

The Ionic Composition of Lakes Fed by Ground Water and Precipitation in the Upper Romerike District

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In the Upper Romerike District the lakes possess widely different chemical characteristics depending on their hydrological conditions. The most dilute lakes are fed only by precipitation, and the more concentrated ones by ground water. In the precipitation fed lakes the total ionic concentration was similar to that of the average precipitation, but the ionic ratio was different. Ionic sorption and exchange affected mostly calcium which decreased in concentration while the monovalent ions increased. The ground water fed lakes were dominated by bicarbonate, and their ionic proportions were constant regardless of total concentrations. The percentage composition was: Ca: 82%, Mg: 10.1%, Na: 6.5%, K: 1.4%, HCO₃: 78.3%, SO₄: 17.1%, Cl: 4.6%.

Introduction

The concentration of dissolved salts in inland water varies to a great extent. General factors affecting the total concentration and ionic composition have been treated by Hutchinson (1957), Gorham (1961), and Livingstone (1963). With the exception of lakes that are greatly influenced by sea spray, the dominant ions will usually be dissolved from rock minerals in the drainage area. Kjensmo (1966) showed that the differences in conductivity (2-390 $\mu\text{S}/\text{cm}$) in Norwegian lakes are fully dependent on the geological conditions.

The most dilute lake waters are most often found in areas with slightly soluble igneous rocks. In these lakes the salts delivered from the atmosphere with precipitation or as dry fallout may give the greatest contribution to the total salts of the waters (Gorham 1961). But the atmospheric contribution is usually so small that its importance is negligible for lakes where more soluble rocks occur in the drainage area.

The proportions between dissolved ions will to a great extent be determined by their availability from different sources. This is especially the case for more concentrated waters where selective bio-geochemical processes are of minor importance to the gross composition. For the more dilute waters, however, different processes both within the drainage area and in the lakes may give noticeable effects upon the ionic composition. Such processes include ionic sorption and exchange by colloids, particles, peat, and vegetation. Ions that are sorbed in the drainage area may later on be released, for instance under changing meteorological conditions. The effects of such processes have been reviewed by Gorham (1961).

Within areas that are relatively homogeneous in geology and drainage conditions, the lakes will often contain waters of a constant proportionate ionic composition. Rodhe (1949) using the material of Lohammar (1938) found that within the county of Uppland in Sweden, the ionic proportions were in accordance with the mean composition of freshwaters of the world, as estimated by Clarke (1924). However, the wealth of material collected by Lohammar also contains information about lakes in other Swedish areas, and it can be seen that the ionic proportions vary. Especially the more dilute lakes differ considerably from the Uppland composition. The treatment of these data by Gorham (1955, 1961) shows that within other areas the lakes have other ionic proportions due to different environmental factors. Gorham (1961) rejected the concept of a »Standard composition« to which all fresh waters of the world would approach if sufficient time was available, and he stated that the final composition of fresh waters depends upon the local environmental conditions.

This has been supported by newer information about ionic composition in different parts of the world. The mean composition of the world calculated by Livingstone (1963) differs from the values of Clarke (1924). According to Livingstone (1963) waters richest in calcium and bicarbonate are found in Europe and the other northern continents, while in the tropics the waters are more dilute and proportionately richer in the monovalent ions.

The purpose of this article is to present an investigation from an area where the two major contributors to water chemistry, the geological formations and the atmosphere, can be studied under otherwise almost identical conditions. The small lakes under considerations are situated in an area where differences in climate, topography, vegetation and history are insignificant.

In its broad features this is probably also valid for the geology. The major difference between the lakes is their drainage conditions. Some of them are fed only by direct precipitation and occasional runoff from the nearest vicinity, while others receive considerable amounts of ground water.

Parallel with the lake investigations, precipitation and ground water have been sampled and analyzed. The change in composition from precipitation to precipitation-fed lakes and from precipitation to ground water and ground water fed lakes can therefore be followed and some suggestions can be made on the mechanisms at work.

Properties of the investigated Area

28 lakes in the Upper Romerike District in south east Norway (60° 12' N, 11° 9' E) have been investigated. This area was chosen as a representative basin for the International Hydrological Decade (Hydrological Data - Norden 1972), and data on quantity and chemical composition of precipitation and ground water are available (Hydrological Data - Norden 1973, 1975). Some characteristics of the climate are given in Table 1. The area has an inland climate. The lakes are normally ice-covered about six months a year, from November to May.

Table 1 - Some characteristics of the climate. From Hydrological Data Norden, Representative basins, Introductory volume (1972)

(1) Temperature, annual mean	+ 4.3° C
(2) Temperature, warmest month	+ 16.0° C (July)
(3) Temperature, coldest month	- 6.9° C (Jan.)
(4) Period with mean temperature below 0° C	Nov. 12 - March 31
(5) Period with mean temperature above + 5° C	April 24 - Oct. 12
(6) Vapour pressure, warmest month	13.1 mb
(7) Annual precipitation	905 mm
(8) Driest half-year	Dec.-May/ Jan.-June
(9) Precipitation for the period (8)	37%
(10) Precipitation for the period (4)	32%
(11) Precipitation for the period (5)	53%
(12) Duration of snow cover	147 days
(13) Period of snow cover	Nov. 20 - Apr. 15

In the period 1969 to 1974 the evaporation from free water surfaces (May-September) varied between 51 and 72 percent of yearly precipitation and potential evapotranspiration from grass covered surfaces from 27 to 55 percent of the precipitation (Hydrological Data - Norden 1973, 1975).

The area consists of glaciofluvial deposits, mostly sand and gravel, from the last deglaciation-period (Holtedahl 1924). The landscape is relatively flat and the lakes vary in elevation from 158 to 208 m (Fig. 1). The area is mostly forest and farmland.

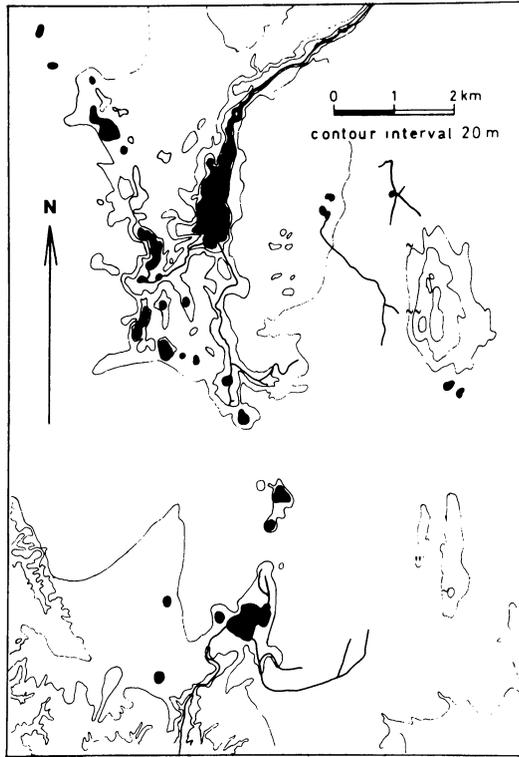


Fig. 1. Map of the investigated area.

The lakes are kettle lakes of various size (0.14-64 ha) and depth (1-23 m). Morphometric values are listed in Table 2. Some lakes have been continuously investigated from 1967/68 to 1973/74 and have not showed significant changes in chemistry. During 1973 the investigation included all 28 lakes. The loose deposits of the area are known to contain a large reservoir of ground water, many places appearing as springs, pools, and lakes at the surface. It was therefore originally assumed that the level of each lake represented the local ground water level. But investigations of level and chemistry of lakes and ground water soon showed that the influence of ground water varied between the lakes. In the lakes richest in electrolytes the ground water influence is obvious. Most of these are drainage lakes and the permanent inlets drain ground water from the vicinity through ditches, brooklets and springs in the littoral. Some of the springs are sublacustrine and are revealed by open holes in the ice during the winter.

It has been more difficult to determine the degree of ground water influence on the seepage lakes which are rich in electrolytes. Because of a much lower rate of flow there are no visible inlets or springs. However, their levels seem to be identical with that of

The Ionic Composition of Lakes

Table 2 - Morphometric values of the investigated lakes at Upper Romerike. D: drainage lake, S: seepage lake.

No	Name	elevation	depth, m		area ha	drainage type
		m	max.	mean		
1	Aurtjern	193	16.5	6.8	12.4	S
2	Bakketjern	173	14.8	6.9	2.4	S
3	Vesle Bakketj.	188	9.5		0.3	S
4	Bönntjern	196	9.0	3.9	4.6	S
5	Dagsjøen	163	7.0	3.8	2.0	D
6	Danielsetertjern	181	5.5		4.8	S
7	Flatnertjernét	199	5.0		1.0	S
8	Fugletjernet	195	1.5		0.6	S
9	Gråvtjern	208	7.0	2.7	1.7	S
10	Hersjøen	158	16.5	7.6	64.0	D
11	Katt-tjern	174	13.5		1.3	S
12	Ljøgodttjern	184	16.3	6.4	2.3	S
13	Majorsetertjern	196	6.5		0.1	S
14	Mjøntjern	170	8.5	3.9	0.6	D
15	Nordbyjtjernet	188	23.0	10.0	26.4	D
16	Nordkulpen	182	3.0		0.5	S
17	Sandtjernet	186	7.0	2.5	1.5	S
18	Skråttjern	175	12.2	5.5	0.9	S
19	Skånetjern	190	5.5		1.1	S
20	Sofrudtjern	209	3.0		1.0	S
21	Stormosan	188	8.0		0.9	S
22	Svarttjern	188	10.5	4.4	2.1	S
23	Svenskestutjern	198	18.0	6.8	2.2	S
24	Sørmotjernet	200	5.0		1.6	S
25	Transjøen	172	22.0	7.7	9.3	D
26	Vesletjern	172	4.0	1.6	0.8	D
27	Vilbergtjern	184	17.0	7.6	2.4	S
28	Vollsnesputten	187	4.0		0.8	S

the ground water and show the same variation. Exchange between lake and ground water is therefore inevitable.

The lakes poorest in electrolytes are all seepage lakes and have rather constant levels. Since the ground water, where the level has been measured, is lower than these lakes, they must be without ground water influence. Although their basins are surrounded by ground water holding deposits, the hydrostatic pressure will prevent inflow. Where the differences between outer and inner level of water are greatest, the extra pressure inside the basins must be considerable. The basin walls must therefore be of a rather extraordinary quality since they do not permit the water to penetrate and

equal out the levels. This quality may be the result of a long term infiltration which has led to clogging of the pores, either by fine particulate suspended matter or by substances precipitated from the water. An investigation of a sediment core from Vilbergstjern (No. 27) (Kjensmo, in press) shows that a layer of precipitated calcium carbonate and ferric hydroxide acts as a seal in the basin. Ohle (1934), in North Germany, and Broughton (1941) and Juday and Meloche (1944), in Northeastern Wisconsin, have described corresponding separations between lake and ground water.

The only inflow to these lakes must be precipitation falling on their surfaces and, to a lesser extent, surface runoff from the surrounding terrain. The latter is minor since the ground consists of easily permeable sand and gravel, and is rather flat except for slopes around the lakes. Surface runoff is therefore most important during the snow-melt. Although not observable, a certain seepage through the lake bottoms must be assumed to make up the difference between measured precipitation and evaporation.

The ground water level of the area changes according to the amount of precipitation. During the investigation period, the level has been continuously sinking. Accordingly, lakes without present ground water inflow may earlier have been influenced. In that way the intermediate electrolyte concentrations of some lakes may have been formed.

The different types of lakes seem to be quite randomly distributed within the area, and the variation in lake chemistry seems not to be related to any geographic parameter (Fig. 2).

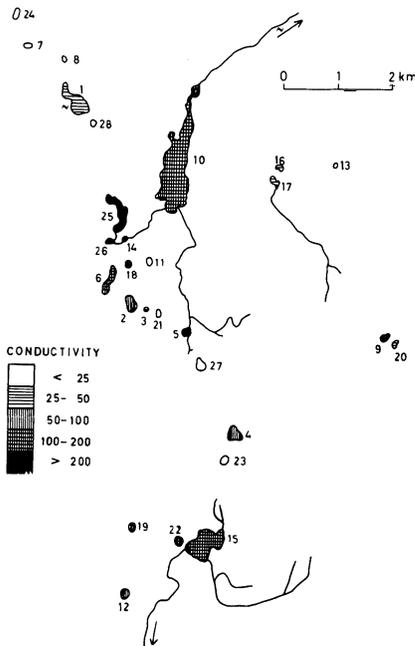


Fig. 2. Mean conductivity of the investigated lakes.

Methods

Water

Sampling: Water samples were taken with a Ruttner water sampler over the greatest depth of each lake. As many samples as necessary (at least three) for a characterization of the stratification were taken in each series.

Analyses: Ca and Mg were analyzed by atomic absorption on a Perkin Elmer 306 AA spectrophotometer. Na and K were analyzed by flame emission on the same instrument. Samples for alkalinity were stored in stoppered bottles and titrated directly in the bottles to their individual equivalence points (Golterman 1971). Chloride was determined by potentiometric titration with AgNO_3 (Standard methods 1971), and sulphate as the difference between total salts of strong acids and chloride (Mackereth 1963). The interference of nitrate was always negligible (concentration range 0-9 $\mu\text{eq/l}$). pH was measured in the field with a Radiometer 29 pH-meter, and conductivity was measured with a Philips measuring bridge type GM 4249 at 18°C.

Sediments

Sampling: Sediment samples were taken from the ice using a loaded 1.5 m, 5 cm i. d. plexiglass tube with an internal piston. The piston could be fixed at a small distance from the bottom while the tube penetrated the bottom by its own weight. The method ensured undisturbed and uncompressed bottom samples.

Analyses: Interstitial water was pressed out of the samples in a nitrogen pressure operated device (Reeburg 1967). A maximum pressure of 5 kg/cm² was employed. Analyses of interstitial water and leachable ions were the same as for water samples. Total CO₂ in sediments was analysed on a Perkin Elmer 3920 gas chromatograph. Sediment samples of a known volume were first enclosed in 60 ml medical septum bottles. Firm sediments were mixed with distilled CO₂-free water to make them more liquid. A constant volume of phosphoric acid was then added through the rubber septum. The amount of acid must be sufficient to acidify the samples to about pH 1.

In this case, the volumes of the samples were made up to 20 ml and 1 ml 5% phosphoric acid was added.

The bottles were then shaken thoroughly and placed in a thermostat bath near room temperature. Standards were prepared from sodium bicarbonate solutions from which volumes equal to the sample volumes were treated in the same way.

0.5 ml of the gas in equilibrium with the samples or standards were taken out through the rubber septum with a gas tight syringe and injected into the chromatograph. This was used with the columns at room temperature and hot wire detector at 100°C. A 3', 1/8" o.d. column packed with Chromosorb 102 was employed for the separation of CO₂ from air. Gas flow 30 ml/min. The fraction of free CO₂ in the sediment was measured after the same procedure but without acidification. The gaseous CO₂ was then in equilibrium with dissolved free CO₂. Removal of CO₂ will change the equilibrium with carbonate or bicarbonate. To avoid overestimation it is therefore important that the volume of the gas fraction is relatively small and that the temperature is moderate.

Ion Concentrations and Conductivity

Table 3 gives the average concentrations of major constituents, conductivity, pH and KMnO_4 -consumption for the lakes. The values are means for the six investigations during 1973. Some of the lakes are meromictic and others have periods with anaerobic conditions in the deep waters, and all values from water devoid of oxygen have been excluded from the calculations. This has been necessary since the stagnant deep waters often show a very changed ionic composition. Bicarbonate may increase with several milliequivalents when ferrous and manganous ions are accumulated and sulphate may be greatly reduced. Sorption and desorption also change the ratios between the cations in this environment. The only exception is lake No. 3 which did not show significant

Table 3 - The average composition of lake waters 1973 and precipitation 1971-1972.

Lake	Ca	Mg	Na	K	HCO_3	Cl	SO_4	conductivity $\mu\text{S/cm}$	pH	KMnO_4 -consumption mg/l
				$\mu\text{eq/l}$						
Aurtjern	201	53	60	12	225	30	77	30.3	6.55	8.8
Bakketjern	718	90	48	17	712	35	110	69.8	6.91	18.6
Vesle Bakketjern	66	36	38	17	0	33	163	26.8	4.39	117.
Bonntjern	504	55	29	11	550	32	117	53.5	6.93	15.0
Dagsjøen	2057	205	108	38	2058	81	333	199.	7.47	9.0
Danielsetertjern	1385	157	84	16	1198	112	242	132.	7.27	11.7
Flatnertjernet	25	13	20	9	0	24	55	13.7	4.40	9.6
Fugletjernet	43	21	20	18	0	26	60	12.2	5.38	13.4
Gråvtjern	513	122	70	9	510	53	134	58.4	6.78	35.1
Hersjøen	1786	242	137	32	1743	86	290	180.	7.62	5.2
Kattjern	43	25	23	24	9	29	68	14.0	5.56	13.6
Ljøgdottjern	603	139	90	47	644	97	113	73.7	6.98	11.9
Majorsetertjern	86	36	30	16	6	26	106	17.2	5.44	19.0
Mjøntjern	2420	267	210	37	2530	132	335	236.	7.59	6.8
Nordbytjernet	1612	260	150	40	1273	144	592	177.	7.23	10.6
Nordkulpen	209	61	58	16	19	51	241	33.8	5.73	48.9
Sandtjernet	229	64	63	13	34	45	259	36.7	5.70	58.6
Skråttjern	1123	107	67	14	1117	32	122	103.	7.12	14.9
Skånetjern	490	70	58	52	524	39	151	53.1	6.94	62.9
Sofrudtjern	141	76	36	31	80	84	54	30.6	6.30	27.0
Stormosan	14	7	23	7	0	26	50	17.3	4.20	57.5
Svarttjern	1702	286	94	25	1218	37	810	180.	7.15	5.6
Svenskestutjern	41	17	25	12	0	30	76	13.7	5.13	5.3
Sørmotjernet	24	12	21	5	0	24	59	13.6	4.59	19.4
Transjøen	2750	337	236	39	2820	165	427	268.	7.71	5.3
Vesletjern	2750	282	412	66	3010	222	337	279.	7.55	5.6
Vilbergtjern	42	18	24	14	5	28	60	12.6	5.61	11.3
Vollnesputten	62	23	33	17	25	39	82	15.7	6.04	12.6
Precipitation	34	9	14	5	0	17	76	30.6	4.51	

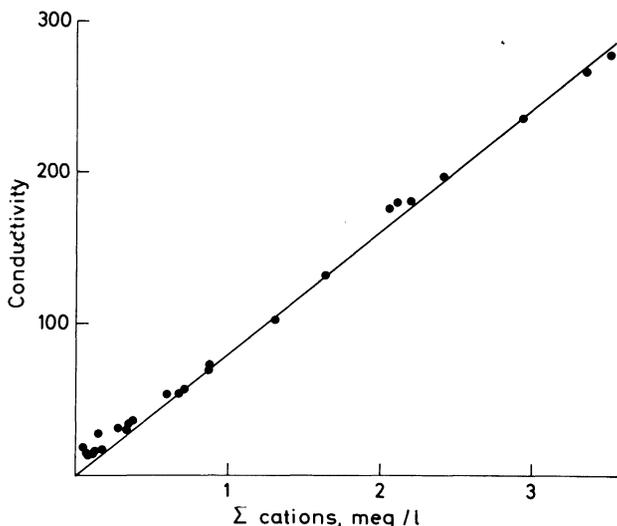


Fig. 3. Relationship between mean conductivity and electrolyte concentration in the lakes. The line indicates the ratio 80:1.

variation with changing oxygen conditions.

The average conductivity varied from 12 to 279 and the corresponding electrolyte content from 0.05 to 3.5 meq/l. The standard deviation for the individual parameters was in most cases less than 10 percent. For the conductivity it was more than 20 percent only in lakes Nos. 8, 20, and 21. For the lakes with more than 1 meq/l, which are the typical bicarbonate lakes, there is a good correlation between total electrolyte content and conductivity. 1 meq/l corresponds to 80 μ S/cm (Fig. 3). A slightly higher conductivity was found for the lakes Nordbytjernet (No. 15) and Svarttjern (No. 22) because of a higher sulphate content than in the others. Below 1 meq/l the ratio between conductivity and electrolyte content increases as their values decrease. While bicarbonate is the dominant anion in the lakes rich in electrolytes, sulphate is most important in the dilute ones. The higher equivalent conductivity of sulphate than of bicarbonate is one reason for the increasing ratio. For the lakes with the lowest electrolyte content there is also a dependence of conductivity on pH.

Similar conditions have been shown by Grøterud (1972, 1973) and Lande (1972) for acid lakes receiving drainage from areas with igneous or metamorphic rocks. For the lakes with less than 0.2 meq/l of total cations, the ratio between conductivity and concentration is shown graphically in Fig. 4a. For pH-values above 5.0 the ratio is about 100:1, but it shows a marked increase with decreasing pH. Fig. 4b shows that the difference between measured conductivity and that estimated as Σ cations \times 100 is in good accordance with the conductivity of the H⁺-ions. The increasing ratio in Fig. 4a is thus caused by the increasing concentration of H⁺-ions which have an equivalent conductivity much higher than the other major constituents.

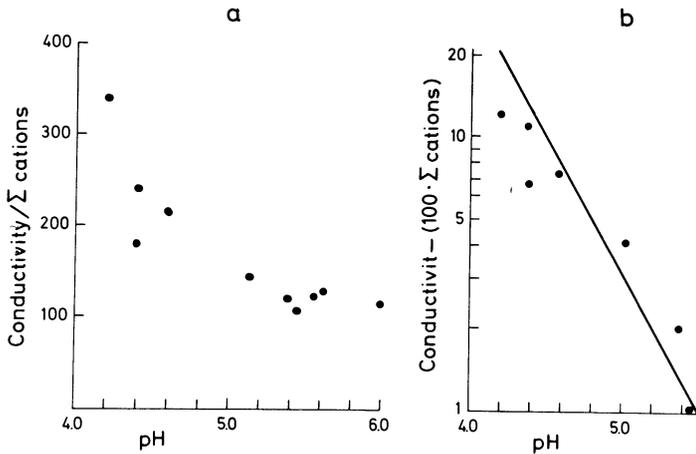


Fig. 4. a) The ratio between lake conductivity and electrolyte concentrations in relation to pH in the most dilute sulphate lakes (total cations less than 0.1 meq/l). b) The difference between measured conductivity and estimated conductivity for sulphate waters ($100 \times$ cations meq/l) in lakes with pH less than 5.5. The line indicates the conductivity of H^+ ions at the actual pH.

Ionic Proportions in the Various Types of Lakes

The major source of dissolved salts in the lakes of Romerike is the glaci-fluvial deposits from which salts are dissolved and transported with the ground water. The total concentration in lake waters varies according to the degree of ground water influence and concentration of ions in ground water in the different areas. Lakes uninfluenced by ground water have the lowest concentration of salts, and to these lakes the other, minor, source of ions may be of importance, namely the supply from the atmosphere.

As the relative importance of the two sources of ions is altered, a change in the proportionate composition of the water accompanies the change in concentration. In Fig. 5 the percentage composition of the major anions and cations is shown as a function of the total concentrations. The lakes richest in electrolytes all have a composition similar to the local ground water. It can be seen from the figure that in these lakes the ratios between the major constituents are very constant. Since both lake and ground water show similar minor variation from place to place, this constant composition should not be interpreted as different dilutions of a common source in the ground water, but rather as an indication that the ionic proportions of the ground water are constant, regardless of its total concentration. The composition of ground and lake waters is determined by the relative availability of the different ions from the minerals. The constant composition of the richer lake waters should therefore also indicate a

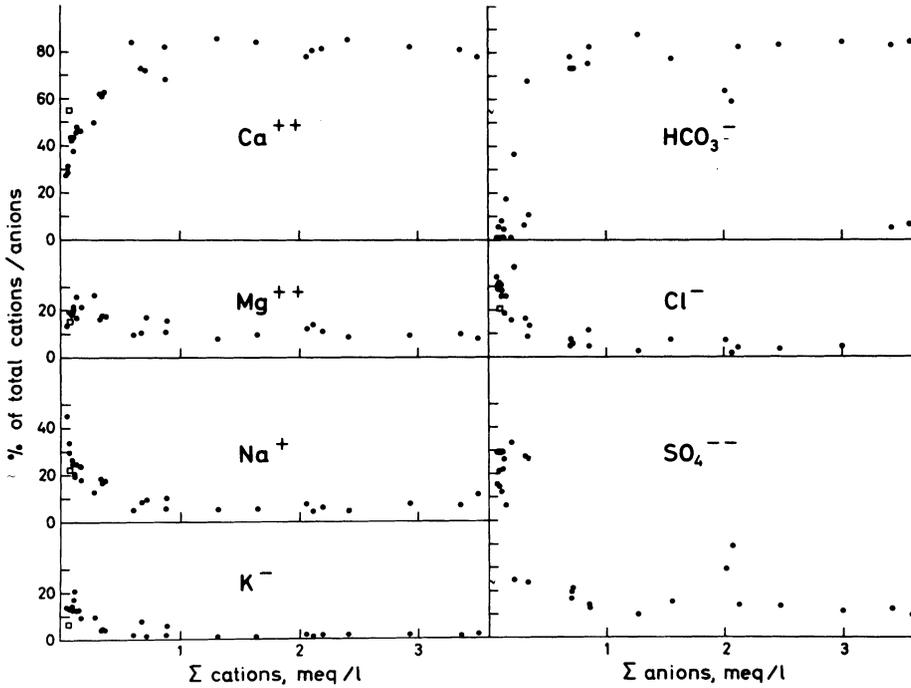


Fig. 5. The percentage distribution of cationic and anionic constituents in lake waters in relation to the total electrolyte content. Each point represents one lake. The open quadrats represent the mean values for the precipitation.

relatively constant composition of the loose deposits of the area. The greatest irregularities among these lakes are for sulphate which in a few lakes increases at the expense of bicarbonate. The reason is local oxidation of pyrites which gives off sulphuric acid and transforms carbonates to CO_2 (Hongve 1974). A comparison of these lakes with the Uppland lakes seems natural, since in that area a similar constant composition was early demonstrated by Rodhe (1949). The mean percentage composition of the Uppland and Romerike lakes is given in Table 4. The differences are evident, probably reflecting differences in the geology of the areas.

The Cambro-Silurian fraction in the loose deposits of Romerike is the source of the high proportion of calcium and bicarbonate in the water. Since these rocks are most easily weathered, they are probably also the main source of other major ionic constituents. As long as the concentrations are moderate, chemical precipitation will not occur and the proportions remain constant. Most of the other rocks in the area, such as the underlying gneisses and granites, sparagmites, etc. in the deposits are only slightly soluble and may be disregarded as major sources of ions.

Table 4 - »Standard composition« of fresh water (Rohde 1949) in comparison with mean percentage composition and standard deviation of ions of Uppland lakes 1-21 (Lohammar 1938) and Romerike lakes with total cation concentration more than 1 meq/l.

Ion	Ca	Mg	Na	K	HCO ₃	SO ₄	Cl
St. Comp.	63.5	17.4	15.7	3.4	73.9	16.0	10.1
Uppland	65.5±7.2	17.7±3.9	14.9±3.7	2.2±1.0	76.4±5.9	15.2±5.9	11.6±6.3
Romerike	82.0±2.8	10.1±2.0	6.5±2.2	1.4±0.3	78.3±10.1	17.1±10.2	4.6±1.9

The other main type of lake is the one where little or no connection has been found between water and the surrounding ground water. This type is dispersed between the richer ones in the central part of the area.

The dilute lakes have relative compositions quite different from the richer ones. The dominance of calcium and bicarbonate decreases strongly with decreasing total ions. Magnesium and potassium increase slightly and sodium increases to be the dominant cation. Among the anions, bicarbonate is often practically lacking due to the low pH, while the importance of chloride and especially sulphate increases.

In the most dilute lakes the total concentration is nearly the same as the mean value for the precipitation. For the two years previous to the present investigation, the mean concentration of precipitation has been estimated to 0.062 meq/l of cations and 0.093 meq/l of anions. The difference is mainly due to hydrogen ions. The five most dilute lakes have total cations less than 0.1 meq/l. The composition of these lakes, however, differs from the mean precipitation. The difference can be seen from Fig. 5. The relationship of cation concentrations in precipitation is Ca>Na>Mg>K. For the extreme of lake waters, Stormosan (No. 21), has this been changed to Na>Ca>Mg>K, and the tendency for the other most dilute lakes seems to be Na=Ca>Mg>K. The most important difference is thus in the concentration of calcium ions which is higher in precipitation than in lake waters of the same total concentration. The magnesium concentration is almost unchanged, and the monovalent sodium and potassium increase their concentrations in lake waters. It seems accordingly as if there are processes in the lakes or their drainage areas that alter the composition of the water without affecting the total ionic concentration. Calcium is thereby replaced by monovalent cations, and of the anions chloride has a higher and sulphate a lower concentration than in the precipitation.

This change in the ionic composition may be caused by several processes. First, there may be an extra supply of ions from atmospheric sources not analysed for. Besides the wet precipitation there is a dry fallout of salts from the atmosphere. Such particles will probably have greater possibilities of attaching to the irregular surfaces of the ground and vegetation than to the smooth surface of a precipitation recorder. The total supply of salts from the atmosphere is therefore probably greater and of a different composition from the recorded values. This possible disagreement between

actual and recorded values can, however, only account for concentrations greater than those of the precipitation and does not explain the removal of divalent ions.

Divalent ions are known to have a greater tendency for sorption to various substrates than the monovalent ones. Especially adsorption of calcium to organic matter may be of great importance. Substrates capable of ion sorption may in the present case be vegetation and plant debris in the drainage areas, humified plant material on the ground, and not least, the sediments of the lakes. All these materials may give rise to processes which modify the water composition both within the drainage areas and the lakes. The actual processes may be selective uptake and release of ions and ionic exchange.

Lastly, evaporation must also be considered as a factor that will increase the concentrations. The ratio between precipitation and evaporation should lead to concentrations in the lakes approximately twice that in the precipitation.

Experiments with Influence of Humus Sediments on Water Chemistry

In order to produce some information on how the sediments of the poorest lakes will influence water from the major sources, ground water and precipitation, a simple experiment was made with sediments from one of these lakes. In Svenskestutjern (No. 13) sediment cores were taken from each second meter of depth, from 2 to 18 m. The depth profile is shown in Fig. 6. From each core two samples were taken and homogenized, one from 0 to 10 cm depth and one from 40 to 50 cm. Interstitial water was pressed out from 110 ml of each sample. The volume of the filtrates varied from 25 to 98 ml depending on the firmness of the sediment. The pressed samples were then weighed and divided in four. Two parts, each corresponding to 50 ml of untreated sediment were shaken overnight, one with 50 ml of distilled water and the other with 50 ml of natural water rich in bicarbonate (taken from the outlet of Hersjøen, No. 10). A third part, corresponding to 5 ml untreated sediment was shaken with 50 ml 1 N ammoniumacetate (AmAc). After this treatment, these three samples were filtered and the filtrates were analysed. The fourth part was analysed for the total CO₂ content.

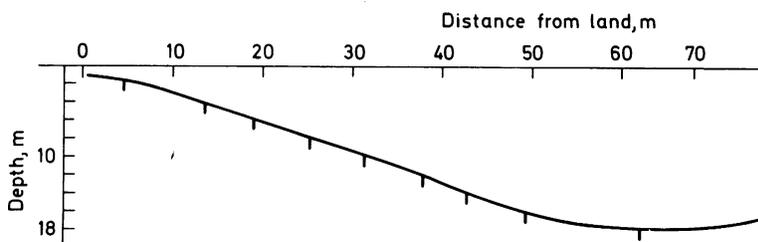


Fig. 6. The sampling spots for sediments on the depth profile in Svenskestutjern. Horizontal and vertical axes are on the same scale.

This procedure was assumed to give comparative measurements, first of the amounts of ions which could be leached from the sediment by water more dilute than the interstitial water, and secondly of the amount that would be leached by, or eventually adsorbed from water with a composition resembling the ground water. The treatment with AmAc gives measurements of the total amount of leachable and exchangeable ions. The measurements of total CO₂ was done to see if there were carbonates or bicarbonates in the solid phase of the sediment in equilibrium with the pore water. This latter test was negative for all samples.

The sediment samples were also tested for water content and ignition loss (Table 5). The loss of weight by drying was on average 96.7% for the upper 0-10 cm and 95.6% for the 40-50 cm samples. Although not differing much in water content, the lower samples were of a much firmer consistence than the upper samples which were quite liquid. The loss on ignition was also invariably high. Visually it had the characteristics of *dy* according to Lundquist (1927).

Unfortunately, some of the samples were filtered through unsatisfactorily washed glass fibre filters. This has especially affected the sodium, potassium, and chloride concentrations. In all analyses which could not be repeated and where contamination from filters is suspected, these values are deleted from the tables.

The main difference between lake water and interstitial water is the higher concentration of the latter, but also other ionic ratios (Table 6). The average ratios between surface interstitial water and lake water were: Ca: 1.7, Mg: 1.1, Na: 2.8, K: 1.6 and Cl: 6.9. In addition, bicarbonate increases from practically zero in the lake to 10 μ eq/l in the interstitial water. Sulphate could not be analysed for in the interstitial water, but chloride and bicarbonate probably replace sulphate in the sediment. The pH value obtained by measurement in the interstitial water is 0.5-1 units higher than by direct measurement in the sediment and bottom water. This is probably due to loss of free CO₂ during filtration.

Diffusion of ions from the sediment is dependent on the concentration gradient, and sodium and chloride must here be assumed to be the constituents with the greatest diffusion rate. For calcium and potassium the gradients are less pronounced than for sodium. For magnesium the difference in concentration between lake and interstitial water is insignificant. The differences in concentrations between the elements in the interstitial water reflect the differences in concentrations of exchangeable ions in the sediment and the differences in equilibrium constants between adsorbed and dissolved ions. A comparison of Tables 5 and 6 shows that only a minor part of the releasable ions in the sediments is in the water phase, although this phase makes up 95 to 98 percent of the weight. The rest is adsorbed to the organic particles. The dissolved fraction is significantly different for the various cations. For calcium it is on average 1.0% of the total, for magnesium 2.2%, for sodium 27% and for potassium 19%. In the undisturbed sediment, a near equilibrium will be established between ions in solution and on particle surfaces, and the equilibrium constants will determine the concentrations in the interstitial water. Calcium occurs in greatest concentration in the sediment,

The Ionic Composition of Lakes

Table 5 - Some properties of the sediments from Svenskestutjern

Sample No.	depth, m		water	ignition loss	exchangeable cations, meq/ l sedim.			
	in lake	in sed.	% of WW	% of DW	Ca	Mg	Na	K
1 a	2	0.0-0.1	97.3	87.9	7.2	0.8	1.0	0.2
1 b	2	0.4-0.5	95.7	96.4	16.3	3.0	0.2	0.1
2 a	4	0.0-0.1	98.4	96.2	5.9	0.5	0.4	0.1
2 b	4	0.4-0.5	92.4	92.5	23.0	1.3	0.3	0.1
3 a	6	0.0-0.1	97.9	94.4	9.5	0.7	0.4	0.1
3 b	6	0.4-0.5	95.5	92.3	15.9	1.3	0.4	0.2
4 a	8	0.0-0.1	97.5	94.8	8.5	1.0	0.2	0.1
4 b	8	0.4-0.5	96.8	93.3	15.3	1.0		
5 a	10	0.0-0.1	97.2	95.9	8.0	1.0	0.3	0.1
5 b	10	0.4-0.5	96.2	93.1	10.4	1.1		
6 a	12	0.0-0.1	97.2	93.9	7.7	1.1	0.5	0.2
6 b	12	0.4-0.5	96.4	94.5	13.6	1.5		
7 a	14	0.0-0.1	97.0	94.7	6.2	1.0		
7 b	14	0.4-0.5	95.4	90.2	11.1	0.7	0.5	0.1
8 a	16	0.0-0.1	98.0	88.9	3.2	0.5	0.2	0.1
8 b	16	0.4-0.5	96.6	95.6	8.1	0.8	0.4	0.2
9 a	18	0.0-0.1	97.6	80.4	3.2	0.3	0.1	0.1
9 b	18	0.4-0.5	95.8	94.3	22.4	1.3	0.6	0.3

Table 6 - Chemical composition of the interstitial water from the sediments of Svenskestutjern

Sample No.	Ca	Mg	Na	K	Cl	tot. CO ₂	HCO	pH
	μeq/ l			mmol/l				
1 a	90	25	52	14	85	0.12	0.05	6.2
1 b	62	21	54	18	155	0.08	0.03	6.2
2 a	72	15	132	16	90	0.02	0.01	6.2
2 b	200	30	212	74	352	0.06	0.03	6.3
3 a	67	14	57	20	141	0.10	0.05	6.4
3 b	129	21	152	50	296	0.07	0.03	6.2
4 a	71	16	65	21	155	0.21	0.12	6.5
4 b	95	18	60	22	144	0.34	0.22	6.6
5 a	60	18	77	30	155	0.29	0.17	6.5
5 b	77	21	160	23	338	0.43	0.25	6.5
6 a	52	16	63	18	121	0.23	0.14	6.6
6 b	74	17	98	20	214	0.43	0.25	6.5
7 a	74	19	77	24	901	0.32	0.17	6.4
7 b	105	17	63	21	127	0.52	0.45	7.2
8 a	114	41	50	15	93	0.07	0.05	6.8
8 b	50	12	59	17	127	0.07	0.04	6.7
9 a	42	8	50	15	127	0.20	0.15	6.9
9 b	64	10	60	14	141	0.28	0.23	7.0
lake (mean)	41	17	25	12	30		0.00	5.1

on average 33 times as much as sodium, but the two ions have about the same concentration in the interstitial water. Magnesium and potassium have also nearly the same concentration in the water phase, about $\frac{1}{4}$ of that of calcium and sodium, while the total magnesium concentration is $\frac{1}{10}$ of calcium, and total potassium is $\frac{1}{80}$ of calcium.

The proportions of the total ions which were removed with the interstitial water have some influence on the results of the following treatment, but this is of minor importance and has not been taken into account.

The treatment with distilled water gave concentrations in the filtrate for calcium and magnesium of nearly the same magnitude as in the interstitial water (Table 7). These values are probably close to the equilibrium values that are reestablished by solution of adsorbed ions.

Table 7 - Ions liberated from Svenskestutjern sediments mixed with distilled water (1:1). $\mu\text{eq}/1$ wet sediment

Sample No.	Ca	Mg	Sample No.	Ca	Mg	Sample No.	Ca	Mg
1 a	89	24	4 a	32	7	7 a	52	11
1 b	34	10	4 b	50	10	7 b	170	51
2 a	29	5	5 a	34	5	8 a	40	13
2 b	250	34	5 b	53	10	8 b	55	10
3 a	37	7	6 a	42	14	9 a	44	12
3 b	118	19	6 b	53	9	9 b	88	20

When sediments were treated with natural water rich in calcium bicarbonate, some distinct changes in the water composition were observed. These consisted in marked decreases in the calcium and magnesium concentrations, and minor increases in the sodium and potassium. Table 8 shows these changes as $\mu\text{eq}/1$ sediment.

The reaction between bicarbonate water and humus sediments has been described by Ohle (1955) for the *Laubdy* of a German lake. In that case he found equivalent decrease in calcium and bicarbonate due to the reaction.

»Humic acid + $\text{Ca}(\text{HCO}_3)_2 = \text{Ca-humate} + 2 \text{CO}_2 + 2 \text{H}_2\text{O}$ « Ohle found that magnesium, sodium, potassium and chloride were unaffected by the treatment, but the results of the present experiment were different. On an average 85% of the added calcium in solution and 76% of the magnesium was absorbed during the treatment. Adsorption should therefore be of importance for both divalent ions. Since the increase in monovalent ions was far less than the calcium and magnesium depletions, these latter ions must have taken the binding sites of H^+ on humic acids according to the reaction above.

For a further study of this assumed reaction mechanism between dissolved bicarbonate salts and humus in sediments, one sediment sample was treated with water of a known, more concentrated composition of calcium, sodium, bicarbonate, and chloride. The original concentration was 5 meq/l for all these constituents and the pH 7.9.

Table 8 - Sediment uptake (+) or liberation (-) of ions when mixed with natural calcium bicarbonate water (1:1), $\mu\text{eq/l}$ wet sediment. Composition of untreated water! $\mu\text{eq/l}$.

Sample No.	Ca	Mg	Na	K	HCO ₃ ⁻
1 a	1280	159	-150	-5	1360
1 b	1404	183	-103	-7	1423
2 a	1320	182	-184	12	1436
2 b	1059	155	-142	-12	1212
3 a	1349	178	-77	7	1443
3 b	1162	152	-269	-47	978
4 a	1378	177	-83	-6	1407
4 b	1370	187		-6	1424
5 a	1419	184	-23	-8	1438
5 b	1416	190		-22	1408
6 a	1223	131		-18	1009
6 b	1264	161		-27	913
7 a	1091	126		0	1050
7 b	1421	198	-220	-15	1436
8 a	1322	149	-61	18	1465
8 b	1301	166	3	-15	1146
9 a	1435	188	-48	-17	1420
9 b	1222	111	-15	-29	1062
untreated water	1540	219	131	30	1500

Sediment sample No. 4 b was used for the test. Two parallel samples of 15 ml sediment were shaken over night with 15 ml of the reagent in closed 60 ml septum bottles. Afterwards both the enclosed air and the mixture of water and sediment were analysed for CO₂. The final pH of the samples was 6.3. The CO₂-concentration in the enclosed air was the same as with an acidified standard solution of 1.90 meq/l bicarbonate. This means that from the original concentration of 2.5 meq/l bicarbonate an amount corresponding to 1.90 meq/l has been transformed to CO₂ while 0.60 meq/l is left as bicarbonate. In the sediment-water mixture the total CO₂ concentration was 1.44 meq/l. These measured concentrations fit very well the theoretical values which according to the pH and total CO₂ (the initial bicarbonate concentration) can be calculated from Murray and Riley (1971) and Rebsdorf (1972). The other ionic concentrations in the water, originally 2.5 meq/l were: Ca: 1.25 meq/l, Na: 2.09 meq/l and Cl: 2.50 meq/l. The difference between total cations and anions was about 7% which may be due to organic components. The water was dark brown in colour.

Thus, when equivalent and rather strong concentrations of calcium and sodium are added to the sediment, both are adsorbed, but calcium to the greatest extent. This is done by exchange with H⁺ which transforms bicarbonate to CO₂. During this experi-

ment the decrease in concentrations of bicarbonate was greater than of sodium and calcium together, and may be caused by the acid properties of the sediments. The humic acids may react with bicarbonate to give CO_2 also without exchange of cations.

Discussion of the Relationship between Lake, Interstitial Water and Sediment Chemistry

In connection with the present and other investigations in the Romerike area, information is available on interstitial water and exchangeable ions from a few other lakes. The values for surface sediments are given in Table 9. It is noteworthy that the concentrations of exchangeable ions vary far less than interstitial water and lake water concentrations. For instance for calcium the latter concentration varies more than forty times while there is only a six times difference in exchangeable concentrations. The interstitial waters are closely related to the lake waters. These differences may primarily be related to differences in speed between processes in the sediments. Weathering of minerals and organic decomposition together with diffusion from concentrated to more dilute solutions are dynamic processes affecting the water composition. If no ions were removed from lake waters, their concentrations would grow until they were equal in lake and interstitial water and in equilibrium with the sediment. In most lakes, however, ions are removed from the water and this state of equilibrium is not reached. The removal of ions may take place through drainage, by chemical precipitation, assimilation in organisms, and adsorption to organic and inorganic matter in the sediment.

The small differences in concentration of interstitial and lake waters, regardless of exchangeable concentrations, indicate that the diffusion through the sediment-water interface is a more rapid process than release of ions to the interstitial water. The latter

Table 9 - Concentrations of major cations in lake and interstitial water and of exchangeable ions in surface sediments. Cons. as meq/l.

	Water								Sediment			
	Lake				Interstitial				Ca	Mg	Na	K
	Ca	Mg	Na	K	Ca	Mg	Na	K				
Svenskestjernet (mean)	0.04	0.02	0.03	0.01	0.07	0.02	0.07	0.02	6.6	0.8	0.4	0.1
Svenskestjernet (zmax)	0.04	0.02	0.03	0.01	0.04	0.01	0.05	0.02	3.2	0.3	0.1	0.1
Vilbergstjernet (3 m)	0.04	0.02	0.02	0.01	0.06	0.02	0.06	0.01	12.	1.3		
Vilbergstjernet (zmax)	0.09	0.03	0.03	0.02					5.0	1.6		
Svartstjernet (zmax)	1.7	0.3	0.1	0.03					7.5	0.8		
Nordbystjernet (9 m)	1.6	0.3	0.2	0.04					20.5	2.1		
Nordbystjernet	2.1	0.3	0.1	0.06	1.4	0.2	0.7	0.02	18.5	1.6		

process will therefore primarily be limiting for the amount of ions given off to the lake water. Probably it is only a minor fraction of the concentrations found by leaching with AmAc that is in direct equilibrium with the more dilute interstitial water solutions.

Higher electrolyte concentrations in interstitial waters than in lakes seem to be normal. Lermann and Brunskill (1971) have pointed out the importance of diffusion from the sediments for the budget of electrolytes in dilute lakes. The origin of interstitial water ions from weathering of minerals has been discussed by Brunskill et al. (1971). Besides mineral weathering, organic decomposition may be an important source of inorganic ions.

The ions set free during organic decomposition have either been assimilated by living organisms or been adsorbed by the organic sediments. In lakes where the sedimentation of humus is considerable, the latter fraction may become important. Ionic adsorption by fresh sediments may in such lakes become an important process for removal of ions from the waters. If it is assumed that no drainage occurs in the dilute Romerike lakes, their concentration would increase unless ions in some way were removed from the waters. The proportions of accumulated dissolved and exchangeable ions in the waters and sediments would then become equal to the average proportions of ions released by processes affecting minerals and organic matter and those delivered from the atmosphere.

As far as known there is no chemical precipitation in these lakes except for iron. The water vegetation certainly takes up ions from the waters, but probably not in significant amounts of the major ions. Excretion and decomposition will also over time reduce the net uptake by organisms.

The concentration of exchangeable ions shows, however, that ions are accumulated in the sediments. These consist of organic products transformed to *dy* and have a great capacity for ionic adsorption. The ratio of exchangeable ions proves further that not all ionic supply has been removed from the waters by sorption, but some seepage must also have taken place. Since the divalent ions have a higher adsorption rate than the monovalent ones, seepage will in particular remove the latter from the lake system.

By interaction of these two main processes, seepage and sorption, the concentrations of lake waters are held constantly at a very low level. Sodium and potassium concentrations are governed chiefly by the ratio between evaporation and run-off, and are approximately doubled in comparison with the precipitation. Sorption of calcium reduces its concentration from precipitation to lake waters, while magnesium falls in an intermediate position.

From the experiments with Svenskestutjern sediments it was seen that calcium adsorption was a result of ionic exchange. An almost equivalent amount of hydrogen ions was set free together with minor amounts of sodium and potassium. The latter fractions are probably too small to have practical importance for their concentrations in natural systems, but the extra supply of hydrogen ions might be of importance in the weakly buffered waters. A drop in pH is probably avoided since the buffer capacity of

the sediments is much greater than of the water. It may be that in these lakes where the bicarbonate buffer system is practically lacking the pH of the waters is governed by contact with the sediments.

In the more concentrated lakes with ground water supply, the importance of the interaction between sediments and lake water will probably be negligible. These processes are overshadowed by the supply and removal of ions through drainage or seepage. The ionic composition of such lakes will therefore be determined by the composition of the ground water in the area. The sediment interstitial water will be different from both lake and ground water according to actual diagenetic processes, and a flux of ions will therefore exist. In the maximum depth sediments from Nordbytjernet (Table 9) the calcium concentration was less than that of lake water. This may be a local phenomenon in the meromictic basin due to supersaturation in the lake water. The concentrations of sodium and potassium had the greatest ratio to lake water and the sediments may give minor contributions to the lake.

Summary

The major ionic composition was investigated in 28 lakes in the Upper Romerike District (60° 12' N, 11° 9' E). The lakes are kettle lakes of varying surface area 0.14-64 ha and depth 1.5-23 m. The variations in chemistry depend on the hydrological conditions. Some lakes have their surface levels higher than the local ground water and are therefore not influenced by it, while other lakes are more or less obviously influenced by ground water.

The average conductivity varied from 12 to 279 $\mu\text{S}/\text{cm}$ and the corresponding electrolyte content from 0.05 to 3.5 meq/l. In the bicarbonate lakes 1 meq/l corresponds to 80 $\mu\text{S}/\text{cm}$. This ratio is changed to 1:100 in the more dilute sulphate lakes. In the most acid lakes the ratio is affected by the high equivalent conductivity of the hydrogen ions.

In the most dilute, precipitation fed lakes the total concentration was similar to that of the average precipitation, but the ionic ratio was changed. The calcium concentration was depleted while especially sodium increased. In the more concentrated lakes the composition was similar to that of the local ground water, and calcium and bicarbonate dominated. The change of water composition in precipitation fed lakes was assumed to be caused partly by processes in the drainage area and partly by processes within the lake. The organic sediments were shown to have a great capacity for calcium sorption. In experiments calcium was exchanged mainly with hydrogen ions, but to a minor extent also with sodium. Magnesium was also adsorbed by the sediment.

In the interstitial water in the sediment of a dilute lake calcium and sodium occurred in about the same concentration although there was a much greater exchangeable

calcium concentration. Magnesium and potassium also had larger dissolved fractions relative to their exchangeable amounts.

The interstitial water was a little more concentrated, but in relative agreement with lake water both in dilute and more concentrated lakes. In contrast, the exchangeable concentrations were not very different between these lake categories. The conclusion was drawn that the ions in the dilute lakes are removed partly by seepage through the bottom and partly by sorption to the organic sediments. Release from the sediments by ionic exchange or decomposition is hardly of importance for the supply.

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