Transjøen, a Groundwater Influenced Lake
with Special Redox and Sulphate Conditions

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Transjøen, a lake in S.E. Norway investigated hydrographically from October 1969 to October 1971, consists of two basins, both of which are meromictic (lake with lower layer which does not participate in the periodic circulations). The lake has a large influx of groundwater of very varying chemical composition. The calcium content is high and precipitated calcium carbonate and electrolyte rich groundwater is assumed to be the main reason for the meromictic stability. The redox potentials of monimolimnion (the lower layer which does not participtate in the periodic circulation) are extremely low, but in spite of this fact the content of sulphate is high.

Introduction

The present study forms part of an investigation in the Romerike area of south-western Norway in connection with the Norwegian contribution to the International Hydrological Decade (IHD). The area has a large number of kettle tarn situated in glacio-fluvial deposits from the last deglaciation period. The chemical composition of the groundwater varies considerably within small distances and therefore the chemical composition of the lake waters are very different. Certain of the lakes have already been investigated (Kjensmo 1970, Hongve 1974) and several studies are still in progress.

Data are now presented from Transjøen a calcium rich meromictic lake which is influenced by groundwater and has some extraordinary redox and sulphate conditions in the monimolimnic waters.

Description of the Study Area

Transjøen is situated at 172 m a.s.l. in south-eastern Norway, about 60 km north of Oslo (60° 13' N.B., 11° 08' E. Gr.). Morphometric data are given in Table 1. The lake basin is a combination of at least two kettle tarns. The north basin is 15.3 m deep and the south basin 21.9 m, and the basins are separated by a ridge with a maximum depth of 3.6 m. Both basins are meromictic.

Table 1 - Transjøen, morphometric values.

	North basin	South basin	Whole lake
Surface area km^2	0.034	0.060	0.094
Volume 10^3 m^3	201	527	728
Maximum depth, m	15.3	21.9	21.9
Mean Depth, m	5.8	8.8	7.7

The lake is relatively well sheltered, but most exposed to southern winds. Because of the neighbouring hills which lie in a north-south direction the main wind direction is along the lake axis. The catchment area is small. Because of permeable deposits in this relatively small area, the lake is only marginally influenced by surface water supply. The lake has no inflowing stream, although there is an outflow stream at the southern end. The lake surface lies at the groundwater level and the only visible inlets are three small groundwater springs along the western side. Therefore, the chemical composition of the lake water is mainly determined by the chemical composition of the groundwater.

According to Norges Geologiske Undersøkelse the area consists of about 50-60% gneiss, the remainder consisting of Cambro-Silurian sediments, quartzite and sparagmite.

The depth contours of Transjøen and the direction of the groundwater flow are shown in Figs. 1 and 2. The average chemical composition of the two springs A and B in Fig. 1 is shown in Table 2. The low position indicates considerable differences in the chemistry of the groundwater flowing into the lake.

There is a groundwater well which pumps about 6000 1/min only a few metres west of the north basin. It is clear that this pumping will decrease the groundwater pressure on the basin, with the result that the groundwater flow through the south

Table 2 - Average values of selected factors in springs *A* and *B*.

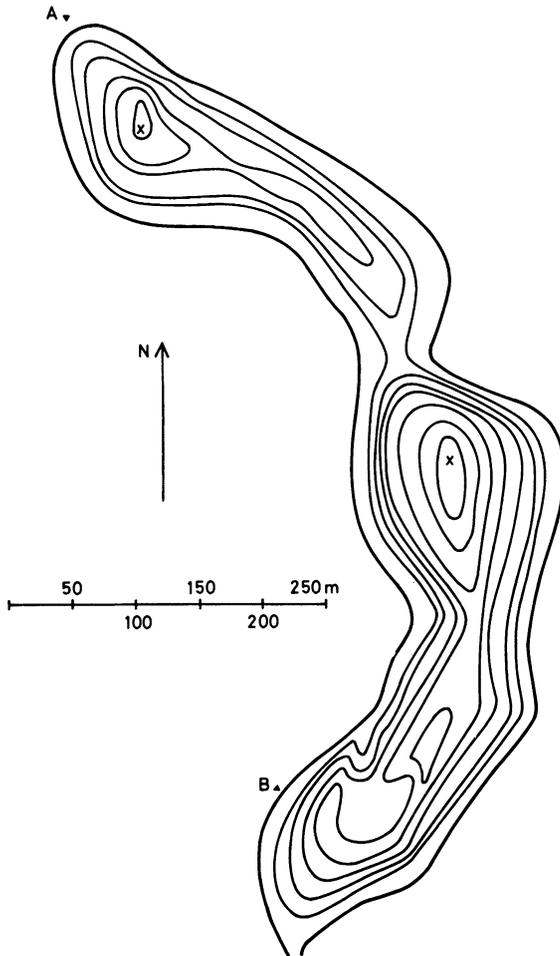|	Temp. °C	pH	H$_{18}$ S/cm	Alk meq/1	Ca mg/1	Mg mg/1	Na mg/1	K mg/1	Fe mg/1	Mn mg/1	SO$_4$ mg/	Cl mg/1	PO$_4$ mg/1
A	5.9	7.4	192	2.14	41.3	2.7	2.3	1.0	0	0	7.9	2.0	0
B	6.3	7.3	434	4.60	83.7	8.1	18.1	1.9	0	0	22.2	22.7	0

Fig. 1. Bathymetric chart of Transjøen. Contour interval 3 m.

basin is much greater than through the north. This difference in flow rate and chemical composition of the groundwater causes chemical differences in the two basins.

Meterological observations are available from Gardermoen, about 2 km south-west of Transjøen. The winter of 1970 was colder than normal while air temperatures during the rest of the investigation period were near normal. The mean annual air temperature was 4.3°C. Annual precipitation was about 800 mm during both years, which is not far from the 30 years' average.

It is presumed that the groundwater which enters the lake is the main reason for the development of the meromixis.
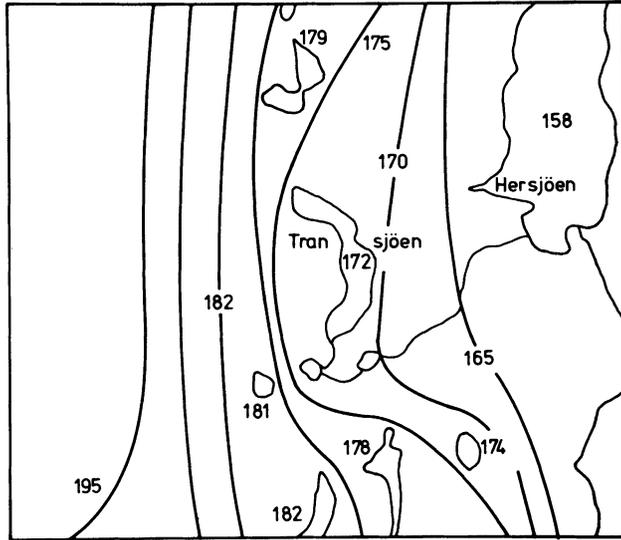
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Fig. 2. Groundwater isobaths of the study area. (Unpublished data.
Norges Geologiske Undersøkelse. Østmo og Klemetsrud).

Methods

Depth: The lake was sounded by means of a Marconi-Ferrograph Inshore Graphic Echo Sounder.

Temperature was measured by a Richter and Wiese reversing thermometer.

Water samples were taken using a Ruttner water sampler. Stoppered glass bottles were employed for oxygen (hydrogen sulphide) and alkalinity. Polyethylene bottles were used for the other analyses.

pH determinations were made with a Hellige colour comparator until February 1971 and subsequently with an electrical pH meter (Radiometer 29).

Transparency and lake colour: A rectangular Secchi disc, 13×18·cm², was used (Strøm 1943).

Water colour as mg Pt/l was measured by a B.H.D. Lovibond Nessleriser.

Oxygen: The unmodified Winkler method described by Gaarder (1915/16) and Fox's tables for saturation were used.

Alkalinity: Direct titration with N/10 HCl according to Mackereth (1963) was employed.

Specific conductivity: A Philips Philoscope apparatus was used. The values are expressed as myohm-¹ at 18° C. (H18, myS/cm).

Chloride was titrated potentiometrically (American Public Health Association 1962).

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Sulphate was taken as the difference between the concentration of strong acid salts and the chloride concentration. Total strong acid salts were determined by the ion-exchange procedure of Mackereth (1963).

Total iron was measured by the orthophenatrolin method (American Public Health Association 1962).

Total manganese: The persulphate method was used (Mackereth 1963).

Calcium and magnesium were determined by E.D.T.A. titration.

Sodium and potassium were determined by use of an E.E.L. Flame photometer.

Redox potential was measured by a Radiometer 25 pH meter according to Golterman (1971).

Primary production was estimated by the C-14 method (Vollenweider 1969).

Optics

Transparency varied between about 3 m and 6 m with maximum values during winter and summer. Lake colour was generally green, with some yellow during the winter. Water colour measured as mg Pt/1 was always less than 5. Measurements of spectral composition showed that green light penetrated deepest. About 1% of these wavelengths remain after about 8m, while the blue and red wavelength are reduced to 1% by about 6m.

Primary Production

Primary production was estimated from January 1971 to October 1971. The phytoplankton production was low and was estimated to be 30 g $C/m^2/yr$, varying from about 310 mg $C/m^2/day$ on 6 June to 40 mg $C/m^2/day$ on 12 October. During the period of ice cover it was less than 1 mg $C/m^2/day$. The dominating algae were *Cyclotella comta* and small green flagellats (my-algae).

The primary production of the purple bacteria below 8 m was not measured.

A rich reed bed, dominated by *Typha latifolia* and *Scirpus lacustris* surrounds most of the lake. In deeper waters there is a luxuriant growth of floating and submerged vegetation. The dominating species are *Hippuris vulgaris*, *Potamogeton lucens* and *P. natans*. *Chara strigosa* and *C. aculeoluta* also occur along the western side.

Temperature

During summer the temperature is highest and the thermocline deepest in the north basin. This is a little unexpected because the north basin is more sheltered from the wind and has a smaller surface area and therefore the thermocline would be expected to lie higher than in the south basin. This temperature development is mainly due to the groundwater well in the north which tends to decrease the groundwater influx. In
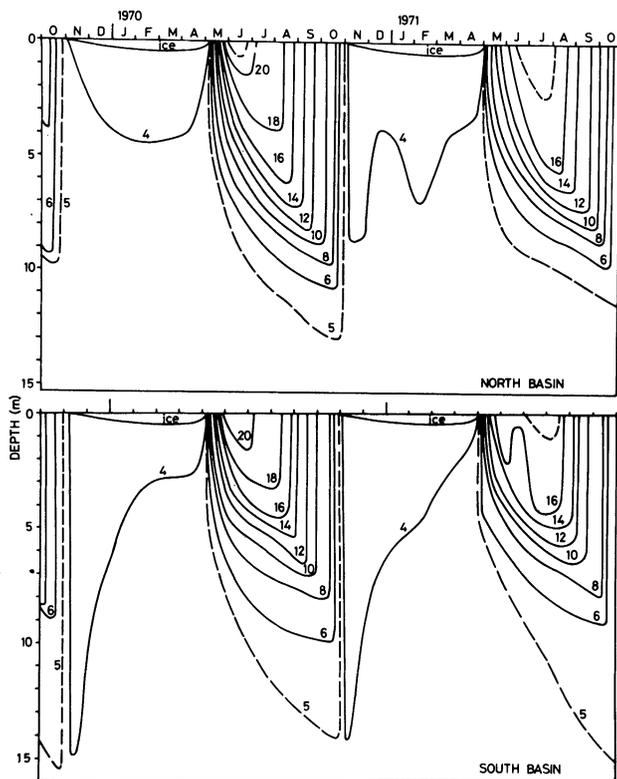
Fig. 3. Depth-time diagram of the distribution of temperature (°C) in Transjøen.

the south the influx is much larger and this supply of cold groundwater will act against the natural development of the thermocline and cause it to lie at a higher level.

During the course of the winter the temperature between about 3 and 12 m depth rose about 0.3°C. This was mainly due to groundwater exchanging with the lake water, but exothermic chemical processes in the water and the supply of heat from the sediments may be of importance.

Oxygen

The isopleths are shown in Fig. 4. The circulating waters had an oxygen concentration of about 60% saturation just before ice formation. This rather low value is a result of several factors, of which the most important seem to be the short period of circulation and mixing with the underlying oxygen free water.

Oxygen values rose in the upper strata after ice break and during 1970 they reached 113% saturation. The values are somewhat lower in the south basin probably
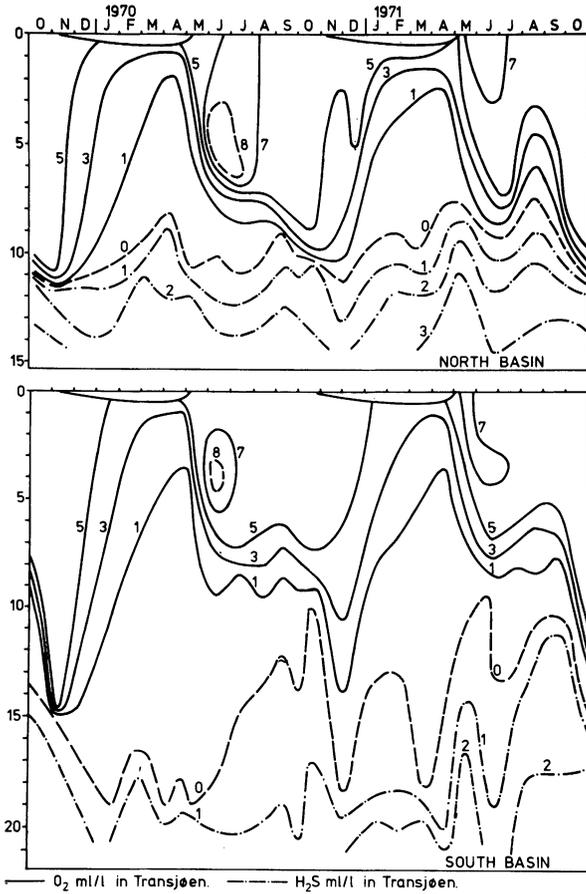
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Fig. 4. Depth-time diagram of the distribution of dissolved oxygen
and hydrogen sulphide in Transjøen.

because of the greater groundwater influx.

In late summer and autumn 1970 several alternating strata of oxygen and hydrogen sulphide were observed (Fig. 5). These strata are caused by sublacustrine groundwater which contains oxygen. A search was made for these sublacustrine inlets, but they were not found. However the farther south one goes along the lake the more electrolyte rich is the groundwater. It is therefore presumed that the deepest oxygen »pockets« have their origin in the southern end of the lake. The temperature of the groundwater and the deeper lake waters are similar and thus the strata in which the groundwater stabilizes is chemically determined. The chemical stability is great and therefore the depth of each stratum is small (Fig. 5). In subsequent years the work was concentrated more on biological factors, and this oxygen pattern was not observed.
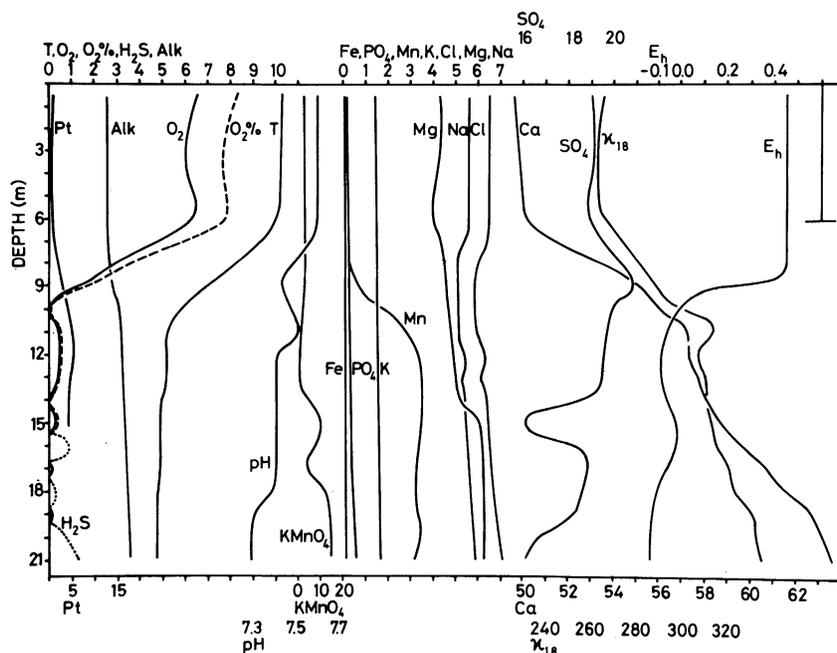
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Fig. 5. Hydrographical diagram from Transjøen, south basin, on 30.09.70. Temperature in $^\circ$C, O_2 and H_2S as ml/1, $O_2\%\cdot 10^{-1}$, Alk as meq/1, $KMnO_4$, Ca, Fe, Mn, K. Cl, Mg, Na, SO_4, PO_4 as mg/1, E_h as volt and Pt as mg Pt/1.

Alkalinity and pH

Alkalinity is rather high as may be expected from the high calcium content. In the trophogenic stratum (upper layer in which organic production takes place) values vary from less than 2.40 meq/1 in the summer to more than 2.60 meq/1 in the winter. This decrease is mostly due to biological factors, and perhaps to a lesser extent to dilution by melt water. In the monimolimnion there are small variations, the values being around 3.50 meq/1.

Values of pH in the mixolimnion (the upper layer which periodically circulates) vary from 7.4 to about 8.5 from winter and summer. In the monimolimnion pH varies from 7.2 til 7.4. In the winter a maximum was observed in the strata around the chemocline. This maximum is certainly due to the photosynthetic activity of the purple bacteria existing in this stratum. This photosynthesis also occurs during the summer, but it was not measured.

Specific Conductivity

Specific conductivity is rather high. In the trophogenic stratum it varies from about 270 in the winter to about 240 uohm-1 in the summer. This decrease is caused mainly

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by biological CO_2 uptake and the resulting precipitation of $CaCO_3$. In the monimo-limnion variation is caused mainly by differences in groundwater influx, the values being about 340-370 uohm-[1] and usually a little higher in the south than in the north basin.

Calcium

Transjøen is very rich in calcium as can be seen from the isopleths in Fig. 6. In the upper water masses the calcium content varies between about 54 mg Ca/l in the winter and about 47 mg Ca/l in the summer. The decrease from winter to summer values is thought to be caused largely by biological CO_2 uptake with the resulting precipitation of calcium carbonate. During the summer a relatively thick layer of precipitated calcium carbonate is apparent in the littoral zone. In addition dilution due to melt water and rain certainly has some influence on the Ca decrease. Accord-
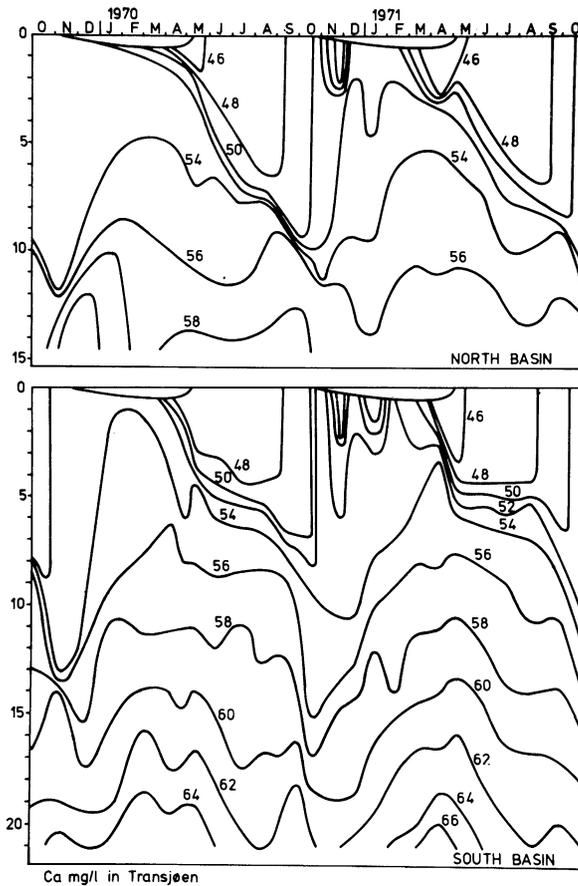
Depth-time diagram of the distribution of calcium (mg Ca/ l) in Transjøen.

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ing to Ohle (1952) it is most likely that there is always some calcium carbonate in suspension in a lake so rich in calcium and in Transjøen this suspended calcium carbonate is probably influencial in producing the green colour of the lake.

During the autumn and winter the calcium content increases in the circulating water masses because deeper strata containing more calcium come into circulation. In addition, CO_2 from decomposition renders the precipitated $CaCO_3$ soluble.

In the monimolimnion the CO_2 content increases, resulting in more of the precipitated $CaCO_3$ coming into solution. This may have been an important factor in the initiation of meromictic stability, and is surely of great importance for its maintenance. In this way one can say the meromixis is more or less biologically determined.

Magnesium, Sodium, Potassium, and Chloride

The magnesium content in the mixolimnion was about 4-5 mg/l while in the monimolimnion it seemed to be somewhat higher. No stratification was apparent for sodium, potassium and chloride. The values were: sodium 5-6 mg/l, potassium 1.5-2 mg/l and chloride 6-7 mg/l. The values were a little higher in the south than in the north basin because of the groundwater.

Redox Potential, Iron, and Manganese

The values for the redox potential are given as E_h because a complete lack of oxygen in monimolimnion means several redox systems other than oxygen are involved and will influence the total potential. In the aerated mixolimnion E_h was always between 0.40 and 0.50 volt, which according to Hutchinson (1957) is a normal value for aerated water. In the monimolimnion the values were negative, between -0.10 and -0.15 volt.

The north basin always had slightly lower values than the south basin, supposedly because of the greater groundwater supply in the south. It is difficult to give an explanation for the extraordinarily low potential and to say which redox system is dominating. Hutchinson (1957) assumed that in the meromictic Lake Mary hydrogen sulphide was of great importance in producing the low potential. Kjensmo (1967) assumed that in the meromictic lake, Store Aaklungen, iron was the dominating factor. In Transjøen the potential is considerably lower than in the former lakes. There is some manganese and hydrogen sulphide in the bottom waters which certainly influence the potential, but whether these two components alone can produce such a low potential is uncertain.

In the circulating periods there is a sharp distinction between oxydating and strongly reducing conditions. In the stagnant period there is a wide region with little oxygen where several redox systems are involved. On 28 April 1970 the oxygen content at 15 m depth was 0.07 ml/l and the E_h was -0.04 volt, while at 18 m depth there were 0.29 ml O_2/l and 0.06 volt.

Table 3 - Redox values in Transjøen, north basin, 1970

Date	3.3	8.4	28.4	12.5	9.7	13.8	30.0
Depth m							
3	0.38	0.42	0.37	-	0.41	0.44	0.45
6	0.33	0.41	0.36	0.40	0.40	-	0.45
9	0.31	0.34	0.25	0.31	-	0.42	0.45
10	-	-	-	-	-	-	0.06
11	-	-	-	-	-	-	0.13
12	-0.11	-0.13	-	-0.14	-0.11	-	-
13	-	-	-	=.	-	-	-0.14
14	-0.10	-0.14	0.11	-0.14	-0.14	-0.12	-0.13

Table 4 - Redox values in Transjøen, south basin, 1970

Date	3.3	8.4	28.4	12.5	9.7	13.8	30.9
Depth m							
3		0.42	0.37	0.41	0.40	0.44	0.46
6		0.41	-	-	-	-	
9		0.42	0.37	0.41	0.39	0.43	0.18
12		0.41	-	-	-	-0.03	-
13		-	-	-	-	-	-0.09
15		-	-0.04	0.34	-0.11	-0.12	-0.02
17		-	-	-	-	-	-0.06
18		-	0.06	0.04	-0.12	-	-0.10
21		-0.08	-0.11	-0.12	-0.12	-0.13	-0.13

As expected from waters with a pH greater than 7.0 and hydrogen sulphide concentration of 3-5 ml/l, only traces of iron were found in Transjøen.

Manganese goes into solution at a higher redox potential than iron (Mortimer 1941/42) and manganese will not precipitate as manganese sulphide under conditions such as those existing in Transjøen (Hutchinson 1957).

The redox potential and manganese content follow each other very closely. There was usually more manganese in the north than in the south basin. This is most probably due to the greater groundwater supply in the south. The highest value measured was 6.1 mg/l, on 9 July 1970. Especially in north basin there was a maximum in the upper anaerobic stratum. Such a maximum has been observed relatively often (Ruttner 1931, Einsele 1940 and Kjensmo 1967). There may be several explanations for such a hetrograde distribution (for uneven, vertical distribution of concentration). In the present case, the main reason is that when the circulation starts, manganese in the highest stratum becomes oxidized and sinks down and reaching sufficiently reducing condition it again goes into solution and accumulates in this stratum.

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Sulphur and Hydrogen Sulphide

The sulphate content in the mixolimnion was higher during the winter than during the summer. According to Devlin (1966) and Odum (1971) sulphate is an important factor in the biological cycle. The decrease from winter to summer is perhaps at least partly due to biological uptake. Another factor which may have some bearing is dilution by melt water and rain. In the south basin the sulphate content was 1-2 mg/l higher than in the north basin because of groundwater differences. There were a great deal of purple bacteria in both basins in the stratum between aerobic and anaerobic conditions.

With a redox potential well below 0 volt one should, according to Mortimer (1941/42), expect that all sulphate would be reduced to hydrogen sulphide. In both basins the observed amounts were very variable. In the north the values in the monimolimnion varied from 12 to 18 mg/l and in the south from 20 to 24 mg/l. It may be that the sulphate measured was due to chemical oxydation of hydrogen
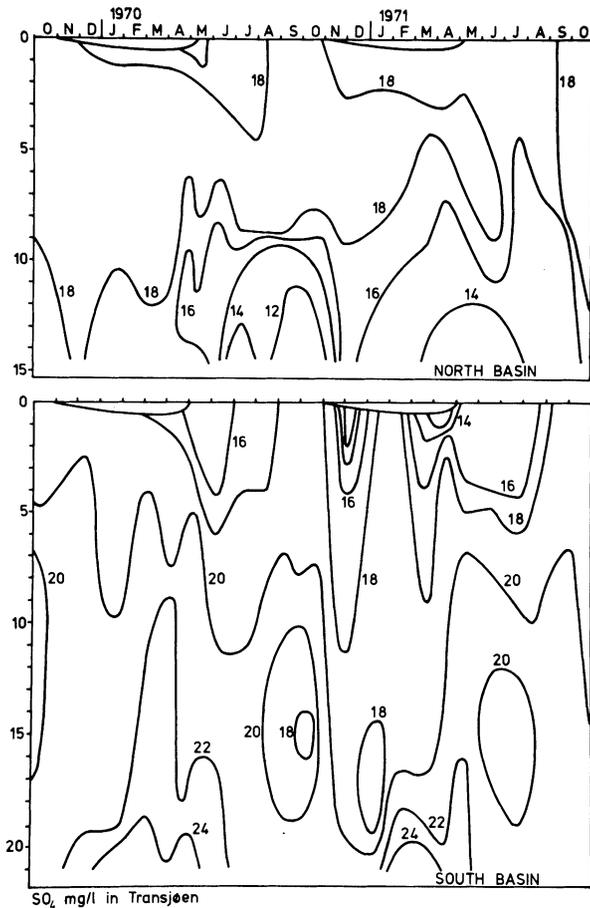

Fig. 7. Depth-time diagram of the distribution of sulphate (mg SO_4/l) in Transjøen.

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sulphide during the time between sampling and analysis. However, the hydrogen sulphide content never equalled the sulphate content found, so there must therefore be some sulphur in the monimolimnion in a higher oxidized state than sulphide. There are two explanations, either the supply of sulphate from the groundwater is so great that the reducing capacity is insufficient to reduce all the sulphate entering the monimolimnion or according to Ohle (1955) lack of organic matter which can act as a hydrogen donor may be a reason why sulphate is not reduced to hydrogen sulphide. In Transjøen the organic production is low and together with bacteriological sulphate reduction it is too low for all sulphate to be transformed to hydrogen sulphide. The water from monimolimnion was several times observed to become »milky«. According to Stumm and Morgan (1970) free sulphur can exist in water under certain conditions. The »milky« water in Transjøen may also be due to free sulphur which is oxidized from hydrogen sulphide by the layer of photosynthetic bacteria (Butlin and Postgate 1954).

Summary

Physical and chemical properties were studied in Transjøen, a lake in south-eastern Norway, (60° 13'N.L. and 11° 08.E.Gr.) situated 172 m a.s.l.

The lake is influenced to a great extent by groundwater of different chemical composition. This is of great importance for the moromictic development of the lake. Primary production due to phytoplankton is low, but macrovegetation is rich. The groundwater is of importance for the temperature development in the lake. Several strata with oxygen and hydrogensulphide above each other, caused by groundwater containing O_2, were found entering the monimolimnion.

Alkalinity was high and pH variations were relatively small. Specific conductivity was determineded mainly by the calcium bicarbonate content. The calcium content is high calcium carbonate precipitating during the summer and being of importance for the meromictic stability. The redox potential is extremely low, there was no correspondance between oxygen and redox potential. As expected only traces of iron were found. Manganese was found to have a positive hetrograde distribution in early circulating periods. In spite of the low redox potential sulphate was found in monimolimnion. Considerable groundwater influx yielding sulphate to the deep water and insufficient chemical and microbiological sulphate reduction may explain this. The monimolimnic water was sometimes »milky« possibly due to oxidation of H_2S to sulphur by photosynthetic bacteria and chemical oxidation.

Acknowledgements

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