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FACTORS CONTROLLING THE EVOLUTION OF SALINITY, PRODUCTIVITY AND ECOLOGICAL STABILITY OF EUTROPHIC LAKES IN CENTRAL NORTH AMERICA (A SUMMARY)

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Management Perspective

This is an invited summary paper to be presented and published at the SIL Symposium on evolution of lakes to be held in Poznan, Poland in May 1990. It is based on Dr Barica's past work on prairie lakes (Freshwater Institute, Winnipeg) conducted prior to his appointment to NWRI, Burlington. It analyzes controlling factors in formation of ionic composition and phytoplankton biomass of the prairie lakes (surface deposits and soils, erosion, topography, lake morphometry, groundwater composition, etc.) and concludes that it is the semi-arid climate and groundwater flow which explain the extreme variability in lakes salinity and production. However, the ecological instability of the lakes (algal collapses and resulting anoxia) is triggered by meteorological factors. The winter anoxia (winterkill) is the result of continental climate and governed by lake morphometry.

Perspective de gestion

La présente étude sommaire fait suite à une invitation au colloque de l'AIL sur l'évolution des lacs. L'événement aura lieu à Poznan (Pologne) en mai 90; la communication sera présentée et publiée à cette occasion. Le contenu s'appuie sur les travaux effectués par M. Barica dans le passé et qui portaient sur les lacs de prairie (Institut des eaux douces, à Winnipeg); les travaux ont été effectués avant sa nomination à l'INRE de Burlington. L'auteur a analysé les facteurs qui déterminent la composition ionique et la biomasse phytoplanctonique dans les lacs de prairie (formations et sols superficiels, érosion, topographie, morphométrie des lacs, composition des eaux souterraines, etc.); il en vient à la conclusion que ce sont le climat semi-aride et l'écoulement souterrain qui expliquent le mieux la variabilité extrême de la salinité des lacs et leur production. L'instabilité écologique des lacs (prostration algale et anoxie concomitante) est déclenchée par des facteurs météorologiques. L'anoxie hivernale (destruction par le froid) est le résultat du climat continental et est commandée par la morphométrie des lacs.

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There are several million small lakes scattered over the semi-arid region of central Canada and mid-western U.S., comparable in size to the entire area of Central Europe. Their total dissolved solids (TDS) content varies from true freshwater lakes (100-300 mg/L TDS) to hypersaline lakes exeeding salinity of the ocean (Rawson and Moore, 1944). Most of them are naturally eutrophic, developing heavy algal blooms. Many of them are unable to sustain these blooms, which results in their collapses and subsequent oxygen depletion and fish mortalities (summerkill). This advanced trophic state is accelerated by shallowness, high solar energy input, high nutrient loading and regeneration, and extended freeze-up. All of these lakes are of glacial origin and are approximately the same age. Yet, their differences in TDS, primary and secondary productivity and fish yields cannot be explained by geology alone, as assumed in the past (Rode, 1949; Alekin, 1953).

In this contribution, the high variability in ionic composition, phytoplankton biomass, production and ecological stability of a group of over 100 small, shallow and moderately saline lakes, distributed over an area of about 20x40 km near Erickson, southwestern Manitoba, Canada (50°30'N- 1000°10'W, altitude 300-650 m in undulating glacial till plain; Sunde and Barica, 1975) is analyzed and factors likely to contribute to the evolution of water quality, productivity, and stability of these lakes into the present state analysed, and previous studies summarized. The lakes of the Erickson area were found to be representative for most of the prairie lakes except for the truly saline ones in southern Saskatchewan and Alberta (Hammer, 1965, 1986).

Salinity levels and phytoplankton biomass

Figure 1 presents spatial distributions of specific conductance (in 134 lakes) and chlorophyll a levels (in 71 lakes). Specific conductance varied significantly from 220-12, 700 umhos/cm and maximum summer chlorophyll a levels from 4-335 ug/L over the study area. Concentration ranges (in mg/L) were 0.8-1075 for Na; 5.9-108 for K; 9-1910 for Mg; 27-380 for Ca; and 1-448 for Cl, 8-9946 for SO_4, 79-743 for HCO_3, 0-333 for CO_3, and 216-13 950 for total ions. Most of the lakes belonged to intermediate and mixed SO_4-HCO_3, Mg-Ca and true SO_4 and Mg types.

Distribution of various chlorophyll a levels (summer maxima, profile averages) is even more irregular and patternless than that of salinity and does not show any sign of grouping or zonation. Highly eutrophic (mostly Aphanizomenon flos-aquae) lakes posing high summerkill risk (>100ug/l chlorophyll a; Barica, 1975b) are distributed evenly across the study area. Frequency distribution of individual chlorophyll a ranges shows that 36.6% of the lakes were in the high summerkill risk group, with 65.4% of them actually summerkilling (23.9% of total lakes). The full range of chlorophyll a concentrations was 4-335ug/l.

Potential factors contributing to the formation of salinity and primary productivity.

Surface deposits and soils. If the geographical distribution of salinity levels is compared with the map of surface deposits and soils (Fig. 6 in Barica, 1978b), no direct relationship can be seen. Most of the lakes are situated within the same system, i.e., end moraine with Erickson clay loam as predominant soil type. Except for exceptional patches of high salinity lakes, the distribution of lakes across the whole experimental area appears to be generally random and independent of major soil types and surface deposits.

Effect of topographic relief. Although it is generally assumed (Rozkowski, 1969) that lake salinity in hummocky terrain is invariably related to altitude, i.e., lower at topographic heights and higher at topographic lows, three North-South cross-sections through the study area (Fig. 9 in Barica 1978b) indicate that lake salinity varies considerably regardless of the general slope. Lakes located in the upper part of the study area are of the lowest salinity (<500 umhos/cm) and culminate in lake 100 (2723 umhos /cm). From then on, however, there is a decrease in salinity again, although the terrain continues to decline in slope. Lake salinity appears to vary considerably regardless of the general slope, which is gradually regressing, from North to South. The highly saline lakes are concentrated in the middle of the regressing profile. Low salinity lakes are located at both higher and lower elevations.

Effect of groundwater on lake water composition. The water budgets of the Erickson lakes are governed chiefly by groundwater seepage and evaporation. It is therefore natural to expect that the chemical composition of the lakes will reflect that of the groundwater in the upper water-bearing horizons. The salinity range of groundwater in the Erickson district (667-3896 umhos/cm) basically corresponds to the majority of lakes under observation. There was no increase in salinity with increasing depth of the well. The observed ranges in groundwater salinity agree with the adjacent lakes only in about 30% of all cases and the rest deviate from them at random; however they remain basically within the above mentioned overall range.

Effect of lake morphometry. A series of regressions were computed, considering lake area, maximum and mean depth, lake volume and drainage area to find out if lake morphometry plays a role in the variability of chemistry and trophic level of lakes of the study area. It was expected that small lakes would be more saline and more eutrophic than large ones, as in the case in larger areas of more homogenous character (Rawson, 1955). The results of correlations did not confirm this assumption for the Erickson area. There were small lakes with low TDS and no algal blooms, and large lakes containing more saline water and heavy Aphanizomenon blooms. Both large and small lakes experienced summerkills at the same time.

Effect of semi-arid climate. Climatic factors, including air temperature, wind velocity, precipitation and rate of surface runoff affect the relative water loss, which results in a gain in the total dissolved solids (Hammer, 1965). The Erickson area, as a part of the prairie region, has relatively high potential evapotranspiration (550 mm) with a mean moisture deficit of about 100 mm. Some effect of net water loss from lakes due to evaporation was observed on a seasonal scale in Erickson lakes (Barica, 1978).

Effect of groundwater flow. Lissey, (1971) developed models of depression-focused transient groundwater flow patterns for the morainic region of the Oak River basin in southwestern Manitoba. Figure 2 illustrates one of the more complicated patterns of groundwater flow that appears applicable for the Erickson area. Regional, intermediate and interrupted intermeadiate flow occurs in the direction of the general slope of the ground surface (from A to F). Local flow from a perched depression (D), however, may run in the opposite direction. The situation illustrated here is representative of flow patterns only when the regional water table is high. If water tables were lowered, there would likely be a cessation of interrupted flow in depressions B and E and local flow from depression D. With further lowering of the regional water table, depression C might become a recharge depression.

This complexity explains why the topographic relief did not show any effect on water salinity. One lake can be connected by groundwater flow with another relatively distant lake and not necessarily with the closest neighbouring lake as it would be normally assumed. Within the overall regional flow there are many local and intermediate flows which carry water and dissolved solids from one lake to another without any uniform pattern. This explains why one lake can differ substantially from another within a distance of a few hundred meters and why the lakes do not show any considerable grouping as it would be expected if only the regional flow existed there. Groundwater flow affects the variability in chlorophyll a values as well. Nutrient input, which governs chlorophyll a values varies considerably also. This variability is a result of different land uses and management practices evident in the study area (Fedoruk, 1971). It can be concluded that the elevated salinity of prairie lakes is produced primarily by semi-arid climatic conditions, and that the development of the lake water chemistry depends on local hydroghraphic and hydrologic conditions. Therefore, the prairie lakes cannot be considered on a large regional scale. Each one is an individual entity, governed by the semi-arid climate and by numerous natural or cultural factors taking place in their basins, particularly rate of soil erosion.

Ecological stability

Due to high natural nutrient input from the drainage area (via ground water and soil erosion) calculated to range from 3.3 to 25 $g/m^2/yr$ with very low N:P ratios (3-5:1), high solar energy input and shallowness (on average 3-6m deep), almost all prairie lakes are eutrophic to hypereutrophic, with blue-green algae dominating the lakes in the summer. This extreme input of nutrients, limited flushing and unsustainable primary productivity leads to frequent and seasonal perturbations of ecological stability resulting in severe dissolved oxygen depletion and consequent massive die-offs of fish populations (Barica, 1980).

There are three major kinds of seasonal ecological instabilities occurring in prairie lakes.

Collapses of algal blooms and summerkill phenomenon. This disturbance takes place when the whole mass of the bloom (usually that of Aphanizomenon flos-aque) suddenly dies and undergoes a rapid bacterial decomposition, resulting in complete oxygen depletion, generation of toxic unionized ammonia and eventually a massive fish kill. This hapens when chlorphyll a concentrations exceed levels of 100 ug/L. The mechanism of this process was described in detail elsewhere, and predictive models developed (Barica, 1975a,b; Barica, 1984; Ayles and Barica, 1977). From the analysis of weather data, it was observed that the algal collapse of various degrees of severity always occurred at the times of both water and air temperature drop or closely following it (Barica, 1978a; Fig. 3). The weather, together with acute nutrient deficiency in the algal cells, appears to trigger the algal bloom collapse and is the major factor controlling this instability.

Winterkill phenomenon. The shallow prairie lakes are regularly subjected to six-month long periods of ice and snow cover, when excessive ice and snow cover prevents oxygen input from primary production and the atmosphere. Bacterial decomposition processes take over and consume available oxygen, which declines to critical levels, resulting again in fish mortalities (winterkill). This process was found to be controlled by the duration of the freeze-up, thickness of snow cover, initial dissolved oxygen levels prior to the freeze-up, and the mean lake depth, respectively volume to sediment surface area ratio (Mathias and Barica, 1980). Models for prediction of this phenomenon were developed and verified (Barica and Mathias, 1979; Barica, 1984). It can be concluded that unlike salinity and productivity, collapses of algal blooms and overall ecological stability controlled primarily by meteorological factors, while the winter anoxia is a result of the continental climate and topography. The critical border line for algal bloom stability was estimated to be around the concentration of 100 ug/L chlorophyll a.

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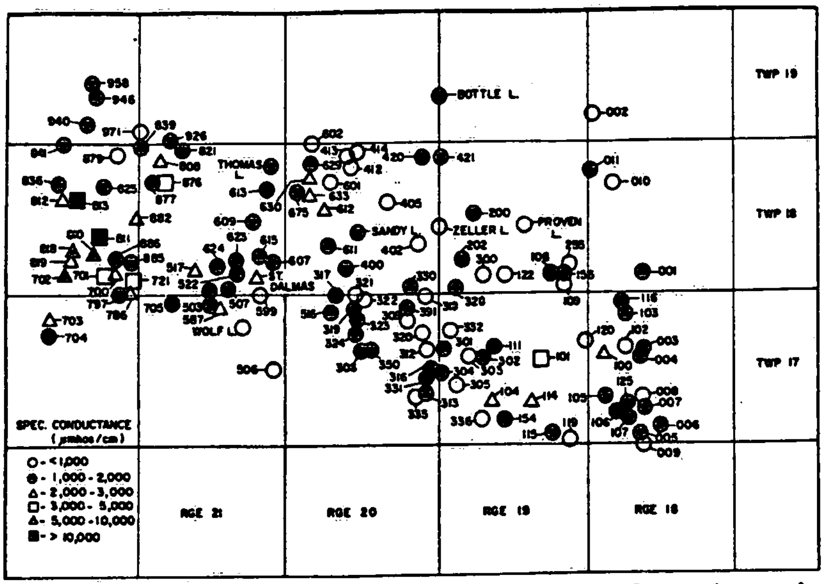


Fig. 7. Areal distribution of different salinity ranges in the study area (as specific conductance). Summer averaged values.

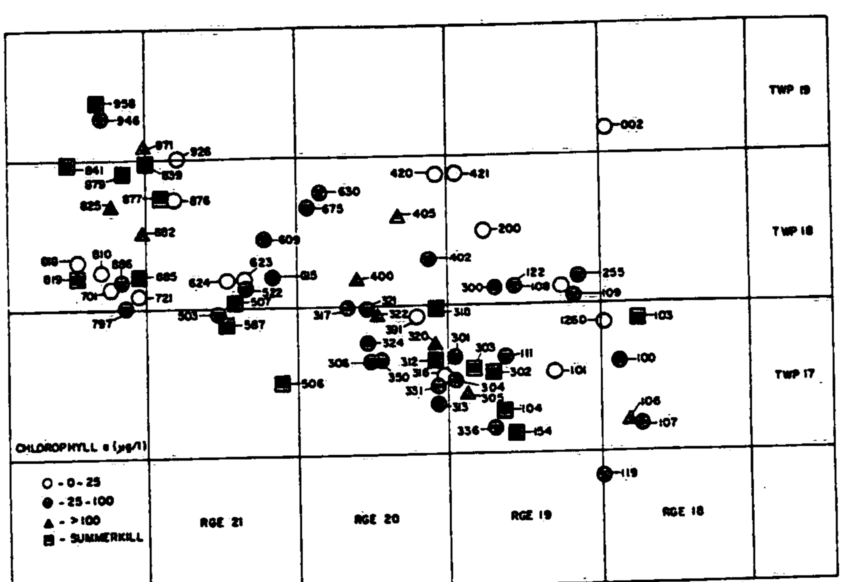
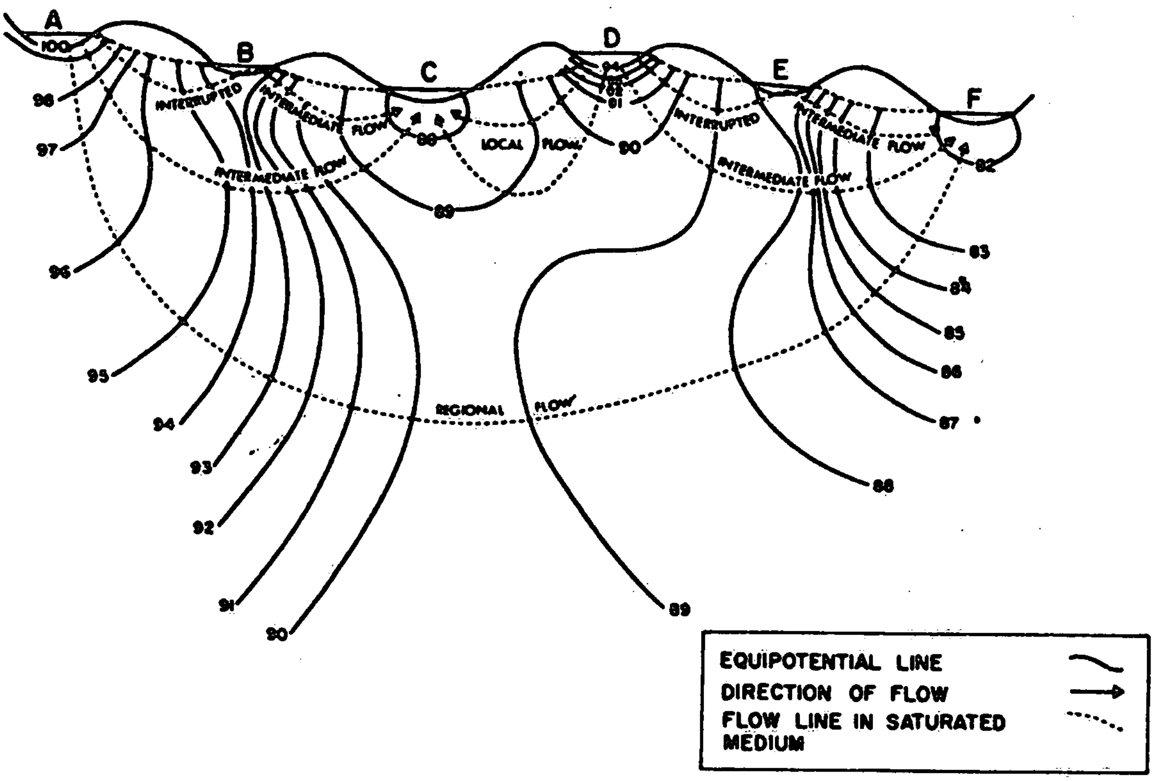


Fig. 8. Areal distribution of different ranges of phytoplankton biomass (as chlorophyll a) in the study area. Maximum summer values (vertical profile averages).

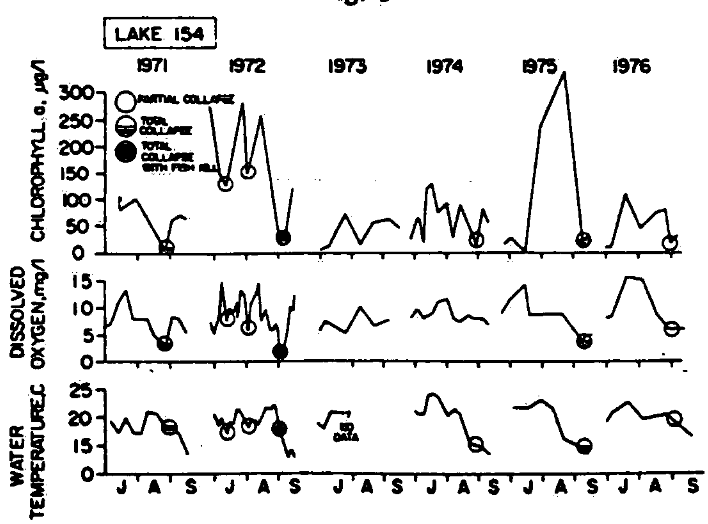
Fig. 1



Groundwater flow patterns in a pothole region. After LISSEY (1971).

Fig. 2

Fig. 3



Lake 154 (10.1 ha, 4.9 m maximum depth, 2.5 m mean depth, TDS 1150 mg/l). Summer chlorophyll *a*, dissolved oxygen and water temperature. Averaged data for 0—2 m. *Aphanizomenon* bloom in 1971, 1972 and 1975; other years a mixed bloom (*Aphanizomenon, Microcystis, Anabaena*).

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