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GEOLOGICAL FACTORS AFFECTING BIOLOGICAL ACTIVITY IN PRECAMBRIAN SHIELD LAKES

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ABSTRACT

Biological activity was investigated for nine lakes in the Precambrian Shield near Sudbury. Morphology (surface area/volume), lithology (surficial and bedrock geology) and the atmosphere were key factors affecting the biosphere.

Biological activity was found to be low in lakes with small surface area to volume ratios and in poorly-buffered lakes. Acid lakes (pH <5.5) resulting from atmospheric loadings in non-calcareous terrain were lowest in biological activity.

Activity was high in lakes with large surface area to volume ratios and in lakes in calcareous terrain.

Atmospheric loading was correlated with high SO_4 concentrations.

RÉSUMÉ

Des recherches ont été effectuées concernant l'activité biologique dans neuf lacs du Bouclier précambrien près de Sudbury. Les facteurs-clés influençant la biosphère étaient la morphologie (l'étendue de surface/volume), la lithologie (géologie superficielle et de fond rocheux) ainsi que l'atmosphère. Il n'y avait pas beaucoup d'activité biologique dans les lacs ayant une petite étendue de surface par rapport au volume ainsi que dans les lacs pauvrement tamponnés. Les lacs acides (pH <5.5) provenant de chargements atmosphériques en terrain non-calcaire possédaient le moins d'activité biologique. Par contre il y avait beaucoup d'activité biologique dans les lacs ayant une grande étendue de surface par rapport au volume et dans les lacs en terrain calcaire. Le chargement atmosphérique était relié à une forte concentration de SO_4.

(Traduit par le journal)

INTRODUCTION

Lakes on the Canadian Shield are typically low in dissolved solids and unproductive. Although Shield lakes occupy a wide range in trophic status — from oligotrophic (clear, cold, nutrient-poor) to eutrophic (turbid, warm, nutrient-enriched) — the majority are classified as oligotrophic. These lakes form an important natural resource since their aesthetic characteristics make them most desirable for outdoor recreational pursuits.

This study attempts to isolate variables related to the lithosphere and atmosphere which exert a control on the biological activity in dilute lentic environments in the Canadian 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.

Aspects of the biotic environment (primary productivity, standing crop and diversity of the primary and secondary trophic levels) are related to physical and chemical variables. Correlation and factor analysis are used to establish significant relationships and factors, and discriminant-function analysis is applied to separate the lakes into appropriate groups on the basis of measured affinities.

PREVIOUS WORK

Major components in the aquatic system

The aquatic system in the lentic environment can be divided into seven components which can be categorized as either abiotic or biotic. The major biotic components are phytoplankton, zooplankton, and fish; the major abiotic components are atmosphere, sunlight, nutrients, and bottom sediments.

Biotic components. The most important biotic reaction is primary productivity and the mechanism of primary productivity is photosynthesis, represented by the classical equation:

$$6CO_2 + 6H_2O \xrightarrow[\text{chlorophyll } a]{hv} (CH_2O)_6 + 6O_2$$

where *hv* 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 & 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:

$$106CO_2 + 16NO_3^{1-} + HPO_4^{2-} + 122H_2O$$
$$+ 18H^+ + \text{trace elements} + \text{energy}$$
$$\text{photosynthesis} \updownarrow \text{respiration}$$
$$(C_{106}H_{263}O_{110}N_{16}P_1) + 138O_2$$
algal protoplasm

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 (Liebig'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.

Abiotic components. The focus of the abiotic system is the nutrient pool including those soluble constituents required in major concentrations (C, N, H, O, P) as well as trace quantities of many other ions. The sediments and the atmosphere act as chemical sinks for the nutrient components and approach equilibrium in the aquatic system. The equations below are examples of interactions in the abiotic system.

SEDIMENT		WATER		ATMOSPHERE	OTHER KEY VARIABLES
$CaCO_3$	↔	CO_3	↔	CO_2	H^+
FeS_2	↔	SO_4	↔	SO_2	biological mediation

Sunlight, the other abiotic component, is constant on a yearly scale when taken within narrow ranges of latitude.

Interactions in the lentic ecosystem

The lentic ecosystem functions by interactions between the components. The key reaction is primary productivity which is controlled by the available nutrient flux and quantity of sunlight.

The question then becomes: what determines the composition of the solutes (nutrient flux) in surface waters? Kramer (1964) states that "the ultimate source of all constituents in fresh water is either the lithosphere (sediment) or atmosphere". 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 dissolved matter in water". Nevertheless, the correlations between water chemistry and geology that have been made by Miller (1961), Feth *et al.* (1964), and Garrels & Mackenzie (1967) for qualified situations, show that reactions of water with lithological material are important in determining the ultimate composition of surface waters.

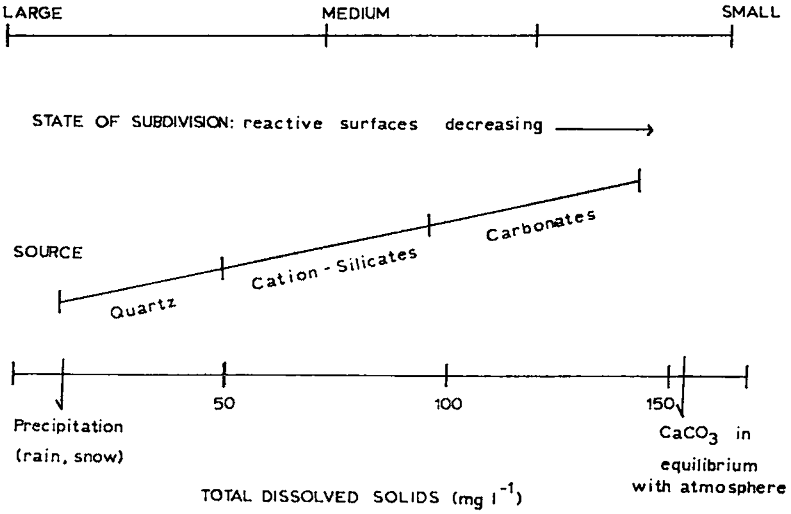

FIG. 1. Nomograph of relation between geological nature of basin (physical and chemical) and total dissolved solids of water.

Table 1 summarizes important lithospheric and atmospheric sources of constituents of fresh water, partly after Kramer (1964).

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 is a nomograph depicting the theoretical relation between the geological nature of the basin (physical and chemical) and the concentration of the solute pool — total dissolved solids (TDS), and Table 2 illustrates the resistivity of minerals to weathering.

TABLE 1. IMPORTANT CHEMICAL SPECIES DERIVED FROM WEATHERING OF MINERALS

chemical species	source
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 Fluoride	Apatites
Sulfate	Pyrite, gypsum
Chloride	Rock inclusions

TABLE 2. STABILITY OF MINERALS IN WEATHERING*

(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

*Rankama & Sahama (1950)

TABLE 3. REFERENCES TO VARIABLES LIMITING AQUATIC PRODUCTION

Limiting Constituent	Source	Area	Comment
Carbon	Kuentzel (1969) Johnson *et al.* (1970) Sakamoto (1971)	general northern Ont. northwestern Ont.	
Nitrogen	Gerlott & Skoog (1957) Sakamoto (1971)	southern Wisconsin northwestern Ont.	rarely limiting
Phosphorus	Campbell (1969) Sakamoto (1971)	lower Great Lakes northwestern Ont.	
Silica	Schelske & Stoermer (1971) Russell-Hunter (1970)	Lake Michigan general	diatoms diatoms
Nitrogen/ Phosphorus ratio	Russell-Hunter (1970) Christie (1968)	general southern Ont.	

Using relationships depicted in Figure 1 and Table 2, predictions can be made that waters high in dissolved solids will occur in alkaline terrains whereas waters lower in dissolved solids will occur in non-alkaline terrains. Hem (1971) develops a relationship between dissolved chemical species in water and lithology and presents data which support the above prediction.

Variables affecting biological productivity

Of the many variables in the nutrient pool, those most often associated with productivity include phosphorus, carbon, nitrogen and silica. Table 3 summarizes variables limiting aquatic production.

In addition, Rawson (1952), Card & Gillespie (1966), Theinemann (1926), and Ryder (1965) isolate variables which bear an empirical relationship to production including interactions of climatic, edaphic and morphometric factors, geology, mean depth, and total dissolved solids.

PLAN OF STUDY

An area of the Canadian Shield near Sudbury, Ontario was selected for the study, since lakes of similar size were available for which the surficial and bedrock geology varies sufficiently to test the lithology-productivity concept. The boundary conditions for the experimental method are summarized as follows: (1) *climatic* — held constant by selecting lakes in the same geographical area; (2) *morphometric* — varied by selecting lakes with a range in surface area to volume ratios (0.8-163 m^{-1}); (3) *lithospheric* — varied by selecting lakes with and without calcareous basins; abundant and limited surficial deposits; (4) *atmospheric* — measured on a regional basis.

Lakes fitting the study plan were selected by reference to maps showing surficial and bedrock geology and by discussion with K. D. Card (pers. comm. 1970). The criteria for lake selection included (1) one lake showing cultural eutrophication; (2) one lake with a low surface area to volume 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 and collections for biological and chemical analyses were made at each of the lakes twice during the summer of 1970 with the exception of Little Lake Penage (sampled only once). Collections of chemical, physical, and biological variables were made according to standard limnological techniques. Diversity was measured using the technique of Margelef (1968), and primary productivity was measured by a modified radioactive-carbon assimilation technique (Michalski *et al.* 1973).

Figure 2 is a sketch map of the study area. The Precambrian Shield can be divided into three geological provinces in the study area: the Superior, the Southern and the Grenville. On the basis of the geology, four significant areas have been defined by Card & 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 underlain by

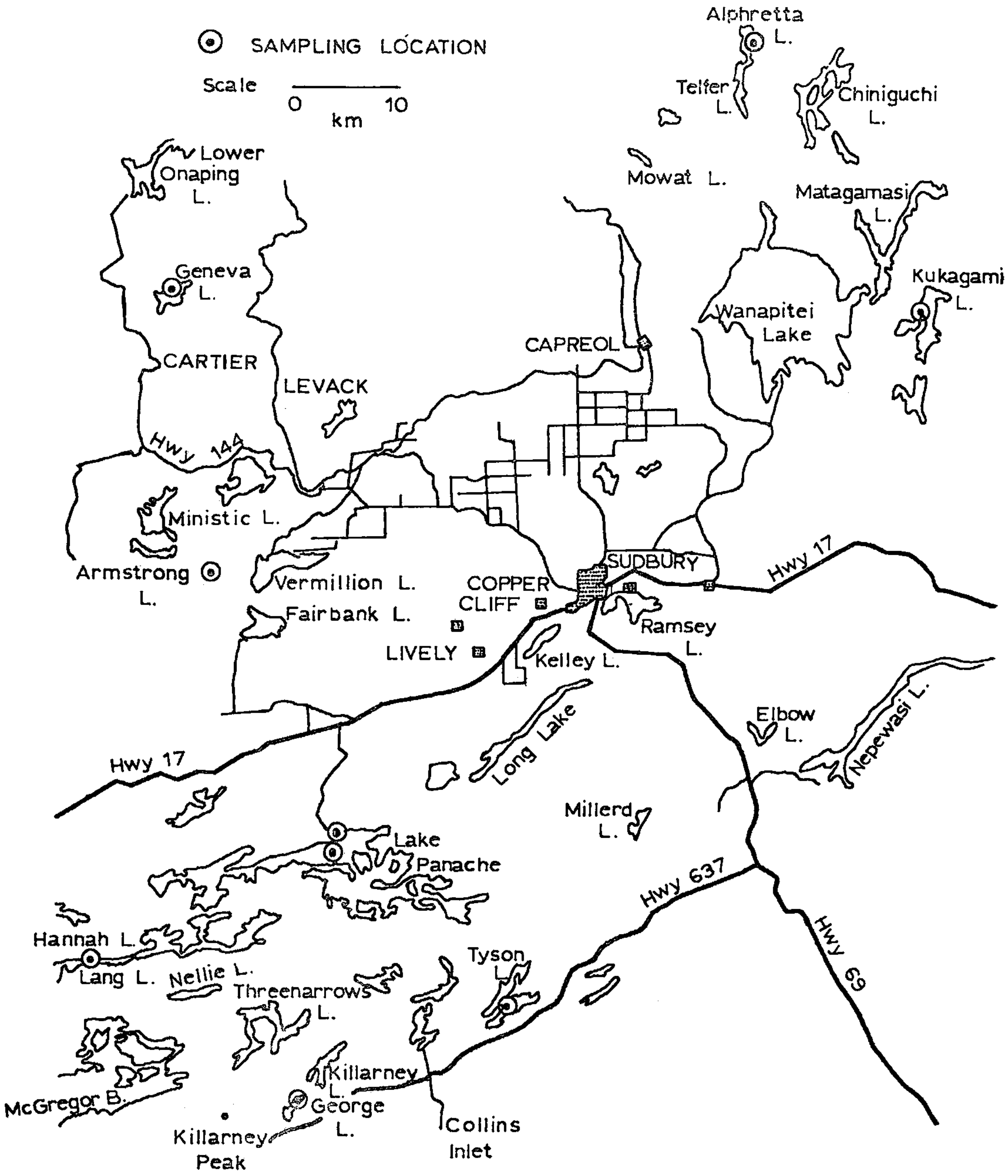

FIG. 2. Sketch map of study area.

granitic rocks. The overburden is thin, discontinuous, and mineralogically similar to the underlying rocks. The overburden within the Cobalt Plain is generally thicker than in the Northwest Granitic and the bedrock includes conglomerate, quartzite, gabbro, greenstone and limestone. Mineralogically, the rocks are largely quartz, Na-K-Al silicates, and Ca-Fe-Mg silicates.

The Sudbury Basin is underlain by mafic and siliceous intrusive rocks, intermediate volcanics, slate, and greywacke. Thick discontinuous glacio-fluvial deposits occur within the Basin.

The rocks of the Huronian Belt are of sedimentary origin and range from orthoquartzites through conglomerates and tillites (moderately rich in calcium, magnesium, soda, potassium, and phosphorus) to limestones (calcium and calcium-magnesium carbonates). Thick, discontinuous, glaciofluvial deposits occur in this area.

The rocks of the Grenville Province are gneisses which represent highly metamorphosed sedimentary, volcanic, and igneous intrusive rocks. They possess high to intermediate levels of soda, potash and phosphorus, and low to intermediate concentrations of calcium and magnesium. Quartz, feldspar, hornblende and biotite are common.

For summary maps of the region see Card *et al.* (1969) and Boissoneau (1963). The descriptive geology of the lake basins studied (Table 4) follows Card (pers. comm. 1970).

Twelve locations were selected to measure the composition of bulk precipitation (rain and dry fallout)[1] from the atmosphere. To accomplish this a precipitation collector was designed to collect from 1 to 3 litres of precipitation per month. Analyses were provided for conductivity, pH, sulfates and twelve metals (soluble fraction) on the filtrate after samples were filtered through prewashed Whatman GF/C and Millipore HA filters.

Results and Discussion

Only variables important in the statistical treatment are included in this paper. A complete list of data is found in Conroy (1971).

Statistical analysis

The data were subjected to principal-component and varimax factor analysis. The results are provided in Tables 5 and 6 for data emphasizing chemical and biological parameters respectively.

Reference to Table 5 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. The second factor is heavily loaded by the physical parameters — depth, temperature and light, whereas factor 3 is loaded by alkalinity, dissolved solids and pH. Factor 4 has two vari-

TABLE 4. DESCRIPTIVE GEOLOGY OF THE LAKE BASINS STUDIED

	Lake	Bedrock	Surficial Deposits	Mineralization
Grenville Province	Tyson	layered paragneiss (biotite-garnet, biotite-hornblende gneiss, amphibolite, calc-silicate gneiss), quartzite, amphibolite, and granite	relatively thin boulder till	none known
	George	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)	thin glacial drift; boulder till	none known
Superior Province	Camp Ten	granitic rocks, including granite (quartz monzonite-granodiorite composition), granitic gneiss, and migmatite.	relatively thick glacio-fluvial outwash sands and gravels	none known, although not far from Sudbury Nickel Irruptive and attendant Ni-Cu mineralization
	Geneva	in a greenstone belt, near an outlier of Hur-Huronian rocks. Superior rocks are mainly granitoid-quartz monzonite-granodiorite composition. Huronian rocks are mainly quartzite and conglomerate. Greenstones include basalts and andesites	moderately thick glacial (boulder till) and glacio-fluvial (outwash sand, gravel, clay and eskers)	deposits of Zn and Ag-bearing sulfides mined; several other occurrences of Ag,Co,Zn,Cu, and Fe known in general area.
	Alphretta	Cobalt Plain; conglomerate and argillite of the Gowganda Formation; some diabase intrusions	moderate glacial (boulder till) and glacio-fluvial (sand, gravel, clay) deposits.	none known
Southern Province	Kukagami	Cobalt Plain; conglomerate and argillite of the Gowganda Fm.; Nipissing and olivine diabase dykes	moderate glacial (till) and glacio-fluvial (outwash) sand, gravel, clay	minor sulfide occurrences - pyrite, galena and chalcopyrite
	Lang	Huronian Belt; conglomerate, argillite, quartzite of the Gowganda Fm.	relatively thin glacial drift - boulder till	minor amounts of sulfides throughout the area
	Penage	Pecors (argillite), Mississagi (quartzite), Bruce (conglomerate), Espanola (limestone, calcareous siltstone), and Serpent formations, and Nipissing diabase	thin to moderate glacial drift-boulder till; some outwash sand, gravel and clay	several sulfide occurrences around shores (pyrite, chalcopyrite, arsenopyrite).

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[1] The precipitation monitoring data are part of a continuing program to assess the significance of the atmosphere as a source and conveyor of materials to lakes (Kramer 1975).

ables with approximately the same weight-nitrate and numbers of zooplankton, whereas factor 5 has pH, sulfates and phytoplankton diversity. The factors have been defined on the basis of important loadings as: (1) production, (2) morphometry, (3) alkalinity, (4) zooplankton, (5) sulfate.

The factor analysis of data emphasizing biological parameters (Table 6) revealed that most of the covariance in the properties of the system may be accounted for by the variation in silica concentrations, 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 contributors. 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, (5) flagellates.

In summary, the results of factor analysis 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 below:

BIOLOGICAL	PHYSICAL	CHEMICAL
primary productivity	depth	pH
chlorophyll *a*	temperature	alkalinity
total phytoplankton	light	dissolved solids
diatom numbers		soluble phosphate
blue-green numbers		silica
total zooplankton		sulfate
phytoplankton diversity		
zooplankton diversity		
copepods		
cladocerans		

TABLE 5. 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
Sulfate	-.173	.072	.077	.139	.661
Chlorophyll a	.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 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
Rotifiers	-.132	.883	.046	.086	.348

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. 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 and/or adsorption of silica as quartz or silicate minerals, 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. In general, dissolved silica was lowest in surface waters where biological activity (diatoms) was high, and highest in bottom waters where biological activity was low. The concentrations of silica found in this study are generally well within the range commonly observed in natural water (*i.e.* 1 to 30 mg l^{-1}). According to Lewin & Guillard (1963) silica becomes limiting at concentrations in the order of 0.1 mg l^{-1}.

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 was somewhat obscured by the utilization of silica by the primary trophic level.

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

A stoichiometric formula for plankton was presented 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 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 (P was too low to measure in many cases).

The principal source of P to the aquatic system is the dissolution of rocks in the basin, especially the mineral apatite. 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 induced source of P to lakes is sewage from various sources. Little Lake Penage is an example of P enrichment by man's activity (Michalski 1969). Drainage from septic tanks and washing facilities was suspected as the main cause of P enrichment in Little Lake Penage.

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

Hydrogen ion. The other major abiotic parameters which were found to be important to this aquatic system can be categorized as variables influencing pH. These include bicarbonate, calcium, and sulfate-ion concentrations.

The hydrogen-ion concentration in the study lakes showed wide variation. 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 dissolution of Al-silicates may contribute also.

The hydrogen-ion concentration, as a function of the ratio of bicarbonate to undissociated carbonic acid, has the form: $(HCO_3^-)/(H_2CO_3) = K_1/(H^+)$, where K_1 is the dissociation constant of the reaction $H_2CO_3 = H^+HCO_3^-$.

In this study the major cationic variable which influenced the pH was the calcium-ion concentration. The reaction involving calcium and bicarbonate can be summarized as: $2[Ca^{2+}] + [H^+] = [HCO_3^-] + 2[CO_3^{2-}] + [OH^-]$ and is discussed by Hem (1971).

The major anionic variable in the study lakes was sulfate. Two sources of sulfur species to lakes are reactions of water with lithological material containing sulfur minerals such as pyrite (FeS_2) or gypsum ($CaSO_4{\cdot}2H_2O$) and rainfall. Of these, rainfall has been reported to be the major source (Junge 1960; Gorham 1961). In this study the concentration of sulfate in the rain was found to be abnormally high as it was in the lakes. Gorham (1961) and Beamish (1970) reported similar results from studies in the same geographical area. The sulfate concentration found in lakes was not as highly correlated to pH as the ratio of calcium to sulfate. The lithological source of sulfate is either the dissolution of gypsum: $CaSO_4{\cdot}2H_2O = Ca^{2+} + SO_4^{2-} + 2H_2O$, or pyrite and marcasite oxidation (Stumm & Morgan 1970): $FeS_{2(s)} + 15/4(O_2) + 5/2H_2O = Fe(OH)_{3(s)} + 2SO_4^{2} + 4H^+$. Of the two reactions, only the latter is acid-generating, providing 4 equivalents of H^+ per mole of FeS_2 oxidized.

In this study there was no correlation between high lake-water sulfate concentration and surface occurrences of sulfide minerals. Sulfate, however, was strongly correlated with the distance from Sudbury, a major point source of sulfur dioxide to the atmosphere.

Gorham & Gordon (1960) present data which show the concentration of sulfates in lakes as a function of distance from the city. These data have been converted to a log-function and are presented in Figure 3. Data collected by the Ontario Water Resources Commission (1970) for more than 75 lakes in the Sudbury district are in essential agreement with the data of Gorham & Gordon.

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

The pH of the lakes correlates with SO_4 concentration. The two potential sources of sulfates to the lake system are the dissolution of sulfides,

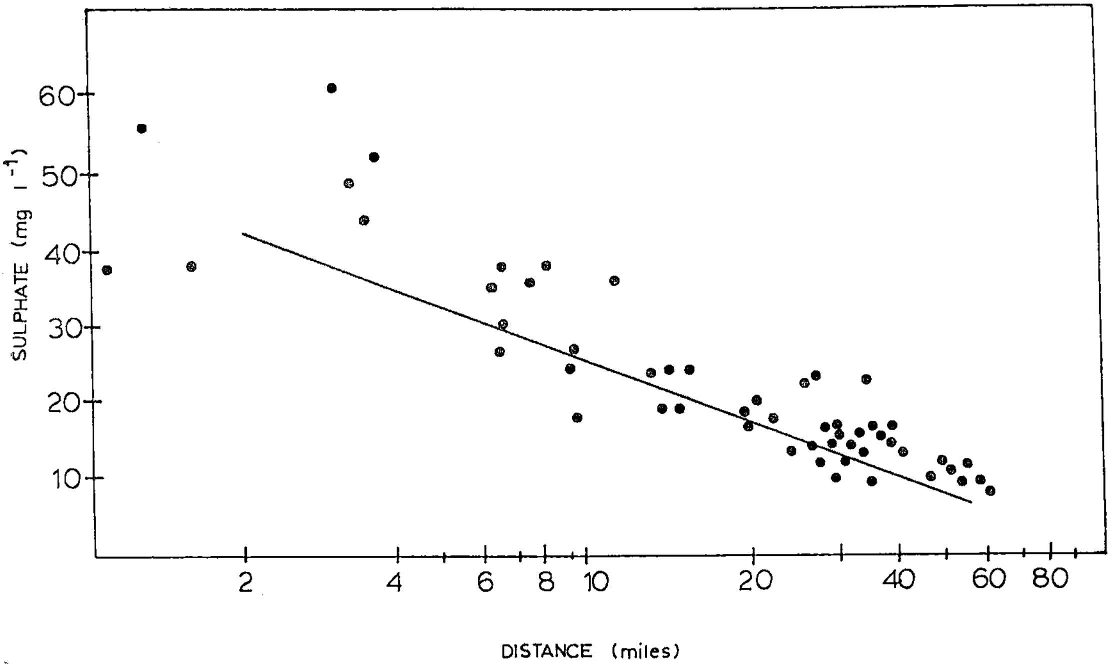

FIG. 3. Plot of lake sulfate concentration versus distances from Sudbury. Line represents data from Gorham & Gordon (1960) and points are data from O.W.R.C. (1970).

and the atmosphere. The latter seems more important in determining the final concentration of sulfates in the lakes.

Lake classification

The lakes were grouped on the basis of morphological and geological (bedrock and surficial) 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 5). Table 7 indicates the groupings of lakes which were used, based on the above considerations.

The results of the discriminant-function analysis on these groupings are shown in Table 8 on the basis of the probability of misclassifying observations.

Using the probability of misclassification from Table 8 a grouping of lakes was established which provided the least possibility of misclassification. The groupings are shown in Table 9.

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.

The most suitable classification scheme utilizes the morphology of the basin as indicated in this study by the surface area to volume ratio (Table 7). However, the classification was improved by regrouping certain lakes as shown in Table 9. The lakes which were reclassified are indicated below.

LAKE	MORPHOLOGICAL GROUPING	MODIFICATION
Penage	1	2
Little Penage	1	2
Alphretta	2	1

Since the groupings emphasize biological relations — productivity and chlorophyll *a* increas-

TABLE 7. LAKE GROUPINGS BASED ON PHYSICAL CHARACTERISTICS OF LAKE BASINS

Morphology		
Group 1	surface area:volume <5 m^{-1}	Kukagami, Tyson, Penage, Little Penage, George
Group 2	surface area:volume 5-100 m^{-1}	Geneva, Alphretta, Lang
Group 3	surface area:volume >100 m^{-1}	Camp Ten
Surficial Geology		
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
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

TABLE 8. PROBABILITY OF MISCLASSIFYING OBSERVATIONS

Basis of Group	Group	% Probability
Morphology	1	37
	2	54
	3	0
Surficial geology	1	35
	2	19
	3	60
Bedrock geology	1	25
	2	73
	3	14

TABLE 9. MODIFIED GROUPING OF LAKES TO MINIMIZE PROBABILITY OF MISCLASSIFYING

Group 1 Lakes	Group 2 Lakes	Group 3 Lakes
Kukagami Tyson George Alphretta	Penage Little Penage Lang	Camp Ten
5*	16*	0*

* % Probability of Misclassification

ing 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, whereas Alphretta Lake shows lower activity than predicted. Of significance in the former two lakes are (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 related more to those lakes with a small surface area to volume ratio than predicted by the morphology, that is, a lower level of biological activity. 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 activity being lower than predicted by the morphology.

Figure 4 is a plot of the logarithm of the surface area 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.

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 dilute lakes on the Precambrian Shield in that lakes with a low surface area to volume ratio

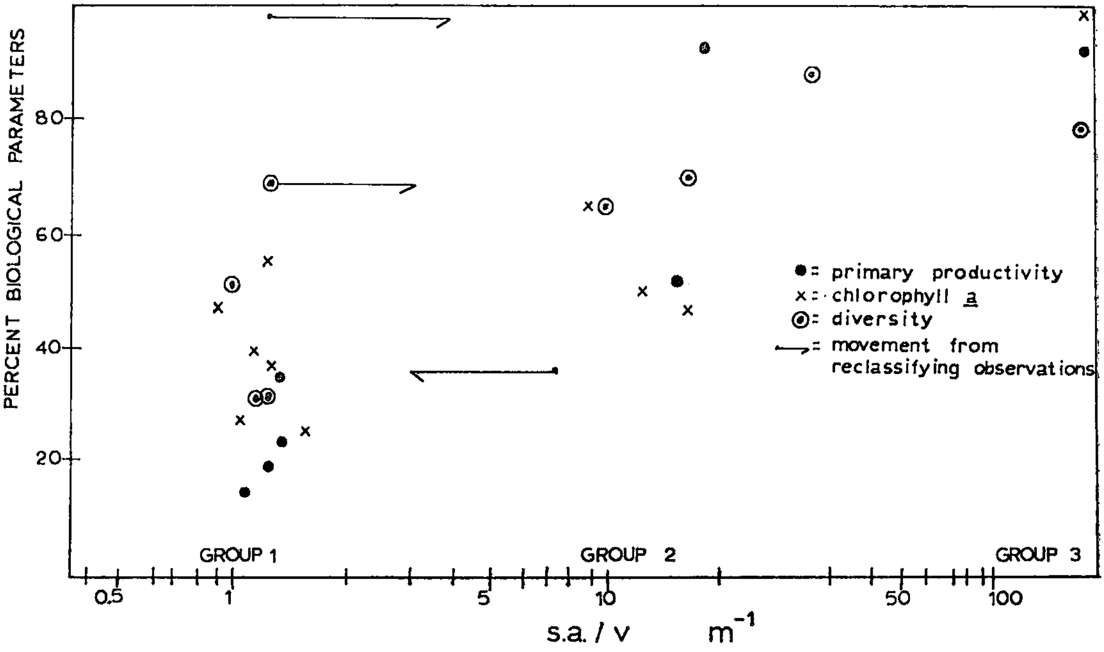

FIG. 4. Relationship of biological factors (diversity, chlorophyll *a* and primary productivity — scaled to per cent of ranges) compared to logarithm (10) of surface area/volume.

will show relatively low biological activity, lakes with intermediate surface area to volume ratios will show moderate biological activity, and lakes with high surface area to volume ratios 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 provide a significant source of calcium. However, the typical resistant rocks of the Shield provide only a minimal source for the dissolved-solids pool and subsequent biological activity.

Concentrations of sulfates derived from the metal-smelting industry near Sudbury (via the atmosphere) affect lakes with low TDS concentrations (poorly buffered) by depressing the pH. Aspects of the biosphere, including productivity and diversity, are depressed in lakes with low pH.

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