

CLASSIFICATION OF PRECAMBRIAN SHIELD LAKES

MASTER OF SCIENCE 1971
Geology

McMASTER UNIVERSITY
Hamilton, Ontario

TITLE: Classification of Precambrian Shield Lakes Based on
 Factors Controlling Biological Activity

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NUMBER OF PAGES: vii, 142

CLASSIFICATION OF PRECAMBRIAN SHIELD LAKES
BASED ON
FACTORS CONTROLLING BIOLOGICAL ACTIVITY

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A Thesis
Submitted to the School of Graduate Studies
in Partial Fulfilment of the Requirements
for the Degree
Master of Science

McMaster University
September, 1971

ABSTRACT

During the summer of 1970 a study was initiated to define factors controlling the biosphere in the lentic environment of the Precambrian Shield. Data were collected from nine lakes of varying size and depth located in a number of geological formations. Chemical, physical and biological conditions in these lakes were investigated at two sampling periods and the lakes were classified on the basis of morphology (surface area to volume area) and lithology (surficial and bedrock geology). Attempts were made to determine the influence of morphology and lithology on the chemical and biological conditions observed. Emphasis was placed on the relationships of these factors to aspects of the primary and secondary trophic levels in the lentic ecosystem including primary productivity and the standing crop and diversity of phytoplankton and zooplankton.

The atmosphere, a third potential factor influencing lakes was investigated by means of a network of air monitoring stations (collecting both precipitation and 'dry fallout') located throughout the greater Sudbury area.

The results of the study indicated that:

1. the lentic ecosystem in the Precambrian Shield area studied can be defined by simple chemical and physical variables.

2. the morphology of the lake basins (surface area to volume ratio) modified by lithology (primarily the presence or absence of limestone) is the major factor influencing biological activity. Lakes with a low surface area to volume ratio showed low productivity while lakes with a high surface area to volume ratio showed high productivity. Silica and calcium concentrations (influenced by the lithosphere) were important since relatively small changes in the concentration of these chemical species stimulated a response in the biosphere

3. some of the lakes were affected by concentrations of sulphates conveyed to the water by the atmosphere. Observed effects included increases in the hydrogen ion concentration in lakes with low calcium concentrations (poorly buffered) and a depression of the diversity of both primary and secondary trophic levels.

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1. INTRODUCTION

1.1 STATEMENT OF PROBLEM

The study was initiated to define factors which exert a control on the biology of the lentic environment in the Precambrian Shield and to classify the lakes on the basis of these factors. The study is pertinent since lakes in the Shield, especially the deep cold-water, highly transparent lakes are significant both in terms of their abundance (approximately three-quarters of the waters within Ontario lie on the Shield) and the aesthetic characteristics which make them desirable for recreational use.

The oligotrophic Shield lakes are low in dissolved solids and the biotic-abiotic relations are delicately balanced and sensitive to relatively minor alterations (Beamish 1970 and Conroy 1970). If the lakes are to be successfully conserved in their natural state a definition of the significant factors which affect the biotic-abiotic relationships must be defined to allow the lakes to be categorized for management purposes.

1.2 ACKNOWLEDGEMENTS

It is with pleasure that I acknowledge the participation of those persons and agencies that played an essential role in the study.

Professor J. R. Kramer, Department of Geology, McMaster University provided valuable supervision and criticism to give the study direction and meaning.

Mr. C. F. Schenk, Supervisor, Biology Branch, Ontario Water Resources Commission, provided his time and consideration in administering my leave of absence. Also, Mr. Schenk provided liaison with the Commission during my absence.

Mr. F. Voegelé, Assistant General Manager, and Mr. J. Neil, Director of Laboratories Division, of Ontario Water Resources Commission, authorized my request for an educational leave of absence.

Mr. W. Keller, technician, O.W.R.C. and Mr. C. Ross, summer assistant, gave valuable assistance in the collection and analysis of data.

Dr. K. D. Card, Department of Mines and Northern Affairs, aided in selecting the study lakes and criticized the manuscript.

The Sudbury Office of the Ontario Department of Lands and Forests provided laboratory facilities and aided in the collection of precipitation samples.

Personnel of the Chemistry Branch, O.W.R.C. and the Water Quality Division of the Canada Centre for Inland Waters performed chemical analyses for this study and the phytoplankton section of the Biology Branch analyzed the phytoplankton samples.

My wife, Carol, helped criticize and typed the manuscript.

1.3 PREVIOUS WORK

A schematic representation of the aquatic system in the lentic environment is shown in figure 1.3.1. Well-defined relationships with simple interactions do not occur in nature and therefore there are inaccuracies inherent in this simplified model. It does serve, however, as a guide to define major interactions. The system has seven components which can be categorized as either abiotic or biotic. These components are indicated in Table 1.3.1.

TABLE 1.3.1 MAJOR COMPONENTS IN THE AQUATIC SYSTEM

BIOTIC - phytoplankton
zooplankton
fish

ABIOTIC - atmosphere
sunlight
nutrients
bottom sediments

Biotic Components

As indicated by Clarke (1954) "green plants form the first step in the ecological cycle in every natural situation. They are the first link in the food chain and hence are the basis of the production pyramid.....". In the lentic environment the most important green plants are microscopic and termed phytoplankton. Productivity of the phytoplankton community, primary productivity or the rate of change of biomass with time, largely controls the productivity of other trophic levels. The mechanism of primary productivity is photosynthesis represented by the classical equation:

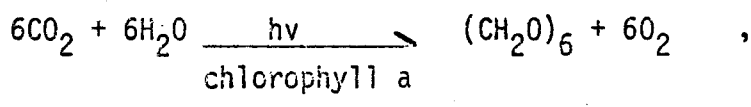
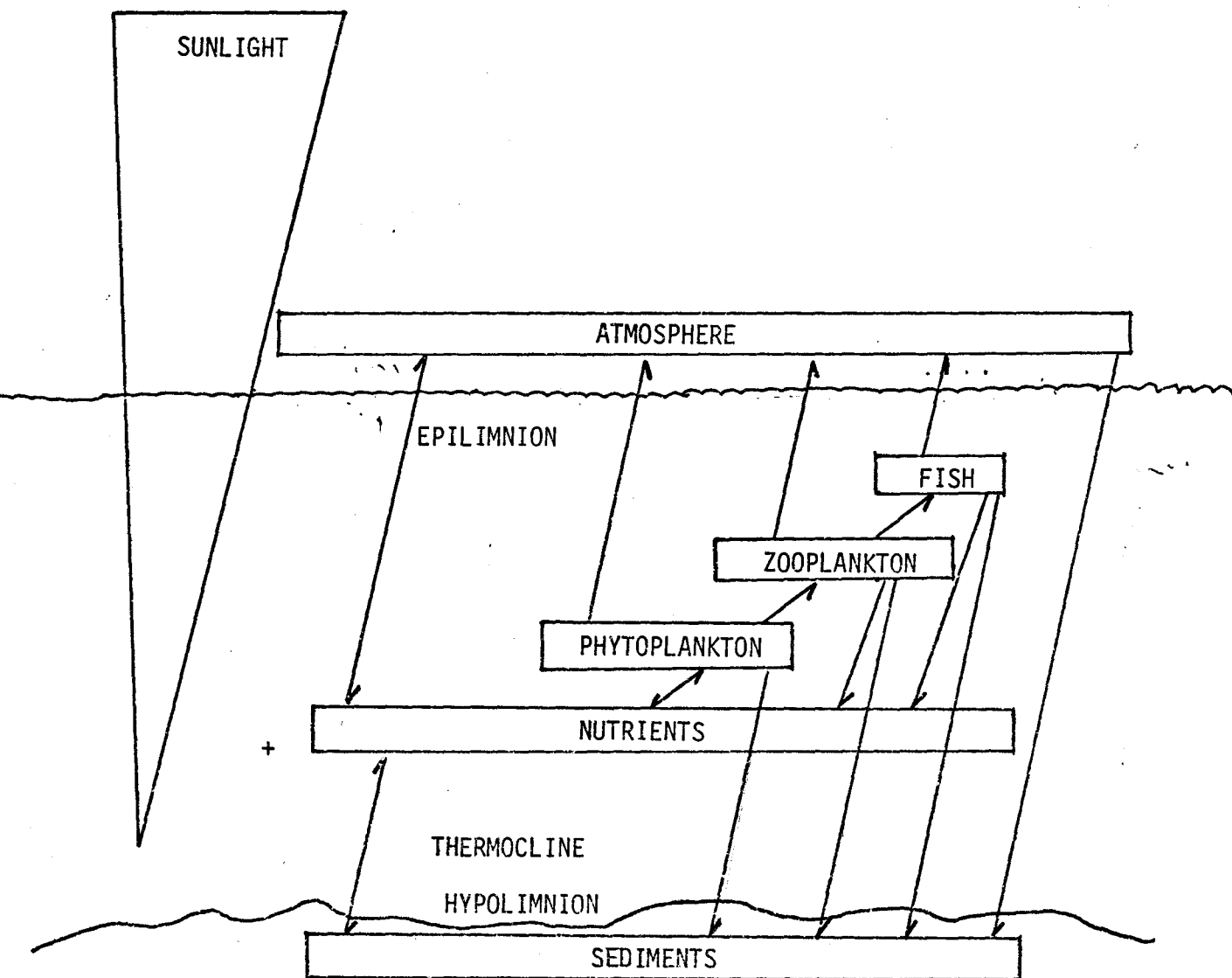
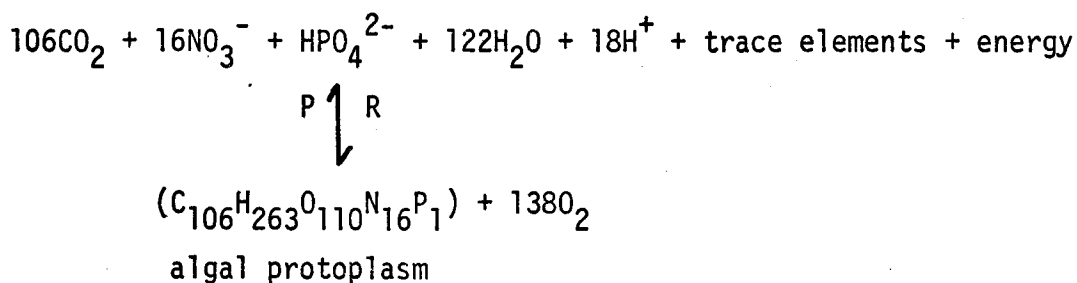


FIGURE 1.3.1 SCHEMATIC DIAGRAM OF COMPONENTS AND
INTERACTIONS IN THE LENTIC ECOSYSTEM



where $h\nu$ symbolizes light energy. The growth of the primary trophic level represented above indicates only one inorganic material - carbon dioxide. In actuality there are many abiotic requirements for growth. Stumm and Morgan (1970) provide a stoichiometric formula for the 'typical' plankton community as $C_{106}H_{263}O_{110}N_{16}P_1$, and an equation of photosynthesis which accounts for major nutrients as:



where P=photosynthesis and R=respiration. Various amounts of many other constituents are required, as indicated by 'trace elements' in the above equation, and biological production is controlled (as any reaction) by the reactant(s) which is/are in minimum supply (Leibig's Law of the Minimum). Unlike a simple chemical reaction for which a single variable is often limiting, the rate of reaction (production) in a lake system may be controlled by the interactions of several variables. For example, a system which is potentially limited by nitrogen could show normal to high primary productivity if the taxa of blue-green algae possessing the ability to fix significant quantities of atmospheric nitrogen were present.

The productivity and composition of other trophic levels in the biotic environment, zooplankton and fish, are directly related to the productivity and composition of the primary trophic level through predation. Each successive level of nourishment as

represented in figure 1.3.1 by phytoplankton, zooplankton and fish form a trophic level. Since assimilation is not 100 per cent efficient, the biomass and energy content of successive trophic levels decreases. Juday (1943) depicts a pyramid of biomass for Weber Lake, Wisconsin in which the biomass of fish is $1/32$ of the phytoplankton biomass.

Another important aspect of biological activity in the lentic environment is the stability of the various trophic levels. Stability in an ecological sense connotes the ability of the system to remain reasonably similar to itself in spite of changes in the abiotic environment. It has been suggested that stability is directly related to diversity. The relation is explained by some ecologists as: the greater the number of different species which are found in association the greater is the number of 'feedback' channels in the community relations and thus with higher diversity there is less opportunity of a change in the abiotic environment causing a catastrophic change in the biological environment (Odum, 1963).

Diversity is an index of the distribution of individuals amongst species represented in a trophic level. It is a maximum when all individuals belong to different taxa and a minimum when all individuals belong to the same taxum. Patten (1967) states that "species diversity decreases in response to stress and that high diversity represents a favourable environment". This generalization is based on studies of the relationship between species diversity and water quality. The work of Wilhm and Dorris (1966), Conroy (1970) and others supports this premise.

Many attempts have been made to determine the "best" index of

ecological diversity. Margelef (1968) reviews the subject of diversity indices and discusses expressions which are based on information theory - specifically communication channels, and redundancy. Margelef's information theory index has the form:

$$D = 1/N \log_2 \frac{N!}{N_a! N_b! \dots N_s!}$$

where D = diversity,

N = number of individuals (total),

N_a = number of individuals belonging to species a, and

N_s = number of individuals belonging to species s.

A simplified index has been developed by Margelef which has the form: $ID = (S-1)/\log_e N$, where S = number of species (taxa), and N = number of individuals.

This index has received wide application in the field of aquatic ecology studies (for examples see Johnson, 1969 and Johnson et al, 1970 and Conroy, 1970) since the index is largely independent of sample size.

Abiotic Components

The focus of the abiotic subsystem is the nutrient pool including those solutes required in major concentrations (C, N, H, O, and P) as well as trace quantities of many other ions. The sediments and the atmosphere act as chemical sinks for the nutrient component and the approach to equilibrium in the aquatic ecosystem. The equations (not balanced) in Table 1.3.2 are examples of interactions in the abiotic subsystem.

TABLE 1.3.2 INTERACTIONS OF SEDIMENT, WATER AND ATMOSPHERE

SEDIMENT	WATER	ATMOSPHERE	OTHER KEY VARIABLES
CaCO_3	$\longleftrightarrow \text{CO}_3$	$\longleftrightarrow \text{CO}_2$	H^+
FeS_2	$\longleftrightarrow \text{SO}_4$	$\longleftrightarrow \text{SO}_2$	biological mediation

Sunlight, the other abiotic component, is a constant when taken within narrow ranges of latitude. The distribution of light in the water column, however, is an important variable which depends on the materials present in the water absorbing the light. The quantity of light reaching a depth is defined by the equation: $I_z = I_0 e^{-n'z}$, where I = intensity, z = depth, and n' = extinction coefficient.

Interactions in the Lentic Ecosystem

The system functions by interactions between the components (the arrows in figure 1.3.1 indicate the direction of flow). The key reaction for this study is primary productivity representing an interaction between sunlight, the nutrient pool and phytoplankton. Primary production is controlled by the available flux of nutrients and the quantity of sunlight (equation of photosynthesis, page 6).

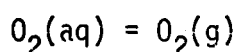
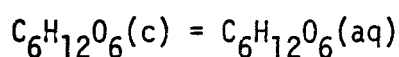
Sources of Nutrients

The question then becomes 'what determines the composition of the solutes (nutrient flux) in surface waters'? Kramer (1964) states

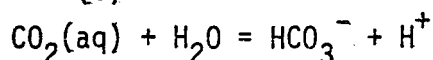
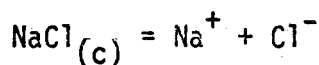
"the ultimate 'source' of all constituents in freshwater is either the lithosphere (sediment) or atmosphere". Many investigators have attempted to relate water quality to lithology. Hem (1971) reviews the subject including the work of Clarke (1924) who cited early studies (mid 19th century) which correlated drainage-basin geology with water composition. Hem states that "investigators since Clarke's time have not been able to develop any simple classification system to relate water (quality) to rock types on the basis of the dissolved matter in the water". Nevertheless, the correlations between water chemistry and geology, which have been made by authors such as Miller (1961), Feth et al (1964) and Garrels et al (1967) for qualified situations, show that the reactions of water with lithological material are important in determining the ultimate composition of surface waters.

An outline and an example of the various types of reactions which add dissolved species to fresh waters is provided below:

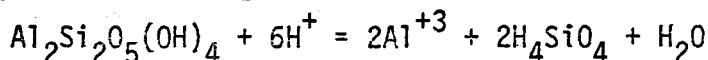
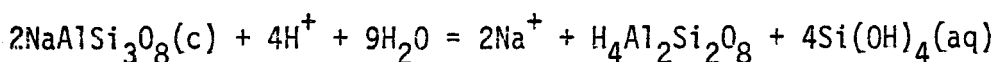
1) SIMPLE SOLUTION:



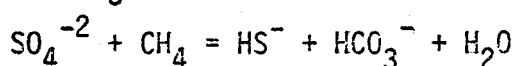
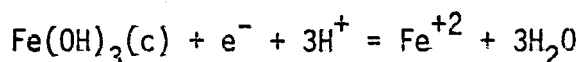
2) IONIZATION:



3) ION EXCHANGE:



4) OXIDATION - REDUCTION:



In natural systems the reactions of water with the lithosphere (and atmosphere) are usually a complex variety of many or all of the above categories. The extent of thermodynamic reversibility depends on the local conditions which prevail and master variables such as E_h and pH. Some reactions, especially oxidation-reduction, are mediated by biological activity. Table 1.3.3 summarizes important lithospheric sources of constituents of fresh-water, (Kramer, 1964).

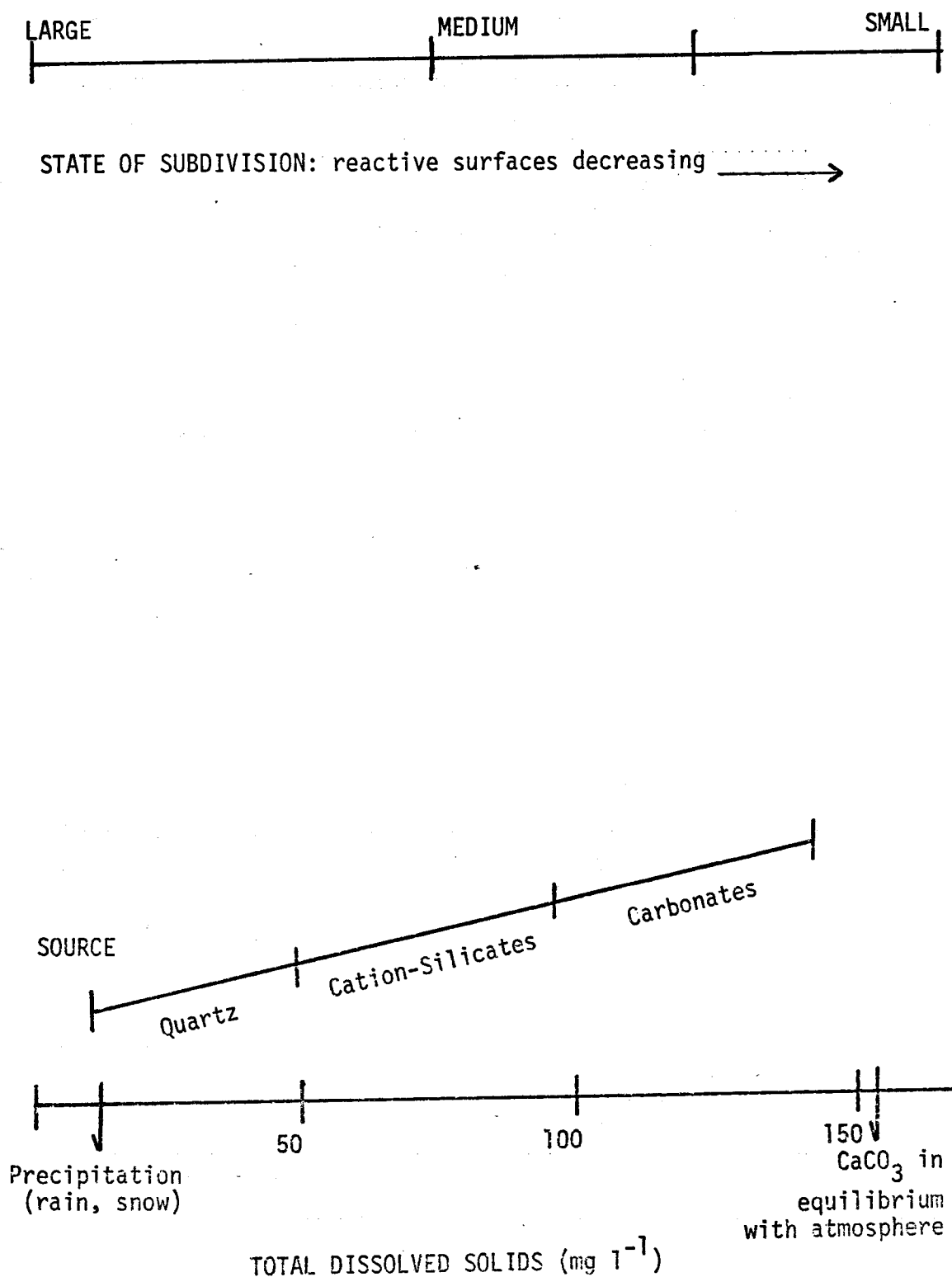
TABLE 1.3.3 IMPORTANT CHEMICAL SPECIES DERIVED FROM
WEATHERING OF MINERALS

<u>CHEMICAL SPECIES</u>	<u>SOURCE</u>
Silica	Solution of quartz and cation silicates
Sodium Potassium	Chemical reactions of feldspars, micas and clays
Calcium Magnesium	Reaction involving carbonates, feldspars, clays, some micas, amphiboles, and pyroxenes
Phosphate Flouride	Apatites
Sulphate	Pyrite, gypsum
Chloride	Rock inclusions

The 'equilibrium' (steady-state) concentration depends on 1)length of time of contact; 2)the degree of mixing of solid, liquid and gaseous phases; and 3)the resistivity of the source to weathering reactions.

Figure 1.3.2 is a nomograph depicting the theoretical relation between the geological nature of the basin (physical and chemical)

FIGURE 1.3.2 NOMOGRAPH OF RELATION BETWEEN GEOLOGICAL NATURE OF
BASIN (PHYSICAL AND CHEMICAL) AND TOTAL DISSOLVED
SOLIDS OF WATER



and the total dissolved solids concentration of the water, and Table 1.3.4 illustrates the resistivity of minerals to weathering.

TABLE 1.3.4 STABILITY OF MINERALS IN WEATHERING

(Rankama and Sahama, 1950)

(Goldich's reaction series)	
Olivine	
	Calcic plagioclase
Hypersthene	
	Calc-alkalic plagioclase
Augite	
	Alkali-calcic plagioclase
Hornblende	Alkalic plagioclase
Biotite	
Potash feldspar	
Muscovite	
Quartz	

Increasing stability
↓

Using relations depicted in figure 1.3.2 and table 1.3.4, one would predict the water to be higher in dissolved ions in basic terrains than in granitic terrains. Hem (1971) develops the relation between dissolved chemical species in the water and lithology and presents data which support the above prediction.

Feth et al (1964), from studying the mineral constituents in water which interact with granitic rocks, concluded that 95% of the total mineral content of surface waters was derived from the

lithosphere. The authors further conclude that pH is the variable controlling the rate and extent of the solubility of chemical components derived from the lithosphere and that the initial hydrogen ion concentration is controlled almost exclusively by the solution of carbon dioxide derived from the atmosphere. Reactions with the lithosphere tend to reduce the hydrogen ion concentration and increase the concentration of mineral species.

Gorham (1961) recognized the importance of the atmosphere in influencing the supply of major ions to inland waters. Using data from quarterly appendices to the journal Tellus, Gorham calculates that the atmosphere supplies approximately 20 per cent of the sodium, 10-20 per cent of the potassium, about 10 per cent of the magnesium, 20-40 per cent of the calcium, 30-50 per cent of the chloride and 50-70 per cent of the sulphate to the rivers near Kuopio and Jyvaskyla in Finland. Three sources of the atmospheric supply outlined by Gorham are the sea, the soil and air pollution.

Gibbs (1970) proposed a theoretical model with three major mechanisms controlling the world's water chemistry:

1. atmospheric precipitation,
2. rock dominance, and
3. the evaporation-fractional crystallization process.

Gibbs further claims that 'second-order' factors such as relief, vegetation and composition of material in the basin dictate only minor deviations within the zones dominated by the three prime factors. These minor deviations caused by material differences in the basin must be important since waters within the same geographical area and which would plot in the same zone in Gibbs'

model have markedly different productivities. The work of Card and Gillespie (1966) is an example. The Gibbs' model is principally a dissolved solids model in which waters low in dissolved solids are dominated by atmospheric precipitation, waters containing moderate dissolved solids are influenced by the lithosphere (rock dominance) and waters high in dissolved solids (seas) are dominated by evaporation-fractional crystallization processes.

Variables and Factors Influencing Biological Productivity

Of the many variables in the nutrient pool, those most often associated with phytoplankton productivity include phosphorus, carbon, nitrogen, and more recently silica. Table 1.3.5 summarizes various literature sources of limiting variables to aquatic production.

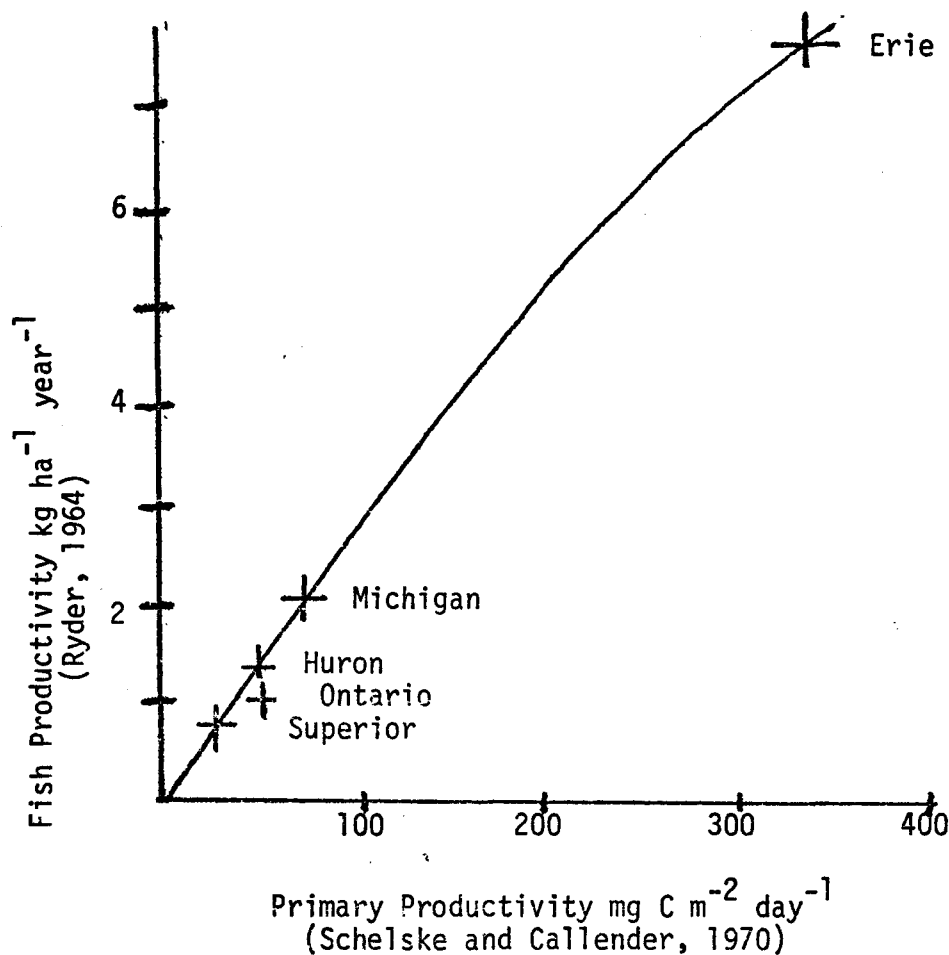
TABLE 1.3.5 REFERENCES TO VARIABLES WHICH LIMIT AQUATIC PRODUCTION

<u>LIMITING CONSTITUENT</u>	<u>SOURCE</u>	<u>AREA</u>	<u>COMMENT</u>
Carbon	Kuntzel (1969) Johnson et al (1970) Sakamoto (1971)	general northern Ontario northwestern Ontario	
Nitrogen	Gerloff (1957) Sakamoto (1971)	southern Wisconsin northwestern Ontario	rarely limiting
Phosphorus	Campbell (1969) Sakamoto (1971)	lower Great Lakes northwestern Ontario	
Silica	Schelske and Stoermer (1971) Russell-Hunter (1970)	Lake Michigan general	diatoms diatoms
Nitrogen/ Phosphorus ratio	Russell-Hunter (1970) Christie (1968)	general southern Ontario	

In addition to relating productivity to specific limiting variables in the aquatic environment, attempts have been made to isolate factors which bear an empirical relation to production. Rawson (1952) claims that the productivity of lakes is controlled by the interaction of climatic, edaphic and morphometric factors. The climatic factor connotes the geographical setting with variables such as latitude, longitude and altitude which affect the intensity of the sun's energy on the water body. The edaphic factor connotes the geological setting, which at least partially controls the composition of the solutes in surface waters. In this regard, Card and Gillespie (1966) attempted to relate indices of wildlife productivity in the Sudbury, Ontario area to surficial and bedrock geology. Their thesis was that geology determined the quantity and composition of the solutes and that these in turn controlled biological productivity. They found that productivity was higher in zones where the dissolved solids concentration of the water was higher. Two zones were distinguished - calcareous terrain (Huronian Belt) where productivity was high and Precambrian Shield terrain (Grenville and Superior Cobalt Plain) where productivity was low.

Rawson's third consideration, a morphometric factor, connotes the relation between the size of the basin and the volume of water. One might express this as the ratio of volume to surface area, per cent littoral zone or mean depth. Rawson notes that a strong correlation exists for the yield of fish from the Great Lakes based on commercial fishing records and the mean depth of the lakes. Fishery production can be related to primary productivity as indicated in Figure 1.3.3 for the Great Lakes.

FIGURE 1.3.3 RELATIONSHIP BETWEEN PRIMARY PRODUCTIVITY
AND FISHERIES PRODUCTIVITY FOR GREAT LAKES



Theinemann (1926) arbitrarily divided lakes into either oligotrophic or eutrophic on the basis of a mean depth of 18 meters at which point the volume of the hypolimnion approximately equals the volume of the epilimnion in north temperate lakes. The morphometric factor is related to the nutrient flux in two ways:

- 1) as the surface area to volume ratio increases the amount of interacting surface between the water and sediment and/or atmosphere increases, thus the potential rate of dissolution increases, and

2) as the surface area to volume ratio decreases the volume of hypolimnetic waters increases and thus during periods of stratification the cycle of nutrients from the bottom sediments to the photosynthetic zone is retarded.

Lakes with a mean depth of less than 18 meters were considered to be eutrophic and those with greater depth as oligotrophic.

Lundbeck (1934) distinguished primary and secondary oligotrophy (eutrophy) where primary connoted 'controlled by edaphic factors' and secondary connoted 'controlled by morphometric factors'.

Ryder (1965) using considerations of morphometric and edaphic control developed a 'morphoedaphic' index for north-temperate lakes (the qualification of 'north-temperate' lakes eliminated Rawson's climatic factor). Ryder uses mean depth as the morphological factor and total dissolved solids as the edaphic factor. The correlation of yield of fish to dissolved solids divided by mean depth provides a correlation with a good fit for Ryder's data.

The factors, which have been suggested as exerting a control on aquatic productivity, are not wholly independent since the depth of the lake (the morphometric factor) controls the temperature distribution resulting from the quantity of energy absorbed from the sun (the climatic factor) via influencing the thermal stratification of the lake. Further, the thermal stratification influences the rate of nutrient cycling from the bottom sediments to the nutrient pool because the onset of a well-defined thermocline during summer stratification isolates the hypolimnion from the epilimnion and retards the diffusion of

solutes to the surface waters. Also, the morphometric factor, if expressed as the ratio of the water volume to shoreline area, exerts a control on the density of the nutrient flux derived from the shoreline of the lake basin. Lindeman (1942) recognized that it was invalid to separate the role of the biosystem in influencing the composition of the abiotic environment - a biological factor.

1.4 PLAN OF STUDY

In summary, lakes in the Precambrian Shield are typically low in dissolved solids and unproductive. Biotic-abiotic relations are delicately balanced and easily disturbed. This study attempts to isolate variables related to the lithosphere and atmosphere which exert a control on biological activity in the lentic environment of the Precambrian Shield (those variables controlling the nutrient flux) and to measure the response of primary and secondary trophic levels to the composition of the nutrient pool.

Table 1.4.1 summarizes the boundary conditions for the experimental method.

TABLE 1.4.1 PLAN OF STUDY

FACTOR

- | | |
|-----------------|--|
| 1. Climatic | - held constant by selecting lakes in the same geographical area |
| 2. Morphometric | - varied by selecting lakes with a range in volume to surface area ratio |
| 3. Lithospheric | - defined within boundary conditions to provide for the relative effects of a variation in surficial and bedrock geology |
| 4. Atmospheric | - measured on a regional basis |

An area of the Precambrian Shield near Sudbury, Ontario was selected for the study since lakes of similar size were available for which the surficial and bedrock geology was known to vary sufficiently to provide ground for attempting to characterize the lakes. The criteria for the selection of the lakes is indicated in section 2.1.

Aspects of the biotic environment(the focus of this study) including primary productivity, standing crop and diversity of primary and secondary trophic levels are related to selected physical and chemical variables. Correlation and Factor Analyses are used to establish significant relationships and factors, and Discriminate Function Analysis is applied to separate the lakes into appropriate groups on the basis of measured affinities.

2. METHODS

2.1 SELECTION OF STUDY LAKES AND STATIONS

Lakes fitting the study plan were selected by reference to maps showing surficial and bedrock geology and by discussions with Card(1970) and Stasson and Hughson(1970). The criteria for selection of the lakes included:

1. one lake showing cultural eutrophication,
2. one lake with a low volume to surface area ratio but with oligotrophic characteristics as defined by biotic associations,
3. seven lakes with relatively similar morphometric characteristics but with variable geology.

One station was selected on each of the nine lakes by applying the following criteria:

1. a depth of 20-25 meters,
2. a location not obviously influenced by local currents or excessive wave action (some degree of protection in the larger lakes),
3. an area which would not be interfered with by recreational activity, and
4. an area not obviously influenced by shore factors or inflows to the lake.

2.2 COLLECTIONS AND ANALYSES

Collections for biological and chemical analyses were made at each lake twice during the summer with the exception of Little Lake Penage (only sampled once).

Samples were collected by pumping water from the specified depth through a 'garden' hose with a 12-volt DC centrifugal pump. The following summary (Table 2.2.1) indicates the parameters investigated at each location.

TABLE 2.2.1 SUMMARY OF COLLECTIONS AND ANALYSES

A. In situ collections and analyses:

- temperature profile
- secchi disc transparency depth
- dissolved oxygen profile
- primary productivity estimates (in part)
- zooplankton collections
- phytoplankton collections
- chemical collections for analyses to be performed in Sudbury and Toronto

B. Analyses performed at field laboratory - Sudbury

- chlorophyll
- alkalinity
- pH
- soluble reactive phosphorus
- soluble reactive silica
- dissolved carbohydrate
- nitrate

- nitrite
- ammonia plus amino acids
- conductivity

C. Analyses performed by OWRC Laboratory Division, Toronto

- total and dissolved solids
- total carbon
- calcium
- magnesium
- sodium
- hardness
- Kjeldahl nitrogen
- chloride
- sulphates
- phytoplankton identification and enumeration

D. Analyses performed by Department of Health, Toronto

- radioactive carbon activity for primary productivity estimates

The detailed analytical methods are provided in Appendix A of this report.

2.3 PRECIPITATION MONITORING¹

Twelve locations were selected to measure the composition of bulk precipitation (rain and dry fallout) from the atmosphere. The site selection was made to reduce the effects of local conditions such as vehicle traffic (air and land) and blowing debris such as sand and dust. The assumption was made that the stations were representative of conditions in the general area.

from one to three litres of precipitation per month. Records of maximum and minimum monthly rainfall for the preceeding five years at the Sudbury Airport (Department of Transport Meteorological Service) were used to determine the diameter of the collector. The locations of the sampling stations are shown in Figure 2.3.1 and the design of the collector is indicated in Figure 2.3.2. Analyses were provided for conductivity, pH, sulphates and twelve metals (soluble fraction) on the filtrate after samples were filtered through prewashed Whatman GF/C and Millipore AA filters.

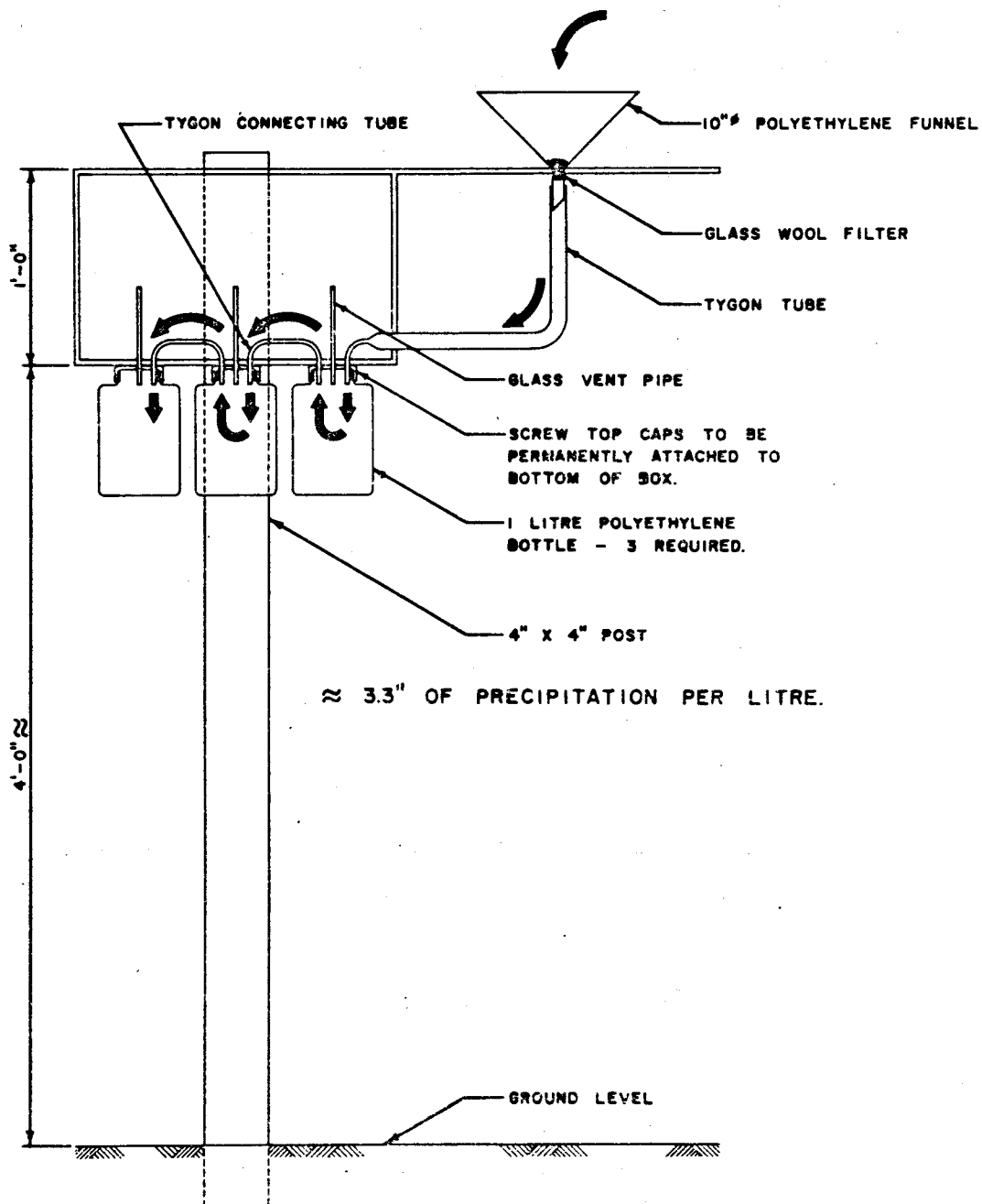
1. The precipitation monitoring data are part of a continuing programme to assess the significance of the atmosphere as a source and conveyor of materials to lakes (Kramer, Conroy and Keller, 1970)

FIGURE 2.3.1 LOCATIONS OF THE PRECIPITATION MONITORING STATIONS. 1970-1971

O = Station Locations
R = Rain
S = Snow

Scale 0 km 20

FIGURE 2.3.2
RAIN COLLECTING STATION
(FRONT VIEW)



2.4 IDENTIFICATION AND ENUMERATION OF PLANKTON

Plankton is a classification of fresh-water and marine organisms including representatives of the animal and plant kingdoms that lack the ability of self-locomotion and thus drift in water, subject to the actions of waves and currents. For the most part, these organisms are microscopic. The phytoplankton or planktonic algae constitute a large part of the primary trophic level or primary producers in the aquatic environment and the zooplankton are part of the secondary trophic level - the primary consumers in the food-web of aquatic environment.

Phytoplankton

The phytoplankton were collected as described in Appendix A and were analyzed by OWRC. All representatives were identified to the generic level of classification with additional specific classification provided where possible. Phytoplankton belong to the subkingdom Thallophyta. Seven divisions of algal thallophytes are recognized (Wilson and Loomis, 1962):

1. Chlorophyta (Green Algae)
2. Cyanophyta (Blue-green Algae)
3. Euglenophyta (Euglenoids)
4. Chrysophyta (Yellow-green Algae and Diatoms)
5. Pyrrophyta (Dinoflagellates)
6. Phaeophyta (Brown Algae)
7. Rhodophyta (Red Algae).

In addition, three divisions including bacteria, actinomycetes

and fungi are included in the subkingdom Thallophyta but are not usually considered as phytoplankton.

The classification used in this study divides the planktonic algae in four groups akin to the divisions. These are:

1. Blue-green Algae (Cyanophyta)
2. Green Algae including Chlorophyta and, in part, the Chrysophyta
3. Flagellates (Euglenophyta and Pyrrophyta in part)
4. Diatoms (Chrysophyta in part).

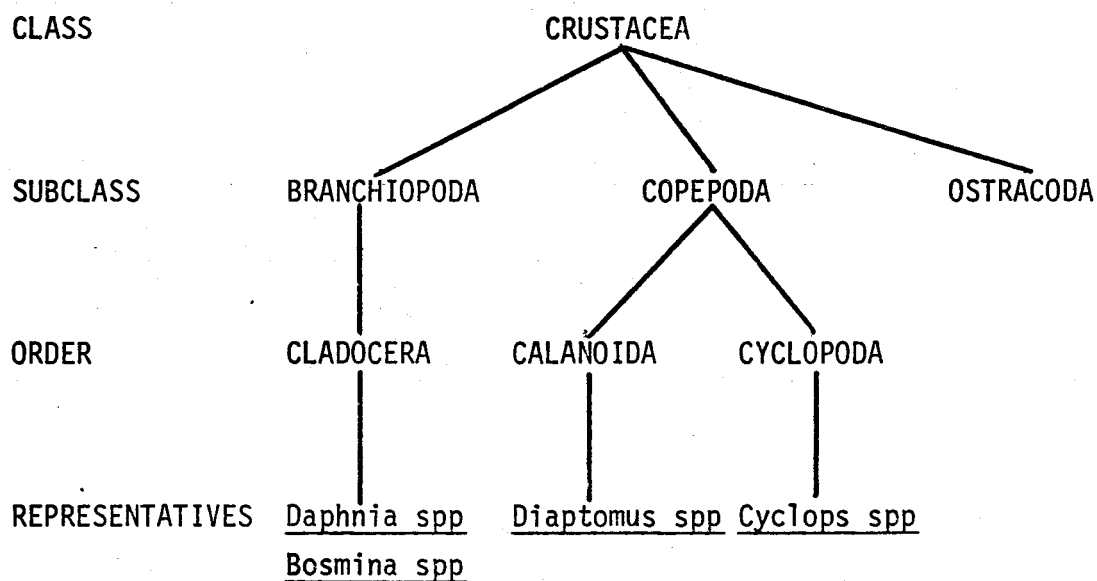
Appendix B provides the results of the identification and enumeration of the phytoplankton samples.

Zooplankton

Zooplankton were collected as outlined in Appendix A. Zooplankton belong to the Animal Kingdom and have representatives largely from two phyla - Aschelminthes and Arthropoda. The planktonic Aschelminthes are from the class Rotifera and the Arthropods from the class Crustacea (Storer and Usinger, 1957). The rotifers were identified to genus and the crustacea to genus and subfamily utilizing the key provided by Edmondson (1966). The classification is shown in Table 2.4.1. The results of the identification and enumeration are presented in Appendix B.

Nauplii are the immature stages (larvae) of the order Copepoda and were treated as a separate taxonomic group. The results of the identification and enumeration are presented in Appendix B.

TABLE 2.4.1 THE TAXONOMY OF CRUSTACEAN ZOOPLANKTERS
UTILIZED IN THIS STUDY



2.5 STATISTICAL ANALYSES

The data were subjected to the following statistical analyses to provide measures of central tendency, variable correlations, associations and differences between groups of lakes:

1. weighted mean,
2. multiple linear correlation,
3. factor analysis, and
4. discriminant function analysis.

A summary of these statistical methods is presented in Appendix A.

3. RESULTS

3.1 LOCATION AND PHYSICAL CHARACTERISTICS OF STUDY LAKES

The lakes which were selected on the basis of the criteria outlined in section 2.1 are indicated in table 3.1.1. The drainage patterns and the relationships between lakes are shown in figure 3.1.1.

As indicated in the study plan (table 1.4.1), lakes were selected which showed a range in morphological characteristics. Table 3.1.2 indicates the morphological features of the lakes and the sampling dates. The lakes ranged in area from 17 to 6876 hectares in Camp Ten Lake and Lake Penage respectively, and in volume from $1.04 \times 10^6 \text{ m}^3$ to $5.36 \times 10^8 \text{ m}^3$ for the same lakes. The mean depth varied from 6.1 meters in Camp Ten Lake to 12.2 meters in George Lake. The surface area to volume ratio was largest in Camp Ten Lake, $1630 \text{ ha m}^{-3} \times 10^6$, and smallest in George Lake, $8 \text{ ha m}^{-3} \times 10^6$.

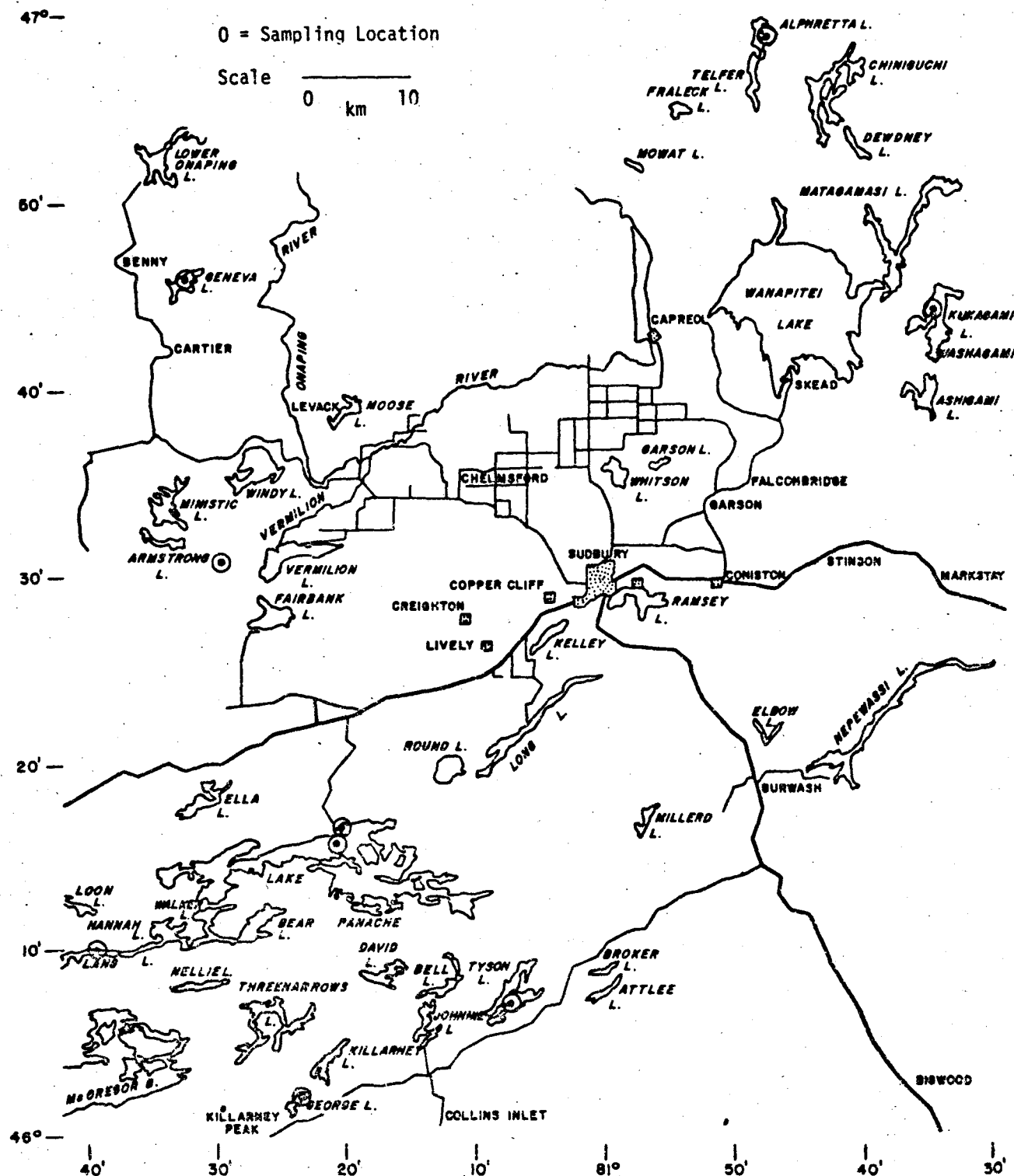
TABLE 3.1.1 NAME AND LOCATION OF STUDY LAKES AND DATES SAMPLED

<u>Name</u>	<u>Geographical Co-ordinates</u>	<u>Dates Sampled</u>
Kukagami	46°45'N, 80°40'W	June 23, August 3
Geneva	46°45'N, 81°32'W	June 7, August 21
Tyson	46°07'N, 81°07'W	June 30, August 8
George	46°02'N, 81°25'W	August 6, September 6
Lang	46°10'N, 81°38'W	June 24, August 26
Penage	46°15'N, 81°20'W	June 30, September 1
Alphretta	46°55'N, 81°31'W	June 12, August 23
Camp Ten	46°31'N, 81°31'W	June 22, September 9
Little Penage	46°16'N, 81°23'W	September 11

TABLE 3.1.2 PHYSICAL CHARACTERISTICS OF STUDY LAKES

<u>Name</u>	<u>Area (ha)</u>	<u>Mean Depth (m)</u>	<u>Volume (m³ x 10⁶)</u>	<u>Surface area/volume (ha m⁻³ x 10⁶)</u>
Kukagami	1896	9.0	170.6	11
Tyson	1140	8.4	95.8	12
Geneva	356	8.6	3.06	190
Alphretta	382	12.0	4.58	83
Camp Ten	17	6.1	1.04	1630
Lang	1472	9.2	5.47	270
Penage	6876	7.8	536	13
George	180	12.2	21.6	8
Little Penage	131	7.6	9.95	13

FIGURE 3.1.1 LOCATIONS
OF STUDY LAKES



3.2 GEOLOGY OF LAKE BASINS

The study area is composed of rocks of Precambrian age with a thin discontinuous veneer of unconsolidated Cenezoic deposits. The Precambrian can be divided into three geological provinces - the Superior, the Southern, and the Grenville. On the basis of geology, four significant areas have been defined (Card and Gillespie, 1966):

1. Northwest Granitic, Superior Province,
2. Cobalt Plain, Southern Province,
3. Sudbury Basin, Southern Province, and
4. Huronian Belt, Southern Province.

The Northwest Granitic area is underlaid by granitic rocks, therefore characterized by feldspars and quartz. The overburden is thin, discontinuous and mineralogically similar to the underlying rocks.

The overburden within the Cobalt Plains area is generally thicker and underlaid with conglomerate, quartzite, gabbro, greenstone and limestone. Mineralogically the rocks are largely quartz and calcium-iron-magnesium silicates.

The Sudbury Basin is underlaid by mafic and silicic intrusive rocks, intermediate volcanics, slate, and greywacke. The mineralogical composition is largely quartz, sodium-potassium-alumino silicates and calcium-magnesium-iron silicates. Thick discontinuous glacio-fluvial deposits occur in the basin.

The rocks in the Huronian Belt are of sedimentary origin with a wide range of chemical and mineralogical compositions ranging from silica-rich quartzites through conglomerates and pelites (intermediately rich in calcium, magnesium, soda, potash, and phosphorus)

to limestones (rich in calcium and calcium-magnesium carbonates). Thick discontinuous glacio-fluvial deposits occur in this area.

The rocks of the Grenville Province are gneissic in nature representing highly metamorphosed sedimentary, volcanic and igneous rocks. They possess high to intermediate levels of soda, potash and phosphorus and low to intermediate concentrations of calcium and magnesium. The mineralogy of the Grenville Province is variable; however, quartz, feldspar, hornblende and biotite are common.

A summary of the bedrock geology of the Sudbury region is given by the Ontario Department of Mines Map # 2188. The surficial geology is outlined on Ontario Department of Lands and Forests Map #S465 (1963).

The descriptive geology of the lake basins studied is presented below (Card, 1970) and is summarized in table 3.2.1.

GRENVILLE PROVINCE

Tyson Lake

Bedrock - located in the Grenville Province, overlaid by layered paragneiss (biotite, biotite-garnet, biotite-hornblende gneiss, amphibolite, calc-silicate gneiss), quartzite, amphibolite, and granite.

Surficial - relatively thin boulder till.

Mineralization - none known.

George Lake

Bedrock - located along the contact between the Grenville and Southern Provinces (Grenville Front). On the north, rocks are quartzite and siltstone of the Bar River Formation (Huronian). On the south, rocks are mainly granite and gneissic granite (quartz monzonite composition).

Surficial - thin glacial drift-boulder till.

Mineralization - none known.

SUPERIOR PROVINCE

Camp Ten Lake

Bedrock - granitic rocks of the Superior Province, including granite (quartz monzonite - granodiorite composition), granitic gneiss, and migmatite.

Surficial - relatively thick glacio-fluvial outwash sands and gravels.

Mineralization - none known, although not far from Sudbury Nickel Irruptive and attendant nickel-copper mineralization.

Geneva Lake

Bedrock - located in the Superior Province near an outlier of Huronian rocks, and in a greenstone belt. Superior rocks are mainly granitoid - quartz monzonite - granodiorite composition. Huronian rocks are mainly quartzite and conglomerate. Greenstones include mafic volcanics - basalt and andesite composition.

Surficial - moderately thick glacial (boulder till) and glacio-fluvial (outwash sand, gravel, clay and eskers).

Mineralization- deposit of silver-bearing sulphide (mainly galena) mined. Several other occurrences of silver, cobalt, and iron known in general area.

COBALT PLAIN

Alphretta Lake

Bedrock - located in the Superior Province, in conglomerate and argillite of the Gowganda Formation. Some diabase intrusions.

Surficial - moderate glacial (boulder till) and glacio-fluvial (sand, gravel, clay) deposits.

Mineralization - none known.

Kukagami Lake

Bedrock - Southern Province - conglomerate and argillite of the Gowganda Formation. Nipissing and olivine diabase dikes.

Surficial - moderate glacial (till) and glacio-fluvial (outwash sand, gravel, clay) deposits.

Mineralization - minor sulphide occurrences - pyrite, galena and chalcopyrite.

HURONIAN BELT

Lang Lake

Bedrock - located in the Southern Province, in conglomerate, argillite, quartzite of the Gowganda Formation.

Surficial - relatively thin glacial drift - boulder till.

Mineralization - minor amounts of sulphides throughout the area.

Penage

Bedrock - located in the Southern Province. Underlaid by rocks of the Pecors (argillite), Mississagi (quartzite), Bruce (conglomerate), Espanola (limestone, calcareous siltstone), and Serpent formations, and Nipissing diabase.

Surficial - thin to moderate glacial drift-boulder till - some outwash sand, gravel and clay.

Mineralization - several known sulphide occurrences around shores (pyrite, chalcopyrite, arsenopyrite).

Little Penage

Essentially the same as Penage.

TABLE 3.2.1 SUMMARY OF GEOLOGY OF LAKE BASINS

<u>Name</u>	<u>Bedrock Geology</u>	<u>Surficial Geology</u>
Kukagami	Gowganda formation	ground moraine
Geneva	Serpent and Gowganda formations	ground moraine and bare bedrock
Tyson	metamorphosed quartzite and conglomerate, granite and biotite gneiss	" " "
George	Lorrain formation and undifferentiated granite	" " "
Lang	Gowganda and Serpent formations	" " "
Penage	Mississagi formation Espanola formation	" " "
Alphretta	Gowganda formation	" " "
Camp Ten	micropegmatite and granophyre	ground moraine
Little Penage	Espanola formation	ground moraine and bare bedrock

3.3 PHYSICAL AND CHEMICAL LIMNOLOGY

Temperature

The study lakes are typical of Precambrian Shield lakes in the vertical distribution of temperature. They fit the classification reviewed by Hutchison (1957) of dimictic (north-temperate) lakes. That is, there are two periods of stratification. In summer a thermogradient prevents circulation and the water body develops three distinct regions:

- 1) epilimnion - surface water of more or less constant temperature,
- 2) thermocline - a discontinuity layer in which the rate of change of temperature with depth is a maximum, and
- 3) hypolimnion - layer of water at the bottom with temperature close to 4°C.

In winter the water body is isothermal and ice cover prevents wind action from mixing the lake. Circulation occurs in spring and fall when the lakes approach isothermy at 4°C. Wind action provides the energy for mixing. A notable exception in this study was Camp Ten Lake which was too shallow to show a well-defined thermocline.

Table 3.3.1 indicates the temperature range and the depth of the thermocline in the study lakes.

As can be seen in the table, the depth of the thermocline appears to move during the summer, being shallower at its onset in the spring, deeper during mid-summer and shallower in the fall. Since the lakes (except Camp Ten) are stratified during the study period, the movement of dissolved species from the sediments to the surface waters would be retarded because the thermocline acts as a barrier to chemical diffusion.

TABLE 3.3.1 TEMPERATURE, SECCHI DISC TRANSPARENCY AND
DISSOLVED OXYGEN CONCENTRATIONS IN STUDY LAKES

<u>Lake Name</u>		<u>Temperature °C.</u>		<u>Thermocline m</u>	<u>Secchi Disc m</u>	<u>Range in Dissolved Oxygen (% Sat.)</u>
		<u>Surface</u>	<u>Bottom</u>			
Kukagami	23/6	18.0	9.0	8.0	7.5	157-43
"	3/8	23.0	11.0	10.0	12.0	172-153
Tyson	30/6	21.0	6.5	6.5	7.0	111-52
"	8/8	24.0	9.0	7.3	5.0	165-107
George	8/8	23.0	8.5	9.2	9.0	178-120
"	6/9	20.0	8.5	8.5	10.0	163-113
Penage	30/6	24.0	10.0	8.3	6.0	145-117
"	1/9	19.0	11.0	6.8	8.0	155-133
Alphretta	12/6	22.0	10.0	9.5	12.0	122-80
"	23/8	21.0	9.0	9.5	10.0	157-129
Geneva	7/6	21.0	8.0	6.5	6.0	120-77
"	21/8	21.5	8.0	6.5	5.0	157-56
Lang	28/7	24.5	10.8	4.5	6.0	154-60
"	26/8	22.0	11.0	5.5	6.0	150-60
Camp Ten	22/6	19.0	11.5	US	5.0	133-45
"	9/9	18.0	13.0	US	6.0	166-39
Little Penage	11/9	18.0	7.0	7.5	5.0	152-61

US = Unstratified

Dissolved Oxygen

Also typical of lakes in the Precambrian Shield is the high epilimnetic dissolved oxygen concentration. The maximum dissolved oxygen occurs in the surface waters and the minimum at the sediment-water interface in the hypolimnion indicating that photosynthesis exceeds respiration in the surface waters and vice versa in the bottom waters. The chemical equation for respiration and photosynthesis (the oxygen-consuming and oxygen-producing reactions) is shown in section 1.3.

Table 3.3.1 provides the range in dissolved oxygen and examples of the vertical distribution of oxygen concentration are shown in figure 3.3.1 for Kukagami and Penage lakes.

A wide range of oxygen distributions with depth existed in the lakes and is summarized in Table 3.3.2 using the information provided by Hutchison (1957).

The atmosphere is the oxygen sink for natural waters since water which is supersaturated tends to give up oxygen to the atmosphere and atmospheric oxygen is dissolved in waters which are undersaturated. The air-water interface retards the movements of oxygen in and out of water allowing the oxygen concentration to deviate from equilibrium.

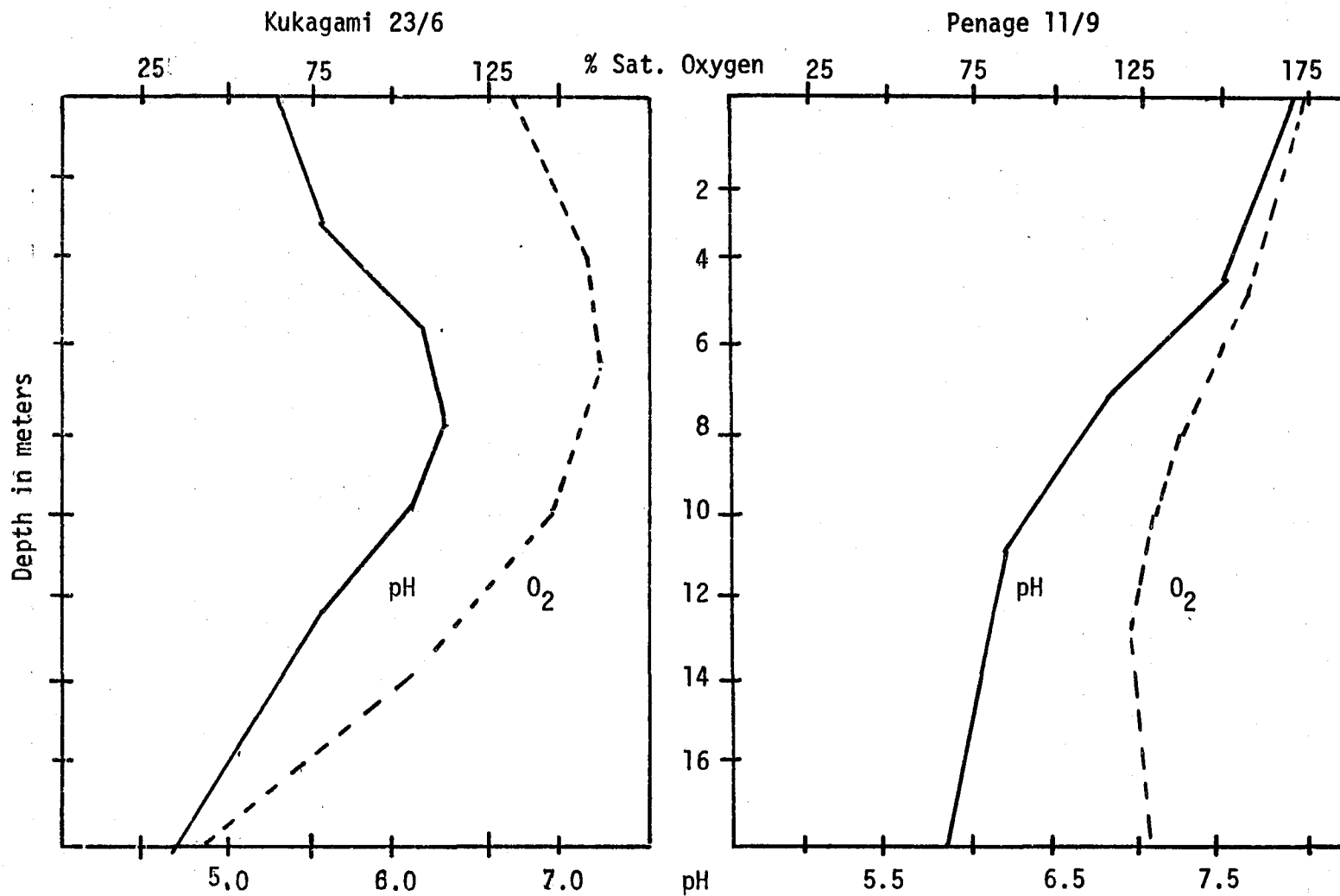


FIGURE 3.3.1 VERTICAL DISTRIBUTION OF pH AND DISSOLVED OXYGEN

TABLE 3.3.2 OXYGEN DISTRIBUTION WITH DEPTH

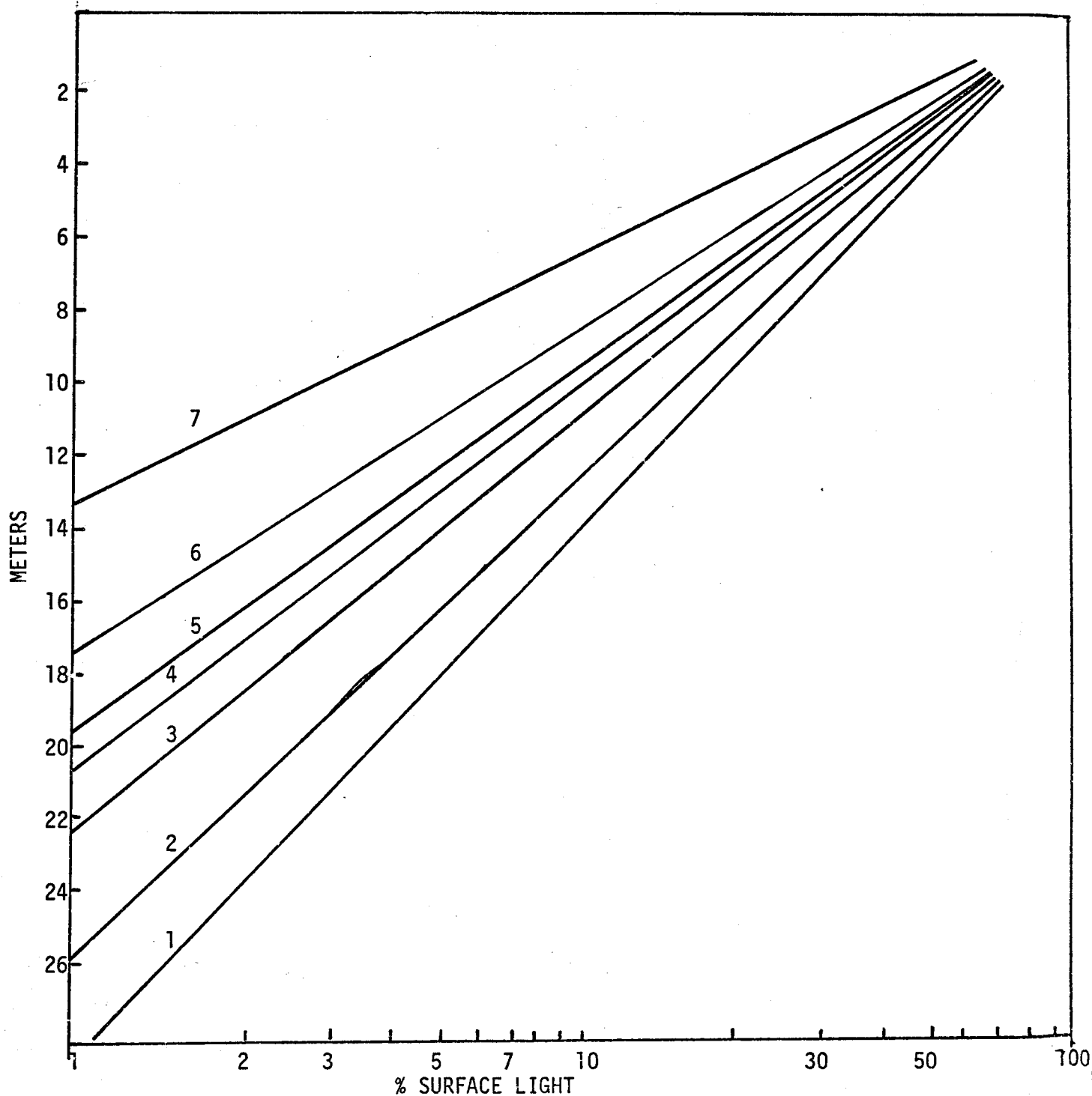
<u>Curve</u>	<u>Definition</u>	<u>Lakes and Date</u>
clinograde	concentration remains high in euphotic zone then falls rapidly with depth	Camp Ten 22/7, 5/9 Little Penage 11/9'
positive heterograde	a marked oxygen maximum in the region of the thermocline	Alphretta 12/7, 23/8 Lang 26/8 Penage 1/9
negative heterograde	a marked oxygen minimum in the region of the thermocline	Tyson 18/8
orthograde	relative uniform decrease of oxygen with depth	Tyson 30/6 George 6/8, 6/9 Penage 30/7 Lang 28/7 Geneva 7/7, 21/8 Kukagami 23/6, 6/8
negative clinograde	mirror image of clinograde curve	Tyson 30/6

Light

The measure of light penetration used in this study was the secchi disc transparency depth. Values varied from 5 to 12 meters. The data presented by Clarke (1954) allows the calculation of an approximate extinction coefficient of light from secchi disc transparency measurements since the plot of $1/\log_e$ of the extinction coefficient against the secchi disc depth is linear with a slope of 0.165. The per cent decrease of light intensity with depth for the study lakes is shown in figure 3.3.2 as a semi-logarithmic plot. Photosynthetic activity derives its energy from solar radiation and is considered to be operative to depths of one per cent of the surface light intensity (euphotic zone). The euphotic zone of the study lakes varied from 13 to 28 meters placing them near the lower limit of most freshwaters (Clarke, 1954).

In general, the secchi disc transparency depth varies inversely with primary productivity. Thus, Lake Superior with a secchi disc reading of 10 meters (Schelske and Callender, 1970, mean of 22 stations) shows low primary productivity while Lake Erie with a secchi disc reading of 1.5 meters (Beeton, 1961, western basin) shows high productivity (ref. figure 1.3.3).

FIGURE 3.3.2 GRAPH OF LIGHT ABSORPTION WITH DEPTH IN STUDY LAKES



Name	Date	Secchi Disc	Name	Date	Secchi Disc
1. Kukagami	3/8/71	12.0	6. Geneva	7/7/71	6.0
2. Alphretta	12/7/71		Camp Ten	5/9/71	
Alphretta	23/8/71	10.0	Lang	28/7/71	
3. Penage	1/9/71	8.0	Lang	26/8/71	
4. Kukagami	27/6/71	7.5	Penage	30/7/71	
5. Tyson	30/6/71	7.0	7. Tyson	18/8/71	
			Geneva	21/8/71	5.0
			Camp Ten	22/7/71	
			Little Penage	11/9/71	

Major Ions

The mean concentrations of major ions in the study lakes are shown in Table 3.3.4. Calcium was the major cation constituting from 60 to 75 per cent of the cationic supply. The calcium concentration was maximum in Little Lake Penage (0.650 meq l^{-1}) and minimum in Tyson Lake (0.200 meq l^{-1}). The major anions were sulphate and/or bicarbonate with a range of 0.156 to 0.481 and 0.03 to 0.560 meq l^{-1} respectively. Sulphates constituted from 35 to 85 per cent of the major anions while bicarbonate made up from 20 to 65 per cent of the anionic supply.

Bicarbonate (as determined by alkalinity) is the only major ion which varied with depth with the exception of sulphate in George Lake on August 6. An unusual distribution showing a surface and bottom minimum of 13 mg l^{-1} and a peak of 26 mg l^{-1} at 5 meters occurred at that station.

The concentration of total carbon dioxide decreased as the summer progressed (except in Camp Ten Lake) indicating that the supply of inorganic carbon was not being regenerated to the surface waters. Also, the fact that the concentration of total carbon dioxide did not increase appreciably in the hypolimnetic waters indicates that most of the carbon in the system was retained during the summer as organic carbon (living and non-living biomass). Similar results were reported by Schindler and Nighswander (1970).

The high sulphate concentrations reported in this study were noted by the above authors in Clear Lake, Haliburton County, Ontario ($45^{\circ}11'N, 78^{\circ}43'W$), - mean sulphate concentration of

0.168 meq l^{-1} . The values reported in the present study were considerably higher (0.240 to 0.480 meq l^{-1}) in all except Geneva Lake. Schindler and Nighswander reported a bicarbonate ion concentration (0.033 meq l^{-1}) similar to the values shown in Table 3.3.4 for Tyson and Alphretta lakes. Further comparative data will be provided as a summary in section 3.

pH

The hydrogen ion activity (pH) varied by nearly three orders of magnitude (10^3 change) in the study lakes - from 4.95 in Kukagami Lake at 3 meters on August 3, to 7.78 in Little Lake Penage at 1 meter on September 11.

The mean pH for each lake is shown in Table 3.3.3 below.

TABLE 3.3.3 MEAN pH OF STUDY LAKES

<u>Name</u>	<u>Date</u>	<u>pH</u>		<u>Name</u>	<u>Date</u>	<u>pH</u>	
		<u>Mean</u>	<u>Range</u>			<u>Mean</u>	<u>Range</u>
Kukagami	23/6	5.55	5.30-6.25	Camp Ten	22/7	7.10	6.82-7.22
	03/8	5.08	4.95-5.28		05/9	7.21	6.68-7.52
Tyson	30/6	6.19	5.78-6.53	Lang	28/7	6.72	6.27-7.07
	18/8	5.33	5.26-5.45		26/8	6.76	6.24-7.30
Geneva	07/7	6.57	6.28-6.88	Penage	30/7	6.81	6.55-6.96
	21/8	6.29	6.10-6.55		01/9	6.72	6.45-7.15
Alphretta	12/7	5.79	5.52-6.02	George	06/8	5.67	5.52-5.86
	23/8	5.42	5.52-5.70		06/9	5.32	5.06-5.52
				Little Penage	11/9	7.24	6.90-7.78

The pH of natural water varies from 6.5 to 8.5 in areas not affected by pollution (Hem 1971). Juday et al (1935) report that the range of pH in lakes in northeastern Wisconsin is 4.4 to 7.5 for seepage lakes and 4.8 to 8.9 for drainage lakes.

Hutchison (1957) summarizes data collected by Stom (1939) from the mountainous areas of Norway. In this study only one lake

TABLE 3.3.4 MEAN CONCENTRATIONS AND IONIC BALANCE
OF MAJOR IONS IN STUDY LAKES meq l⁻¹

		Ca ²⁺	Mg ²⁺	Na ⁺	Total	SO ₄ ²⁻	HCO ₃ ⁻	Cl ⁻	Total
Kukagami	23/6	0.345	0.083	0.035	0.467	0.438	0.042	0.020	0.500
	3/8	0.300	0.083	0.035	0.438	0.440	0.040	0.020	0.500
Tyson	18/8	0.250	0.083	0.035	0.373	0.266	0.030	0.039	0.335
	30/6	0.200	0.083	0.035	0.326	0.240	0.036	0.060	0.336
Geneva	7/7	0.250	0.083	0.035	0.259	0.162	0.040	0.040	0.246
	21/8	0.264	0.083	0.035	0.382	0.156	0.150	0.014	0.320
Alphretta	12/7	0.250	0.083	0.035	0.368	0.286	0.036	0.049	0.361
	23/8	0.256	0.083	0.035	0.374	0.268	0.030	0.060	0.349
Camp Ten	22/7	0.398	0.171	0.020	0.624	0.274	0.270	0.078	0.622
	5/9	0.426	0.167	0.070	0.643	0.216	0.420	0.021	0.657
Lang	28/7	0.465	0.132	0.087	0.684	0.475	0.140	0.064	0.679
	26/8	0.392	0.167	0.087	0.646	0.450	0.190	0.062	0.702
Penage	30/7	0.475	0.170	0.087	0.732	0.481	0.140	0.070	0.691
	1/9	0.442	0.167	0.087	0.696	0.480	0.130	0.078	0.688
George	6/8	0.200	0.084	0.044	0.528	0.420	0.050	0.077	0.547
	6/9	0.249	0.084	0.044	0.377	0.240	0.040	0.056	0.307
Little Penage	11/9	0.650	0.192	0.044	0.886	0.308	0.560	0.028	0.896

was found to have a pH of less than 6.0 (all depths being considered). Hutchison (1957) claims that at pH values below 6.0 acids other than carbonic may be suspected of influencing pH.

Biological activity will influence pH; photosynthesis consumes carbon dioxide thus affecting the hydrogen ion buffer in natural waters and raising pH; respiration tends to lower the pH. The vertical distribution of pH provides an indication of the influence of the biota in determining the pH of the system. Since the biota is liberating oxygen while consuming carbon dioxide, the vertical distribution of oxygen should be similar to that of pH. The distributions of oxygen and pH with depth for Kukagami Lake on June 23 and Little Lake Penage on September 11 are provided in figure 3.3.1 to show the effect of biological activity on pH.

Silica

Dissolved silica concentrations in the study lakes varied from a low of 0.02 mg l^{-1} as SiO_2 in Kukagami Lake at 7 meters on August 3, to a high of 15.1 in Camp Ten Lake at 8 meters on June 22. The mean and range for each station is shown in Table 3.3.5 below.

TABLE 3.3.5 MEAN AND RANGE IN DISSOLVED SILICA
CONCENTRATION (mg l^{-1}) in STUDY LAKES

<u>Name</u>	<u>Mean</u>	<u>Range</u>	<u>Name</u>	<u>Mean</u>	<u>Range</u>
Kukagami	0.9 0.08	0.14-1.46 0.02-0.14	Camp Ten	11.87 12.27	10.30-15.10 10.70-16.70
Tyson	3.25 2.46	2.86-3.91 2.10-2.70	Lang	1.86 1.98	1.30-2.90 1.30-3.40
Geneva	2.23 2.26	0.66-3.80 0.70-4.70	Penage	1.14 1.76	1.00-1.40 1.60-2.00
Alphretta	1.24 0.85	0.85-1.68 0.42-1.18	George	2.92 2.60	2.60-3.20 2.00-3.10
			Little Penage	1.08	0.30-1.90

According to Hem (1971) natural water normally has more dissolved silica than the quartz equilibrium value (6.0 mg l^{-1} @ 25°C), but less than the values shown for amorphous silica (115 mg l^{-1} @ 25°C). The equilibrium concentrations of silica have been reported by Morey et al (1962). Most commonly the values range from less than 1 to 30 mg l^{-1} and a median silica value for surface waters has been

quoted as 14 mg l^{-1} (Hem, 1971 from Davis, 1964). The depth distribution of silica mirrors that of oxygen indication interaction with the biosphere (principally diatoms). As an example the depth distribution of silica for Lang Lake on June 28 and Geneva Lake on August 6 is compared with the chlorophyll a concentration (an indication of the activity of the primary trophic level) in figure 3.3.3.

As can be observed from the figure for Geneva and Lang lakes and from Appendix B for the other study lakes, silica was consistently higher in the hypolimnion, reaching a maximum at the sediment water interface. Three mechanisms probably contribute to the accumulation of silica in the bottom waters:

1. utilization of silica in the euphotic zone,
2. dissolution of silica in the sediments mainly from the decomposition of diatom frustules, and
3. retardation of silica diffusion from hypolimnetic to epilimnetic waters by the thermocline.

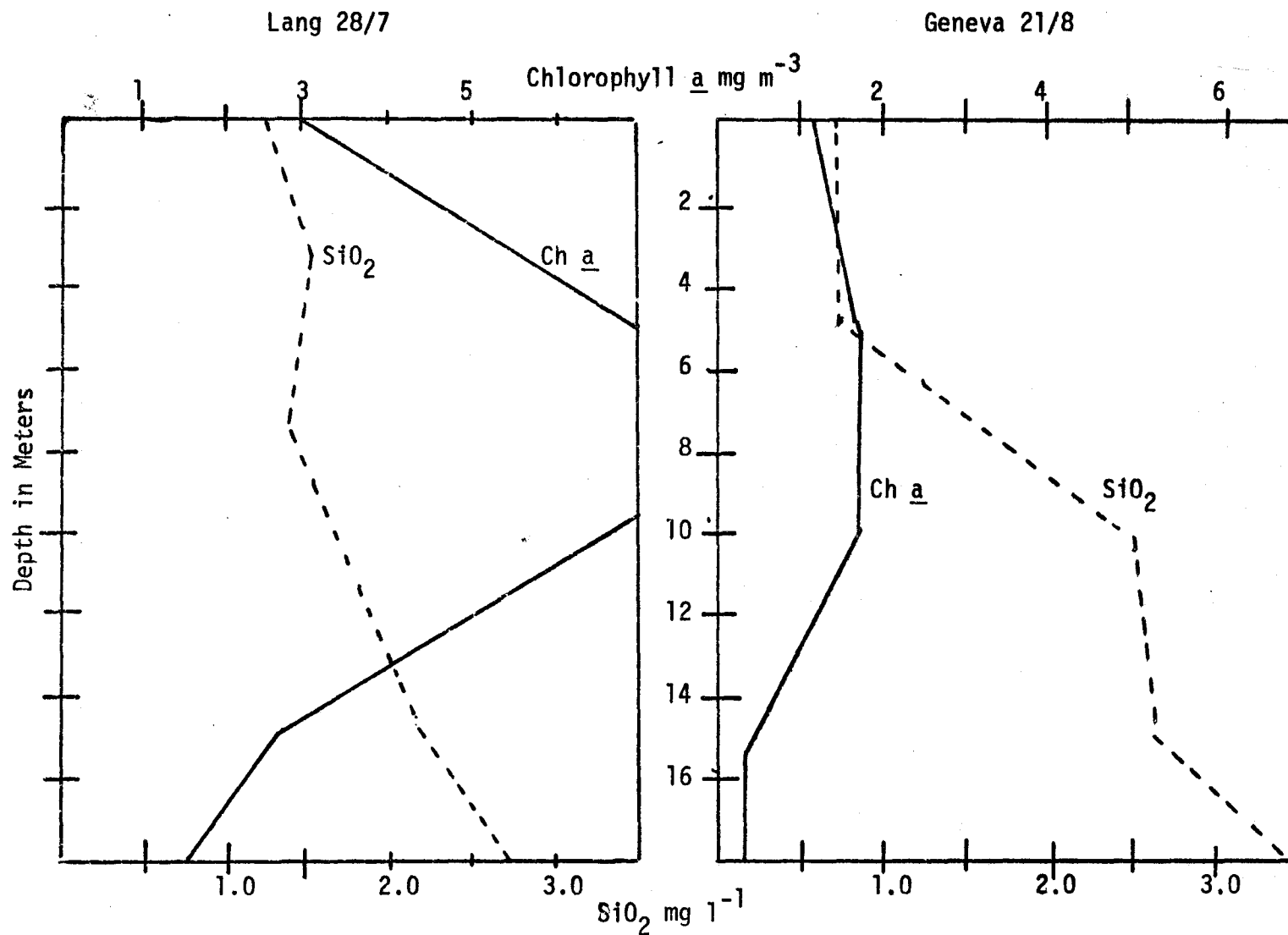


FIGURE 3.3.2 VERTICAL DISTRIBUTION OF CHLOROPHYLL a AND DISSOLVED SILICA CONCENTRATION

Nitrogen and Phosphorus

Mean concentrations and ranges of nitrate-nitrogen and total phosphorus for the study lakes are indicated in Appendix B. Both nutrients were in extremely low supply in the lakes and were not detectable on many occasions, especially as the season progressed (second sampling date). The values reported for Kjeldahl nitrogen (ammonia plus organic nitrogen) indicate that most of the nitrogen is in the organic form, likely incorporated in the biomass of the primary trophic level.

3.4 PRECIPITATION MONITORING

The results of the precipitation monitoring programme for June, July, August and September are summarized in table 3.4.1 and indicate that the atmosphere is a significant source of ions to the lakes in the Sudbury area. Mean conductivity of precipitation (12 stations x 4 months) was $35.9 \text{ umho cm}^{-1}$ @ 25°C with a range of 3 to 110 umho cm^{-1} @ 25°C . By comparison, conductivity in the study lakes ranged from 35.7 to $102.0 \text{ umho cm}^{-1}$ @ 25°C with a mean of 68.6.

The major anion in the bulk precipitation samples (excepting carbonate and bicarbonate) was sulphate, showing a mean concentration of 3.4 mg l^{-1} and a range of 0.3 to 15.2 mg l^{-1} . A negative relation existed between distance from Sudbury and the concentration of sulphate measured in the precipitation samples. The pattern is similar to zones of sulphur dioxide damage to vegetation reported by Driesinger and McGovern (1970).

The hydrogen ion concentration in the bulk precipitation samples varied from pH= 3.71 to 7.21 with a mean of 4.71. Other cations such as calcium, sodium and potassium were present in only trace amounts - 5×10^{-5} molar. An ionic balance using sulphate in the form of sulphuric acid as the pH-determining ion usually gave slightly greater (approximately 10 per cent) hydrogen ion concentrations than that measured in the sample.

TABLE 3.4.1 SUMMARY OF PRECIPITATION MONITORING
DATA - SELECTED PARAMETERS

<u>Station¹</u>	<u>pH</u>	<u>Conductivity</u> <u>umho cm⁻¹</u>	<u>Sulphate</u> <u>mg l⁻¹</u>	<u>Rainfall</u> <u>cm</u>
1	4.54	20	0.5	-
2	4.10	36	11.7	10.13
3	4.40	30	0.7	-
4	6.29	42	0.3	7.80
5	5.51	58	-	-
6	4.35	33	1.9	12.32
7	4.56	54	1.1	10.19
8	4.98	24	0.9	11.18
9	4.99	12	1.1	11.58
10	4.12	31	1.9	11.53
11	5.12	44	0.5	12.62
12	4.27	44	12.4	12.83
Grand Mean	4.71	36	3.4	11.94
Range	3.71-7.21	3-110	<0.3-15.2	2.36-23.40

1. Station locations provided in figure 2.3.1.

3.5 BIOLOGY OF PRIMARY AND SECONDARY TROPHIC LEVELS

The measures of biological activity made during the study are discussed under the following headings:

- 1) Primary Productivity,
- 2) Standing Stocks of Phytoplankton,
- 3) Chlorophyll a Concentrations,
- 4) Standing Stocks of Zooplankton, and
- 5) Diversity of Primary and Secondary Trophic Levels.

Primary Productivity

Primary productivity or rate of incorporation of inorganic carbon into living cells of the primary trophic level is shown in Appendix B in units of $\text{mg carbon m}^{-3}\text{hr}^{-1}$. Table 3.5.1 below, indicates the integral mean productivity in units of $\text{mg carbon m}^{-2}\text{hr}^{-1}$ for the study lakes.

TABLE 3.5.1 MEAN PRODUCTIVITY IN STUDY LAKES $\text{mg C m}^{-2}\text{hr}^{-1}$

<u>Name</u>	<u>Date</u>	<u>Productivity</u>	<u>Name</u>	<u>Date</u>	<u>Productivity</u>
Kukagami	23/6 3/8	1.5 2.8	Camp Ten	5/9	21.4
Tyson	30/6 18/8	5.0 4.8	Lang	26/8	20.5
Geneva	7/7 21/8	67.6 35.4	Penage	1/9	8.1
Alphretta	12/7 23/8	13.5 14.7	George	6/9	22.9
			Little Penage	11/9	14.1

The productivities show the lakes to be above and below the range as indicated by Johnson et al (1970) who reported a mean productivity of $12.6 \text{ mg C m}^{-2} \text{ hr}^{-1}$ for Dunlop Lake and 7.0 and $3.3 \text{ mg C m}^{-2} \text{ hr}^{-1}$ for Quirke and Pecors lakes respectively. The latter lakes were polluted by discharges from the uranium milling industry. Schindler and Nighswander (1970) reported on a highly productive lake in the Precambrian Shield which showed a mean (average of ice-free period) productivity of approximately $100 \text{ mg C m}^{-2} \text{ hr}^{-1}$.

Standing Stocks of Phytoplankton

The standing stocks of total phytoplankton and major taxonomic groups expressed in a.s.u. ml^{-1} are shown in Appendix B. The weighted mean value and the range for each lake and date is indicated in Table 3.5.2. As with primary productivity the range in values reported for these lakes exceeds those reported by Johnson et al (1970). The authors reported a mean of 206, 168 and 31 for Dunlop, Quirke and Pecors lakes respectively. Reference to Table 3.5.2 indicates a mean of $7449 \text{ a.s.u. ml}^{-1}$ for Alphretta Lake on July 12, 1971 and $36 \text{ a.s.u. ml}^{-1}$ for George Lake on August 6, 1971.

The vertical distribution of phytoplankton for the study lakes by major taxonomic groupings is shown in figure 3.5.1. Of interest in this figure is the large bloom of diatoms ($3397 \text{ a.s.u. ml}^{-1}$) in Kukagami Lake on June 23 which accounts, at least in part, for the low dissolved silica values reported in Table 3.3.4. In August the count was down with maximum of $500 \text{ a.s.u. ml}^{-1}$ and yet the silica value remained low. The

TABLE 3.5.2 RANGE AND MEAN VALUES OF PLANKTON AND CHLOROPHYLL a

Lake Name	Date	Total Phytoplankton a.s.u. ml ⁻¹		Total Zooplankton no. m ⁻³		Chlorophyll <u>a</u> mg m ⁻³	
		Mean	Range	Mean	Range	Mean	Range
Kukagami	23/6	1952	297-3397	661	187-1145	3.42	1.0-4.54
	3/8	121	25-534	1255	530-2083	2.60	0.07-6.42
Tyson	30/6	354	43-613	359	215-610	1.55	0.30-2.51
	18/8	240	139-577	457	115-876	2.43	0.87-5.35
Geneva	7/7			590	284-1580	3.49	1.55-8.30
	21/8	317	125-1019	411	170-1270	0.89	0.26-1.52
Alphretta	12/7	7449	17-13,159	411	90-642	6.45	0.38-11.30
	23/8	880	13-3569	997	560-1420	3.31	0.75-7.21
Camp Ten	22/7	1072	42-2625	338	207-1551	7.54	1.36-17.30
	5/9	2061	310-4845	998	618-1265	7.28	1.15-16.10
Lang	28/7	255	1-736	1365	495-2305	3.46	1.18-9.00
	26/8	329	131-675	716	90-1195	1.31	0.34-2.81
Penage	30/7	108	73-128	659	512-910	0.93	0.89-1.64
	1/9	156	101-205	753	378-1056	1.25	0.74-1.70
George	6/8	36	4-69	288	68-856	1.57	0.63-2.73
	6/9	43	22-55	168	60-401	1.52	0.38-2.18
Little Penage	11/9	535	254-856	1399	204-2970	2.40	0.67-4.77

same trend is shown in Alphretta. Both Kukagami and Alphretta are in the Gowganda Formation of the Cobalt Plain. Extremely low concentrations of phytoplankton (less than 200 a.s.u. ml^{-1}) are indicated in George Lake on both sampling dates and Penage on June 30.

A comparison of figure 3.5.1 with table 3.3.2 and figure 3.3.1 indicates that the vertical distribution of phytoplankton is similar to that of dissolved oxygen.

In particular, the negative clinograde oxygen distribution in Tyson Lake on June 30 corresponds to a phytoplankton pulse of flagellates and diatoms below the thermocline (6.5 meters). The euphotic zone extended to the lake bottom in Tyson Lake on that date.

Chlorophyll a

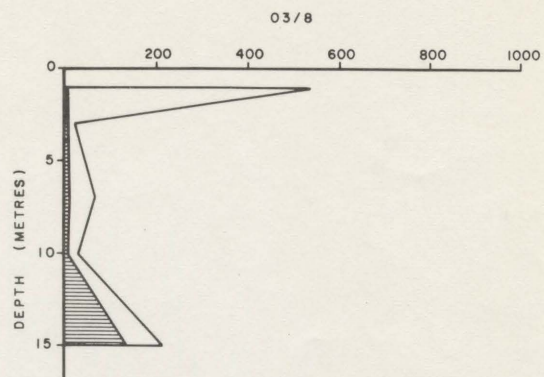
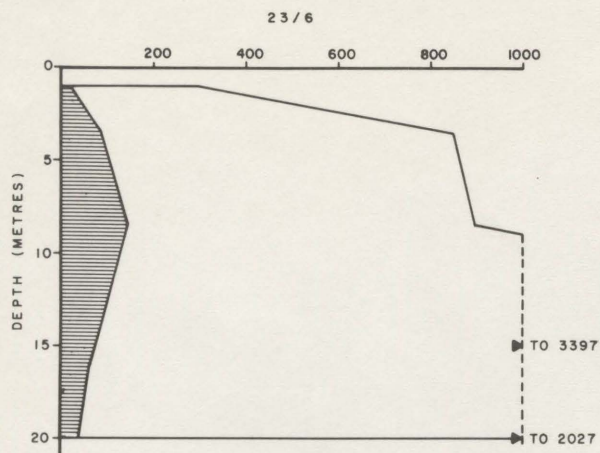
Chlorophyll a concentrations are shown in Appendix B. The weighted mean concentration for each lake studied is shown in Table 3.5.2 in $\text{mg chlorophyll a m}^{-3}$. Typical distributions of chlorophyll a with depth are shown in figure 3.3.3 for Geneva and Lang lakes. The depth profile of chlorophyll a was in general similar to the distribution of primary productivity especially at points of maximum dissolved oxygen concentration. The relationship is predictable since chlorophyll a is the organic molecule providing for the conversion of radiant energy to chemical energy during photosynthesis. Assuming the same activity for each equal weight of chlorophyll a, one would expect this positive relationship

VERTICAL DISTRIBUTION OF PHYTOPLANKTON IN STUDY LAKES IN A.S.U. ML⁻¹

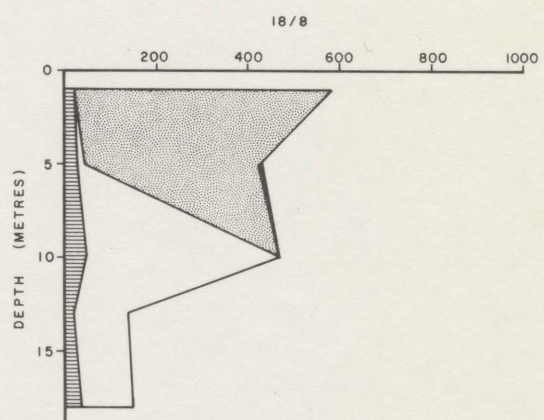
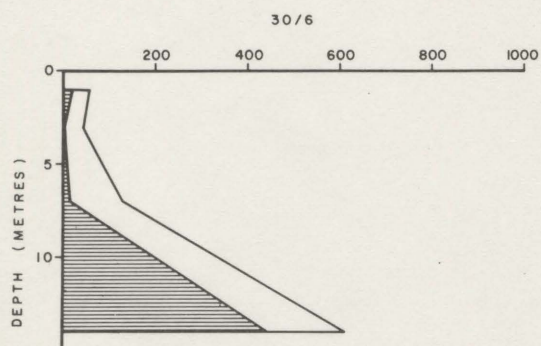
63

FIGURE 3.5.1

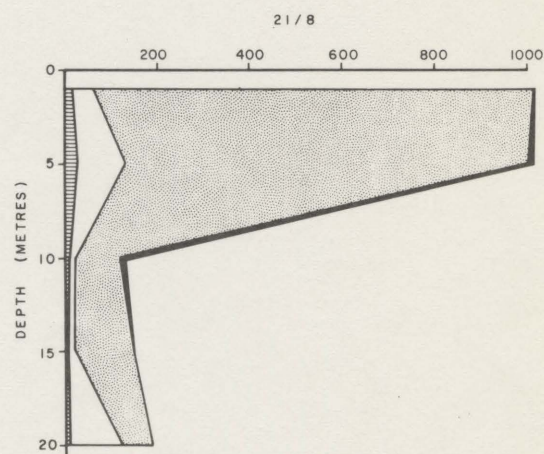
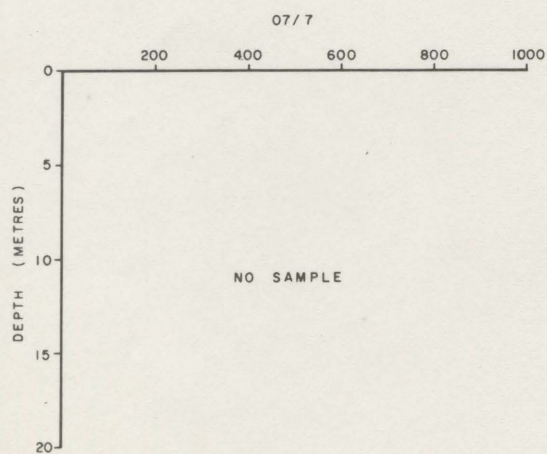
KUKAGAMI



TYSON



GENEVA

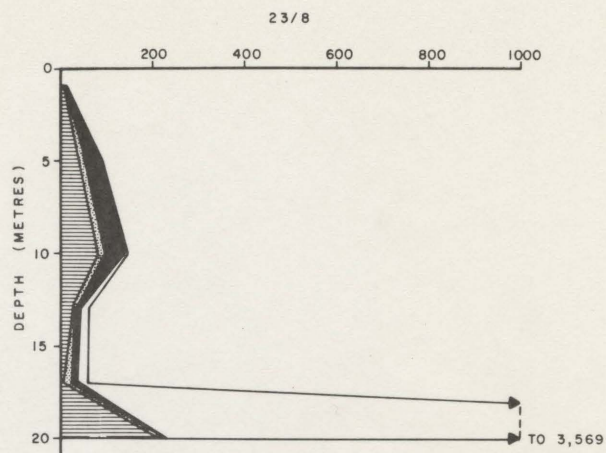
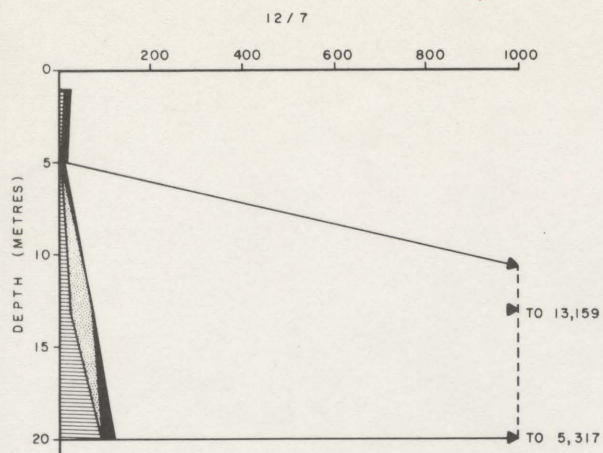


LEGEND

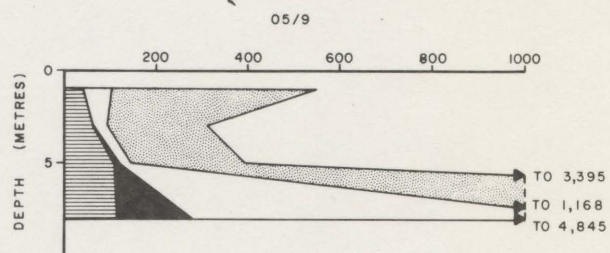
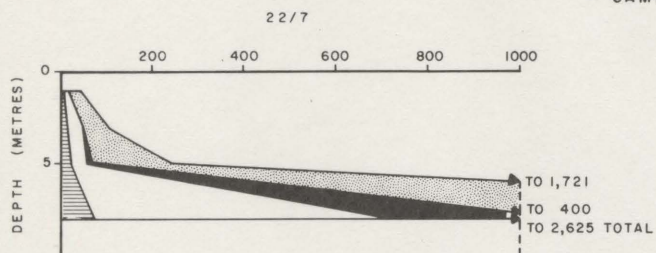
FLAGELLATES DIATOMS BLUE GREENS GREENS

FIGURE 3.5.1 CONT.

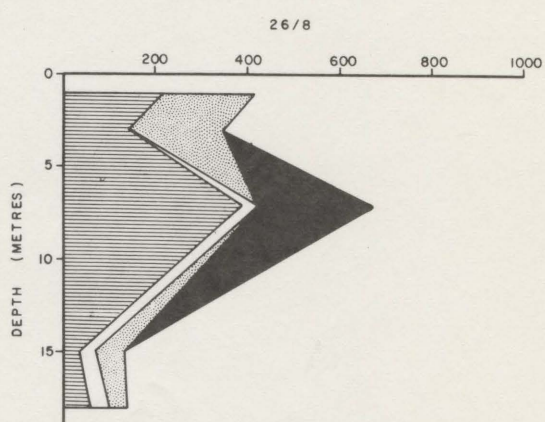
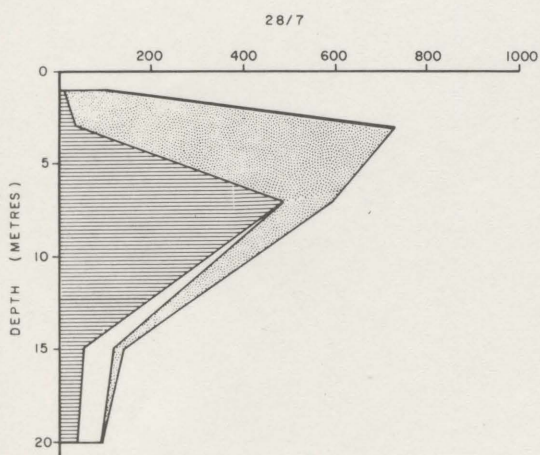
ALPHRETTA



CAMP TEN



LANG



LEGEND

FLAGELATES



DIATOMS



BLUE GREENS

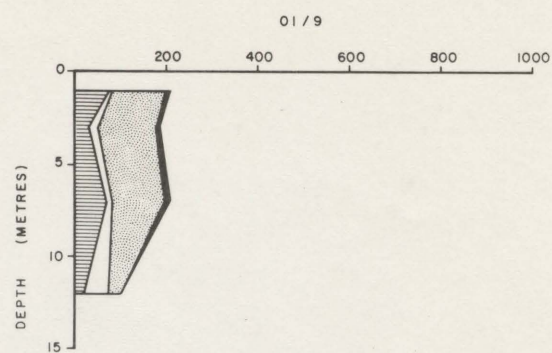
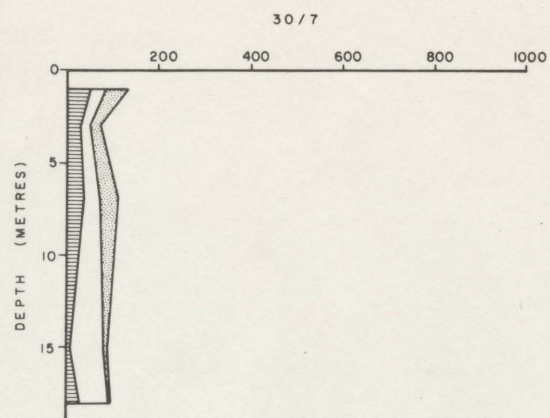


GREENS

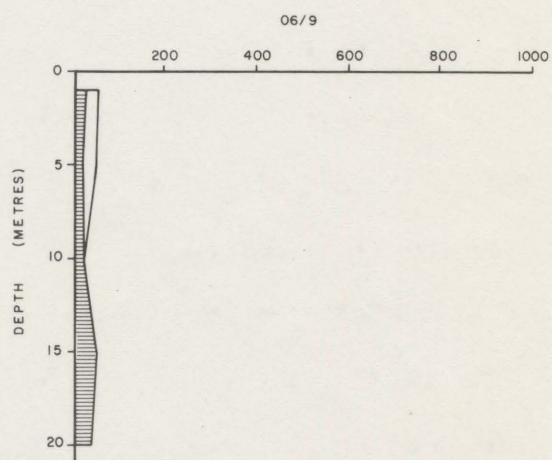
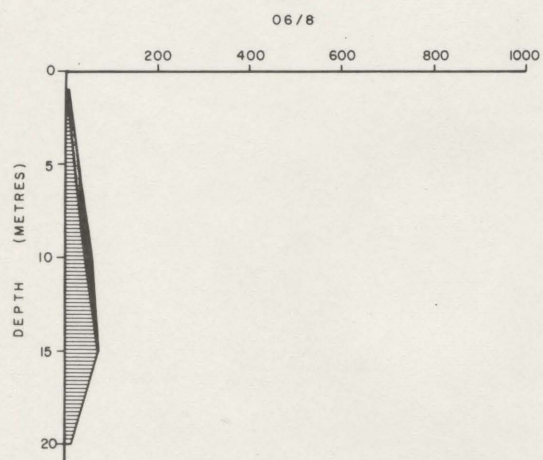


FIGURE 3.5.1 CONT.

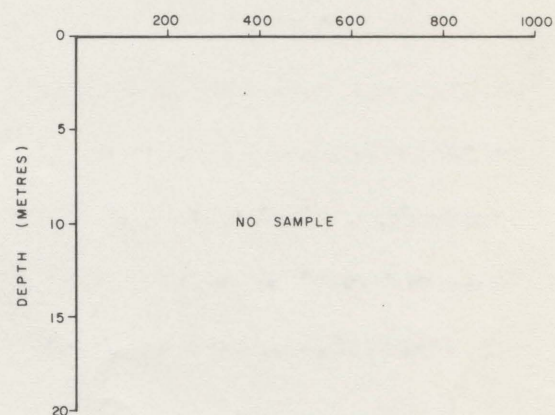
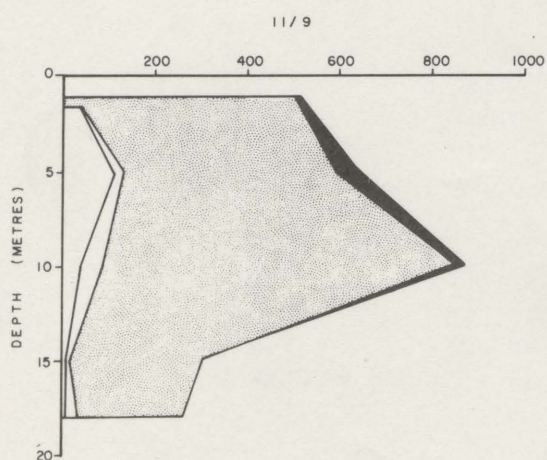
PENAGE



GEORGE



LITTLE PENAGE



LEGEND

FLAGELLATES DIATOMS BLUE GREENS GREENS

between the concentration of chlorophyll a and primary productivity. Schindler and Nighswander (1970) report a chlorophyll a range in Clear Lake, Ontario of 0.5 to 4.2 mg chlorophyll a m^{-3} . The range in chlorophyll a reported in the present study was 0.07 to 16.1 mg m^{-3} .

Standing Stocks of Zooplankton

Zooplankton populations, expressed as numbers of major taxonomic groups m^{-3} are shown in Appendix B. The weighted mean value and range of the data are indicated in Table 3.5.2. Conroy (1970) reported on the mean concentration of zooplankton in the lakes in the Precambrian Shield for which Johnson et al (1970) reported primary productivity data. Mean concentrations in that study varied from 680 to 2350 zooplankters m^{-3} in reference lakes to as low as 20 zooplankters m^{-3} in lakes polluted by sulphuric acid from mine effluents. The weighted mean in the present study varied from 60 to 2305 zooplankters m^{-3} in George Lake on September 9 and Lang Lake on July 28, respectively.

The vertical distribution of zooplankton is shown in figure 3.5.2 indicates that zooplankton populations are inversely related to the distribution of phytoplankton in some cases and directly related in others. For example, the maximum in the zooplankton distribution at ten meters in Geneva Lake on August 21 corresponds to a minimum in the standing stock of phytoplankton while Camp Ten Lake on June 22 and Lang Lake on August 26 depict a direct relationship.

VERTICAL DISTRIBUTION OF ZOOPLANKTON
IN STUDY LAKES IN N° M⁻³

FIGURE 3.5.2

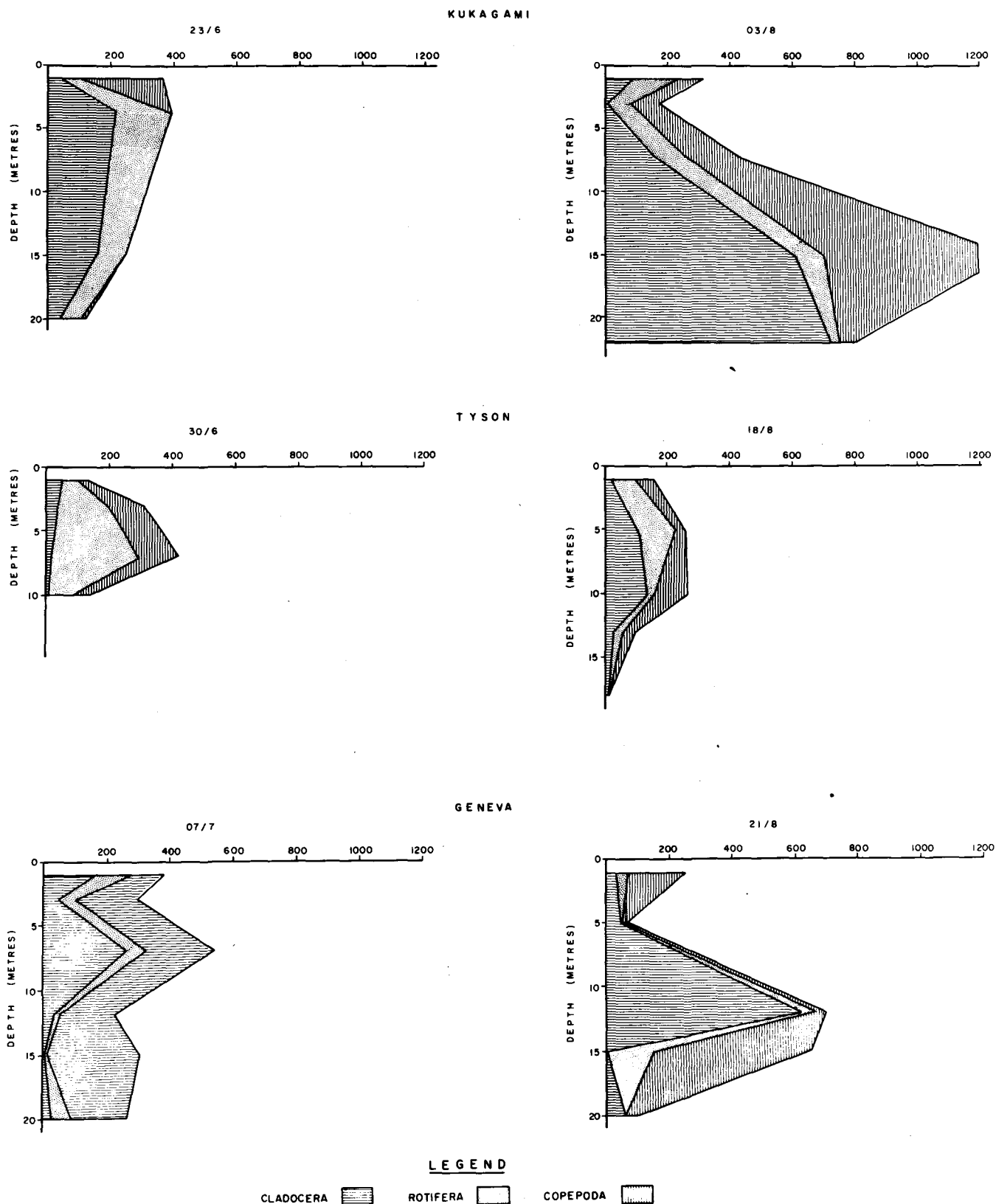
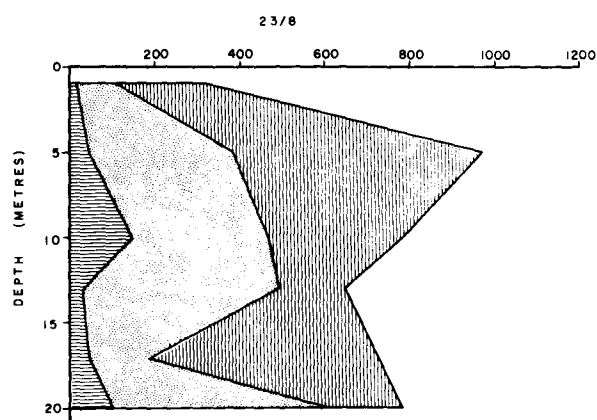
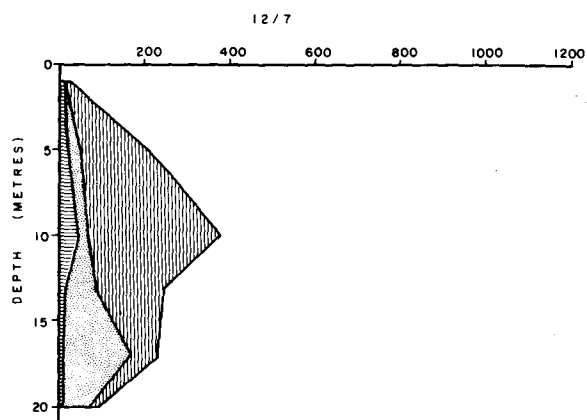
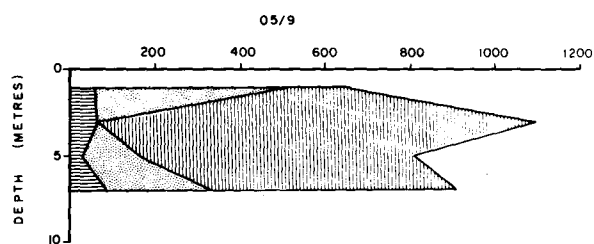
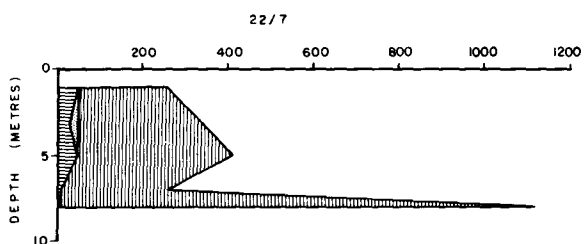


FIGURE 3.5.2 CONT.

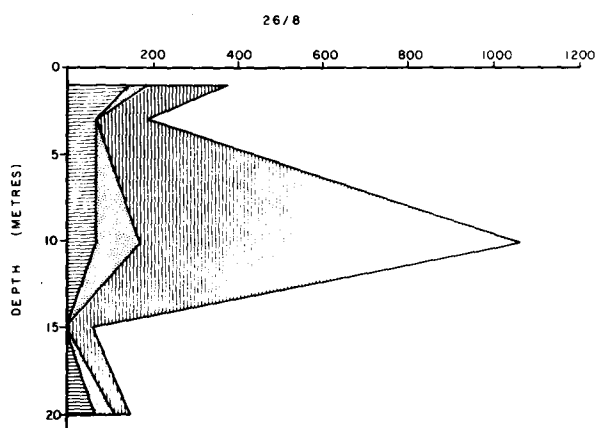
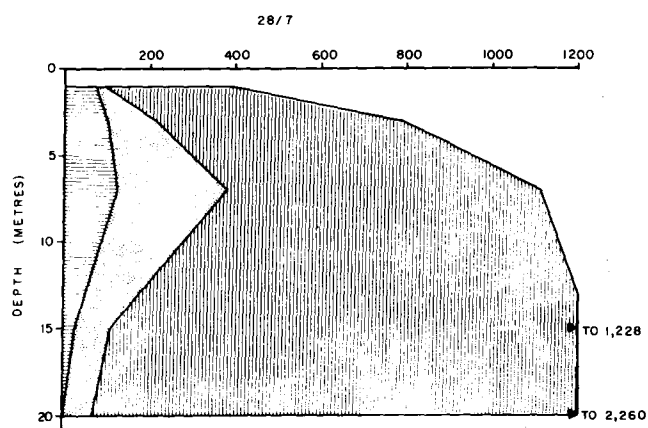
ALPHRETTA



CAMP TEN



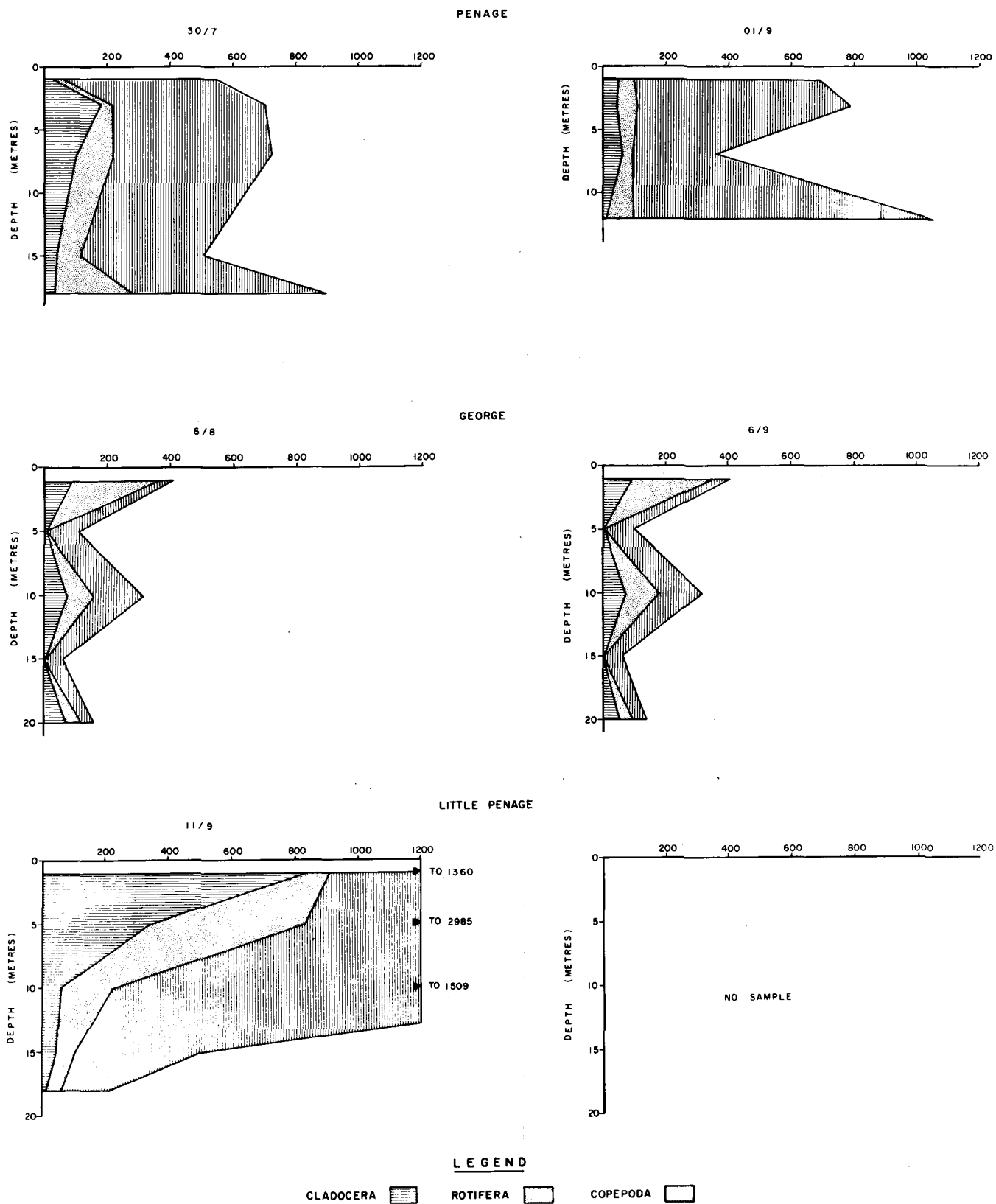
LANG



LEGEND

CLADOCERA ROTIFERA COPEPODA

FIGURE 3.5.2 CONT.



Diversity of Plankton Populations

The mean and range values of the index of diversity for phytoplankton are shown in Table 3.5.3. The mean diversity of the phytoplankton community varied from 0.57 in Tyson Lake on August 18 to 3.24 in Camp Ten Lake on July 22.

Johnson et al (1970) report a mean phytoplankton diversity of 6.05 for Dunlop Lake (the reference lake in their study) for 23 analyses during 1966 and 1967, and 3.13 for Quirke Lake (lake polluted by acid mine drainage). Michalski and Robinson (1970) report a range in phytoplankton diversity in Riley Lake, Haliburton County for one of the stations sampled as 1.5 to 3.7 with a mean of 2.4. Evidence was found that Riley Lake was affected by cultural eutrophication. Therefore, phytoplankton diversity would be expected to be depressed.

From figure 3.5.1, it is evident that the number of taxa is low in lakes with both very high and very low standing stocks of plankton. Kukagami on June 23 is an example of the former and George Lake on both dates of the latter condition. In these cases, the stability of the lake systems appears to be in jeopardy (Patten 1967). Reference to Table 3.5.3 shows that Alphretta Lake on June 12 and Tyson Lake on both dates fall into the same category - low mean diversity of the phytoplankton community.

TABLE 3.5.3 MEAN AND RANGE OF INDEX OF DIVERSITY OF PHYTOPLANKTON

<u>Lake Name</u>	<u>Date</u>	<u>Index of Diversity</u>	
		<u>Mean</u>	<u>Range</u>
Kukagami	23/6	0.64	0.53-0.70
	3/8	1.06	0.72-1.41
Tyson	30/6	1.15	0.61-2.19
	18/8	0.57	0.16-1.15
Geneva	21/8	2.17	1.75-2.90
Alphretta	12/7	1.65	0.51-3.22
	23/8	2.20	0.37-3.01
Camp Ten	22/7	3.24	1.30-4.61
	5/9	2.15	1.42-2.69
Lang	28/7	2.70	1.81-3.22
	26/8	2.69	1.59-3.88
Penage	30/7	3.23	2.60-3.72
	1/9	3.09	2.82-3.40
George	6/8	1.51	0.17-2.56
	6/9	1.93	1.52-2.29
Little Penage	11/9	2.10	1.67-2.44

3.6 COMPARATIVE SUMMARY OF DATA

A comparative summary of data from this and other studies is presented in Table 3.6.1. It is to be noted from this table that variables measured in this study show a range that places them at the same order of magnitude as analyses from other lakes in the Precambrian Shield. They are more oligotrophic than most lakes not in the Shield or those where evidence of cultural eutrophication was found (Michigan, Erie and Riley). For a listing of comparative data on other Precambrian Shield lakes see Armstrong and Schindler (1971).

Superior	6.0- 14.0					<0.5- 0.6	2.5- 3.0		1.70- 2.18	47			
8 Clear Lake	10	30	5.0- 7.0	2.5				8.07		1020	0.5- 4.2		

LEGENDS AND COMMENTS

- 1) present study
- 2) Beeton and Chandler (1963) - summary of literature
- 3) Kramer (1968) - zooplankton data by Conroy
- 4) Johnson et al (1970) and Conroy (1970) - Dunlop Lake is in the Precambrian Shield in the territorial district of Algoma twenty-five miles north of the Serpent Harbour on the North Channel of Lake Huron
- 5) Michalski and Robinson (1970) - Riley Lake is in the Muskoka District, Ontario; evidence of cultural eutrication was found by the authors.
- 6) Sakamoto (1971), and Schindler and Homgren (1971) - results from the Fisheries Research Board of Canada Experimental Lakes Area in Northwestern Ontario and Manitoba
- 7) Schelske and Callender (1970) - productivity expressed in $\text{mg C m}^{-3} \text{ day}^{-1}$ while other results in column are expressed in $\text{mg C m}^{-2} \text{ day}^{-1}$
- 8) Schindler and Nighswander (1970) - Clear Lake is located in the Precambrian Shield in the district of Haliburton, Ontario

NOTE: For a more complete review of comparative data see Armstrong and Schindler (1971).

3.7 STATISTICAL ANALYSIS

Correlation

The data (Appendix B) were subjected to correlation analysis to test for significant correlations between variables. A matrix was generated for correlations emphasizing physical and chemical variables in the study lakes and for correlations emphasizing biological parameters.

The correlation coefficients which were significant at the 95 per cent confidence limits are shown in Tables 3.7.1 and 3.7.2. Obvious relationships which can be explained on the basis of a knowledge of classical limnology, such as the relation between temperature or light and water depth, are not considered. Of interest were the variables which were correlated with biological parameters - productivity, chlorophyll a, phytoplankton and zooplankton numbers, diversity of primary and secondary trophic levels and major taxonomic groups of phytoplankton and zooplankton.

The results of the correlation analyses, using the biological parameters listed above as a focus, showed the following significant correlations:

- productivity and pH
 - dissolved silica
 - soluble phosphate
 - chlorophyll a
 - total phytoplankton
 - diatoms
 - blue-greens
 - greens
 - copepods
- chlorophyll a and dissolved silica
 - soluble phosphorus
- total phytoplankton and phytoplankton diversity (negative)
 - copepods

phytoplankton diversity and pH
blue-greens (negative)

zooplankton and copepods
nauplii
rotifers

cladocerans and pH

nauplii and rotifers.

Factor Analysis

The correlation matrices from Tables 3.7.1 and 3.7.2 were subjected to factor analyses including principle component and varimax factor analyses. Using the criterion of the eigenvalue being significant if greater than 1.0, five factors were selected to explain the variability of the data. Tables 3.7.3 and 3.7.4 indicate results of the principle component and a rotated factor analysis referred to as Varimax Factor Analysis for the parameters emphasizing chemical data and Tables 3.7.5 and 3.7.6 for data emphasizing biological parameters. The cumulative per cent eigenvalues of Tables 3.7.3 and 3.7.5 summarize the percentage of the covariance which is explained by each factor. The data emphasizing chemical variables was able to explain 81 per cent of the covariance in five factors and the data emphasizing biological parameters accounted for 90.7 per cent of the covariance in five factors.

Reference to Table 3.7.4 shows that most of the covariance in the properties of the system may be accounted for by the variance in the concentration of soluble phosphate, primary productivity, chlorophyll a, silica and total phytoplankton. Factor 2 is heavily loaded on the physical parameters - depth, temperature and light. Factor 3 is loaded by alkalinity, dissolved solids and pH. Factor 4

TABLE 3.7.1 MATRIX OF CORRELATION COEFFICIENTS EMPHASIZING CHEMICAL PARAMETERS

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22		
1																								Depth
2	X																							Temperature
3																								pH
4																								Alkalinity
5				X	X																			Dissolved Solids
6				X		X																		Calcium
7			X																					Dissolved Oxygen
8																								Silica
9																								Sulphates
10																								Nitrates
11								X																Phosphates
12								X			X													Chlorophyll <u>a</u>
13											X	X												Total Phytoplankton
14										X														Total Zooplankton
15				X				X			X	X	X											Primary Productivity
16			X																					Diversity of Phytoplankton
17																								Diversity of Zooplankton
18																								Flagellates
19													X											Diatoms
20																								a Conductivity
21	X	X																						Light
22				X																				Carbon Dioxide

TABLE 3.7.2 MATRIX OF CORRELATION COEFFICIENTS EMPHASIZING BIOLOGICAL PARAMETERS

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
1																pH
2																Silica
3		X														Primary Productivity
4																Flagellates
5		X	X													Diatoms
6			X		X											Blue-Greens
7		X	X		X	X										Greens
8		X	X		X	X	X									Total Phytoplankton
9																Total Zooplankton
10																Zooplankton Diversity
11						X		X								Phytoplankton Diversity
12		X	X		X	X	X	X	X							Copepods
13									X							Nauplii
14	X															Cladocerans
15									X				X			Rotifers

TABLE 3.7.3 PRINCIPLE COMPONENT ANALYSIS EMPHASIZING CHEMICAL PARAMETERS

FACTOR	1	2	3	4	5
Depth	.241	.926	.146	-.139	-.078
Temperature	-.432	-.800	-.068	.270	.087
pH	.540	-.052	-.725	.029	.204
Alkalinity	.517	-.212	-.549	-.436	-.268
Dissolved Solids	.398	.064	-.650	-.392	-.188
Nitrate	.465	.028	-.149	.668	-.315
Silica	.569	-.099	.296	-.301	.580
Sulphate	-.105	.307	-.357	.389	.337
Chlorophyll <u>a</u>	.874	-.107	.201	.117	.176
Primary Productivity	.862	-.380	.128	.037	.088
Total Phytoplankton	.821	-.223	.308	.104	-.071
Total Zooplankton	.534	-.018	-.227	.447	-.451
Zooplankton Diversity	-.116	-.469	-.069	-.510	-.222
Light	-.443	-.794	-.126	.130	.122
Phytoplankton Diversity	-.058	.188	-.565	.130	.665
Soluble Phosphorus	.847	-.192	.258	-.042	.175
CUM. PERCENT EIGENVALUES	30.7	48.1	61.3	71.6	81.0

TABLE 3.7.4 VARIMAX FACTOR MATRIX WITH EMPHASIS ON CHEMICAL PARAMETERS

FACTOR	1	2	3	4	5
Depth	-.035	.976	.053	.008	.067
Temperature	-.129	-.933	.156	.007	-.015
pH	.286	-.035	-.681	.225	.514
Alkalinity	.204	-.006	-.898	.094	-.137
Dissolved Solids	.025	.176	-.857	.065	.066
Nitrate	.195	.041	-.007	.855	.120
Silica	.814	.113	-.017	-.401	.109
Sulphate	-.173	.072	.077	.139	.661
Chlorophyll <u>a</u>	.877	.145	-.077	.251	.031
Primary Productivity	.877	-.092	-.220	.245	-.099
Total Phytoplankton	.810	.073	-.053	.338	-.236
Total Zooplankton	.191	.069	-.236	.801	-.036
Zooplankton Diversity	-.062	-.342	-.374	-.293	-.449
Light	-.144	-.916	.055	-.109	-.013
Phytoplankton Diversity	-.046	-.042	-.168	-.181	.867
Soluble Phosphorus	.900	.101	-.114	.113	-.084

TABLE 3.7.5 PRINCIPLE COMPONENT ANALYSIS EMPHASIZING BIOLOGICAL
PARAMETERS

FACTOR	1	2	3	4	5
pH	.125	.166	.863	-.231	.120
Silica	.596	-.564	.158	-.212	.241
Primary Productivity	.931	.015	.161	-.170	-.075
Flagellates	.120	.381	-.022	.527	.710
Diatoms	.923	-.316	-.104	-.055	.023
Blue-Greens	.904	-.044	-.048	.123	-.288
Greens	.963	-.188	-.044	-.111	.045
Total Phytoplankton	.962	-.047	-.065	.160	-.072
Total Zooplankton	.467	.844	.075	-.169	-.028
Zooplankton Diversity	-.000	.259	-.640	-.476	-.063
Phytoplankton Diversity	-.530	-.376	.354	-.550	.333
Copepods	.908	.102	.056	-.039	.313
Nauplii	.107	.868	-.097	-.342	-.040
Cladocerans	.015	.433	.656	.223	-.442
Rotifers	.030	.934	-.069	-.045	.220
CUM. PER CENT EIGENVALUES	40.7	63.2	75.3	83.2	90.7

TABLE 3.7.6 VARIMAX FACTOR MATRIX WITH EMPHASIS ON BIOLOGICAL DATA

FACTOR	1	2	3	4	5
pH	.150	.182	.721	-.529	.024
Silica	.727	-.368	-.056	-.366	-.005
Primary Productivity	.925	.190	.169	.010	-.092
Flagellates	.023	.178	.016	.090	.950
Diatoms	.962	-.133	-.127	.075	-.024
Blue-Greens	.858	.041	.105	.393	-.116
Greens	.987	.005	-.069	.033	-.007
Total Phytoplankton	.923	.036	.046	.319	.080
Total Zooplankton	.315	.892	.212	.125	.091
Zooplankton Diversity	-.021	.466	-.644	.033	-.272
Phytoplankton Diversity	-.356	-.242	-.019	-.868	-.146
Copepods	.888	.230	.022	-.050	.307
Nauplii	-.026	.943	-.002	.033	-.034
Cladocerans	-.092	.258	.854	.208	-.127
Rotifers	-.132	.883	.046	.086	.348

has two variables with approximately the same weight - nitrate and numbers of zooplankton - while factor 5 has pH, sulphates and the diversity of the phytoplankton community. The factors have been defined on the basis of the important loadings as:

- 1) production,
- 2) morphometry,
- 3) alkalinity,
- 4) zooplankton, and
- 5) sulphate.

The factor analysis of data emphasizing biological parameters (Table 3.7.6) revealed that most of the variance in the properties of the system may be accounted for by the variance of silica concentration, total phytoplankton, copepods, diatoms, and green and blue-green algae. Factor 2 is weighted on variables of the secondary trophic level - zooplankton, nauplii, and rotifers. The third factor emphasizes the variances of pH, zooplankton diversity and cladocerans of which the latter two are negative contributions. The fourth factor weights pH and phytoplankton diversity as a negative contribution. The final factor of the varimax factor analysis was weighted on a single variable, flagellates. The factors have been defined on the basis of important loadings as:

- 1) phytoplankton,
- 2) zooplankton,
- 3) zooplankton diversity,
- 4) phytoplankton diversity, and
- 5) flagellates.

Classification

The lakes were grouped on the basis of morphological, bedrock and surficial geological characteristics and the groupings were tested in a discriminant function analysis using the variables from the first

factor of the varimax factor analysis emphasizing chemical data (Table 3.7.4) including pH, silica, phosphorus and chlorophyll a concentrations and productivity. Table 3.7.7 indicates the groupings of lakes which were used based on the morphology and surficial and bedrock geological considerations.

TABLE 3.7.7 LAKE GROUPINGS BASED ON PHYSICAL
CHARACTERISTICS OF LAKE BASINS

Morphological

- Group 1 - surface area:volume ratio less than $50 \text{ ha m}^{-3} \times 10^6$.
 - Kukagami
 - Tyson
 - Penage
 - Little Penage
 - George
- Group 2 - surface area;volume ratio between 50 and $1000 \text{ ha m}^{-3} \times 10^6$.
 - Geneva
 - Alphretta
 - Lang
- Group 3 - surface area:volume ratio greater than $1000 \text{ ha m}^{-3} \times 10^6$.
 - Camp Ten

Surficial

- Group 1 - light glacial deposits.
 - Tyson
 - Lang
 - George
- Group 2 - Medium glacial deposits.
 - Kukagami
 - Alphretta
 - Penage
 - Little Penage
- Group 3 - heavy glacial deposits.
 - Geneva
 - Camp Ten

Table 3.7.7 continued

Bedrock Geology

Group 1 - Grenville Province
 - Tyson
 - George

Group 2 - Cobalt Plain
 - Camp Ten
 - Geneva
 - Alphretta
 - Kukagami

Group 3 - Huronian Belt
 - Lang
 - Penage
 - Little Penage

The results of the discriminant function analysis on these groupings are shown in Table 3.7.8 on the basis of the probability of misclassifying observations.

TABLE 3.7.8 PROBABILITY OF MISCLASSIFYING OBSERVATIONS

<u>Basis of Group</u>	<u>Group</u>	<u>% Probability</u>
Morphological	1	37
	2	54
	3	0
Surficial	1	35
	2	19
	3	60
Bedrock	1	25
	2	73
	3	14

Using the probability of misclassification from Table 3.7.8, a grouping of lakes was established which provided the least possibility of misclassification. The groupings are shown in Table 3.7.9 below.

TABLE 3.7.9 MODIFIED GROUPING OF LAKES TO MINIMIZE
PROBABILITY OF MISCLASSIFICATION

	<u>Group 1 Lakes</u>	<u>Group 2 Lakes</u>	<u>Group 3 Lakes</u>
	Kukagami Tyson George Alphretta	Penage Little Penage Lang	Camp Ten
% Probability of Misclassification	5	16	0

Since the variables used to define the relationships are those which influence productivity, the classification defines differences in productivities of the lakes. Biological activity is greatest in group 3 and least in group 1.

4. INTERPRETATION
AND
DISCUSSION

4.1 CORRELATION OF VARIABLES

Inspection of the first factor of the varimax factor matrix emphasizing chemical parameters, (Table 3.7.4) shows that most of the covariance in the properties of the system may be accounted for by the variance of three biotic parameters - primary productivity, chlorophyll a, and total phytoplankton - plus two inorganic variables - silica and soluble phosphate concentrations. The three biological variables are self-correlated as indicated in the correlation matrix (Table 3.7.1). Also from the correlation matrix, total phytoplankton concentration was correlated with the diatom population. Figure 3.5.1 shows the relative distribution of the various phytoplankton groups which were measured. Diatoms are high in silica concentrations since the frustule (exo-skeleton) of diatoms is siliceous. Schelske and Stoermer (1971) have reported that silica becomes a limiting variable to productivity in Lake Michigan. Phosphorus as indicated in this study by soluble phosphate concentration has been associated with phytoplankton productivity in many studies (Kramer et al, 1970, and Cambell, 1969). Also, the similarity in coefficients for silica and soluble phosphorus suggests that these chemical species have the same natural origin.

The second factor shows that the three principal physical parameters of depth, temperature and light are important in explaining the remainder of the covariance in the system.

These variables are related to each other by mathematical equations. The relation between depth and light is indicated in the results and the relation between temperature and depth is treated by Hutchison (1957). It is a function of the latitude, the depth of the lake and water move-

ments. The lakes in this study, with the exception of Camp Ten Lake, are dimictic. That is, they show a twice annual circulation and are thermally stratified during summer and winter. Camp Ten Lake, although exhibiting some summer thermal stratification, was too shallow to have a well-defined thermocline except in a small portion of the lake. The thermocline was easily disrupted by wind mixing.

The alkalinity factor is weighted on three related chemical properties of the system - alkalinity, dissolved solids, and pH. These variables are involved in the carbonate buffering of water. In the correlation matrix (Table 3.7.1) a relation exists between dissolved solids, calcium and bicarbonate concentrations. The covariance in the third factor which is associated with the dissolved solids concentration can be attributed to calcium (not shown) and alkalinity (bicarbonate).

While sulphate was the major anion in the system (Table 3.3.4) the third factor does not weight that parameter. This indicates that a simple relationship between pH and sulphate concentration does not exist partially due to the fact that the sulphate concentration does not show a distribution with depth indicating an interaction between sulphate and the biosphere as do the variables involved in the alkalinity factor. Also, it suggests that the source of sulphate is different from the source of other major ions in the system.

The fourth factor is weighted on one chemical and one biological variable - nitrate and total zooplankton numbers. This relation is recorded in the co-relation matrix also. The association is likely indirect since the usual source of nutrients,

including nitrate, for the secondary trophic level is via predation on the primary trophic level. The fact that numbers of zooplankters do not correlate with other biological parameters suggests that at least in some of the lakes a barrier to the transfer of energy from one trophic level to another may exist.

Factor five shows that a relation exists between phytoplankton diversity, sulphate concentration and pH, suggesting that the sulphate concentration influences the hydrogen ion concentration and that the hydrogen ion concentration influences the diversity of phytoplankton.

The first or phytoplankton factor of the varimax factor analysis with emphasis on biological data (Table 3.7.6) loads the variance on the phytoplankton variables - productivity, diatoms, blue-green and green algae and the zooplankton group copepods - indicating all the major phytoplanktonic groups, except flagellates, are important in defining the biological variability in the system. Copepods are shown to be correlated with parameters of the primary trophic level including productivity, total phytoplankton and the major taxonomic groups of phytoplankton (Table 3.7.2) and as such are the main link between primary and higher trophic levels.

The second or zooplankton factor indicates that the variance of zooplankton, nauplii (immature copepods), and rotifers were important in explaining the remainder of the covariance. Nauplii and immature copepods are the small (tiny) representatives of the zooplankton community. In the correlation matrix (Table 3.7.2), there was significant correlation between zooplankton and both nauplii and rotifers. The latter were also correlated.

The third factor, defined as the zooplankton diversity factor,

weights two secondary trophic level parameters - zooplankton diversity and numbers of cladocerans and the hydrogen ion concentration or pH. The relation between cladocerans and pH has been observed previously (Conroy, 1971) in lakes polluted by acid-mine drainage. The remaining significant variable, zooplankton diversity, bears a negative relationship to the other two variables. This indicates that zooplankton diversity depends on the presence or absence of cladocerans and cladocerans are influenced by the concentration of hydrogen ion, as indicated previously.

The fourth or phytoplankton diversity factor is weighted on three variables - blue-green algae, pH and phytoplankton diversity, (the latter two in a negative sense). The relationship of pH and diversity has been observed previously; Conroy (1970) observed that stream bottom fauna diversity was directly related to the hydrogen ion activity. Stream bottom fauna constitute the secondary and tertiary trophic level of the lotic environment. Blue-green algae, the third variable weighted in this factor, has been associated with water pollution, especially accelerated eutrophication, by phosphorus enrichment. In this study, only Little Lake Penage showed minimal signs of blue-green algae blooms and phosphorus enrichment (Michalski, 1969; see figure 3.5.1).

The final factor of the varimax factor analysis puts weight on one variable - the phytoplanktonic taxum of flagellates. The vertical distribution of flagellates within and between lakes is shown in figure 3.5.1. The distribution follows that of other phytoplankters.

In Tyson, Lang, and George lakes flagellates were the major taxum of phytoplankton present.

In summary, the results of the correlation and factor analyses indicated that the variability in the system studied could be explained on the basis of measurements made in the system, most of which had been reported in the same context by other studies. The important parameters are summarized in Table 4.1.1 below.

TABLE 4.1.1 IMPORTANT PARAMETERS IN THE ASSIGNING OF VARIABILITY
IN THE STUDY LAKES

<u>Biological</u>	<u>Physical</u>	<u>Chemical</u>
primary productivity	depth	pH
chlorophyll a	temperature	alkalinity
total phytoplankton	light	dissolved solids
diatom numbers		soluble phosphate
blue-green numbers		silica
total zooplankton		sulphate
phytoplankton diversity		
zooplankton diversity		
copepods		
cladocerans		

The chemical parameters indicated in the above table are discussed in the following section in context of their importance in controlling the biology of the lentic environment.

4.2 SOURCE AND CONTROL OF IMPORTANT CHEMICAL PARAMETERS

Silica

The source of silica is the dissolution of rocks in the drainage basin. Three variables important in determining the rate of solution of silica are: 1) mineralogy of the basin, 2) state of subdivision of the lithological material, and 3) reaction time (see Table 1.3.4 and figure 1.3.2). The resulting concentration in the water is a function of these factors plus the surface area to volume ratio of the basin and the rate of removal of silica from the system. The three mechanisms for removal of silica from water are: 1) outflow of water, 2) precipitation of silica as quartz or another silicate mineral, and 3) removal by the biosphere.

The distribution of silica with depth follows a pattern associated with a variable which interacts with the biosphere - that is, bearing an inverse relationship to the primary trophic level. The concentrations of silica found in this study are well within the range commonly observed in natural water (i.e. 1 to 30 mg l⁻¹). According to Lewin and Guillard (1963) silica becomes limiting at concentrations in the order of 0.1 mg l⁻¹. In two cases in this study, the silica concentration approached limiting concentrations - Kukagami at 3 and 7 meters on August 3, and Little Lake Penage at 3 meters on September 11.

Silica may also be significant in buffering the hydrogen ion concentration in the aquatic system. Sillen (1967) introduced the concept of the buffering capability of sediment-water interactions involving silicates. Hem (1971) claims "this kind of buffering system might be capable of controlling the concentration of many

elements in sea water and could perhaps maintain the composition nearly constant for long periods of time".

The silica concentration in the study lakes bears a more direct relation to the surficial geology of the lake basin and the volume to surface area ratio of the lakes than to the bedrock geology, although lakes associated with quartzite terrains were moderately high in silica. This relationship is somewhat obscured by the utilization of silica by the primary trophic level discussed in section 3.3.

Phosphorus

Of all the elements present in water, phosphorus is likely to be the most important to interactions between the biosphere and the water since the ratio of phosphorus to other major nutrients tends to be greater in the biosphere than in the hydrosphere.

A stoichiometric formula for plankton was presented in section 1.3 after Stumm and Morgan (1970) as $C_{106}H_{263}O_{110}N_{16}P_1$.

For maximum interaction between the biosphere and the hydrosphere the ratio of P:N must therefore be greater than or equal to 1:16. The mean P:N ratio in this study was 1:1200 and ranged from 1:72 in Little Lake Penage to greater than 1:3000 (phosphorus was actually too low to measure in many cases).

The principal source of phosphorus to the aquatic system is the dissolution of rocks in the basin, especially the mineral apatite (calcium orthophosphate). As such, the source of phosphate is similar to that of silica and the same mechanisms apply to the control of the final concentration.

The most commonly referred to source of phosphorus to lakes is sewage from various sources. Little Lake Penage is an example of phosphorus enrichment by man's activity as reported by Michalski (1969). Drainage from septic tanks and washing facilities was suspected as the main cause of the phosphorus enrichment to Little Lake Penage.

Rain is not a usual source of phosphate as reported by Gorham (1961). The values (not reported since concentrations too low to measure) found in rain in this study essentially agree with the data presented by Gorham in that the phosphorus content of rain was less than 1 mg m^{-3} . Data collected by Shiomi (1970), however, would indicate that atmospheric precipitation is a potential source of significant phosphorus, at least to the lower Great Lakes, Ontario and Erie.

Hydrogen Ion

The other major abiotic parameters which were found to be important to the aquatic ecosystem can be categorized as variables influencing the pH. These include bicarbonate, calcium, and sulphate ion concentrations.

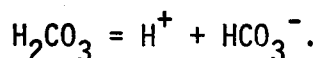
The hydrogen ion concentration in the study lakes showed wide variation in values as shown in Table 3.3.3.

The pH of natural waters is a residual effect - the remainder after the requirements of the system are satisfied. The main chemical reaction, which is considered to control the hydrogen ion concentration, is the dissociation of carbonic acid, although, as mentioned previously the dissociation of dissolved silica species may contribute also.

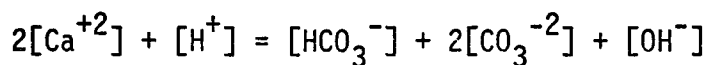
The hydrogen ion concentration, as a function of the ratio of bicarbonate to undissociated carbonic acid, has the form:

$$\frac{[\text{HCO}_3^-]}{[\text{H}_2\text{CO}_3]} = \frac{K_1}{[\text{H}^+]}$$

where K_1 is the dissociation constant of the reaction



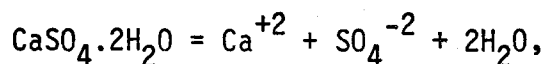
In this study the major cationic variable which influenced the pH was the calcium ion concentration (Table 3.3.4). The reaction involving calcium and bicarbonate can be summarized as:



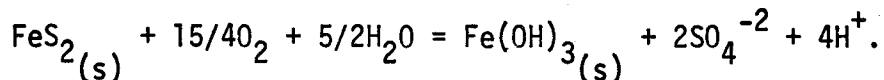
and is discussed by Hem (1971).

As indicated previously (section 3.3, and Table 3.3.4), the major anionic variable in the study lakes was sulphate. Two sources of sulphur species to lakes are reactions of water with lithological material containing sulphur minerals such as pyrite (FeS_2) or gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and rainfall. Of these, rainfall has been reported to be the major source (Junge, 1960 and Gorham, 1961). In this study the concentration of sulphate in the rain was found to be abnormally high (Table 3.4.1) as it was in the lakes. Gorham (1961) and Beamish (1970) reported similar results from studies in the same geographical area. The sulphate concentration found in lakes was not as highly correlated to pH as the ratio of calcium to sulphate. This relationship is shown in figure 4.2.1 and would indicate that the hydrogen ion is not determined directly by sulphate but rather by the "excess" sulphate. The lithological

source of sulphate is either the dissolution of gypsum:



or pyrite and marcasite oxidation (Stumm and Morgan, 1970):



Of the two reactions, only the latter is acid generating, providing 4 equivalents of H^+ per mole of FeS_2 oxidized.

The lakes which had sulphide ore occurrences in the vicinity (section 3.2) did not necessarily show high sulphate concentrations as indicated in Table 4.2.1. The association was positive only 60% of the time.

TABLE 4.2.1 ASSOCIATION BETWEEN SULPHIDE OCCURRENCE
AND SULPHATE CONCENTRATION IN STUDY LAKES

<u>Lake</u>	<u>Sulphide Occurrence</u>	<u>Sulphate Concentration¹</u>
Kukagami	+	+
Tyson	-	-
Alphretta	-	-
Penage	+	+
George	-	+
Little Penage	+	-
Camp Ten	-	-
Geneva	+	-
Lang	+	+

1. + sulphate = $> 20 \text{ mg l}^{-1}$
 - sulphate = $< 20 \text{ mg l}^{-1}$

Neither calcium nor bicarbonate were directly correlated with pH in this study. However, the ratio of calcium to sulphate showed a correlation to pH as indicated in figure 4.2.2. This correlation

is predictable from the relation between calcium and bicarbonate indicated above. That is, as the calcium ion concentration increases the bicarbonate ion concentration increases. Therefore, the buffering capacity increases. In situations of relatively high buffering capacity acid-sulphates would not depress the pH to the same extent as in conditions of low buffering capacity. Therefore lakes with a low concentration of calcium would be more susceptible to an increase in hydrogen ion concentration from an acid input.

If the atmosphere was the major source of sulphates through the oxidation of sulphur dioxide, one would expect a relation to exist between distance from the mineral smelting industry (a large SO_2 generator) and sulphate concentration in the water. Table 4.2.2 indicates a wind-vector distance of the lakes from Sudbury, based on the data provided by Dreisinger and McGovern (1970), and the sulphate concentration.

TABLE 4.2.2 ASSOCIATION BETWEEN VECTOR DISTANCE FROM
SUDBURY AND SULPHATE CONCENTRATION

<u>Lake</u>	<u>Vector Distance (miles)</u>		<u>Sulphate ($\text{mg l}^{-1} \text{SO}_4^{-2}$)</u>	
Kukagami	+	15	+	20
Tyson	-	29	-	13
Alphretta	-	28	-	13
Penage	+	20	+	23
George	+	20	+	20
Little Penage	+	20	-	15
Camp Ten	-	32	-	13
Geneva	-	36	-	9
Lang	+	18	+	23

+ = $\leq$ 20 miles

- = $>$ 20 miles

+ = $\geq$ 20 $\text{mg l}^{-1} \text{SO}_4^{-2}$

- = $<$ 20 $\text{mg l}^{-1} \text{SO}_4^{-2}$

Using an arbitrary categorization of sulphate concentration and vector distance as indicated in Table 4.2.2 a strong association exists between distance from Sudbury and sulphate concentration of the lakes (90%).

Gorham and Gordon (1960) present data which shows the concentration of sulphates in lakes as a function of distance from the city. Their data have been converted to a log-function and are presented in figure 4.2.3. Data collected by the Ontario Water Resources Commission for more than seventy-five lakes in the Sudbury district (Fitz, 1970) are in essential agreement with the data of Gorham and Gordon.

In summary the important inorganic variables relating the biology of the study lakes are silica, phosphorus, alkalinity (bicarbonate), and sulphates. The natural source of silica and phosphorus is the dissolution of lithological material. Phosphorus is a limiting variable when considered in a ratio of total phosphorus to nitrogen.

The pH of the lakes is indirectly controlled by sulphates. There are two potential sources of sulphates to the lake system - the dissolutions of sulphides and the atmosphere of which the latter seems more important in determining the final concentration of sulphates in the lakes.

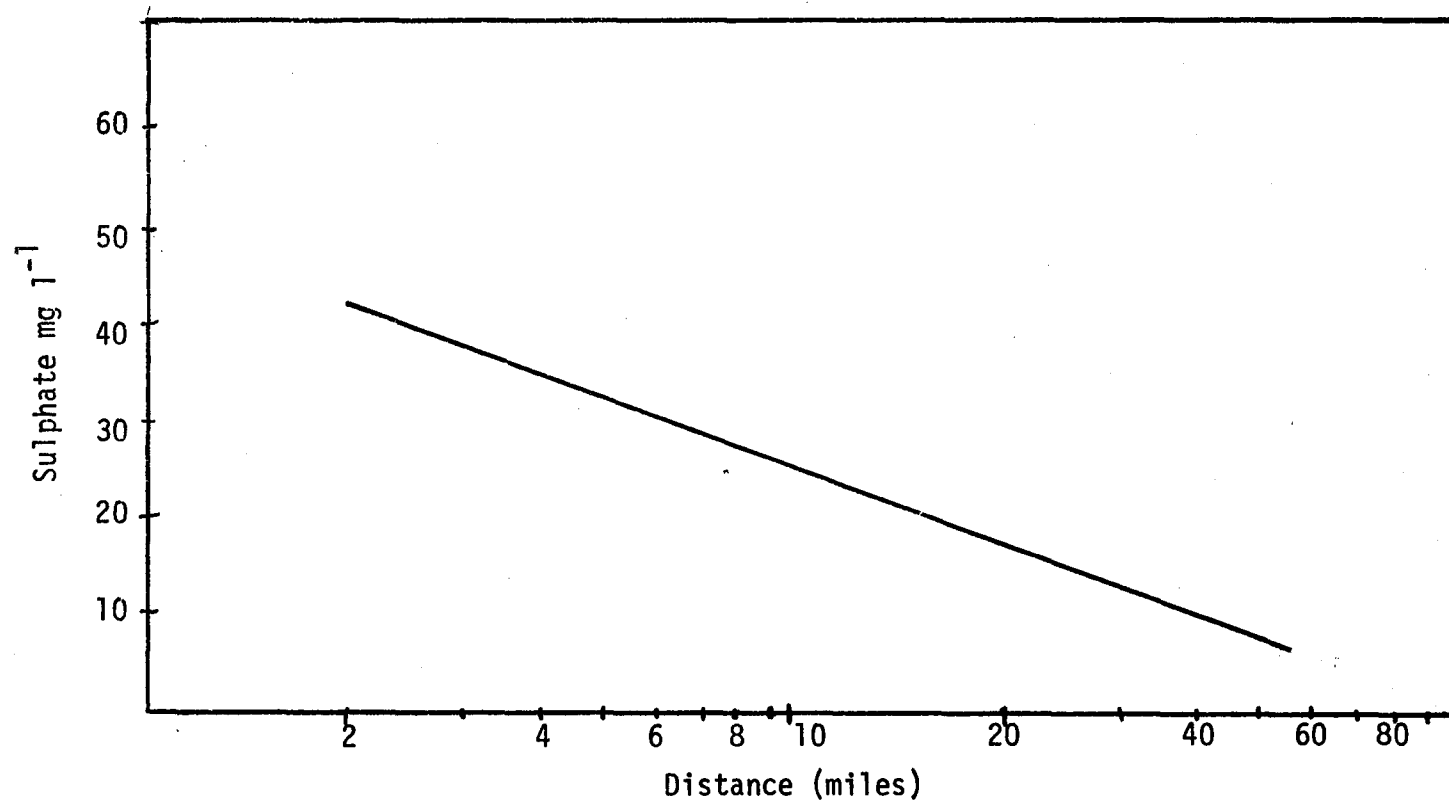
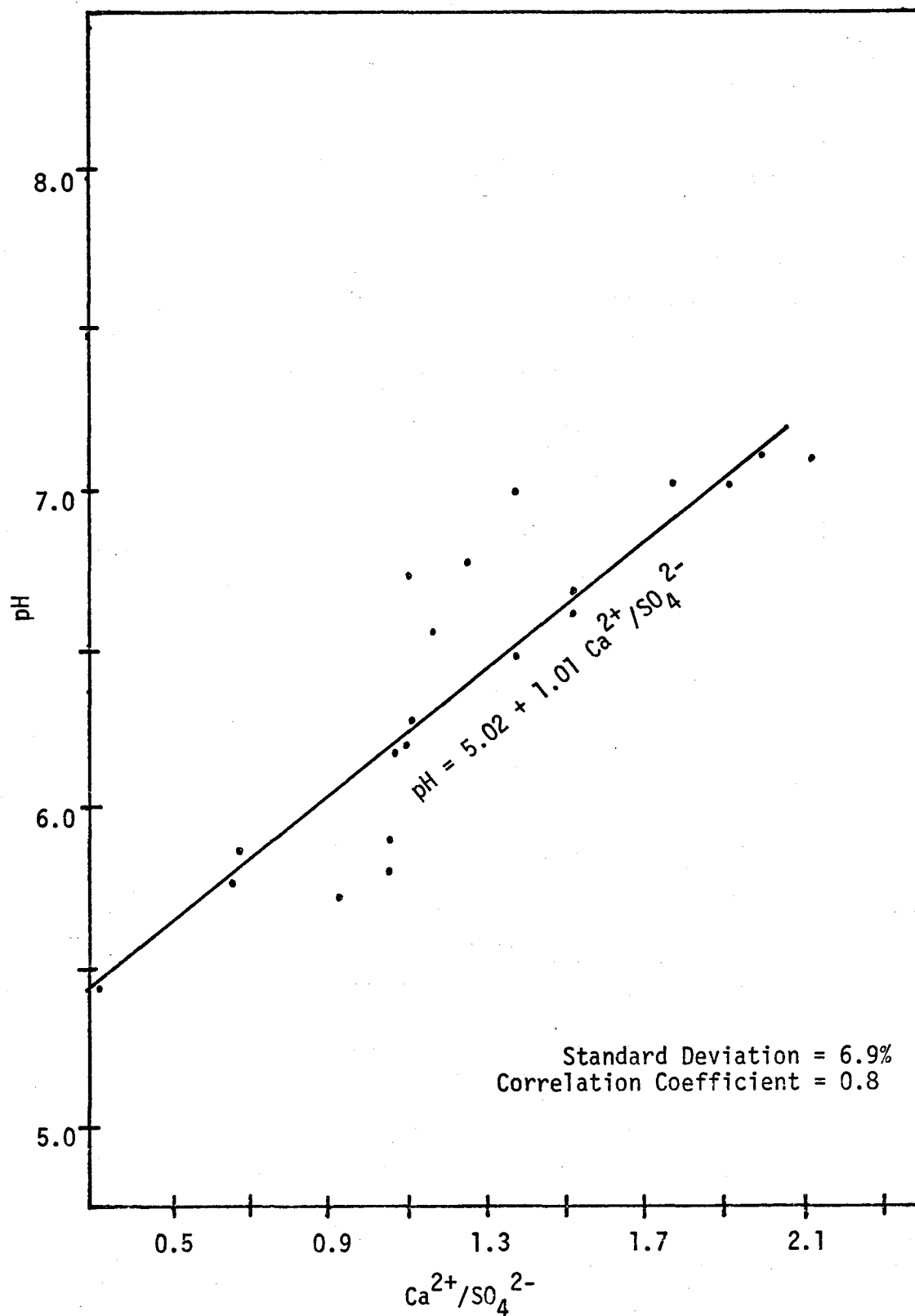


Figure 4.2.1 LAKE SULPHATE CONCENTRATION V. LOGARITHMIC DISTANCE FROM SUDBURY
(Gorham and Gordon, 1960)

Figure 4.2.2 RELATIONSHIP BETWEEN pH AND
RATIO OF CALCIUM TO SULPHATE



4.3 CLASSIFICATION

The most suitable classification scheme utilizes the morphology of the basin as indicated in this study by the surface area to volume ratio (Table 3.7.7). However, the classification was improved by regrouping certain lakes as shown in Table 3.7.9. The lakes which were reclassified are indicated below in Table 4.3.1.

TABLE 4.3.1 MISCLASSIFIED LAKES AND REGROUPING
BASED ON DISCRIMINANT FUNCTION ANALYSIS

<u>Lake</u>	<u>Morphological grouping</u>	<u>Modification</u>
Penage	1	2
Little Penage	1	2
Alphretta	2	1

Since the groupings emphasize biological relations - productivity and chlorophyll a increasing from group 1 to group 3 - the above regrouping indicates that Penage Lake and Little Lake Penage show higher biological activity than predicted by morphological considerations while Alphretta Lake shows lower activity than predicted. Of significance in these lakes is:

- 1) the shorelines of Lake Penage and Little Lake Penage are heavily populated with cottages and evidence of cultural eutrophication was found in Little Lake Penage (Michalski, 1969), and
- 2) the bedrock geology of both lakes includes some limestone of the Espanola formation and calcium concentrations in the water are relatively high.

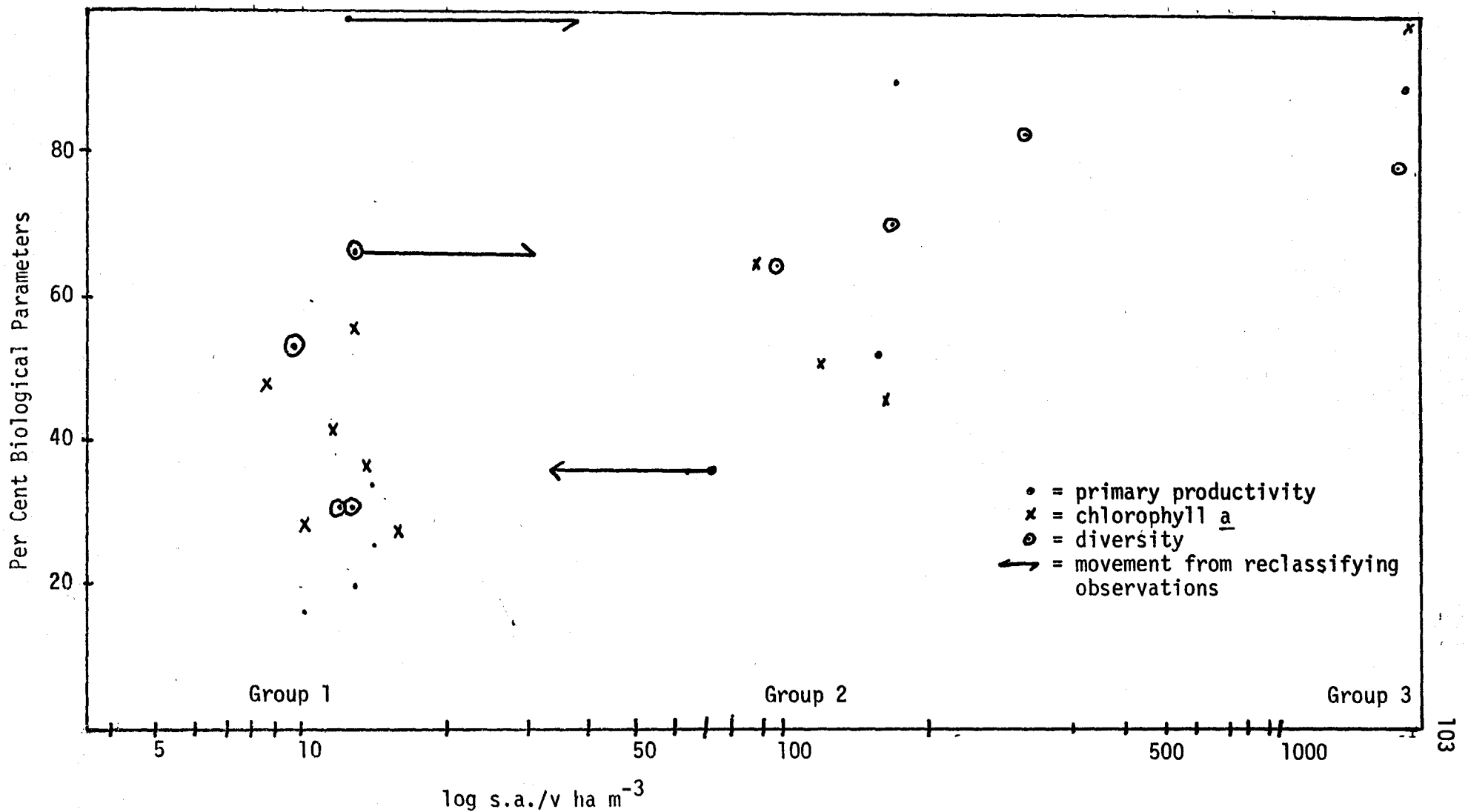
Alphretta Lake, on the other hand, is more related to those lakes with a small surface area to volume ratio than predicted by the morphology - that is, a lower level of biological activity. As

indicated previously, the phytoplankton diversity of the lakes was low (see Table 3.5.2). The correlation analysis emphasizing biological parameters showed a positive relationship between biological parameters and pH. The pH of Alphretta was low (mean of less than 6.0) and was probably responsible for the biological conditions being lower than predicted by the morphology.

Figure 4.3.1 is a graph of the relationship between the logarithm of the surface to volume ratio and the mean productivity, chlorophyll a and diversity. The biological parameters in the figure have been scaled to percentages of the range for that variable. The separation between groups is indicated and shows the degree of overlap between groups.

In summary, the morphology of the lake basins expressed as the surface area to volume ratio is a valid factor for classifying the productive capacity of lakes in that lakes with a surface area to volume ratio less than $50 \text{ ha m}^{-3} \times 10^6$ will show relatively low biological activity, lakes with surface area to volume ratio of 50 to $1000 \text{ ha m}^{-3} \times 10^6$ will show moderate biological activity, and lakes with a surface area to volume ratio of greater than $1000 \text{ ha m}^{-3} \times 10^6$ will show relatively high biological activity. Lithological considerations are important to the extent that finely divided surficial material allows more surfaces for interactions and thus contributes more dissolved species to the nutrient pool. Further, even small associations with limestone provides a significant source of calcium.

Figure 4.2.3 DIVERSITY, CHLOROPHYLL a AND PRIMARY PRODUCTIVITY (SCALED TO PER CENT OF RANGE) V. LOGARITHMIC SURFACE AREA TO VOLUME RATIO



In this study a source of calcium was important in stabilizing the hydrogen ion concentration and silica was positively related to plankton populations. The importance of a calcium source was suggested by Card and Gillespie (1966) and implied by Ryder (1965) in his morphoedaphic index.

Finally, the atmosphere is important in supplying ions to the lake system. In this study, its importance was in determining the sulphate ion concentration. The sulphate ion (particularly in lakes in non-calcareous terrain - the majority of the Precambrian Shield) is the major abiotic variable influencing biological activity in lakes where there is a significant source of sulphate from the atmosphere (probably also from a sulphide ore deposit since the sulphide to sulphate conversion is a potent hydrogen ion generator). Beamish (1970) suggested that the hydrogen ion concentration of lakes south of Sudbury (in the vicinity of George and Tyson Lakes) had been altered by atmospheric input of sulphates and that the carrying capacity of these waters for fish had been reduced as a consequence. Drolet, Stasson and Hughson (1970) hypothesize the same relation for lakes in other parts of the Sudbury District.

4.4 FUTURE WORK

1. To further substantiate that biological activity of lakes in the Precambrian Shield is determined by morphological considerations expressed as the surface area to volume ratio, study areas remote from major sources of atmospheric contamination such as the metal smelting industry at Sudbury must be selected. Also, a wider range in morphological features would have to be chosen. In this regard Schindler (1971) presents an excellent summary of morphological control of the nutrient flux and biological activity in the Experimental Lakes Area in northwestern Ontario. Schindler hypothesizes that in igneous and metamorphic terrains the influence of the lithological material on the nutrient flux to lakes is minimal and that the major source of input to the system is atmospheric precipitation. Therefore, the morphological features of the lakes, defined as $(A_d + A_o) / V$, where A_d is the terrestrial portion of the drainage basin and A_o the surface area of the lake and V is the volume of the lake, influence the nutrient flux in the waters. Support for the hypothesis is found in many parameters including phosphorus, nitrogen, chlorophyll a and primary productivity.

The results of the present study, however, indicate that although the influence of the geology may be small in terms of affecting the concentration of nutrients in the system it is variable over a significant range and can influence the biological activity of the lakes. This lithological variability must be accounted for to properly classify Shield lakes

2. The calcium concentration was shown to be involved in guarding the lakes from pH depression as a result of atmosphere-water interactions. As an extension and a test of this postulate, it would be valuable to increase the calcium ion concentration in lakes showing a low calcium to sulphate ratio and apparent pH depression and subsequently measure the response of the biology of the system.

4.5 SUMMARY

1. The variability in the study lakes can be defined by simple chemical, physical and biological variables as indicated in Table 4.1.1.

2. Two factors are significant in controlling biological activity in Precambrian Shield lakes. Firstly, the morphology (expressed in this study as the surface area to volume ratio) is important in that lakes with a low surface area to volume ratio show low biological activity while lakes with a large surface area to volume ratio show high biological activity. Secondly, lithological considerations including bedrock and surficial geology are important in determining the calcium and silica concentrations. Biological activity responds to relatively minor changes in these lithologically derived chemical species.

Further research is necessary (to a large extent already underway, see Schindler, 1971) to concretely define the relation between morphology and the biological activity in lakes in the Precambrian Shield.

3. Concentrations of sulphates derived from the metal smelting industry near Sudbury (via the atmosphere) affect lakes with low calcium concentrations (poorly buffered) by depressing the pH. Aspects of the biosphere including productivity and diversity are

depressed in lakes with low pH. Efforts must be made to significantly reduce the concentration of sulphur dioxide gaining access to lakes that are poorly buffered for hydrogen ion concentration.

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APPENDICES

APPENDIX A METHODS

1. Phytoplankton
2. Zooplankton
3. Plant Pigments
4. Primary Productivity
5. Temperature
6. Dissolved Oxygen
7. Secchi Disc Transparency
8. pH, Alkalinity and Total Carbon Dioxide
9. Reactive Silica
10. Reactive Phosphate
11. Nitrite and Nitrate
12. Ammonia and Amino Acids
13. Weighted Mean
14. Multiple Linear Correlation
15. Principle Component Analysis
16. Factor Analysis
17. Discriminant Function Analysis

1. Phytoplankton

A 1.0 l sample was pumped from specified depths at each station for phytoplankton analyses and preserved in sufficient Lugol's solution (10 g of potassium iodide and 5 g of iodine crystals per 100 ml of distilled water) to give the sample a deep amber colour. The preserved samples were labelled and a record was made of station, date, time and depth. The bottles were stored for subsequent identification.

Identification was provided by the Eutrophication and Phytoplankton section, Biology Branch of the Ontario Water Resources Commission according to standardized methods. The results of the identification and enumeration of phytoplankton are provided in Appendix B.

2. Zooplankton (Net Plankton)

Water samples for zooplankton analyses were pumped from specified depths at each station and filtered through a plankton net of number 25 mesh bolting silk (62,000 meshes cm^{-2}). The contents of the net were washed into 35 ml vials to which a formalin solution (1.85 per cent w/v formaldehyde) was added to provide a final concentration of 5 per cent formaldehyde. The vials were labelled and stored for subsequent analysis and a record made of station, depth, time and volume of sample.

To determine the volume filtered, the pumping operation was timed with a stop-watch. Calibration of flow rate was checked frequently during the sampling program and found to be consistently 6 l min^{-1} .

The method of Frolander (1968) was modified to identify net plankton. The enumeration and identification of net plankton samples appears in Appendix B.

3. Plant Pigments

The method of Strickland and Parsons (1968) was used. Samples of water were pumped from specified depths into clean 1.0 l polyethylene bottles and stored in a portable cooler in the dark. A record of the station, date, depth and time of sampling was made and the samples were appropriately labelled.

At the laboratory on the same day as the collection, samples were filtered through glass-fibre filters (Whatman GF/C) under vacuum until the filter was clogged (approximately 800 ml of water). A record of the volume was made and the filter was placed in a graduated centrifuge tube containing 10 ml of 90 per cent w/v acetone and the tubes were capped.

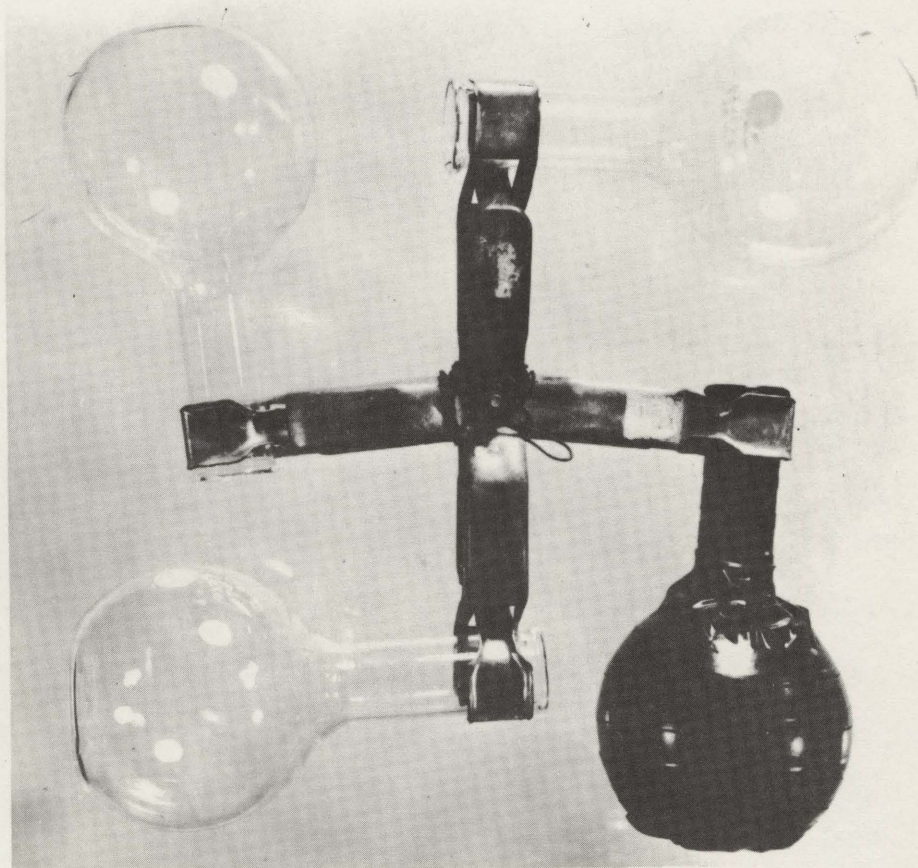
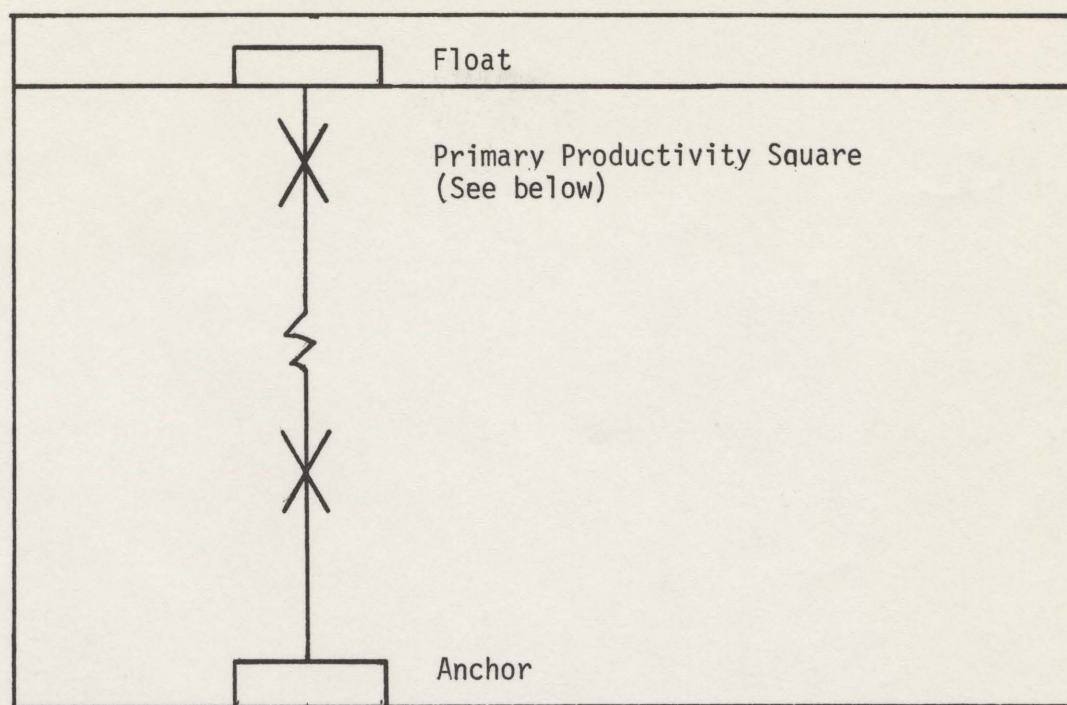
The filter was disintegrated by shaking the tube vigorously and the sample was incubated in the dark at 4°C for 20-24 hours. The tube was warmed to room temperature, the volume adjusted to 12 ml with acetone and the sample centrifuged at approximately 3500 rpm for 10-12 minutes. The tube was removed from the centrifuge and swirled to remove particles of the dispersed filter from the walls and centrifuged for a further 2 minutes. An aliquot of the sample was poured into a 1 cm cuvette and the transmittance was read on a Coleman Spectrophotometer, Model 101 at 750, 665, 645, 630 and 480 nanometers of wavelength against a blank of 90% v/v acetone.

Chlorophyll a, b, and c and carotenoid concentrations were calculated using a computer program with the equations given by Strickland and Parsons (1968). The concentrations of the various plant pigments are tabled in Appendix B.

4. Primary Productivity

Primary productivity was calculated at 4 depths per station in replicated experiments by measuring (only when the ceiling and visibility were unlimited) the amount of radioactive carbon incorporated into biological cells in a specified period of time. The technique used was a modification of the method provided in Strickland and Parsons (1968), and involved measuring the incorporation at various depths in 280 ml samples of lake water, incubated in situ for 3 to 5 hours. The apparatus used is shown in Figure A-1. The water was placed in 250 ml florence flasks (4 per depth) and inoculated with 1 ml of sodium bicarbonate solution (1.18 M) with a carbon-14 activity of 10 microcuries per ml (from New England Nuclear Supply, Boston, Mass.). Care was taken to ensure that the water sample to be inoculated was not exposed to direct sunlight while preparing the experiment. The florence flask was positioned at the depth from which the water sample was taken. After 3 to 5 hours incubation, the sample was removed and biological activity was stopped by the addition of 1.0 ml of mercuric chloride solution. The sample was held in the dark until it was filtered through a Millipore HA membrane filter (0.45 micron pore size). The filters were dried and stored in vials of scintillation medium appropriately identified.

Figure A-1 PRIMARY PRODUCTIVITY APPARATUS



The concentration of radioactive carbon was measured with a scintillation counter at the Ontario Department of Health Laboratories in Toronto. To allow error estimates to be calculated, three aliquots were run on each sample. Four samples were incubated at each depth - two light bottles and two dark bottles.

The primary productivity was calculated according to the equation provided in Strickland and Parsons (1968) utilizing a computer program, OWRASSIM, prepared by Ontario Water Resources Commission. The program permitted the determination of the mean integral primary production in mg C m^{-2} as well as productivity in mg C m^{-3} for each depth. The results are provided in Appendix B.

5. Temperature

A temperature profile was calculated for each station with the use of a telethermometer calibrated periodically using a mercury thermometer as a reference.

6. Dissolved Oxygen

Dissolved oxygen was measured at specified depths at each station by the modified Winkler technique provided in kit form by Hach Chemicals. It was recognized that measuring dissolved oxygen by this technique allowed some error ($\pm 10\%$). However, it was felt that dissolved oxygen was not a critical parameter in limnological considerations of Precambrian Shield lakes. The dissolved oxygen concentration in milligrams per litre was converted into per cent saturation using the nomogram of Hutchison (1957) for temperature correction.

7. Secchi Disc Transparency

Secchi disc readings were made with a disc 20 cm in diameter. The disc was lowered in the water to the depth at which it disappeared and raised to the point where it reappeared. The mid-point of the two readings was recorded to the nearest 0.25 m. All measurements were made in the shade of the boat with the eye approximately level with the gunwale.

8. pH, Alkalinity and Total Carbon Dioxide

Samples of lake water (1.0 l) were collected from specified depths by pumping and were stored in sterile polyethylene bottles in a portable cooler until they were returned to the laboratory. In all cases the measurements were made within four hours of collection. Tests showed that the alkalinity and pH of samples stored as indicated above were not significantly different than samples measured at the time of collection.

The hydrogen ion activity (pH) was measured on a Beckman Expando-matic pH meter equipped with a Beckman glass pH electrode and an Orion single junction reference electrode. It was recognized that pH was a difficult parameter to measure in dilute solutions such as Precambrian Shield lakes since even the small additions of ion from the reference electrode caused a change in the inherent hydrogen ion activity. It was found that the electrodes used provided satisfactory results if the sample was stirred continuously during the measurement.

The pH of a 150 ml sample was measured to the nearest 0.005 pH unit while the sample was stirred with a magnetic stirrer. The sample was then titrated with 0.010 hydrochloric acid to a pH of less than 3.70 and the final pH to the nearest 0.005 pH unit and the volume of

acid used to the nearest 0.005 ml were recorded. Alkalinity was calculated from the relationship shown below:

$$\text{Alkalinity (meq/l)} = [(C_a V_a) + (V_s \times 10^{-\text{pH}_i}) - (10^{-\text{pH}_f})] / (V_s + V_a)$$

where C_a = concentration of the acid in equivalents per litre,

V_a = volume of acid added in millilitres,

V_s = volume of sample in millilitres,

pH_i = initial pH, and

pH_f = final pH.

A computer program was written to generate the results provided in Appendix B.

The total carbon dioxide concentration was calculated from the bicarbonate concentration, hydrogen ion concentration and temperature by assuming equilibrium conditions. Carbonate was not considered in the calculations since the pH was so low. The following relations were utilized:

$$\frac{(\text{H}^+)(\text{HCO}_3^-)}{(\text{H}_2\text{CO}_3)} = \text{Keq}$$

The equilibrium constant, Keq, was taken from Garrels and Christ (1965) and the temperature dependence of Keq was assumed to be linear and predicted by $\text{pKeq}_T = 0.0085T + 6.57$ where T is the temperature of the sample being measured in degrees Kelvin.

The results were generated from a computer program and are shown in Appendix B.

9. Reactive Silica

Silica was measured spectrophotometrically by a modification of the method outlined by Govett (1961).

To 10 ml of water sample in a cuvette of 25.4 mm diameter, 3.3 ml 1N sulphuric acid and 3.3 ml ammonium molybdate solution (2.65 g ammonium molybdate in 40 ml deionized water brought to a pH of 8 to 9 with concentrated sodium hydroxide and the final volume adjusted to 50 ml with deionized water) were added. A blank was similarly set up substituting deionized water for sample. The cuvettes were thoroughly mixed, by swirling, and the absorbance of the unknown was measured at a wave length of 440 nanometers on a 'Spectronic 20' against the blank. Calibration was obtained with two concentrations of silica standard made up from fused quartz - 5 and 10 mg l⁻¹ silicon dioxide (9.33×10^{-5} and 1.87×10^{-4} molar SiO₂ respectively). A calibration solution of 50 mg l⁻¹ (9.33×10^{-4} molar) was stored in polyethylene bottles and appropriately diluted at each measurement. The results are recorded in Appendix B.

10. Reactive Phosphate

It was suspected from the results of previous investigations (Kramer, 1969) that the concentration of reactive phosphate would be extremely low. The method was specifically designed to measure low levels of reactive phosphate (Stevens, 1963, and Murphy and Riley, 1962) and appropriately modified to allow prepackaging of chemicals (Kramer, 1969).

It is convenient to describe the method in two parts - a solution phase A, and a solid phase B.

Solution A consisted of 20 ml ammonium molybdate solution (15 g

ammonium molybdate of formula 1236, diluted to 500 ml with distilled water), 10 ml potassium-antimony titrate (0.34 g diluted to 500 ml with distilled water), and 50 ml of 5N sulphuric acid. This solution was made up in bulk and stored in 1.0 l polyethylene bottles.

B consisted of 1.08 g ascorbic acid (dry) made up in individual vials before proceeding to the field station.

At the time of measurement, 1 vial of ascorbic acid (B) was dissolved in 80 ml solution A and the final volume was adjusted to 100 ml.

To extract reactive phosphate from the sample, 10 ml of the combined reagent (A and B from above) was added to 100 ml of sample in a 250 ml capacity separatory funnel and shaken for 20 seconds. Then, 20 ml of isobutanol was added and the funnel shaken for 30 seconds.

The water fraction was allowed to separate from the butanol fraction and the former was carefully extracted and discarded. The isobutanol fraction was poured into calibrated 25.4 mm cuvettes and 1.0 ml of ethanol (96.4%) was added. The absorbance of the solution was measured at a wavelength of 690 nanometers in a 'Spectronic 20' against a blank of distilled water treated in the same manner as the sample.

Calibration was obtained from a solution of "Fisher" primary phosphate standard (potassium dihydrogen phosphate) at a concentration of 50 mg l^{-3} phosphorus (1.613×10^{-6} moles phosphorus per litre). The standard was diluted to 10 mg l^{-3} (3.26×10^{-7} moles phosphorus per litre). The concentration of reactive phosphate in the water samples is recorded in Appendix B.

11. Nitrite and Nitrate

The method for the determination of nitrite and nitrate concentrations was modified from Strickland and Parsons (1968). Concentrations of nitrite were measured directly, and of nitrite plus nitrate by reduction to nitrite. The nitrate concentration was calculated from the nitrite plus nitrate concentration (reduction process) minus the nitrite concentration (direct).

The reduction of nitrate to nitrite was accomplished by passing 100 ml sample plus 2 ml concentrated ammonium chloride (175 g ammonium chloride and 500 ml distilled water) through a cadmium-copper reduction column. The initial 5 ml were used to flush the column, and approximately 30 ml used to rinse a 125 ml flask. Immediately after 50 ml of solution had been collected from the column, 1 ml of sulfanilamide solution (5 g sulfanilamide in 50 ml concentrated hydrochloric acid plus 300 ml distilled water, diluted to a final volume of 500 ml) was added. After an incubation period of 8 minutes, 1 ml of N-naphthyl-ethylenediamine dihydrochloride solution (0.50 g of the dihydrochloride in 500 ml distilled water) was added.

Following an incubation period of two hours at room temperature, the absorbance of the solution was measured in a 25.4 mm cuvette at 543 nanometers against a blank of distilled water.

Potassium nitrate solutions of suitable concentrations to bracket the nitrate concentrations in the water were used as standards treated in the same manner as above. The measurement of nitrite concentration was made by the same method as nitrite plus nitrate except that the cadmium-copper reduction column step was omitted.

The concentration of nitrite and nitrate in the water samples is recorded in Appendix B.

12. Ammonia and Amino Acids

The method, adapted from Strickland and Parsons (1968), measures ammonia and a considerable fraction of amino acid by oxidizing the ammonia to nitrite and determining spectrophotometrically the nitrite concentration.

In a 125 ml Erlenmeyer flask, 10.0 ml of oxidizing agent (1.5 ml 1.5N sodium hypochlorite in 100 ml sodium hydroxide solution - 165 g NaOH pellets per l) and 1.0 ml potassium bromide solution (1.5 g KBr in 250 ml distilled, deionized water) were added to 50 ml of sample. After incubation for 3 to 4 hours at room temperature, 2 ml sodium arsenite solution (20 g arsenic trioxide and 30 g sodium hydroxide diluted to 500 ml with distilled-deionized water) were added and the contents of the flask swirled. Ten ml of acidifying solution (diluted hydrochloric acid) and 1.0 ml of sulphanilamide solution (as per nitrate analysis above) were added. After a short incubation (3 to 8 minutes) 1.0 ml naphthyl- ethylene-diamine solution (as per nitrate method above) was added and the extinction was read at 543 nanometers in a 25.4 mm cuvette against a blank of distilled water.

Standards were prepared from ammonium sulphate solution, in the range 1-10 $\mu\text{g.at. N l}^{-1}$, and treated in a similar manner to the samples.

The concentration of ammonia (plus amino acids) is provided in Appendix B.

13. Weighted Mean

The distribution of chemical parameters, involved in the biosphere with depth, is non-parametric. Typical examples are the orthograde and clinograde oxygen curves shown in Hutchison (1957).

A weighted mean was employed to provide a measure of central tendency for these parameters. The generalized equation of the weighted mean is:

$$\bar{x}_w = \frac{v_1 d_1 + v_2 d_2 + v_3 d_3 \dots + v_n d_n}{\sum d_n}$$

where v_1 = the concentration of the variable measured at the first depth,

d_1 = the first depth interval in meters,

v_n = the concentration of the variable at depth n , and

d_n = the n^{th} depth interval in meters.

14. Multiple Linear Correlation

Multiple correlation in the R-mode is a measure of the covariance between pairs of variables and is defined as:

$$r_{12} = \frac{\text{cov.}(x_1 x_2)}{[\text{var.}(x_1) \text{var.}(x_2)]^{1/2}} = \frac{\sigma_{x_1 x_2}}{\sigma_{x_1} \sigma_{x_2}}$$

It is convenient to arrange the correlation coefficients in a symmetrical matrix in the form:

$$\begin{array}{ccccc}
 r_{11} & r_{12} & r_{13} & \cdots & r_{1n} \\
 r_{21} & r_{22} & r_{23} & \cdots & r_{2n} \\
 r_{31} & r_{32} & r_{33} & \cdots & r_{3n} \\
 \vdots & \vdots & \vdots & \vdots & \vdots \\
 \vdots & \vdots & \vdots & \vdots & \vdots \\
 \vdots & \vdots & \vdots & \vdots & \vdots \\
 r_{n1} & r_{n2} & r_{n3} & \cdots & r_{nn}
 \end{array}$$

where n = correlation coefficient.

The principle diagonal of the correlation matrix ($r_{11} - r_{nn}$), since it represents the correlation of a variable to itself, is unity.

The significance of a correlation coefficient can be tested using tables of the distribution of Students' t by calculating

$$t = \frac{r(N - 2)^{\frac{1}{2}}}{(1 - r^2)^{\frac{1}{2}}}$$

and entering the table with $N - 2$ degrees of freedom (Moroney, 1962).

15. Principle Component Analysis

Principle component analysis is an extension of correlation analysis. Dawdy et al (1967) define principle component analysis as a method of redistributing the explained variance in a correlation coefficient matrix among a set of factors (eigenvectors) which reveal linear combinations of the original variables. Each factor

involves a varying proportion of the variable covariance and takes the form: $F_1 = a_1x_1 + a_2x_2 + \dots + a_nx_n$.

Principle components are extracted from the correlation matrix such that the first principle component explains the largest amount of the variance and covariance and the second principle component explains the largest amount of the remaining variance and covariance.

16. Factor Analysis

Factor analysis, an extension of principle component analysis, is designed to add interpretability to the numerical analysis. Varimax rotation, in which the principle component matrix is scaled so that the sum of squares of the coefficients is unity, was used in this study. The scaled factors are transformed (rotated) so that the sum of squares of all coefficients is constant but the variance of the squares is maximized. This clusters the factors close to ± 1 (a high degree of association) or 0 (no relation).

17. Discriminant Function Analysis

Discriminant function analysis was formulated by Fisher as a procedure for distinguishing between groups of objects and testing the significance of the differences between the groups. Hodges (1950) and Rao (1952) review the use of discriminant function analyses and applications of the method can be found in Wallis (1965), Middleton (1962) and Shaw and Kudo (1965).

Discriminant functions are sets of equations of the form:

$$X_k = \sum_i l_{ki} x_i - K_k$$

where $1 = w^{ij}d_j$,

w^{ij} = inverse of the pooled within groups dispersion matrix, and

K_k = constants.

Discriminant function analysis tends to minimize the 'within group' variance and to maximize the 'between group' variance.

The Mahalanobis' generalized distance between groups or D^2 is defined as $D^2 = \sum_i 1_i d_i$, and it can be shown that if the variables are uncorrelated that D^2 represents the actual scaled distance between the groups (Middleton, 1969).

The use of discriminant function analysis requires that groupings of the data be established apriorily. In this study, the discriminant function analysis was used to test the significance of the groupings based on differences in morphology and bedrock and surficial geology of the lake basins. The probability of misclassifying data assigned to any group were used as the criterion for determining the validity of the established classifications. A computer program was available to calculate the discriminant functions of the groups (Kramer, 1970).

APPENDIX B RESULTS

TABLE 1 CHEMICAL AND BIOLOGICAL DATA TABLES

TABLE 2 PHYTO PLANKTON DATA TABLES

TABLE 3 ZOOPLANKTON DATA TABLES

CAMP	TEN	22/7	1.0		19.0		7.22	0.24	2.1	133.	50.0	45.0	7.0	3.0		29.	7.5	3.0	.357	*
CAMP	TEN	22/7	3.0		18.0		7.21	0.24	2.0	122.	55.0	50.0	8.0	2.0		27.	3.5	3.0	.989	14.0
CAMP	TEN	22/7	5.0	5.0	15.5		7.18	0.24	2.1	144.	55.0	50.0	8.0	2.0		29.	6.5	3.0	.288	7.0
CAMP	TEN	22/7	7.0		12.5					101.										
CAMP	TEN	22/7	8.0		11.5		6.82	0.36	3.5	43.	60.0	55.0	8.0	2.0		30.	9.0	4.5	.267	7.6
CAMP	TEN	05/9	1.0		18.0	74.1	7.52	0.35	2.8	166.	50.0	45.0	9.0	2.0	2.0	30.	7.5	2.5		20.1
CAMP	TEN	05/9	3.0		18.0	74.6	7.42	0.33	2.7	157.	60.0	55.0	8.0	2.0	2.0	28.	7.5	3.0		9.0
CAMP	TEN	05/9	5.0	6.0	17.0	71.0	7.22	0.33	2.9	145.	80.0	75.0	8.0	2.0	2.0	28.	8.0	3.5		1.8
CAMP	TEN	05/9	7.0		14.0					46.										
CAMP	TEN	05/9	8.0		13.0	77.5	6.68	0.53	5.4	38.	70.0	60.0	9.0	2.0	2.0	32.	15.5	8.5		17.7
LANG		28/7	1.0		24.5		7.07	0.16	1.4	154.	40.0	35.0	10.0	1.0		29.	5.0	1.0		35.0
LANG		28/7	3.0		24.0		7.06	0.14	1.2	136.	50.0	45.0	9.0	1.0		28.	6.0	1.0		13.0
LANG		28/7	7.0	6.0	19.0		6.84	0.14	1.3	124.	50.0	45.0	9.0	2.0		29.	6.0	1.5		18.0
LANG		28/7	15.0		11.8		6.38	0.14	1.5	92.	75.0	70.0	10.0	1.0		29.	6.0	1.5		12.0
LANG		28/7	20.0		10.8		6.27	0.13	1.5	90.	70.0	65.0	9.0	2.0		30.	5.0	1.0		13.0
LANG		26/8	1.0		22.0	66.6	7.14	0.26	2.3	150.	35.0	25.0	9.0	2.0	2.0	30.	6.0	1.0		
LANG		26/8	3.0		22.0	66.6	7.30	0.30	2.5	141.	60.0	55.0	9.0	2.0	2.0	30.	6.0	1.0		
LANG		26/8	5.0		22.0			0.16	1.6	169.										
LANG		26/8	7.0	6.0	19.5	66.6	6.70	0.16	1.6	135.	60.0	55.0	9.0	2.0	2.0	30.	6.0	1.0		
LANG		26/8	10.0		15.0					98.										
LANG		26/8	15.0		12.0	67.6	6.46		1.6	84.	40.0	35.0	9.0	2.0	2.0	30.	6.0	2.0		
LANG		26/8	18.0		11.0	69.5	6.24	0.19	2.2	60.	50.0	45.0	8.0	2.0	2.0	28.	7.0	2.0		
PENAGE		30/7	1.0		24.0		6.96	0.12	1.1	145.	70.0	65.0	10.0	1.0		29.	6.0	1.0		
PENAGE		30/7	3.0		22.5		6.96	0.14	1.2	142.	70.0	65.0	8.0	2.0		29.	6.5	1.0		
PENAGE		30/7	7.0	6.0	18.0		6.85	0.12	1.1	139.	60.0	55.0	10.0	1.0		29.	5.0	1.0		6.2
PENAGE		30/7	15.0		10.5		6.74	0.15	1.4	133.	70.0	65.0	9.0	2.0		30.	5.0	1.0		
PENAGE		30/7	18.0		10.0		6.55	0.14	1.5	117.	80.0	75.0	10.0	1.0		30.	5.5	1.5		
PENAGE		01/9	1.0		19.0	74.6	6.45	0.20	2.1	151.	70.0	65.0	8.0	2.0	2.0	28.	5.5	1.0		
PENAGE		01/9	3.0		19.5	73.5	7.15	0.15	1.2	134.	60.0	55.0	8.0	2.0	2.0	28.	5.5	1.0		
PENAGE		01/9	7.0	8.0	19.5	74.6	6.90	0.14	1.3	143.	60.0	55.0	9.0	2.0	2.0	30.	5.5	1.0		
PENAGE		01/9	12.0		12.0	74.6	6.57	0.12	1.2	136.	50.0	45.0	9.0	2.0	2.0	30.	5.5	1.0		
PENAGE		01/9	16.0		11.0	82.3	6.56	0.12	1.3	133.	60.0	55.0	9.0	2.0	2.0	30.	6.1	1.0		
GEORGE		06/8	1.0		23.0		5.72	0.15	.6	162.	60.0	55.0	4.0	1.0		14.	3.0	0.0		9.1
GEORGE		06/8	5.0		22.0		5.52	0.14	.5	178.	35.0	30.0	4.0	1.0		14.	3.0	0.0		9.6
GEORGE		06/8	10.0	9.0	12.0		5.86	0.09	.6	152.	45.0	30.0	4.0	1.0		14.	2.5	0.0		9.3
GEORGE		06/8	15.0		9.5		5.75	0.09	.6	151.	40.0	35.0	4.0	1.0		14.	2.5	0.0		
GEORGE		06/8	20.0		8.5		5.53	0.09	.8	120.	45.0	40.0	4.0	1.0		14.	3.0	0.0		
GEORGE		06/9	1.0		20.0	35.7	5.66	0.02	.4	163.	30.0	25.0	4.0	1.0	1.0	16.	3.0	0.0		
GEORGE		06/9	5.0		19.5	35.7	5.29	0.02	.3	143.	30.0	25.0	4.0	1.0	1.0	14.	3.0	0.0		
GEORGE		06/9	10.0	10.0	13.5	35.7	5.52	0.04	.6	176.	60.0	55.0	5.0	1.0	1.0	16.	3.0	0.0		
GEORGE		06/9	15.0		9.5	35.7	5.31	0.04	.6	145.	40.0	35.0	5.0	1.0	1.0	16.	3.0	1.0		
GEORGE		06/9	20.0		8.5	35.7	5.43	0.04	.7	113.	30.0	25.0	4.0	1.0	1.0	14.	3.0	1.0		
LIT. PENAG		11/9	1.0		18.0	78.1	7.78	0.61	4.7	152.	90.0	85.0	13.0	2.0	1.0	42.	12.0	5.0		7.9
LIT. PENAG		11/9	5.0	5.0	16.0	79.4	7.60	0.57	4.5	142.	60.0	55.0	13.0	3.0	1.0	44.	12.5	5.5		5.9
LIT. PENAG		11/9	10.0		8.5	76.9	6.98	0.56	5.3	85.	90.0	85.0	13.0	3.0	1.0	44.	14.0	8.0		6.5
LIT. PENAG		11/9	15.0		7.0	76.9	6.95	0.54	5.2	75.	80.0	75.0	13.0	2.0	1.0	42.	13.0	6.0		2.6
LIT. PENAG		11/9	18.0		7.0	76.9	6.90	0.56	5.5	61.	80.0	75.0	13.0	2.0	1.0	13.	14.5	7.5		5.2

CAMP	TENN	22/7	1.0	.11		.00*	10.8	13.	3.0	1.36	0.80	0.034	1.02	0.90	7.	9.	25.	1.	42.
CAMP	TENN	22/7	2.0	.15		.00*	10.4	13.	3.0	1.38	0.45	1.34	1.09		16.	27.	47.	8.	90.
CAMP	TENN	22/7	5.0	.11		.00*	10.3	13.	3.0	2.17	0.16	0.84	2.43	0.10	26.	29.	178.	8.	241.
CAMP	TENN	22/7	7.0	.25		.30*	15.1	10.	3.0	17.3	2.25	2.94	7.83	4.99	76.	64.	1721.	400.	2625.
CAMP	TENN	05/9	1.0	.31		*	10.7	13.	1.0	1.15	1.50	0.44	0.60		39.	64.	444.	2.	549.
CAMP	TENN	05/9	3.0	.16		*	10.9	13.	1.0	1.55	1.43	0.46	0.67		61.	28.	221.		310.
CAMP	TENN	05/9	5.0	.20		*	10.8	12.	1.0	3.26	0.18	1.20	1.52		105.	31.	250.	6.	392.
CAMP	TENN	05/9	8.0	.62		*	16.7	8.	2.0	16.1	0.002	3.40	6.76		115.	1168.	3395.	167.	4845.
LANG		28/7	1.0	.20	1.15	.004	1.3	23.	3.0	3.64	-5.67	0.25	1.15	0.30	38.	3.	90.	3.	104.
LANG		28/7	3.0	.14	.55	.006	1.5	23.	3.0						38.	22.	689.	3.	136.
LANG		28/7	7.0	.15	.55	.019	1.4	23.	3.0	9.00	1.23	3.61	3.17	0.11	487.	22.	106.	2.	597.
LANG		28/7	15.0	.19	.55	.025	2.4	23.	3.0	1.46	4.34	0.27	0.78	0.05	35.	22.	23.	3.	141.
LANG		28/7	20.0	.20	.75	.027	2.3	23.	3.0	1.18	1.45	0.53	0.39		41.	25.	4.		11.
LANG		26/8	1.0	.24		*	1.3	22.	2.0	2.81	0.13	-0.43	1.23		220.		202.		422.
LANG		26/8	3.0	.22		*	1.4	22.	2.0	2.65	0.09	0.90	1.20		146.		205.		
LANG		26/8	5.0			*													
LANG		26/8	7.0	.21		*	1.3	21.	2.0	0.34	4.19	3.07	2.91		391.	28.	2.	254.	675.
LANG		26/8	10.0			*													
LANG		26/8	15.0	.30		.003	3.5	22.	2.0	1.07	-0.55	1.37	0.53		36.	31.	61.	2.	131.
LANG		26/8	18.0	.23		.71	3.4	21.	2.0	1.86	0.33	0.42	1.06		57.	38.	36.	2.	133.
PENAGE		30/7	1.0	.19		.004	1.1	24.	2.0	1.05	-0.11	0.69	0.56	0.23	54.	31.	56.	5.	128.
PENAGE		30/7	3.0	.20		.006	1.0	25.	3.0	1.64	-0.19	0.50	0.58		29.	18.	22.	4.	73.
PENAGE		30/7	7.0	.17		.005	1.0	25.	3.0	1.10	-0.48	0.50	0.30	0.12	43.	34.	37.	3.	113.
PENAGE		30/7	15.0	.15		.001	1.1	24.	3.0	0.89	1.09	0.15	0.76	0.03	13.	60.	7.	2.	113.
PENAGE		30/7	18.0	.14		.020	1.2	24.	3.0						27.	60.	6.		102.
PENAGE		01/9	1.0	.24		*	1.6	23.	3.0	1.70	-0.19	0.57	0.75		24.	68.	121.	4.	205.
PENAGE		01/9	3.0	.27		.002	1.6	23.	3.0	1.90	-0.04	0.65	0.86		29.	21.	119.	7.	176.
PENAGE		01/9	7.0	.23		.002	1.6	24.	3.0	1.69	-0.18	0.57	0.95		71.	11.	114.	7.	203.
PENAGE		01/9	12.0	.20		*	2.0	23.	2.0	1.12	-0.82	-0.52	0.56		21.	41.	31.	2.	101.
PENAGE		01/9	16.0	.19		.005	1.50	24.	2.0	0.74	0.05	-0.57	0.49						
GEORGE		06/8	1.0	.12		*	2.7	13.	2.0	0.63	-0.15	1.02	0.46	0.09	4.				4.
GEORGE		06/8	5.0	.10		.010	2.6	13.	3.0	0.87	-0.19	0.50	0.52		17.		4.		21.
GEORGE		06/8	10.0	.08		*	2.6	13.	3.0	1.36	-0.28	0.50	0.57	0.04	38.			6.	44.
GEORGE		06/8	15.0	.17		*	3.1	23.	3.0	2.73	-0.27	0.50	1.33	0.01	68.			1.	69.
GEORGE		06/8	20.0	.10		*	3.3	22.	3.0	1.39	-0.21	0.86	0.45		13.			1.	14.
GEORGE		06/9	1.0	.18	.67	.003	1.0	10.	1.0	0.38	-0.14	0.57	0.40	0.11	41.		26.		93.
GEORGE		06/9	5.0	.18	.67	.001	1.0	10.	1.0	0.69	-0.57	0.53	0.53		22.				48.
GEORGE		06/9	10.0	.24	.67	.003	1.0	10.	1.0	1.42	-0.04	0.64	0.88	0.21	22.			1.	25.
GEORGE		06/9	15.0	.20	.67	.003	1.0	10.	1.0	2.18	-0.23	0.72	0.88	0.44	20.			4.	35.
GEORGE		06/9	20.0	.20	.001	.26	3.1	10.	1.0	2.04	-0.48		0.83		42.		1.	4.	47.
LIT. PENAG		11/9	1.0	.36		*	.5	15.	2.0	3.30	-0.17	0.16	1.30	1.46	28.	14.	470.	14.	510.
LIT. PENAG		11/9	5.0	.33		*	.3	15.	2.0	4.77	-0.02	0.56	1.65	2.14	106.	14.	413.	14.	639.
LIT. PENAG		11/9	10.0	.30		*	.6	15.	2.0	2.95	0.43	0.10	0.91	0.06	40.	16.	759.	10.	856.
LIT. PENAG		11/9	15.0	.22		.005	1.6	15.	2.0	0.83	0.37	0.45	0.23		7.	20.	220.	2.	306.
LIT. PENAG		11/9	18.0				1.9	15.	2.0	0.67	0.32	1.11	0.59		9.	16.	224.	2.	254.

TABLE 2 CONTINUED, LEGEND TO DATA TABLES

DEP	depth, m
SEC	secchi disc transparency, m
TEMP	temperature, °C
COND	conductivity, $\mu\text{mho cm}^{-1}$ at 25°C
PH	pH
ALK	alkalinity, meq l^{-1}
CO2	carbon dioxide, meq l^{-1}
O2	oxygen, per cent saturation
T.S.	total solids
D.S.	dissolved solids
CA	calcium
MG	magnesium
NA	sodium
HARD	hardness as CaCO_3
T.C.	total carbon
I.C.	inorganic carbon
P.C.	particulate carbon
CH2O	carbohydrate
K.N.	total Kjeldahl nitrogen
NH3	ammonia and amino acids
NO2	nitrite
NO3	nitrate
PO4	phosphate, mg m^{-3}
SI02	silica as SiO_2
SO4	sulphate
CL	chloride
CHL-A	chlorophyll a, mg m^{-3}
CHL-B	chlorophyll $\underline{\text{b}}$, "
CHL-C	chlorophyll $\underline{\text{c}}$, "
CAROT	carotin, "
PROD	primary productivity, mg m^{-3}
FLAG	flagellates, a.s.u. ml^{-1}
BL-GR	blue-greens, "
GREN	greens, "
DIATOM	diatoms, "
T.PHYT	total phytoplankton, a.s.u. ml^{-1}
*	not detectable
-	less than

NOTE: results expressed in mg l^{-1} unless otherwise stated.

			GREENS															FLAGELLATES														
NAME	DATE	DEPTH	<i>Oocystis</i>	<i>Stenotomonas</i>	<i>Amphitetras</i>	<i>Monosira</i>	<i>Stauroneis</i>	<i>Coscinodiscus</i>	<i>Guillardia</i>	<i>Prorocentrum</i>	<i>Chlorococcoides</i>	<i>Chlorella</i>	<i>Trachionema</i>	<i>Yarrowia</i>	<i>Stenodactylus</i>	<i>Scolecococcus</i>	<i>Closterium</i>	<i>Desmarestia</i>	<i>Prorocentrum</i>	<i>Closterium</i>	<i>Glenodinium</i>	<i>Synechococcus</i>	<i>Dinobryon</i>	<i>Chlamydomonas</i>	<i>Peridinium</i>	<i>Chlamydomonas</i>	<i>Euglena</i>	<i>Trachelomonas</i>	<i>Paramecium</i>	<i>Leptodermella</i>		
Kukagami	23/6	1.0																			7	15	2									
		3.5	P																		7	74	7									
		8.5	8																		67	67	11									
		15																			19	40	9	1	3							
		20																			16	17	6									
Kukagami	3/8	1.0																			P	1	1	P								
		3.0																				1	1	3		6						
		7.0																					1	1	1							
		15																				3	6	P								
		22																			15		120									
Tyson	30/6	1.0	P	P	P																	7	1	16								
		3.0																				1	1	P								
		7.0	P																			1	11	3								
		14.0																				9	423	12								
Tyson	18/8	1.0				2																										
		5.0	P																													
		10.0																														
		13.0																														
		18.0																			P											
Geneva	21/8	1.0				3																										
		5.0	4				3															8	4	8			3					
		12.0	1					1	1	3													1	18								
		15.0								P													1	3				P				
		20.0																				1	1	3								
Alphretta	12/7	1.0	2								5	P	P									4	P	3								
		5.0	P								6											1	1	6			3					
		13.0			3						35											1	1	19								
		20.0			3						24												6	84	8							
Alphretta	23/8	1.0				6					1			3	P							P	1	1								
		5.0									11			23								30	2	8								
		10.0	1			29	7		P	2				1								77	1	5								
		13.0	P								3											21	2	3								
		17.0	4								4	1			P										13							
		20.0																						125	96							
Camp Ten	22/7	1.0	1		P									P	P							5	2	P			P					
		3.0												P	P							7	3	1								
		5.0	8											P								14	8	2								
		8.0																						46	30							

TABLE 2 PHYTOPLANKTON DATA

FLAGELLATES

Table 2 Continued

BLUE-GREENS															DIATOMS															
NAME	DATE	DEPTH	<i>Oscillatoria</i>	<i>Aphanizomenon</i>	<i>Chroococcoides</i>	<i>Aphanizomenon</i>	<i>Microcystis</i>	<i>Dactylococcoides</i>	<i>Coelastrum</i>	<i>Lyngbya</i>	<i>Agmenella</i>	<i>Coelastrum</i>	<i>Aphanizomenon</i>	<i>Rhodospira</i>	<i>Aphanizomenon</i>	<i>Lyngbya</i>	<i>Asterionella</i>	<i>Coelastrum</i>	<i>Taeniocapsa</i>	<i>Thalassiosira</i>	<i>Nitzschia</i>	<i>Skeletonema</i>	<i>Cyclotella</i>	<i>Rhizosolenia</i>	<i>Skeletonema</i>	<i>Navicula</i>	<i>Diatoma</i>	<i>Pinna</i>	<i>Achnanthes</i>	<i>Unkn.</i>
Kukagami	23/6	1.0															269	4												
		3.5															680		60											
		8.5															754													
		15.0															3,305		20											
		20.0															1,959		29											
Kukagami	3/8	1.0															523		4											
		3.0															17		1											
		7.0	P														50		4											
		15.0	P														23			1										
		22.0															71				7									
Tyson	30/6	1.0			2	1											29			2										
		3.0															40		2											
		7.0															106		8											
		14.0															145		24											
Tyson	18/8	1.0					560										7					3								
		5.0					395	P									422													
		10.0															118													
		13.0															105		4											
		18.0																												
Geneva	21/8	1.0	30	1	19	892	10	2	3														44	2	1					
		5.0	45	6	18	775			4			30	1						9				91		1					
		12.0		1	7	75	8	P	2			1											14		1					
		15.0	P		1	116	6		1								4						11		1					
		20.0	1		1	49											11		103				9		3	3				
Alphretta	12/7	1.0															8		1				P				1			
		5.0															3													
		13.0															13,089		7											
		20.0															5,063		131				2			2				
Alphretta	23/8	1.0			1																									
		5.0			15												4													
		9			9																									
		10.0			2							3					21								P	1				
		13.0	P		1		4										3		1		P		P	20	4					
		17.0	2		1							5																		
		20.0			15												3,333													
Camp Ten	22/7	1.0		1	22				1		1						4	3	P			1		P				1	1	
		3.0		1	42			P	1		1						1	12	9	1		3		P			1	P		
		5.0		2	161						1						6		13		1		6		3				5	
		8.0										1,721							546				28		69					

Table 2 Continued

BLUE-GREENS													DIATOMS																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
NAME	DATE	DEPTH	Desulfonella	Anabaena	Chaetoceros	Ankistrodesmus	Mastigodictyon	Dactylopusia	Coelastrum	Lyngbya	Microcystis	Phormidium	Scenedesmus	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella	Chlorella

Table 2 Continued

TABLE 3 ZOOPLANKTON DATA

NAME	DATE	DEPTH	COPEPODA			CLADOCERA				ROTIFERA			
			Calanoida	Cyclopoida	Nauplii	Euphrasia	Bosmina	Polyphe-mus	Utracoda	Kellicottia	Keratella	Polysartha	Trichocerca
Kukagami	23/6	1.0	160	.95	780		50				60		
		3.5			425		220				175		
		8.5											
		15.0		12	230		160				130		
		20.0		7	65		40				75		
Kukagami	3/8	1.0	125	60	485		95			19	50	70	
		3.0	60	30	550		6				50	25	
		7.0	125	50	320	31	150			75	25		
		15.0	440	150	88		535		75		45	50	
		22.0		25	40		660		80			35	
Tyson	30/6	1.0	45	10	160	6	30	6	3	6		10	10
		3.0	100	6	310	12		15	12	125	10	25	
		7.0	125	15	125	10	12			100	40	80	40
		10.0	60		80	4			6	60		10	
	18/8	1.0	30	35	100	6	10	6	6	65			
		5.0		25	625	6	65	15	10	100	20	10	
		10.0	60	40	475	25	75	30		20		6	
		13.0	20	12	30		20					35	
		18.0			100	6	5		4				
Geneva	7/7	1.0	90	60	160	45		120		120			6
		3.0	125	65	180	50				60			
		7.0	120	100	1025	225			30	25	30		15
		12.0	125	60	55	12	25			10	4		
		15.0	200	80	30	6				6			4
		20.0	125	60	55	12	20			25			30
	21/8	1.0	156	120	375	12	12	12		35		6	
		5.0	25		95	25		25					
		12.0	20	10	130	625				20	4	12	
		15.0	375	130	625						80	60	
Alphretta	12/7	1.0	10	6	40	10			6	10	6	2	
		5.0	60	100	80	10			18	20			
		10.0	205	110	215	25			20	65			
		13.0	140	20	300	10			6	130	10	6	12
		17.0	60		150	6			6	65			
		20.0	10	10	40	6				75	80	12	
	23/8	1.0	120	60	900		6			280	60		
		5.0	510	75	375	25			20	300	18	12	
		10.02	205	110	215	25	110			200	190	62	
		13.0	100	55	225		35			50	25	60	
		17.0	100	50	215	25	20			235	210	160	
		20.0	125	50	280		95		10				

= bloom of phytoplankton

= sample contaminated with sediment material

Table 3 Continued

NAME	DATE	DEPTH	COPEPODA				CLADOCERA				NOTIFERA			
			Calanoida	Cyclopoida	Nauplii	Daphnia	Bosmina	Polyphemus	Ostracoda	Kellicottia	Keratella	Polyarthra	Trichocera	
Camp Ten	22/7	1.0	50	45	110	25	25							
		3.0	225	10	85				35			12		
		5.0	120	40	100	20	30							
		7.0	155	45	200				12					
		8.0	800	85	212	12								
	5/9	1.0	40	25	100	8	40			420	12	4	6	
		3.0	225	106	700	12	53							
		5.0	180	68	400	10	20			125		8	6	
		7.0	120	70	400	12	60			225		10	6	
		8.0												
Lang	28/7	1.0	95	45	170	20	12	6	40	5			6	
		3.0	200	100	280	80	13		6	70		35	6	
		7.0	310	85	350	50	75			175		80		
		15.0	190	25	800	25		25	6	82				
		20.0	100	45	2045	45				20		50		
	26/8	1.0	130		55	35	90	12		50				
		3.0	50	7	65	30	16	25						
		5.0												
		7.0												
		10.0	40	10	840	60	12			15		60	20	
Penage	30/7	1.0	110	25	360	12	12	10		12			12	
		3.0	160	30	400	12	40	40	90			25	8	
		7.0	90	110	300	40	60			60			60	
		15.0	110	35	250		40			40		25	12	
		18.0	150		490		35			125	35	75		
	1/9	1.0	260	50	275			50		50				
		3.0	135		520		25		18	100				
		7.0	140	25	100	40	25			30				
		12.0	40	20	900	18				6	12	60		
George	6/8	1.0	6		40		35	50		260			12	
		5.0	10	6	85									
		10.0	20		120		45	6	25		45	50	6	
		15.0			60									
		20.0	25	8	10	40		12	15	10		25	8	
	6/9	1.0	6		40		35	50		260			12	
		5.0	10	6	85									
		10.0	20		120		45	6	25		45	50	6	
		15.0			60									
		20.0	25	8	10		40		12	8		25	8	
Little Penage	11/9	1.0	140	60	260	750			100	50				
		5.0	125	225	1800	240	25		75	420		75		
		10.0	140	120	1020	12	12		40	75	40	50		
		15.0	120	10	140		6		40	100	6			
		18.0	40		100		6		8	30	10	5	4	