

Chemical composition of saline and subsaline lakes of the northern Great Plains, western Canada¹

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Abstract

The northern Great Plains of Canada stretch from the Precambrian Shield near Winnipeg, Manitoba, westward for ~1,700 km to the Rocky Mountains foothills. This vast region of flat to gently rolling terrain contains a very large number of salt lakes. Major ion chemical data on ~500 of them are available. Although the average brine (salinity, 37 ppt) is a Na⁺-SO₄²⁻ type of water, the lakes exhibit a wide range of salinities and ionic compositions. This diversity is confirmed by Q-mode cluster analysis; it identified thirteen major water chemistry types. Most ions display distinct trends, both spatially and with increasing salinity. All dissolved components increase with increasing salinity, but at different rates. The relative proportions of Ca²⁺ and HCO₃⁻+CO₃²⁻ ions show a strong decrease with increasing brine salinity, whereas SO₄²⁻ ions increase with increasing salinity. The ionic proportions of Na⁺, Mg²⁺, K⁺ and Cl⁻ exhibit no significant relationship with salinity. R-mode factor analysis of the lake water chemistry, combined with selected environmental parameters, identifies groundwater composition, climate, and the elevation of the lake within the drainage system as most important in controlling brine chemistry and salinity on a regional basis. Variability in source of ions, reaction processes and products are undoubtedly key factors in helping to explain brine chemistry of an individual basin or variation from a local perspective, but these factors are generally poorly understood and not quantified on a regional basis.

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Introduction

'In this region, there are numerous ponds and small lakes in the hollows among the hills, most of them being more or less brackish or nauseous to the taste from the presence of sulphates of magnesia and soda and other salts. During the dry season of autumn, the water evaporates completely from many of these ponds leaving their beds covered by the dry white salts, which look like snow and are blown about in the wind. Around all the ponds, except those which become completely dry, there is a rank growth of reeds, sedges and grasses, the deep green colour of which forms a strong contrast to the dull grey appearance of the stunted and scanty grass of the hills, which indeed, in many places are almost bare.' J. S. Bell (1875).

The northern Great Plains of western Canada contain large numbers of saline and hypersaline lakes of great diversity in size, basin morphology, hydrology, hydrochemistry, and sedimentary and biological characteristics. As Bell (1875) noted in one of the first scientific reports on this region, in much of the area, ponded saline brines are the only natural surface waters. An understanding of the nature and variability of this lake water composition and salinity is essential to ensure optimum resource management and use in this water stressed region of North America.

Salinity has a significant impact on the emergent vegetation of the lake's littoral zone and thus on the value of the area as a waterfowl nesting and staging ground. In fact, these lakes collectively act as a major breeding ground for over 80 per cent of North America's ducks. In addition, future industrial and agricultural development in the Great Plains will likely lead to conflicts and potential environmental problems associated with the lakes in the region. For example, western Canada is presently the world's leading producer of natural Na_2SO_4 (sales contribute >\$50 million annually to the Canadian prairie economy). This valuable industrial mineral is extracted by solution and open pit mining of deposits in the more saline lakes of the region. If the demand for Na_2SO_4 continues to increase as it has in the last decade, more lakes will be leased and more mining operations initiated. Increased industrial development of this type will have a profound impact on the wetlands resource.

If future industrial and agricultural development is to take place with minimal damage to the natural environment, high priority must be given to the study and understanding of the salinity and chemistry of the lakes and factors that control their chemical variability. This paper aims to: (i) provide an overview of the chemical characteristics of salt lakes of the region, (ii) identify regional spatial trends in these chemical characteristics; and (iii) discuss interrelationships between brine composition and controlling factors.

Methods

Much of the data derives from published sources. For Saskatchewan lakes most information is from Rozkowska and Roskowski (1969), Rutherford (1970), Hammer (1978), and Last (1984a, 1989a); for Alberta lakes, mainly from Govett (1958) and Bierhuizen and Prepas (1985); and for Manitoba lakes, mainly from Thomas (1959), Driver (1965) and Barica (1978). Because of their proximity to the Canada-U.S.A. border, some lakes in North Dakota and Montana have also been included. These data are mainly from Grossman (1949) and Sahinen (1956). In addition to 370 published analyses, 121 original analyses are also included. Thus, analyses from 491 lakes are discussed. Of these, ~10 per cent are in Manitoba, 70 per cent in Saskatchewan and 20 per cent in Alberta (Fig. 1). For the purposes of spatial analysis, the positions of these lakes comprise a statistically uniform (i.e., non-clustered and non-random) sample database.

Nearly all analyses used standard gravimetric, atomic absorption and turbidimetric methods (APHA, 1981 or earlier versions). Analyses in which the sum of cations and anions was >5 per cent different were excluded. Most analyses relate to single samples collected on one occasion. However, some data are averages of numerous samples collected over months or even years. Although some published analyses have included data on trace and nutrient element concentrations and dissolved gases, only major ion concentrations were used. Because only a relatively small proportion of published data include pH, Eh and conductivity values, it was not possible to consider these important parameters in this analysis. Sample collection techniques, including time of year, location in lake and location in water column, were not consistent among investigators. Data from lakes modified by human action are not included. Thus, data from twelve basins known or suspected to have been strongly influenced by either mining activities or major water diversion schemes prior to analysis were eliminated. However, most of the northern Great Plains region is intensively agricultural and it is likely, therefore, that all lakes have been affected by humans.

Compilation of water analyses was statistically manipulated in a variety of ways. Mapping of the spatial variation in composition and ionic proportion used the computer program SURFER (Golden Software, Inc.). Raw concentration and proportion data were gridded using a kriging method. This gridded data base was smoothed before contouring using a cubic spline. Cluster and factor analyses of the standardized data base were done using the various subroutines of SAS (Ray, 1982).

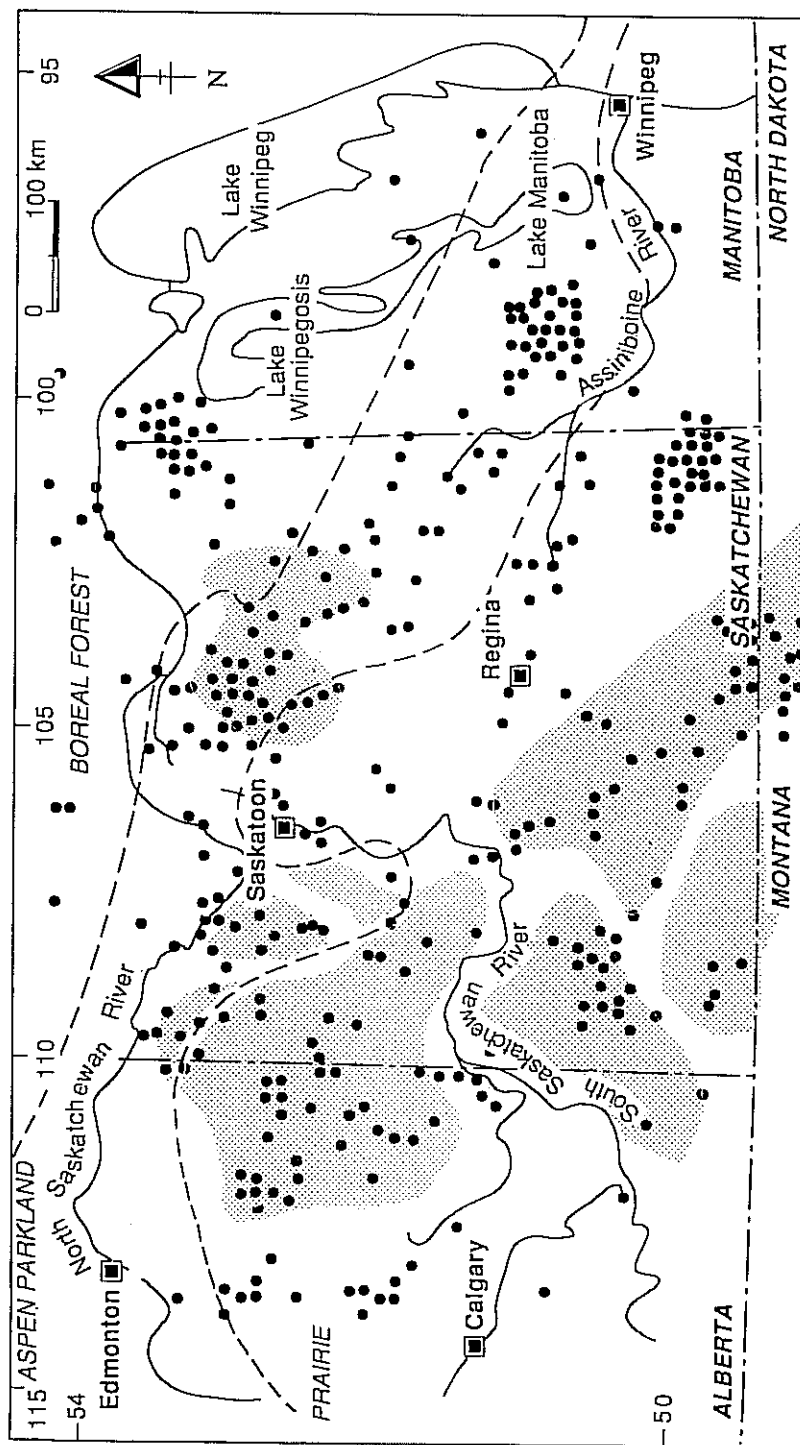


Fig. 1. Northern Great Plains of western Canada and northern United States. Areas of internal drainage stippled. Dots indicate locations of the 491 lakes for which data on water chemistry are available. Dot size is not related to lake basin size. Also shown are approximate boundaries of prairie, aspen parkland, and boreal forest vegetation zones.

The northern Great Plains: a regional setting

The northern Great Plains, of area $>350,000 \text{ km}^2$, is the agricultural heartland of Canada, and has most of the population of western Canada. It is characterized by flat to gently rolling topography and has a cold, semi-arid climate. Both east-west and north-south climatic gradients exist. The warmest and driest part of the region, so-called Palliser's Triangle, comprises most of south-eastern Alberta and south-western to south-central Saskatchewan. North, east, and west of this area, mean annual evaporation rates and temperatures decrease and precipitation increases. Pleistocene continental glaciation has resulted in a thick sequence of unconsolidated glacial, glaciofluvial and glaciolacustrine sediment mantling the generally flat-lying Phanerozoic sedimentary bedrock. Over much of the region, fine-grained, marine siliciclastic Cretaceous bedrock dominates. However, outcrop and subcrop belts of older Palaeozoic carbonate and Precambrian igneous and metamorphic bedrock are present in the east and north.

With regard to the development of salt lakes, the two most important physical features of the region are high evaporation to precipitation ratios, and large areas of endorheic drainage. Although the mean annual temperature of $\sim 3^\circ\text{C}$ implies relatively low evaporation rates, high winds, low humidity and elevated summer temperatures create annual evaporation: precipitation values of, generally, 3–10. These climatic features, combined with poorly integrated drainage (~ 40 per cent of southern Saskatchewan and eastern Alberta is topographically closed; Fig. 1), have resulted in the development of a large number of saline lakes of diverse morphologies and geochemical and sedimentological characteristics. In contrast to many other regions of the world where salt lakes are abundant, the northern Great Plains region is tectonically very stable, does not exhibit striking topographic relief, and there is no dramatic lithologic diversity of either the glacial deposits or the bedrock on a local or regional scale.

Groundwater normally plays an important role in the overall hydrology and hydrochemistry of saline lakes. For the Great Plains, many authors (e.g., Witkind, 1952; Rueffel, 1968; Freeze, 1969) have noted strong correlations between the occurrence of salt lakes and buried glacial and preglacial valleys and have surmised that the buried valleys supply water to the lakes. Although groundwater hydrodynamics and interaction with individual salt lake basins in the northern Great Plains are poorly studied and understood, regional subsurface water composition and spatial variation are, nonetheless, reasonably well known. Briefly, regional groundwater composition is of several main types. Most groundwater in unconsolidated surficial deposits is of low to moderate salinity ($<3 \text{ g L}^{-1}$) and dominated by Ca^{2+} , Mg^{2+} , and HCO_3^- . In areas of lowest precipitation

(western Saskatchewan and eastern Alberta), shallow drift groundwater is usually dominated by SO_4^{2-} rather than HCO_3^- . The shallow bedrock aquifers (Upper Cretaceous and younger rocks) are mainly $\text{Na}^+\text{--HCO}_3^-$ dominated in southern Alberta, $\text{Ca}^{2+}\text{--Mg}^{2+}\text{--Na}^+\text{--SO}_4^{2-}$ dominated in Saskatchewan, and $\text{Ca}^{2+}\text{--Mg}^{2+}\text{--Na}^+\text{--HCO}_3^-$, in western Manitoba. The deeper Paleozoic and Cenozoic bedrock contains much higher salinity water (up to 300 ppt) that is usually dominated by Na^+ and Cl^- .

A century of lacustrine hydrochemistry

The saline nature of surface waters and lacustrine deposits of the northern Great Plains was well known to aboriginal groups before European settlement in the mid-19th century. Although the first chemical analyses of salt lake waters from the region were published in the 1890s, it was not until nearly half a century later that the extent and degree of diversity of the salt lakes were recognized. For over three decades after the 1890s, the only scientific efforts and data came from economic geologists interested in exploitable reserves of initially nitrate and later sodium and magnesium salts in the lakes. Indeed, the results of a regional survey of these economic deposits undertaken by the Canadian government in the early 1920s (Cole, 1926) still ranks as one of the best and most extensive summaries of the salt lake hydrogeochemistry.

Although still not as good as in some other parts of North America, our knowledge of the chemistry of the surface waters in the Canadian Great Plains has progressed from these early geological and geochemical reconnaissance efforts. In one of the first systematic limnological surveys of the region, Rawson and Moore (1944) reported on the water chemistry of 53 lakes from southern Saskatchewan. Rutherford (1970) showed that Mg^{2+} , Na^+ and SO_4^{2-} ions are the most common ions in a large number of Saskatchewan lakes and recognized five main hydrochemical types. He also related the spatial variation of these to north-south climatic gradients and shallow groundwater composition in the province. More recently, Hammer (1978) reported on the water chemistry for 60 saline lakes in southern Saskatchewan and also stressed the importance of Mg^{2+} , Na^+ , and SO_4^{2-} . Much of this regional work has been summarized by Northcote and Larkin (1963) and Hammer (1986).

Other important contributions covering smaller geographic areas include: Govett (1958) and Bierhuizen and Prepas (1985) for central and eastern Alberta; Hartland-Rowe (1966) for south-eastern Alberta; Rozkowski (1965) for the Moose Mountain area of south-eastern Saskatchewan; Lieffers and Shay (1983), and Driver and Peden (1977) for central Saskatchewan; and Driver (1965) and Barica (1975) for western

Manitoba. Although not directly included in the following analyses, the water chemistry of lakes in the United States portion of the northern Great Plains is also of interest in this context. The regional syntheses of Winter (1977) and Gorham *et al.* (1983) are of particular interest.

Chemical character of the lake waters

The waters of lakes of the northern Great Plains show a considerable range in ionic composition and concentration. Salinity ranges from relatively low values (0.1 g L^{-1}) to values more than an order of magnitude greater than that in sea-water (Fig. 2). Whereas average lake water has a salinity of ~ 37 ppt (Table 1), about half of the lakes surveyed have salinities < 5 ppt.

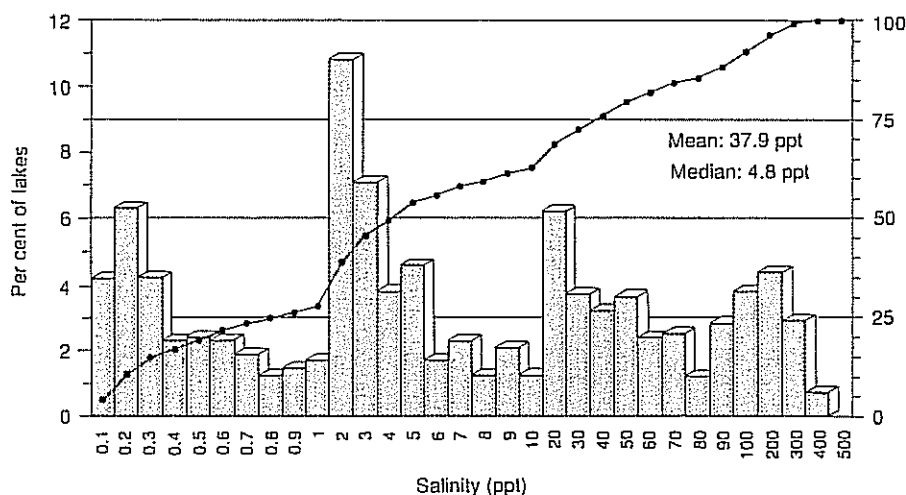


Fig. 2. Frequency distribution (bars, left axis) and cumulative per cent distribution (line, right axis) of salinities of the 491 lakes on a \log_{10} basis.

Although the lakes are dominated by only a few major ions, these exhibit a considerable range in concentrations and relative proportions. The frequency distributions of Mg^{2+} , $\text{Na}^{+} + \text{K}^{+}$, Cl^{-} and SO_4^{2-} concentrations are broad and in some cases approach multimodal distribution patterns (on a \log_{10} basis) as opposed to alkalinity and Ca^{2+} ions which show much narrower patterns (Figs 3 and 4).

Ionic ratios. Nearly every major hydrochemical type is represented (Fig. 5). SO_4^{2-} and $\text{HCO}_3^{-} + \text{CO}_3^{2-}$ clearly dominate anions (in > 95 per cent of all lakes), but cation ratios are much more diverse, with the abundance

Table 1. Mean chemical composition of 491 saline lakes of the northern Great Plains. Concentration units in mmol L⁻¹ except for Total Dissolved Solids (TDS), which are in parts per thousand. Values in brackets indicate the range of values followed by the standard deviation.

Parameter	Value
TDS	36.8 (0.1–419.6; 62)
Ca ²⁺	5.8 (0.0–1150.0; 53)
Mg ²⁺	68.6 (0.0–2814.1; 199)
Na ⁺	310.8 (0.0–4832.7; 712)
K ⁺	5.3 (0.0–644.5; 35)
HCO ₃ ⁻	15.3 (0.0–1010.0; 65)
CO ₃ ²⁻	11.5 (0.0–1008.0; 69)
Cl ⁻	49.1 (0.0–2961.6; 177)
SO ₄ ²⁻	173.1 (0.0–2667.0; 330)

of all three major types comprising approximately subequal proportions. Ion dominances in the average lake in the area are: Na⁺>Mg²⁺>Ca²⁺=K⁺ and SO₄²⁻>Cl⁻>HCO₃⁻>CO₃²⁻ (Table 1).

Trends and interrelationships among major ions. Most solutes increase in *concentration* with increasing total salinity (Figs 6 and 7). SO₄²⁻ and Na⁺ show the closest correlations with salinity, Ca²⁺ and CO₃²⁻, the widest. The *proportions* of some solutes also systematically change with salinity (Figs 8 and 9). SO₄²⁻ increases in relative ionic proportion from <30 per cent equivalents in dilute lakes to generally >90 per cent in lakes with salinities >10 ppt. Both Ca²⁺ and alkalinity proportions show an inverse relationship with salinity, decreasing from >70 per cent equivalents in dilute waters to <5 per cent in lakes with salinities >20 ppt. The proportions of Na⁺, Mg²⁺ and Cl⁻ show no systematic trends with salinity. Except in two lakes, K⁺ is always <20 per cent of total cations and exhibits no specific change in proportion with increasing salinity.

Spatial variation. The widespread distribution of lakes for which chemical data exist enables changes in surface brine composition to be examined on a spatial basis at a regional scale not usually possible elsewhere. Previously, Last and Schweyen (1983) presented isohaline maps for Saskatchewan and discussed regional trends evident from a database comprising 79 saline lakes. Their data can now be extended: Figs 10–14 show the regional spatial variations in ionic concentration, proportion and salinity using the more extensive database (491 lakes). As expected, general trends in the *concentrations* of individual ions are similar to the spatial trend exhibited by salinity (cf. Figs 10, 11 and 14).

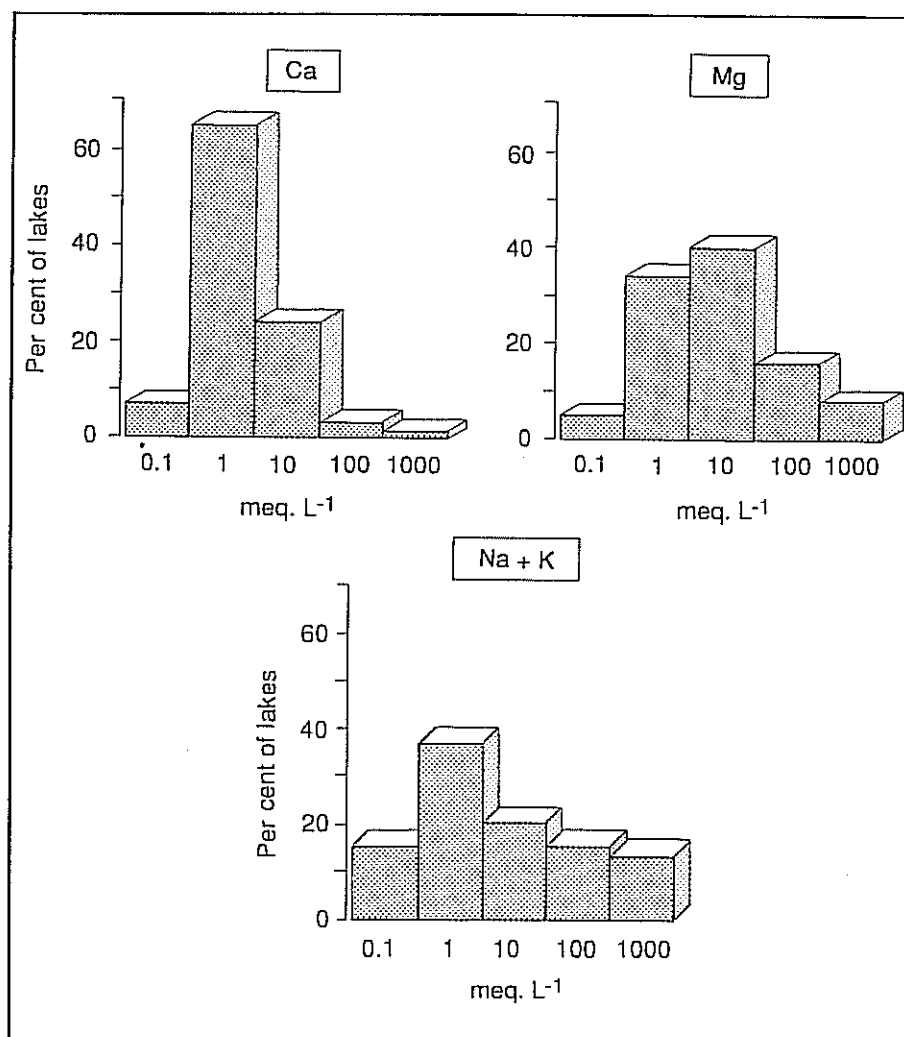


Fig. 3. Frequency distribution of major cations of the 491 lakes on a \log_{10} basis.

Lakes with the highest salinity and concentrations of Na^+ , Mg^{2+} , K^+ , Cl^- and SO_4^{2-} generally occur in east-central Alberta and west-central Saskatchewan, whereas lakes with relatively low total salinities and individual ion concentrations occur in eastern and northern parts of the region. Similarly, lakes with relatively high *proportions* of Na^+ and SO_4^{2-} occur in west-central Saskatchewan and east-central Alberta, whereas Ca^{2+} - and CO_3^{2-} -rich brines dominate in the north and east. In addition, Figs 12 and 13 also indicate that Cl^- and Mg^{2+} -rich lakes occur in western and central Manitoba.

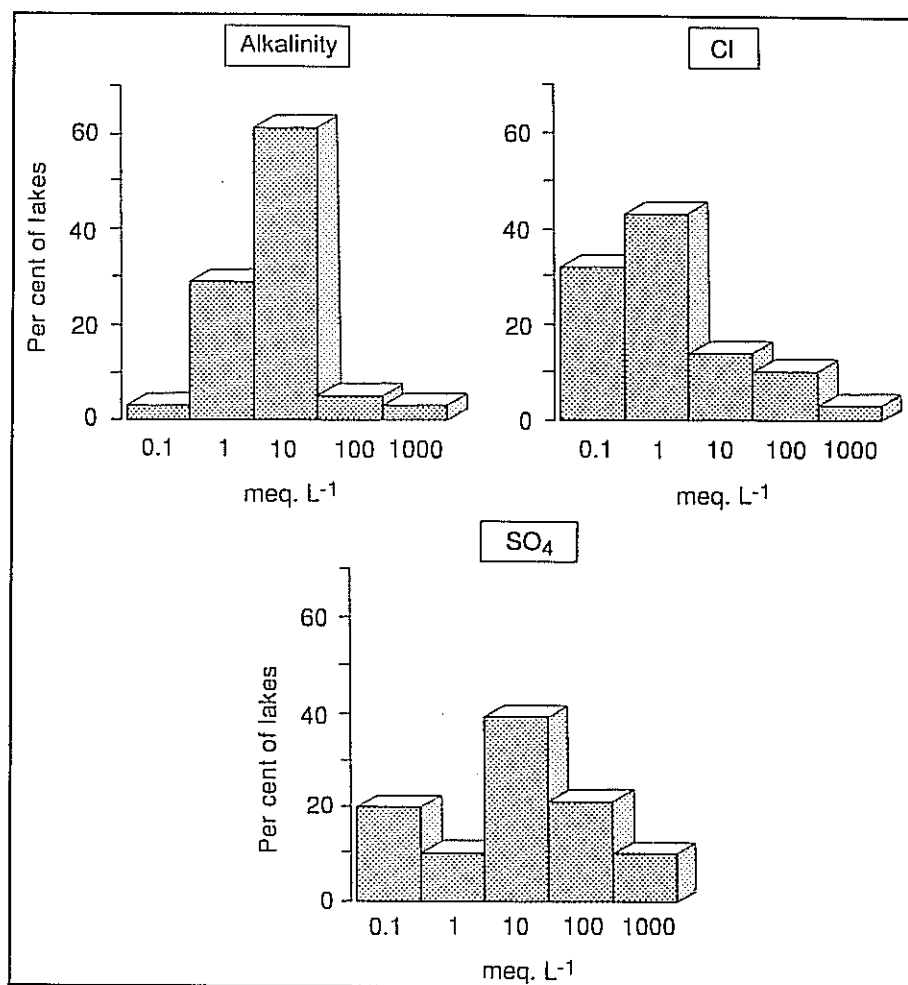


Fig. 4. Frequency distribution of major anions of the 491 lakes on a log₁₀ basis.

Statistical analyses

Various statistical techniques have been successfully used in other hydrochemical studies to help identify groups of lakes, classify lake basins and variables, or assist in deciphering the relative importance of environmental factors in controlling the chemical composition of water (e.g. Reeder *et al.*, 1972; Dean and Gorham, 1976; Winter, 1977). The data for salt lakes of the northern Great Plains were subjected to both cluster analysis and factor analysis. Jöreskog *et al.* (1976), Howarth and Singling-Larsen (1983), Drever (1988) and Rock (1988) provide pertinent background information and discuss the application of factor and cluster analyses to geochemical and hydrochemical studies.

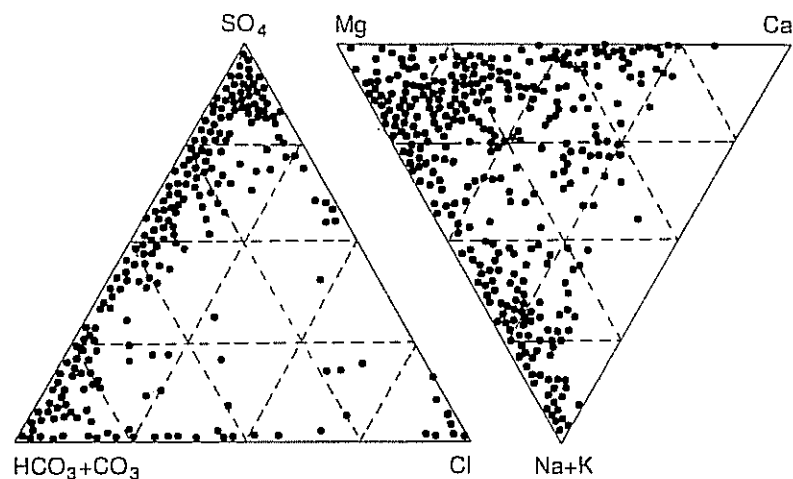


Fig. 5. Trilinear diagrams (per cent equivalents) of ionic composition of lakes in the northern Great Plains. Each dot, one lake.

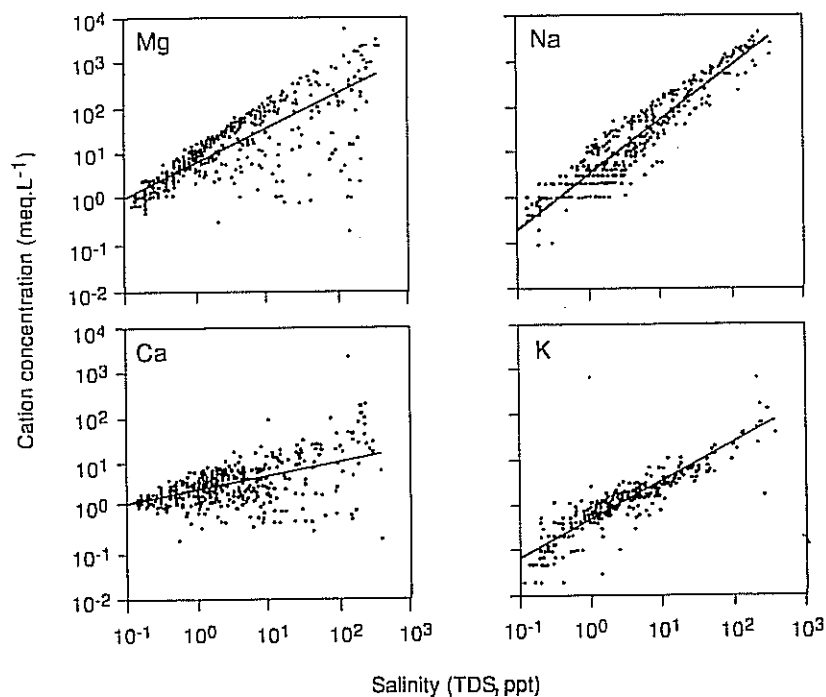


Fig. 6. Scatter diagrams showing variation in concentration (meq L^{-1}) of major cations with increasing salinity. Each dot, one lake. Best-fit regression line calculated from all non-zero data. Linear correlation coefficients (r) for regression lines are: Ca^{2+} : 0.66; Mg^{2+} : 0.85; Na^{+} : 0.98; K^{+} : 0.95. All r values are statistically significant at 0.99 confidence level.

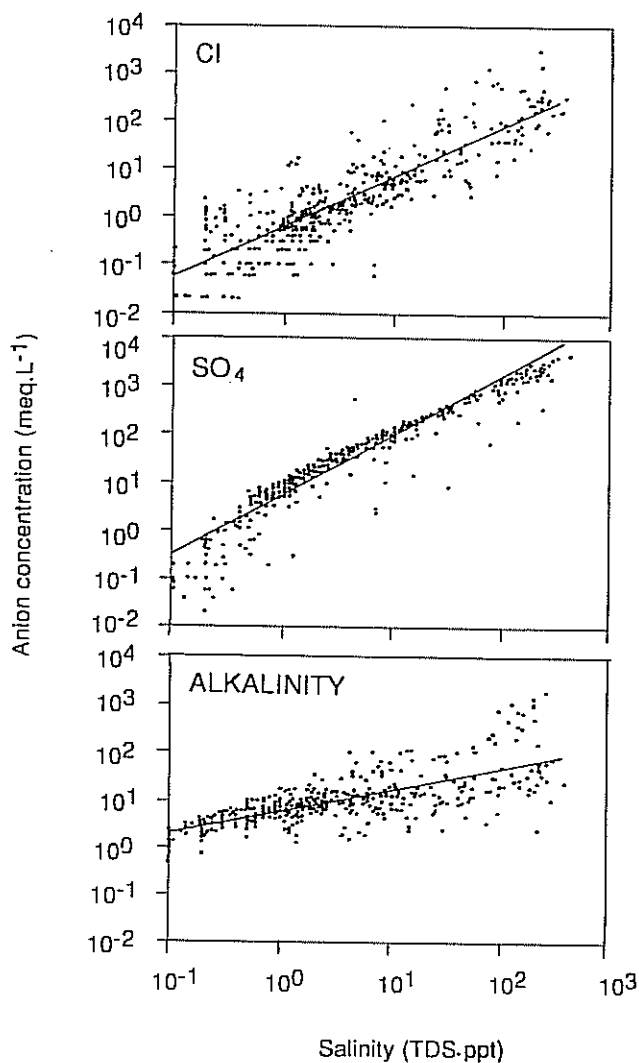


Fig. 7. Scatter diagrams showing variation in concentrations (in meq L^{-1}) of major anions with increasing salinity. Each dot, one lake. Best-fit regression line calculated from all non-zero data. Linear correlation coefficients (r) for regression lines are: Cl^- : 0.90; SO_4^{2-} : 0.96; alkalinity: 0.78. All r values are statistically significant at 0.99 confidence level.

Simple correlation analysis. One straightforward way to investigate the association among chemical variables is by correlation analysis. Simple linear correlation coefficients of the \log_{10} ion concentration and proportion data were calculated for all possible variable pairs. As indicated in Figs 6 and 7, the concentrations of all ions show a significant positive

correlation with salinity. Not surprisingly, then, the positive covariations in concentrations among the major cations (Ca^{2+} – Mg^{2+} – Na^+) and the major anions (SO_4^{2-} – HCO_3^- – Cl^-) are also well established (Fig. 15). In addition, concentrations of Na^+ and Mg^{2+} both vary positively with Cl^- . Importantly, the concentrations of Na^+ and SO_4^{2-} do not show statistically significant linear correlation.

Figure 15 also shows that only the proportions of Ca^{2+} and HCO_3^- exhibit significant positive covariation, whereas the ionic percentages of Mg^{2+} and K^+ vary inversely with that of Na^+ . Similarly, as the percentage of SO_4^{2-} increases, the proportions of both HCO_3^- and Ca^{2+} decrease.

Cluster analysis. A Q-mode analysis was undertaken to identify quantitatively groupings within the 491 lakes on the basis of their composition and salinity. The raw data on major ion concentration and salinity were standardized (mean = 0, standard deviation = 1) and then clustered using both average linkage and Ward's method (Ray, 1982). The

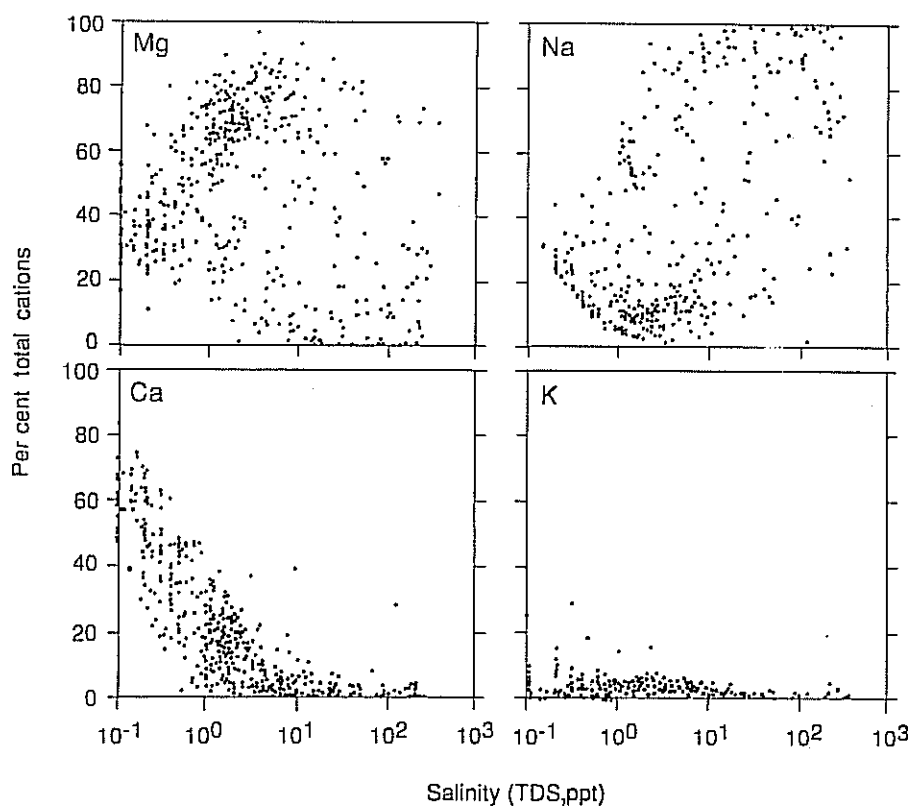


Fig. 8. Scatter diagrams showing variation in per cent equivalents of cations with increasing salinity. Each dot, one lake.

two techniques gave similar groupings. The lakes can be divided into two major clusters: a group of high salinity lakes (salinity >20 ppt), and one characterized by lower salinities. Although a useful summary, this two-fold subdivision of lakes is much too broad to be meaningful. Each major cluster was further divided into smaller groups as related to the lakes' major ion composition. All of these subgroupings were identified using distance coefficients of greater than 1.5.

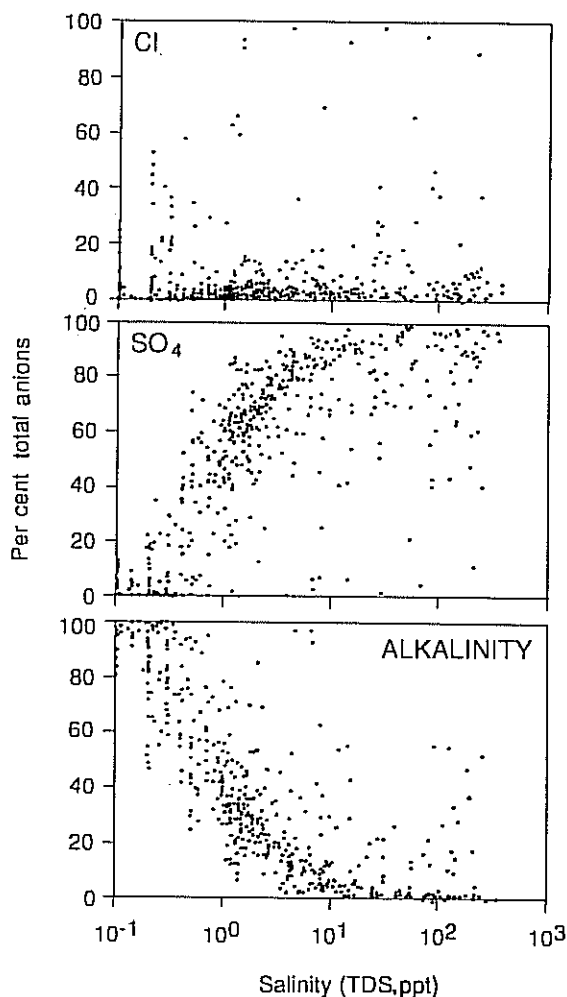


Fig. 9. Scatter diagrams showing variation in per cent equivalents of anions with increasing salinity. Each dot, one lake.

As Fig. 16 shows, seven subclusters of lakes were identified within the high-salinity group. Cluster IA includes lakes dominated by SO_4^{2-} - Cl^- and Na^+ , with minor amounts of Mg^{2+} and $\text{HCO}_3^- + \text{CO}_3^{2-}$. Lakes in Clusters IB and IF have similar cation ratios but different anion contents:

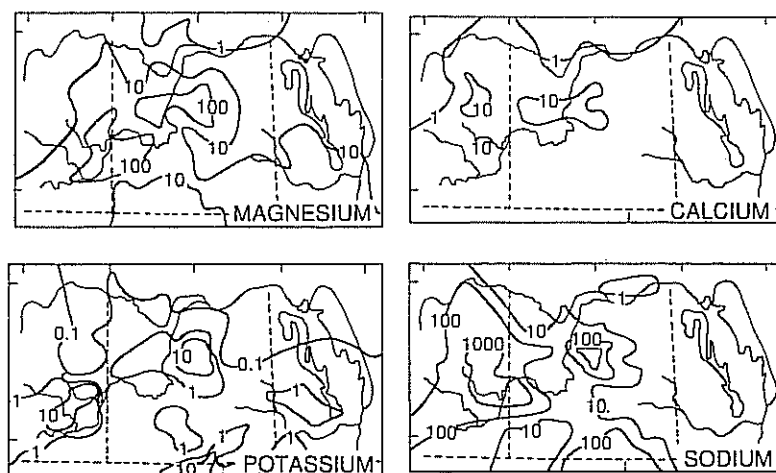


Fig. 10. Contour maps showing regional variation in cation concentration (mmol L^{-1}) in salt lakes of the northern Great Plains. Note logarithmic contour interval. Control points and geographic entities as in Fig. 1.

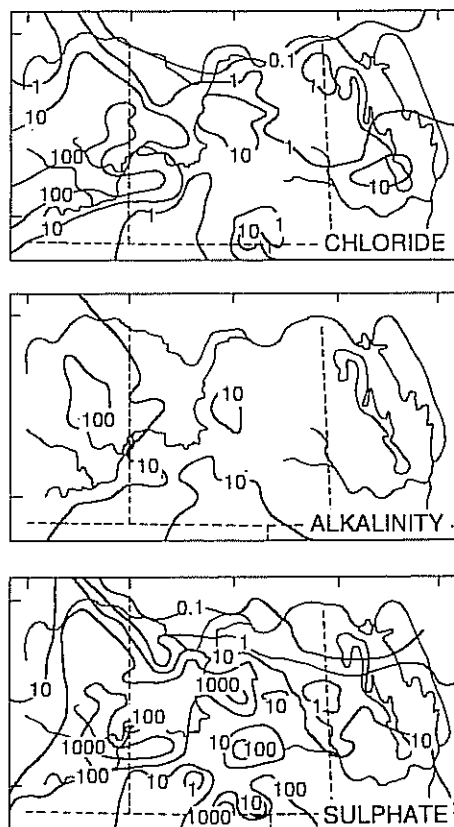


Fig. 11. Contour maps showing regional variation in anion concentration (mmol L^{-1}) in salt lakes of the northern Great Plains. For further explanation, refer Fig. 10.

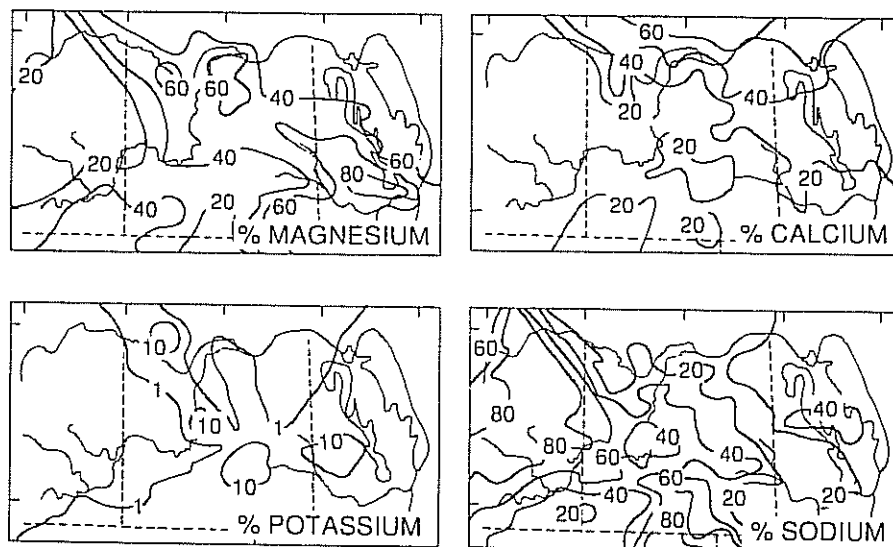


Fig. 12. Contour maps showing regional variation in cation proportions (per cent equivalents) in salt lakes of the northern Great Plains. The contour interval is 20 per cent except for K^+ which has a logarithmic contour interval. Control points and geographic entities as in Fig. 1.

IB lakes have subequal proportions of SO_4^{2-} , Cl^- and $HCO_3^-+CO_3^{2-}$; IF lakes have mainly Cl^- with minor amounts of $HCO_3^-+CO_3^{2-}$. The lake waters of Clusters IC, ID and IG are all dominated by Na^+-Mg^{2+} and $SO_4^{2-}-Cl^-$. Cluster ID lakes also have minor amounts of Ca^{2+} and $HCO_3^-+CO_3^{2-}$, whereas Cluster IG lakes also contain K^+ . Finally, the lakes of Cluster IE have $SO_4^{2-}-Cl^-$ as the dominant anions and $Mg^{2+}-Na^+$ as the dominant cations, with minor proportions of both K^+ and Ca^{2+} .

The lakes of the six subclusters recognized within the lower salinity group contain a somewhat more diverse assemblage of ionic ratios. Cluster IIA lakes are the only ones within each major cluster group to be dominated by $Ca^{2+}-Mg^{2+}$ and $HCO_3^-+CO_3^{2-}$ ions. The cations of Clusters IIB and IIF lakes both comprise subequal proportions of Na^+ , Mg^{2+} , and Ca^{2+} , whereas IIB waters are dominated by Cl^- and IIF by $HCO_3^-+CO_3^{2-}$ ions. The lakes in the final three clusters (IIC, IID, and IIE) are all dominated by $SO_4^{2-}-HCO_3^-+CO_3^{2-}$ and Mg^{2+} but have somewhat different proportions of additional cations (Fig. 16).

Factor analysis. To identify and evaluate objectively the interrelationships among the large amount of lake hydrochemical data and various environmental factors of possible importance in controlling lake composition, an R-mode factor analysis was undertaken. As used by others (e.g. Hitchon *et al.*, 1971; Reeder *et al.*, 1972), two R-mode factor analyses

were conducted. The first was undertaken to examine the complex interrelationships within the data on ion concentration and salinity; the second sought to determine relationship between the factors extracted from the first analysis and selected environmental data. The factor scores from the first analysis were combined with data from thirteen environmental parameters in this second analysis. In both cases, the raw variable data was transformed by a \log_{10} transformation and then standardized (mean = 0, standard deviation = 1). Varimax rotation was used to derive an optimum set of factors. Factors with eigenvalues less than 1.0 were not considered.

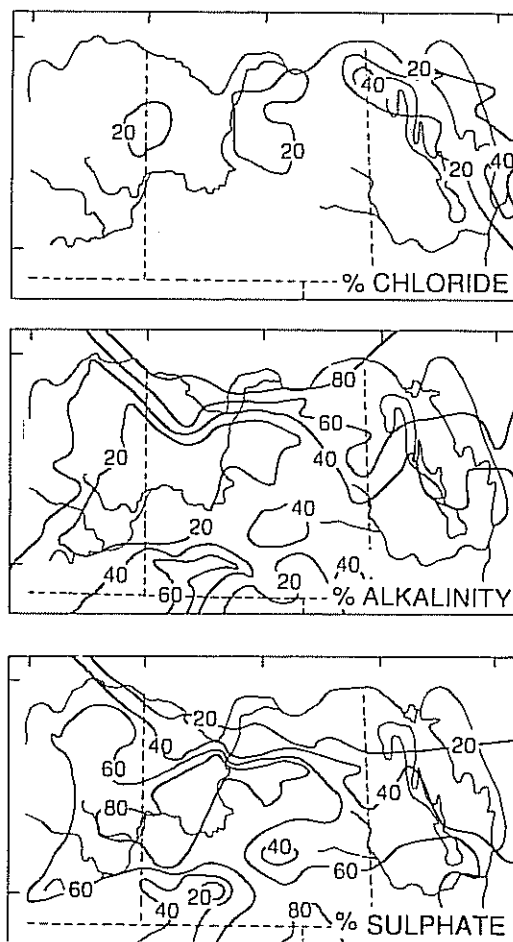


Fig. 13. Contour maps showing regional variation in anion proportions (per cent equivalents) in salt lakes of the northern Great Plains. Contour intervals are 20 per cent. Control points and geographic entities as in Fig. 1.

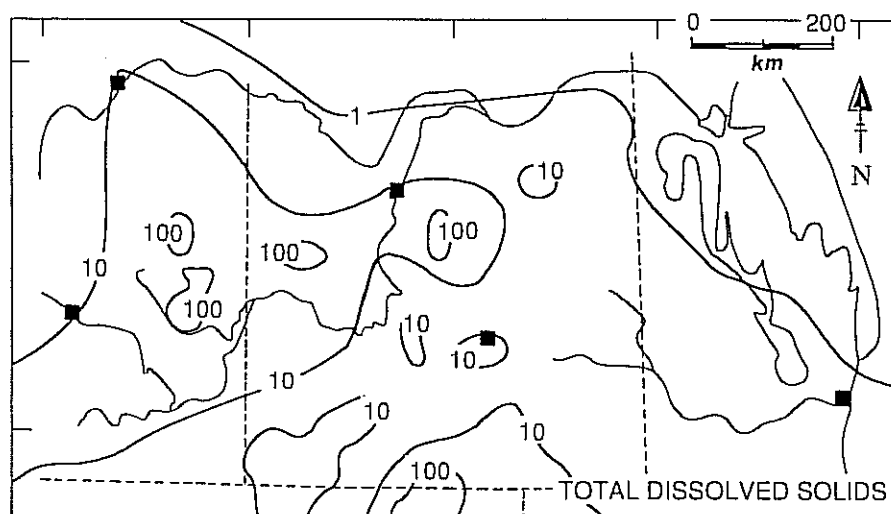


Fig. 14. Contour map showing regional variation in salinity (ppt TDS) in lakes of the northern Great Plains. Contour intervals are logarithmic. Control points and geographic entities as in Fig. 1.

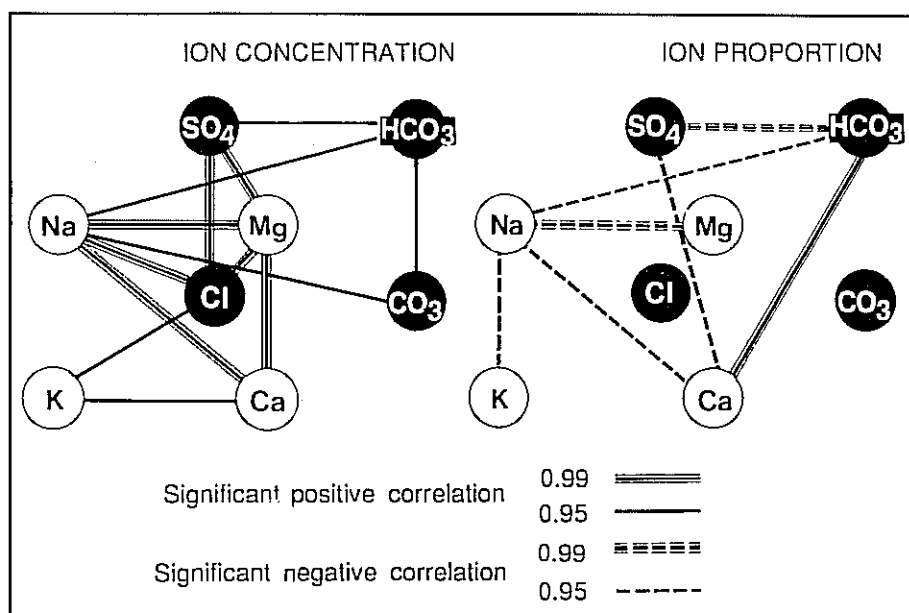


Fig. 15. Diagrams showing statistically significant linear correlations between ion pairs for concentration data (\log_{10} mmol L^{-1}) and proportion data (meq per cent).

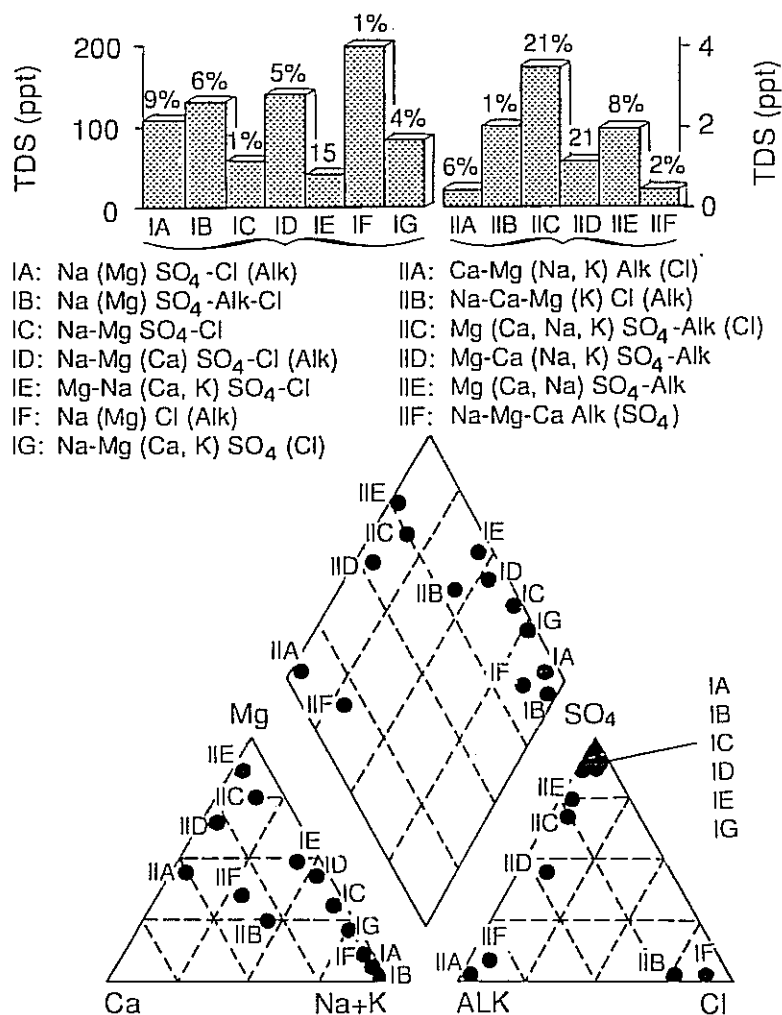


Fig. 16. Results of Q-mode cluster analysis. The upper figure shows the subdivision into two major clusters based on salinity and the description of the subclusters under each major salinity group. Percentage figures on the histograms are the relative number of lakes in each subcluster. The lower figure shows the ion means of each subcluster (meq per cent) plotted on trilinear diagrams.

The goal of R-mode factor analysis is statistically to explain variation in a large number of variables by identifying a small number of 'factors' which represent empirical combinations of the original variables. The choice of variables to include in the analysis is highly subjective. Clearly, it is not possible to include quantitative information on all possible environmental factors that may be relevant to the chemical composition of

the lakes. Nonetheless, as emphasized by Joreskog *et al.* (1976), the analysis can only extract factors that are functions of the original parameters. Thus, if an important parameter is not included in the data set, its influence cannot be evaluated by the statistical analysis.

The choice of environmental parameters included in this factor analysis was dictated partly by results from previous investigations and partly by the availability of quantitative, site-specific data for the parameters. In general terms, the composition of surface waters is controlled by the interaction of a broad suite of factors including climate, hydrology, geology and rock type, drainage basin relief, morphology and vegetation, lake basin morphology, length of time the water has had to react with the soils and bedrock of the basin, and chemical and biological processes within the water column itself (Gibbs, 1967; Eriksson, 1985; Drever, 1988). Unfortunately, few of these parameters are known in sufficient quantitative detail for all or even most of the lakes referred to in this report. For example, while precipitation, evaporation and even till and bedrock lithology are generally well known on a regional basis, such factors as basin hydrology and groundwater hydrodynamics are unknown for nearly all lakes in the region.

Thirteen environmental parameters were measured for each lake used in this study. Climate is represented by the single parameter of mean annual precipitation to evaporation ratio interpolated mainly from maps in CNC/IHD (1978) and McKay and Stichling (1961). The morphological information available for each basin (from topographic maps) include: (i) ratio of drainage basin area to lake area, and (ii) relative position of the lake within the major watershed (calculated according to Winter, 1977). Geological parameters measured consist of: (i) relative proportion of each major bedrock lithology in the immediate drainage basin (i.e., carbonate versus siliciclastic versus igneous plus metamorphic rock), and (ii) amount of 'soluble' material (i.e. carbonate and sulphate minerals) in the glacial drift. This geological information was obtained from a variety of published and unpublished maps, reports and theses. The latter variable, the per cent of soluble components in the drift, exhibited low communality in the factor analysis, indicating that a large part of its variance was not accounted for by the factors extracted. Finally, the parameters used to evaluate groundwater composition were the milliequivalent percentages of six major ions (Ca^{2+} , Mg^{2+} , Na^+ , SO_4^{2-} , Cl^- , alkalinity) in the shallowest subsurface waters. Most of this information was estimated from regional maps and cross-sections, and compilation reports (e.g. Brown, 1967; Freeze, 1969; Meneley and Whitaker, 1970; Whitaker, 1974).

The R-mode varimax factor loadings of the chemical data from the lakes (analysis 1) and the combined water composition-environmental

parameters (analysis 2) are shown in Fig. 17. Three factors account for approximately 90 per cent of the variance in the hydrochemical data, with nearly 50 per cent of the variance explained by one factor. Factor 1 has high positive loadings on Na^+ , total salinity and $\text{HCO}_3^- + \text{CO}_3^{2-}$. Factor 2, accounting for about 20 per cent of total variance, is essentially a $\text{K}^+ - \text{Cl}^-$ factor, with moderate loading for salinity. Factor 3, also explaining about 20 per cent of the data variance, shows high positive loading on Ca^{2+} , Mg^{2+} and SO_4^{2-} , and intermediate negative loading on $\text{HCO}_3^- - \text{CO}_3^{2-}$. Virtually all of the variance of the alkaline earth metals and about half of the variance of SO_4^{2-} in the lake waters is accounted for by this factor. The appearance of TDS with significant loading in all three factors suggests complex salinity control, although it is dominant only in factor 1. Similarly, complex chemical controls are suggested by the presence of both the SO_4^{2-} and CO_3^{2-} ion variables in two of the factors.

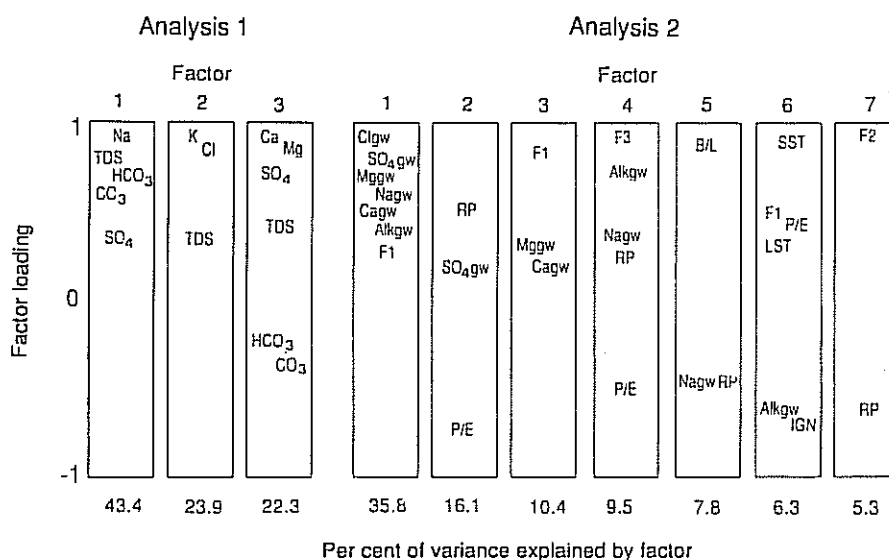


Fig. 17. Diagrammatic representation of factors from R-mode varimax analysis of chemical and environmental data from 491 salt lakes in the northern Great Plains. Each rectangle is a single factor with the variables placed according to their loading on that factor. Variables with loadings between 0.25 and -0.25 are not shown. Analysis 1 factored the lake water chemistry and salinity data only; analysis 2 combined the factor scores from analysis 1 with environmental variables. Abbreviations: TDS, total dissolved solids; P/E, mean annual precipitation to evaporation ratio; B/L, ratio of drainage basin area to lake area; RP, relative elevation of lake within the watershed; SST, per cent of siliciclastic bedrock in drainage basin; LST, per cent of carbonate bedrock in drainage basin; IGN, per cent of igneous + metamorphic bedrock in drainage basin; gw refers to ionic composition of groundwater. One environmental variable included in analysis 2, per cent of soluble material in the glacial drift, does not exhibit high loading on any of the seven factors extracted.

The second R-mode analysis extracted seven significant factors accounting for just over 90 per cent of the sample variance. Over one third of the total variance is explained by essentially a groundwater factor which combines the groundwater composition variables with the lake water Na^+ -salinity-alkalinity variables of factor 1 from the first analysis. This Na^+ -salinity-alkalinity factor is also prominent in factor 3 of the second analysis, again in combination with Ca^{2+} and Mg^{2+} of the groundwater. Together, these two factors indicate that nearly 50 per cent of the variance is accounted for by groundwater composition. Factor 2 of the second analysis accounts for 16 per cent of the variance and exhibits high negative loading on the climate variable (precipitation/evaporation) and intermediate positive loadings on the groundwater SO_4^{2-} content and the relative position of the lake in the watershed. Factor 4 combines the lake water Ca^{2+} - Mg^{2+} - SO_4^{2-} variables of the first analysis (i.e. factor 3) with high positive loading on groundwater alkalinity and inverse loading on the precipitation-evaporation ratio. Interestingly, neither of the alkaline earth metals or SO_4^{2-} variables from the groundwater appear in this factor, suggesting that Ca^{2+} , Mg^{2+} and SO_4^{2-} concentrations in the lakes are controlled by somewhat more complex or different processes than simple groundwater influx-evaporative concentration. Factor 5 is essentially unique, with a high positive score on the variable relating drainage basin area to lake area. Factor 6 is best described as a bedrock factor, with high positive loading on the siliciclastic bedrock variable, intermediate positive loading on carbonate bedrock as well as the lake water Na^+ -salinity-alkalinity variable from analysis 1, and high negative loading on the igneous rock type variable. Finally, Factor 7, accounting for about 5 per cent of the total variance, emphasizes the inverse relationship of the K^+ - Cl^- variables of the lake water with the lake's relative position within the watershed.

In summary, this second R-mode factor analysis indicated that, *of the parameters evaluated*, the most important controls of lake brine composition on a regional basis in the northern Great Plains are the groundwater composition, precipitation to evaporation ratio, and elevation or position of the basin within the drainage system. Variables related to bedrock type, glacial drift composition and lake morphology appear to be statistically less important. These quantitative results are in accord with observations and conclusions from other regional studies. Winter (1977) similarly identified groundwater salinity and precipitation-evaporation balance as two of the most important factors in quantitatively classifying lakes in the mid-west region of the United States. In addition, however, his principal components statistical analysis also showed high component loadings on drainage basin area lake area, basin depth, and stream inflow/outflow parameters. Likewise, Gorham *et al.* (1983) identified climate as a major controlling factor for spatial variation in composition and salinity

of lakes in this region of northern United States. They also suggested that lake major ion composition was controlled by drift mineralogy; this factor does not appear to be as important in the northern Great Plains. Sloan (1972) emphasized that the relative topographic setting of the lake within the hydrologic basin is most important in dictating water salinity and chemistry in a complex of small, ephemeral lakes in central North Dakota. He showed that dissolution/oxidation products from reactions taking place in the near-surface environment tended to accumulate in the lower altitude lakes of a hydrologic basin, thereby increasing the salinity and, in his study, $\text{Na}^+\text{--SO}_4^{2-}$ concentrations.

The environmental parameters included in this statistical examination do not represent, of course, a comprehensive coverage of all possible controlling factors. For example, authigenic and endogenic mineral precipitation within the salt lake basin clearly exerts a major control on water chemistry of lakes (e.g. Jones and van Denburgh, 1966; Eugster and Jones, 1979; Arakel *et al.*, 1990; Renaut, 1990). However, the lack of data for this important parameter for most of the salt lakes of the region precludes its use in this initial statistical appraisal. Further field collection of data, including both sediment mineral composition and basic morphological information such as lake depth, will likely modify these interpretations.

Sources of salts

The origin and ultimate source of the ions in the lakes of the northern Great Plains have been topics of considerable discussion in the scientific literature (Sloan, 1972). Some early work suggested that deeply-buried Palaeozoic evaporites could be a possible source for salts in the lakes. Grossman (1968) attempted to show a correlation between the occurrence of Na_2SO_4 deposits in salt lakes at the surface and the presence of various salt units in the Devonian Prairie Formation in the subsurface of southern Saskatchewan. However, recent mapping of the Na_2SO_4 deposits fails to demonstrate any spatial correspondence with the trends of these Palaeozoic salt sequences (Last, 1984a; Last and Slezak, 1987), nor is there any evidence on the isohaline maps (Figs 10–13) suggesting a correlation with the Palaeozoic salt solution edge or any other subsurface bedrock feature. It is evident, however, that hypersaline groundwater from Palaeozoic rocks is an important direct source of ions to surface waters in the eastern prairies where lakes with relatively high Na^+ and Cl^- concentrations occur (Fig. 13; see also discussions in van Everdingen, 1971, and Last, 1984b).

In contrast to these Palaeozoic carbonate-evaporite units, the shallow Cretaceous and Tertiary bedrock, which is mainly marine shale and

continental sandstone and siltstone, has been implicated as the source of at least some of the dissolved components in the lakes (Cole 1926; Sahinen 1956; Wallick and Krouse 1977, 1980; Wallick 1981). In addition to providing a direct source of water and ions to some of the basins, these strata, which immediately underlie the glacial debris in much of the region, are the ultimate source for most of the reduced sulfur components that occur in the overlying Quaternary sediments. Although the source of sulphate ions and sulphate salts in the near-surface environments of western Canada is still not well understood, oxidation of reduced-S minerals such as pyrite and marcasite, as well as organic matter, and hydrolysis of sulphate minerals, whether in the bedrock itself or within the glacial deposits, could readily contribute elevated SO_4^{2-} concentrations in the shallower groundwater and, ultimately, to the saline lakes. Indeed, there is already a considerable wealth of stable isotope information and soil/efflorescent crust mineralogical data to support this general hypothesis. For example, Hendry *et al.* (1986) have shown that the SO_4^{2-} concentration in pore water from till in a small area of southern Alberta is derived mainly from oxidation of reduced organic sulphur. Mermut and Arshad (1987) demonstrated that soil salinization in the Weyburn area of south-eastern Saskatchewan is produced by the precipitation of sulphate salts. According to Mermut and Arshad (1987), the high SO_4^{2-} concentrations in the soil pore water are the result of the reactions: $\text{FeS}_2 + 15/4\text{O}_2 + 7/2\text{H}_2\text{O} \rightarrow \text{Fe}(\text{OH})_3 + 2\text{SO}_4^{2-} + 4\text{H}^+$ (oxidation of pyrite) and $\text{NaFe}_3(\text{SO}_4)_2(\text{OH})_6 + 3\text{H}_2\text{O} \rightarrow 3\text{Fe}(\text{OH})_3 + 2\text{SO}_4^{2-} + 3\text{H}^+ + \text{Na}^+$ (hydrolysis of natrojarosite). By examining the stable sulphur and oxygen isotope ratios of the sulphate minerals in efflorescent crusts at nearly 60 sites in southern Saskatchewan, Dowuona *et al.* (1992) were able to confirm this general reaction scheme and further emphasize the important role of bedrock facies in dictating the isotopic composition of the newly precipitated salts.

Finally, regardless of the ultimate source(s) or derivation of 'oxidizable' and readily soluble components, there is considerable evidence to indicate that the chemical reactions and processes responsible for generating the ions take place within a few metres of the ground surface and probably in the immediate vicinity of the lake itself (Rozkowski, 1967; Rutherford 1970; Sloan 1972; Moran *et al.*, 1978; Groenewold *et al.*, 1983). The presence of large quantities of glacier-comminuted material containing soluble and sparingly soluble mineral components, in combination with a moderate amount of infiltration, results in a complex suite of physico-chemical and biochemical reactions in the near-surface environment. Oxidation of detrital pyrite and (more likely) kerogenous organic matter derived from underlying marine shales has already been mentioned as an important source of SO_4^{2-} . These simple oxidation reactions also generate CO_2 and carbonic acid which, in turn, cause

dissolution of detrital carbonates and silicates to liberate alkaline earth metals and create high alkalinity. Cation exchange of Ca^{2+} for Na^+ on the smectite-rich clays of the glacial deposits has long been considered important in accounting for the high Na^+ content of the salt lakes (Cole, 1926; Keller *et al.*, 1991). The association of the siliciclastic bedrock variable with the lake water Na^+ and salinity variables in the factor analysis discussed above suggests that this cation exchange may also be taking place on the bentonitic shales within the bedrock. Finally, once in the shallow groundwater systems of the prairies, dissolved constituents undergo further complex fractionation and 'evolution' due largely to temperature induced mineral precipitation-dissolution (Timpson and Richardson, 1986; Arndt and Richardson, 1992). The Na^{2+} - Mg^{2+} - SO_4^{2-} aqueous system is particularly susceptible to enormous changes in salt solubility and stability at near-surface temperatures (Timpson *et al.*, 1986), thereby affecting not only the sediment record in the lacustrine basin, but also the overall chemical composition of the brine when the system is exposed to the dramatic temperature fluctuations characteristic of the northern Great Plains.

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