	734	304 '73	13.00	-0	-0	-0	-0	-0	3.0
	735	304 '74	8.00	-0	-0	-0	-0	-0	-0
	741	KAMLOOPS	.35	-0	-0	-0	-0	-0	2.9
N OF LAKES		23	23	0	0	0	0	0	8
MEAN			13.6587	M	M	M	M	M	3.325
ST DEV			11.7821	M	M	M	M	M	.694
MINIMUM			.35	M	M	M	M	M	2.6
MAXIMUM			44.00	M	M	M	M	M	4.6

A5.3.3 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR ALGAL BIOMASS AND CHLOROPHYLL IN UNUSUAL CANADIAN CIRCUMSTANCES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	ANNUAL EUPHOTIC CHLOROPHYLL MG M-3	SPRING EUPHOTIC CHLOROPHYLL MG M-3	MAXIMUM EUPHOTIC CHLOROPHYLL MG M-3	MINIMUM EUPHOTIC CHLOROPHYLL MG M-3	EUPHOTIC ALGAL BIOMASS (PER VOLUME) G M-3	EUPHOTIC ALGAL BIOMASS (PER SURFACE) G M-2	ANNUAL SECCHI DEPTH M
MESOTROPHIC									
	702	AYLMER	-0	-0	-0	-0	-0	-0	1.2
	704	BROMPTON	4.20	-0	-0	-0	-0	-0	2.3
	705	LOVERING	7.00	-0	-0	-0	-0	-0	2.1
	707	MASSAWPI	10.30	-0	-0	-0	-0	-0	2.1
	709	PT BROMP	3.40	-0	-0	-0	-0	-0	2.3
	710	ST FRAN	-0	-0	-0	-0	-0	-0	1.3
	714	ROXTON	6.10	-0	-0	-0	-0	-0	1.7
	740	BABINE	1.50	-0	-0	-0	-0	-0	5.4
	742	KOOTN'76	-0	-0	-0	-0	-0	-0	-0
	743	KOOTN'77	-0	-0	-0	-0	-0	-0	6.7
	745	OKANG'77	1.20	-0	-0	-0	-0	-0	6.8
	746	OKANG'78	1.94	-0	-0	-0	-0	-0	6.0
N OF LAKES		12	8	0	0	0	0	0	11
MEAN			4.4550	M	M	M	M	M	3.445
ST DEV			3.1663	M	M	M	M	M	2.338
MINIMUM			1.20	M	M	M	M	M	1.2
MAXIMUM			10.30	M	M	M	M	M	6.8

A5.3.3 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR ALGAL BIOMASS AND CHLOROPHYLL IN UNUSUAL CANADIAN CIRCUMSTANCES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	ANNUAL EUPHOTIC CHLOROPHYLL MG M-3	SPRING EUPHOTIC CHLOROPHYLL MG M-3	MAXIMUM EUPHOTIC CHLOROPHYLL MG M-3	MINIMUM EUPHOTIC CHLOROPHYLL MG M-3	EUPHOTIC ALGAL BIOMASS (PER VOLUME) G M-3	EUPHOTIC ALGAL BIOMASS (PER SURFACE) G M-2	ANNUAL SECCHI DEPTH M
EUTROPHIC									
	701	PINK	1.90	-0	-0	-0	-0	-0	3.2
	706	MAGOG	11.50	-0	-0	-0	-0	-0	1.7
	712	BOIVIN	8.20	-0	-0	-0	-0	-0	.9
	713	BROME	11.30	-0	-0	-0	-0	-0	2.1
	715	WATERLOO	40.00	-0	-0	-0	-0	-0	1.0
	716	LT OTTER	31.20	-0	-0	-0	-0	-0	1.0
	736	MASOUA	12.70	-0	-0	-0	-0	-0	1.6
	737	ECHO	9.90	-0	-0	-0	-0	-0	1.6
	738	MISSION	12.90	-0	-0	-0	-0	-0	-0
	739	KATEPWA	11.10	-0	-0	-0	-0	-0	2.1
	744	WOOD	9.80	-0	-0	-0	-0	-0	2.5
	747	SKAHA'77	3.22	-0	-0	-0	-0	-0	3.5
	748	SKAHA'78	4.15	-0	-0	-0	-0	-0	3.4
	749	OSOOY'77	4.98	-0	-0	-0	-0	-0	2.6
	750	OSOOY'78	5.54	-0	-0	-0	-0	-0	2.7
	751	GRAVNH B	8.62	-0	-0	-0	-0	-0	2.7
N OF LAKES		15	16	0	0	0	0	0	15
MEAN			11.6881	M	M	M	M	M	2.174
ST DEV			10.0637	M	M	M	M	M	.863
MINIMUM			1.90	M	M	M	M	M	.9
MAXIMUM			40.00	M	M	M	M	M	3.5
TOTAL									
N OF LAKES		51	47	0	0	0	0	0	34
MEAN			11.4215	M	M	M	M	M	2.872
ST DEV			10.5798	M	M	M	M	M	1.573
MINIMUM			.85	M	M	M	M	M	.9
MAXIMUM			44.00	M	M	M	M	M	6.8

A5.4.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR OXYGEN-RELATED VARIABLES IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	HYPOLIMNION SURFACE AREA KM2	HYPOLIMNION VOLUME 1CE6 M3	PRIMARY PRODUCTION (PER SURFACE) G C M-2 Y-1	HYPOLIMNETIC OXYGEN DEPLETION (PER VOLUME) G O2 M-3	HYPOLIMNETIC OXYGEN DEPLETION (PER SURFACE G O2 M-3	H.O.D. MONTHLY RATE (PER VOLUME) G O2 M-3 MO-1	H.O.D. MONTHLY RATE (PER SURFACE) G O2 M-2 MO-1
OLIGOTROPHIC									
	110	PAJAN-2	-0	-0	-0	-0	2.50	-0	1.00
	112	PAJAN-4	-0	-0	-0	-0	2.10	-0	1.00
	113	PAJAN-5	-0	-0	-0	-0	2.00	-0	.90
	114	PAAJARVI	-0	-0	15.600	-0	1.70	-0	.80
	201	LUNZER U	.4	2.900	30.200	5.47	38.41	.91	7.44
	202	FELOSEE	.1	.960	-0	2.14	46.00	.54	16.00
	214	ATTERSEE	40.0	-0	77.200	-0	-0	-0	-0
	222	VWS URNE	24.3	3285.000	-0	1.40	219.70	.20	31.40
	236	TAZENAT	.3	4.880	54.300	-0	-0	-0	-0
	306	BIWA NOR	-0	-0	131.000	-0	121.50	-0	20.50
	406	DOGFISH	-0	-0	-0	-0	-0	-0	-0
	407	GEORGE	-0	-0	7.200	-0	-0	-0	-0
	409	LAMB	-0	-0	-0	-0	-0	-0	-0
	410	MEANDER	-0	-0	-0	-0	-0	-0	-0
	420	TAHOE	-0	-0	5.600	-0	-0	-0	-0
	423	WALDO	-0	-0	-0	-0	-0	-0	-0
	426	WASHINGT	-0	-0	354.000	-0	-0	-0	-0
	501	WAKOOK P	-0	-0	-0	-0	-0	-0	-0
	502	BLHILL N	-0	-0	-0	-0	-0	-0	-0
	503	BLHILL S	-0	-0	-0	-0	-0	-0	-0
	504	MINCHN P	-0	-0	-0	-0	-0	-0	-0
	505	YUDDLE N	-0	-0	-0	-0	-0	-0	-0
	506	PINEHL P	-0	-0	-0	-0	-0	-0	-0
	507	BENNETT	-0	-0	-0	-0	-0	-0	-0
	511	KEJIM	-0	-0	-0	-0	-0	-0	-0
	512	MOUNTAIN	-0	-0	-0	-0	-0	-0	-0
	513	PEBBLGCH	-0	-0	-0	-0	-0	-0	-0
	515	FRESHWTR	-0	-0	-0	-0	-0	-0	-0
	516	MC DOUG	-0	-0	-0	-0	-0	-0	-0
	523	BOWKER	-0	-0	-0	-0	-0	-0	-0
	528	MONTJOIE	-0	-0	-0	-0	-0	-0	-0
	531	STUKLEY	-0	-0	-0	-0	-0	-0	-0
	536	BEECH	-0	-0	-0	-0	-0	-0	-0
	537	BOB	-0	-0	-0	-0	-0	-0	-0
	539	CRANBRY	-0	-0	-0	-0	-0	-0	-0
	540	EAGL-MCC	-0	-0	-0	-0	-0	-0	-0
	542	HALLS	-0	-0	-0	-0	-0	-0	-0
	543	MAPLE	-0	-0	-0	-0	-0	-0	-0
	544	OBL-HALI	-0	-0	-0	-0	-0	-0	-0
	545	PINE	-0	-0	-0	-0	-0	-0	-0
	546	RAVEN	-0	-0	-0	-0	-0	-0	-0
	547	TALBOT	-0	-0	-0	-0	-0	-0	-0
	548	12MI-BOS	-0	-0	-0	-0	-0	-0	-0
	550	JERRY	-0	-0	-0	-0	-0	-0	-0
	552	LTL JOS	-0	-0	20.000	-0	-0	-0	-0
	554	ROSSEAU	-0	-0	22.000	-0	-0	-0	-0
	556	SKELTN B	-0	-0	23.000	-0	-0	-0	-0
	557	BREWER	-0	-0	-0	-0	-0	-0	-0
	558	CLARKE	-0	-0	-0	-0	-0	-0	-0
	559	COSTELLO	-0	-0	-0	-0	-0	-0	-0
	560	FOUND	-0	-0	-0	-0	-0	-0	-0
	561	KEARNEY	-0	-0	-0	-0	-0	-0	-0
	562	L MC CAU	-0	-0	-0	-0	-0	-0	-0
	563	BIGWIND	-0	-0	-0	-0	-0	-0	-0
	564	BL CHALK	-0	-0	-0	-0	-0	-0	-0
	565	BUCK	-0	-0	-0	-0	-0	-0	-0
	567	CROSSON	-0	-0	-0	-0	-0	-0	-0
	570	HAPP	-0	-0	-0	-0	-0	-0	-0
	571	JERRY	-0	-0	-0	-0	-0	-0	-0

A5.4.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR OXYGEN-RELATED VARIABLES IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	HYPOLIMNION SURFACE AREA KM2	HYPOLIMNION VOLUME 10E6 M3	PRIMARY PRODUCTION (PER SURFACE) G C M-2 Y-1	HYPOLIMNETIC OXYGEN DEPLETION (PER VOLUME) G O2 M-3	HYPOLIMNETIC OXYGEN DEPLETION (PER SURFACE G O2 M-3	H.O.D. MONTHLY RATE (PER VOLUME) G O2 M-3 MO-1	H.O.D. MONTHLY RATE (PER SURFACE) G O2 M-2 MO-1
OLIGOTROPHIC	(CONT.)								
	572	L CLEAR	-0	-0	-0	-0	-0	-0	-0
	573	RC CHAL	-0	-0	-0	-0	-0	-0	-0
	574	SOLITR	-0	-0	-0	-0	-0	-0	-0
	575	WALKER	-0	-0	-0	-0	-0	-0	-0
	576	SUPERICR	-0	-0	50.600	-0	-0	-0	-0
	578	HURON	-0	-0	93.600	-0	-0	-0	-0
	583	114	-0	-0	42.100	-0	-0	-0	-0
	584	120	-0	-0	-0	-0	-0	-0	-0
	585	223	-0	-0	46.600	-0	-0	-0	-0
	586	224	-0	-0	28.000	-0	-0	-0	-0
	587	239	-0	-0	85.000	-0	-0	-0	-0
	588	240	-0	-0	52.500	-0	-0	-0	-0
	589	303	-0	-0	30.600	-0	-0	-0	-0
	593	KALAMLKA	-0	-0	-0	-0	-0	-0	-0
N OF LAKES		73	5	4	19	3	6	3	8
MEAN			13.020	823.43500	60.92105	3.0033	59.7387	.5500	10.1050
ST DEV			18.325	1541.04411	77.64782	2.1680	79.3487	.3551	11.7828
MINIMUM			.1	.960	5.600	1.40	1.70	.20	.60
MAXIMUM			40.0	3285.000	354.600	5.47	219.70	.91	31.40

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A5.4.1  DATA LISTING BY TROPHIC CATEGORY WITH
        BASIC STATISTICS FOR OXYGEN-RELATED
        VARIABLES IN NATURAL LAKES.

TROPHIC             LAKE  LAKE NAME HYPOLIMNION HYPOLIMNION     PRIMARY     HYPOLIMNETIC HYPOLIMNETIC     H.O.D.          H.O.D.
 GROUP                     (ABBR)     SURFACE     VOLUME       PRODUCTION      OXYGEN       OXYGEN      MONTHLY RATE    MONTHLY RATE
                                       AREA                  (PER SURFACE)   DEPLETION    DEPLETION    (PER VOLUME)    (PER SURFACE)
                                        KM2       10E6 M3     G C M-2 Y-1  (PER VOLUME) (PER SURFACE  G O2 M-3 MO-1   G O2 M-2 MO-1
                                                                              G O2 M-3    G O2 M-3

MESOTROPHIC

                     111 PAJAN-3          -0          -0            -0            -0           -0             -0              -0
                     204 MERGOZZO        1.4      43.100       170.000          3.57       111.40            .51           16.00
                     213 OSSIACHE        4.8      89.500       354.500          7.00       288.00           1.35           44.50
                     216 WALLENSE       23.0    2095.000            -0            -0           -0             -0              -0
                     220 VWS KREU       45.0    3645.000       233.600          3.35       236.77            .21           31.67
                     221 VWS GERS       23.5    3718.000            -0          1.40       180.37            .18           22.95
                     223 MAGGIORE      169.0   32476.000       315.000           .52        89.44            .13           22.68
                     224 WALLENSE       23.0    2095.000       272.000          1.31       241.50            .23           26.80
                     227 LEMAN         535.1          -0       223.000            -0       285.00             -0           36.00
                     230 MONTORFA         -0          -0       117.900            -0           -0             -0           20.70
                     231 ANNONE           -0          -0       170.800            -0           -0             -0           11.80
                     234 D ANNECY       12.0          -0       134.900            -0       127.90             -0           15.90
                     237 PAVIN            -0      13.600       179.900            -0           -0             -0              -0
                     303 LOUGH LE         -0          -0       226.000            -0           -0             -0              -0
                     404 CAYUGA           -0          -0        53.000            -0           -0             -0              -0
                     418 SAMMAMIS         -0          -0       238.000            -0           -0             -0              -0
                     427 WEIR             -0          -0        36.000            -0           -0             -0              -0
                     509 WOLFE            -0          -0            -0            -0           -0             -0              -0
                     510 GRAFTON          -0          -0            -0            -0           -0             -0              -0
                     514 LTL REPP         -0          -0            -0            -0           -0             -0              -0
                     517 PRESCUL          -0          -0            -0            -0           -0             -0              -0
                     518 WARREN           -0          -0            -0            -0           -0             -0              -0
                     519 MEMPH N          -0          -0       175.000            -0           -0             -0              -0
                     520 MEMPH C          -0          -0       200.000            -0           -0             -0              -0
                     522 AYLMER           -0          -0            -0            -0           -0             -0              -0
                     524 BROMPTON         -0          -0            -0            -0           -0             -0              -0
                     526 LOVERING         -0          -0            -0            -0           -0             -0              -0
                     527 MASSAWI          -0          -0            -0            -0           -0             -0              -0
                     529 PT BROMP         -0          -0            -0            -0           -0             -0              -0
                     530 ST FRAN          -0          -0            -0            -0           -0             -0              -0
                     534 BOXTON           -0          -0            -0            -0           -0             -0              -0
                     538 CAMERON          -0          -0            -0            -0           -0             -0              -0
                     541 4-MI             -0          -0            -0            -0           -0             -0              -0
                     549 DUDLEY P         -0          -0            -0            -0           -0             -0              -0
                     551 HARP             -0          -0            -0            -0           -0             -0              -0
                     553 MUSKOKA          -0          -0            -0            -0           -0             -0              -0
                     555 SIMCOE           -0          -0            -0            -0           -0             -0              -0
                     556 CHUR             -0          -0            -0            -0           -0             -0              -0
                     568 DICKIE           -0          -0            -0            -0           -0             -0              -0
                     569 GULFEATH         -0          -0            -0            -0           -0             -0              -0
                     577 MICHIGAN         -0          -0       145.000            -0           -0             -0              -0
                     580 CB ERIE          -0          -0       230.000            -0           -0             -0              -0
                     581 EB ERIE          -0          -0       180.000            -0           -0             -0              -0
                     582 ONTARIO          -0          -0       185.000            -0           -0             -0              -0
                     594 OKANAGAN         -0          -0            -0            -0           -0             -0              -0

N OF LAKES                     45          9           8            20             6            8              6              10
   MEAN                                95.197   5521.90000     192.23000        2.9417     195.0475          .4350         24.9000
  ST DEV                              174.749  10957.77374      76.16458        2.3045      78.8346          .4677         10.1029
 MINIMUM                                  1.4       13.600        36.000           .52        89.44            .13           11.80
 MAXIMUM                                535.1    32476.000       354.500          7.00       288.00           1.35           44.50
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A5.4.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR OXYGEN-RELATED VARIABLES IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	HYPOLIMNION SURFACE AREA KM2	HYPOLIMNION VOLUME 10E6 M3	PRIMARY PRODUCTION (PER SURFACE) G C M-2 Y-1	HYPOLIMNETIC OXYGEN DEPLETION (PER VOLUME) G O2 M-3	HYPOLIMNETIC OXYGEN DEPLETION (PER SURFACE G O2 M-3	M.O.D. MONTHLY RATE (PER VOLUME) G O2 M-3 MO-1	M.O.D. MONTHLY RATE (PER SURFACE) G O2 M-2 MO-1
EUTROPHIC									
	101	ESRUM	-0	-0	263.300	-0	9.10	-0	1.60
	102	MOSSO 1	-0	-0	293.300	-0	-0	-0	-0
	103	MOSSO 2	-0	-0	446.300	-0	-0	-0	-0
	104	GJERSJO	-0	-0	237.500	-0	9.60	-0	1.90
	105	MJOSA	-0	-0	77.700	-0	.10	-0	-0
	106	BOREN	-0	-0	-0	-0	-0	-0	-0
	107	MALAREN	-0	-0	-0	-0	-0	-0	2.70
	108	VATTERN	-0	-0	-0	-0	-0	-0	-0
	109	PAJAN-1	-0	-0	-0	-0	2.00	-0	.90
	115	TUUSULAN	-0	-0	-0	-0	-0	-0	-0
	203	BODENSEE	393.6	39266.000	-0	.93	97.26	.21	21.19
	205	PONTE LU	.8	-0	-0	1.28	30.01	.43	10.00
	206	CAPOLAGO	1.8	-0	-0	.70	39.99	.23	13.33
	207	MELIDE L	3.9	-0	-0	.97	50.17	.32	16.72
	208	GONDFIA	15.4	-0	-0	.03	5.91	.01	1.97
	209	LUGANO L	10.2	-0	-0	.47	67.40	.15	22.47
	210	AEAC LUG	1.3	-0	300.000	1.05	44.81	.35	14.94
	211	MARCOTE	2.5	-0	-0	1.28	42.12	.43	14.04
	212	FIGINO L	5.5	-0	-0	1.05	57.08	.35	19.03
	215	GREIFENS	7.5	96.300	479.000	10.53	271.20	2.13	30.15
	217	BALDEGGE	4.5	124.500	422.000	10.56	786.42	1.75	131.07
	218	HALLWILL	9.0	226.000	353.000	5.67	319.60	.95	53.27
	219	SEMPACHE	13.0	237.500	177.000	4.20	343.12	.84	68.62
	225	ZURICH U	49.7	2255.600	335.000	2.66	314.70	.44	44.96
	226	ZURICH G	10.4	163.800	245.000	9.22	170.60	1.15	16.96
	228	OGGIONO	-0	-0	407.000	-0	-0	-0	12.10
	229	PUSIANO	-0	-0	362.100	-0	-0	-0	8.20
	232	SEGRINO	-0	-0	334.000	-0	-0	-0	11.10
	233	D ALSERI	-0	-0	599.600	-0	-0	-0	24.50
	235	MANTUA	1.3	-0	255.400	-0	125.00	-0	41.70
	238	AYDAT	-0	-0	336.500	-0	-0	-0	-0
	301	LOUGH NE	-0	-0	410.000	-0	-0	-0	-0
	302	LOCH LEV	-0	-0	-0	-0	-0	-0	-0
	304	LOUGH EA	-0	-0	-0	-0	70.00	-0	39.50
	305	BIWA SOU	-0	-0	136.000	-0	-0	-0	-0
	307	KASUMI G	-0	-0	565.670	-0	-0	-0	-0
	308	KASUMI N	-0	-0	502.000	-0	-0	-0	-0
	401	BROWNIE	-0	-0	-0	-0	-0	-0	-0
	402	CALHOUN	-0	-0	-0	-0	-0	-0	-0
	403	CANADARA	-0	-0	169.000	-0	-0	-0	-0
	405	CEDAR	-0	-0	-0	-0	-0	-0	-0
	406	HARRIET	-0	-0	-0	-0	-0	-0	-0
	411	MENDOTA	-0	-0	1100.000	-0	-0	-0	-0
	412	LOWER MI	-0	-0	440.000	-0	-0	-0	-0
	413	LOWER MI	-0	-0	320.000	-0	-0	-0	-0
	414	POTOMAC	-0	-0	-0	-0	-0	-0	-0
	415	POTOMAC	-0	-0	-0	-0	-0	-0	-0
	416	POTOMAC	-0	-0	-0	-0	-0	-0	-0
	417	SALLIE	-0	-0	-0	-0	-0	-0	-0
	419	SHAGAWA	-0	-0	-0	-0	-0	-0	-0
	421	EAST TWI	-0	-0	474.000	-0	-0	-0	-0
	422	WEST TWI	-0	-0	576.000	-0	-0	-0	-0
	424	WASHINGT	-0	-0	-0	-0	-0	-0	-0
	425	WASHINGT	-0	-0	766.000	-0	-0	-0	-0
	428	WINGRA	-0	-0	870.000	-0	-0	-0	-0
	508	MCLAREN	-0	-0	-0	-0	-0	-0	-0
	521	MEMPH S	-0	-0	219.000	-0	-0	-0	-0
	526	MAEDG	-0	-0	-0	-0	-0	-0	-0
	532	BOIVIN	-0	-0	-0	-0	-0	-0	-0

A5.4.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR OXYGEN-RELATED VARIABLES IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	HYPOLIMNION SURFACE AREA KM2	HYPOLIMNION VOLUME 10E6 M3	PRIMARY PRODUCTION (PER SURFACE) G C M-2 Y-1	HYPOLIMNETIC OXYGEN DEPLETION (PER VOLUME) G O2 M-3	HYPOLIMNETIC OXYGEN DEPLETION (PER SURFACE G O2 M-3	H.O.D. MONTHLY RATE (PER VOLUME) G O2 M-3 MO-1	H.O.D. MONTHLY RATE (PER SURFACE) G O2 M-2 MO-1
EUTROPHIC	(CONT.)								
	533	BROME	-0	-0	-0	-0	-0	-0	-0
	535	WATERLOO	-0	-0	-0	-0	-0	-0	-0
	579	WB ERIE	-0	-0	-0	-0	-0	-0	-0
	590	WINNIPEG	-0	-0	-0	-0	-0	-0	-0
	591	CROOKED	-0	-0	-0	-0	-0	-0	-0
	592	ROUND	-0	-0	-0	-0	-0	-0	-0
	595	SKAHA	-0	-0	-0	-0	-0	-0	-0
	596	OSOYOOS	-0	-0	-0	-0	-0	-0	-0
N OF LAKES	67		16	7	31	15	21	15	25
MEAN			33.366	6095.67143	418.21639	3.3747	136.0119	.6487	25.8048
ST DEV			96.765	14646.94281	227.16745	3.7832	166.8647	.6071	23.5213
MINIMUM			.8	96.300	77.700	.03	.10	.01	.90
MAXIMUM			393.6	39266.000	1100.000	10.55	786.42	2.10	131.07
TOTAL									
N OF LAKES	185		30	19	70	24	37	24	43
MEAN			46.524	4744.13345	256.66457	3.2200	132.2843	.5829	22.6735
ST DEV			119.723	11103.17349	221.35631	3.2156	154.5472	.5399	23.3570
MINIMUM			.1	.960	5.000	.03	.10	.01	.50
MAXIMUM			535.1	39266.000	1100.000	10.56	786.42	2.10	131.07

A5.4.2 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR OXYGEN-RELATED VARIABLES IN SHALLOW LAKES AND RESERVOIRS.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	HYPOLIMNION SURFACE AREA KM2	HYPOLIMNION VOLUME 10E6 M3	PRIMARY PRODUCTION (PER SURFACE) G C M-2 Y-1	HYPOLIMNETIC OXYGEN DEPLETION (PER VOLUME) G O2 M-3	HYPOLIMNETIC OXYGEN DEPLETION (PER SURFACE G O2 M-3	H.O.D. MONTHLY RATE (PER VOLUME) G O2 M-3 MO-1	H.O.D. MONTHLY RATE (PER SURFACE) G O2 M-2 MO-1
OLIGOTROPHIC									
	602	OLFF	-0	-0	-0	-0	131.00	-0	43.65
	605	VEFSE	-0	-0	-0	-0	86.00	-0	13.00
	606	SOSE	-0	-0	-0	-0	40.50	-0	6.70
	608	FUFWIGEE	-0	-0	-0	-0	405.00	-0	84.00
	623	EUPEN	-0	-0	11.030	-0	92.60	-0	27.40
	635	VFCHTEN	-0	-0	90.000	-0	-0	-0	-0
N OF LAKES		6	0	0	2	0	5	0	5
MEAN			M	M	50.51500	M	151.0200	M	34.9500
ST DEV			M	M	55.84022	M	145.5044	M	30.8968
MINIMUM			M	M	11.030	M	40.50	M	6.70
MAXIMUM			M	M	90.000	M	405.00	M	84.00

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A5.4.2  DATA LISTING BY TROPHIC CATEGORY WITH
        BASIC STATISTICS FOR OXYGEN-RELATED
        VARIABLES IN SHALLOW LAKES
        AND RESERVOIRS.

TROPHIC             LAKE  LAKE NAME HYPOLIMNION HYPOLIMNION    PRIMARY    HYPOLIMNETIC HYPOLIMNETIC    H.O.D.        H.O.D.
 GROUP                      (ABBR)    SURFACE     VOLUME     PRODUCTION      OXYGEN       OXYGEN    MONTHLY RATE  MONTHLY RATE
                                       AREA                (PER SURFACE)   DEPLETION    DEPLETION   (PER VOLUME)  (PER SURFACE)
                                        KM2      10E6 M3    G C M-2 Y-1  (PER VOLUME) (PER SURFACE G O2 M-3 MO-1 G O2 M-2 MO-1
                                                                           G O2 M-3     G O2 M-3

MESOTROPHIC

                     619 MT BOLD            -0          -0      260.000           -0        54.45            -0            -0
                     620 PROSPECT           -0          -0      159.680           -0           -0            -0            -0
                     621 EL RUREI           -0          -0      160.000           -0       305.00            -0         85.30

N OF LAKES                       3           0           0            3            0            2             0             1
  MEAN                                       M           M    193.22667            M     179.7250             M       85.3000
 ST DEV                                      M           M     57.82762            M     177.1656             M             M
MINIMUM                                      M           M      159.680            M        54.45             M         85.30
MAXIMUM                                      M           M      260.000            M       305.00             M         85.30
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A5.4.2    DATA LISTING BY TROPHIC CATEGORY WITH
          BASIC STATISTICS FOR OXYGEN-RELATED
          VARIABLES IN SHALLOW LAKES
          AND RESERVOIRS.

TROPHIC                 LAKE  LAKE NAME HYPOLIMNION HYPOLIMNION     PRIMARY     HYPOLIMNETIC HYPOLIMNETIC     H.O.D.          H.O.D.
 GROUP                            (ABBR)     SURFACE      VOLUME     PRODUCTION      OXYGEN       OXYGEN     MONTHLY RATE   MONTHLY RATE
                                              AREA                 (PER SURFACE)   DEPLETION    DEPLETION    (PER VOLUME)   (PER SURFACE)
                                              KM2        1GE6 M3    G C M-2 Y-1  (PER VOLUME) (PER SURFACE  G O2 M-3 MO-1  G O2 M-2 MO-1
                                                                                   G O2 M-3      G O2 M-3

EUTROPHIC

                         601 VANBACH            -0          -0      308.330          -0           -0              -0             -0
                         603 SORPE              -0          -0           -0          -0           -0              -0          27.00
                         604 MOHNE              -0          -0           -0          -0        88.00              -0          25.50
                         607 ENNEPE             -0          -0           -0          -0           -0              -0             -0
                         609 DE GROTE           -0          -0           -0          -0           -0              -0             -0
                         610 BRIELSE            -0          -0           -0          -0           -0              -0             -0
                         611 PETRUSPL           -0          -0           -0          -0           -0              -0             -0
                         612 HONDRED            -0          -0           -0          -0           -0              -0             -0
                         613 BRAAKMAN           -0          -0           -0          -0           -0              -0             -0
                         614 BRAAKMAN           -0          -0           -0          -0           -0              -0             -0
                         615 TJEUKEME           -0          -0      770.000          -0           -0              -0             -0
                         616 QUEEN EL           -0          -0       95.000          -0           -0              -0             -0
                         617 FARMOOR            -0          -0      637.000          -0           -0              -0             -0
                         619 GRAFHAM            -0          -0           -0          -0           -0              -0             -0
                         622 MISRANCH           -0          -0     1167.500          -0        33.25              -0          16.75
                         624 BLACKHAW           -0          -0           -0          -0           -0              -0             -0
                         625 CAMELOT            -0          -0           -0          -0           -0              -0             -0
                         626 COX HOLL           -0          -0           -0          -0           -0              -0             -0
                         627 DUTCH HC           -0          -0           -0          -0           -0              -0             -0
                         628 ISLES              -0          -0           -0          -0           -0              -0             -0
                         629 KERR RCA           -0          -0      171.000          -0           -0              -0             -0
                         630 KERR NUT           -0          -0      249.000          -0           -0              -0             -0
                         631 REDSTONE           -0          -0           -0          -0           -0              -0             -0
                         632 STEWART            -0          -0           -0          -0           -0              -0             -0
                         633 TWIN VAL           -0          -0           -0          -0           -0              -0             -0
                         634 VIRGINIA           -0          -0           -0          -0           -0              -0             -0
                         636 PIBURGER           .1        .510       69.100          -0         8.10              -0           1.80
N OF LAKES                        27             1           1            8           0            3               0              4
  MEAN                                        .080      .51000    433.36625           M      43.1167               M        17.7625
 ST DEV                                          M           M    389.02515           M      40.8536               M        11.5618
MINIMUM                                         .1        .510       69.100           M         8.10               M           1.80
MAXIMUM                                         .1        .510     1167.500           M        88.00               M          27.00

TOTAL
N OF LAKES                        36             1           1           13           0           10               0             10
  MEAN                                        .080      .51000    319.04923           M     124.3900               M        33.1100
 ST DEV                                          M           M    337.32433           M     128.6568               M        29.6318
MINIMUM                                         .1        .510       11.030           M         8.10               M           1.80
MAXIMUM                                         .1        .510     1167.500           M       405.00               M          85.30
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A5.4.3 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR OXYGEN-RELATED VARIABLES IN UNUSUAL CANADIAN CIRCUMSTANCES.

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TROPHIC              LAKE  LAKE NAME HYPOLIMNION HYPOLIMNION     PRIMARY     HYPOLIMNETIC HYPOLIMNETIC     H.O.D.         H.O.D.
 GROUP                      (ABBR)     SURFACE      VOLUME      PRODUCTION      OXYGEN       OXYGEN     MONTHLY RATE   MONTHLY RATE
                                        AREA                  (PER SURFACE)   DEPLETION    DEPLETION    (PER VOLUME)  (PER SURFACE)
                                        KM2       1CE6 M3     G C M-2 Y-1   (PER VOLUME) (PER SURFACE G O2 M-3 MO-1 G O2 M-2 MO-1
                                                                               G O2 M-3     G O2 M-3

OLIGOTROPHIC

                      703  BOWKER            -0          -0            -0           -0           -0            -0            -0
                      708  MONTJOIE          -0          -0            -0           -0           -0            -0            -0
                      711  STUKELY           -0          -0            -0           -0           -0            -0            -0
                      717  226N '73          -0          -0            -0           -0           -0            -0            -0
                      718  226N '74          -0          -0        90.200           -0           -0            -0            -0
                      719  226S '73          -0          -0            -0           -0           -0            -0            -0
                      720  226S '74          -0          -0        55.300           -0           -0            -0            -0
                      721  227  '69          -0          -0        42.000           -0           -0            -0            -0
                      722  227  '70          -0          -0       109.000           -0           -0            -0            -0
                      723  227  '71          -0          -0       105.000           -0           -0            -0            -0
                      724  227  '72          -0          -0       174.000           -0           -0            -0            -0
                      725  227  '73          -0          -0            -0           -0           -0            -0            -0
                      726  227  '74          -0          -0       161.200           -0           -0            -0            -0
                      727  261  '73          -0          -0            -0           -0           -0            -0            -0
                      728  261  '74          -0          -0        51.000           -0           -0            -0            -0
                      729  302N '72          -0          -0            -0           -0           -0            -0            -0
                      730  302N '73          -0          -0            -0           -0           -0            -0            -0
                      731  302N '74          -0          -0        70.500           -0           -0            -0            -0
                      732  304  '71          -0          -0            -0           -0           -0            -0            -0
                      733  304  '72          -0          -0            -0           -0           -0            -0            -0
                      734  304  '73          -0          -0            -0           -0           -0            -0            -0
                      735  304  '74          -0          -0        59.400           -0           -0            -0            -0
                      741  KAMLOOPS          -0          -0        32.000           -0           -0            -0            -0

# OF LAKES                         23         0           0            11            0            0             0             0
  MEAN                                        M           M      86.69091            M            M             M             M
  ST DEV                                      M           M      47.38742            M            M             M             M
MINIMUM                                       M           M        32.000            M            M             M             M
MAXIMUM                                       M           M       174.000            M            M             M             M
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A5.4.3   DATA LISTING BY TROPHIC CATEGORY WITH
         BASIC STATISTICS FOR OXYGEN-RELATED
         VARIABLES IN UNUSUAL CANADIAN
         CIRCUMSTANCES.

TROPHIC                   LAKE  LAKE NAME HYPOLIMNION HYPOLIMNION    PRIMARY      HYPOLIMNETIC HYPOLIMNETIC    H.O.D.          H.O.D.
 GROUP                           (ABBR)     SURFACE     VOLUME      PRODUCTION       OXYGEN       OXYGEN     MONTHLY RATE    MONTHLY RATE
                                             AREA                 (PER SURFACE)   DEPLETION    DEPLETION    (PER VOLUME)    (PER SURFACE)
                                              KM2        10E6 M3   G C M-2 Y-1  (PER VOLUME) (PER SURFACE G O2 M-3 MO-1 G O2 M-2 MO-1
                                                                                 G O2 M-3      G O2 M-3

MESOTROPHIC

                           702  AYLMER             -0          -0           -0           -0           -0            -0              -0
                           704  BROMPTON           -0          -0           -0           -0           -0            -0              -0
                           705  LOVERING           -0          -0           -0           -0           -0            -0              -0
                           707  MASSAWPI           -0          -0           -0           -0           -0            -0              -0
                           709  PT BROME           -0          -0           -0           -0           -0            -0              -0
                           710  ST FRAN            -0          -0           -0           -0           -0            -0              -0
                           714  ROXTON             -0          -0           -0           -0           -0            -0              -0
                           740  BARINE             -0          -0       60.000           -0           -0            -0              -0
                           742  KOOTN'76           -0          -0           -0           -0           -0            -0              -0
                           743  KOOTN'77           -0          -0           -0           -0           -0            -0              -0
                           745  OKANG'77           -0          -0           -0           -0           -0            -0              -0
                           746  OKANG'78           -0          -0           -0           -0           -0            -0              -0
N OF LAKES                               12         0           0            1            0            0             0               0
  MEAN                                              M           M      60.00000           M            M             M               M
  ST DEV                                            M           M            M            M            M             M               M
MINIMUM                                             M           M       60.000            M            M             M               M
MAXIMUM                                             M           M       60.000            M            M             M               M
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A5.4.3 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR OXYGEN-RELATED VARIABLES IN UNUSUAL CANADIAN CIRCUMSTANCES.

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TROPHIC           LAKE  LAKE NAME HYPOLIMNION HYPOLIMNION   PRIMARY     HYPOLIMNETIC HYPOLIMNETIC    H.O.D.          H.O.D.
GROUP                    (ABBR)    SURFACE     VOLUME     PRODUCTION      OXYGEN       OXYGEN     MONTHLY RATE   MONTHLY RATE
                                    AREA                 (PER SURFACE)   DEPLETION    DEPLETION   (PER VOLUME)  (PER SURFACE)
                                    KM2       10E6 M3    G C M-2 Y-1   (PER VOLUME) (PER SURFACE G O2 M-3 MO-1 G O2 M-2 MO-1
                                                                        G O2 M-3     G O2 M-3

EUTROPHIC

                  701 PINK             -0          -0       198.000        -0           -0            -0             -0
                  706 MAGOG            -0          -0            -0        -0           -0            -0             -0
                  712 BOIVIN           -0          -0            -0        -0           -0            -0             -0
                  713 BROME            -0          -0            -0        -0           -0            -0             -0
                  715 WATERLOO         -0          -0            -0        -0           -0            -0             -0
                  716 LT OTTER         -0          -0            -0        -0           -0            -0             -0
                  736 PASQUA           -0          -0            -0        -0           -0            -0             -0
                  737 ECHO             -0          -0            -0        -0           -0            -0             -0
                  738 MISSION          -0          -0            -0        -0           -0            -0             -0
                  739 KATEPWA          -0          -0            -0        -0           -0            -0             -0
                  744 WOOD             -0          -0            -0        -0           -0            -0             -0
                  747 SKAHA'77         -0          -0            -0        -0           -0            -0             -0
                  748 SKAHA'78         -0          -0            -0        -0           -0            -0             -0
                  749 OSOOY'77         -0          -0            -0        -0           -0            -0             -0
                  750 OSOOY'78         -0          -0            -0        -0           -0            -0             -0
                  751 GRAVNH P         -0          -0            -0        -0           -0            -0             -0
N OF LAKES                      16      0           0             1         0            0             0              0
  MEAN                                  M           M     198.00000         M            M             M              M
 ST DEV                                 M           M             M         M            M             M              M
MINIMUM                                 M           M       198.000         M            M             M              M
MAXIMUM                                 M           M       198.000         M            M             M              M

TOTAL
N OF LAKES                      51      0           0            13         0            0             0              0
  MEAN                                  M           M      93.20000         M            M             M              M
 ST DEV                                 M           M      53.99676         M            M             M              M
MINIMUM                                 M           M        32.000         M            M             M              M
MAXIMUM                                 M           M       198.000         M            M             M              M
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A5.5.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR PHOSPHORUS-RELATED VARIABLES AND RATIOS IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	MEAN INFLOW PHOSPHORUS MG M-3	MEAN OUTFLOW PHOSPHORUS MG M-3	ABSOLUTE RESIDENCE TIME OF P Y	RELATIVE RESIDENCE TIME OF P	PHOSPHORUS SEDIMENTATION COEFFICIENT Y-1	APPARENT SETTLING VELOCITY OF P M Y-1	CHL/P RATIO OF MEANS	SUMMER CHL/ EUPHOTIC P RATIO
OLIGOTROPHIC										
	110	PAJAN-2	28.30	22.75	.37	.525	1.253	25.85	.140	.430
	112	PAJAN-4	22.36	17.14	.42	.691	.744	15.03	.150	.330
	113	PAJAN-5	27.40	13.93	.51	.391	1.197	16.73	.130	.170
	114	PAAJARVI	85.42	20.47	.44	.108	2.021	29.13	.200	.340
	201	LUNZER L	9.18	6.84	.33	.910	.276	5.52	.220	.240
	202	FELDSEE	4.69	3.75	.45	.925	.155	2.03	.560	.730
	214	ATTERSEE	19.95	11.54	1.89	.270	.337	32.59	.250	.270
	222	VWS URNE	43.71	16.07	.67	.393	.507	120.03	-0	-0
	236	TAZENAT	-0	-0	-0	-0	-0	-0	-0	-0
	306	BIWA NOR	39.93	7.34	.70	.117	1.261	58.22	.430	-0
	406	DOGFISH	17.50	-0	2.00	.571	.214	.95	.300	-0
	407	GEORGE	31.11	-0	2.19	.273	.333	5.94	-0	-0
	409	LAMB	17.25	-0	1.07	.725	.105	.03	.320	-0
	410	MEANDER	16.20	-0	1.75	.643	.231	1.01	.140	.190
	420	TAHOE	111.42	-0	16.78	.027	.052	16.22	.100	.070
	423	WALDO	4.92	-0	6.35	.303	.110	3.45	.100	.000
	426	WASHINGT	31.27	-0	1.38	.576	.307	10.14	.330	.040
	501	JAPCOR P	-0	-0	-0	-0	-0	-0	.240	-0
	502	ALHILL K	-0	-0	-0	-0	-0	-0	.450	-0
	503	BLHILL S	-0	-0	-0	-0	-0	-0	.300	-0
	504	HINCHA P	-0	-0	-0	-0	-0	-0	.240	-0
	505	YUGDLE K	-0	-0	-0	-0	-0	-0	.120	-0
	506	PIKEHL P	-0	-0	-0	-0	-0	-0	.150	-0
	507	BENNETT	9.20	-0	.03	.652	13.348	30.17	.230	-0
	511	KEJIM	10.00	-0	.14	.920	.695	3.55	.130	-0
	512	MOUNTAIN	5.42	-0	.93	.941	.065	.53	.200	-0
	513	PEBBLGCH	10.77	-0	.23	.475	.059	.22	.150	-0
	515	FRESHWTR	-0	-0	-0	-0	-0	-0	.350	-0
	516	MC COUG	-0	-0	-0	-0	-0	-0	.140	-0
	523	BOWKER	24.50	-0	1.32	.259	.552	13.43	.270	-0
	528	MONTJOIE	17.20	-0	.79	.465	.676	5.37	.160	-0
	531	STUKLEY	21.00	-0	.60	.238	1.279	16.75	.340	-0
	536	BEECH	7.89	-0	.05	.938	1.352	13.25	.140	-0
	537	BOB	26.00	-0	.74	.246	1.021	18.33	.190	-0
	539	CRANBRY	6.31	-0	.03	1.569	21.300	74.57	.110	-0
	540	EAGL-MOR	6.10	-0	.61	.780	.542	6.93	.100	-0
	542	HALLS	8.48	-0	.49	.435	1.154	31.37	.300	-0
	543	MAPLE	10.76	-0	.13	.864	1.646	12.15	.120	-0
	544	OPL-HALI	21.95	-0	.69	.214	1.143	23.13	.230	-0
	545	PINE	9.27	-0	.07	1.270	3.654	27.11	.110	-0
	546	RAVEN	21.50	-0	.03	.366	21.151	15.42	.100	-0
	547	TALBOT	23.36	-0	.13	.663	2.530	2.15	.130	-0
	548	12MI-BCS	9.41	-0	.31	.646	1.132	20.47	.200	-0
	550	JERRY	34.34	-0	.62	.416	.936	12.73	-0	-0
	552	LTL JOS	28.40	-0	.71	.310	.959	16.47	.280	-0
	554	ROSSEAU	28.30	-0	1.28	.267	.571	14.55	.220	-0
	556	SKELTN B	26.19	-0	.10	.420	5.756	54.11	.140	-0
	557	BREWER	16.30	-0	.55	.521	.872	4.97	.350	-0
	558	CLARKE	10.20	-0	.06	.980	.280	1.57	.310	-0
	559	COSTELLO	19.60	-0	.44	.516	1.105	9.28	.410	-0
	560	FOUND	70.70	-0	1.98	.099	.455	5.23	.160	-0
	561	KEARNEY	13.02	-0	.40	.929	.176	1.27	.210	-0
	562	L MC CAU	22.30	-0	.30	.318	2.246	8.54	.470	-0
	563	BIGWIND	-0	-0	-0	-0	-0	-0	.320	-0
	564	BL CHALK	-0	-0	-0	-0	-0	-0	.310	-0
	565	BUCK	-0	-0	-0	-0	-0	-0	.330	-0
	567	CROSSON	-0	-0	-0	-0	-0	-0	.230	-0
	570	HARP	-0	-0	-0	-0	-0	-0	.370	-0
	571	JERRY	-0	-0	-0	-0	-0	-0	.400	-0

A5.5.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR PHOSPHORUS-RELATED VARIABLES AND RATIOS IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	MEAN INFLOW PHOSPHORUS MG M-3	MEAN OUTFLOW PHOSPHORUS MG M-3	ABSOLUTE RESIDENCE TIME OF P Y	RELATIVE RESIDENCE TIME OF P	PHOSPHORUS SEDIMENTATION COEFFICIENT Y-1	APPARENT SETTLING VELOCITY OF P M Y-1	CHL/P RATIO OF MEANS	SUMMER CHL/ EUPHOTIC P RATIO
OLIGOTROPHIC	(CONT.)									
	572	L CLEAR	-0	-0	-0	-0	-0	-0	.270	-0
	573	RD CHAL	-0	-0	-0	-0	-0	-0	.390	-0
	574	SOLITR	-0	-0	-0	-0	-0	-0	.360	-0
	575	WALKER	-0	-0	-0	-0	-0	-0	.300	-0
	576	SUPERIOR	62.50	-0	13.62	.074	.068	10.07	.150	-0
	579	HURON	28.30	-0	4.09	.194	.197	12.00	.220	-0
	583	114	94.30	-0	.20	.127	4.231	7.28	.920	-0
	584	120	-0	-0	-0	-0	-0	-0	.240	-0
	585	223	26.60	-0	1.24	.375	.503	3.02	.350	-0
	586	224	43.00	-0	2.03	.163	.413	4.74	.290	-0
	587	239	29.90	-0	1.40	.264	.513	5.33	.160	-0
	588	240	16.00	-0	.76	.686	.419	2.53	.230	-0
	589	303	46.00	-0	.24	.239	3.182	4.77	.180	-0
	593	KALAMLKS	65.30	-0	5.31	.144	.135	7.96	.190	-0
N OF LAKES		73	53	9	53	53	53	53	69	11
MEAN			27.3572	14.3756	1.5675	.50928	1.99065	15.9363	.25364	.31545
ST DEV			22.4475	7.9120	3.2434	.33339	4.34698	20.9361	.12935	.21477
MINIMUM			4.68	3.75	.03	.027	.052	.12	.100	.060
MAXIMUM			111.82	28.47	18.78	1.567	21.306	120.60	.920	.730

A5.5.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR PHOSPHORUS-RELATED VARIABLES AND RATIOS IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	MEAN INFLOW PHOSPHORUS MG M-3	MEAN OUTFLOW PHOSPHORUS MG M-3	ABSOLUTE RESIDENCE TIME OF P Y	RELATIVE RESIDENCE TIME OF P	PHOSPHORUS SEDIMENTATION COEFFICIENT Y-1	APPARENT SETTLING VELOCITY OF P M Y-1	CHL/P RATIO OF MEANS	SUMMER CHL/ EUPHOTIC P RATIO
MESOTROPHIC										
	111	PAJAN-3	41.33	29.33	.34	.847	.452	6.73	.100	.240
	204	MERGOZZO	54.37	6.21	.48	.102	1.672	84.98	.570	.660
	213	OSSIACHE	71.40	13.51	.39	.203	2.044	40.67	.230	.140
	216	WALLENSE	67.92	-0	.57	.409	1.031	104.12	-0	-0
	220	VWS KREU	24.47	20.61	1.46	1.054	-.037	-2.90	-0	-0
	221	VWS GEPS	23.70	16.70	1.23	.789	.171	26.74	-0	-0
	223	MAGGIORE	76.51	27.34	1.15	.287	.621	109.84	.140	-0
	224	WALLENSE	55.00	16.06	.72	.511	.684	68.43	-0	-0
	227	LEMAN	106.51	34.58	9.49	.863	.614	2.21	.080	.190
	230	MONTORFA	72.77	14.55	.33	.220	2.350	9.75	.540	.750
	231	ANNONE	688.50	24.30	.03	.038	31.456	125.83	.650	.730
	234	D ANNECY	35.53	6.70	-0	-0	-0	-0	-0	-0
	237	PAVIN	-0	-0	-0	-0	-0	-0	.140	.080
	303	LOUGH LF	24.09	-0	-0	-0	-0	-0	-0	-0
	404	CAYUGA	126.24	-0	1.36	.158	.618	33.05	.270	-0
	418	SAMPANIS	71.19	-0	.76	.421	.793	13.50	.170	.200
	427	WEIR	93.33	-0	.90	.214	.673	5.53	.300	.050
	509	WOLFF	6.59	-0	.48	1.151	.313	1.20	.510	-0
	510	GRAFTON	10.00	-0	.15	1.050	.340	.93	.200	-0
	514	LTL KEPP	-0	-0	-0	-0	-0	-0	-0	-0
	517	PRESQUL	-0	-0	-0	-0	-0	-0	.240	-0
	518	WAPFEN	6.57	-0	.25	.430	.273	4.34	.110	-0
	519	MEMPH A	8.28	-0	.37	1.534	1.451	21.33	.500	-0
	520	MEMPH C	27.55	-0	.61	.485	.651	37.59	.330	-0
	522	AYLMER	27.00	-0	.23	1.011	.436	.53	-0	-0
	524	BROMPTON	29.00	-0	.59	.310	1.153	14.53	.480	-0
	525	LOVERING	30.30	-0	.36	.367	1.735	17.02	-0	-0
	527	PASSAMP	41.30	-0	.40	.266	1.621	73.20	.770	-0
	529	PT ARUPF	105.00	-0	.44	.114	2.017	14.73	.260	-0
	530	ST FRAN	35.00	-0	.59	.049	.575	4.24	-0	-0
	534	ROXTON	69.00	-0	.22	.391	2.611	4.03	.230	-0
	539	CAMERON	15.56	-0	.03	.537	4.351	101.87	.180	-0
	541	4-MI	50.00	-0	.69	.158	1.237	11.51	.160	-0
	549	DUDLEY B	40.71	-0	.52	.308	1.226	8.21	.100	-0
	551	HARP	45.30	-0	.85	.243	.892	12.34	.180	-0
	553	MUSKOKA	41.30	-0	.21	.225	3.666	61.00	.220	-0
	555	SMCOE	157.00	-0	2.53	.121	.347	8.79	.130	-0
	566	CHUB	-0	-0	-0	-0	-0	-0	.330	-0
	568	DICKIE	-0	-0	-0	-0	-0	-0	.420	-0
	569	GULFEATH	-0	-0	-0	-0	-0	-0	.310	-0
	577	MICHIGAN	135.10	-0	6.72	.059	.140	11.75	.250	-0
	580	CB ERIE	62.80	-0	.47	.309	1.450	25.97	.230	-0
	581	EP ERIE	27.50	-0	.57	.623	.657	13.00	.190	-0
	582	ONTARIC	66.50	-0	2.49	.315	.275	23.64	.260	-0
	594	OKANAGAN	195.30	-0	2.26	.038	.426	32.09	.190	-0
N OF LAKES		45	39	11	37	37	37	37	35	9
MEAN			73.5672	19.6264	1.1143	.46451	2.18598	31.0457	.29029	.33778
ST DEV			109.6128	8.7519	1.8319	.36715	5.47368	35.0865	.16771	.28861
MINIMUM			6.57	6.21	.03	.038	-.037	-2.90	.080	.050
MAXIMUM			688.50	34.58	9.49	1.534	31.456	125.83	.770	.750

A5.5.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR PHOSPHORUS-RELATED VARIABLES AND RATIOS IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	MEAN INFLOW PHOSPHORUS MG M-3	MEAN OUTFLOW PHOSPHORUS MG M-3	ABSOLUTE RESIDENCE TIME OF P Y	RELATIVE RESIDENCE TIME OF P	PHOSPHORUS SEDIMENTATION COEFFICIENT Y-1	APPARENT SETTLING VELOCITY OF P M Y-1	CHL/P RATIO OF MEANS	SUMMER CHL/ EUPHOTIC P RATIO
EUTROPHIC										
	101	ESRUM	626.11	273.01	5.52	.378	.113	1.53	.030	.030
	102	MOSSO 1	200.97	156.31	1.58	.685	.200	2.05	.370	.060
	103	MOSSO 2	-0	-0	.01	-0	-0	-0	.470	.600
	104	GJERSJC	167.22	29.78	.98	.169	.946	21.52	.540	1.360
	105	MJOSA	30.39	9.32	1.90	.290	.376	60.55	.280	.030
	106	BOFEN	57.50	25.00	.12	.397	5.073	30.44	.220	.330
	107	MALAREN	196.69	72.28	.42	.348	1.555	26.75	.120	.340
	108	VATTERN	159.74	-0	3.12	.050	.305	11.67	.050	.130
	109	PAJAN-1	23.51	19.44	.43	.860	.326	5.97	.110	.280
	115	TUUSULAN	663.23	230.55	.20	.183	4.063	12.57	.270	.400
	203	BODENSEE	200.31	27.76	1.75	.397	.344	34.41	.050	.240
	205	PONTE LU	-0	-0	2.04	-0	-0	-0	.030	.030
	206	CAPOLAGO	-0	-0	1.51	-0	-0	-0	.040	.100
	207	MELIDE L	-0	-0	16.65	-0	-0	-0	.030	.070
	208	GONDRIA	-0	-0	24.57	-0	-0	-0	.030	.030
	209	LUGANO L	-0	-0	6.32	-0	-0	-0	.050	.080
	210	AGNO LUG	442.00	-0	.90	.373	.692	37.29	.350	.060
	211	MARCOTE	-0	-0	1.61	-0	-0	-0	.030	.070
	212	FIGINO L	-0	-0	5.92	-0	-0	-0	.040	.060
	215	GREIFENS	208.17	191.80	2.56	1.854	-.334	-5.41	.040	.160
	217	BALDEGGE	381.14	229.41	3.55	1.425	-.050	-1.64	-0	-0
	216	HALLWILL	406.02	304.51	2.09	.510	.235	4.15	-0	-0
	219	SEMPACHE	390.95	104.02	3.12	.189	.260	11.95	.150	.600
	225	ZURICH U	-0	70.00	-0	-0	-0	-0	-0	-0
	226	ZURICH S	-0	-0	-0	-0	-0	-0	-0	-0
	228	OGGIONO	431.75	107.94	.54	.394	1.132	7.13	.190	.310
	229	PUSIANO	231.63	44.69	.17	.244	4.456	63.72	.320	.340
	232	SEGRINO	133.49	29.15	.12	.267	3.421	16.77	.650	.700
	233	D ALSERI	720.97	104.47	.07	.193	11.549	51.07	.530	.740
	235	MANTUA	65.60	56.31	-0	-0	-0	-0	-0	-0
	238	AYCAT	-0	-0	-0	-0	-0	-0	.420	.310
	301	LOUGH NE	177.47	80.76	.30	.682	.339	3.33	.150	-0
	302	LOCH LEV	149.74	77.46	.27	.463	1.963	7.65	.570	-0
	304	LOUGH EA	229.39	66.07	.54	.290	1.310	9.92	.400	-0
	305	BIWA SCL	22.37	19.51	.33	.896	3.403	13.24	.230	-0
	307	KASUMI N	231.49	56.31	.14	.229	5.217	21.52	.570	-0
	308	KASUMI K	155.49	64.87	.13	.283	5.497	22.54	.460	-0
	401	BROWNIE	347.36	-0	-0	-0	-0	-0	-0	.060
	402	CALHOUN	292.36	-0	1.31	.363	.438	5.17	-0	.140
	403	CANADARA	62.34	-0	.43	.722	.642	4.49	.220	.360
	405	CEDAR	155.34	-0	.36	.290	.740	4.52	.360	.060
	409	HARRIET	193.34	-0	.77	.320	.685	7.73	-0	-0
	411	MENDOTA	450.30	-0	1.50	.333	.444	5.33	.070	.460
	412	LOWER PI	-0	-0	1.00	-0	-0	-0	.330	.380
	413	LOWER PI	-0	-0	3.05	-0	-0	-0	.240	.120
	414	POTOMAC	708.33	-0	.34	1.057	-1.339	-6.57	.120	.170
	415	POTOMAC	292.35	-0	.24	1.346	-1.428	-7.23	.170	-0
	416	POTOMAC	141.57	-0	.27	.318	2.527	18.20	.330	-0
	417	SALLIE	645.70	-0	.79	.542	.583	3.73	-0	.620
	419	SHAGAWA	59.25	-0	.49	.611	.797	4.54	.250	-0
	421	EAST TWI	91.98	-0	.64	.870	.205	1.03	.350	-0
	422	WEST TWI	112.31	-0	1.43	.975	.017	.07	.270	.680
	424	WASHINGT	87.27	-0	.56	.275	1.079	36.25	.500	.460
	425	WASHINGT	157.27	-0	.35	.395	.639	21.10	.300	-0
	428	WINGRA	150.30	-0	.17	.467	2.657	6.35	-0	-0
	508	MCLAREN	33.55	-0	.07	.612	5.753	29.35	.460	-0
	521	MEMPH S	23.22	-0	.24	.801	.829	5.14	.320	-0
	526	MAGOG	31.30	-0	.03	1.387	4.801	47.05	.550	-0
	532	AAIVIN	124.30	-0	.32	1.008	6.657	10.40	.070	-0

A5.5.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR PHOSPHORUS-RELATED VARIABLES AND RATIOS IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	MEAN INFLOW PHOSPHORUS MG M-3	MEAN OUTFLOW PHOSPHORUS MG M-3	ABSOLUTE RESIDENCE TIME OF P Y	RELATIVE RESIDENCE TIME OF P	PHOSPHORUS SEDIMENTATION COEFFICIENT Y-1	APPARENT SETTLING VELOCITY OF P M Y-1	CHL/P RATIO OF MEANS	SUMMER CHL/ EUPHOTIC P RATIO
EUTROPHIC	(CONT.)									
	533	ARGME	64.00	-0	.39	1.250	.286	1.65	.140	-0
	535	WATERLOO	70.00	-0	.17	.743	1.489	4.32	.770	-0
	579	WB ERIE	77.00	-0	.03	.510	6.004	45.63	.260	-0
	590	WINNIPEG	84.50	-0	2.48	.709	.117	1.40	.050	-0
	591	CROOKED	401.20	-0	.17	.551	2.643	22.11	.070	-0
	592	POUND	313.40	-0	.11	.559	3.855	31.28	.050	-0
	595	SKAHA	49.50	-0	.35	.293	2.013	33.34	.230	-0
	596	OSOYOOS	53.22	-0	.27	.671	1.224	25.34	.220	-0
N OF LAKES		67	54	25	62	52	52	52	57	37
MEAN			223.3646	98.3692	1.3393	.57610	1.95673	10.6575	.25491	.34081
ST DEV			186.7092	84.3159	3.9134	.37816	2.55632	18.1291	.19319	.28763
MINIMUM			22.37	9.32	.01	.050	-1.420	-7.24	.030	.030
MAXIMUM			720.97	304.51	24.57	1.654	11.548	63.92	.770	1.360
TOTAL										
N OF LAKES		185	146	45	152	142	142	142	161	57
MEAN			112.1968	62.3222	1.5680	.52412	2.03391	20.1353	.26163	.33544
ST DEV			153.9842	74.6401	3.2722	.35927	4.12502	25.2427	.16265	.27097
MINIMUM			4.68	3.75	.01	.027	-1.426	-7.21	.030	.030
MAXIMUM			720.97	304.51	24.57	1.554	31.452	125.83	.920	1.360

A5.5.2 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR PHOSPHORUS-RELATED VARIABLES AND RATIOS IN SHALLOW LAKES AND RESERVOIRS.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	MEAN INFLOW PHOSPHORUS MG M-3	MEAN OUTFLOW PHOSPHORUS MG M-3	ABSOLUTE RESIDENCE TIME OF P Y	RELATIVE RESIDENCE TIME OF P	PHOSPHORUS SEDIMENTATION COEFFICIENT Y-1	APPARENT SETTLING VELOCITY OF P M Y-1	CHL/P RATIO OF MEANS	SUMMER CHL/ EUPHOTIC P RATIO
OLIGOTROPHIC										
	602	OLEF	7.79	10.32	.75	1.433	-.591	-8.54	.330	-0
	605	VERSE	32.30	24.34	.51	.341	1.233	25.73	.260	-0
	606	SOSE	10.18	5.33	.22	.459	2.512	45.21	.220	-0
	608	FURWIGGE	16.80	7.66	.17	.426	3.374	28.00	.300	-0
	623	EUPEN	-0	-0	-0	-0	-0	-0	-0	-0
	635	VECHTEN	-0	-0	-0	-0	-0	-0	-0	-0
N OF LAKES		6	4	4	4	4	4	4	4	0
MEAN			17.2650	12.0375	.4113	.66475	1.64680	22.6138	.27750	M
ST DEV			11.0841	8.5046	.2697	.51457	1.71510	22.5111	.04787	M
MINIMUM			7.79	5.33	.17	.341	-.591	-8.54	.220	M
MAXIMUM			32.30	24.34	.75	1.433	3.374	45.21	.330	M

A5.5.2 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR PHOSPHORUS-RELATED VARIABLES AND RATIOS IN SHALLOW LAKES AND RESERVOIRS.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	MEAN INFLOW PHOSPHORUS MG M-3	MEAN OUTFLOW PHOSPHORUS MG M-3	ABSOLUTE RESIDENCE TIME OF P Y	RELATIVE RESIDENCE TIME OF P	PHOSPHORUS SEDIMENTATION COEFFICIENT Y-1	APPARENT SETTLING VELOCITY OF P M Y-1	CHL/P RATIO OF MEANS	SUMMER CHL/ EUPHOTIC P RATIO
MESOTROPHIC										
	619	MT BOLD	178.75	120.55	.21	.535	2.227	29.39	.033	[illegible]
	620	PROSPECT	13.36	11.55	.10	.816	1.881	18.25	.280	[illegible]
	621	EL BURGI	80.01	28.17	.19	.519	2.508	49.41	.270	[illegible]
N OF LAKES		3	3	3	3	3	3	3	3	[illegible]
MEAN			90.7067	53.4333	.1663	.62333	2.20537	32.3495	.19333	[illegible]
ST DEV			83.2122	58.7136	.0598	.16705	.31334	15.7862	.14154	[illegible]
MINIMUM			13.36	11.55	.10	.519	1.881	18.25	.033	[illegible]
MAXIMUM			178.75	120.55	.21	.816	2.508	49.41	.283	[illegible]

A5.5.2 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR PHOSPHORUS-RELATED VARIABLES AND RATIOS IN SHALLOW LAKES AND RESERVOIRS.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	MEAN INFLOW PHOSPHORUS MG M-3	MEAN OUTFLOW PHOSPHORUS MG M-3	ABSOLUTE RESIDENCE TIME OF P Y	RELATIVE RESIDENCE TIME OF P	PHOSPHORUS SEDIMENTATION COEFFICIENT Y-1	APPARENT SETTLING VELOCITY OF P M Y-1	CHL/P RATIO OF MEANS	SUMMER CHL/ EUPHOTIC P RATIO
EUTROPHIC										
	601	WAHNBACH	87.45	20.92	.25	.244	2.901	52.45	.250	-0
	603	SORPE	197.32	49.16	.23	.202	3.461	70.51	.210	-0
	604	MOHNE	411.65	63.34	.13	.186	6.171	74.81	.210	-0
	607	ENNEPE	676.30	319.18	.07	.205	11.718	142.95	-0	-0
	609	DE GROTE	524.55	81.36	.07	.154	12.445	63.47	.220	-0
	610	BRIELSE	1051.48	554.07	.09	.276	7.723	41.70	.050	-0
	611	PETRUSPL	337.90	194.66	.06	.562	7.784	40.53	.030	-0
	612	HONDERD	498.32	325.66	.15	.662	2.325	34.13	.020	-0
	613	BRAAKMAN	546.70	291.20	.27	.476	1.959	15.73	.190	-0
	614	BRAAKMAN	227.51	52.98	.19	.220	4.034	33.03	.540	-0
	615	TJEUKEME	-0	-0	-0	-0	-0	-0	-0	-0
	616	QUEEN EL	-0	-0	-0	-0	-0	-0	-0	-0
	617	FARMOOR	534.52	239.29	.21	.452	2.635	23.72	.080	-0
	619	GRAFHAM	4902.53	1501.89	-0	-0	-0	-0	-0	-0
	622	MISSANCH	82.50	40.40	-0	-0	-0	-0	-0	-0
	624	BLACKHAW	226.53	-0	.27	.530	1.776	9.70	.120	-0
	625	CAMELOT	100.46	-0	.05	.348	12.583	37.75	.160	-0
	626	COX HOLL	292.11	-0	.21	.342	3.202	12.17	.260	-0
	627	DUTCH HO	533.00	-0	.77	.425	.751	2.02	.140	-0
	628	ISLES	451.11	-0	.15	.244	5.165	13.02	-0	.480
	629	[illegible] SEA	100.77	-0	.55	.297	11.629	121.93	.490	.700
	630	KEGG NUT	435.37	-0	.35	.069	2.650	21.73	.710	.600
	631	REDSTONE	309.37	-0	.31	.380	2.092	9.00	.120	-0
	632	STEWART	270.74	-0	.02	.295	29.803	56.65	.150	-0
	633	TWIN VAL	223.92	-0	.12	.266	6.007	23.65	.320	-0
	634	VIRGINIA	1425.54	-0	.20	.165	4.597	7.31	.190	-0
	636	PIBURGER	10.54	10.54	4.21	1.537	-.128	-1.66	.020	1.030
N OF LAKES		27	25	14	23	23	23	23	21	4
MEAN			580.5498	267.5729	.3658	.36996	6.24507	42.0553	.24095	.70250
ST DEV			953.4249	386.9192	.8525	.29492	6.40771	38.7517	.19793	.23613
MINIMUM			10.54	10.54	.02	.069	-.128	-1.66	.020	.480
MAXIMUM			4902.53	1501.89	4.21	1.537	29.803	142.96	.710	1.030
TOTAL										
N OF LAKES		36	32	21	30	30	30	30	28	4
MEAN			464.2136	196.3081	.3519	.43460	5.22830	38.4930	.24107	.70250
ST DEV			868.5557	334.6854	.7505	.33107	5.91570	35.4624	.16838	.23613
MINIMUM			7.76	5.33	.02	.069	-.581	-8.54	.020	.480
MAXIMUM			4902.53	1501.89	4.21	1.537	29.803	142.95	.710	1.030

A5.5.3 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR PHOSPHORUS-RELATED VARIABLES AND RATIOS IN UNUSUAL CANADIAN CIRCUMSTANCES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	MEAN INFLOW PHOSPHORUS MG M-3	MEAN OUTFLOW PHOSPHORUS MG M-3	ABSOLUTE RESIDENCE TIME OF P Y	RELATIVE RESIDENCE TIME OF P	PHOSPHORUS SEDIMENTATION COEFFICIENT Y-1	APPARENT SETTLING VELOCITY OF P M Y-1	CHL/P RATIO OF MEANS	SUMMER CHL/ EUPHOTIC P RATIO
OLIGOTROPHIC										
	703	BOWKER	25.50	-0	1.32	-0	.562	13.44	-0	-0
	708	MONTJOIE	30.13	-0	.45	-0	1.627	12.85	-0	-0
	711	STUKELY	32.44	-0	.64	-0	1.164	15.24	-0	-0
	717	226N '73	-0	-0	.09	-0	11.345	56.73	-0	-0
	718	226N '74	-0	-0	.09	-0	11.331	56.65	-0	-0
	719	226S '73	65.79	-0	.70	-0	1.199	6.83	-0	-0
	720	226S '74	53.00	-0	.63	-0	1.328	7.57	-0	-0
	721	227 '69	-0	-0	.06	-0	-0	-0	-0	-0
	722	227 '70	139.15	-0	.11	-0	8.749	38.44	-0	-0
	723	227 '71	286.51	-0	.17	-0	5.583	24.55	-0	-0
	724	227 '72	315.50	-0	.17	-0	5.620	24.73	-0	-0
	725	227 '73	352.06	-0	.21	-0	4.409	19.43	-0	-0
	726	227 '74	390.73	-0	.24	-0	3.847	16.93	-0	-0
	727	261 '73	-0	-0	.12	-0	-0	-0	-0	-0
	728	261 '74	92.31	-0	.17	-0	4.646	13.45	-0	-0
	729	302N '72	657.22	-0	.17	-0	5.821	33.13	-0	-0
	730	302N '73	394.31	-0	.15	-0	6.440	36.71	-0	-0
	731	302N '74	-0	-0	.19	-0	-0	-0	-0	-0
	732	304 '71	-0	-0	-0	-0	-0	-0	-0	-0
	733	304 '72	-0	-0	-0	-0	-0	-0	-0	-0
	734	304 '73	-0	-0	-0	-0	-0	-0	-0	-0
	735	304 '74	-0	-0	-0	-0	-0	-0	-0	-0
	741	KAMLOOPS	38.31	-0	.04	-0	20.354	-0	-0	-0
N OF LAKES		23	14	0	19	0	16	15	0	0
MEAN			208.3114	M	.2998	M	5.87606	25.1207	M	M
ST DEV			193.5154	M	.3206	M	5.14377	16.1112	M	M
MINIMUM			25.50	M	.04	M	.562	6.83	M	M
MAXIMUM			657.22	M	1.32	M	20.354	56.73	M	M

A5.5.3 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR PHOSPHORUS-RELATED VARIABLES AND RATIOS IN UNUSUAL CANADIAN CIRCUMSTANCES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	MEAN INFLOW PHOSPHORUS MG M-3	MEAN OUTFLOW PHOSPHORUS MG M-3	ABSOLUTE RESIDENCE TIME OF P Y	RELATIVE RESIDENCE TIME OF P	PHOSPHORUS SEDIMENTATION COEFFICIENT Y-1	APPARENT SETTLING VELOCITY OF P M Y-1	CHL/P RATIO OF MEANS	SUMMER CHL/ EUPHOTIC P RATIO
MESOTROPHIC										
	702	AYLMER	46.54	-0	.14	-0	3.064	26.05	-0	-0
	704	BROMPTON	48.54	-0	.34	-0	2.393	29.78	-0	-0
	705	LOVERING	32.56	-0	.33	-0	1.969	19.29	-0	-0
	707	MASSAWPI	63.43	-0	.32	-0	2.513	101.02	-0	-0
	709	PT BROMP	64.35	-0	.79	-0	1.022	7.46	-0	-0
	710	ST FRAN	65.72	-0	.31	-0	2.092	32.64	-0	-0
	714	ROXTON	111.72	-0	.13	-0	5.705	18.26	-0	-0
	740	BABINE	11.34	-0	6.66	.524	.071	3.93	.250	-0
	742	KOOTN'76	22.96	-0	1.75	-0	.014	1.35	-0	-0
	743	KOOTN'77	14.17	-0	2.34	-0	.137	12.85	-0	-0
	745	OKANG'77	465.47	-0	2.59	-0	.278	28.49	-0	-0
	746	OKANG'76	144.27	-0	1.92	-0	.497	37.45	-0	-0
N OF LAKES		12	12	0	12	1	12	12	1	0
MEAN			90.9600	M	1.4726	.52400	1.65551	26.5436	.25000	M
ST DEV			124.1555	M	1.6738	M	1.67420	26.1744	M	M
MINIMUM			11.34	M	.13	.524	.014	1.35	.250	M
MAXIMUM			465.47	M	6.66	.524	5.705	101.02	.250	M

A5.5.3 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR PHOSPHORUS-RELATED VARIABLES AND RATIOS IN UNUSUAL CANADIAN CIRCUMSTANCES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	MEAN INFLOW PHOSPHORUS MG M-3	MEAN OUTFLOW PHOSPHORUS MG M-3	ABSOLUTE RESIDENCE TIME OF P Y	RELATIVE RESIDENCE TIME OF P	PHOSPHORUS SEDIMENTATION COEFFICIENT Y-1	APPARENT SETTLING VELOCITY OF P M Y-1	CHL/P RATIO OF MEANS	SUMMER CHL/ EUPHOTIC P RATIO
EUTROPHIC										
	701	PINK	77.14	-0	.44	.259	1.433	17.43	.100	-0
	705	MAGCE	28.29	-0	.04	-0	10.119	49.17	-0	-0
	712	BOIVIN	120.50	-0	.02	-0	1.800	2.16	-0	-0
	713	SPOME	61.55	-0	.91	-0	.329	1.91	-0	-0
	715	WATERLOO	128.97	-0	.09	-0	6.728	19.51	-0	-0
	716	LT OTTER	16.30	-0	.56	6.750	3.519	23.30	.280	-0
	736	PASQUA	389.33	-0	.50	1.419	.643	4.89	.020	-0
	737	ECHO	402.02	-0	.38	1.117	.305	2.80	.020	-0
	738	MISSION	404.24	-0	.23	1.165	.821	7.15	.030	-0
	739	KATEPWA	392.30	-0	.81	1.246	.304	4.29	.026	-0
	744	WOOD	107.33	-0	12.01	.858	.012	.23	.110	-0
	747	SKAHA'77	47.52	-0	.27	-0	2.516	77.33	-0	-0
	748	SKAHA'78	49.52	-0	.44	-0	1.459	39.67	-0	-0
	749	OSOOY'77	33.22	-0	.35	-0	1.455	30.11	-0	-0
	750	OSOOY'78	33.22	-0	.38	-0	1.034	21.40	-0	-0
	751	FRAVNH B	1934.10	-0	.04	.020	23.852	161.23	.200	-0
N OF LAKES		16	16	0	16	9	16	16	8	0
MEAN			264.2906	M	1.0857	1.60675	3.86532	33.2073	.09750	M
ST DEV			470.3893	M	2.9257	2.13578	6.16639	48.4527	.09753	M
MINIMUM			16.30	M	.02	.020	.012	.23	.020	M
MAXIMUM			1934.10	M	12.01	6.750	23.852	161.23	.280	M
TOTAL N OF LAKES		51	42	0	47	9	44	43	9	0
MEAN			196.1079	M	.8668	1.48644	3.99518	28.3602	.11444	M
ST DEV			319.3125	M	1.9739	2.03018	5.10499	33.4307	.10442	M
MINIMUM			11.34	M	.02	.020	.012	.23	.020	M
MAXIMUM			1934.10	M	12.01	6.750	23.852	161.22	.250	M

A5.6.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR NITROGEN-RELATED VARIABLES AND RATIOS IN NATURAL LAKES.

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TROPHIC          LAKE  LAKE NAME   MEAN       MEAN      ABSOLUTE   RELATIVE    TN/TP1      N/P        N/P        N/P
GROUP                  (ABBR)     INFLOW     OUTFLOW   RESIDENCE  RESIDENCE  RELATIVE   LOADING    OUTFLOW  MEAN CONC.
                                 NITROGEN   NITROGEN   TIME OF N  TIME OF N    TIMES     RATIO      RATIO      RATIO
                                  MG M-3     MG M-3        Y

OLIGOTROPHIC

                 110  PAJAN-2      616.00     717.50      .381       .763      1.039     22.000     31.540     31.470
                 112  PAJAN-4      662.86     545.71      .403       .660       .533     29.000     31.830     29.530
                 113  PAJAN-5      677.86     622.14      .568       .631      1.116     24.330     44.670     39.240
                 114  PAAJARVI    1793.75    1110.42     2.178       .531      4.927     21.030     39.000    103.370
                 201  LUNZER U     247.26     793.40      .379      1.050      1.156     92.293    113.050    105.390
                 207  FELDSEE      287.75     308.67      .521      1.063      1.150     61.470     32.420     73.670
                 214  ATTERSEE     254.39     250.24        -0         -0         -0     12.750     21.500         -0
                 222  VWS URNE     651.68     508.72     1.356       .798      2.027     14.910     30.150     30.230
                 236  TAZENAT          -0         -0        -0         -0         -0         -0         -0         -0
                 306  BIWA NOR     575.81     256.11     2.739       .457      3.913     14.423     44.840     56.390
                 406  DOGFISH          -0         -0        -0         -0         -0         -0         -0         -0
                 407  GEORGE       800.00         -0        -0         -0         -0     25.710         -0         -0
                 409  LAMA             -0         -0        -0         -0         -0         -0         -0         -0
                 410  MEANDER          -0         -0        -0         -0         -0         -0         -0         -0
                 420  TAHOE       1162.94         -0        -0         -0         -0     10.400         -0         -0
                 423  WALDO        192.50         -0        -0         -0         -0     19.410         -0         -0
                 426  WASHINGT     320.00         -0        -0         -0         -0     10.230         -0         -0
                 501  JBRCOK F         -0         -0        -0         -0         -0         -0         -0         -0
                 502  BLHILL N         -0         -0        -0         -0         -0         -0         -0         -0
                 503  BLHILL S         -0         -0        -0         -0         -0         -0         -0         -0
                 504  MINCHN P         -0         -0        -0         -0         -0         -0         -0         -0
                 505  YUDCLE A         -0         -0        -0         -0         -0         -0         -0         -0
                 506  PINEHL P         -0         -0        -0         -0         -0         -0         -0         -0
                 507  BENNETT          -0         -0        -0         -0         -0         -0         -0         -0
                 511  KEJIM            -0         -0        -0         -0         -0         -0         -0         -0
                 512  MOUNTAIN         -0         -0        -0         -0         -0         -0         -0         -0
                 513  PEBBLOCH         -0         -0        -0         -0         -0         -0         -0         -0
                 515  FRESHWTR         -0         -0        -0         -0         -0         -0         -0         -0
                 516  MC DOUG          -0         -0        -0         -0         -0         -0         -0         -0
                 523  POWKER           -0         -0        -0         -0         -0         -0         -0         -0
                 528  MONTJOIE         -0         -0        -0         -0         -0         -0         -0         -0
                 531  STUKLEY          -0         -0        -0         -0         -0         -0         -0         -0
                 536  BEECH            -0         -0        -0         -0         -0         -0         -0         -0
                 537  BOB              -0         -0        -0         -0         -0         -0         -0         -0
                 539  CRANBRY          -0         -0        -0         -0         -0         -0         -0         -0
                 540  EAGL-MCC         -0         -0        -0         -0         -0         -0         -0         -0
                 542  HALLS            -0         -0        -0         -0         -0         -0         -0         -0
                 543  MAPLE            -0         -0        -0         -0         -0         -0         -0         -0
                 544  DBL-HALI         -0         -0        -0         -0         -0         -0         -0         -0
                 545  PINE             -0         -0        -0         -0         -0         -0         -0         -0
                 546  RAVEN            -0         -0        -0         -0         -0         -0         -0         -0
                 547  TALBOT           -0         -0        -0         -0         -0         -0         -0         -0
                 548  12MI-BOS         -0         -0        -0         -0         -0         -0         -0         -0
                 550  JERRY            -0         -0        -0         -0         -0         -0         -0         -0
                 552  LTL JOS          -0         -0        -0         -0         -0         -0         -0         -0
                 554  ROSSFAU          -0         -0        -0         -0         -0         -0         -0         -0
                 556  SKFLTN B         -0         -0        -0         -0         -0         -0         -0         -0
                 557  BREWER           -0         -0        -0         -0         -0         -0         -0         -0
                 558  CLARKE           -0         -0        -0         -0         -0         -0         -0         -0
                 559  COSTELLO         -0         -0        -0         -0         -0         -0         -0         -0
                 560  FOUND            -0         -0        -0         -0         -0         -0         -0         -0
                 561  KEARNEY          -0         -0        -0         -0         -0         -0         -0         -0
                 562  L MC CAU         -0         -0        -0         -0         -0         -0         -0         -0
                 563  BIGWIND          -0         -0        -0         -0         -0         -0         -0         -0
                 564  BL CHALK         -0         -0        -0         -0         -0         -0         -0         -0
                 565  BUCK             -0         -0        -0         -0         -0         -0         -0         -0
                 567  CROSSCR          -0         -0        -0         -0         -0         -0         -0         -0
                 570  HARP             -0         -0        -0         -0         -0         -0         -0         -0
                 571  JEFFY            -0         -0        -0         -0         -0         -0         -0         -0
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A5.6.1

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        DATA LISTING BY TROPHIC CATEGORY WITH
        BASIC STATISTICS FOR NITROGEN-RELATED
        VARIABLES AND RATIOS IN
        NATURAL LAKES.

TROPHIC               LAKE  LAKE NAME   MEAN       MEAN      ABSOLUTE    RELATIVE    TN/TP;      N/P         N/P        N/P
 GROUP                        (ABBF)   INFLOW     OUTFLOW   RESIDENCE   RESIDENCE   RELATIVE    LOADING     OUTFLOW   MEAN CONC.
                                      NITROGEN   NITROGEN   TIME OF N   TIME OF N    TIMES       RATIO       RATIO      RATIO
                                       MG M-3     MG M-3        Y

OLIGOTROPHIC         (CONT.)

                      572 L CLEAR          -0         -0         -0          -0          -0          -0          -0          -0
                      573  PC CHAL         -0         -0         -0          -0          -0          -0          -0          -0
                      574 SOLITR           -0         -0         -0          -0          -0          -0          -0          -0
                      575 WALKER           -0         -0         -0          -0          -0          -0          -0          -0
                      576 SUPERICR         -0         -0         -0          -0          -0          -0          -0          -0
                      579 HURON            -0         -0         -0          -0          -0          -0          -0          -0
                      583 114              -0         -0         -0          -0          -0          -0          -0          -0
                      594 120              -0         -0         -0          -0          -0          -0          -0          -0
                      595 223              -0         -0         -0          -0          -0          -0          -0          -0
                      635 224              -0         -0         -0          -0          -0          -0          -0          -0
                      657 239              -0         -0         -0          -0          -0          -0          -0          -0
                      638 240              -0         -0         -0          -0          -0          -0          -0          -0
                      639 303              -0         -0         -0          -0          -0          -0          -0          -0
                      593 KALAMLKA         -0         -0         -0          -0          -0          -0          -0          -0

# OF LAKES                        73       13          9          8           8           2          13           9           8
  MEAN                               680.2315   579.4789    1.05622      .74674     2.03906    27.53231    49.11111    58.39875
 ST DEV                              431.5030   270.5524     .52832      .22151     1.53020    23.52829    30.53640    32.22330
MINIMUM                               192.50     250.24       .378        .457        .933      13.230      21.500      23.530
MAXIMUM                              1793.75    1110.42      2.739       1.063       4.927      92.290     110.050     100.590
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A5.6.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR NITROGEN-RELATED VARIABLES AND RATIOS IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	MEAN INFLOW NITROGEN MG M-3	MEAN OUTFLOW NITROGEN MG M-3	ABSOLUTE RESIDENCE TIME OF N Y	RELATIVE RESIDENCE TIME OF N	TN/TP RELATIVE TIMES	N/P LOADING RATIO	N/P OUTFLOW RATIO	N/P MEAN CONC. RATIO
MESOTROPHIC										
	111	PAJAK-2	749.33	632.00	.145	.727	.429	18.130	21.550	15.560
	204	MERGOZZO	-0	-0	-0	-0	-0	-0	-0	121.430
	213	OSSIACHE	3226.37	435.14	.522	.272	1.340	45.190	32.210	60.550
	216	HALLENSE	-0	-0	-0	-0	-0	-0	-0	-0
	220	VUS KRIL	564.51	494.96	1.296	.939	.890	23.070	24.020	20.540
	221	VHS GEFS	548.60	542.50	1.470	.942	1.194	23.150	29.010	27.650
	223	MAGGIORE	-0	-0	-0	-0	-0	-0	-0	-0
	224	WALLENSE	-0	-0	-0	-0	-0	-0	-0	-0
	227	LEMAN	-0	-0	-0	-0	-0	-0	-0	6.340
	230	MONTORFA	294.72	-0	-0	-0	-0	4.050	-0	-0
	231	ANNONE	2733.75	-0	-0	-0	-0	3.970	-0	-0
	234	D ANNECY	-0	-0	-0	-0	-0	-0	-0	-0
	237	PAVIN	-0	-0	-0	-0	-0	-0	-0	-0
	303	LOUGH LE	-0	-0	-0	-0	-0	-0	-0	-0
	404	CAYUGA	2256.51	-0	-0	-0	-0	17.670	-0	-0
	418	SAMMAMIS	1322.03	-0	-0	-0	-0	18.570	-0	-0
	427	WEIR	1733.33	-0	-0	-0	-0	18.570	-0	-0
	509	WOLFE	-0	-0	-0	-0	-0	-0	-0	-0
	510	GRAFTON	-0	-0	-0	-0	-0	-0	-0	-0
	514	LTL DEEP	-0	-0	-0	-0	-0	-0	-0	-0
	517	PRESQUIL	-0	-0	-0	-0	-0	-0	-0	-0
	518	WARREN	-0	-0	-0	-0	-0	-0	-0	-0
	519	MEMPH N	-0	-0	-0	-0	-0	-0	-0	-0
	520	MEMPH C	-0	-0	-0	-0	-0	-0	-0	-0
	522	AYLMER	-0	-0	-0	-0	-0	-0	-0	-0
	524	BROMPTON	-0	-0	-0	-0	-0	-0	-0	-0
	525	LOVERING	-0	-0	-0	-0	-0	-0	-0	-0
	527	MASSAWIP	-0	-0	-0	-0	-0	-0	-0	-0
	529	PT BROME	-0	-0	-0	-0	-0	-0	-0	-0
	530	ST FRAN	-0	-0	-0	-0	-0	-0	-0	-0
	534	ROXTON	-0	-0	-0	-0	-0	-0	-0	-0
	536	CAMERON	-0	-0	-0	-0	-0	-0	-0	-0
	541	4-MI	-0	-0	-0	-0	-0	-0	-0	-0
	549	DUDLEY P	-0	-0	-0	-0	-0	-0	-0	-0
	551	HARP	-0	-0	-0	-0	-0	-0	-0	-0
	553	MUSKOKA	-0	-0	-0	-0	-0	-0	-0	-0
	555	SMOKE	-0	-0	-0	-0	-0	-0	-0	-0
	566	CHUB	-0	-0	-0	-0	-0	-0	-0	-0
	568	DICKIE	-0	-0	-0	-0	-0	-0	-0	-0
	569	GULFEATH	-0	-0	-0	-0	-0	-0	-0	-0
	577	MICHIGAN	-0	-0	-0	-0	-0	-0	-0	-0
	580	CB ERIE	-0	-0	-0	-0	-0	-0	-0	-0
	581	ER ERIE	-0	-0	-0	-0	-0	-0	-0	-0
	582	ONTARIO	-0	-0	-0	-0	-0	-0	-0	-0
	594	OKANAGAN	-0	-0	-0	-0	-0	-0	-0	-0
N OF LAKES		45	9	4	4	4	4	9	4	6
MEAN			1492.1278	526.1500	.85840	.72001	.96329	19.17444	26.69750	42.01167
ST DEV			1058.1155	83.1208	.62894	.31517	.40255	12.09978	4.80975	43.10343
MINIMUM			294.72	435.14	.145	.272	.429	3.970	21.550	6.340
MAXIMUM			3226.37	632.00	1.470	.942	1.340	45.190	32.210	121.430

AS.6.1 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR NITROGEN-RELATED VARIABLES AND RATIOS IN NATURAL LAKES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	MEAN INFLOW NITROGEN MG M-3	MEAN OUTFLOW NITROGEN MG M-3	ABSOLUTE RESIDENCE TIME OF N Y	RELATIVE RESIDENCE TIME OF N	TN/TP: RELATIVE TIMES	N/P LOADING RATIO	N/P OUTFLOW RATIO	N/P MEAN CONC. RATIO
EUTROPHIC	(CONT.)									
	533	BROME	-0	-0	-0	-0	-0	-0	-0	-0
	535	WATERLOO	-0	-0	-0	-0	-0	-0	-0	-0
	579	WB ERIE	-0	-0	-0	-0	-0	-0	-0	-0
	590	WINNIPEG	-0	-0	-0	-0	-0	-0	-0	-0
	591	CROOKED	-0	-0	-0	-0	-0	-0	-0	-0
	592	POUND	-0	-0	-0	-0	-0	-0	-0	-0
	595	SKAHA	-0	-0	-0	-0	-0	-0	-0	-0
	596	OSOYOOS	-0	-0	-0	-0	-0	-0	-0	-0
N OF LAKES	67		36	19	19	19	19	44	17	28
MEAN			2666.0617	1236.8168	1.76935	.45609	1.23049	13.52313	20.93526	19.05214
ST DEV			1793.9377	818.3407	2.55837	.24943	.92058	9.57521	15.05395	12.37303
MINIMUM			334.55	319.49	.021	.153	.271	1.020	3.350	3.120
MAXIMUM			6458.06	3619.35	10.490	.987	3.362	46.970	64.050	65.370
TOTAL N OF LAKES	105		59	32	31	31	31	55	32	42
MEAN			2039.1597	989.2322	1.47036	.56592	1.40496	17.05313	29.58000	30.22697
ST DEV			1695.8615	732.7556	2.07832	.27950	1.05782	14.55651	23.07079	27.55961
MINIMUM			142.50	250.24	.021	.153	.271	1.020	3.350	3.120
MAXIMUM			6458.06	3619.35	10.490	1.063	4.927	92.290	116.050	121.430

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A5.6.2  DATA LISTING BY TROPHIC CATEGORY WITH
        BASIC STATISTICS FOR NITROGEN-RELATED
        VARIABLES AND RATIOS IN
        SHALLOW LAKES AND RESERVOIRS.

TROPHIC            LAKE  LAKE NAME   MEAN        MEAN      ABSOLUTE   RELATIVE    TN/TP;      N/P        N/P        N/P
GROUP                     (ABBR)    INFLOW     OUTFLOW    RESIDENCE  RESIDENCE  RELATIVE   LOADING    OUTFLOW   MEAN CONC.
                                   NITROGEN    NITROGEN   TIME OF N  TIME OF N   TIMES      RATIO      RATIO      RATIO
                                    MG M-3      MG M-3        Y

OLIGOTROPHIC

                   602 OLEF             -0     1238.10         -0         -0        -0         -0     114.380         -0
                   605 VEFSE       2886.28     3222.94       .853       .565     1.659     89.350     132.410    148.180
                   605 SOSE             -0          -0         -0         -0        -0         -0          -0         -0
                   608 FURWIGGE    2745.59     1401.93       .235       .590     1.338    146.150     219.500    202.500
                   623 FUPEN            -0          -0         -0         -0        -0         -0          -0         -0
                   635 VECHTEN          -0          -0         -0         -0        -0         -0          -0         -0

N OF LAKES                    5          2           3          2          2         2          2           3          2
  MEAN                         2516.6350   2047.6233     .54433     .57724   1.52334  117.75000   155.43000  175.34000
 ST DEV                          96.4929   1041.6799     .43619     .01767    .19194   40.16367    56.21332   38.41004
MINIMUM                          2746.99     1238.10       .235       .565     1.388     89.350     114.380    148.180
MAXIMUM                          2886.28     3222.94       .853       .590     1.659    146.150     219.500    202.500
```

A5.6.2 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR NITROGEN-RELATED VARIABLES AND RATIOS IN SHALLOW LAKES AND RESERVOIRS.

```
TROPHIC        LAKE  LAKE NAME    MEAN        MEAN      ABSOLUTE   RELATIVE    TN/TP)      N/P        N/P         N/P
 GROUP                (ABBR)     INFLOW     OUTFLOW    RESIDENCE  RESIDENCE   RELATIVE   LOADING    OUTFLOW    MEAN CONC.
                                NITROGEN   NITROGEN    TIME OF N  TIME OF N    TIMES      RATIO      RATIO       RATIO
                                 MG M-3     MG M-3         Y

MESOTROPHIC

               619 MT BOLD      1825.91    1672.27       .296       .759      1.417     10.210     13.870      14.490
               620 PROSPECT      390.93     373.48       .111       .923      1.131     29.260     32.250      33.120
               621 FL BURGI     1094.97     854.57       .390      1.054      2.031     13.690     30.330      27.810

N OF LAKES                    3        3          3          3          3          3          3          3           3
  MEAN                        1103.9367   966.7733     .26565     .91226    1.52626   17.72000   25.48333    25.14000
 ST DEV                        717.5320   656.0247     .14205     .14755     .45593   10.14527   10.10315     9.59770
MINIMUM                        390.93     373.48       .111       .759      1.131     10.210     13.870      14.490
MAXIMUM                       1825.91    1672.27       .390      1.054      2.031     29.260     32.250      33.120
```

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A5.6.2   DATA LISTING BY TROPHIC CATEGORY WITH
         BASIC STATISTICS FOR NITROGEN-RELATED
         VARIABLES AND RATIOS IN
         SHALLOW LAKES AND RESERVOIRS.

TROPHIC               LAKE  LAKE NAME   MEAN        MEAN      ABSOLUTE   RELATIVE     TN/TP:      N/P        N/P         N/P
 GROUP                       (ABBR)    INFLOW     OUTFLOW    RESIDENCE  RESIDENCE   RELATIVE   LOADING    OUTFLOW   MEAN CONC.
                                      NITROGEN   NITROGEN   TIME OF N  TIME OF N     TIMES      RATIO      RATIO      RATIO
                                       MG M-3     MG M-3        Y

EUTROPHIC

                      601 WANBACH           -0          -0        -0         -0          -0         -0         -0         -0
                      603 SOPPE        2800.00     1662.06      .659       .567       2.896     19.210     34.200     55.750
                      604 MOHNE        4797.18     3472.95      .444       .625       3.354     11.653     54.400     37.220
                      607 ENNEPE       5463.93     4192.62      .225       .661       3.305      8.060     13.140     25.770
                      609 DE GROTE     5323.14     3147.02      .250       .568       3.675     10.150     34.710     37.310
                      610 BRIELSE      9518.52     4300.37      .171       .506       1.824      8.000      7.700     15.210
                      611 PETRUSPL     5516.13     5200.00      .072       .525       1.651     16.320     20.720     26.340
                      612 HONGRED      5996.39     5330.88      .145       .691       1.342     12.000     15.370     16.160
                      613 BRAAKMAN    12860.00     8912.60      .255       .474        .997     23.550     30.650     23.450
                      614 BRAAKMAN     6296.10     3034.88      .592       .672       3.055     22.110     55.670     86.000
                      615 TJEUKEME          -0          -0        -0         -0          -0         -0         -0         -0
                      616 QUEEN EL          -0          -0        -0         -0          -0         -0         -0         -0
                      617 FARMCOR           -0          -0        -0         -0          -0         -0         -0         -0
                      618 GRAFHAM           -0          -0        -0         -0          -0         -0         -0         -0
                      622 MISSARON          -0          -0        -0         -0          -0         -0         -0         -0
                      624 BLACKHAW     2387.76          -0        -0         -0          -0     10.540         -0         -0
                      625 CAMELOT      1354.00          -0        -0         -0          -0     13.750         -0         -0
                      626 COX HOLL     3015.79          -0        -0         -0          -0     10.320         -0         -0
                      627 DUTCH HO     6240.00          -0        -0         -0          -0     10.510         -0         -0
                      628 ISLES             -0          -0        -0         -0          -0         -0         -0         -0
                      629 KEEP SCA      702.91          -0        -0         -0          -0      6.900         -0         -0
                      630 KEEP OUT     1492.68          -0        -0         -0          -0      3.430         -0         -0
                      631 REDSTONE     3577.91          -0        -0         -0          -0     11.600         -0         -0
                      632 STEWART      3059.95          -0        -0         -0          -0     11.450         -0         -0
                      633 TWIN VAL     2068.53          -0        -0         -0          -0      9.210         -0         -0
                      634 VIRGINIA    19914.71          -0        -0         -0          -0     13.770         -0         -0
                      636 RIBOUFEL      659.22      779.85     1.713       .625        .407     65.400     74.000     26.600

N OF LAKES                        27        20          10        10         10          10         20         10         10
  MEAN                        5202.3925   4003.0630   .44175     .65523    2.25272   15.26620   35.15000   32.43400
 ST DEV                       4567.4086   2242.5090   .47517     .14865    1.14473   13.08385   21.05435   21.34103
MINIMUM                          659.22      779.85     .072       .474       .407      3.430      7.700     15.210
MAXIMUM                        19914.71     8918.00    1.713       .925      3.675     65.400     74.000     86.000

TOTAL
N OF LAKES                        36        25          15        15         15          15         25         15         15
  MEAN                        4519.6572   3067.1138   .43357     .69624    2.01013   23.75433   55.39025   52.02933
 ST DEV                       4319.2602   2212.1559   .41451     .17482    1.00031   31.81535   56.16236   54.17745
MINIMUM                          390.93      373.48     .092       .474       .407      3.430      7.760     14.490
MAXIMUM                        19914.71     8916.00    1.713      1.054      3.675    146.150    219.500    202.500
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A5.6.3 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR NITROGEN-RELATED VARIABLES AND RATIOS IN UNUSUAL CANADIAN CIRCUMSTANCES.

TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	MEAN INFLOW NITROGEN MG M-3	MEAN OUTFLOW NITROGEN MG M-3	ABSOLUTE RESIDENCE TIME OF N Y	RELATIVE RESIDENCE TIME OF N	TN/TP; RELATIVE TIMES	N/P LOADING RATIO	N/P OUTFLOW RATIO	N/P MEAN CONC. RATIO
OLIGOTROPHIC										
	702	ADVKER	-0	-0	-0	-0	-0	-0	-0	-0
	708	MONTJOIE	-0	-0	-0	-0	-0	-0	-0	-0
	711	STUKELY	-0	-0	-0	-0	-0	-0	-0	-0
	717	226N '73	-0	-0	-0	-0	-0	-0	-0	-0
	718	226N '74	-0	-0	-0	-0	-0	-0	-0	-0
	719	226S '73	-0	-0	-0	-0	-0	-0	-0	-0
	720	226S '74	-0	-0	-0	-0	-0	-0	-0	-0
	721	227 '69	-0	-0	-0	-0	-0	-0	-0	-0
	722	227 '70	-0	-0	-0	-0	-0	-0	-0	-0
	723	227 '71	-0	-0	-0	-0	-0	-0	-0	-0
	724	227 '72	-0	-0	-0	-0	-0	-0	-0	-0
	725	227 '73	-0	-0	-0	-0	-0	-0	-0	-0
	726	227 '74	-0	-0	-0	-0	-0	-0	-0	-0
	727	261 '73	-0	-0	-0	-0	-0	-0	-0	-0
	728	261 '74	-0	-0	-0	-0	-0	-0	-0	-0
	729	302N '72	-0	-0	-0	-0	-0	-0	-0	-0
	730	302N '73	-0	-0	-0	-0	-0	-0	-0	-0
	731	302N '74	-0	-0	-0	-0	-0	-0	-0	-0
	732	304 '71	-0	-0	-0	-0	-0	-0	-0	-0
	733	304 '72	-0	-0	-0	-0	-0	-0	-0	-0
	734	304 '73	-0	-0	-0	-0	-0	-0	-0	-0
	735	304 '74	-0	-0	-0	-0	-0	-0	-0	-0
	741	KAMLOOPS	-0	-0	-0	-0	-0	-0	-0	-0
N OF LAKES		23	0	0	0	0	0	0	0	0
MEAN			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ST DEV			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MINIMUM			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MAXIMUM			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

A5.6.3 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR NITROGEN-RELATED VARIABLES AND RATIOS IN UNUSUAL CANADIAN CIRCUMSTANCES.

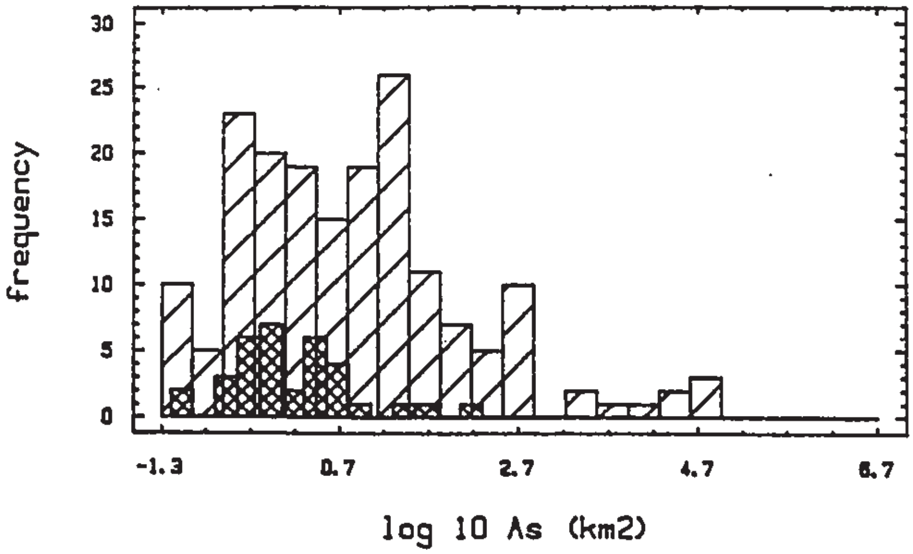
TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	MEAN INFLOW NITROGEN MG M-3	MEAN OUTFLOW NITROGEN MG M-3	ABSOLUTE RESIDENCE TIME OF N Y	RELATIVE RESIDENCE TIME OF N	TN/TP: RELATIVE TIMES	N/P LOADING RATIO	N/P OUTFLOW RATIO	N/P MEAN CONC. RATIO
MESOTROPHIC										
	702	AYLMER	-0	-0	-0	-0	-0	-0	-0	-0
	704	BROMPTON	-0	-0	-0	-0	-0	-0	-0	-0
	705	LOVERING	-0	-0	-0	-0	-0	-0	-0	-0
	707	MASSAWPI	-0	-0	-0	-0	-0	-0	-0	-0
	709	PT BROMP	-0	-0	-0	-0	-0	-0	-0	-0
	710	ST FRAN	-0	-0	-0	-0	-0	-0	-0	-0
	714	ROXTON	-0	-0	-0	-0	-0	-0	-0	-0
	740	SABINE	-0	-0	-0	-0	-0	-0	-0	-0
	742	KOOTN'76	-0	-0	-0	-0	-0	-0	-0	-0
	743	KOOTN'77	-0	-0	-0	-0	-0	-0	-0	-0
	745	OKANG'77	-0	-0	-0	-0	-0	-0	-0	-0
	746	OKANE'78	-0	-0	-0	-0	-0	-0	-0	-0
N OF LAKES		12	0	0	0	0	0	0	0	0
MEAN			*	*	*	*	*	*	*	*
ST DEV			*	*	*	*	*	*	*	*
MINIMUM			*	*	*	*	*	*	*	*
MAXIMUM			*	*	*	*	*	*	*	*

A5.6.3 DATA LISTING BY TROPHIC CATEGORY WITH BASIC STATISTICS FOR NITROGEN-RELATED VARIABLES AND RATIOS IN UNUSUAL CANADIAN CIRCUMSTANCES.

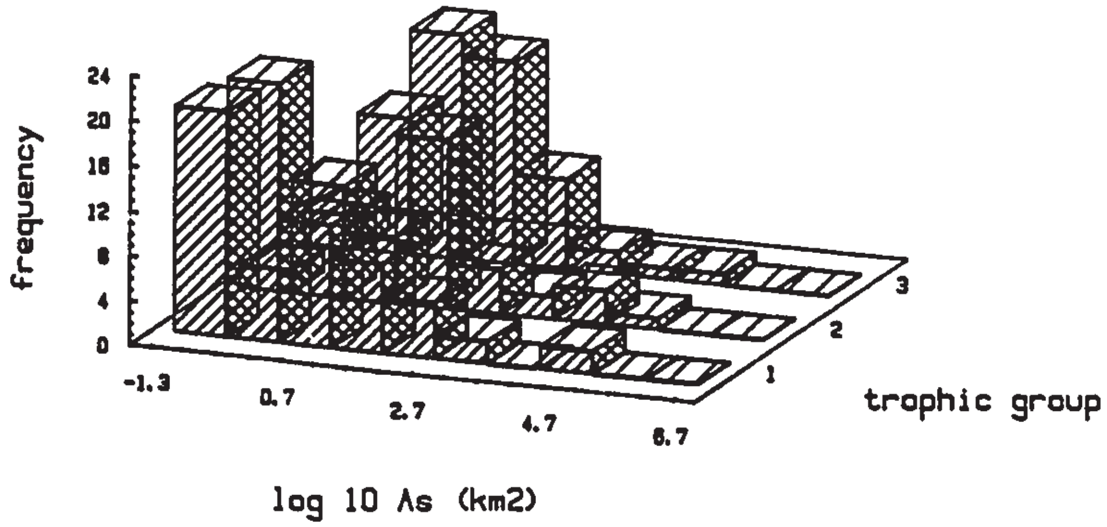
TROPHIC GROUP	LAKE	LAKE NAME (ABBR)	MEAN INFLOW NITROGEN MG M-3	MEAN OUTFLOW NITROGEN MG M-3	ABSOLUTE RESIDENCE TIME OF N Y	RELATIVE RESIDENCE TIME OF N	TN/TP: RELATIVE TIMES	N/P LOADING RATIO	N/P OUTFLOW RATIO	N/P MEAN CONC. RATIO
EUTROPHIC										
	701	PINK	-0	-0	-0	-0	-0	-0	-0	-0
	706	MAGOG	-0	-0	-0	-0	-0	-0	-0	-0
	712	MCIVIN	-0	-0	-0	-0	-0	-0	-0	-0
	713	BROME	-0	-0	-0	-0	-0	-0	-0	-0
	715	WATERLOO	-0	-0	-0	-0	-0	-0	-0	-0
	716	LT OTTER	-0	-0	-0	-0	-0	-0	-0	-0
	736	PASQUA	-0	-0	-0	-0	-0	-0	-0	-0
	737	ECHO	-0	-0	-0	-0	-0	-0	-0	-0
	738	MISSION	-0	-0	-0	-0	-0	-0	-0	-0
	739	KATEPWA	-0	-0	-0	-0	-0	-0	-0	-0
	744	WOLF	-0	-0	-0	-0	-0	-0	-0	-0
	747	SKAHA'77	-0	-0	-0	-0	-0	-0	-0	-0
	748	SKAHA'78	-0	-0	-0	-0	-0	-0	-0	-0
	749	OSOOY'77	-0	-0	-0	-0	-0	-0	-0	-0
	750	OSOOY'78	-0	-0	-0	-0	-0	-0	-0	-0
	751	GRAVAH B	-0	-0	-0	-0	-0	-0	-0	-0
N OF LAKES		16	0	0	0	0	0	0	0	0
MEAN			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ST DEV			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MINIMUM			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MAXIMUM			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL N OF LAKES		51	0	0	0	0	0	0	0	0
MEAN			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ST DEV			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MINIMUM			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MAXIMUM			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Appendix 6. Histograms for 48 variables: a) Natural lakes vs Shallow Lakes and Reservoirs and b) trophic groups.

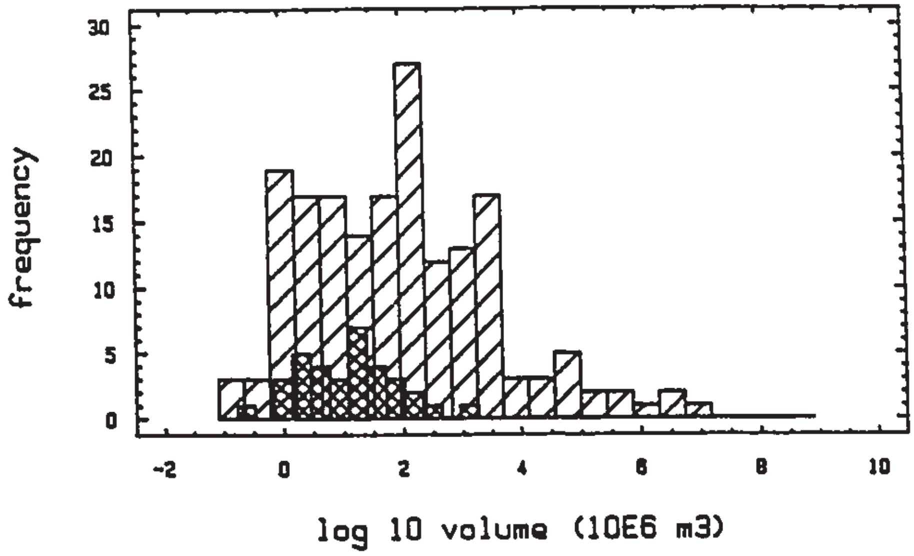
A6.1 a Surface area distribution in all waterbodies.



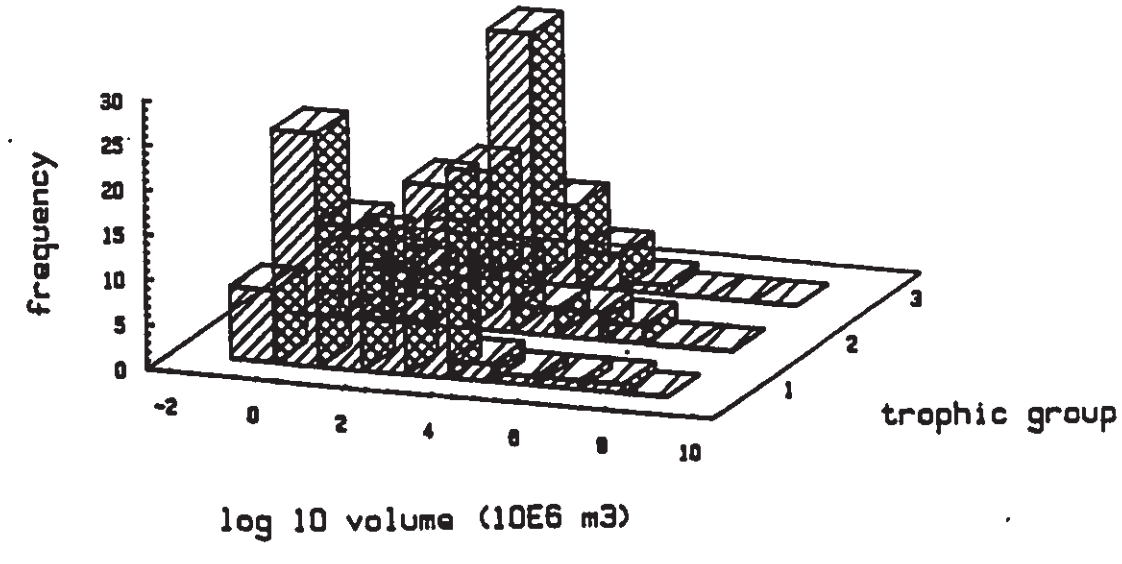
A6.1 b Surface area with trophic breakdown (1 oligo., 2 meso., 3 eu.).



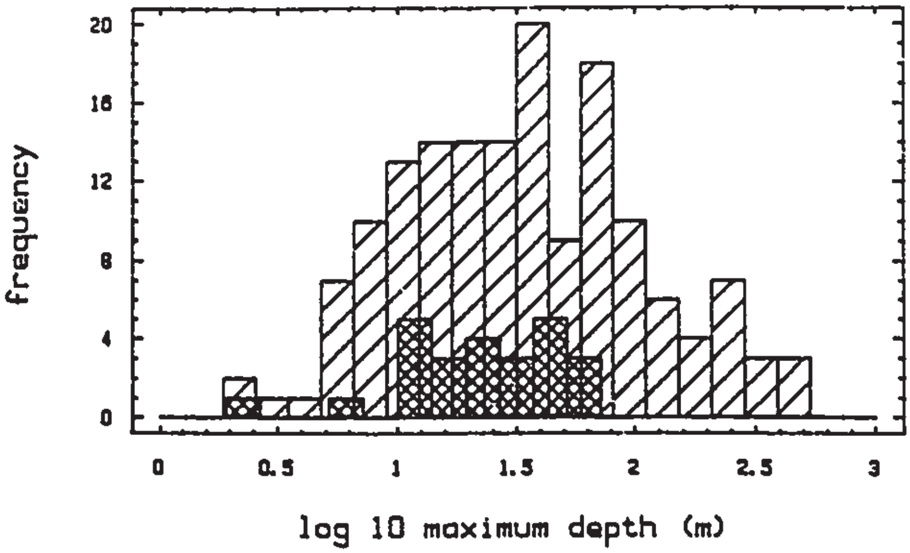
A6.2 a Volume distribution in all waterbodies.



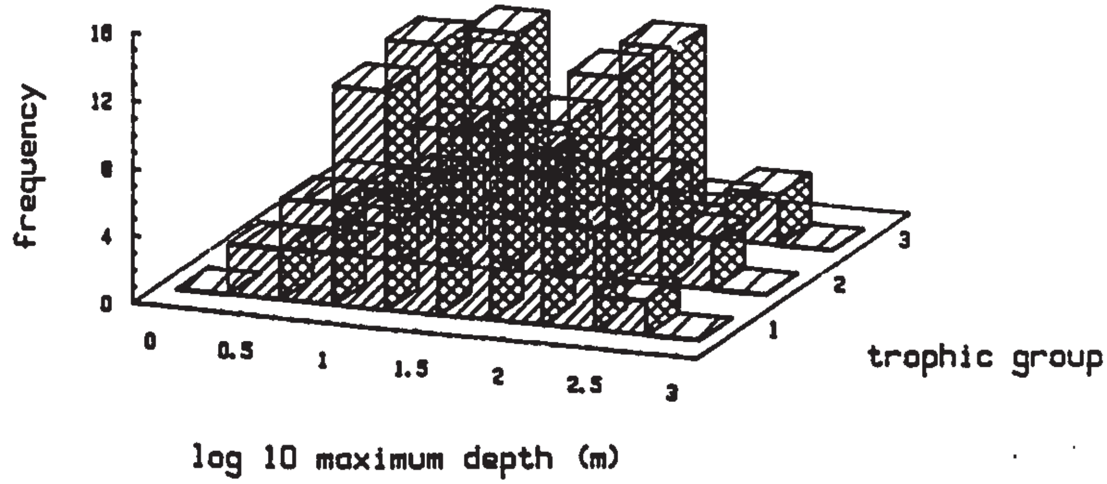
A6.2 b Volume with trophic breakdown (1 olig., 2 meso., 3 eu.).



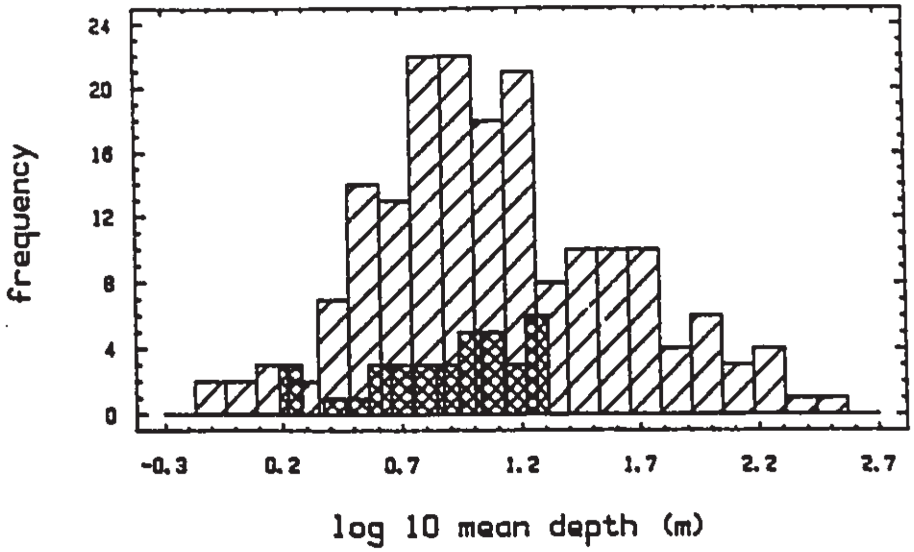
A6.3 a Maximum depth distribution in all waterbodies (xx = SLR).



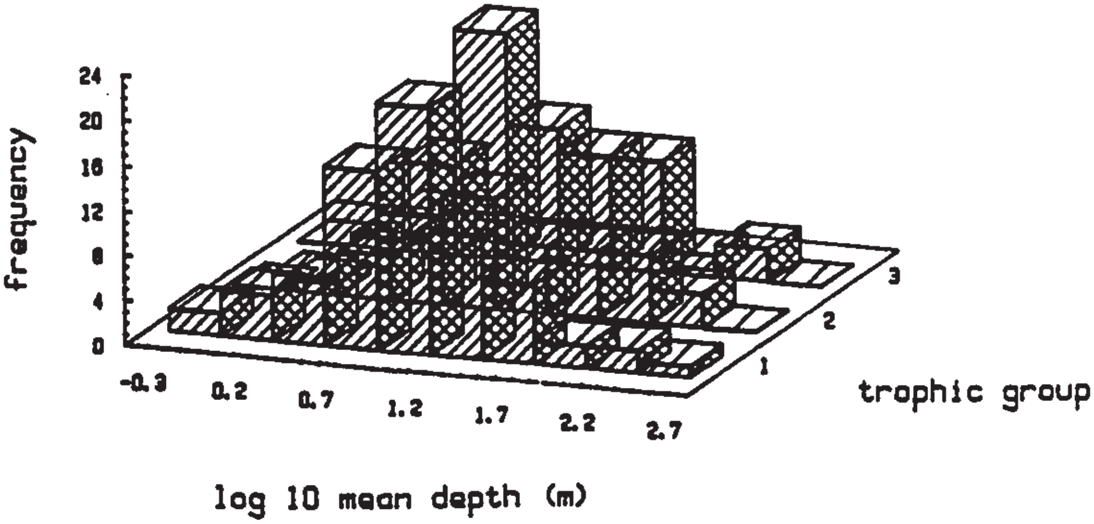
A6.3 b Maximum depth with trophic breakdown (1 oligo., 2 meso., 3 eu.).



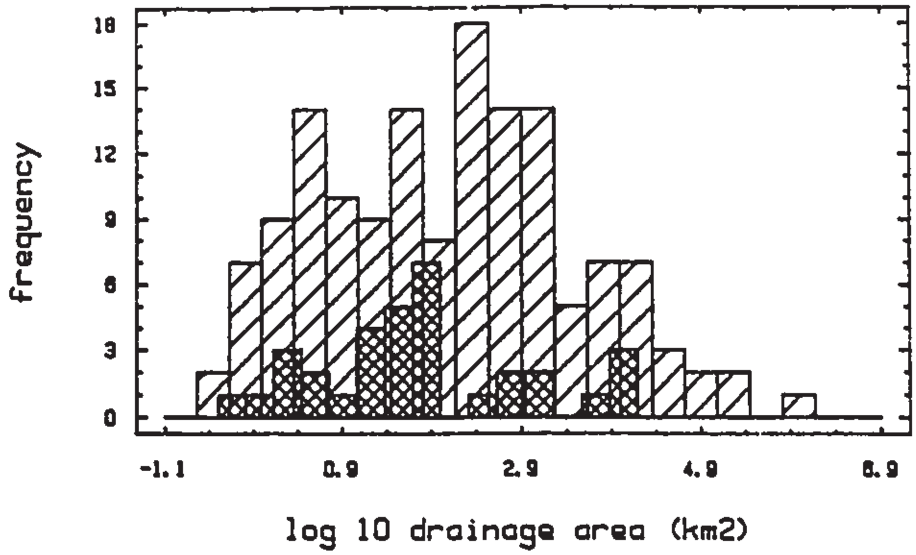
A6.4 a Mean depth distribution in all waterbodies (xx = SLR).



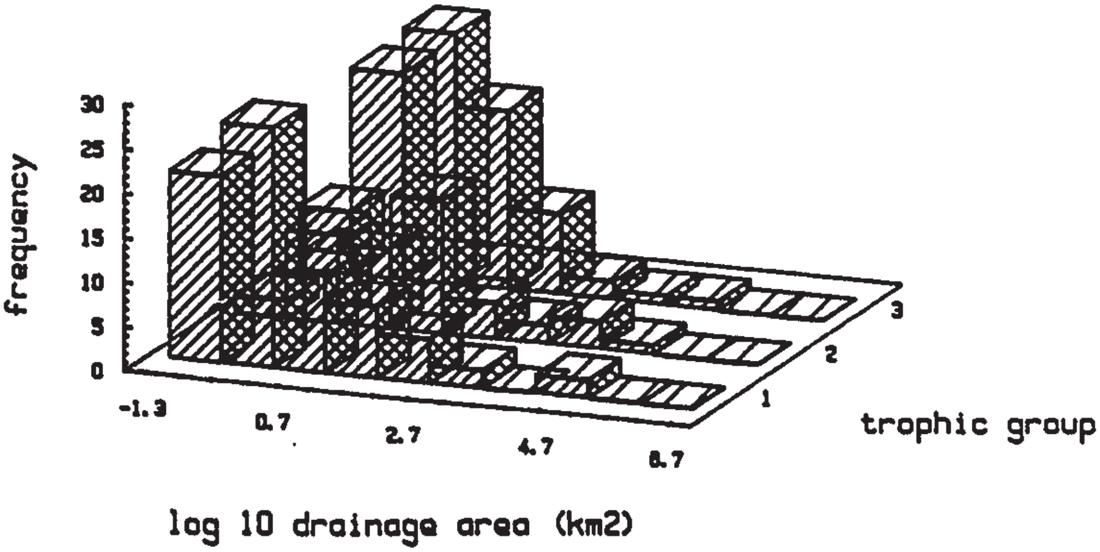
A6.4 b Mean depth with trophic breakdown (1 oligo., 2 meso., 3 eu.).



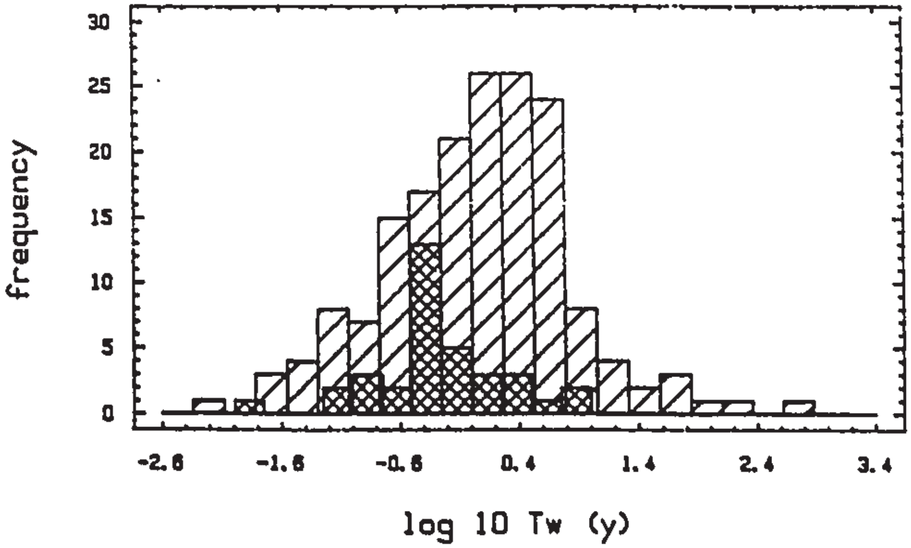
A6.5 a Drainage basin area distribution in all waterbodies (xx = SLR).



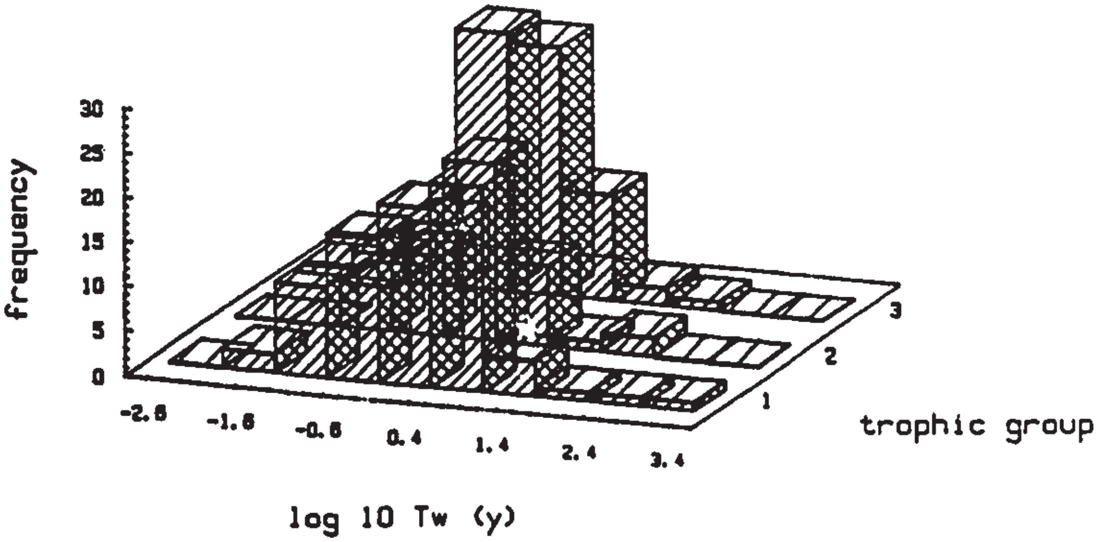
A6.5 b Drainage basin area with trophic breakdown (1 oligo., 2 meso., 3 eu.).



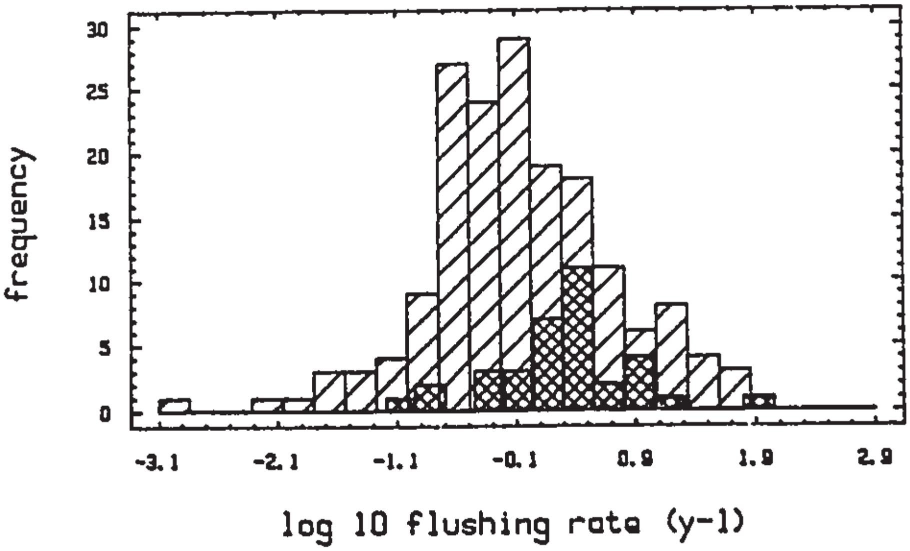
A6.6 a Water residence time in all waterbodies (xx = SLR).



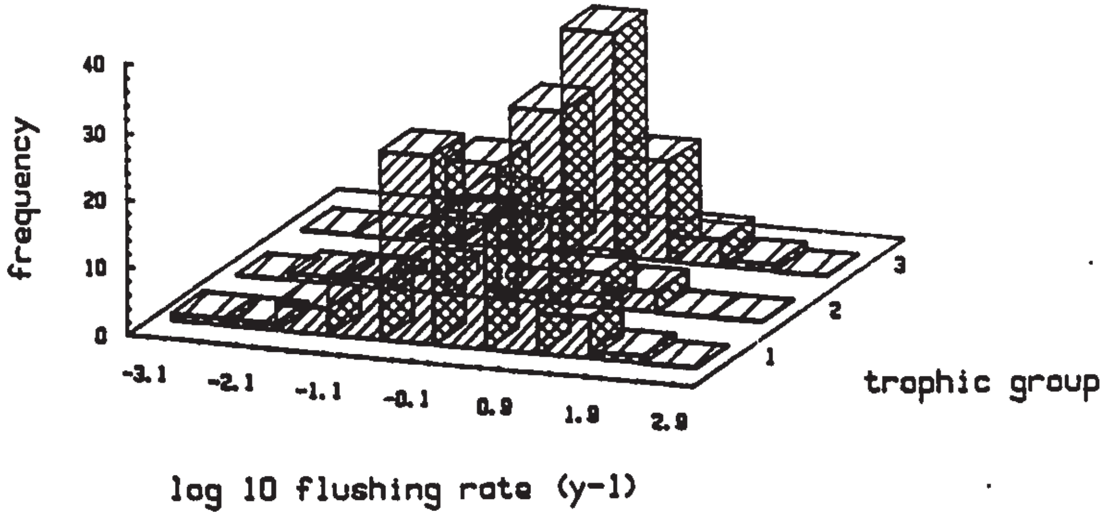
A6.6 b Water residence time with trophic breakdown (1 oligo., 2 meso., 3 eu.).



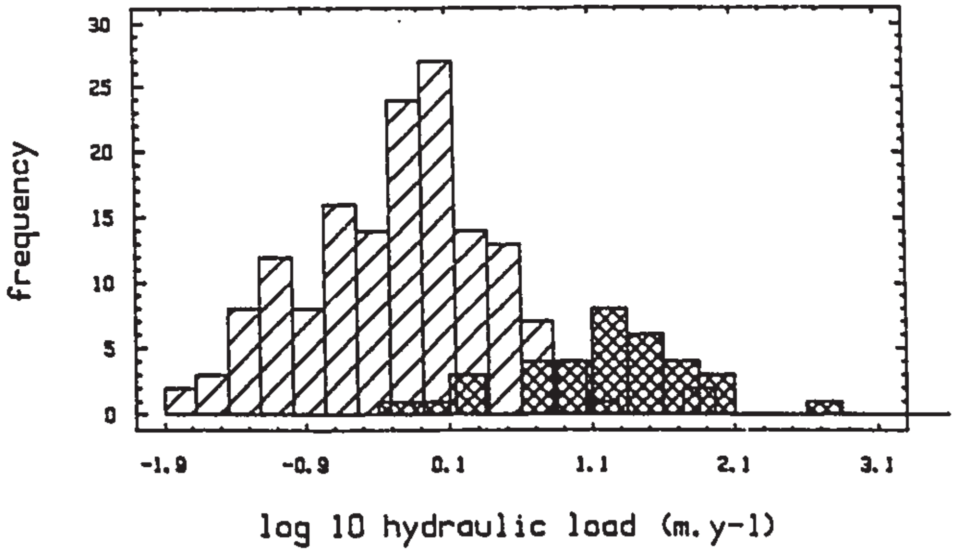
A6.7 a Flushing rate distribution in all waterbodies (xx = SLR).



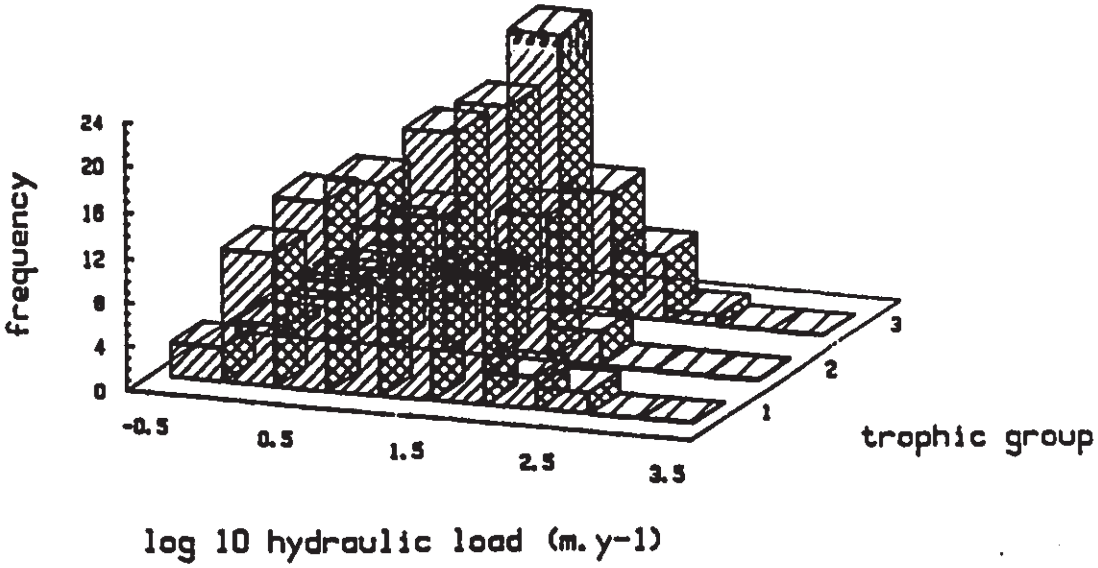
A6.7 b Flushing rate with trophic breakdown (1 oligo., 2 meso., 3 eu.).



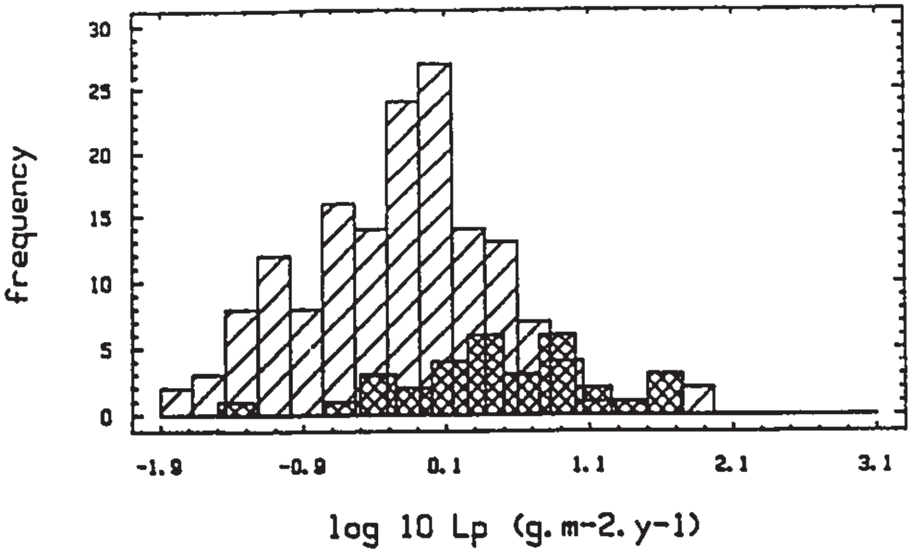
A6.8 a Hydraulic load distribution in all waterbodies (xx = SLR).



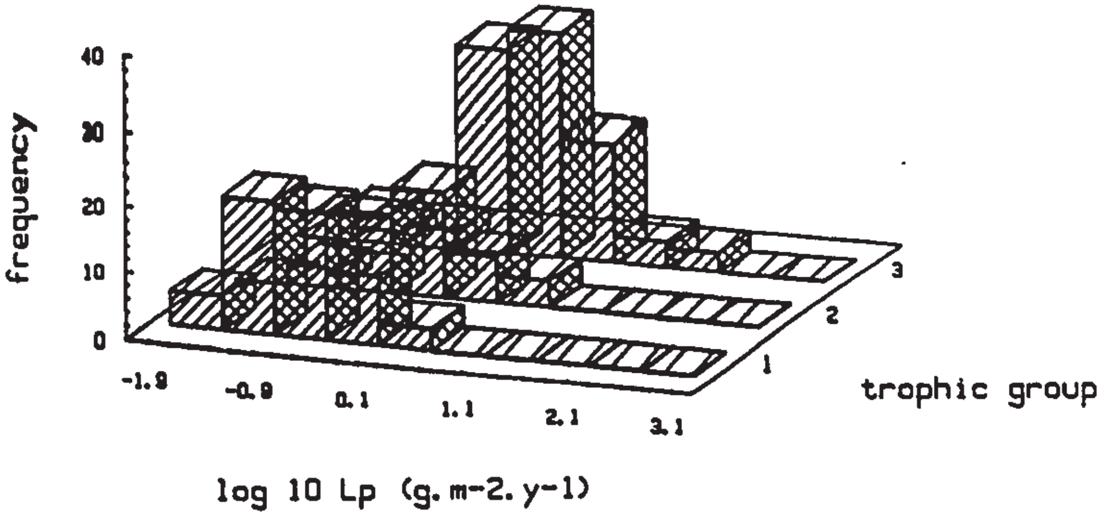
A6.8 b Hydraulic load with trophic breakdown (1 oligo., 2 meso., 3 eu.).



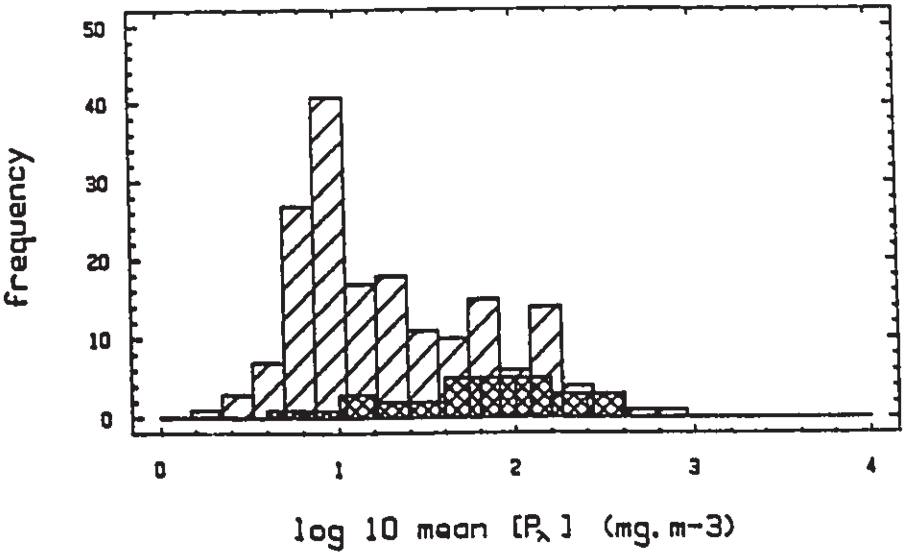
A6.9 a Phosphorus load distribution in all waterbodies (xx = SLR).



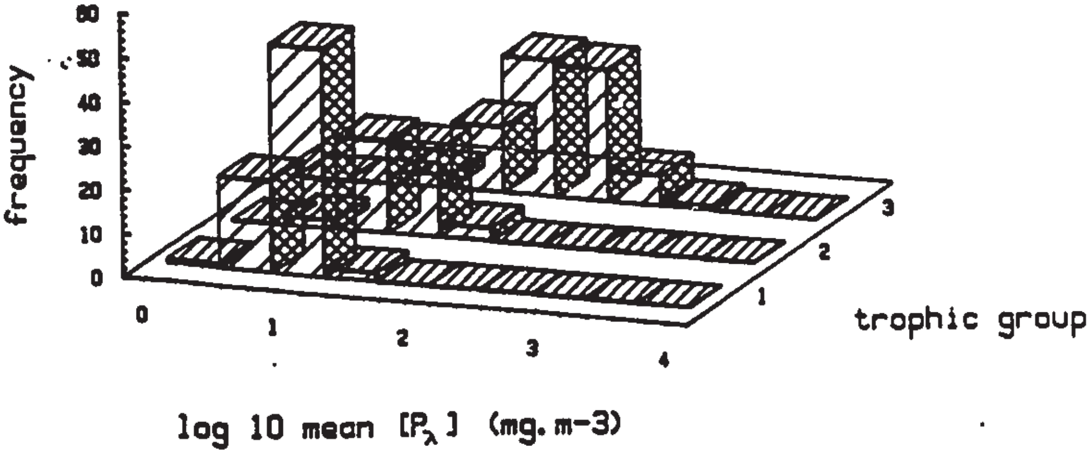
A6.9 b Phosphorus load with trophic breakdown (1 oligo., 2 meso., 3 eu.).



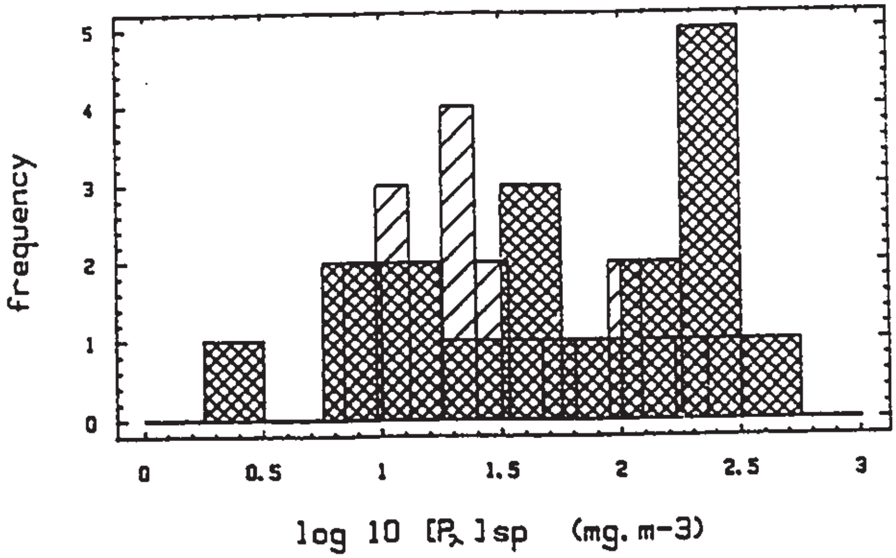
A6.10 a Annual mean [P_λ] distribution in all waterbodies (xx = SLR).



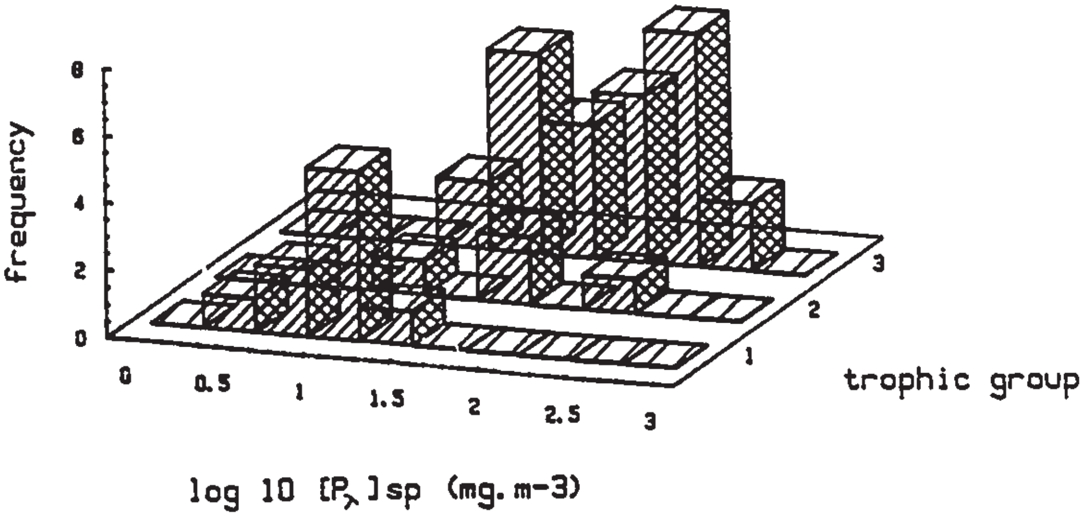
A6.10 b Annual mean [P_λ] with trophic breakdown (1 oligo., 2 meso., 3 eu.).



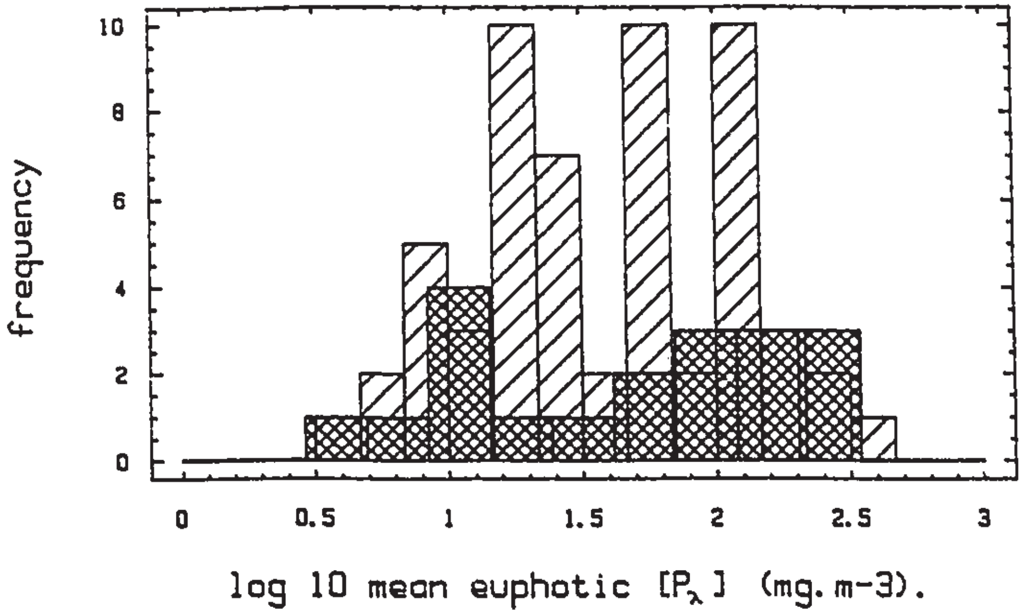
A6.11 a Spring turnover [P_λ] distribution in all waterbodies (xx = SLR).



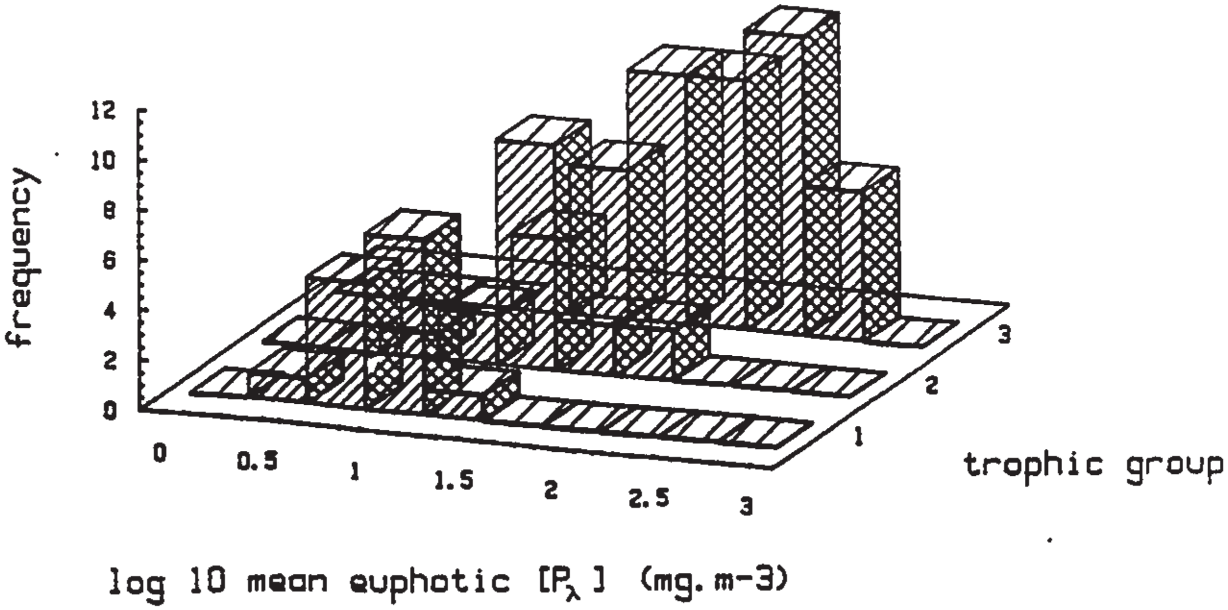
A6.11 b Spring turnover [P_λ] with trophic breakdown (1 oligo., 2 meso., 3 eu.).



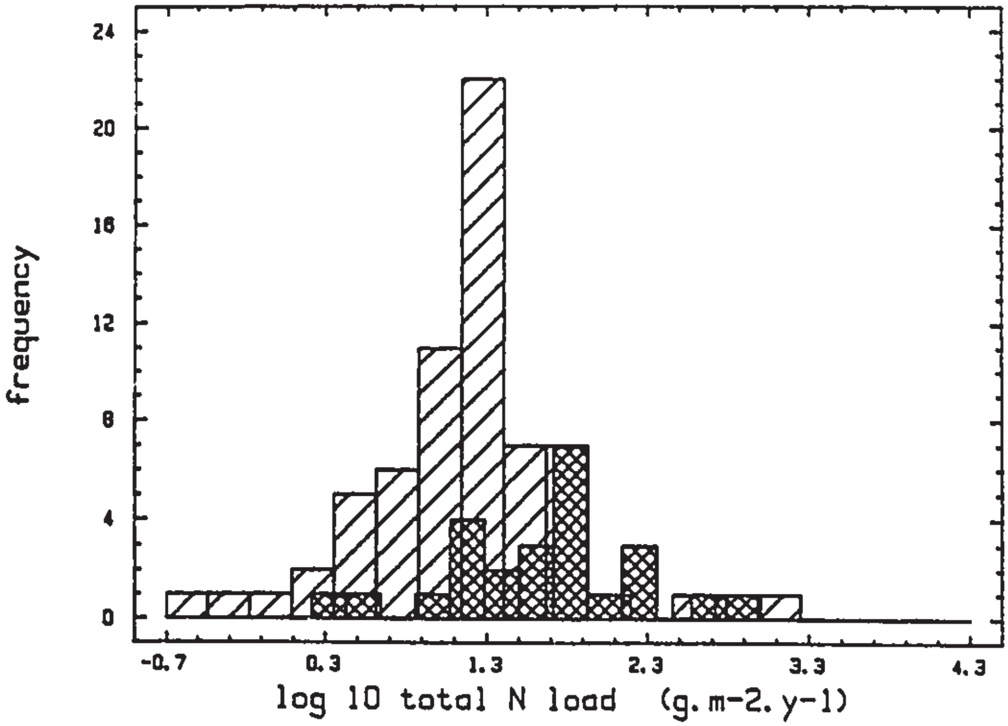
A6.12 a Annual mean euphotic [P_λ] distribution in all waterbodies (xx = SLR).



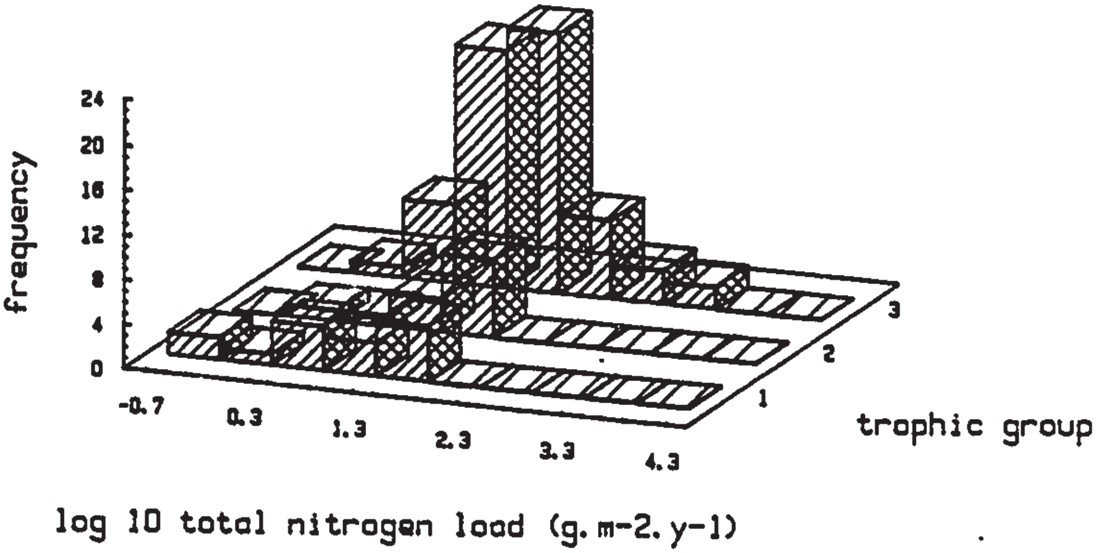
A6.12 b Annual euphotic [P_λ] with trophic breakdown (1 oligo., 2 meso., 3 eu.).



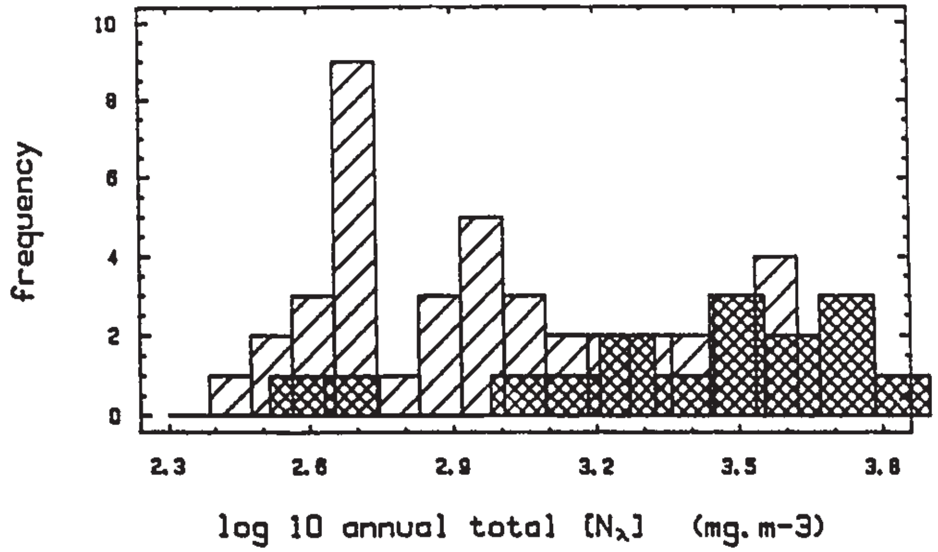
A6.13 a Total N load distribution in all waterbodies (xx = SLR).



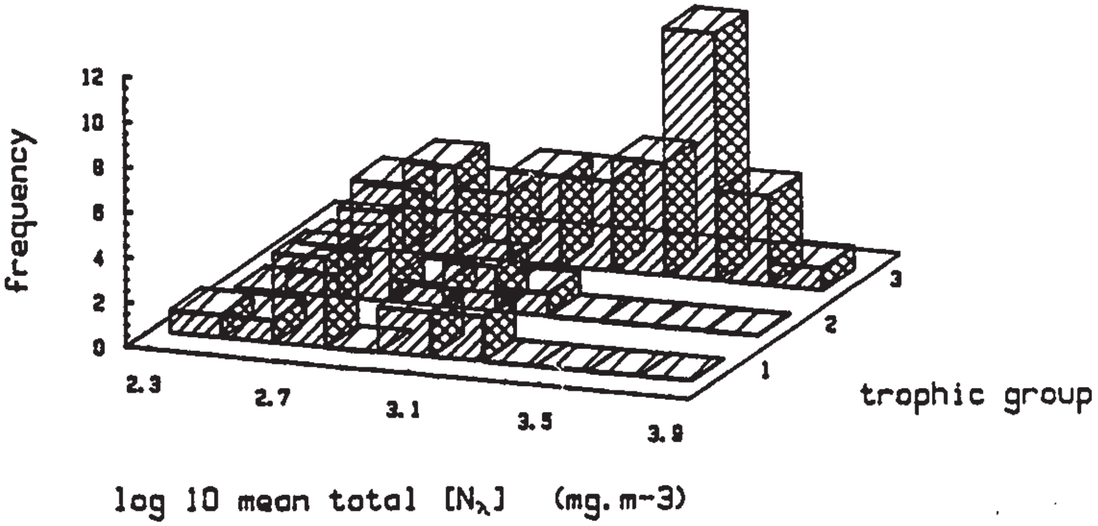
A6.13 b Total N load with trophic break down (1 oligo., 2 meso., 3 eu.).



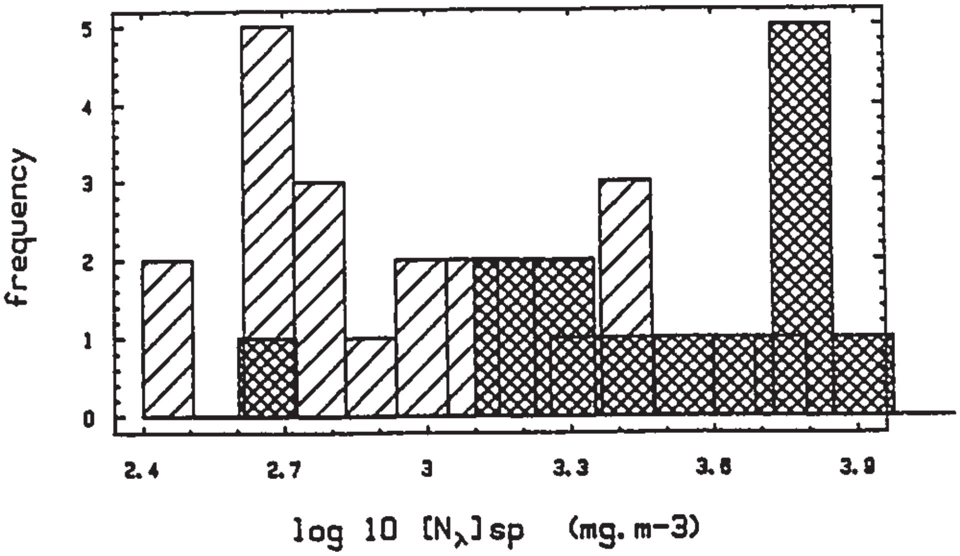
A6.14 a Annual total [N_λ] distribution in all waterbodies (xx = SLR).



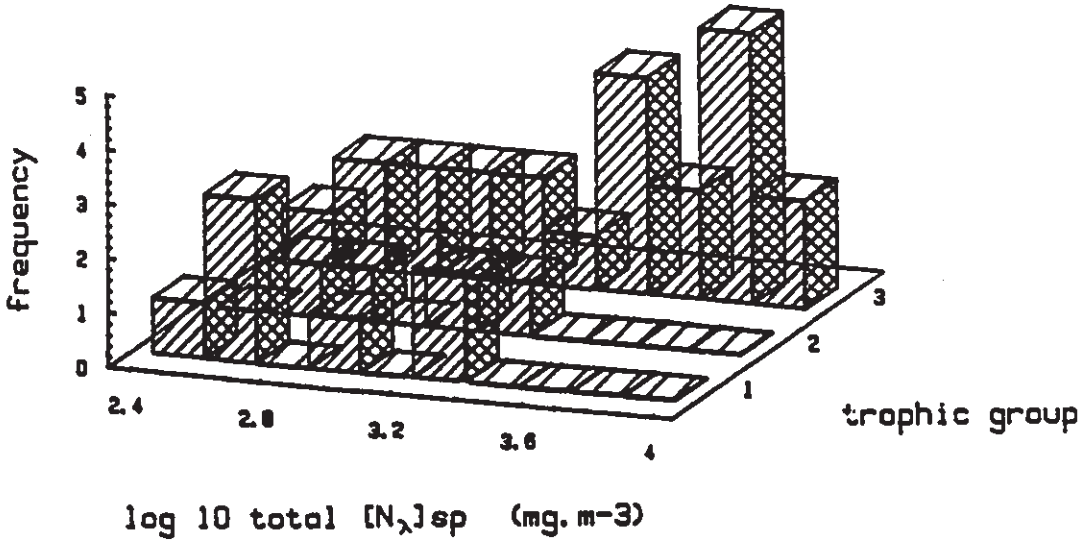
A6.14 b Annual mean total [N_λ] with trophic breakdown (1 oligo., 2 meso., 3 eu.).



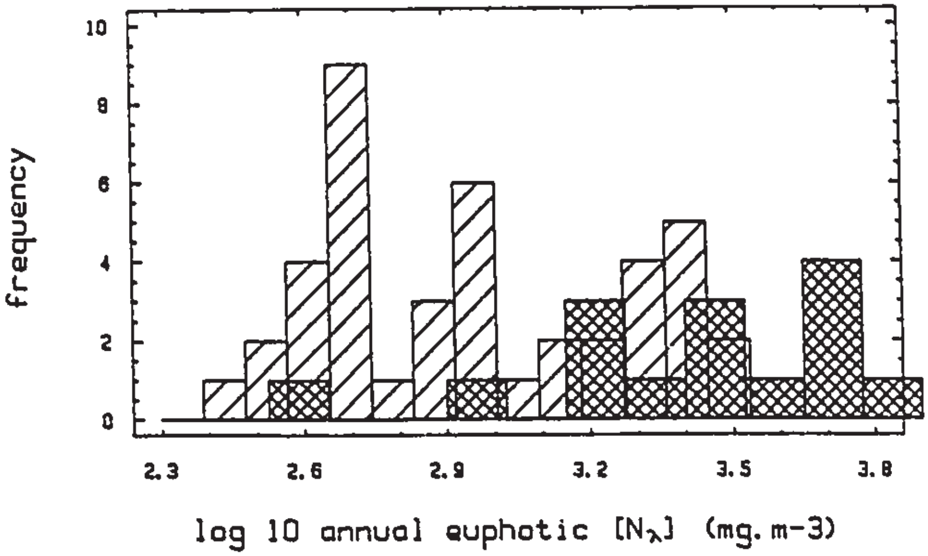
A6.15 a Spring turnover [N_λ] distribution in all waterbodies (xx = SLR).



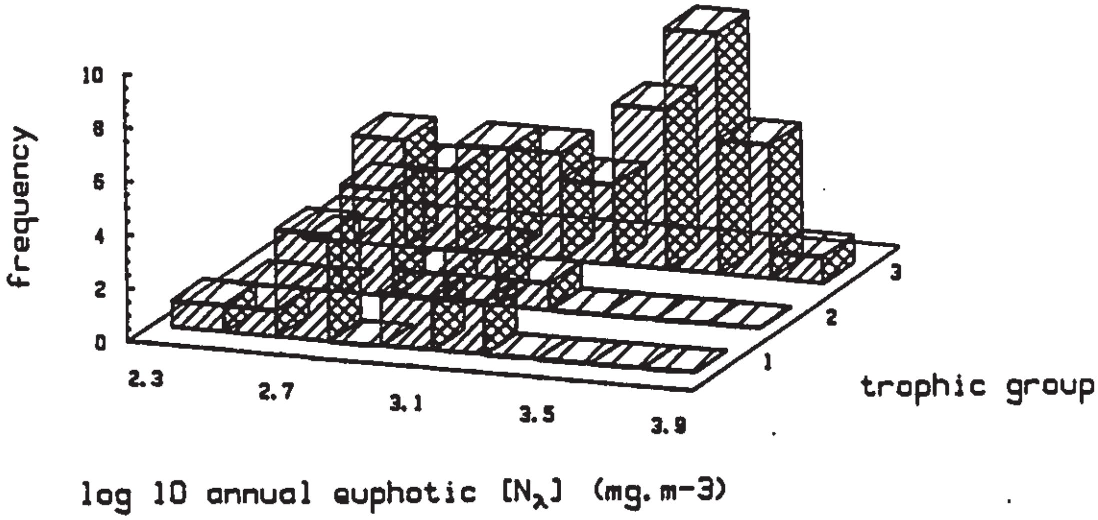
A6.15 b Spring turnover [N_λ] with trophic breakdown (1 oligo., 2 meso., 3 eu.).



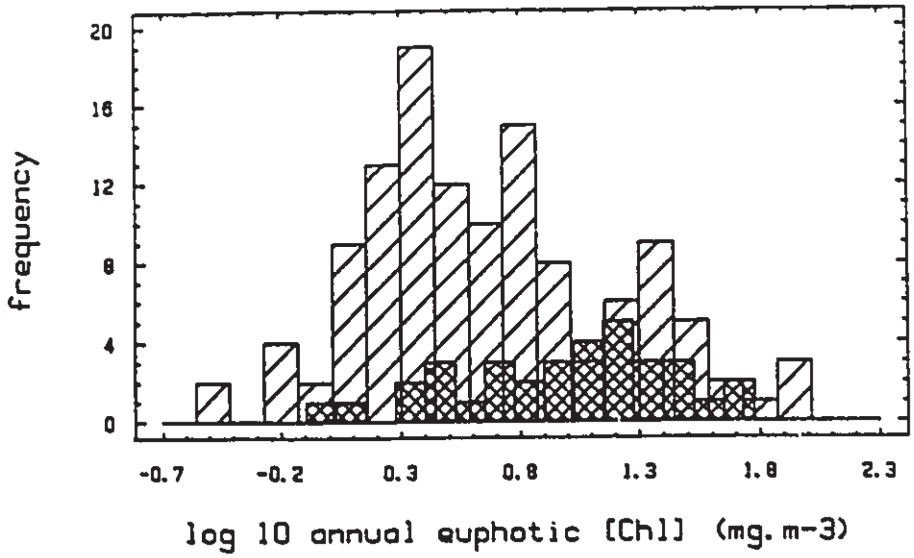
A6.16 a Annual euphotic $[N_\lambda]$ distribution in all waterbodies (xx = SLR).



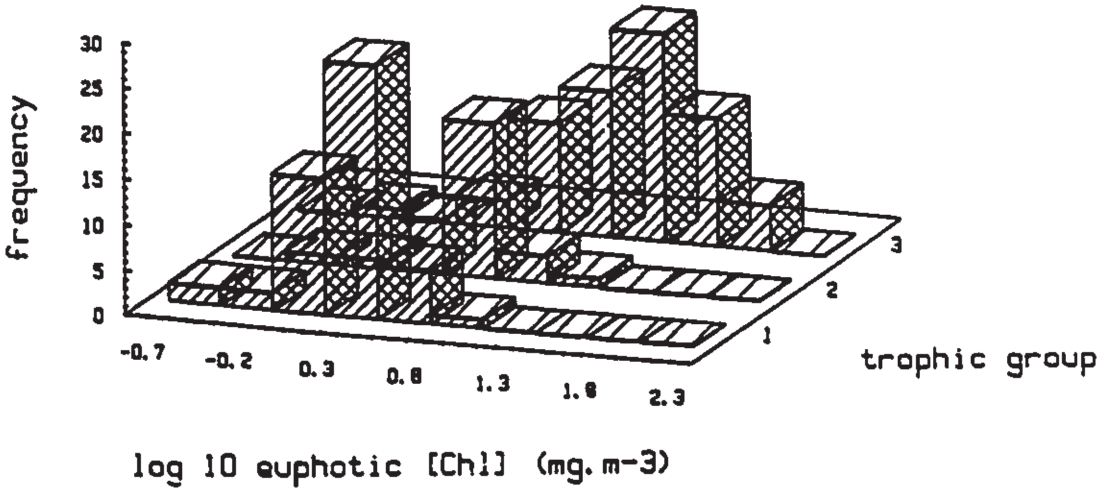
A6.16 b Annual euphotic $[N_\lambda]$ with trophic breakdown (1 oligo., 2 meso., 3 eu.).



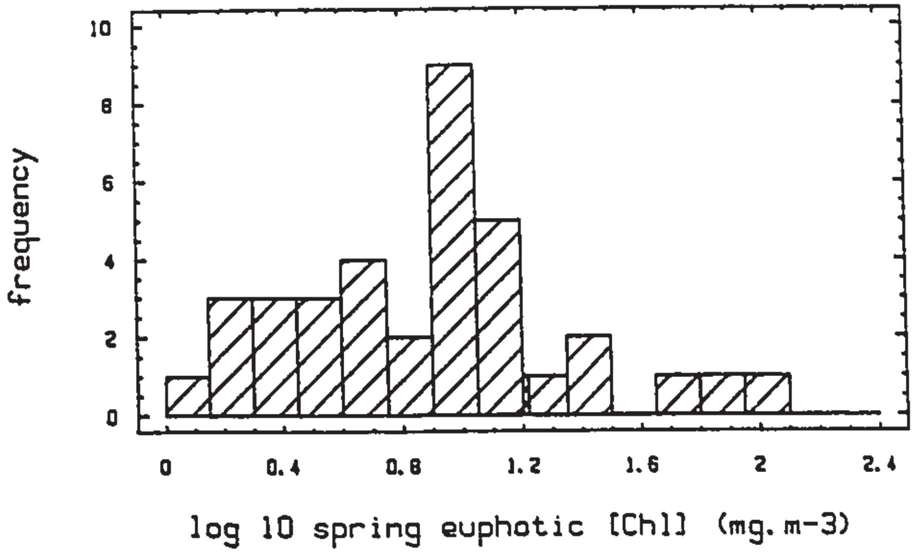
A6.17 a Annual euphotic [Chl] distribution in all waterbodies (xx = SLR).



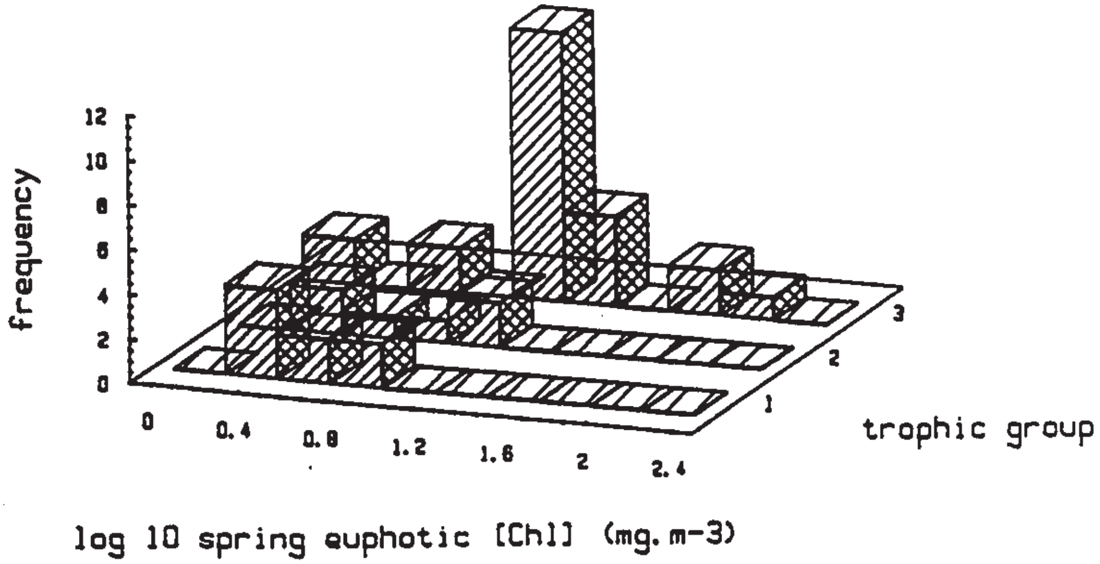
A6.17 b Annual euphotic [Chl] with trophic breakdown (1 oligo., 2 meso., 3 eu.).



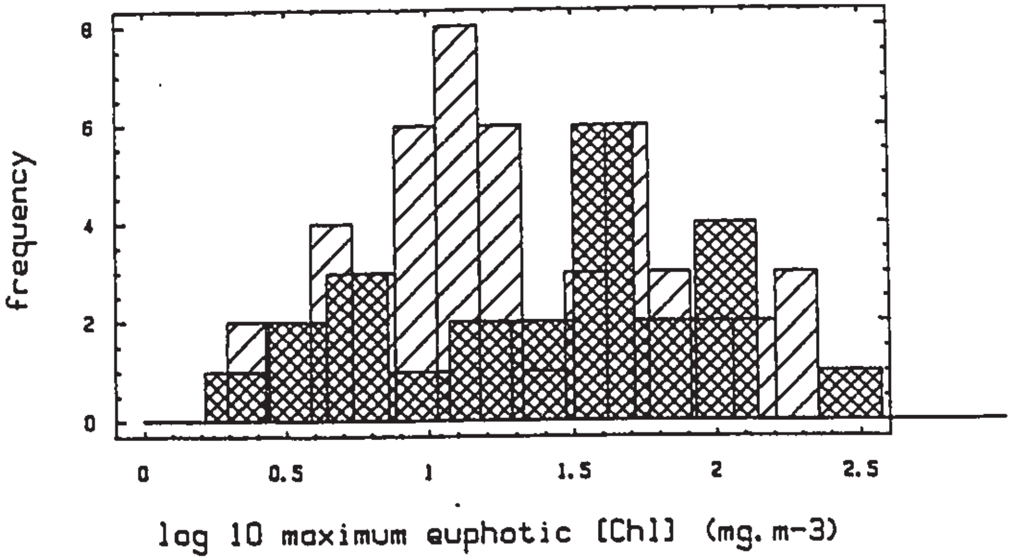
A6.18 a Spring euphotic [Chl] distribution in all waterbodies (xx = SLR).



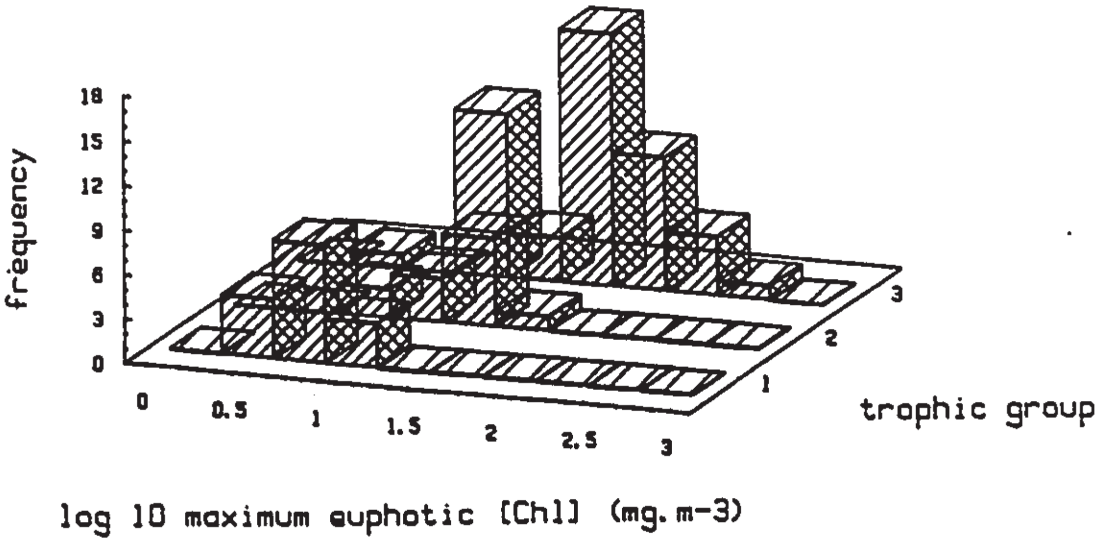
A6.18 b Spring euphotic [Chl] with trophic breakdown (1 oligo., 2 meso., 3 eu.).



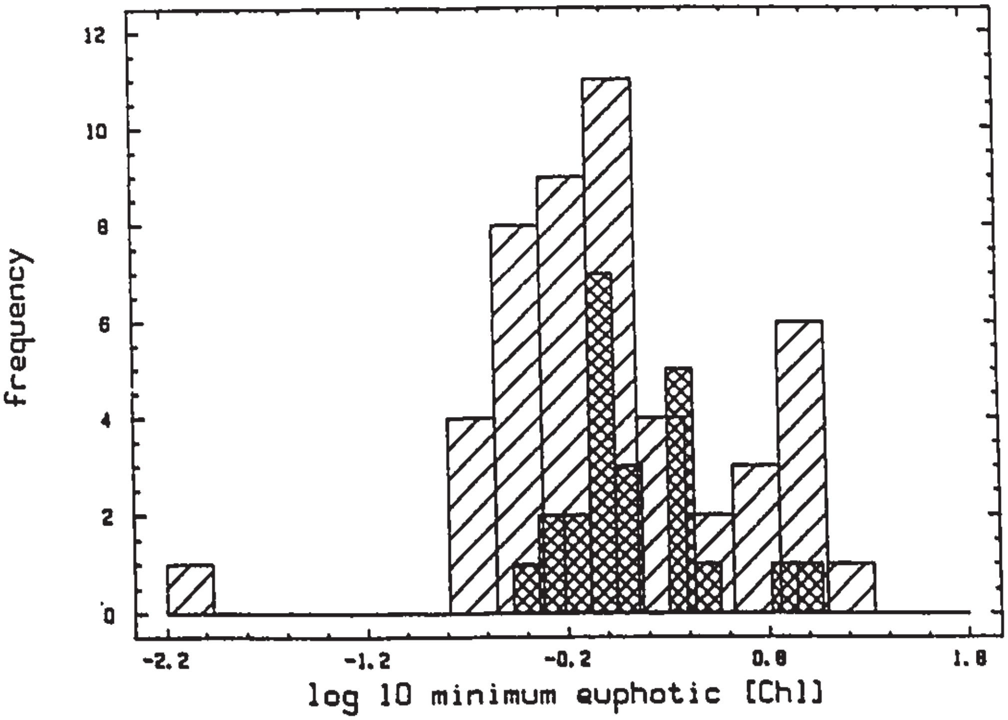
A6.19 a Maximum euphotic [Chl] distribution in all waterbodies (xx = SLR).



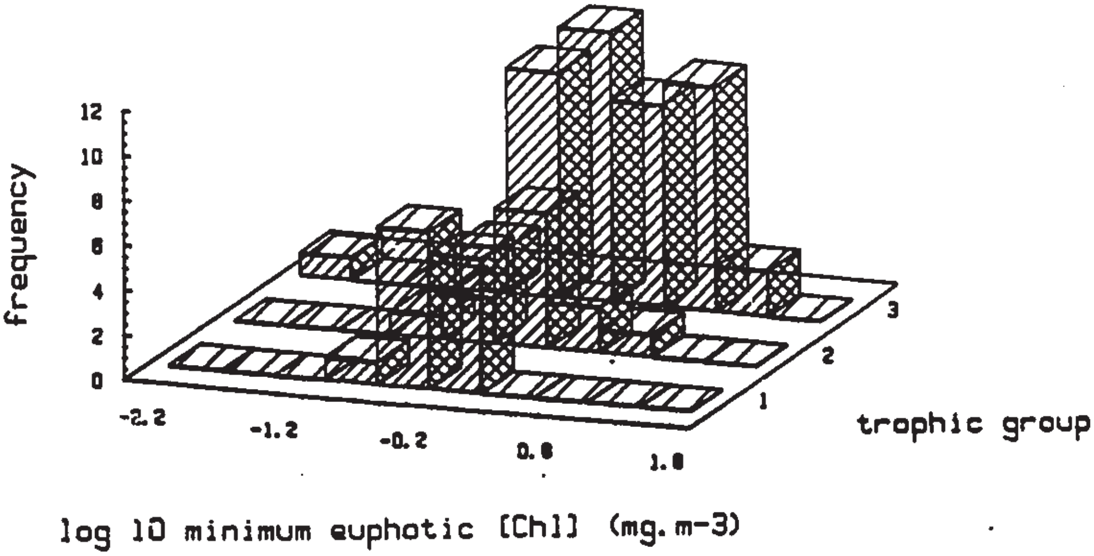
A6.19 b Maximum euphotic [Chl] with trophic breakdown (1 oligo., 2 meso., 3 eu.).



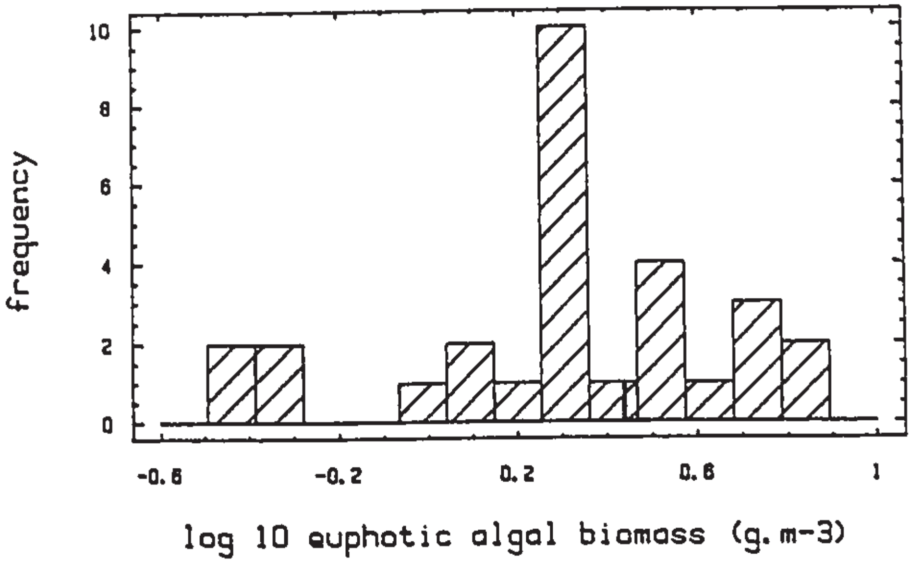
A6.20 a Minimum euphotic [Chl] distribution in all waterbodies (xx = SLR).



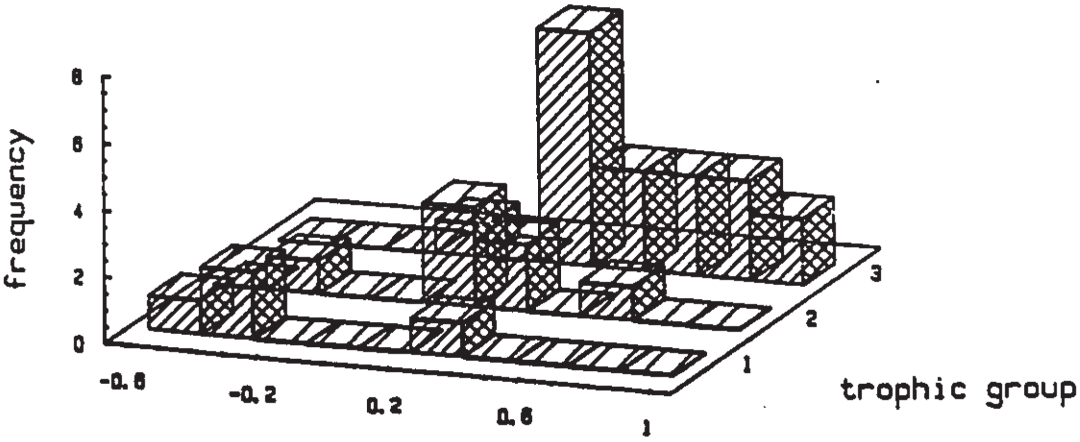
A6.20 b Minimum euphotic [Chl] with trophic breakdown (1 oligo., 2 meso., 3 eu.).



A6.21 a Annual euphotic algal biomass distribution in all waterbodies(xx=SLR).

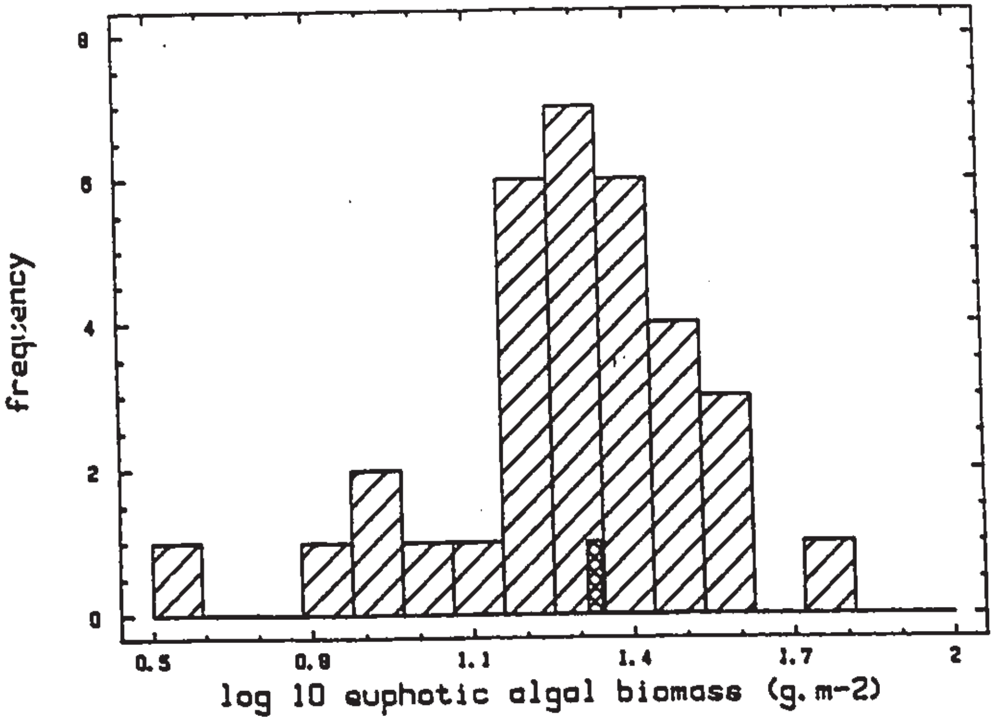


A6.21 b Annual euphotic algal biomass with trophic breakdown (1olig, 2meso, 3eu)

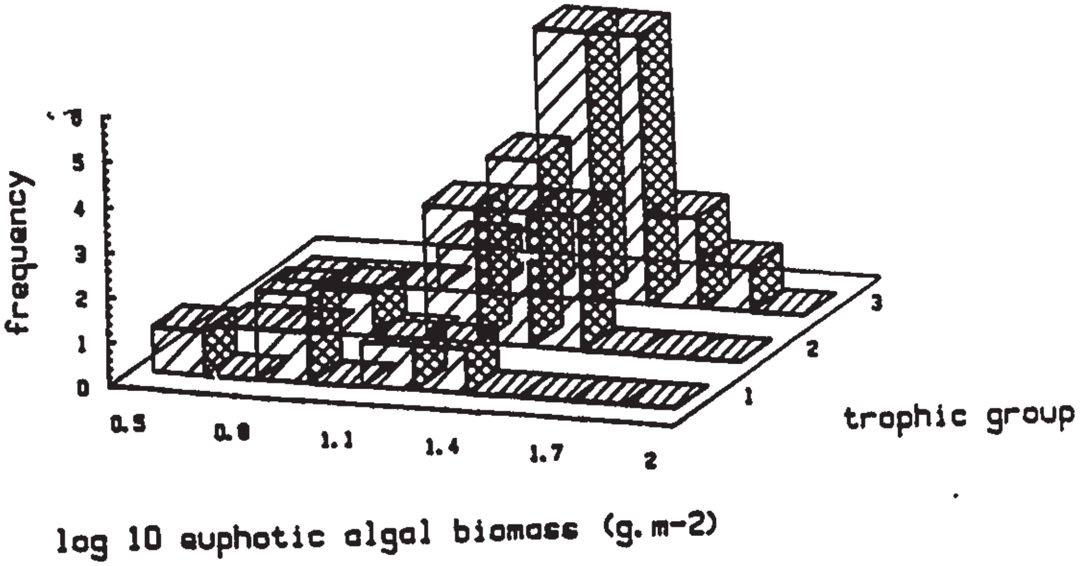


log 10 euphotic algal biomass (g.m-3)

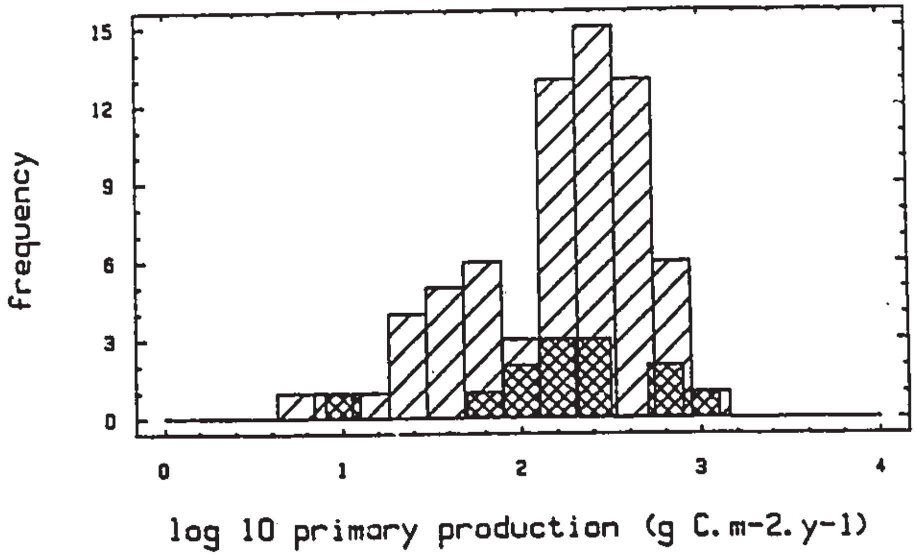
A6.22 a Areal euphotic algal biomass distribution in all waterbodies(xx=SLR).



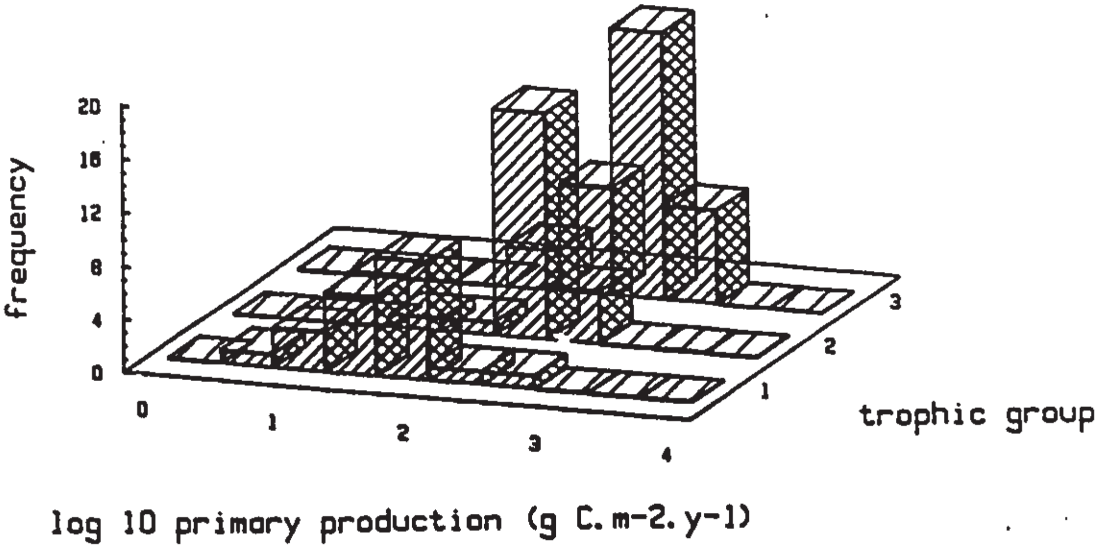
A6.22 b Areal euphotic algal biomass with trophic breakdown(1olig.2meso.3eu).



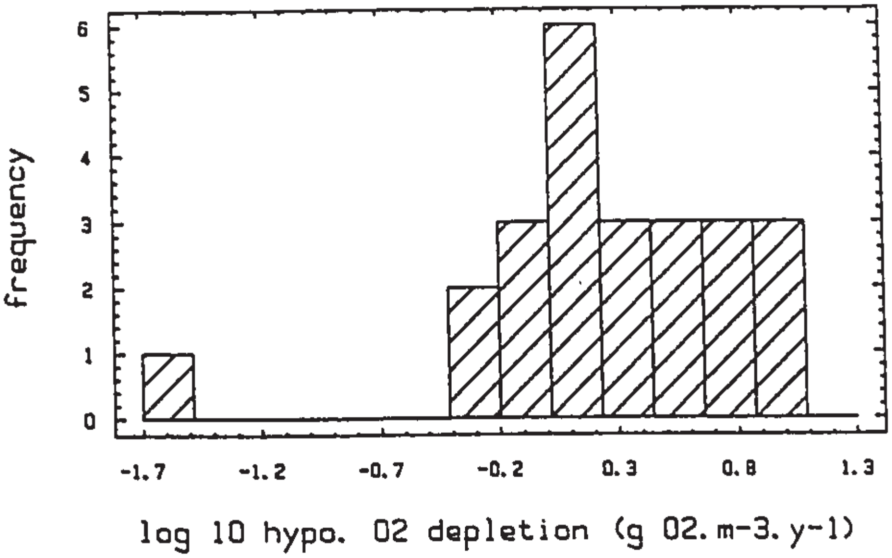
A6.23 a Areal primary production distribution in all waterbodies (xx = SLR).



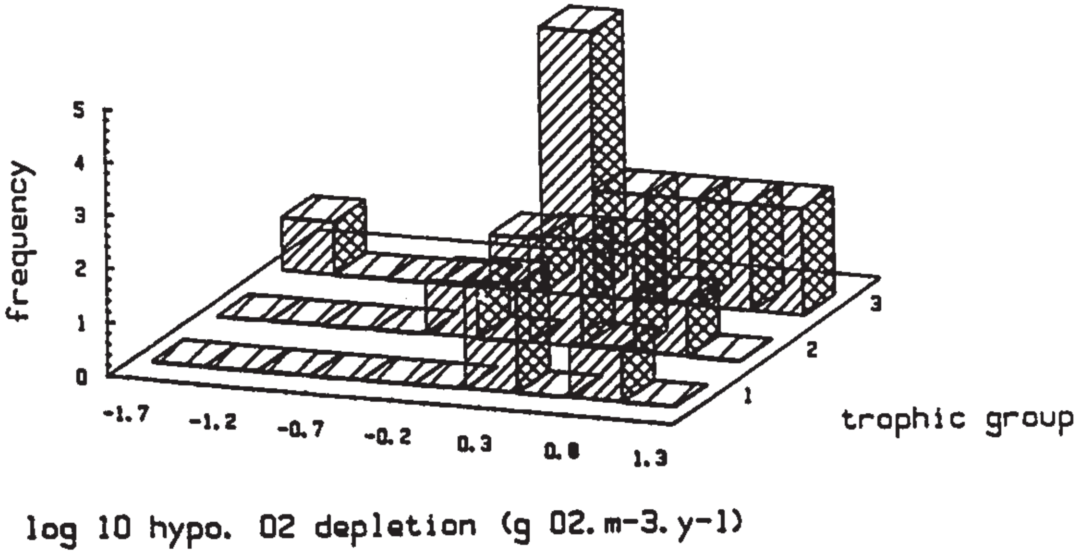
A6.23 b Mean primary production with trophic breakdown (1 oligo, 2 meso, 3 eu).



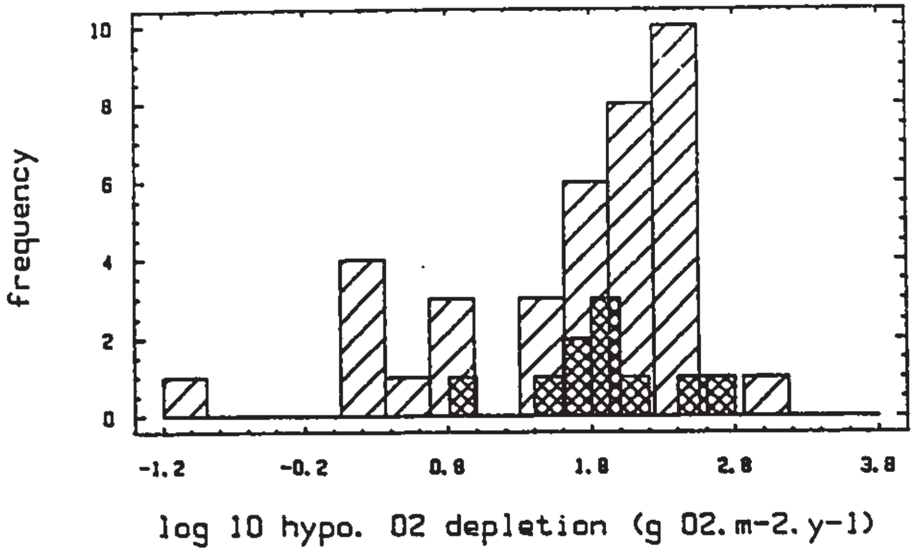
A6.24 a Volumetric hypolimnetic oxygen depletion distribution in natural lakes.



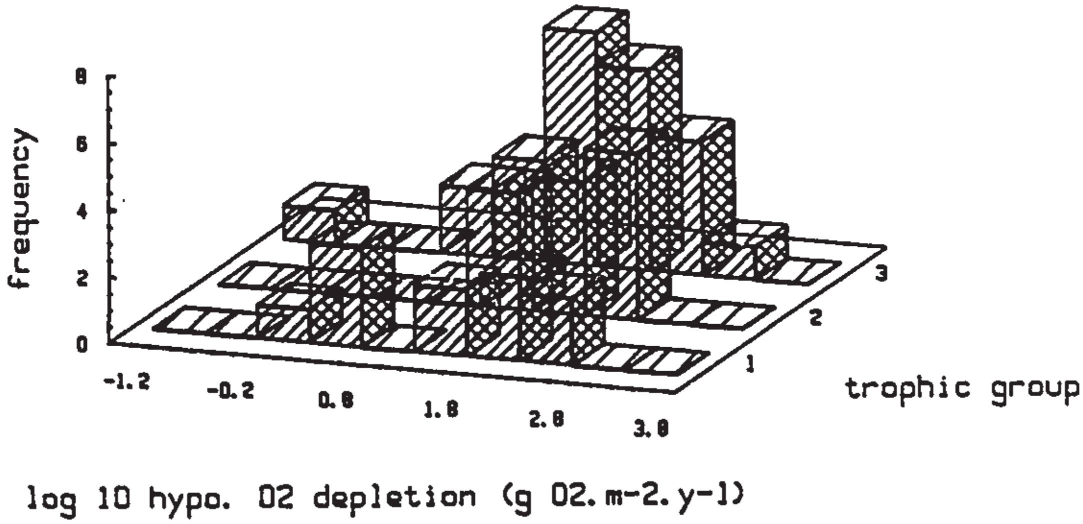
A6.24 b Hypolimnetic oxygen depletion with trophic breakdown(1oligo, 2meso, 3eu)



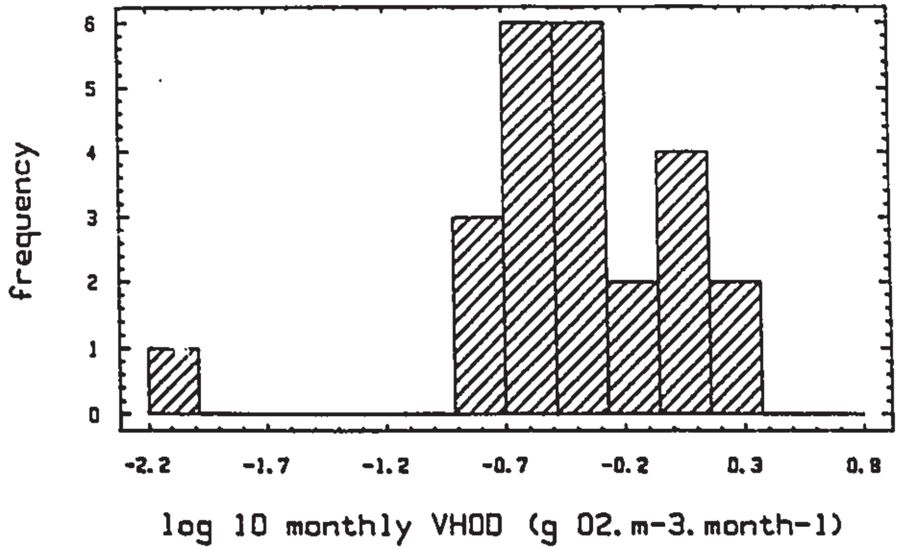
A6.25 a Areal hypolimnetic oxygen depletion distribution in all waterbodies.



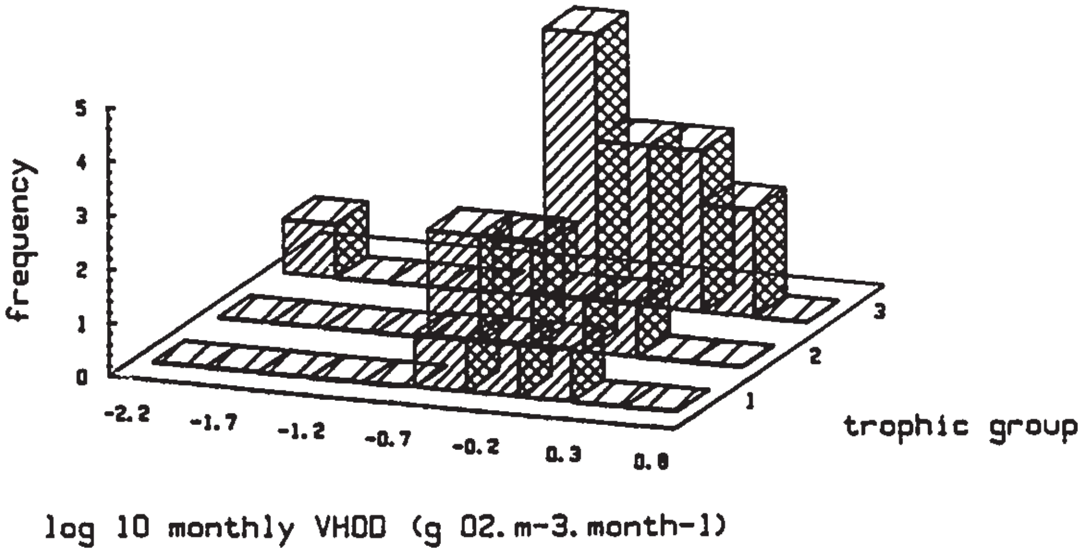
A6.25 b Areal hypolimnetic oxygen depletion with trophic breakdown(1 o, 2 m, 3 e)



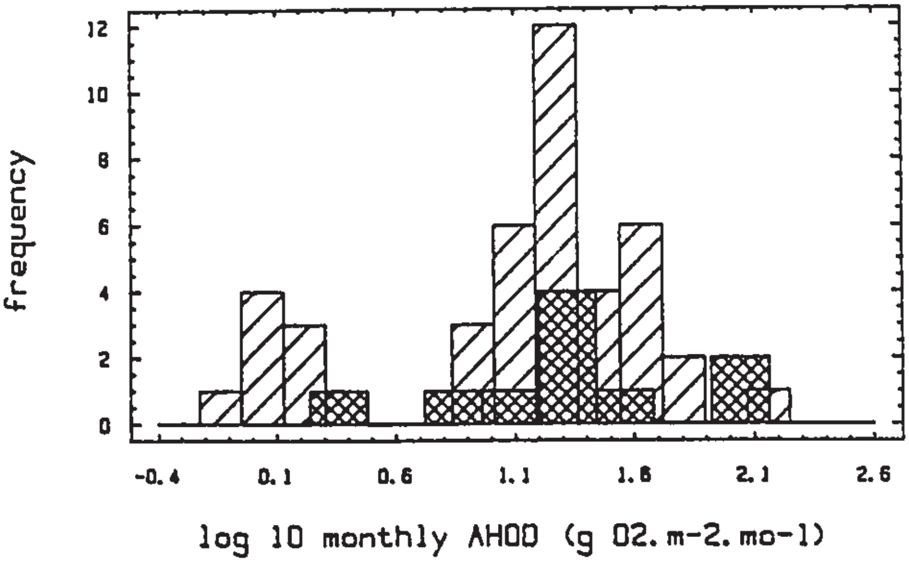
A6.26 a Monthly VHOD distribution in natural waterbodies.



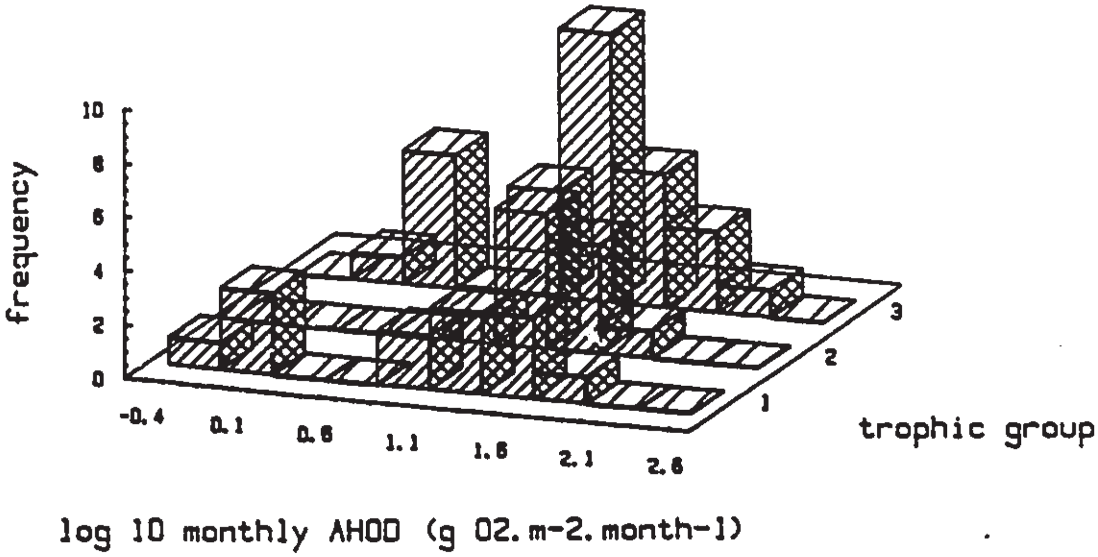
A6.26 b Monthly VHOD with trophic breakdown (1 oligo., 2 meso., 3 eu.).



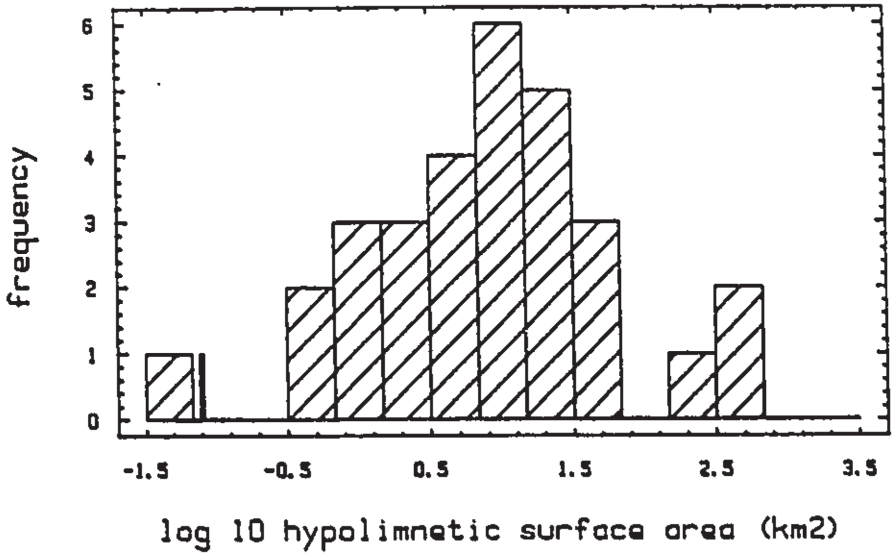
A6.27 a Monthly AHOD distribution in all waterbodies (xx = SLR).



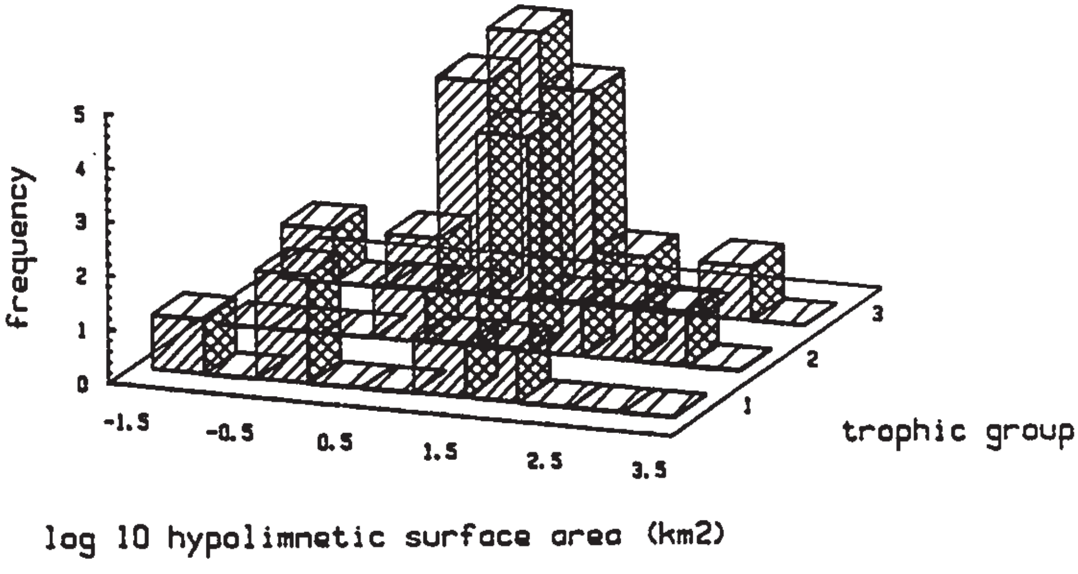
A6.27 b Monthly AHOD with trophic breakdown (1 oligo., 2 meso., 3 eu.).



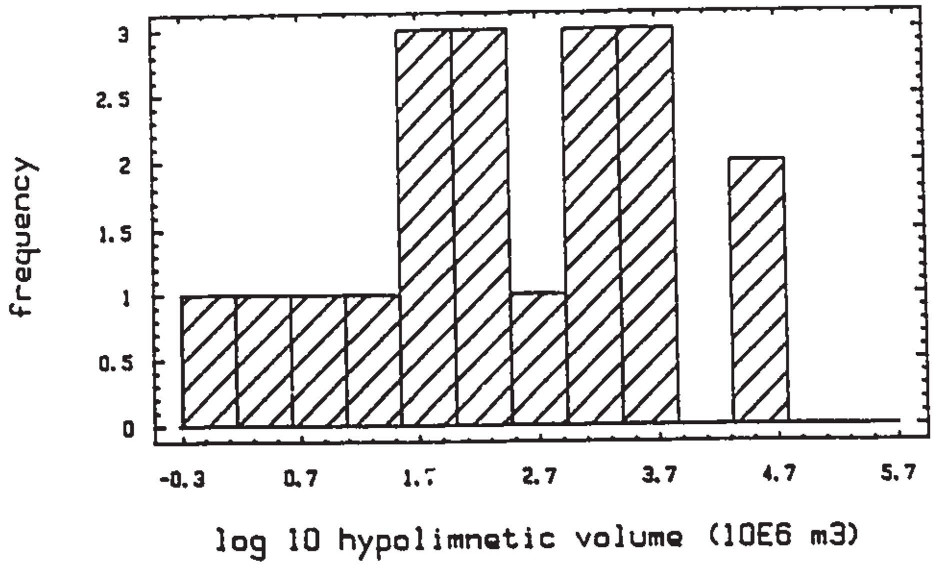
A6.28 a Hypolimnetic surface area distribution in all waterbodies(xx = SLR).



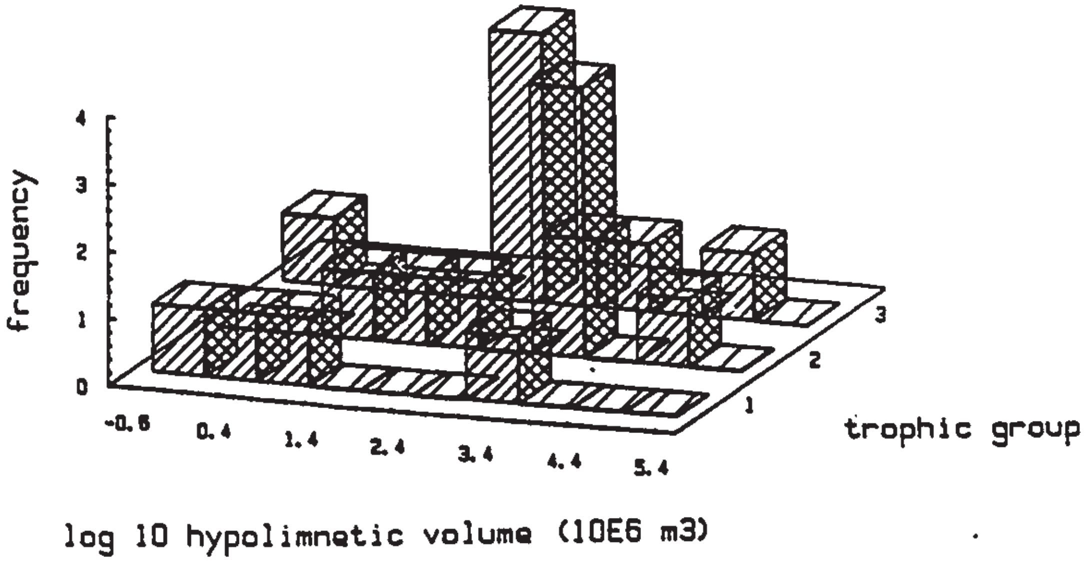
A6.28 b Hypolimnetic surface area with trophic breakdown (1 oligo, 2 meso, 3 eu).



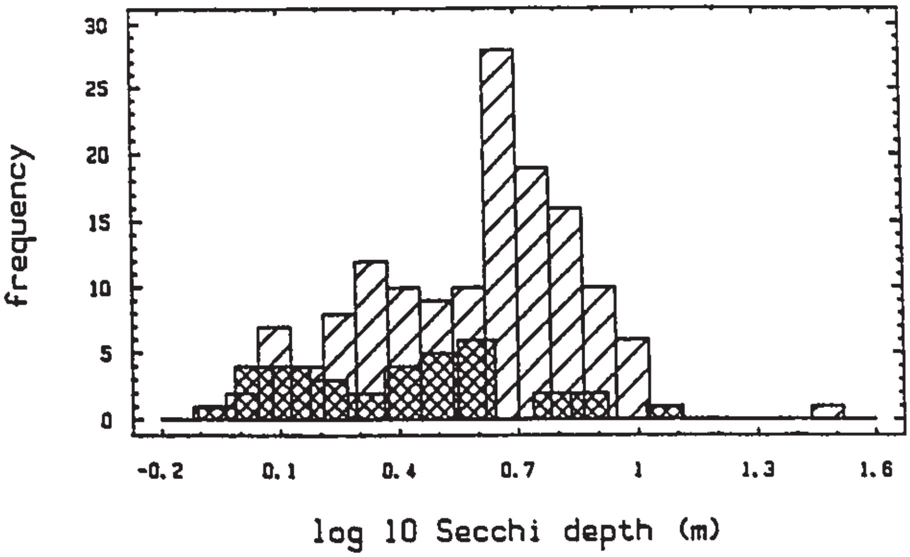
A6.29 a Hypolimnetic volume distribution in all waterbodies (xx = SLR).



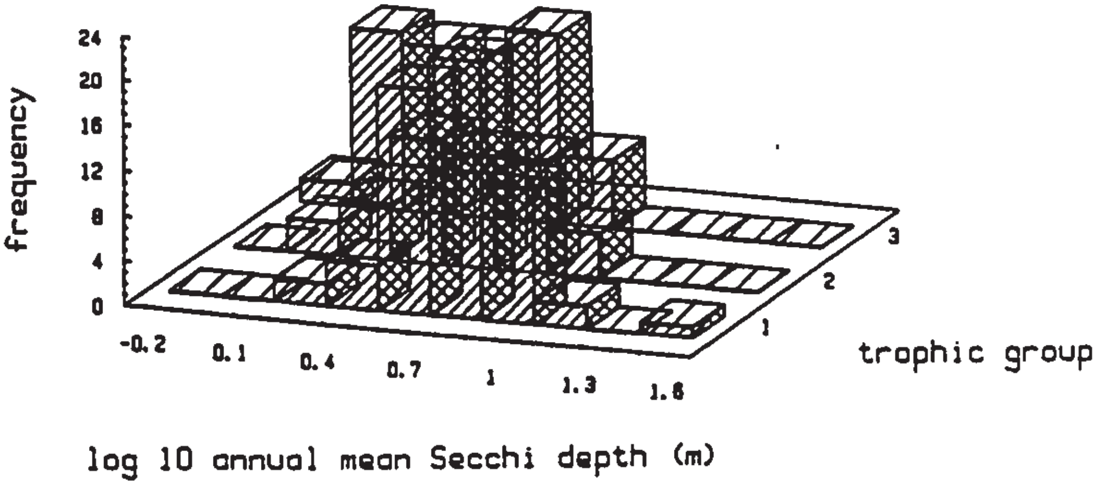
A6.29 b Hypolimnetic volume with trophic breakdown (1 oligo., 2 meso., 3 eu.).



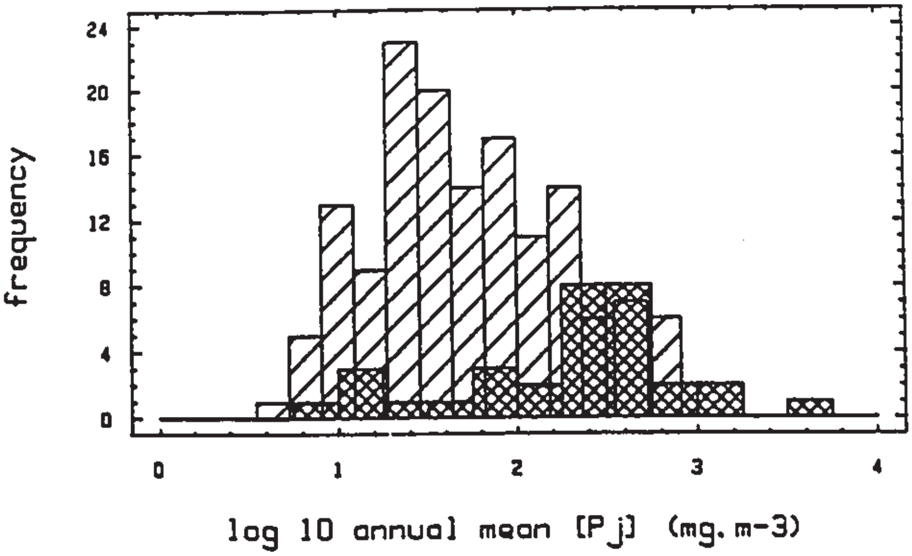
A6.30 a Mean Secchi depth distribution in all waterbodies (xx = SLR).



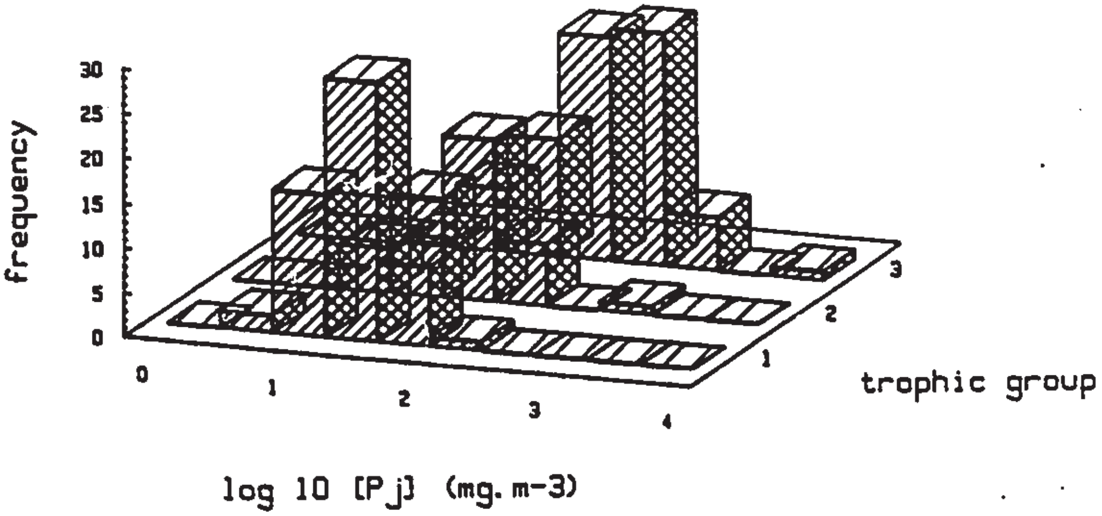
A6.30 b Annual mean Secchi depth with trophic breakdown (1 olig., 2 meso., 3 eu)



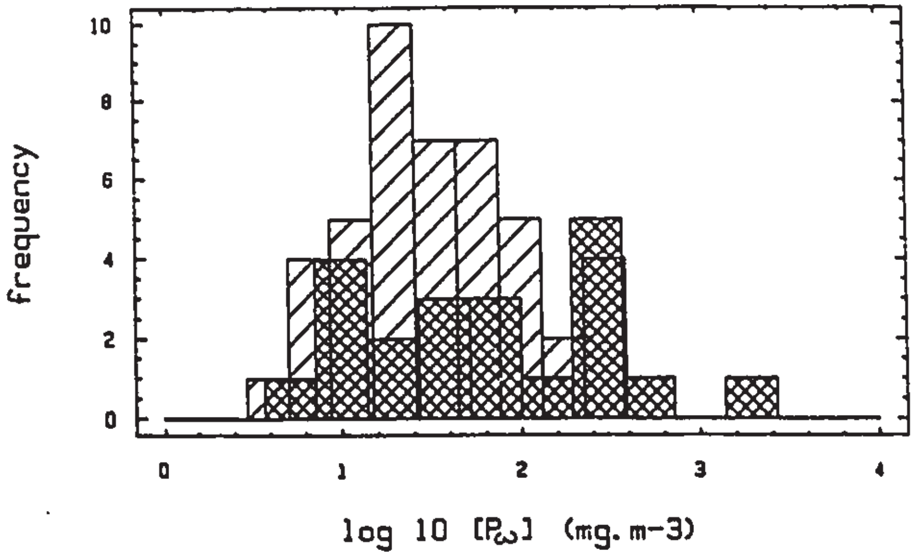
A6.31 a Inflow [Pj] distribution in all waterbodies (xx = SLR).



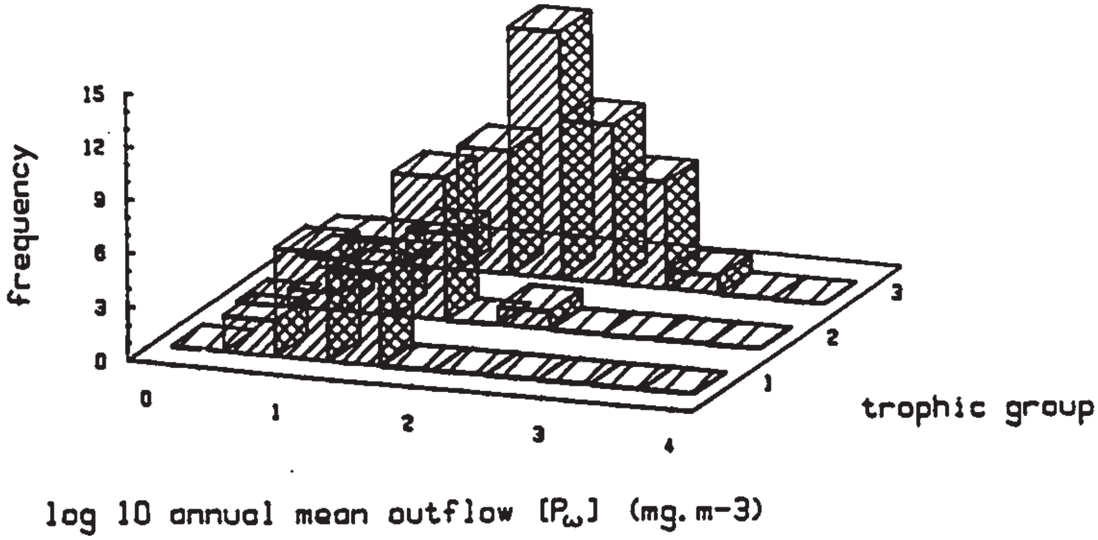
A6.31 b Inflow [Pj] with trophic breakdown (1 oligo., 2 meso., 3 eu.).



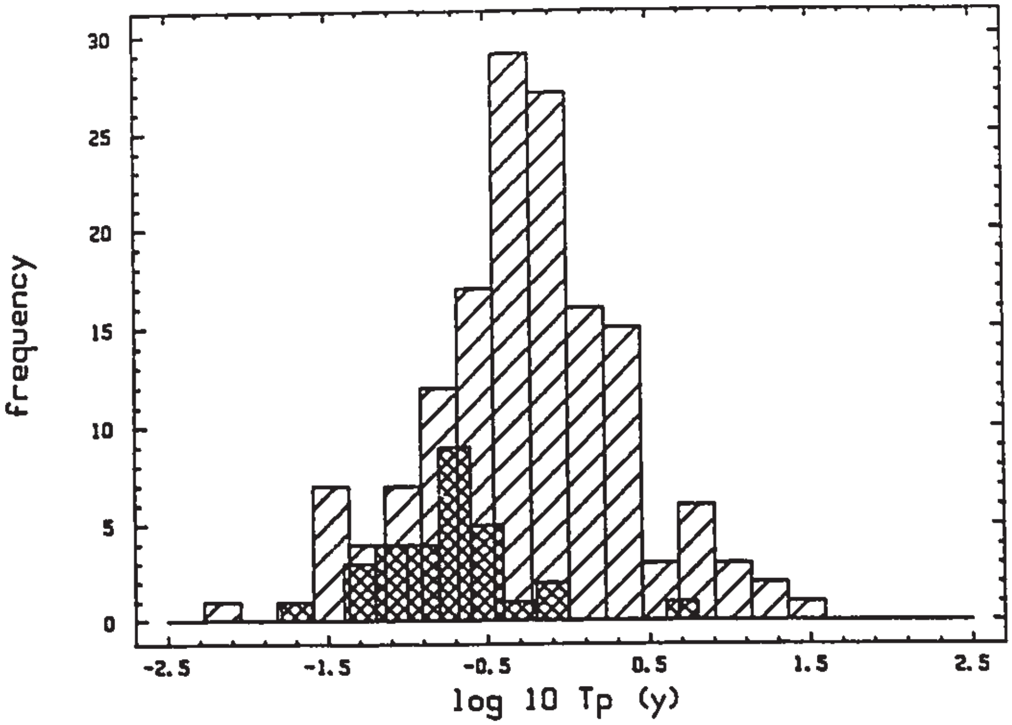
A6.32 a Outflow [P_ω] distribution in all waterbodies (xx = SLR).



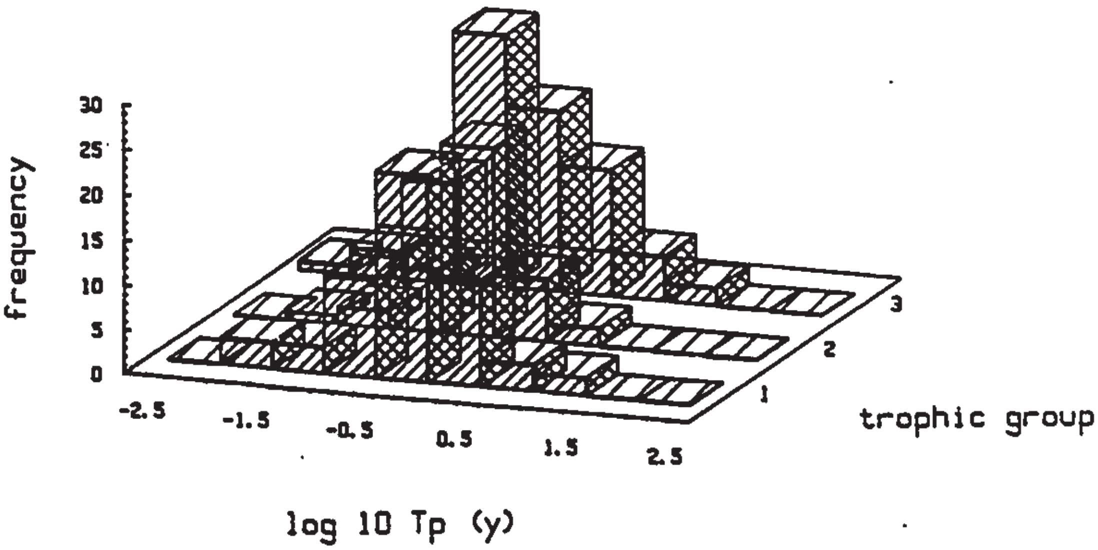
A6.32 b Outflow [P_ω] with trophic breakdown (1 oligo., 2 meso., 3 eu.).



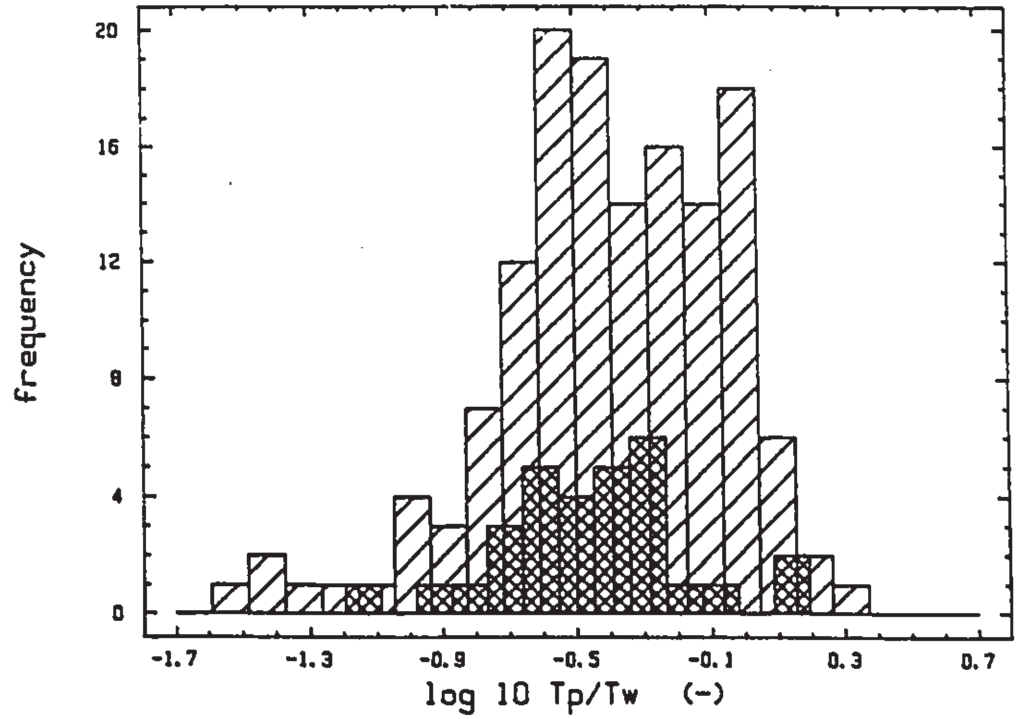
A6.33 a Absolute P residence time distribution in all waterbodies (xx = SLR).



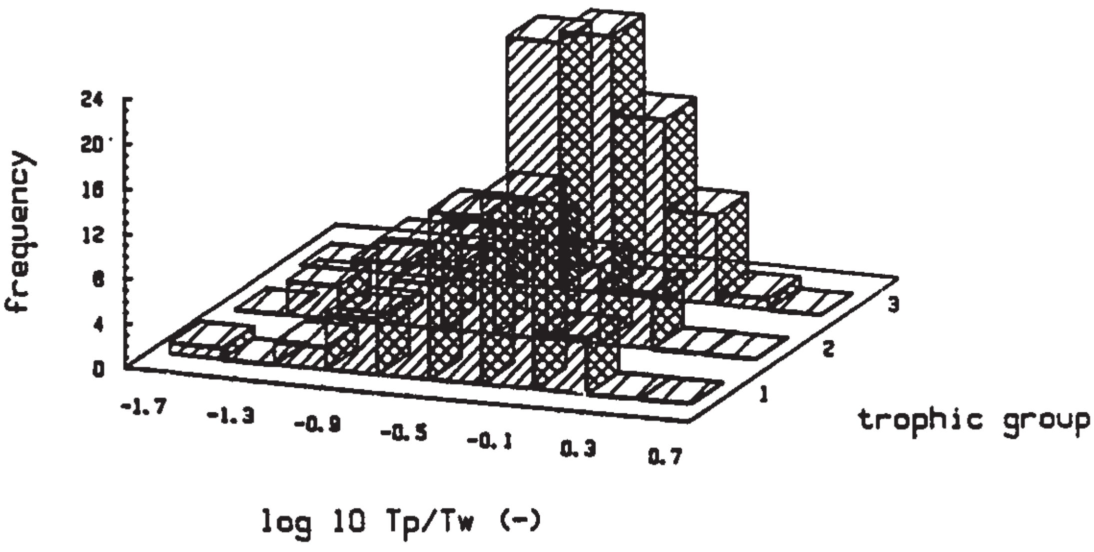
A6.33 b Absolute P residence time with trophic breakdown (1 oligo, 2 meso, 3 eu).



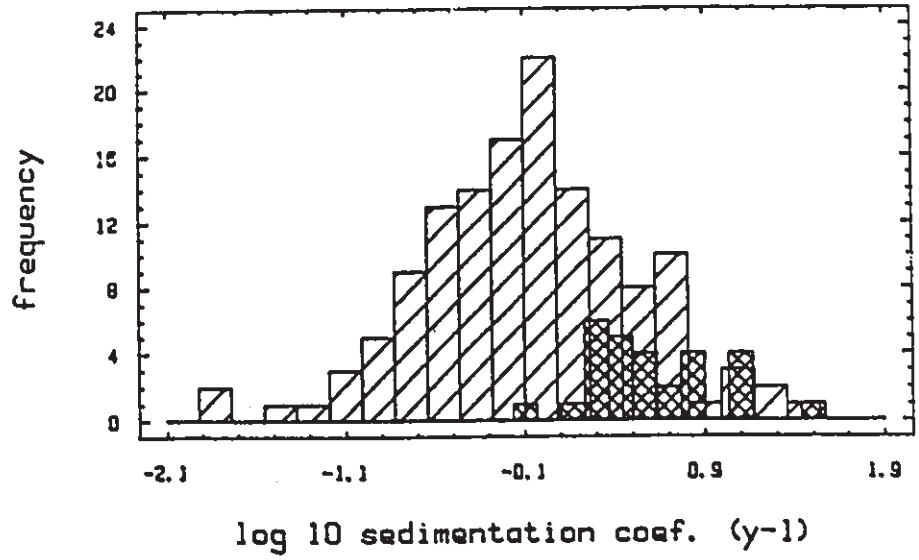
A6.34 a Tp/Tw distribution in all waterbodies (xx = SLR).



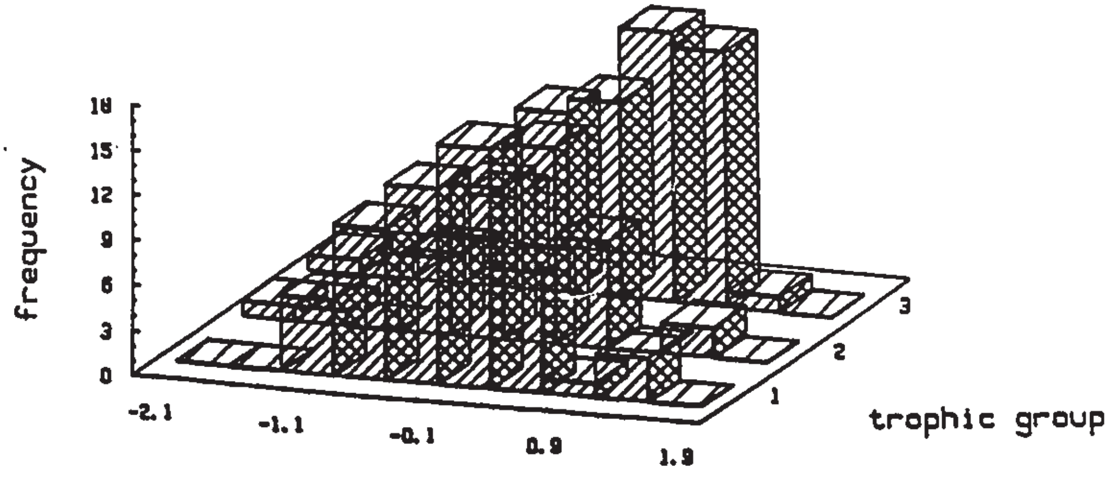
A6.34 b Tp/Tw with trophic breakdown
(1 oligo., 2 meso., 3 eu.).



A6.35 a Sedimentation coefficient distribution in all waterbodies(xx = SLR).

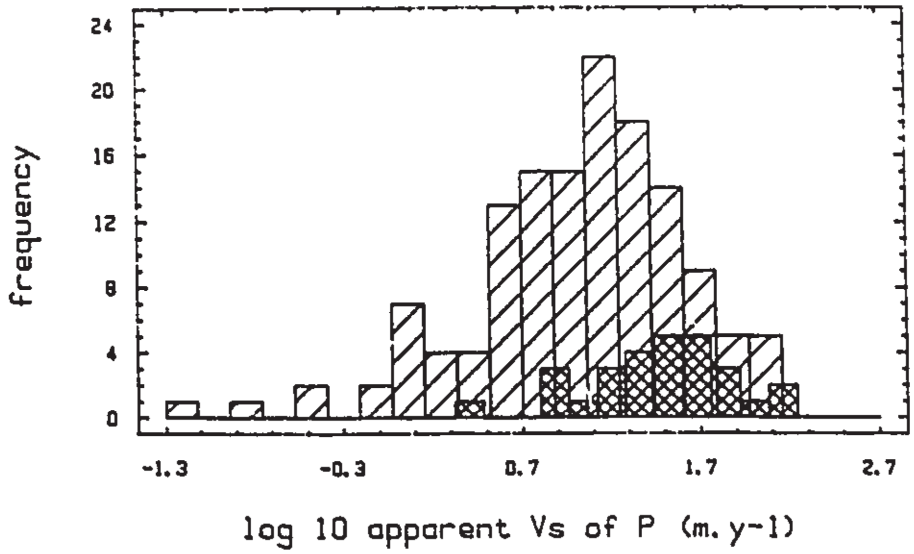


A6.35 b Sedimentation coefficient with trophic breakdown (1 oligo, 2 meso, 3 eu).

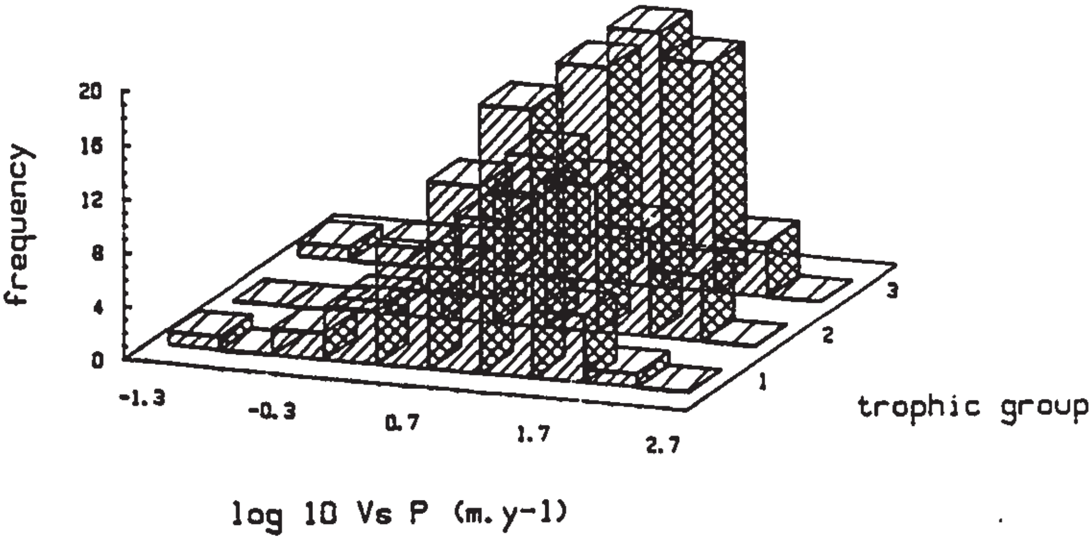


log 10 sedimentation coefficient (y-1)

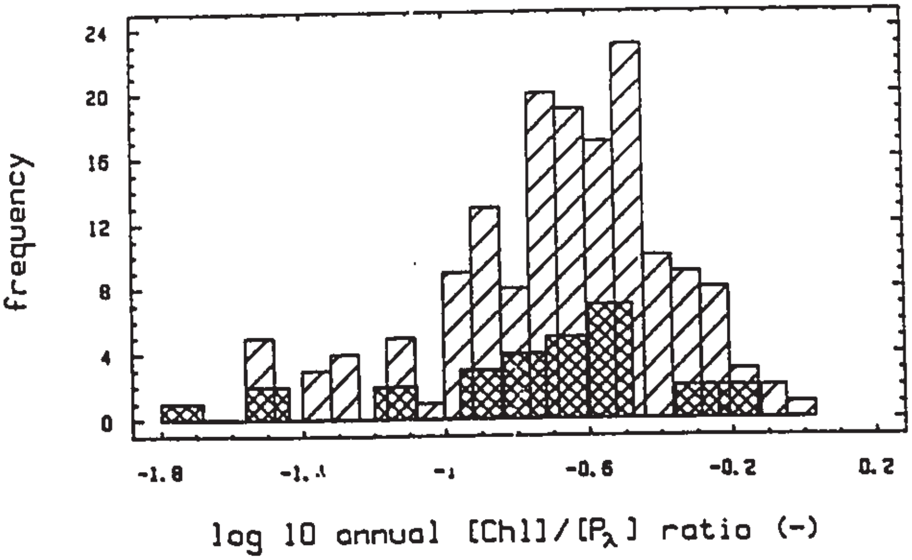
A6.36 a Apparent sedimentation velocity of P distribution in all waterbodies.



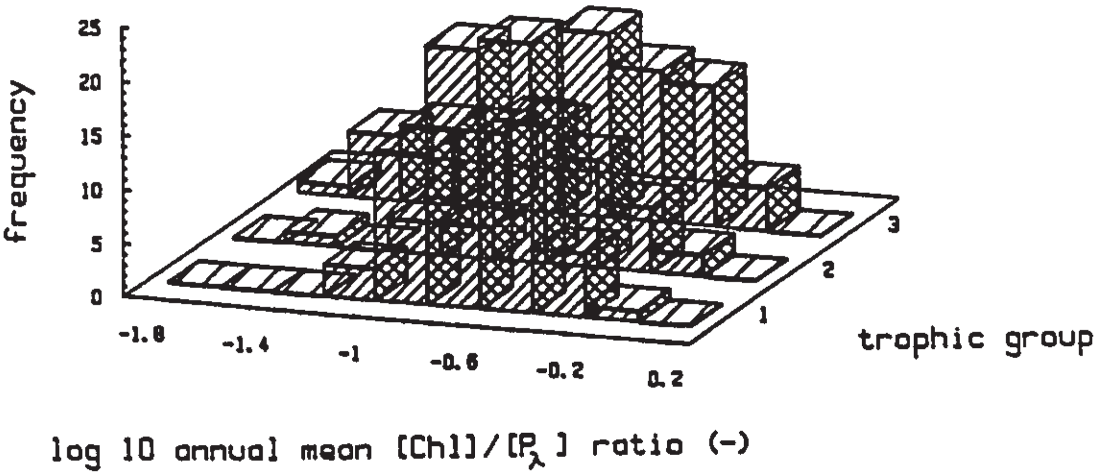
A6.36 b Apparent sedimentation velocity of P with trophic breakdown(1 o, 2 m, 3 e)



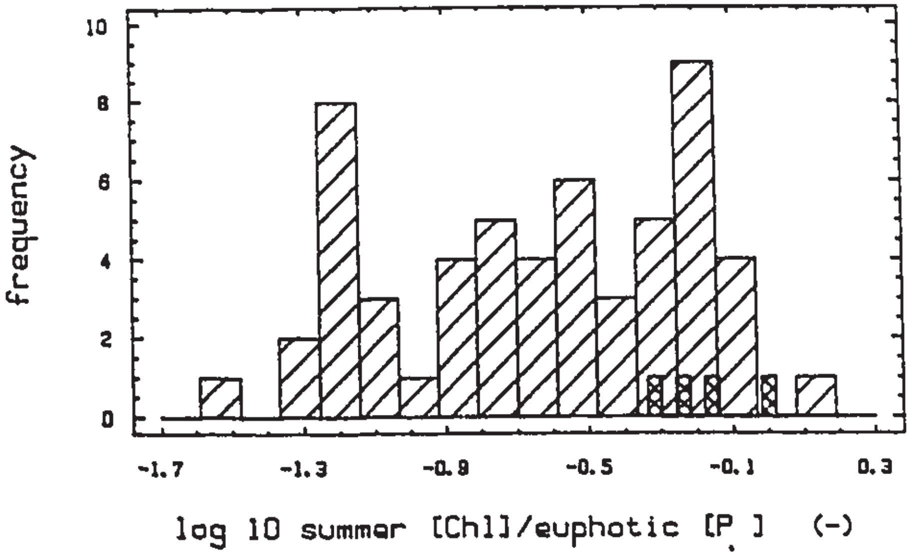
A6.37 a Annual [Chl]/[P_λ] ratio distribution in all lakes (xx = SLR).



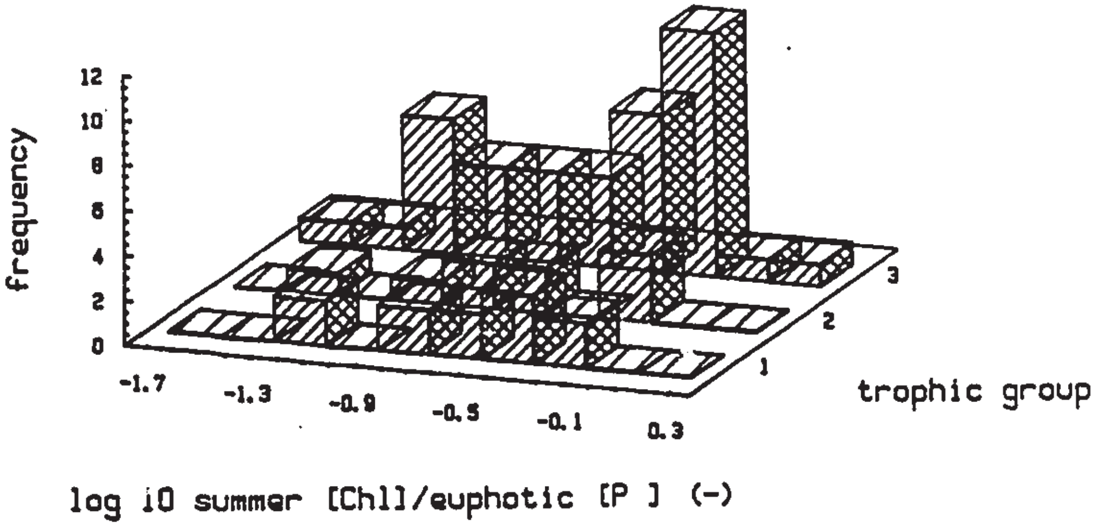
A6.37 b Annual mean [Chl]/[P_λ] with trophic breakdown (1 oligo., 2 meso., 3 eu.).



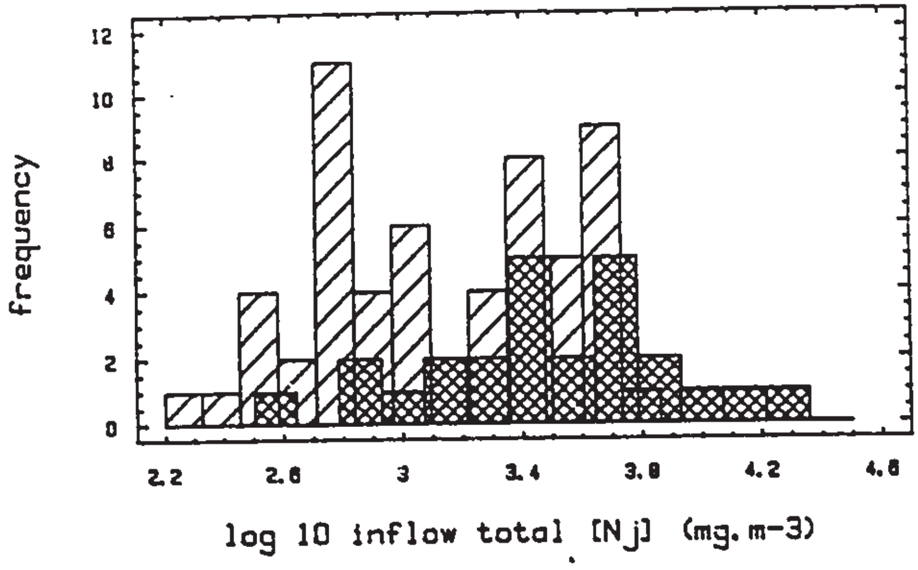
A6.38 a Summer [Chl]/euphotic [P] ratio distribution in all lakes (xx = SLR).



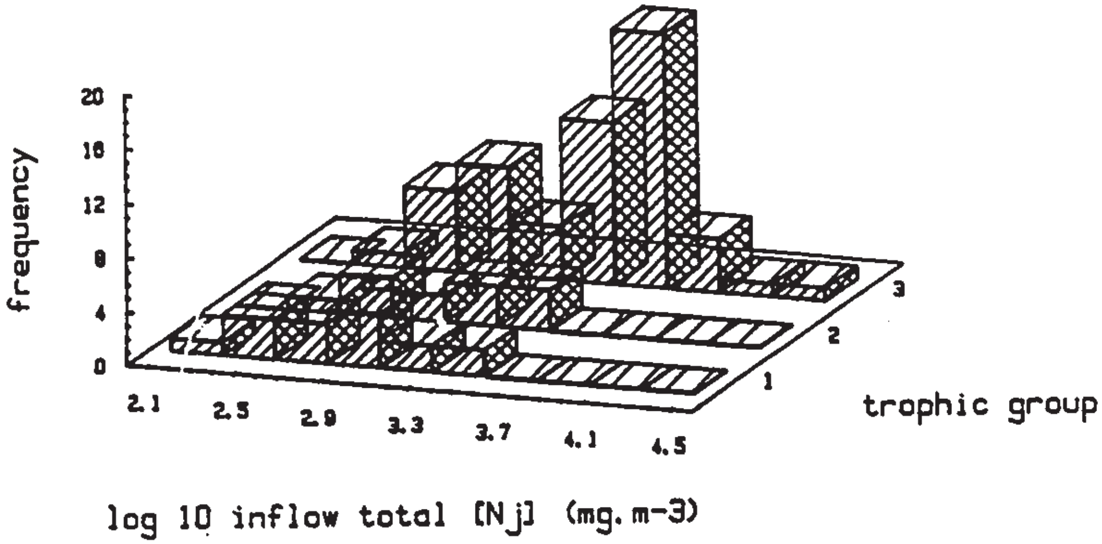
A6.38 b Summer [Chl]/euphotic [P] ratio with trophic breakdown(1olig, 2meso, 3eu).



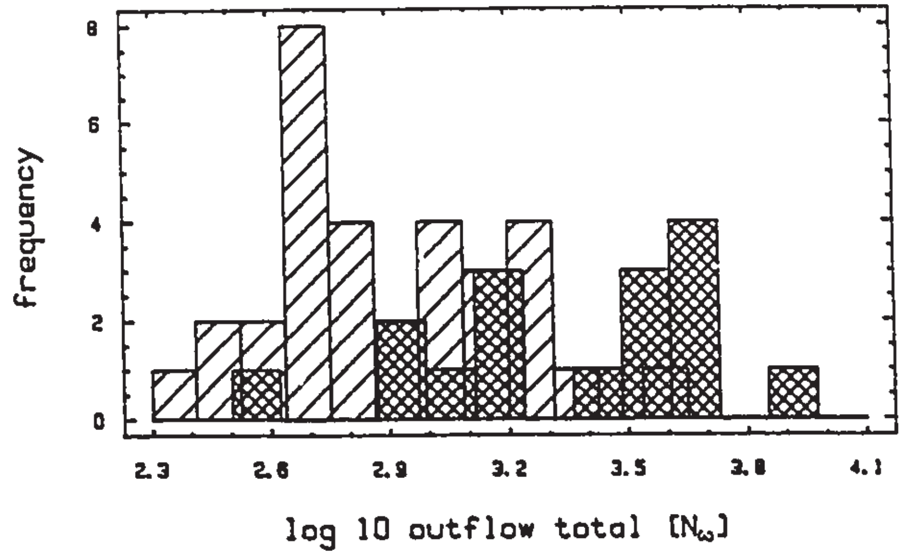
A6.39 a Inflow total [Nj] distribution in all waterbodies (xx = SLR).



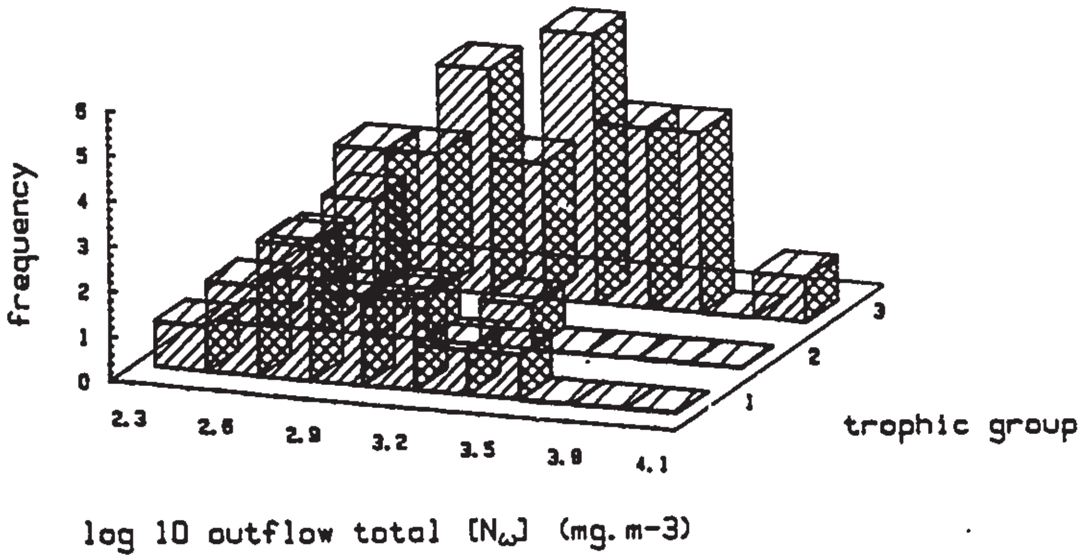
A6.39 b Inflow total [Nj] with trophic breakdown (1 oligo., 2 meso., 3 eu.).



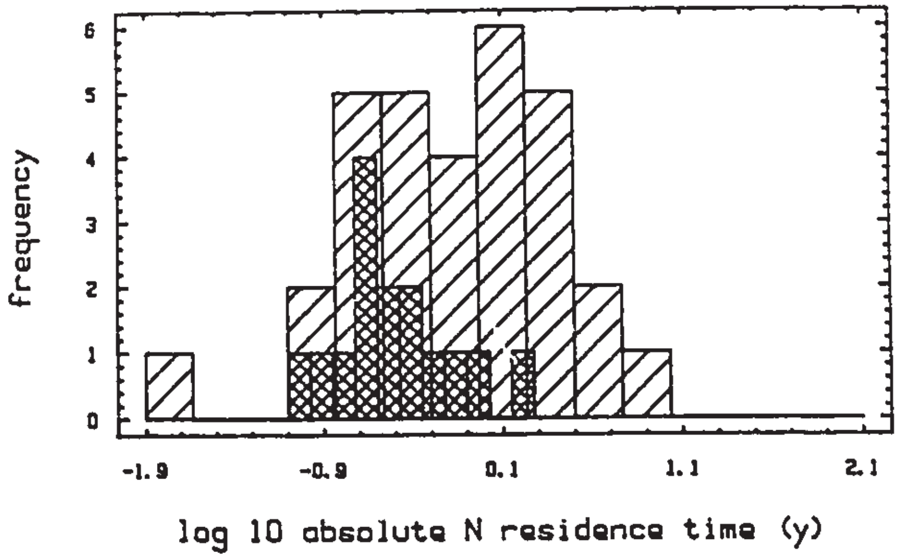
A6.40 a Outflow total [N_ω] distribution in all waterbodies (xx = SLR).



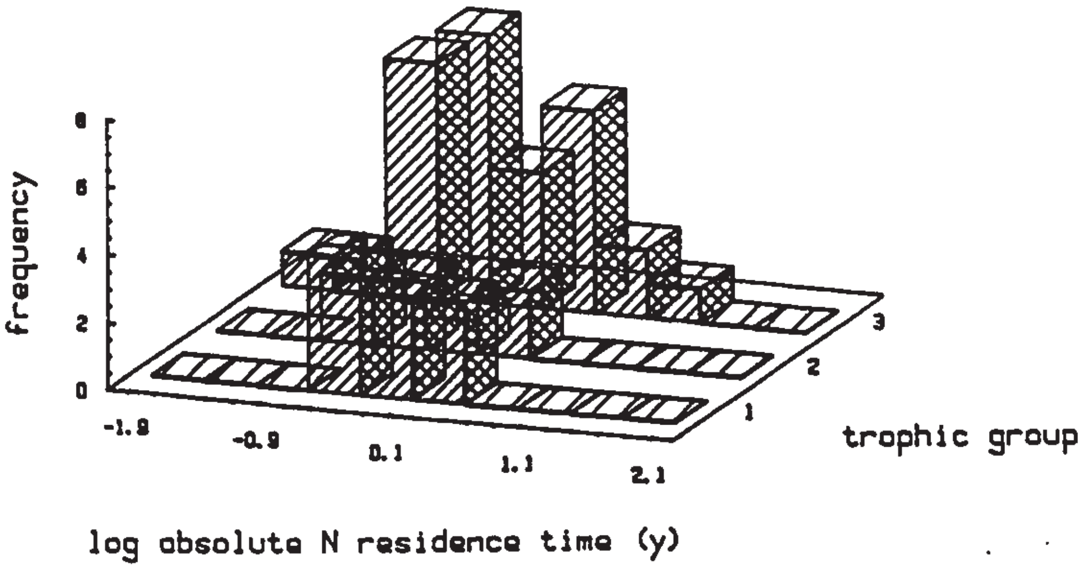
A6.40 b Outflow total [N_ω] with trophic breakdown (1 oligo., 2 meso., 3 eu.).



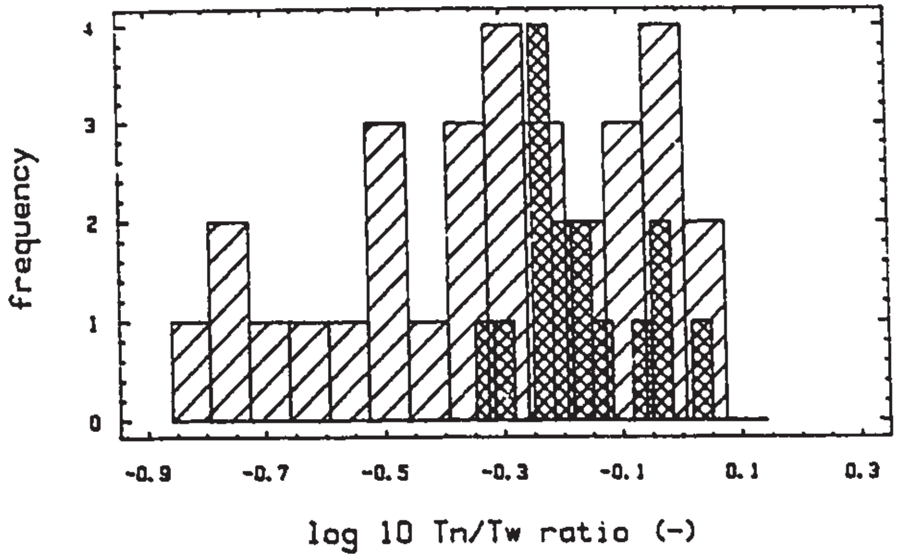
A6.41 a Absolute nitrogen residence time distribution in all waterbodies(xx = SLR



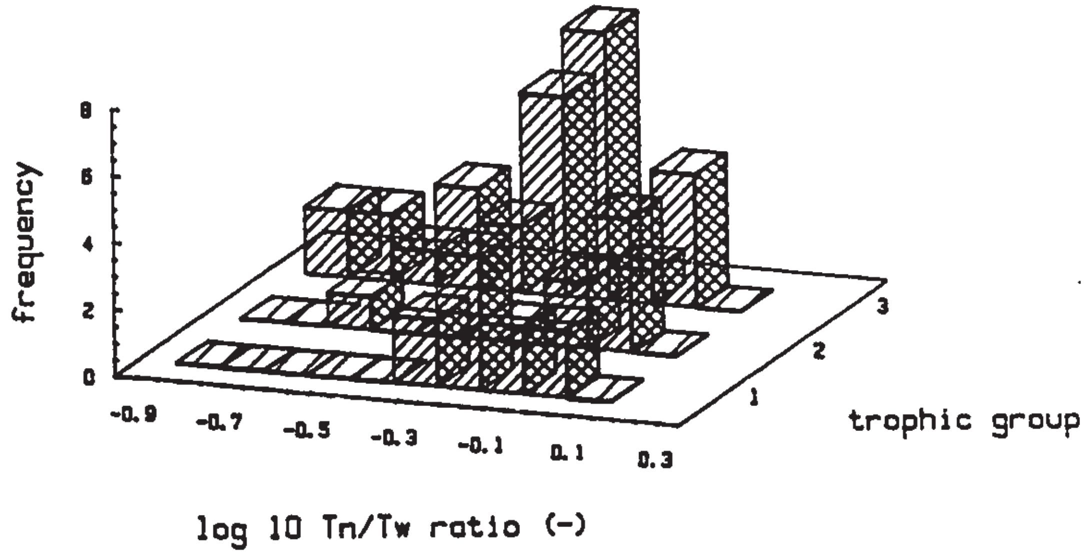
A6.41 b Absolute N residence time with trophic breakdown(1 oligo., 2 meso., 3 eu)



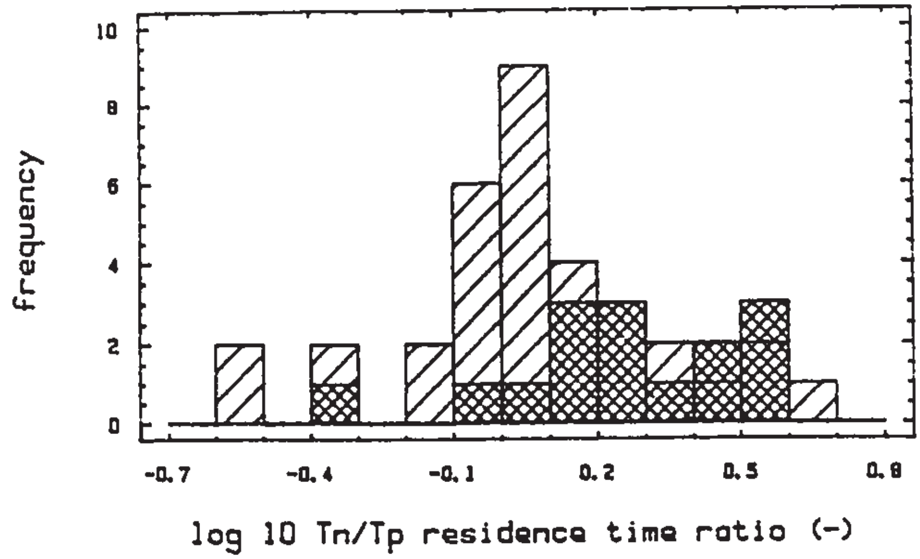
A6.42 a Tn/Tw distribution in all waterbodies (xx = SLR).



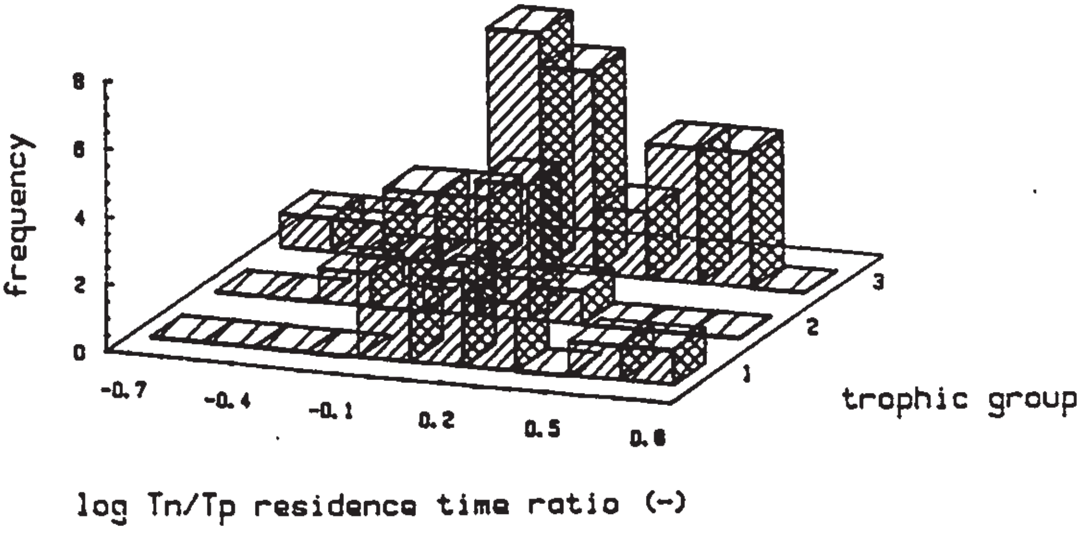
A6.42 b Tn/Tw distribution with trophic breakdown (1 oligo., 2 meso., 3 eu.).



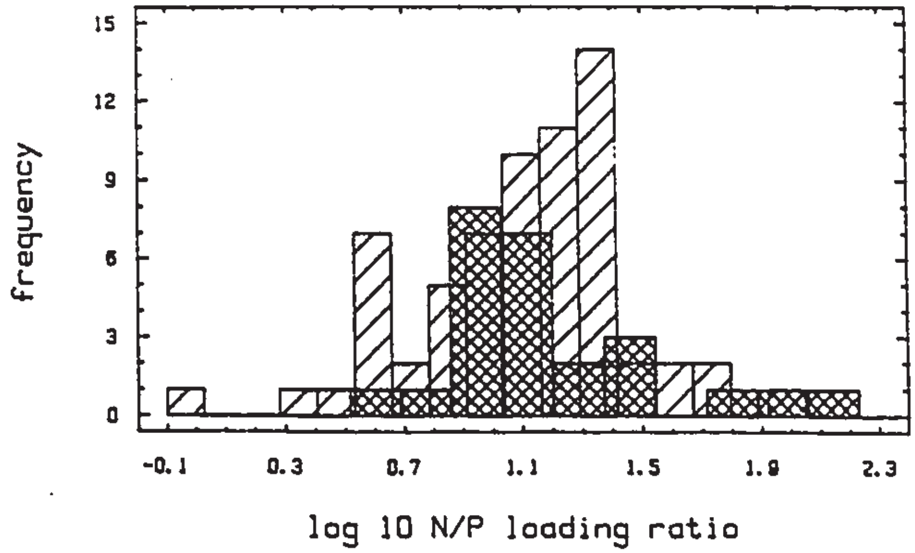
A6.43 a Tn/Tp residence time ratio distribution in all waterbodies (xx = SLR).



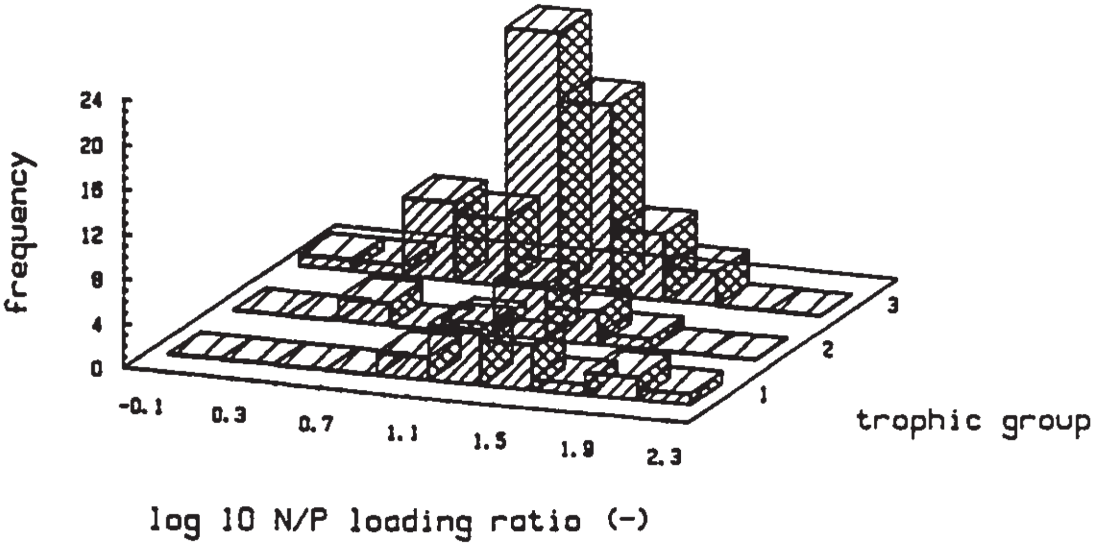
A6.43 b Tn/Tp residence time ratio with trophic breakdown (1 oligo, 2 meso, 3 eu).



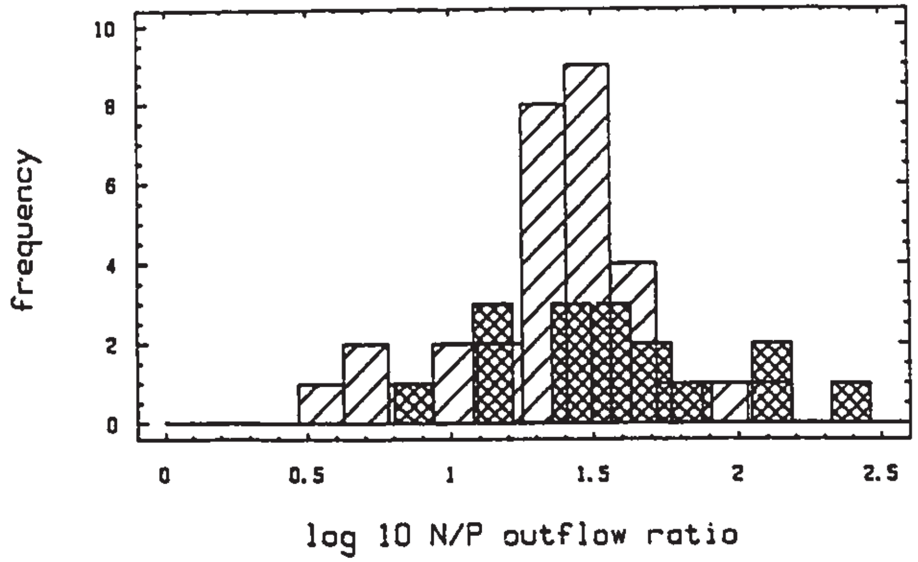
A6.44 a N/P loading ratio distribution in all waterbodies (xx = SLR).



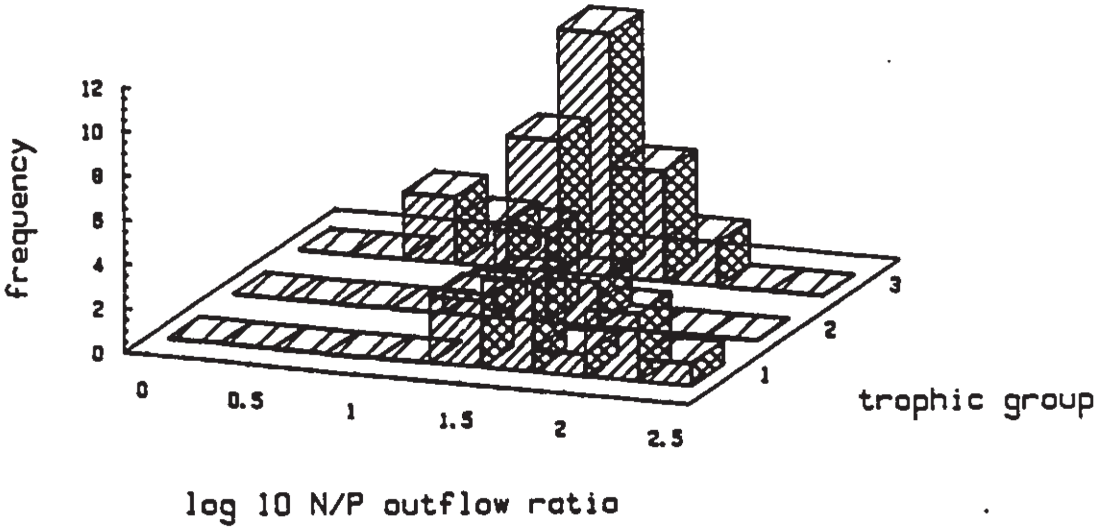
A6.44 b N/P loading ratio with trophic breakdown (1 oligo., 2 meso., 3 eu.).



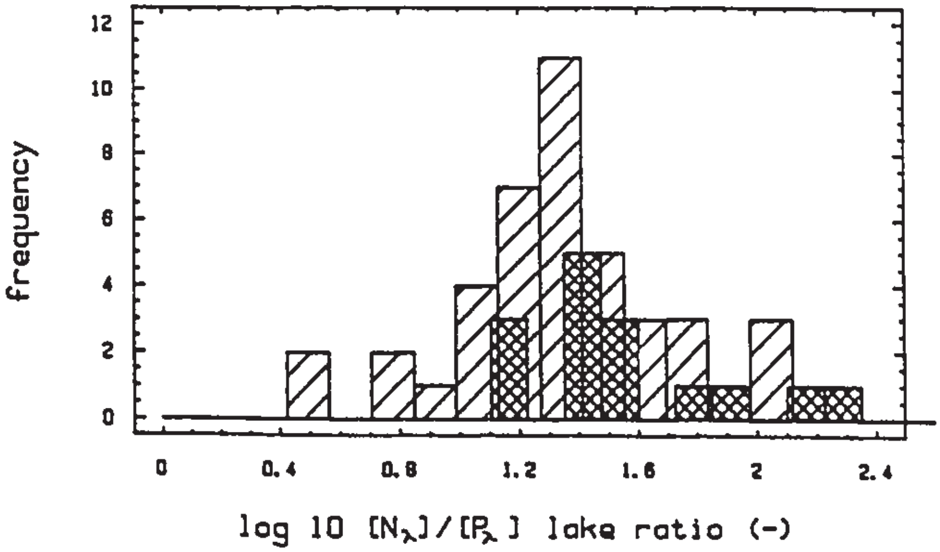
A6.45 a N/P outflow ratio distribution in all waterbodies (xx = SLR).



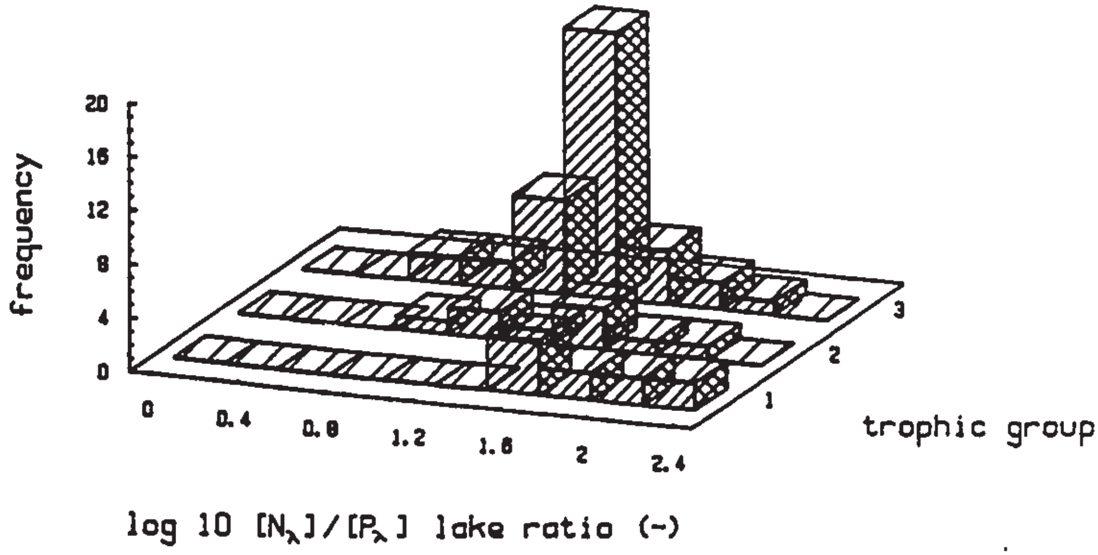
A6.45 b N/P outflow ratio with trophic breakdown (1 oligo., 2 meso., 3 eu.).



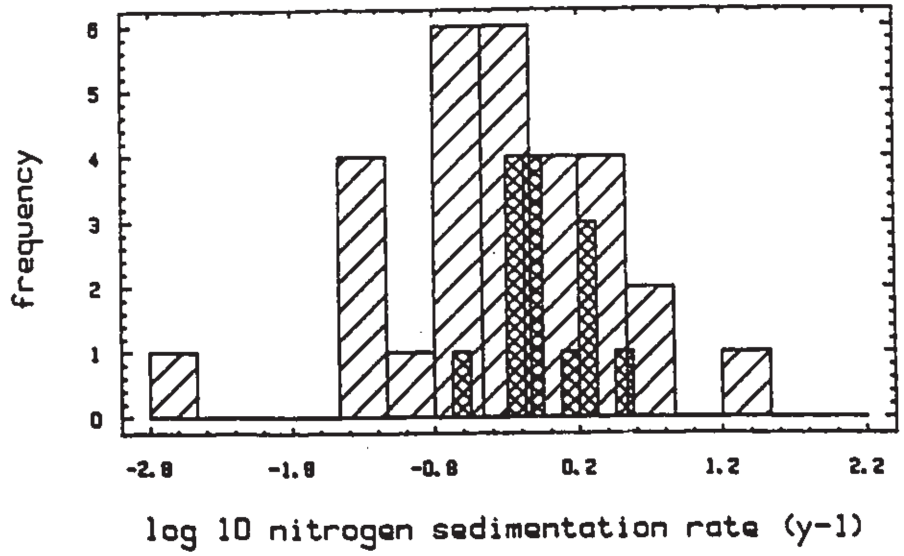
A6.46 a [N_λ]/[P_λ] lake ratio distribution in all waterbodies (xx = SLR).



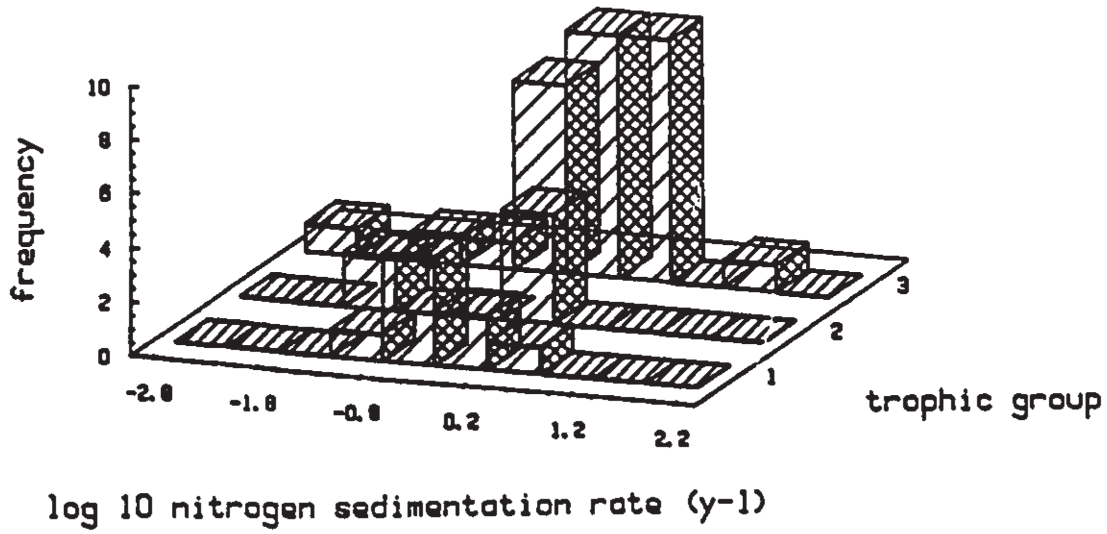
A6.46 b [N_λ]/[P_λ] ratio with trophic breakdown (1 oligo., 2 meso., 3 eu.).



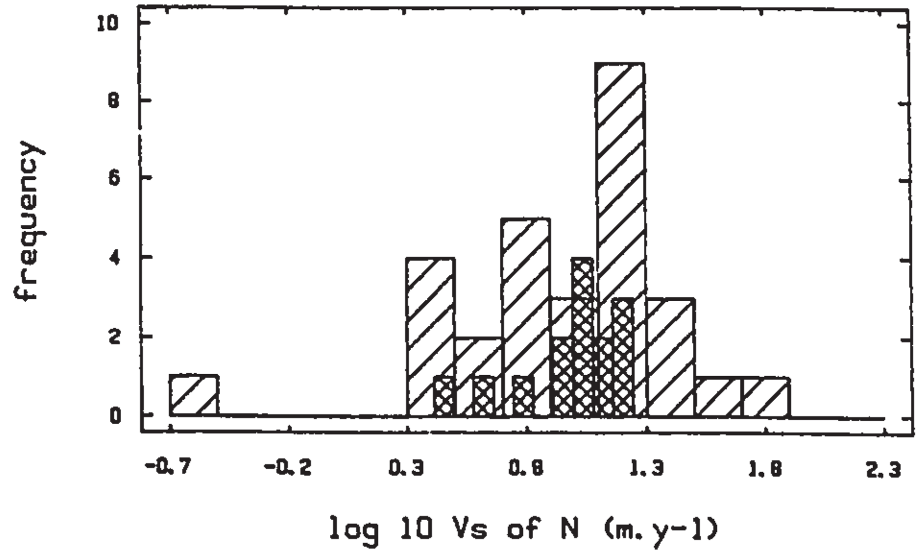
A6.47 a Nitrogen sedimentation rate distribution in all waterbodies(xx=SLR).



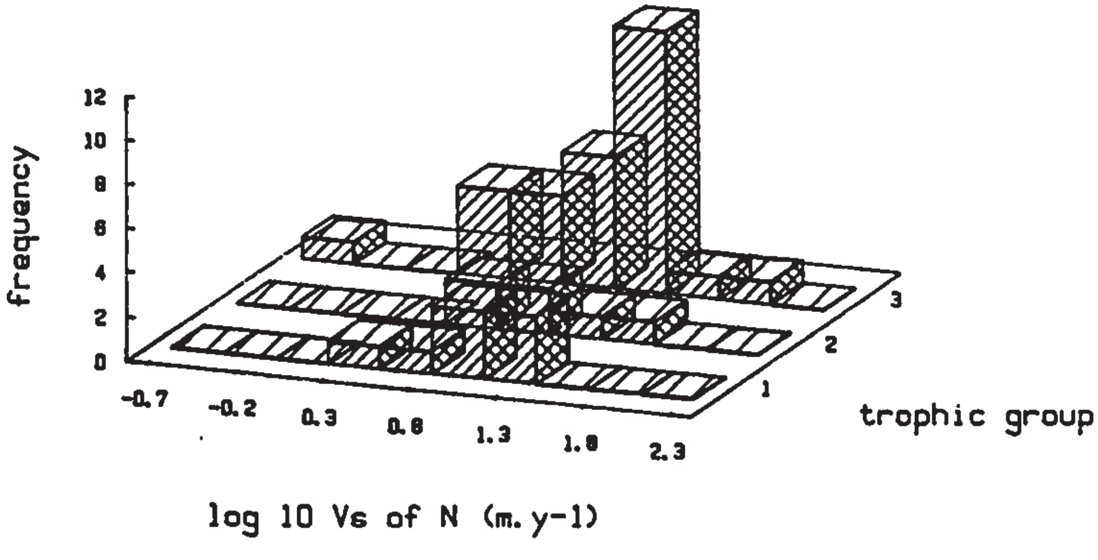
A6.47 b Nitrogen sedimentation rate with trophic breakdown(1olig, 2meso, 3eu).



A6.48 a Apparent sedimentation velocity of nitrogen in all waterbodies (xx=SLR).



A6.48 b Apparent sedimentation velocity of N with trophic breakdown(1 o, 2 m, 3 e)



Appendix 7. Scatterplots for variables significantly correlated with τ_p, (τ_p/τ_w), τ_n, and (τ_n/τ_w).

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Appendix 7 cont.

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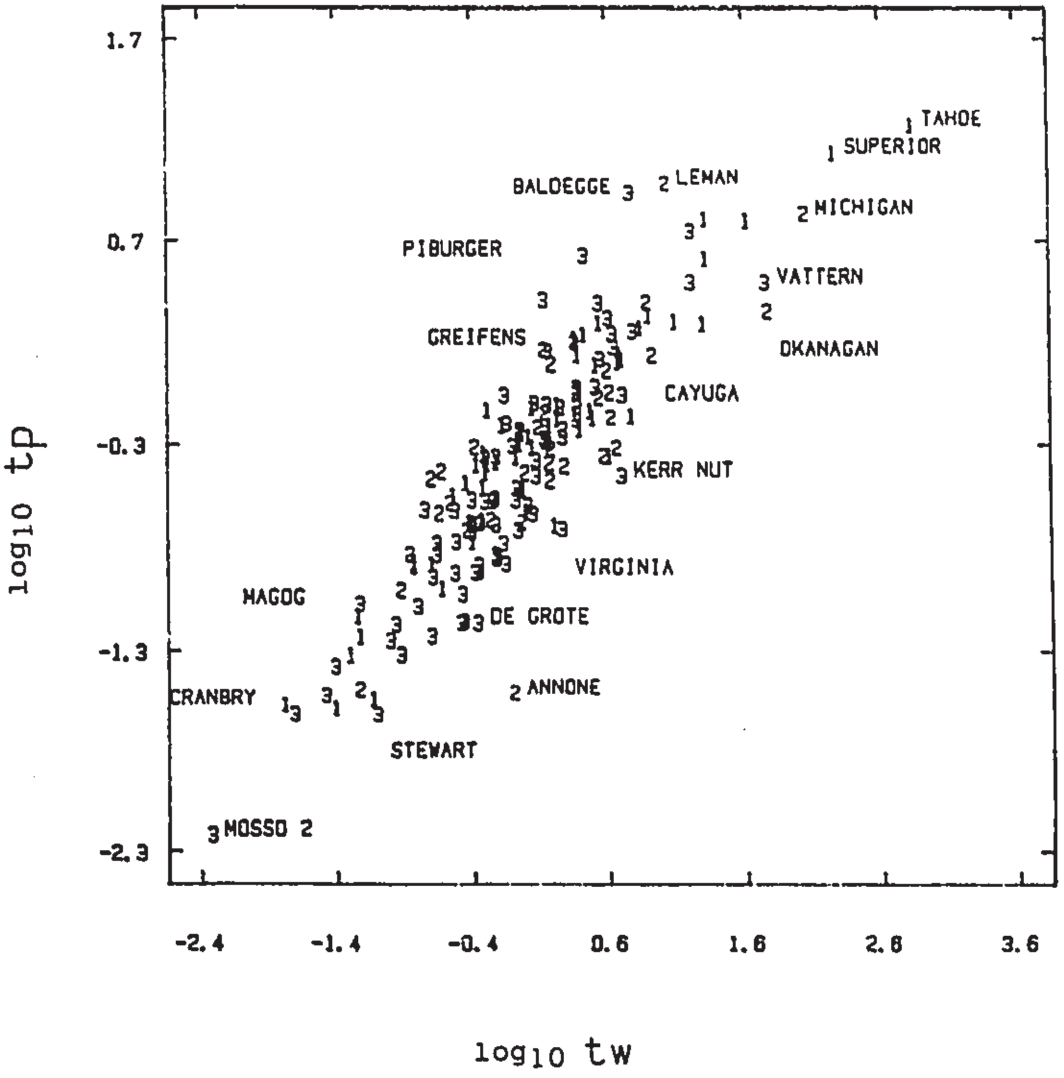
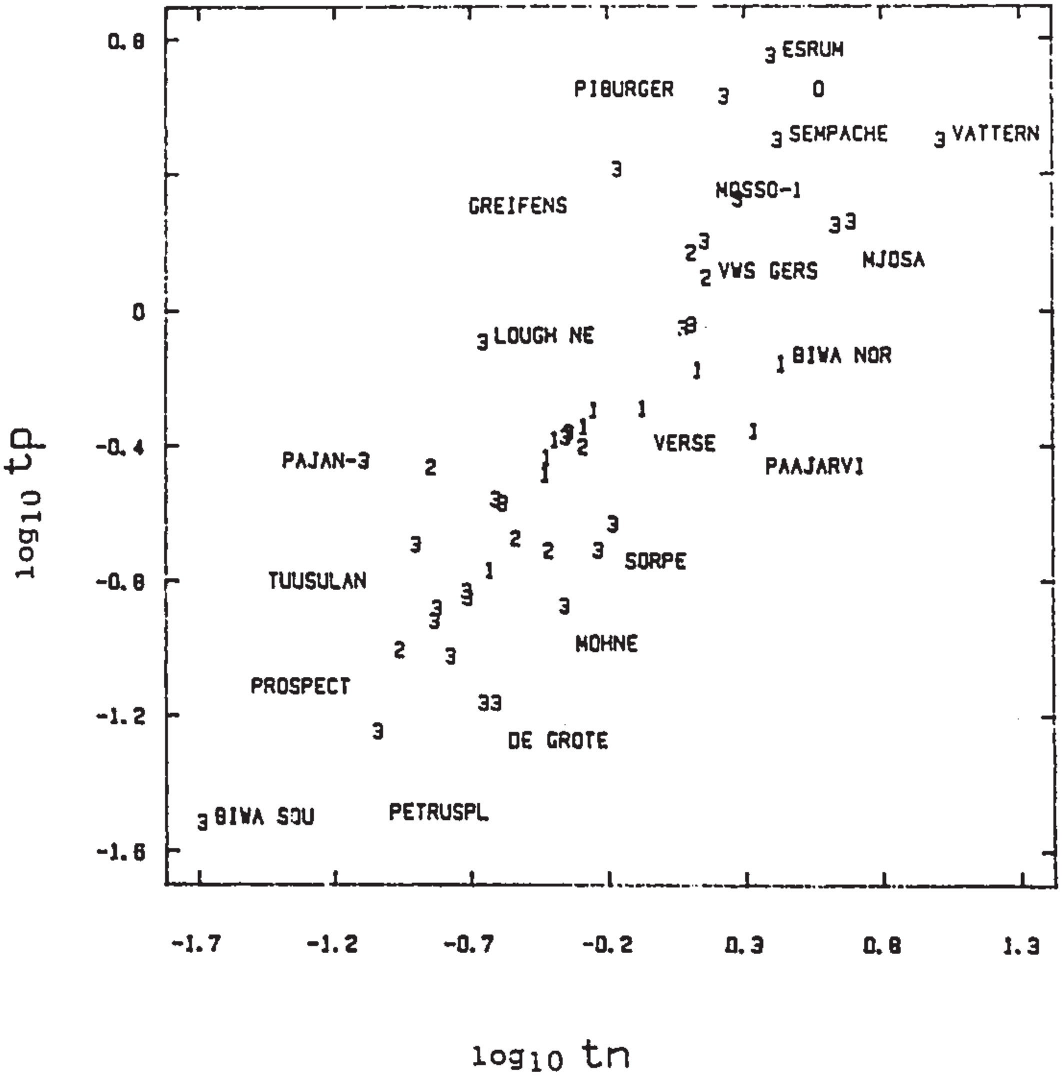
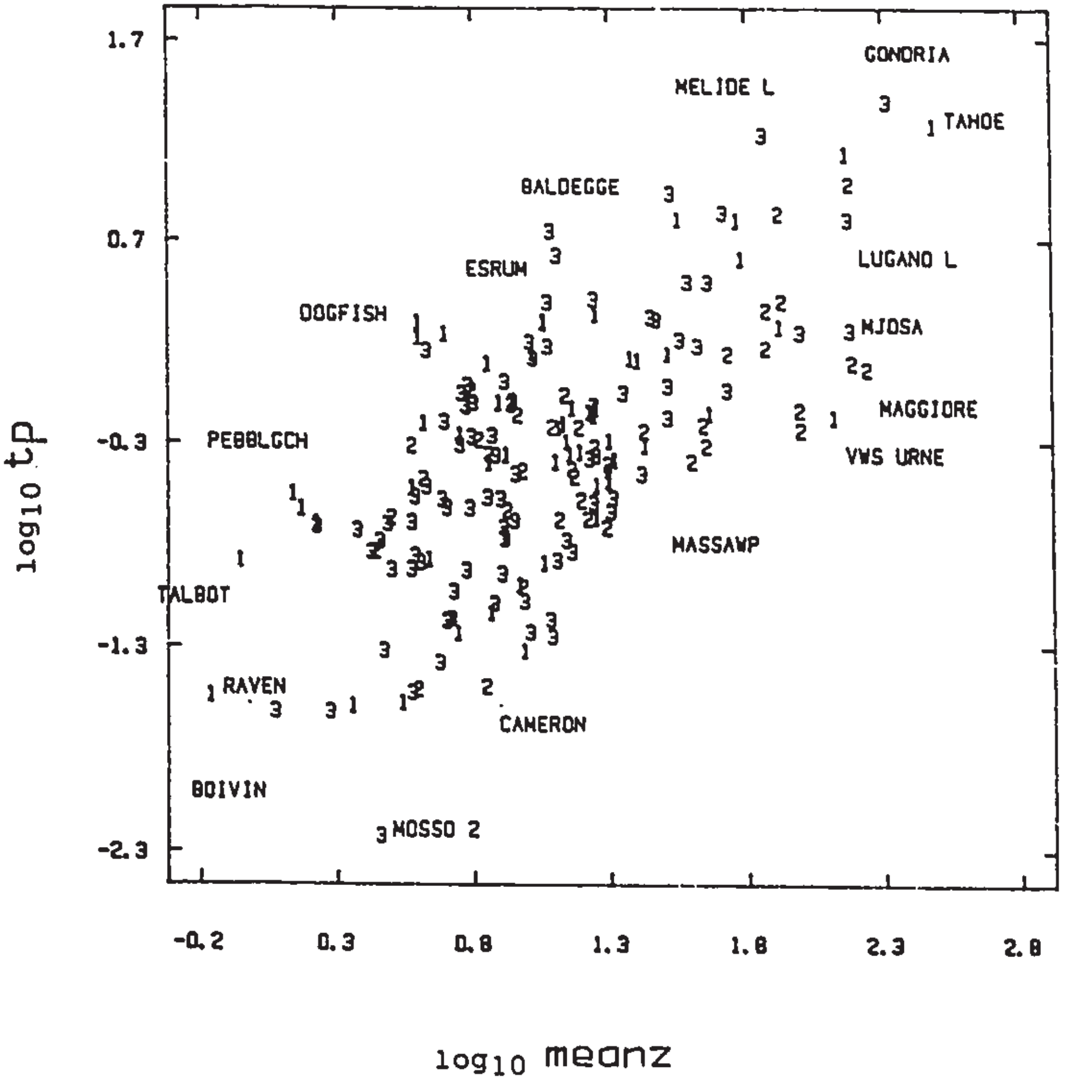


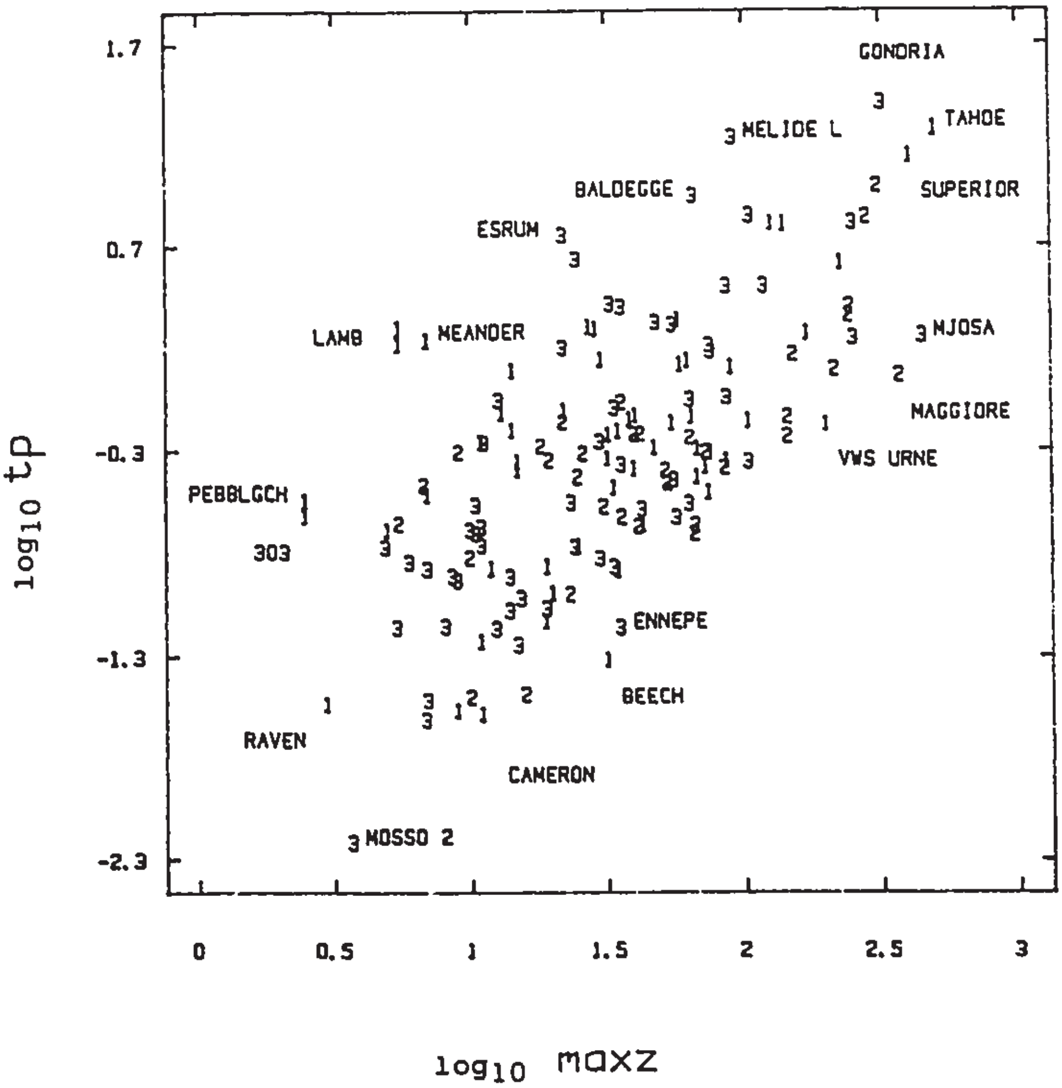
A7.1 Absolute phosphorus residence time vs water residence time ($r^2 = .81$).



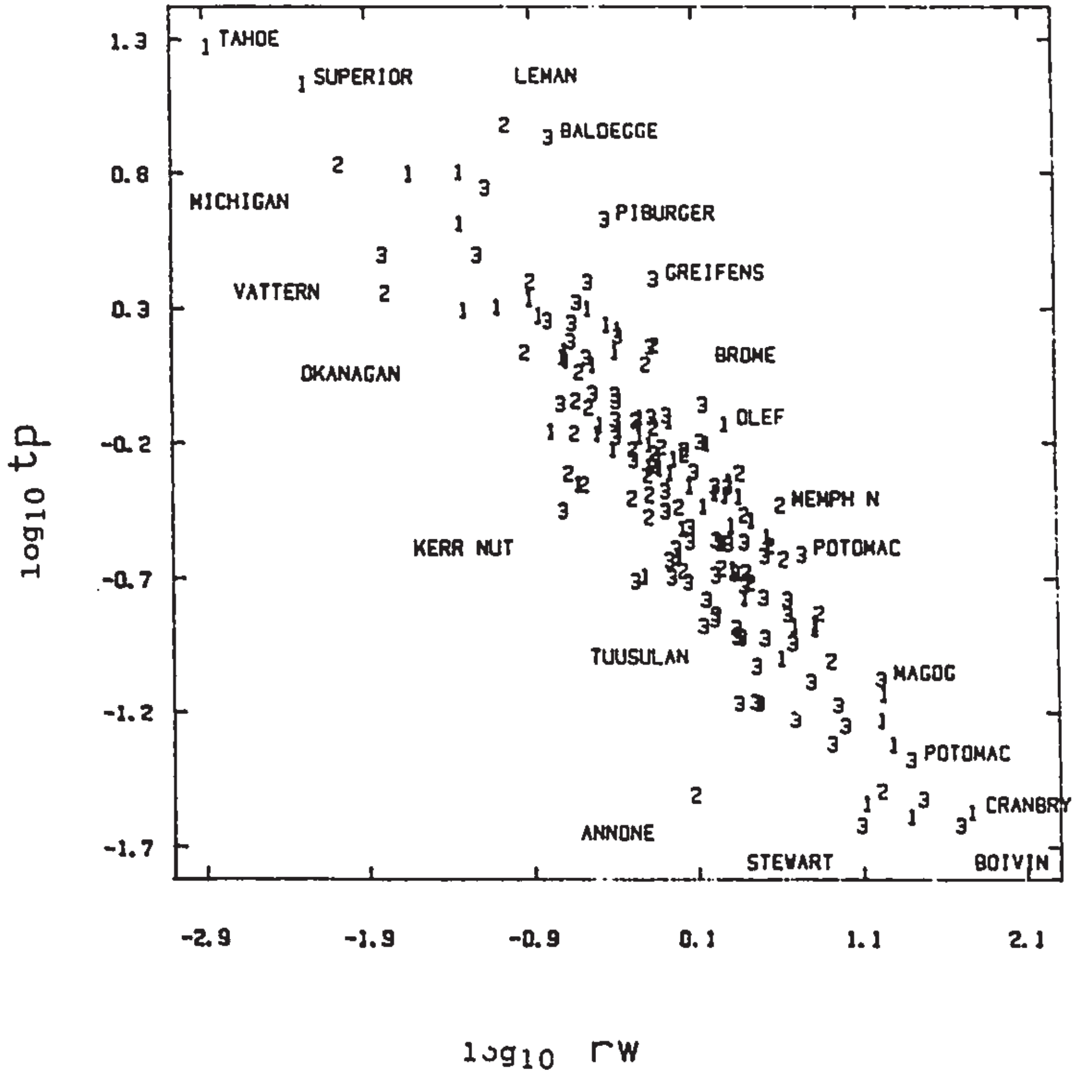
A7.2 Absolute phosphorus residence time vs absolute nitrogen residence time ($r^2 = .73$).



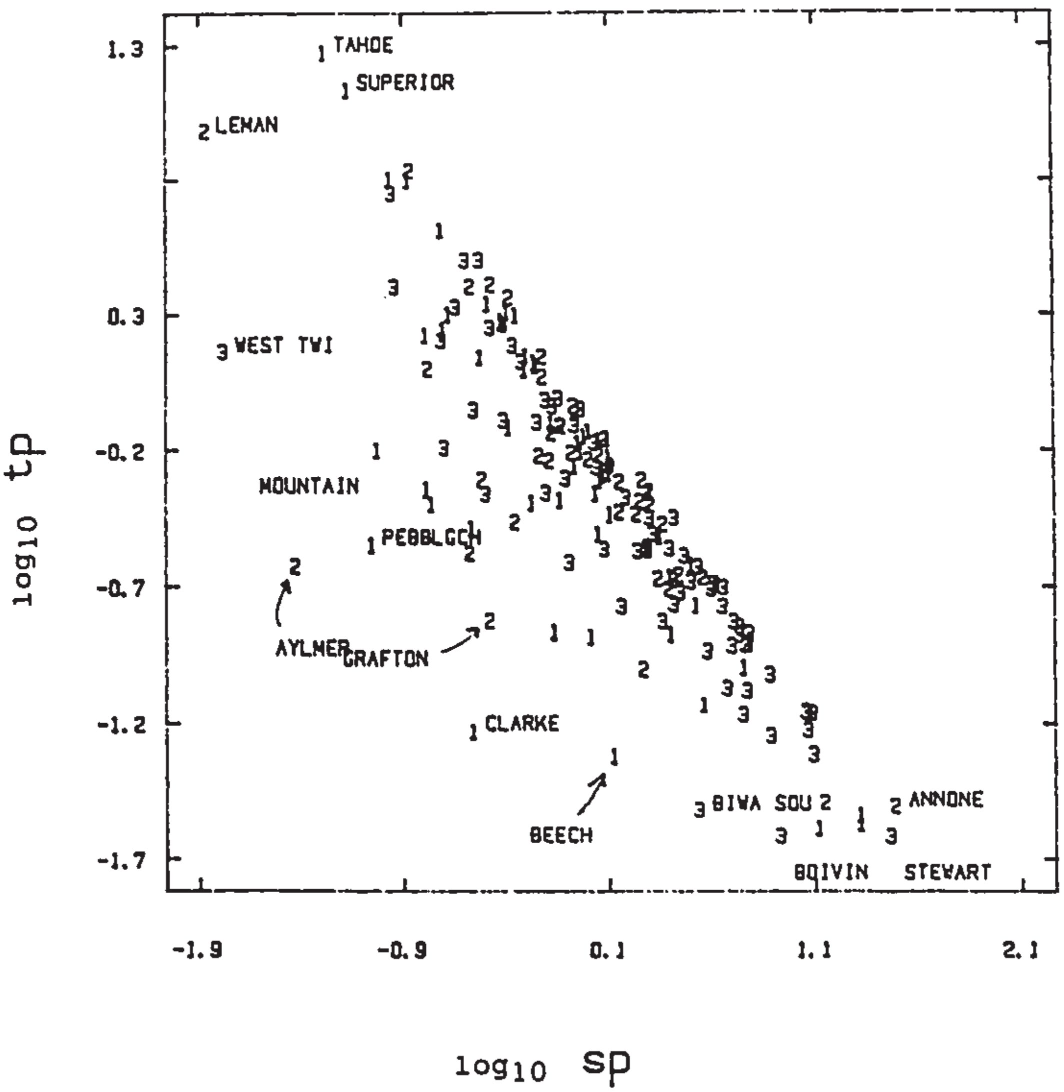
A7.3 Absolute phosphorus residence time vs mean depth ($r^2 = .45$).



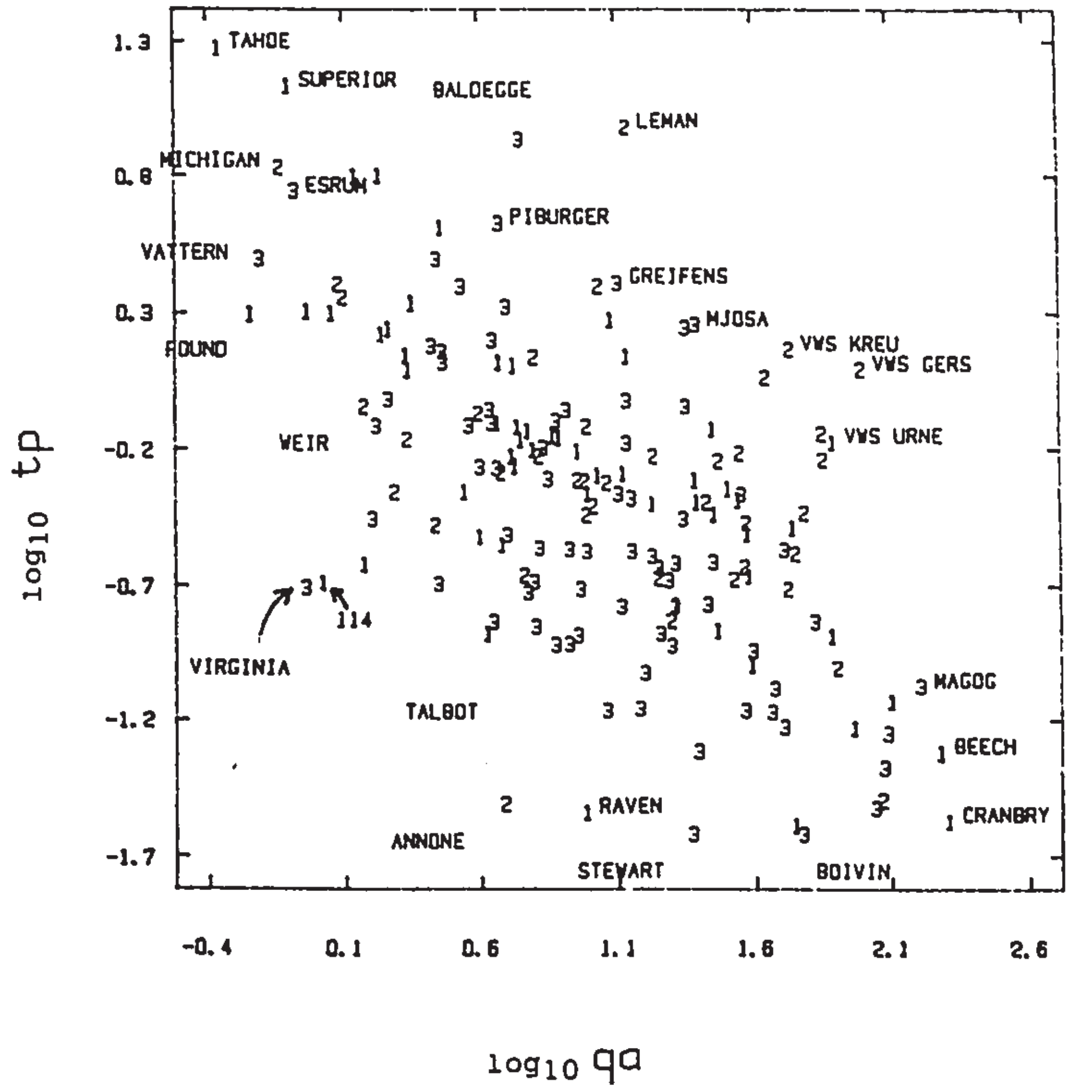
A7.4 Absolute phosphorus residence time vs maximum depth (r^2 = .42).



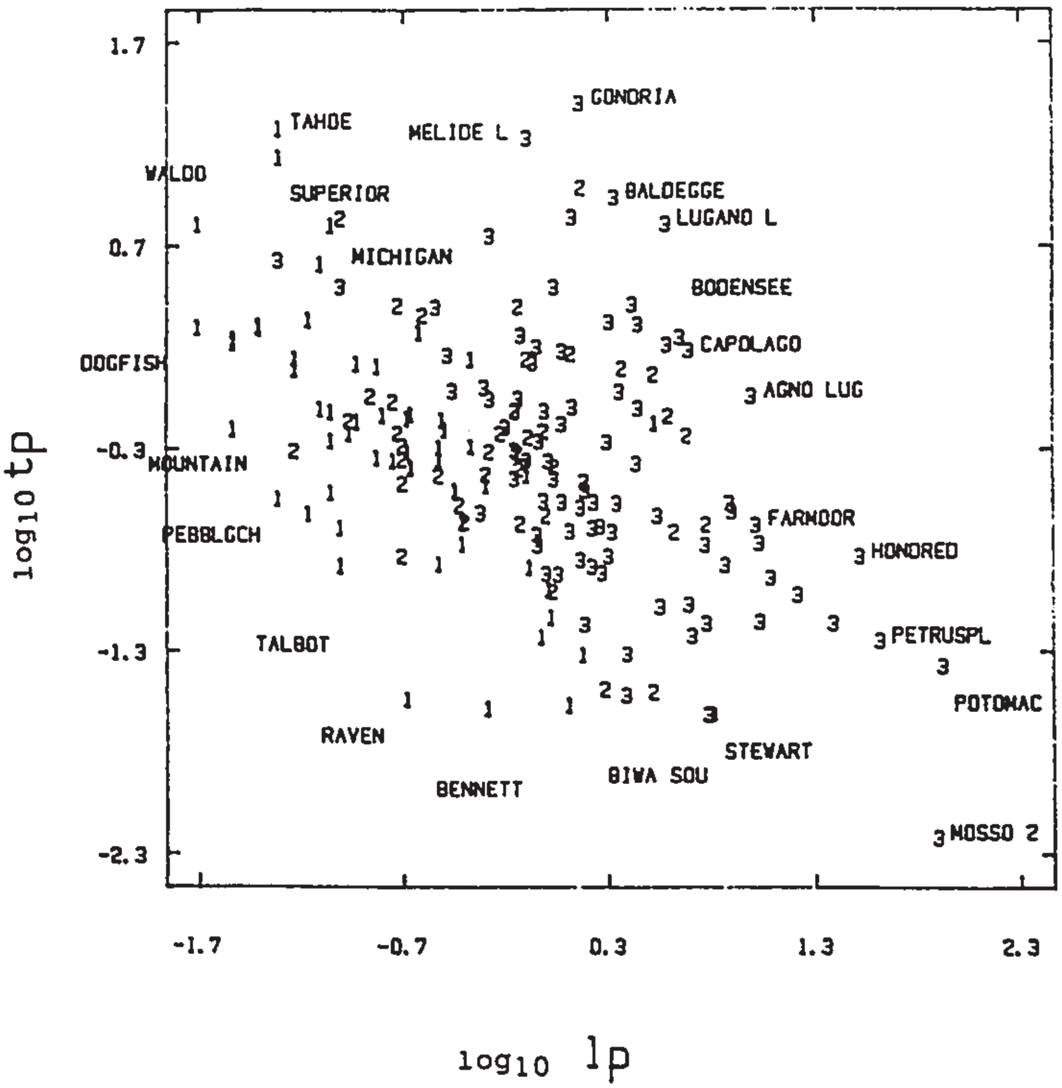
A7.5 Absolute phosphorus residence time vs flushing rate (r^2 = .80).



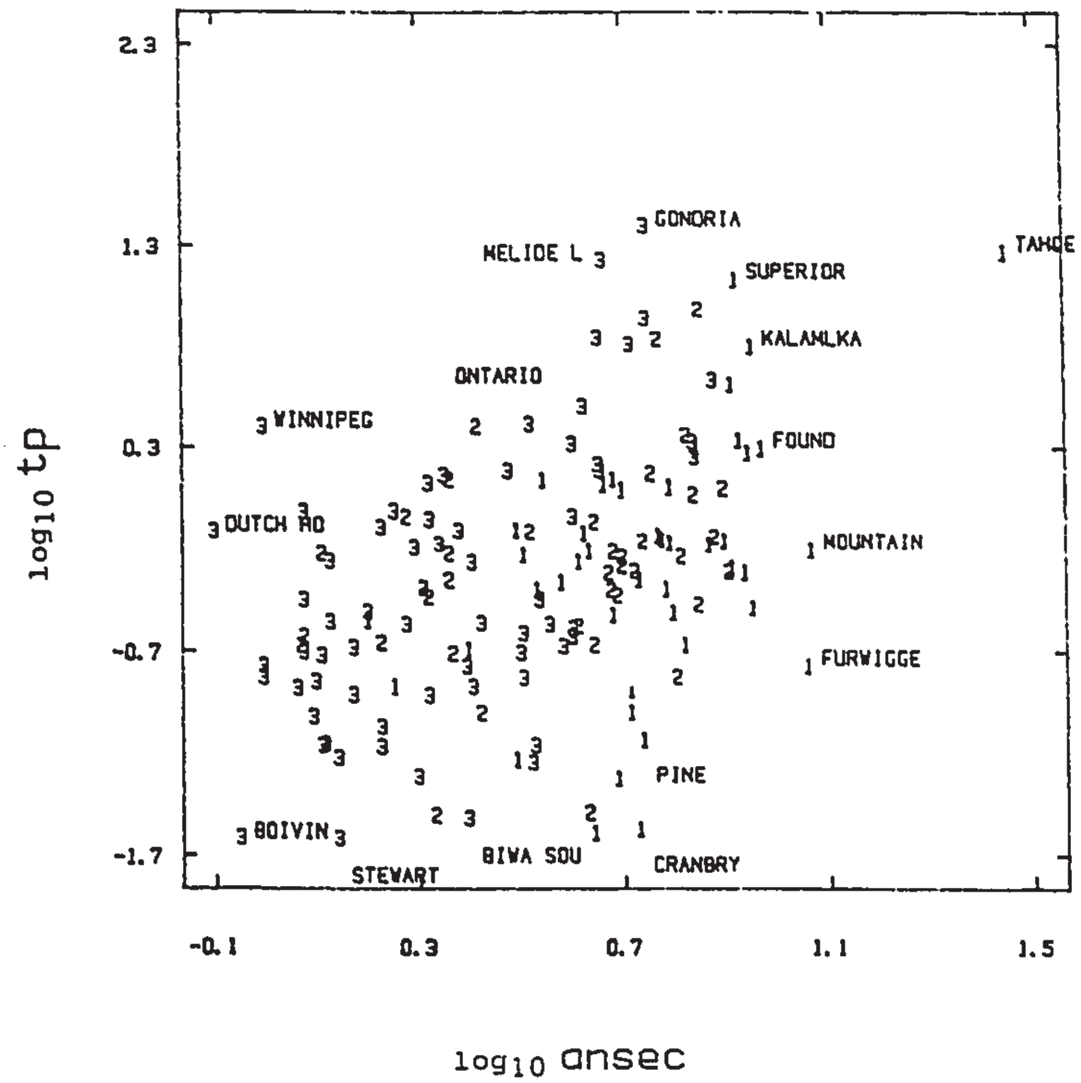
A7.6 Absolute phosphorus residence time vs phosphorus sedimentation rate (r^2 = .67).



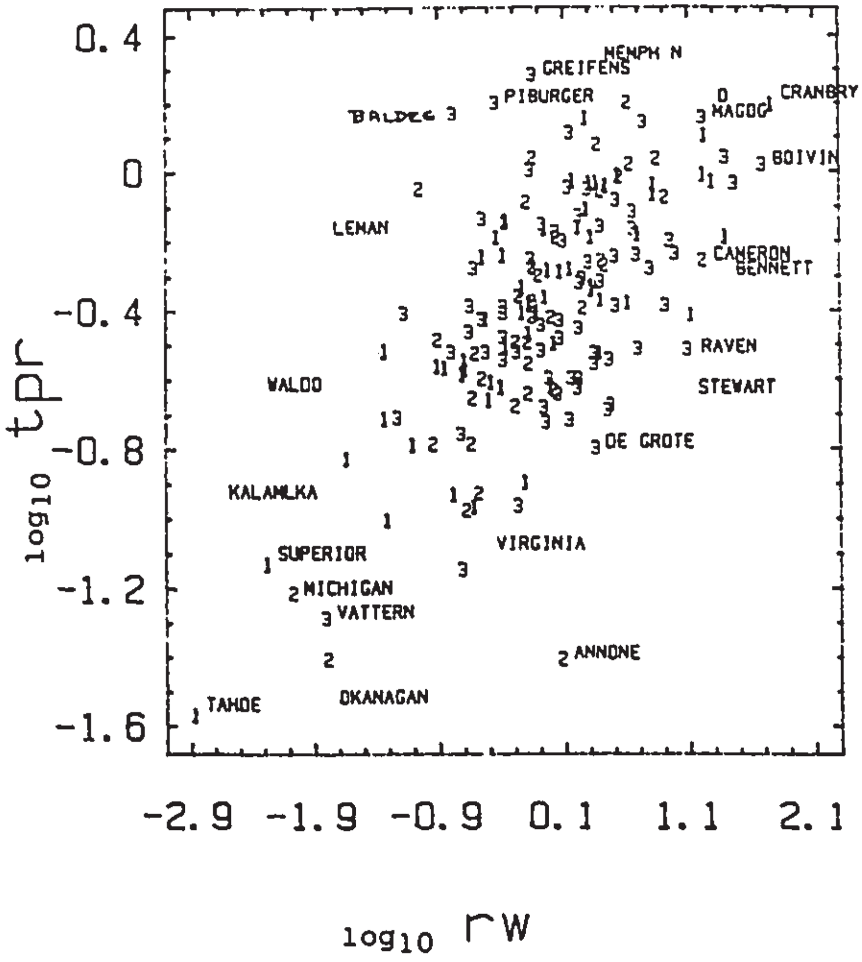
A7.7 Absolute phosphorus residence time vs hydraulic load ($r^2 = .37$).



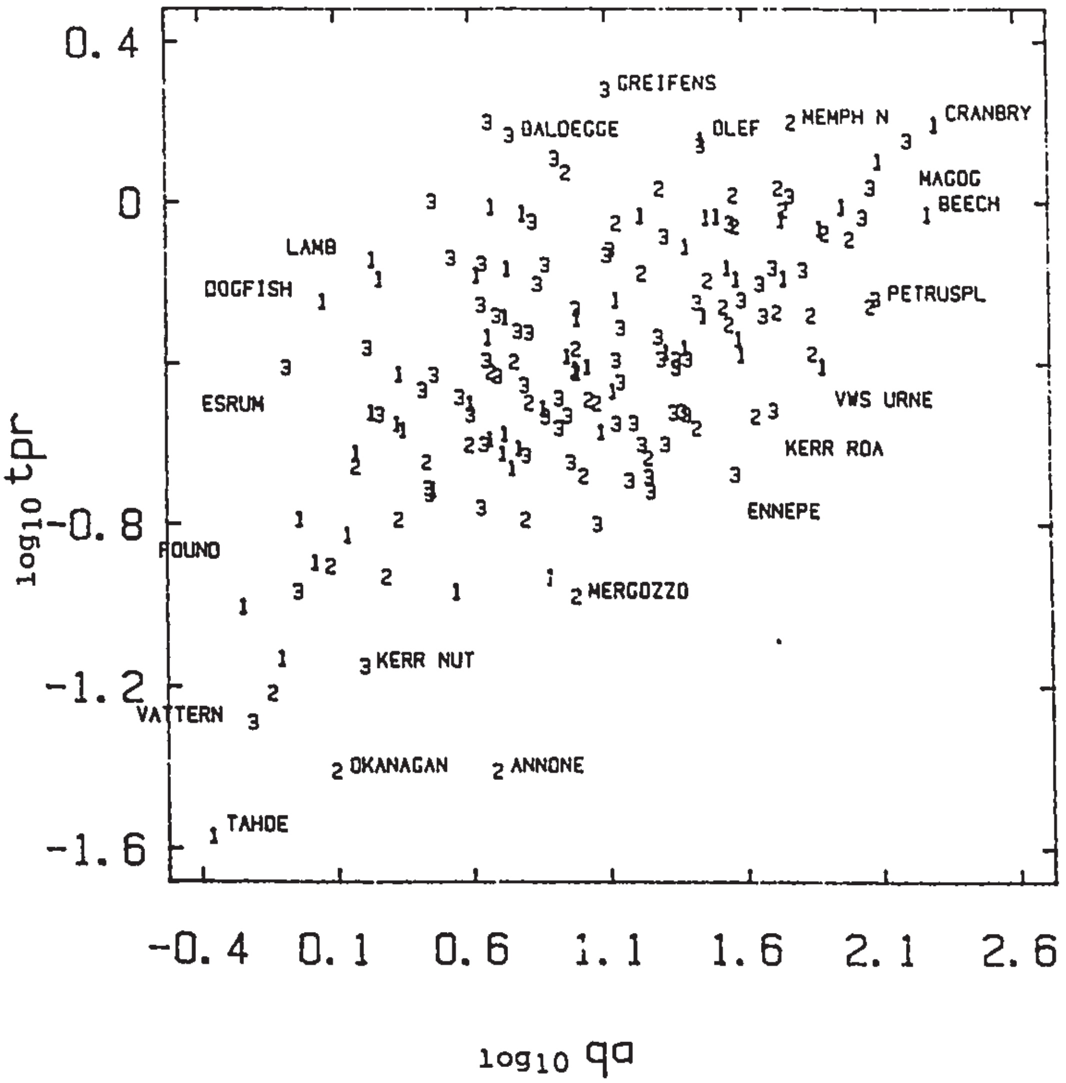
A7.8 Absolute phosphorus residence time vs areal phosphorus loading rate (r^2 = .21).



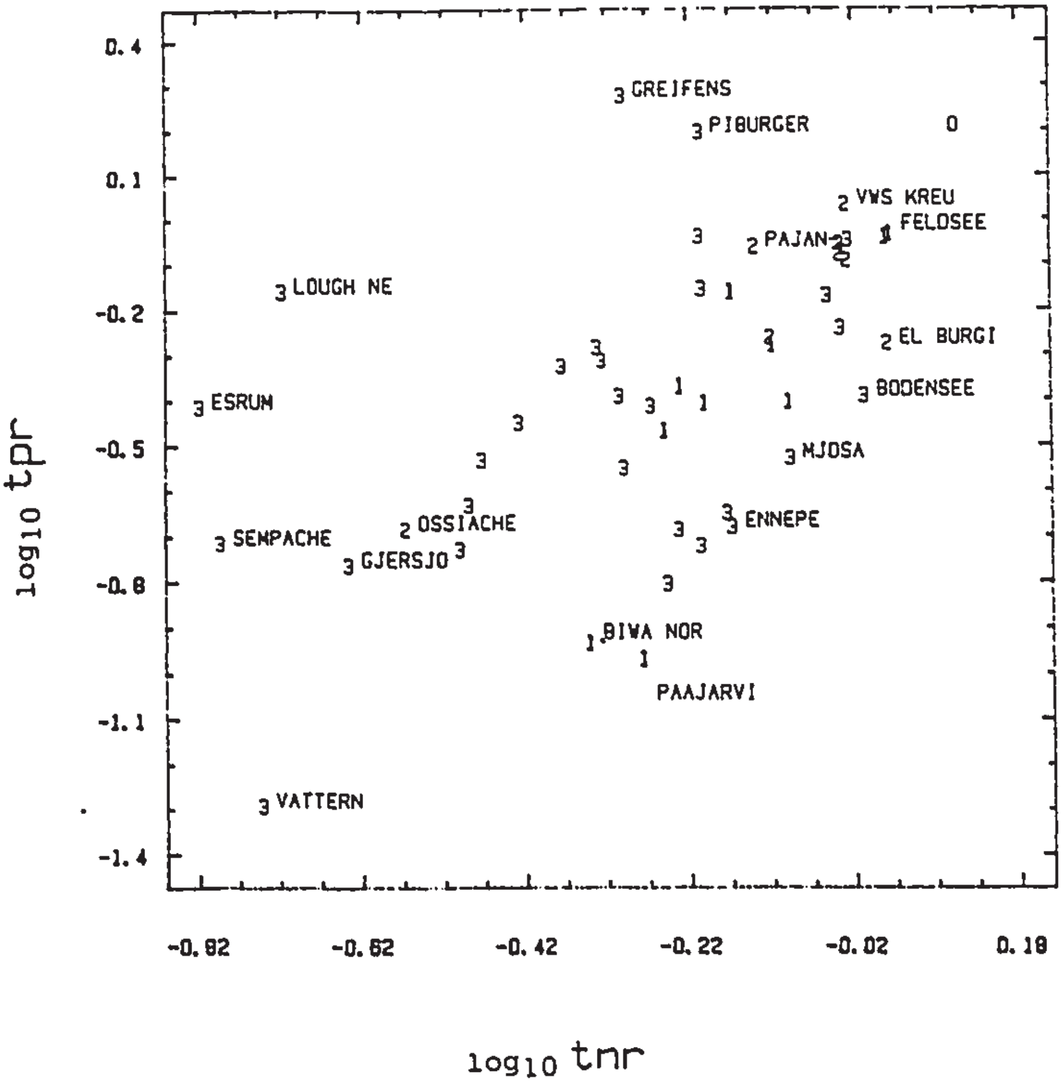
A7.9 Absolute phosphorus residence time vs Secchi depth (r^2 = .20).



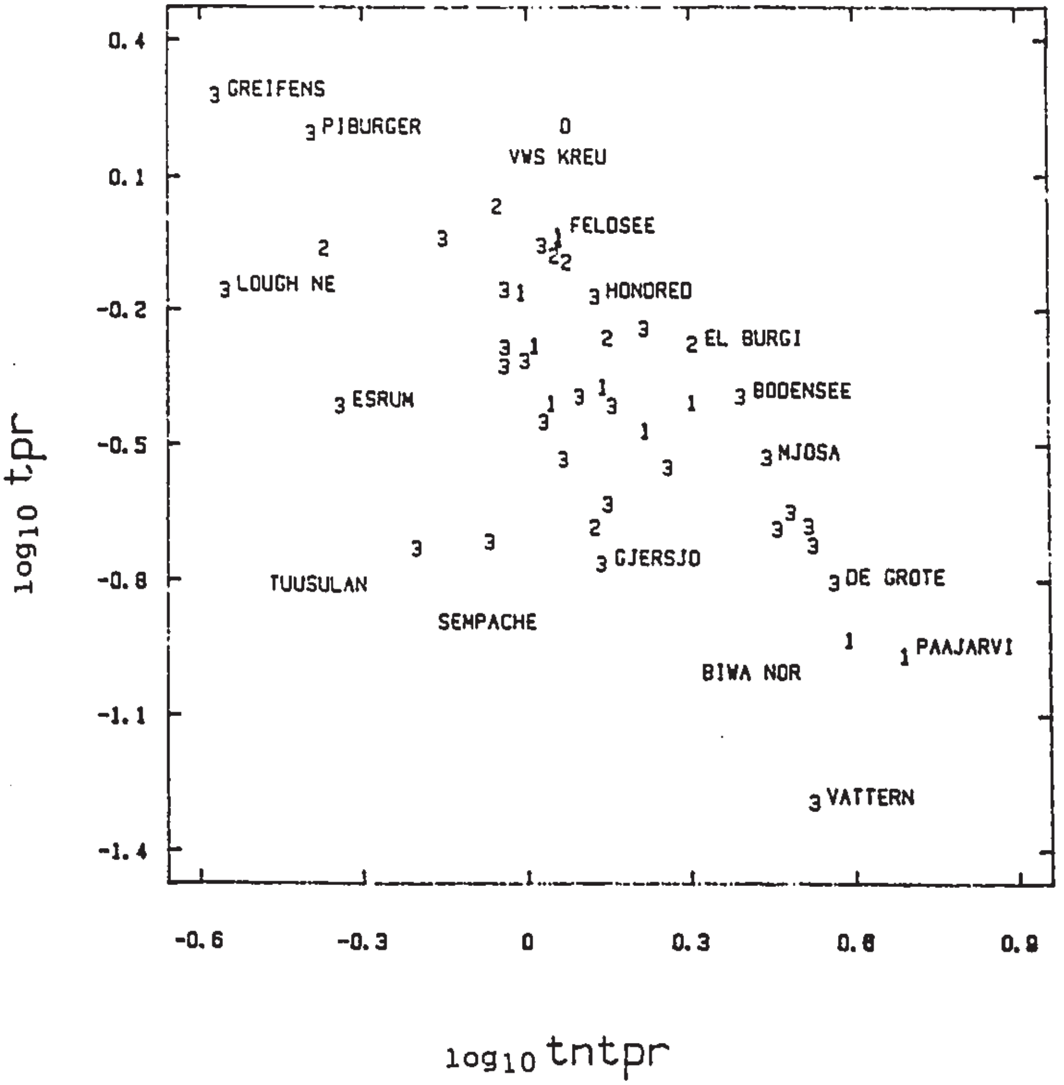
A7.10 Phosphorus relative residence time vs flushing rate (r^2 = .40).



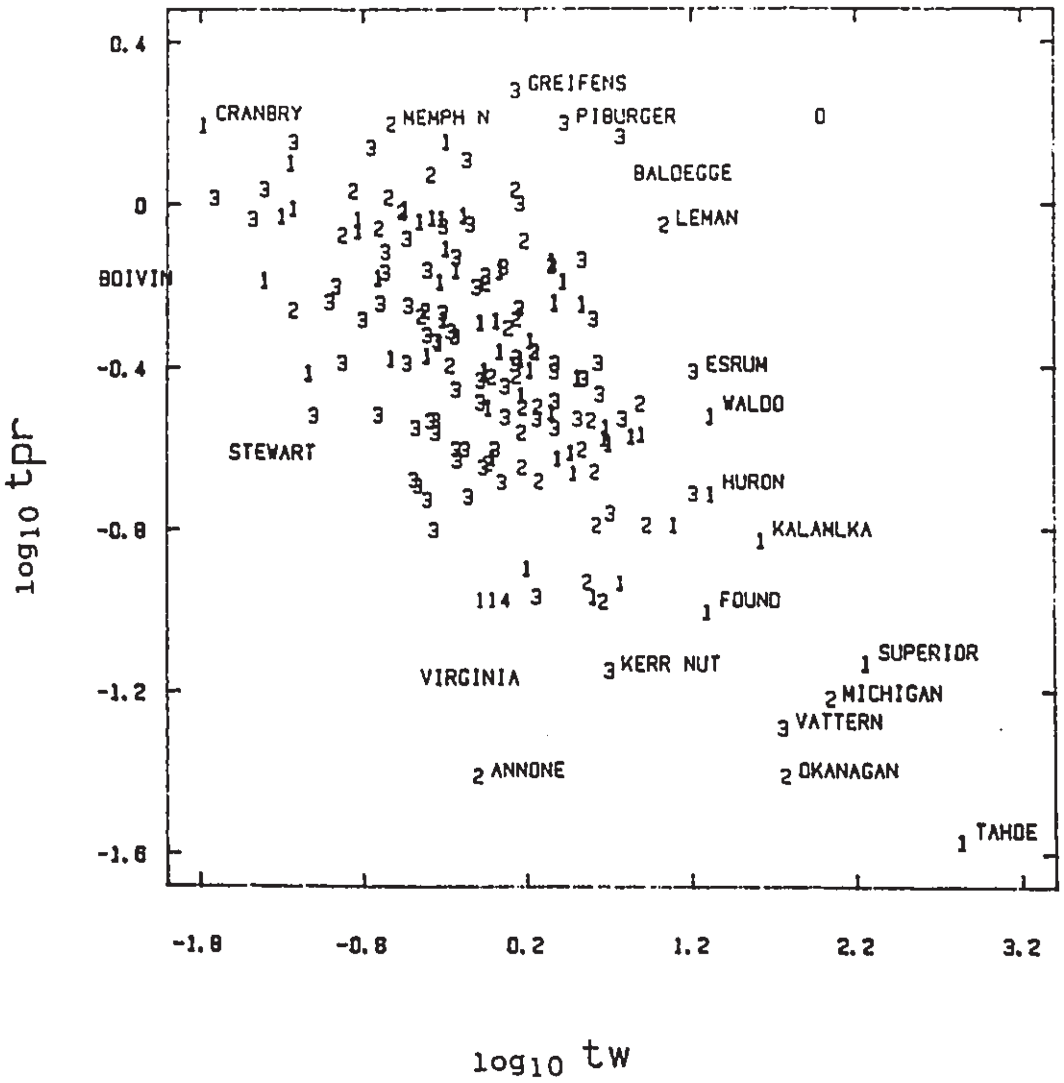
A7.11 Phosphorus relative residence time vs hydraulic load (r^2 = .36).



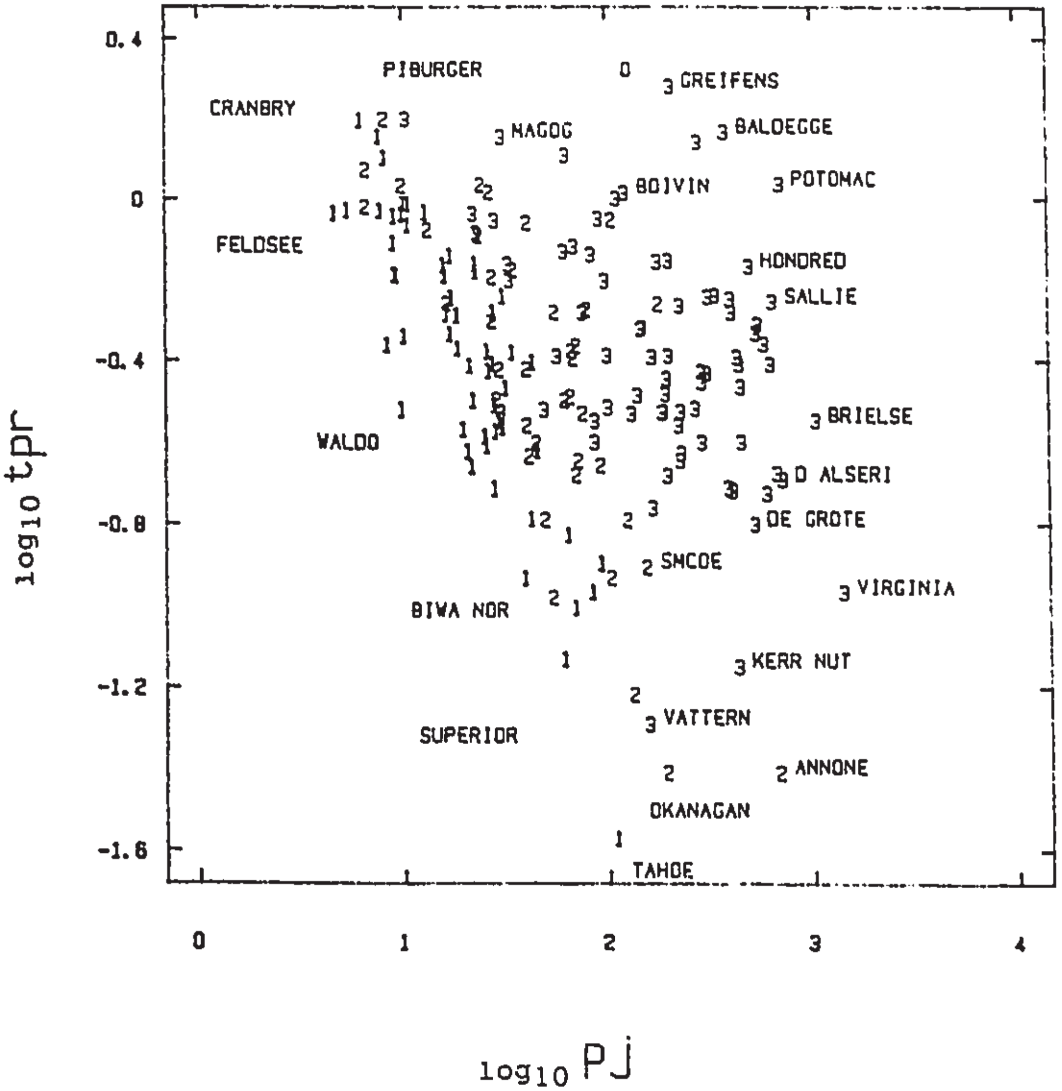
A7.12 Phosphorus relative residence time vs nitrogen relative residence time (r^2 = .25).



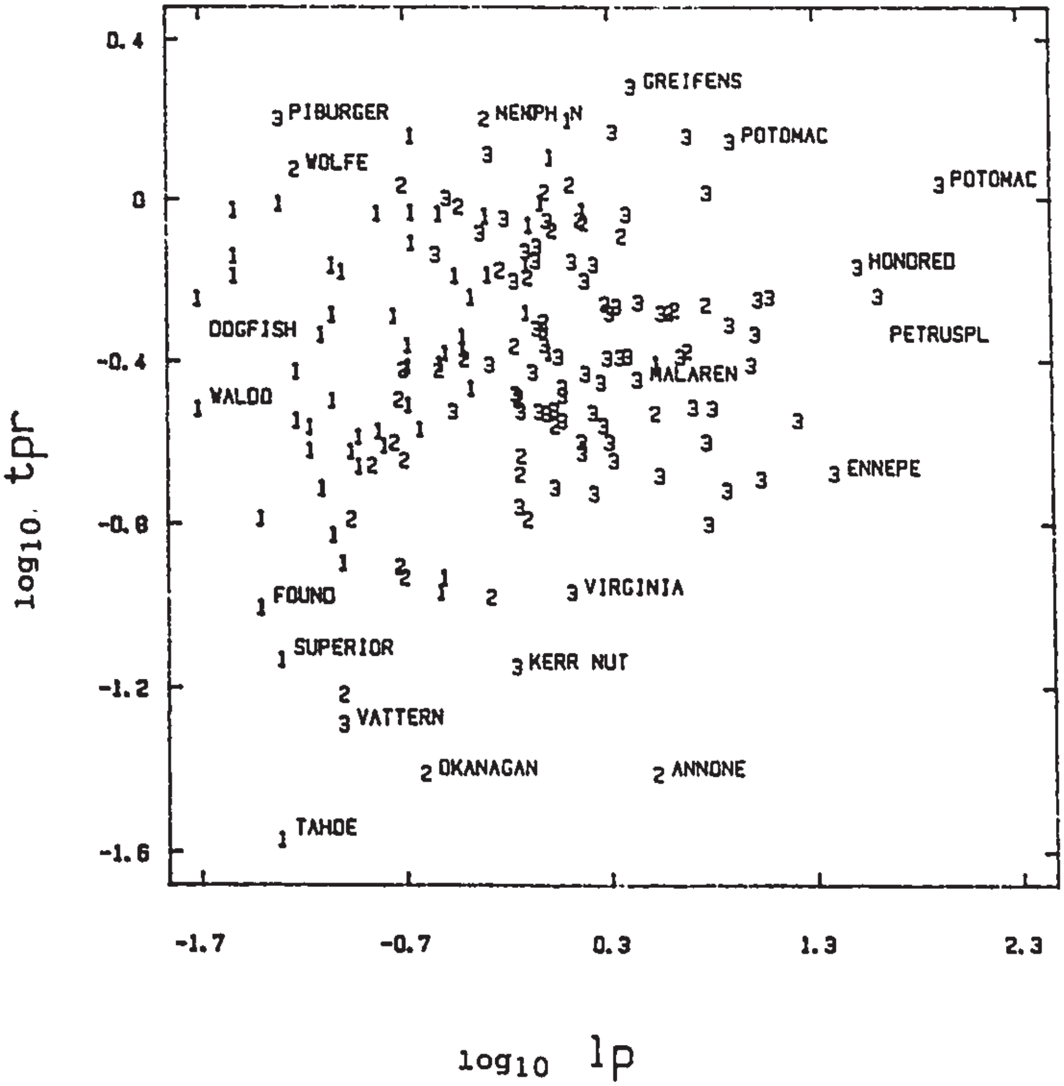
A7.13 Phosphorus relative residence time vs (T_n/T_p) (r^2 = .48).



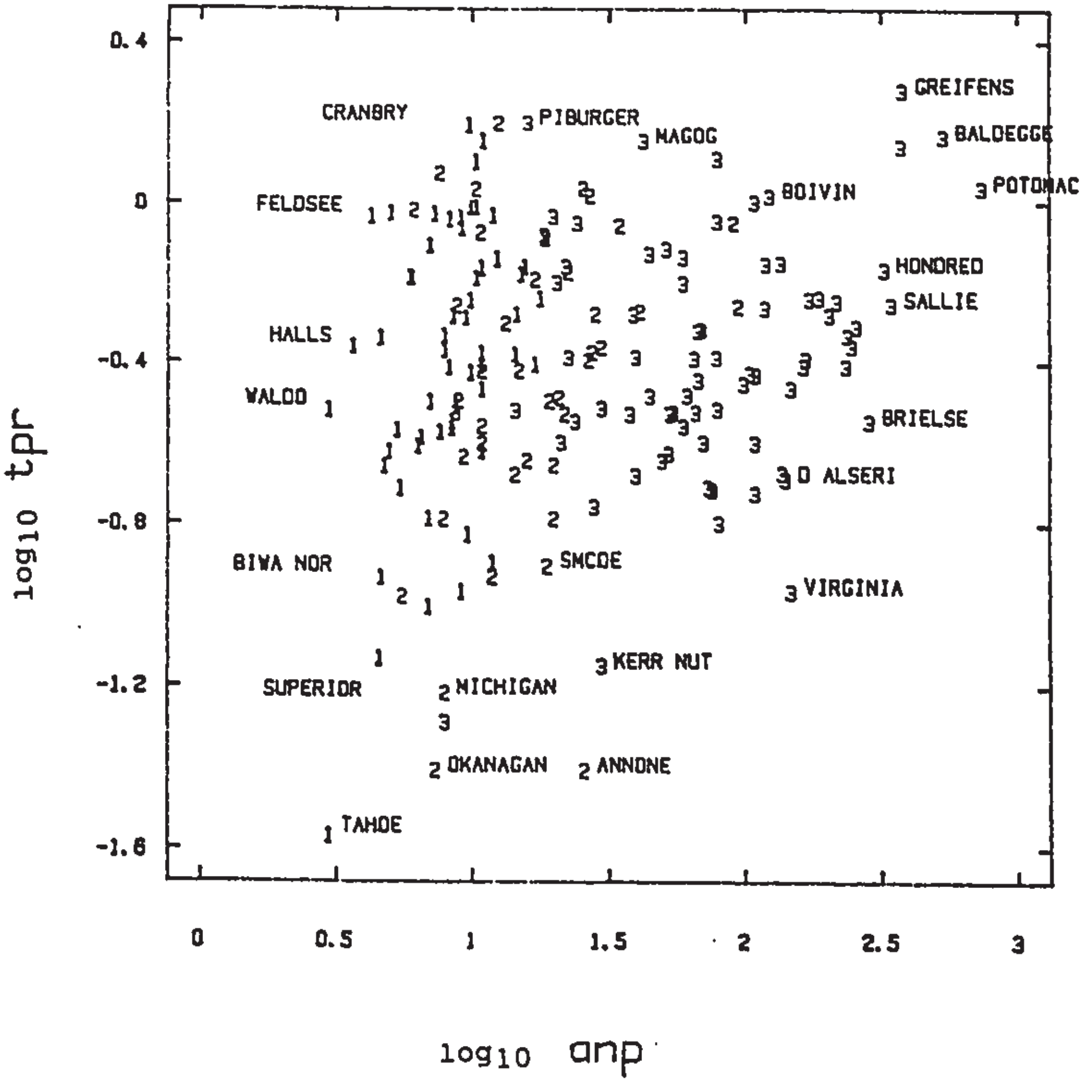
A7.14 Phosphorus relative residence time vs water residence time ($r^2 = .39$).



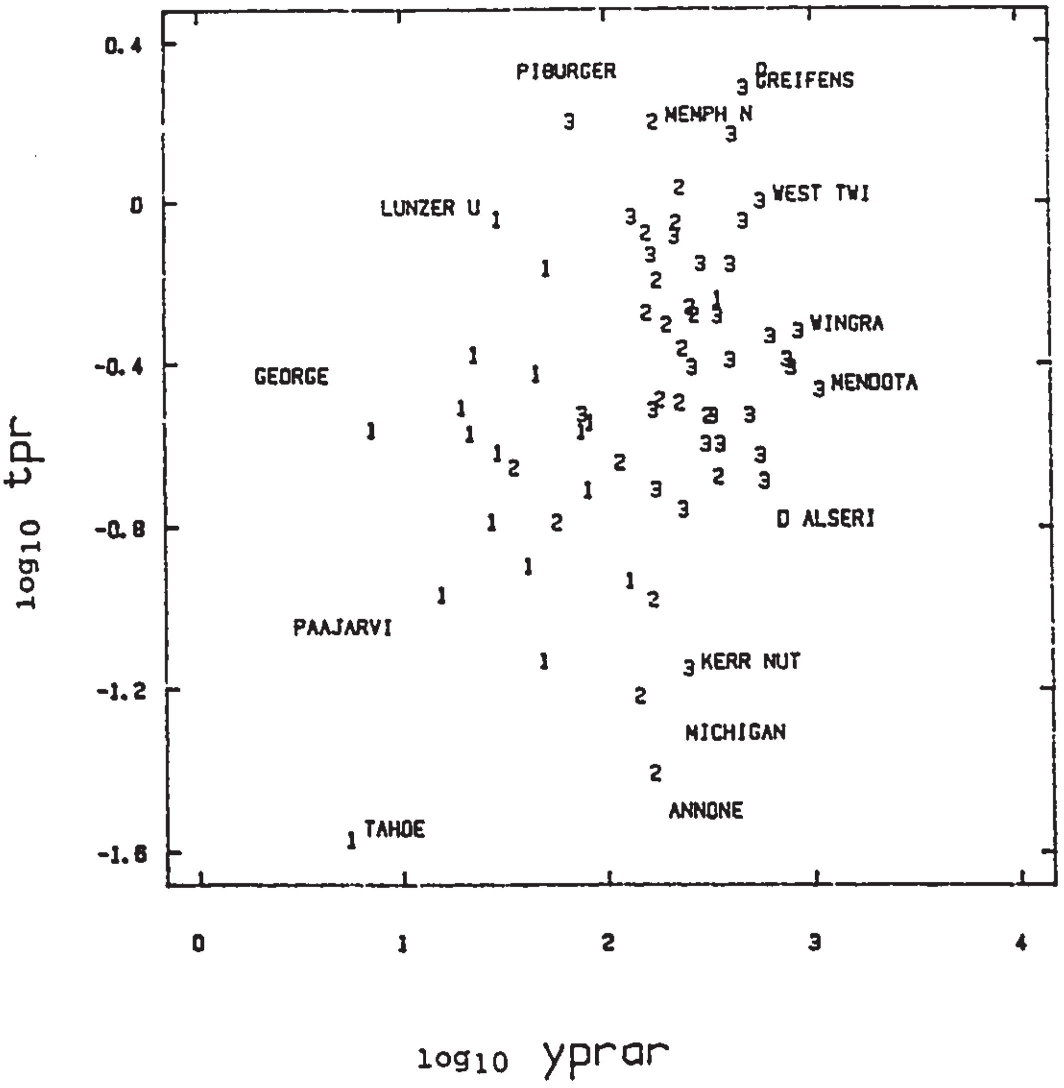
A7.15 Phosphorus relative residence time vs phosphorus inflow concentration (r^2 = .16).



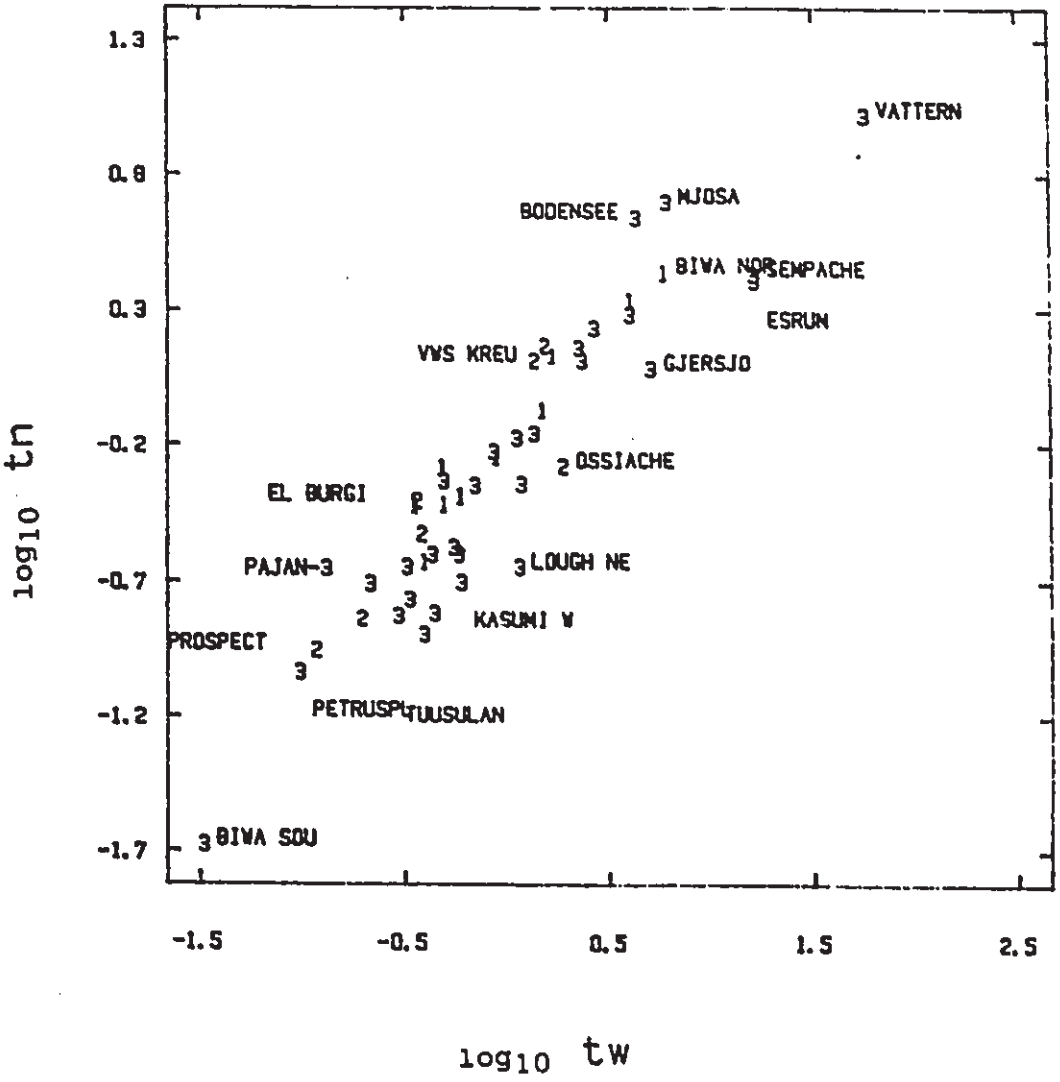
A7.16 Phosphorus relative residence time vs phosphorus areal loading rate ($r^2 = .03$).



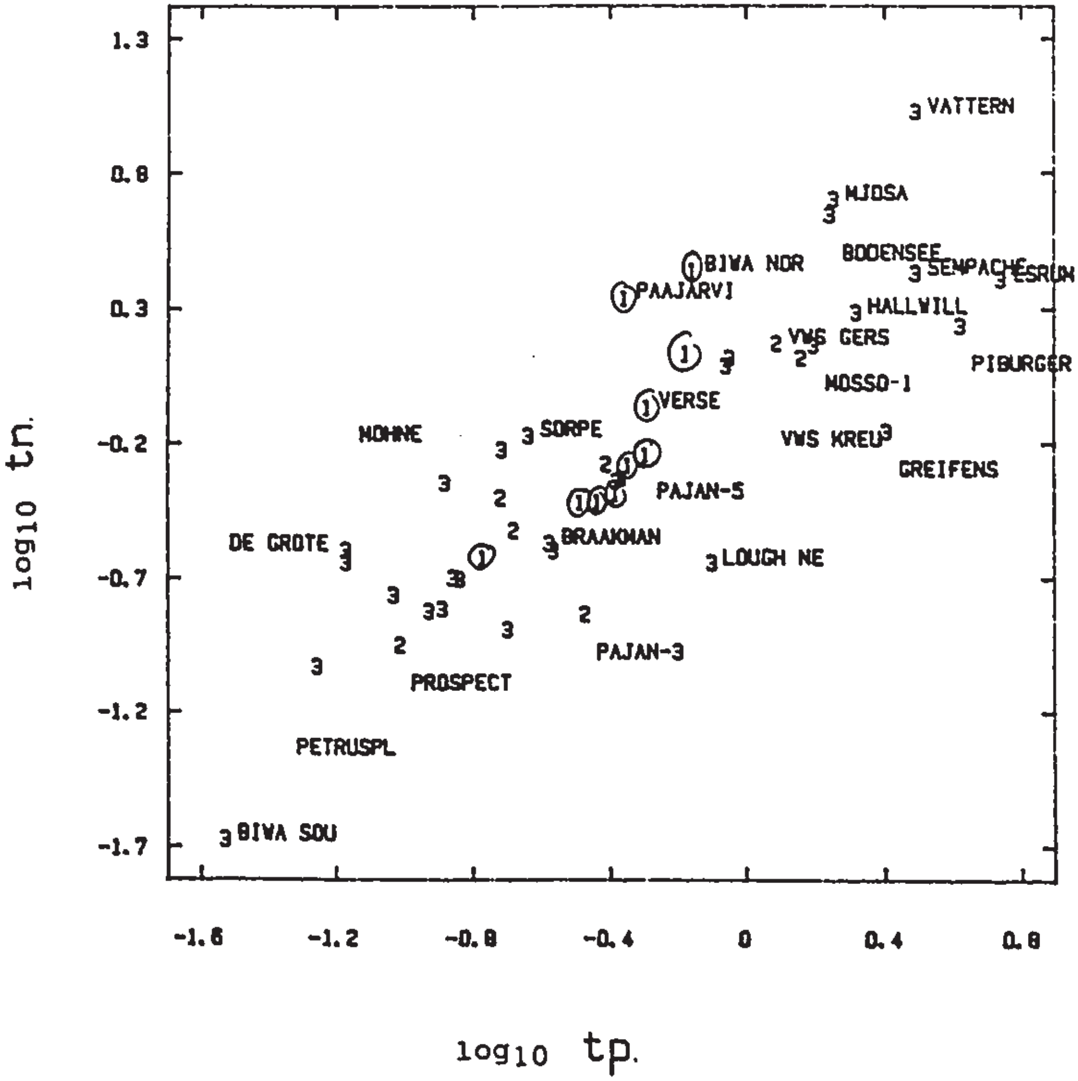
A7.17 Phosphorus relative residence time vs annual average phosphorus concentration ($r^2 = .04$).



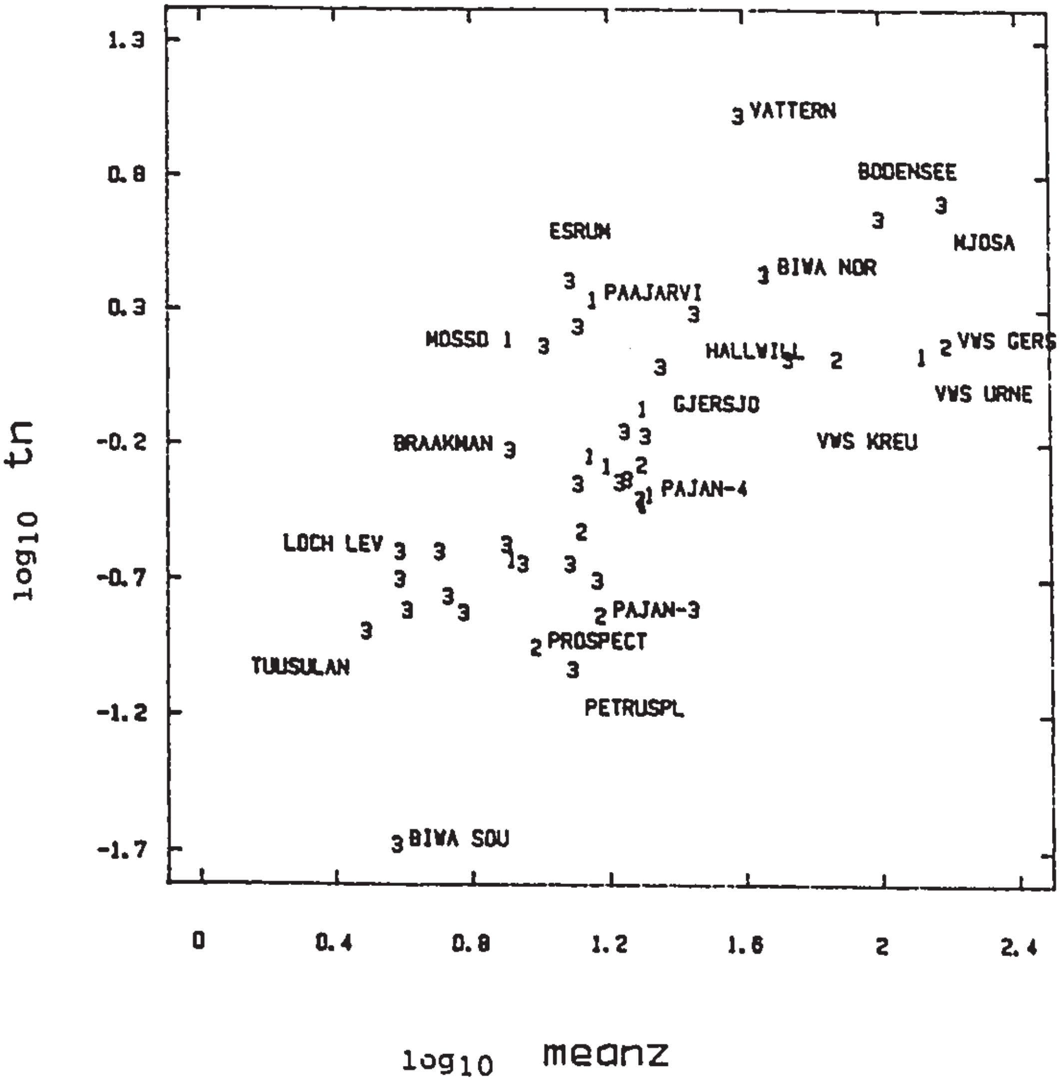
A7.18 Phosphorus relative residence time vs annual areal primary production ($r^2 = .12$).



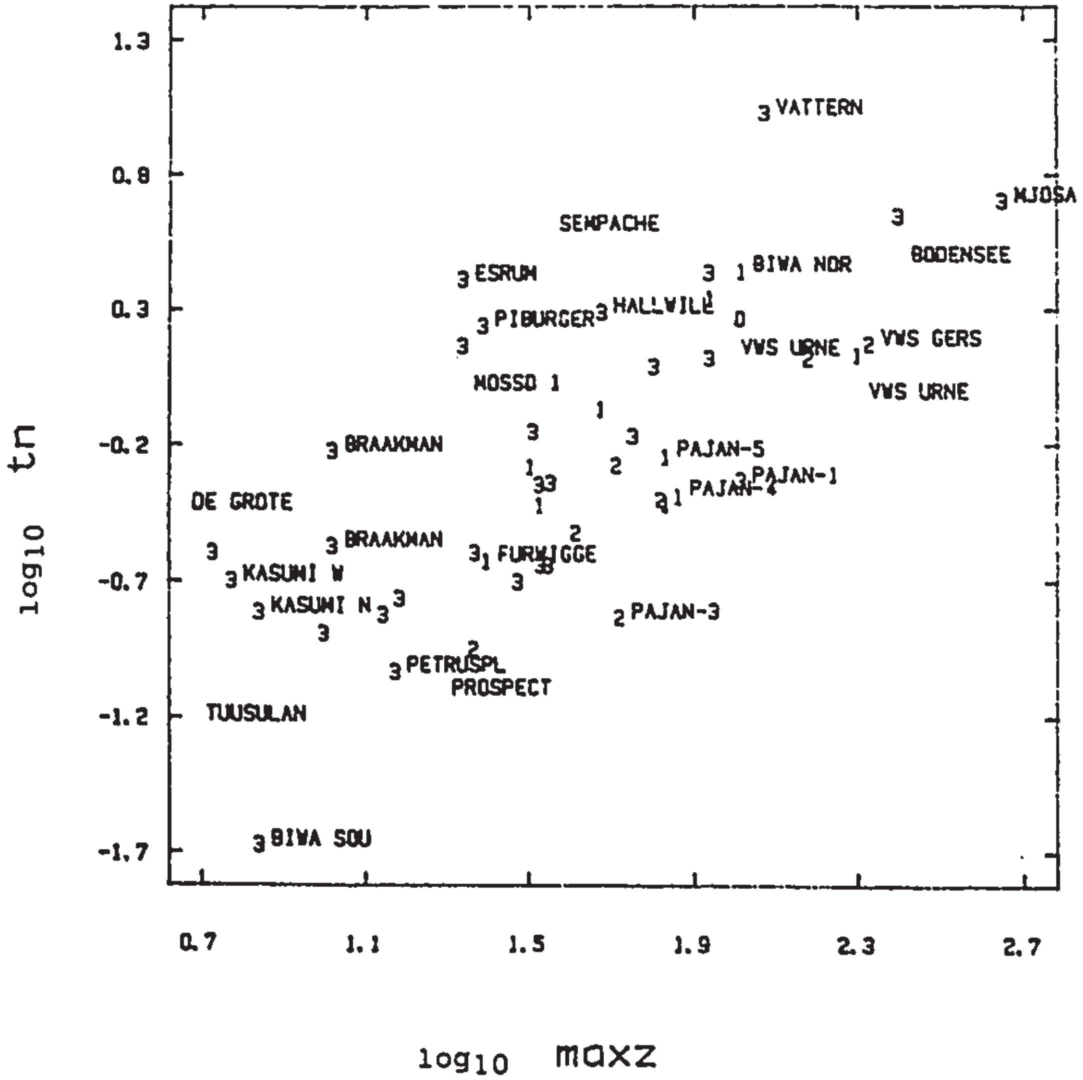
A7.19 Absolute nitrogen residence time vs water residence time (r^2 = .87).



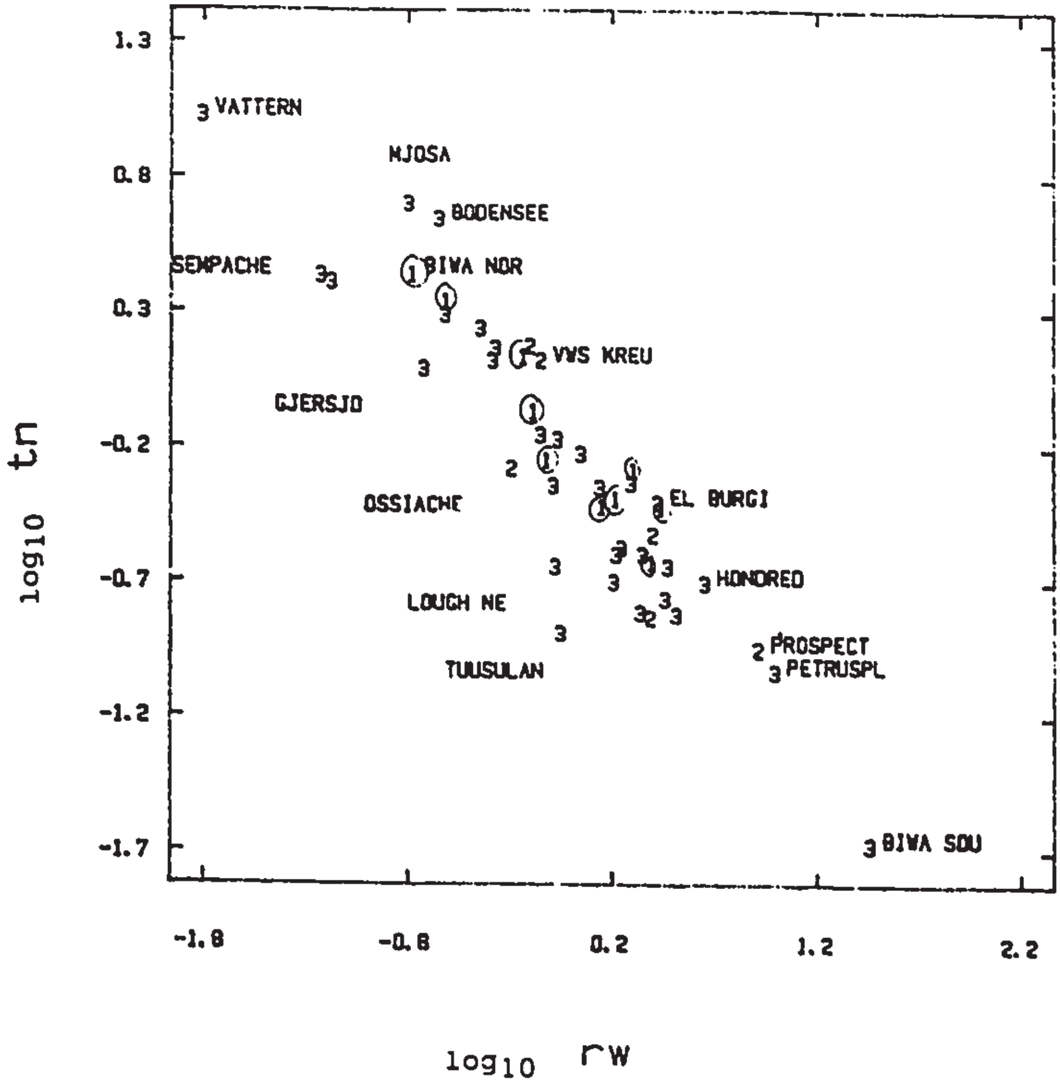
A7.20 Absolute nitrogen residence time vs absolute phosphorus residence time ($r^2 = .73$).



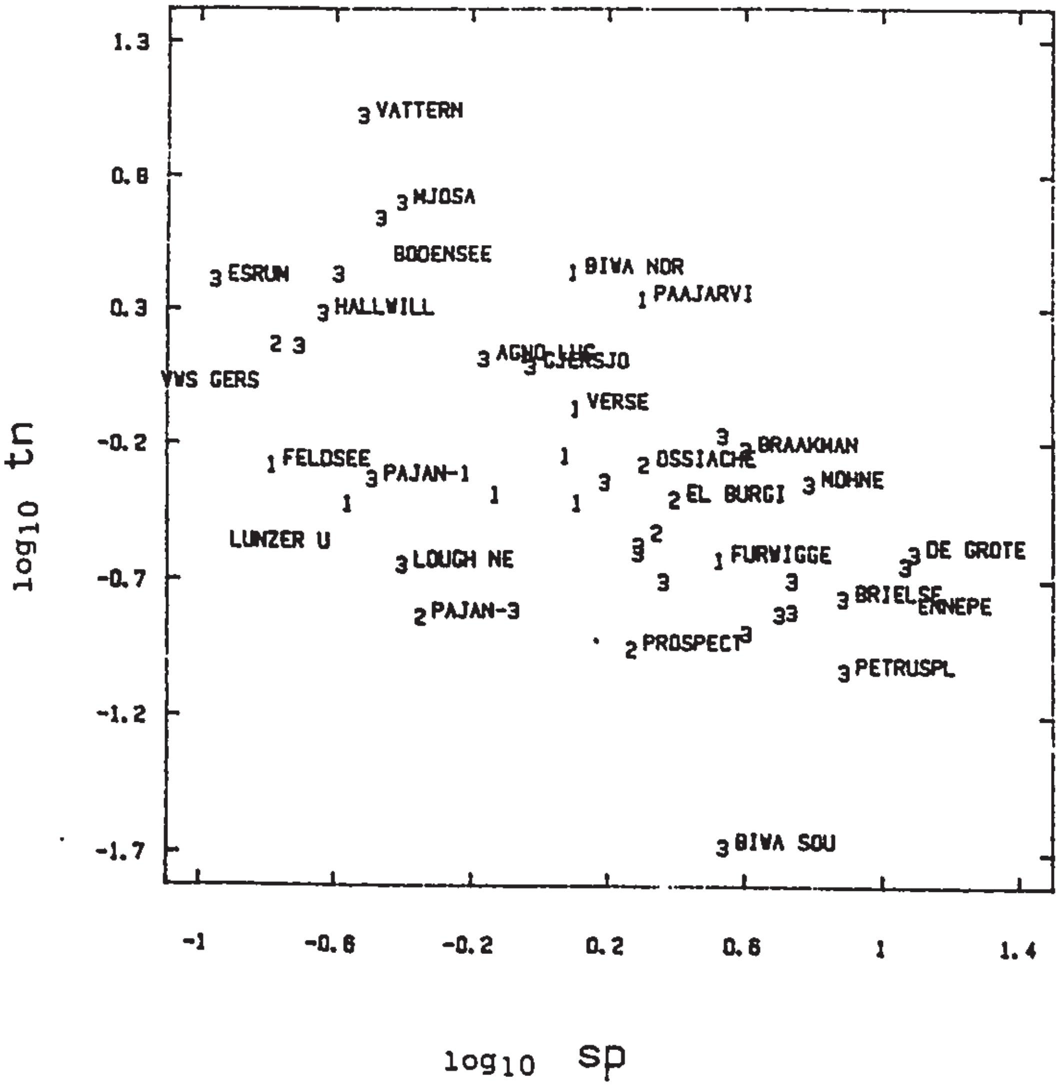
A7.21 Absolute nitrogen residence time vs mean depth (r^2 = .54).



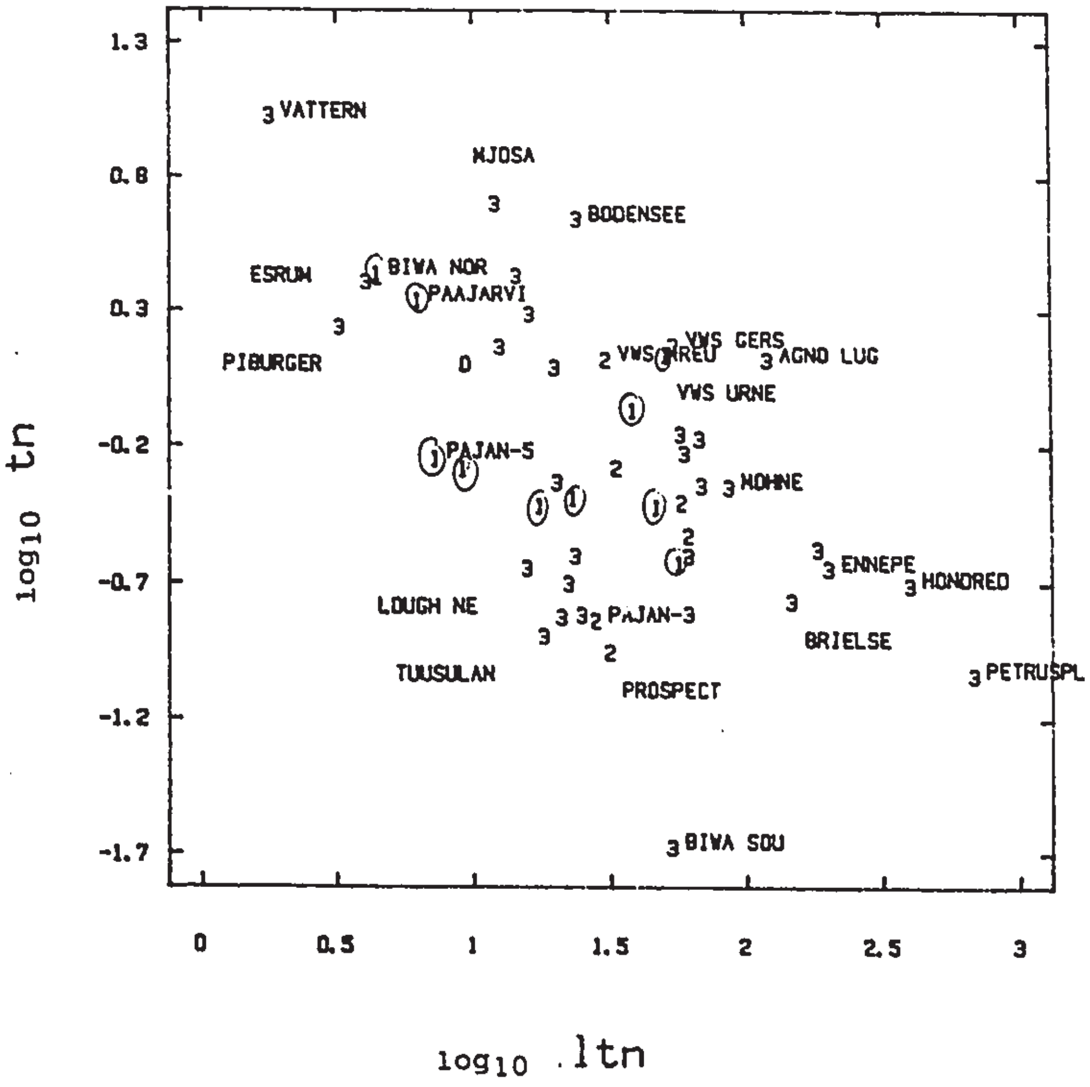
A7.22 Absolute nitrogen residence time vs maximum depth (r^2 = .49).



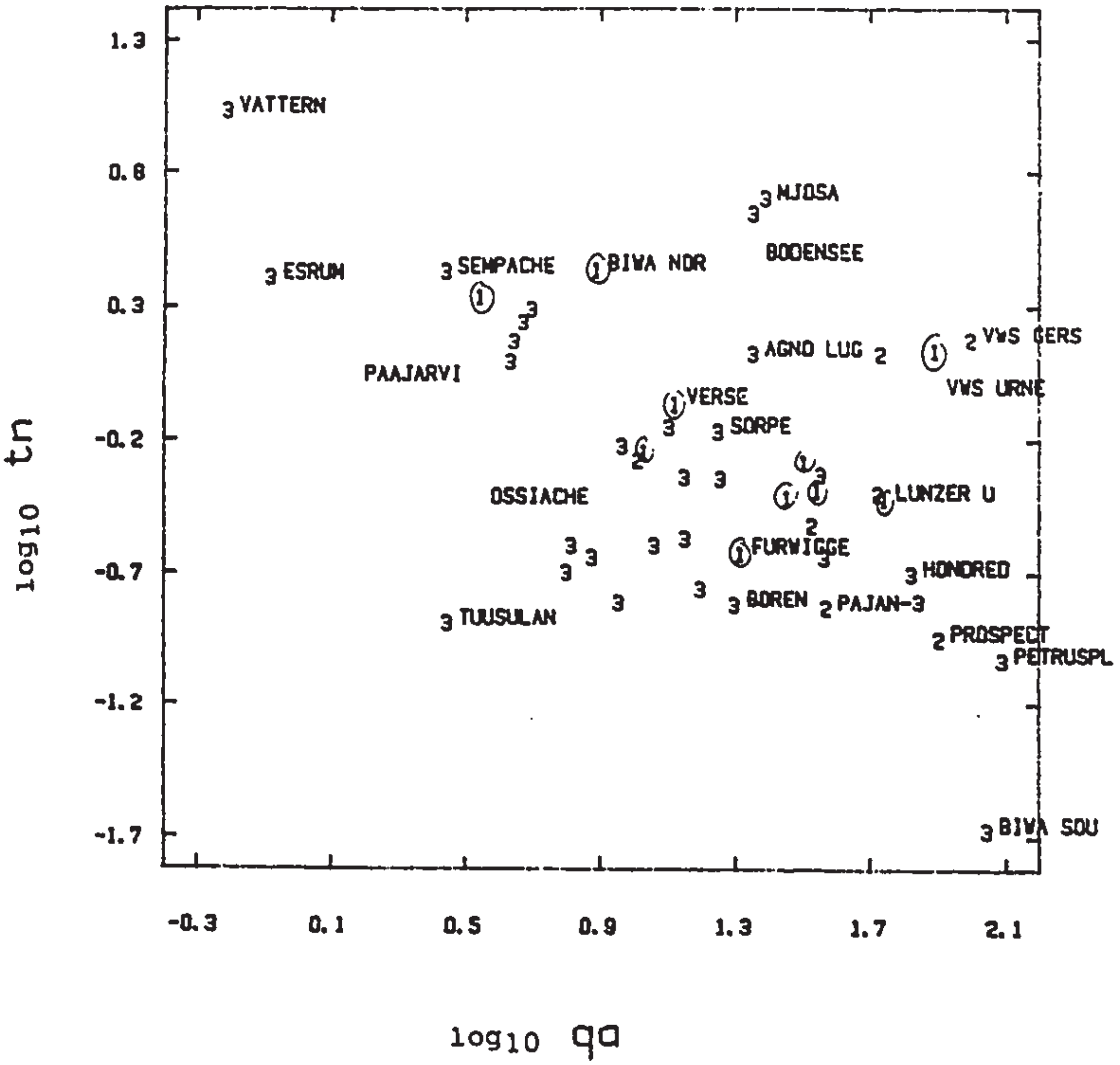
A7.23 Absolute nitrogen residence time vs flushing rate (r^2 = .84).



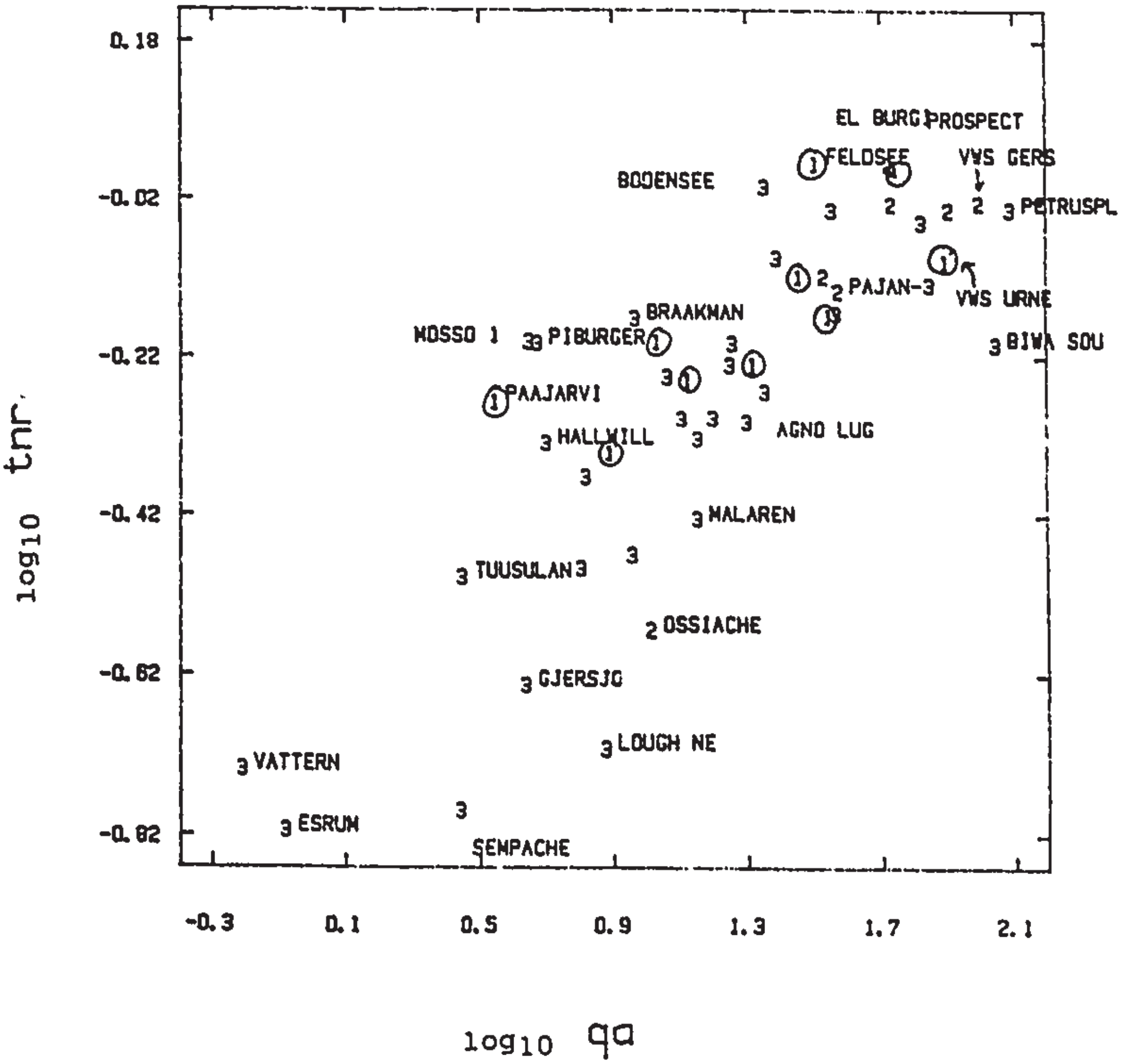
A7.24 Absolute nitrogen residence time vs phosphorus sedimentation rate (r^2 = .38).



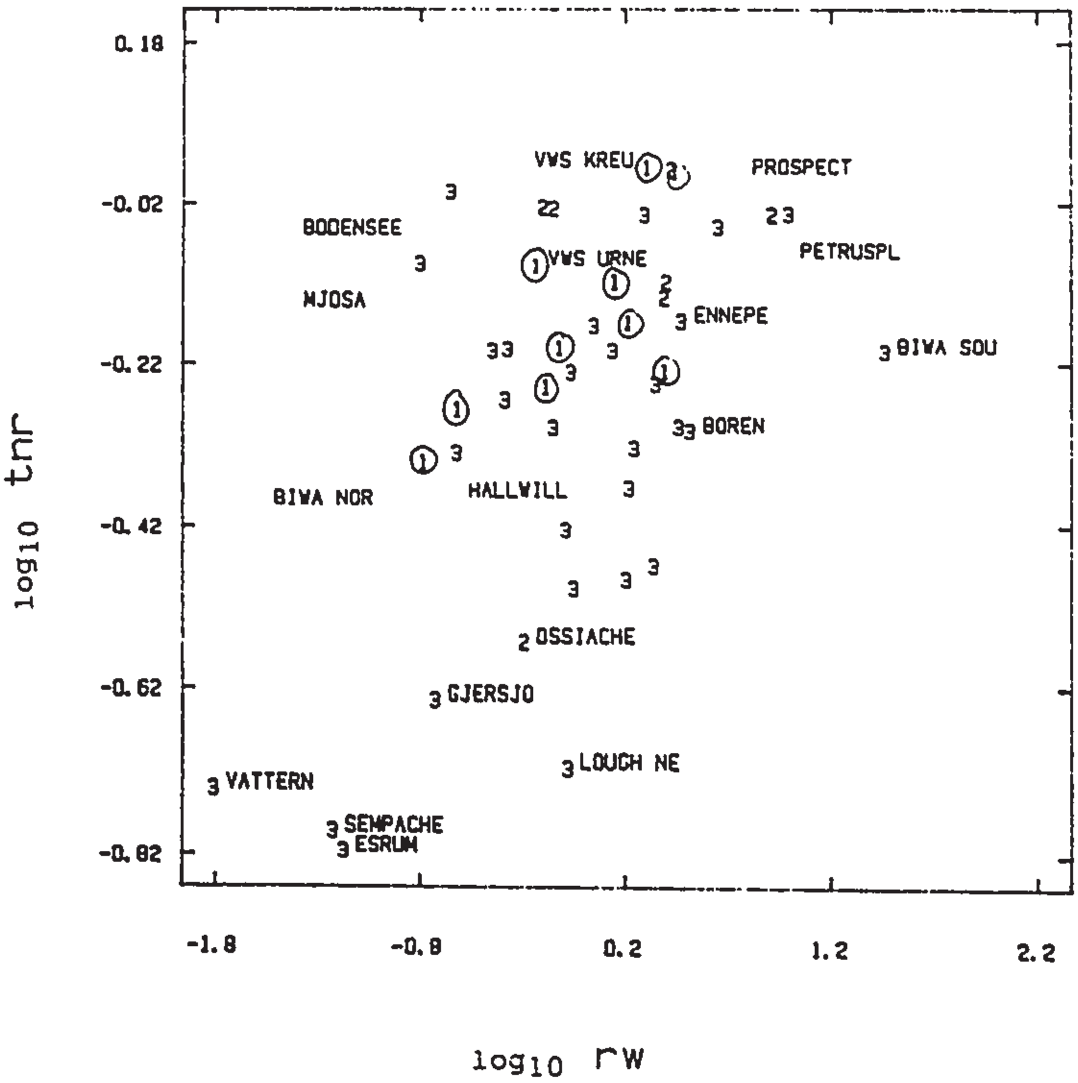
A7.25 Absolute nitrogen residence time vs areal nitrogen loading rate ($r^2 = .30$).



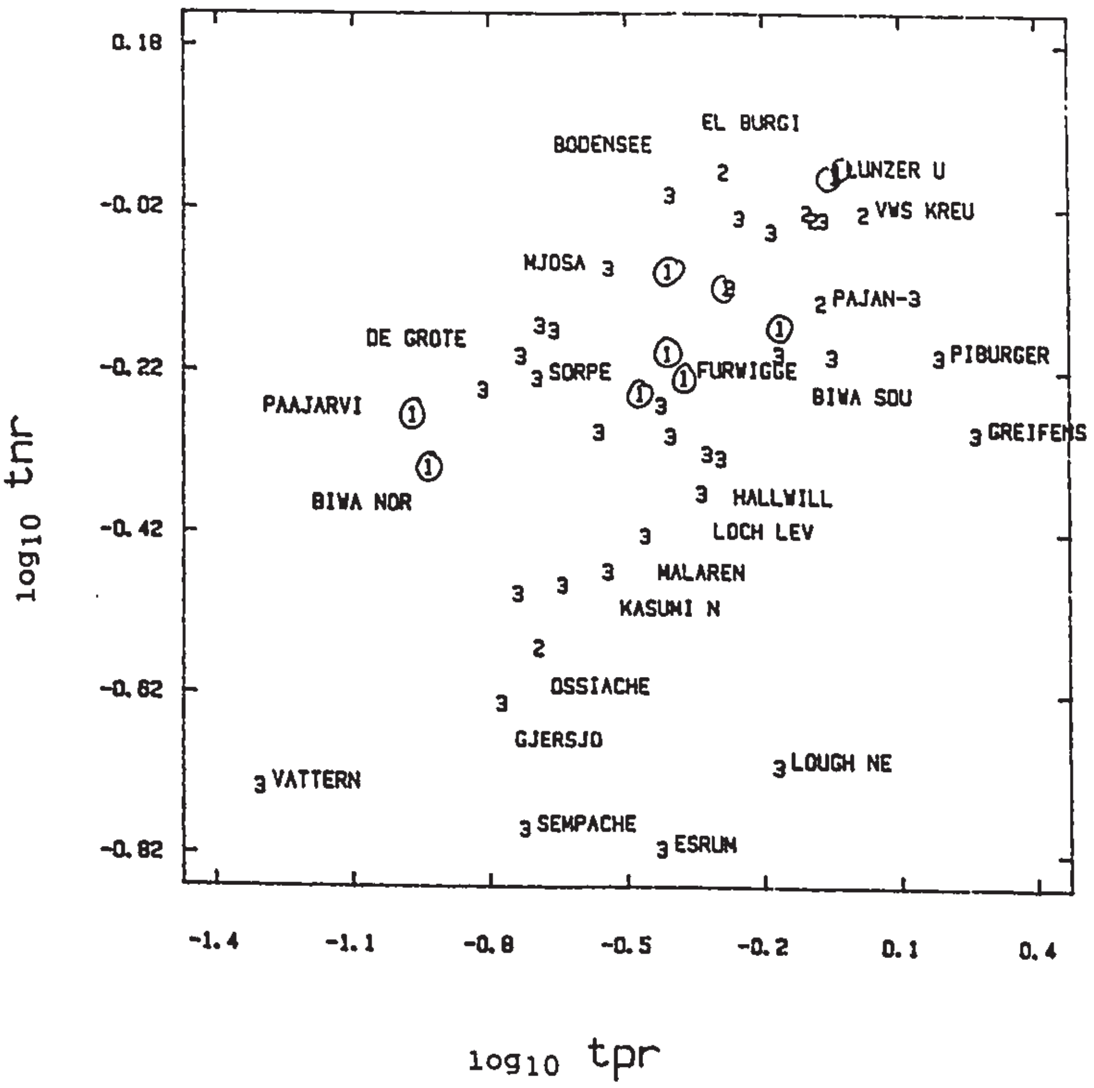
A7.26 Absolute nitrogen residence time vs hydraulic load (r^2 = .23).



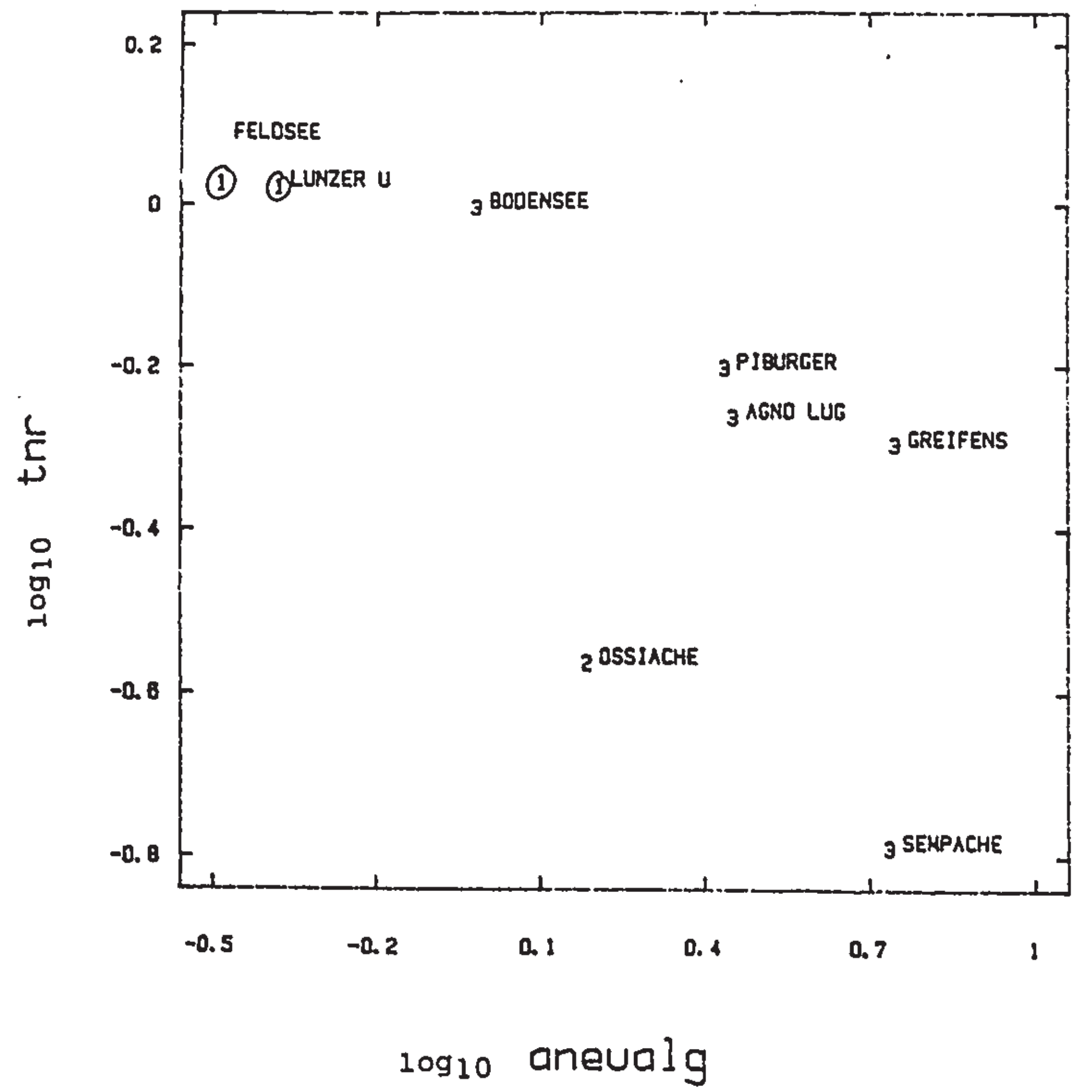
A7.27 Nitrogen relative residence time vs hydraulic load (r^2 = .66).



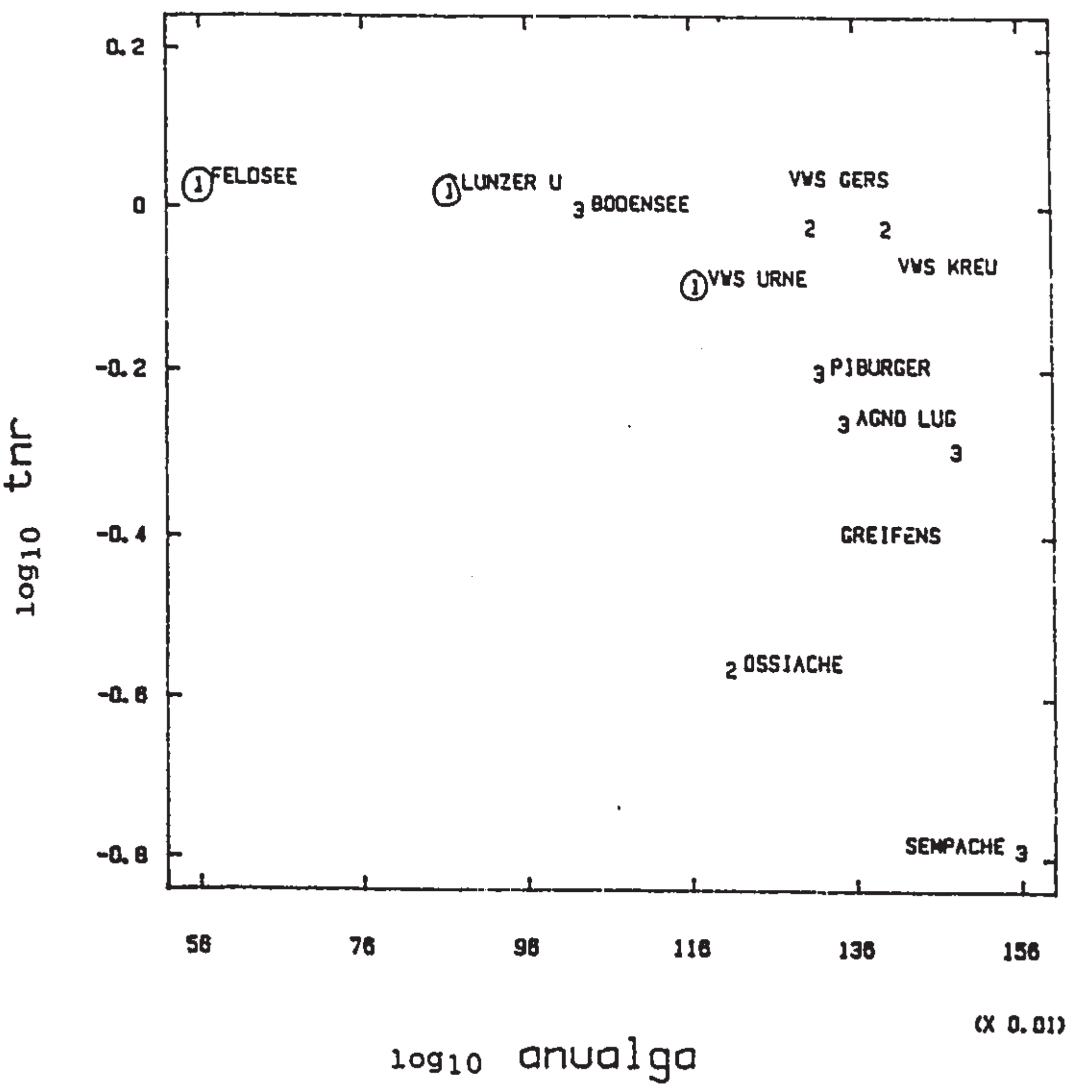
A7.28 Nitrogen relative residence time vs flushing rate (r^2 = .30).



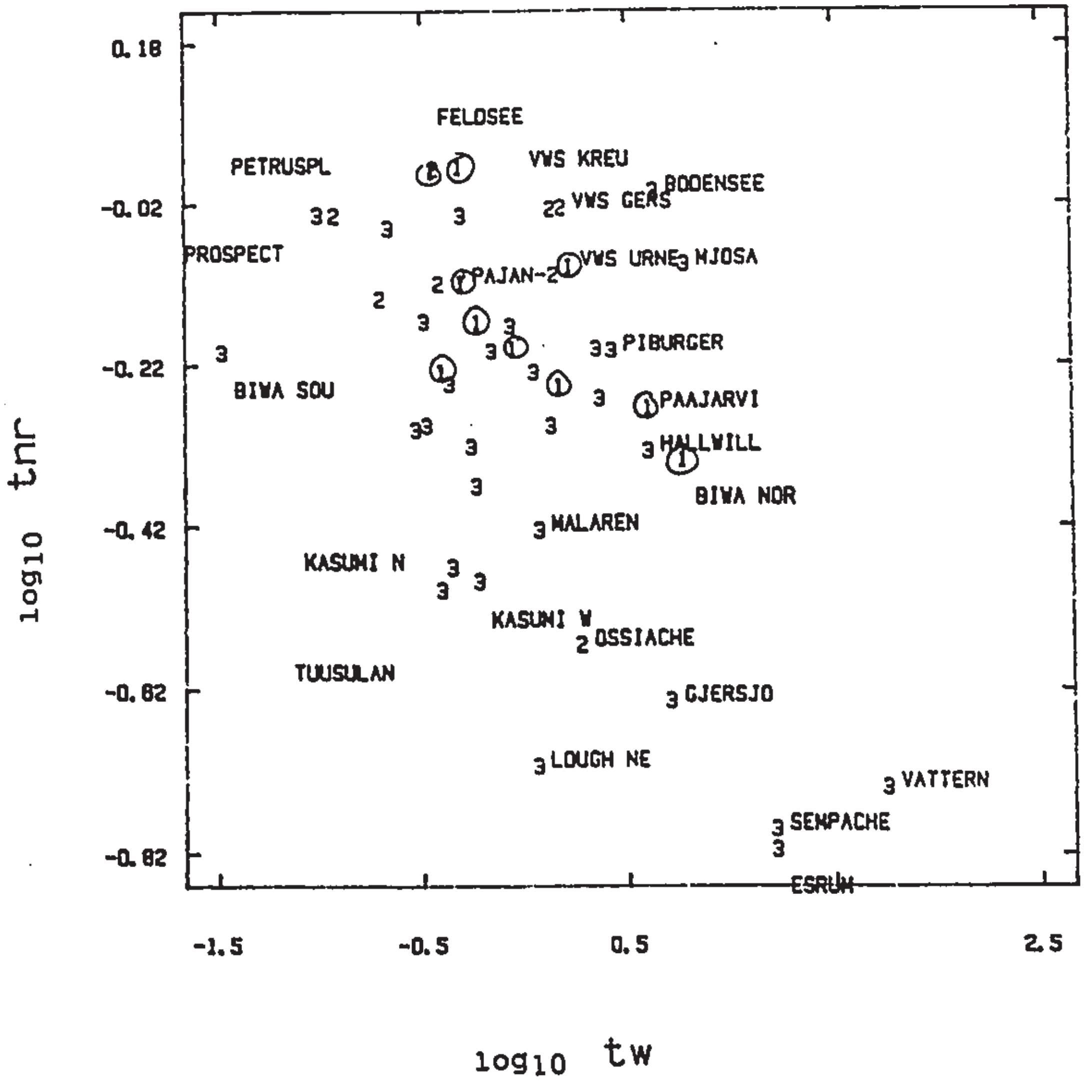
A7.29 Nitrogen relative residence time vs phosphorus relative residence time ($r^2 = .26$).



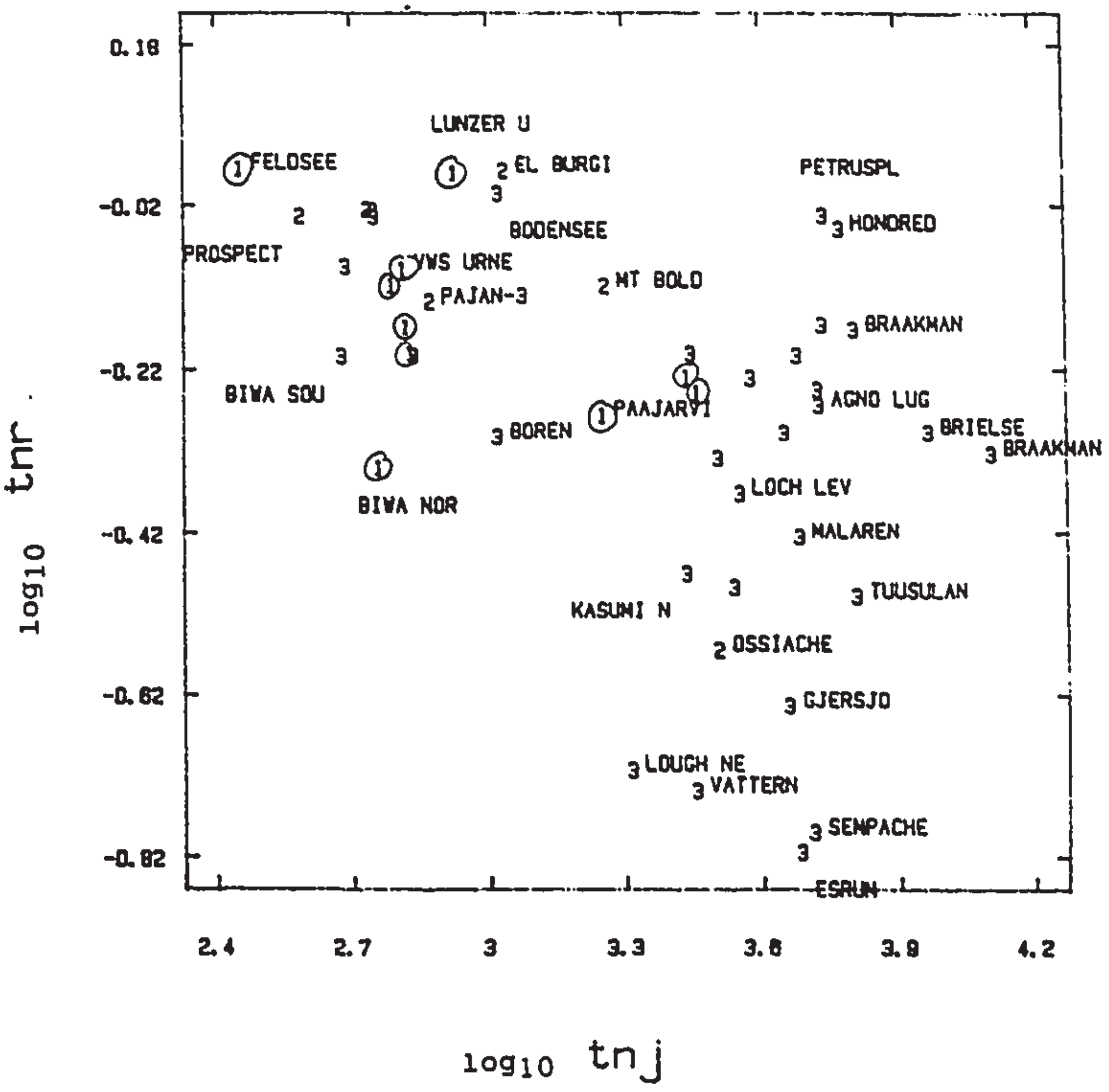
A7.30 Nitrogen relative residence time vs annual average euphotic algal biomass ($r^2 = .52$).



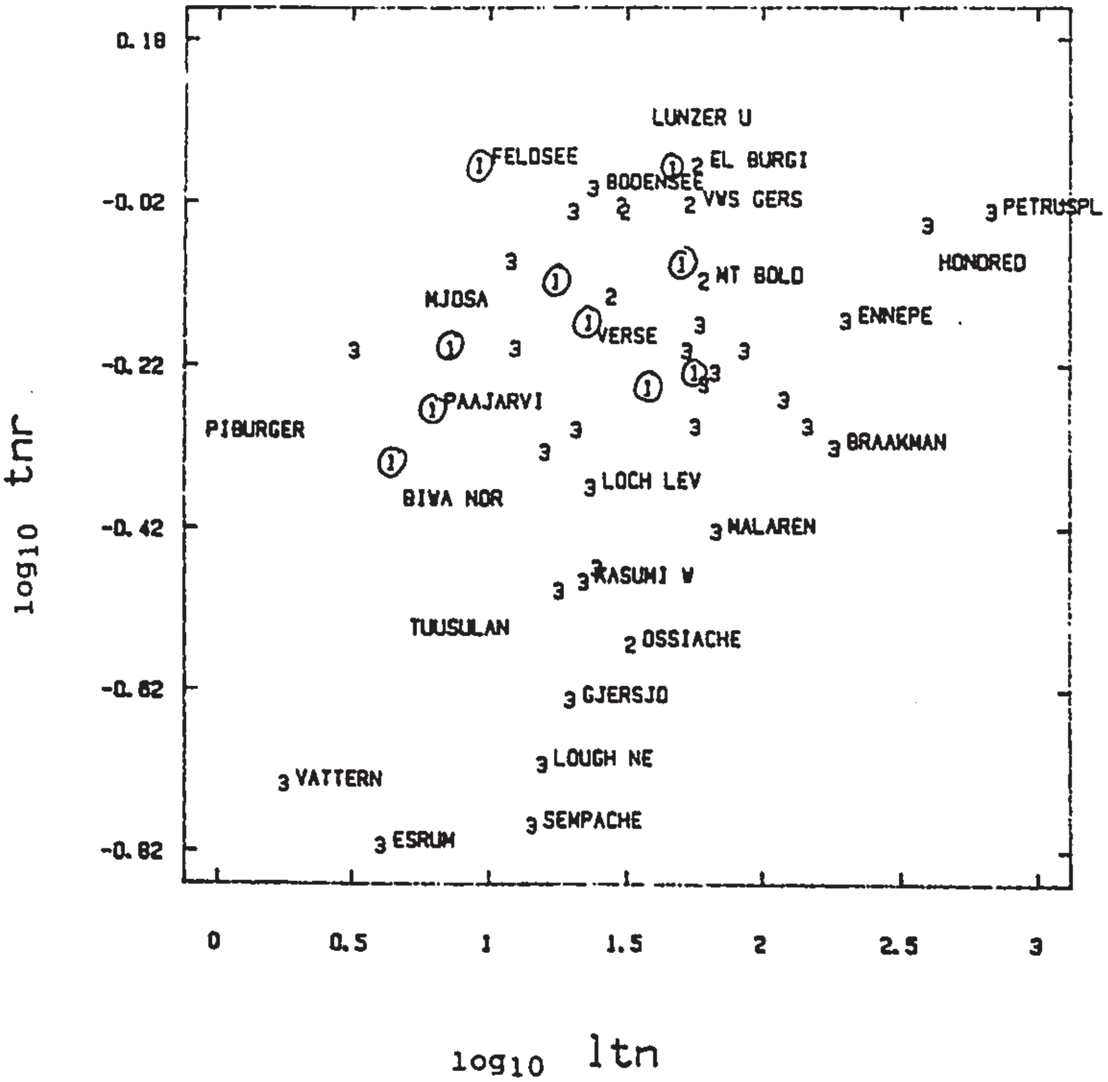
A7.31 Nitrogen relative residence time vs annual average areal euphotic algal biomass (r^2 = .35).



A7.32 Nitrogen relative residence time vs water residence time (r^2 = .28).



A7.33 Nitrogen relative residence time vs nitrogen inflow concentration ($r^2 = .25$).



A7.34 Nitrogen relative residence time vs areal nitrogen loading rate (r^2 = .15).