

Recent Hypolimnetic Sediment in Lake Gjersjøen, a Eutrophicated Lake in SE Norway

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During the last decades Lake Gjersjøen has developed from an oligotrophic state to a level of high eutrophy. The present state is characterized by an intense primary production in the trophogenic zone and anaerobic conditions in the lower part of the hypolimnion during periods of thermal stratification.

The deterioration of the lake as a resource has resulted in research on main components of the ecosystem. Most of the limnological data about the lake are to be found in Johansen (1955), Skulberg (1968), Norwegian Institute for Water Research (1969, 1972), Holtan (1972) and Lillevold (1975).

The intention of the present investigation was to reveal in which way the rapid eutrophication has been manifested in the hypolimnetic sediments and to search for processes in the sediment that could influence a suggested development towards meromixis. This investigation may provide data for further and more specific research on the sediments in Lake Gjersjøen.

The Lake Investigated

Morphometrical and hydrological data of Lake Gjersjøen are given in Table 1 and the bathygraphical map appears in Fig.1. The lake is situated in south-eastern Norway in the Oslofjord area (Fig.1.). The maximum depth is 64 m and the depth of cryptodepression is 22 m. The lake is rather long and narrow, situated in a hilly terrain and is therefore only moderately exposed to wind. The bedrock consists of

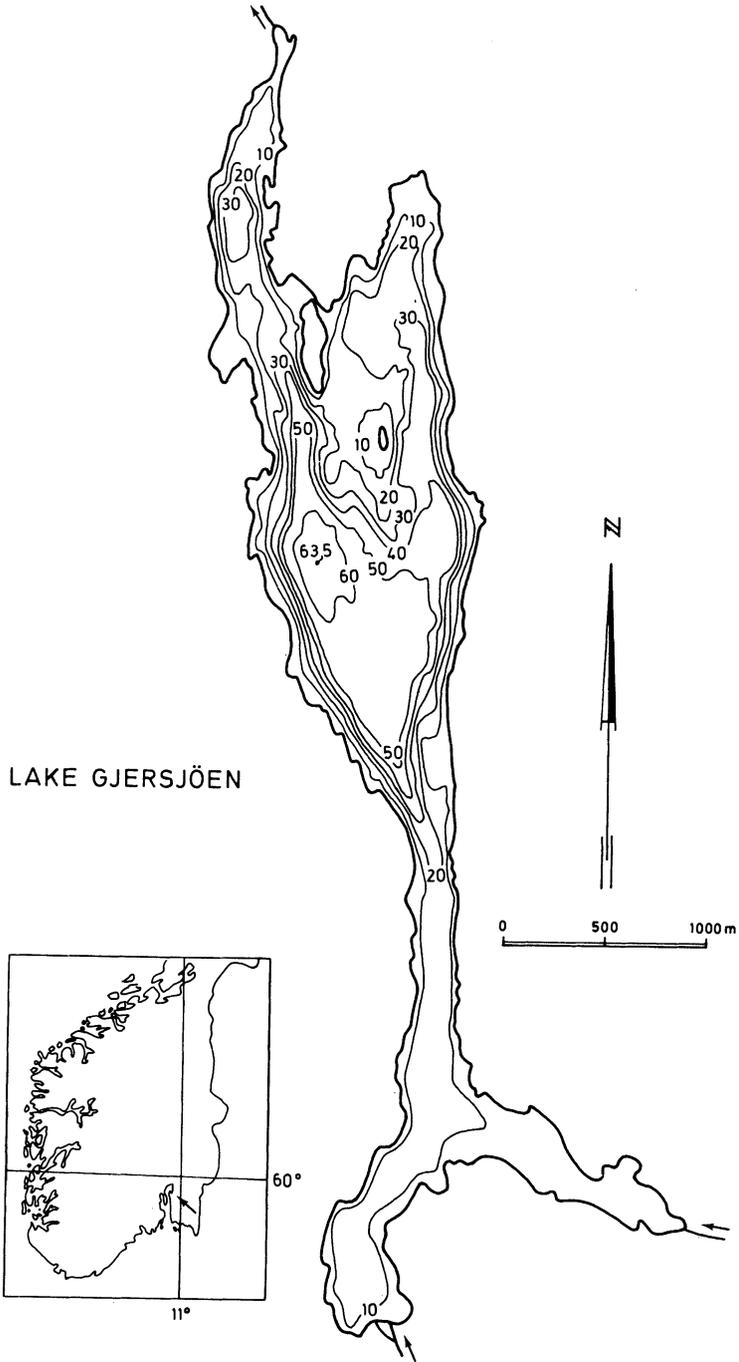


Fig. 1. Situation and bathymographical map of Lake Gjersjøen.

Table 1 - Morphometrical and hydrological data of Lake Gjersjøen (Skulberg 1968, Holtan 1972).

Altitude above sea	42 m
Surface area (A)	2.68 km ²
Catchment area	84 km ²
Maximum depth	64 m
Volume (V)	61.2×10 ⁶ m ³
Mean depth (V/A)	23 m
Maximum length	5 km
Maximum width	0.9 km
Average drainage	1.3 m ³ /sec
Theoretical renewal	1.5 years

Table 2 - Mean values of main constituents in the water of Lake Gjersjøen (Holtan 1972).

Component	Ca	Mg	Na	K	HCO ₃	SO ₄	Cl
Concentration (mg/l)	9,5	2,3	5,3	2,2	31,7	8,6	9,6

gneiss and gneiss granites. The drainage area is partly covered by quaternary marine deposits. The chemical data given in Table 2, show that compared with most lakes in Norway the content of dissolved salts in the lake water is rather high (see Kjensmo 1966). The relatively high salt content and the chemical composition are the result of the watershed location below the marine limit (Holtan 1972).

From 1964 onward water blooms of blue-green algae (especially *Oscillatoria agardhii*) began to appear annually. Due to algal blooms the water in the trophogenic zone is supersaturated with oxygen and obtains high values of pH.

In the course of eutrophication the lake has reached a high level of primary production: 270 gC/m² for the year 1973 (Lillevoold 1975).

The oxygen consumption has resulted in anaerobic conditions for long periods in the lower part of the hypolimnion. During anaerobic conditions iron and manganese compounds are reduced in the sediment, migrate into the water and accumulate in the lower part of the hypolimnion together with nutrients, especially phosphorus compounds. Hydrographical and biological conditions in lakes are to a high degree a function of geology, soil, vegetation, and human activities in the drainage area. In Lake Gjersjøen this is illustrated by loading estimations. For the year 1972 the net input of inorganic matter, mainly clay, was 429 g/m² surface of the lake, and that of organic matter was 37 g/m² surface of the lake (Lillevoold 1975). The net input of total phosphorus the same year was 0.81 g P/m² and that of total nitrogen was 9.8 g

N/m² surface of the lake (Holtan 1973). During the year 1972 the lake received untreated or mechanically treated sewage from a population of approximately 15,000 persons (Holtan 1972).

Discussing the eutrophication of Lake Gjersjøen Holtan (1972) stated that the eutrophic development of the lake was undoubtedly due to support of sewage and industrial waste water. He emphasized that Lake Gjersjøen in its original state contained a heavy concentration of allochthonous organic matter (humic substances) and that dystrophic lakes in general are unsuitable as recipients of polluted water.

Owing to morphometry and moderate exposure to wind the biannual overturns last for a short time and the water does not obtain any high degree of oxygen saturation before thermal stratification appears. These inefficient overturns together with anaerobic conditions and accumulation of dissolved salts in the lower part of the hypolimnion have resulted in a probable development towards meromixis (see Norwegian Institute for Water Research 1969).

Methods

Sediment Sampling

Two sediment cores (both ca. 80 cm long) were collected from the central, deepest part of the lake basin by means of a sampler described in Züllig (1956, Fig. 2.) One core was cut out into slices of 5 cm length with the exception of the interval between 15 and 25 cm below the sediment surface. These samples were destined for analyses of the total amounts of elements and the amount of extractable ions. The second core was cut into seven slices and the samples uses for analyses of interstitial water.

Analytical Methods

Water content: loss of weight after drying at 110°C for 24 hours.

Ignition loss: loss of weight after ignition at 600°C for 1 hour.

Total amounts of elements: the method described by Mackereth (1963, 1966).

Sedimentary chlorophyll: a slight modification of the method given by Vallentyne (1955). Concentration of sedimentary chlorophyll is calculated according to the definition given by Vallentyne (op.cit.)

Extractable cations: 2 g of fresh sediment was soaked in 25 ml 1 N ammonium acetate (pH 7), continuously shaken overnight and then filtered (Whatman GF/C).

Interstitial water: fresh sediment was centrifuged at 4000 r/min for half an hour and then filtered. pH was measured immediately after centrifugation by means of Radiometer pH-meter 29.

Iron, manganese, calcium, magnesium, copper, zinc and lead were determined on a Perkin-Elmer Atomic Absorption Spectrophotometer Mod. 303.

Sodium and potassium were analysed by flame photometry (EEL). Phosphate-phosphorus was determined colorimetrically with antimony molybdate and ascorbic acid (Golterman 1969). Chloride was analysed by potentiometric titration according to the American Public Health Association (1962). For colorimetric analyses a Zeiss Spektralphotometer PMQ II was used.

Hydrographical parameters are analysed at the Norwegian Institute for Water Research.

Results and Discussion

Hydrographical conditions at the time of sediment sampling (Figs. 2&3).

The vertical distribution of temperature showed that the summer stratification was almost broken down and the autumn overturn was imminent. The concentration of oxygen was decreasing rapidly with depth. At the depth of ca. 30 m the percentage of saturation was ca. 30; below the depth of ca. 55 m there were completely anaerobic conditions and hydrogensulphide was present.

Below the depth of ca. 55 m the concentration of iron and manganese increased very markedly owing to reduction of these elements in the sediment and migration into the water. The higher concentration of manganese in relation to iron in the upper part of the hypolimnion depends on the reduction of manganese at a higher redox potential than iron. The chemical conditions below the depth of ca. 55 m will allow precipitation of iron and sulphide as heavy soluble FeS. The marked increase in phosphorus compounds below the depth of ca. 55 m depends primarily on liberation of phosphorus in the sediment.

As can be seen from Fig.3 the total amount of nitrogen increase very markedly in the anaerobic zone below the depth of ca. 55 m. At the depth of 59 m particulate nitrogen (measured as the difference between unfiltered and filtered water samples) constitutes ca. 49% of the total amount of nitrogen. This indicates an accumulation of particulate organic matter in the anaerobic zone where the degradation processes are slow. Nitrate is not present at the existing redox conditions below the depth of ca. 55 m. The remaining fraction of the total amount of nitrogen therefore constitutes of ammonia and dissolved organic compounds liberated by the degradation processes of organic matter in the water and the sediment. Unfortunately, no analysis have been carried out to separate these nitrogen compounds.

If the breakdown of stratification was complete this year a considerable amount of the accumulated nutrients in the deeper part of the hypolimnion might have supported the primary production in the trophogenic zone.

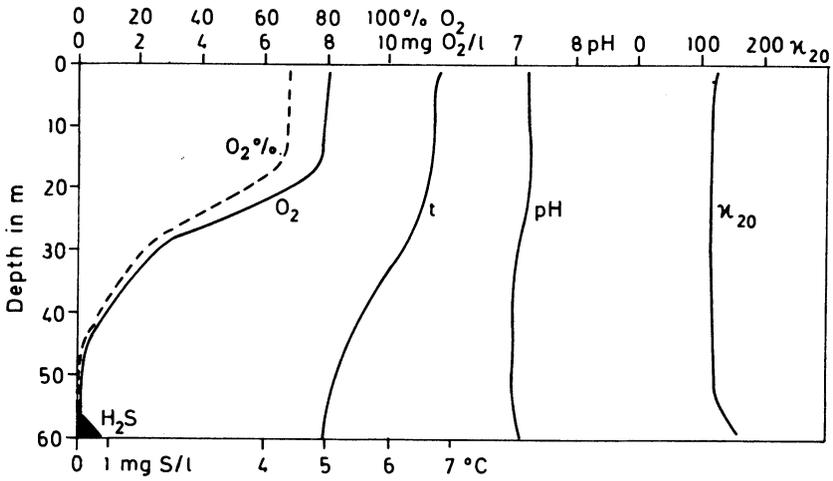


Fig. 2. Vertical distribution of oxygen, hydrogen sulphide, temperature, pH and specific conductivity, H_2O ($\mu S/cm$) in Lake Gjørsjøen, 29 October, 1973.

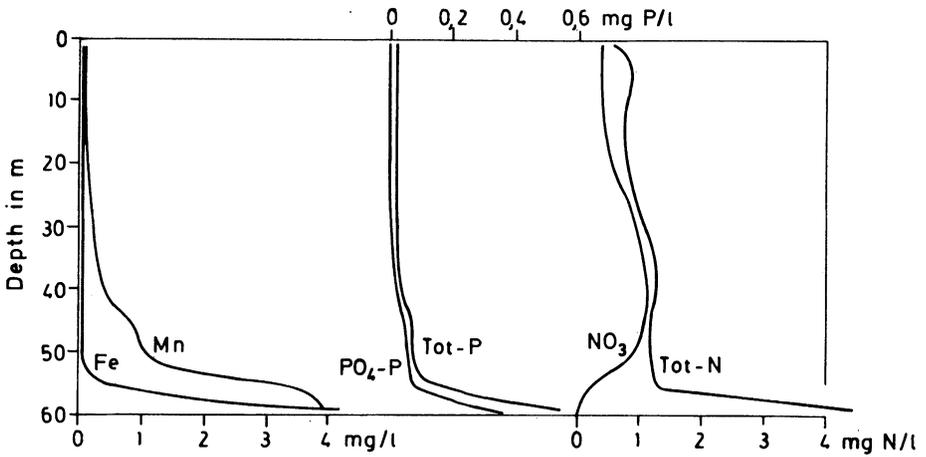


Fig. 3. Vertical distribution of total iron, total manganese, ortho-phosphate, nitrate and total nitrogen in Lake Gjørsjøen, 29 October, 1973.

Macroscopical description of the sediment cores

The two sediment cores showed exactly the same stratifications. On the basis of macroscopical examination the following description can be given.

0-15 cm. This interval was characterized as relatively unconsolidated, but clearly stratified gyttja. The upper 2 cm were completely black owing to FeS and there was formation of gas bubbles. Throughout this interval there were very distinct layers of FeS with layers of brown, grey or whitish colour between. Such stratifications might be expected in lakes where the oxygen concentration in the bottom water fluctuates during the year and no bottom fauna or turbulence disturbs the sediment. It is reasonable to assume that the amount of sediment between each layer of FeS represents the annual desposition. On this basis the following average rates of deposition may be calculated:

2-8 cm layer: 4-6 mm per year

8-15 cm layer: 2-4 mm per year

Accordingly, the upper 15 cm of the sediment might have been deposited during a period of 25 to 50 years.

15-18 cm. This interval consisted of homogeneous clay which was separated from the gyttja by very distinct boundaries.

This layer of clay must be the result of very drastic changes within the lake or its drainage area, and is probably induced by human activities. Activities like the clearing of forest, the clearing of ground, road construction or regulation of the watercourse might have caused an increase in erosion of the marine deposits in the drainage area. Unfortunately, there has been no success in recording such events historically. If successful, this would have given an excellent opportunity of dating the recent sediments. In this connection it may be mentioned that Edmondson (1969) estimated the mean rate of deposition in Lake Washington to be 3.1 mm per year (for a period of 50 years) on the basis of some sand beach that was redeposited in the deeper part of the lake basin when the lake level were lowered.

18-33 cm. The upper part of this interval consisted of clay gyttja with thin layers of FeS. The clay content decreased with depth and the lower part of this interval was characterized as brown gyttja with some thin layers of FeS. The layers of FeS indicate that the lake at this time was characterized by clinograde oxygen distribution, periodically anaerobic conditions and precipitation of FeS. Erosion of clay in the drainage area seems to have increased gradually during this periode.

33-48 cm. This layer consisted of brown gyttja with very fine layers of grey, brown and dark brown colour. There were rather few layers of FeS.

48-80 cm. The brown gyttja in this interval were occasionally interrupted by layers of grey and dark brown colour. There were no traces of FeS.

Content of Water, Ignition Loss and Sedimentary Chlorophyll

The vertical variation of water content and ignition loss is shown in Fig.4.

The water content varied between 70 and 80% with the exception of the less consolidated upper 5 cm in which the water content was ca. 90%.

In this investigation the ignition loss may be used only as an approximate estimation of organic matter. Mackereth (1966) pointed out that estimating the organic content from ignition loss may lead to serious error in largely inorganic samples. In the upper 35 cm of the sediment the ignition loss varied between 9.2 and 15.7%. Below 35 cm the variation was between 16.0 and 22.3%. The lower values of ignition loss in the upper part of the sediment depend primarily on the increase in deposition of inorganic matter, mainly as clay. Thus, ignition loss when calculated on dry weight basis does not reflect the increase in primary production during the eutrophication.

Total organic matter in the sediment is often used for interpretation of the trophic development of lakes. However, total organic matter calculated on a dry weight basis may be regarded as a too insensitive parameter for this purpose because it does

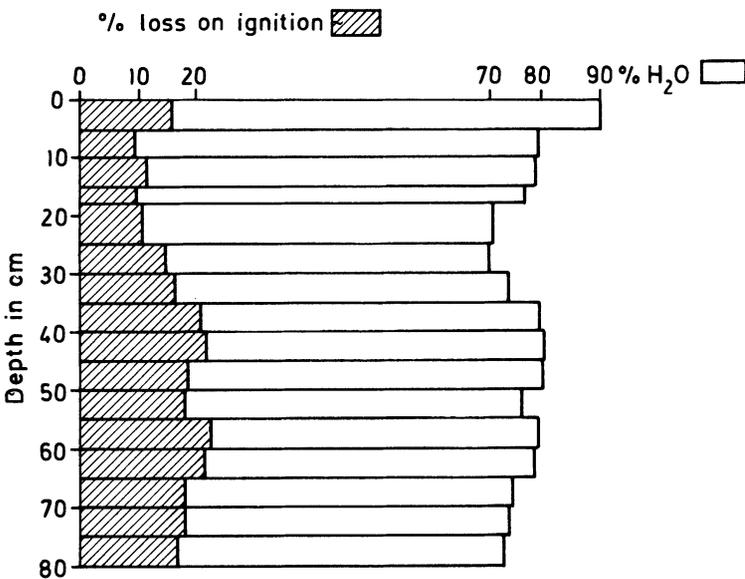


Fig. 4. Distribution in depth of per cent water content and loss on ignition in a hypolimnetic sediment core from Lake Gjørsjøen.

not discriminate between the sources of the organic matter i.e., autochthonous vs. allochthonous, and because the rate of deposition are only rarely known. Sedimentary chlorophyll has been shown to be a relevant parameter to indicate changes in productivities in the past (Wetzel 1970) and to characterize lakes with regard to trophic state (Gorham 1960).

The vertical variations in sedimentary chlorophyll are shown in Fig. 5. The allochthonous contribution to the sedimentary chlorophyll may be regarded as constant in this connection and the vertical variation in sedimentary chlorophyll in all essentials reflects the autochthonous primary production. Because of the relatively small variation in ignition loss the sedimentary chlorophyll when calculated on a dry weight and on an ignition loss basis shows the same pattern. When calculated on an ignition loss basis the sedimentary chlorophyll becomes independent on the deposition of inorganic matter. The very pronounced increase in the upper 15 cm evidently indicates the changes in productivity during the eutrophication. It may be mentioned that conditions for stability of chlorophylls against degradation have become more favourable owing to the more reduced hypolimnion during this period. However, the increase in sedimentary chlorophyll and the development of a more reduced hypolimnion are mainly effects of the same cause i.e. the change in trophic state of the lake.

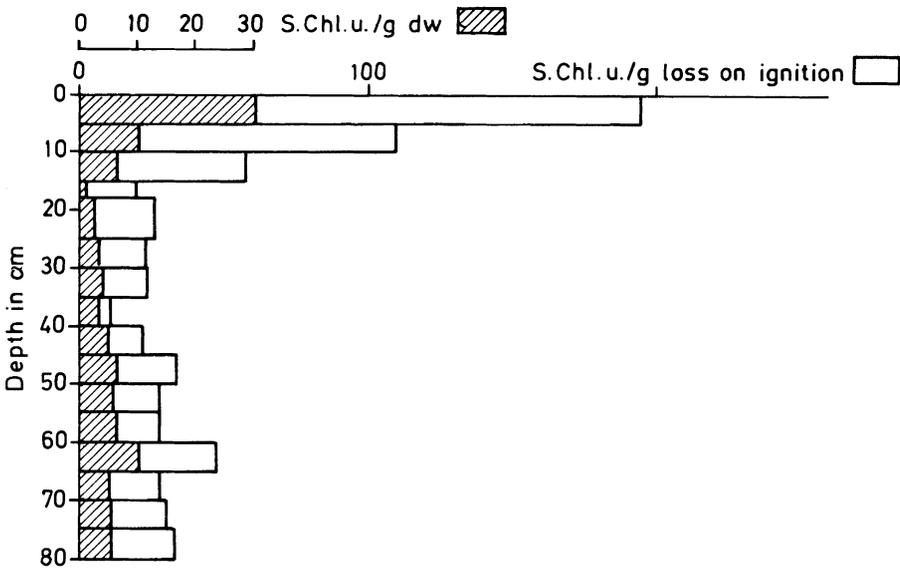


Fig. 5. Distribution in depth of sedimentary chlorophyll (S.Chl.u.) in a hypolimnetic core from Lake Gjørsjøen.

Total Amounts Elements (Fig.6)

Analyses of total amount of elements in sediments usually give little information concerning the availability of the elements in the biogeochemical cycles. On the other hand, total amounts of elements are often used to characterize the sediment with respect to origin and, for example, the degree of autotrophy/allotrophy.

In paleolimnological studies total amounts of elements are often used to reflect pronounced changes in limnological features of the lake and in the drainage area. Among the elements analysed in this investigation iron is the dominating element in the sediment, while calcium is dominating in the lake water. The deposition of calcium, magnesium, sodium, and potassium occurs independently of redox conditions, and these elements therefore show little vertical variation. A maximum of calcium and magnesium in the layer 35-40 cm below the sediment surface coincides with a minimum of sodium in the same layer.

Solubility of iron and manganese is highly dependent on redox conditions and the vertical distribution of these elements therefore shows significant variation.

There is no clear pattern of the distribution of iron, but the concentrations are highest in the layer 25-50 cm below the sediment surface. The marked vertical decrease above 25 cm may partly depend on a lower content of iron in the clay but the most important part of the decrease is due to reduction of iron in the sediment, migration into the water and transport out of the lake because of the development towards more reducing conditions during the period when the upper part of the sediment was deposited. The minor increase in iron in the upper 10 cm probably depends on reprecipitation of iron as FeS.

There is a very marked increase in manganese from 25 cm and towards the sediment surface. A possible explanation of this distribution is higher content of manganese in the clay or a marked increase in support of manganese to the lake in associations other than clay. However, neither of these explanations suffices. Lynn and Bonatti (1965) report a relatively high content of manganese at the top of several deep-sea sediment cores from the Pacific. They suggest that manganese dissolves upon burial in reduced sediments, then migrates and accumulates in the oxidized top strata. Such a post-depositional migration mechanism might be expected to work in freshwater too.

The vertical distribution of manganese in the sediment of Lake Gjersjøen can hardly be explained by the mechanism mentioned. The most serious objections to such a post-depositional migration mechanism in this case are the onset of reducing conditions and the long duration of the reducing conditions in the lower part of the hypolimnion during the eutrophication period.

One more possibility may be mentioned, namely the precipitation of manganese as $MnCO_3$. The diagenetic accumulation of manganese as $MnCO_3$ in the upper parts of reduced sediments in marine environment is well known (Mannheim 1961) and precipitation of $MnCO_3$ is shown to take place in freshwater (Hongve 1974). In the

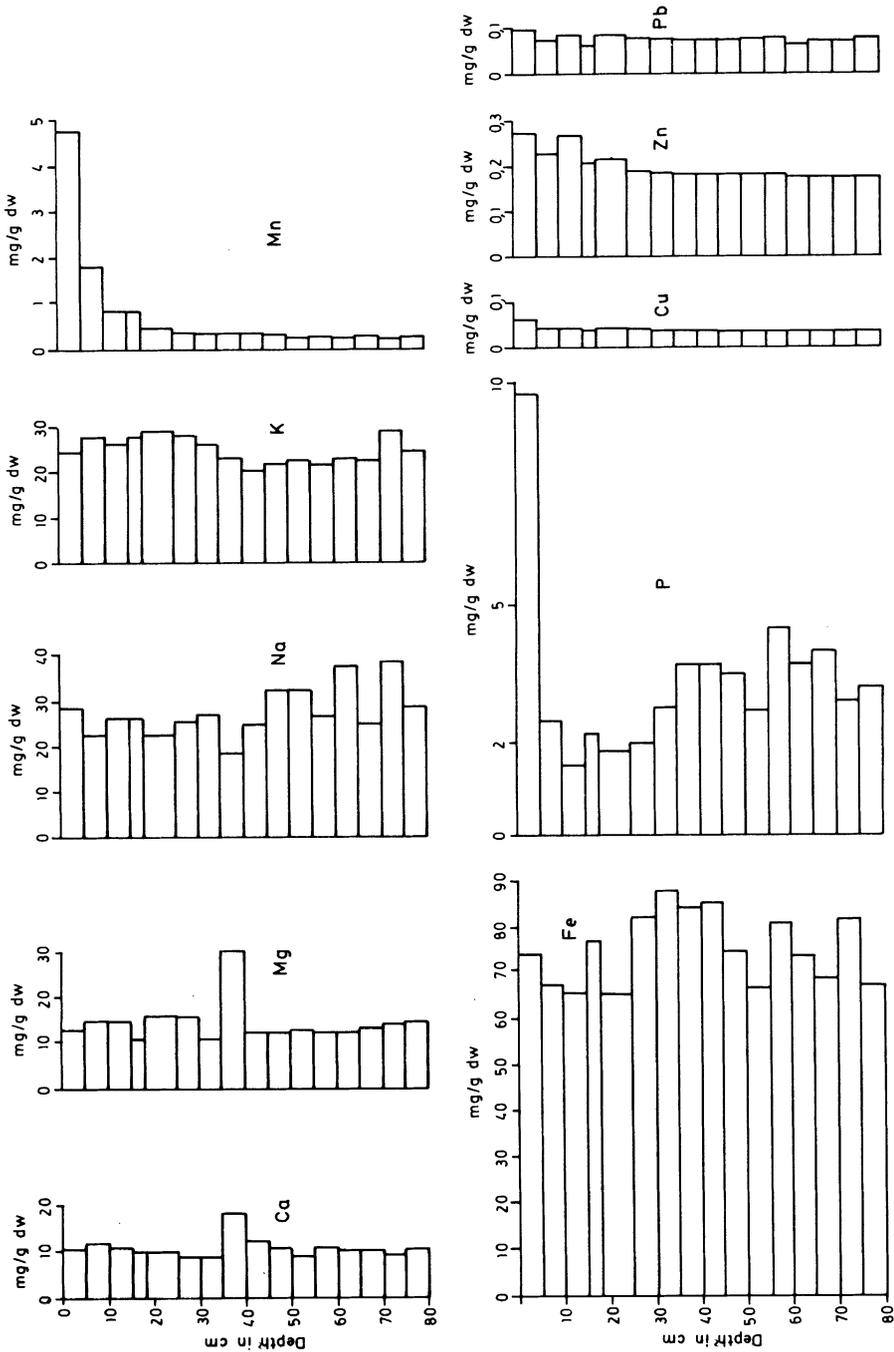


Fig. 6. Distribution in depth of total amounts (mg/g dry weight) of calcium, magnesium, sodium, potassium, manganese, iron, phosphorus, copper, zinc, and lead in a hypolimnetic sediment core from Lake Gjørsjøen.

interstitial water in the upper 15 cm of the sediment the concentration of manganese was 4.4 mg/l, the bicarbonate alkalinity was ca. 2.0 meq/l and pH was 7.4. Precipitation of MnCO_3 may be a possibility under these conditions and must be taken into account when explaining the vertical distribution of manganese.

The amount of total phosphorus in the layer ca. 35-80 varied between 2.7 and 4.5 mg P/g dry weight. From ca. 35 cm and upwards the amount decreased and there was a minimum of 1.5 mg P/g dry weight in the layer 10-15 cm. This decrease coincides with the increase in deposition of clay and the development towards periodic anaerobic conditions in the lower part of the hypolimnion during this period. In the uppermost ca. 5 cm the total amount of phosphorus was high; 9.5 mg P/g dry weight. This very pronounced increase may be explained in several ways. The increase may be related to the eutrophication of the lake and thus the increased loading of phosphorus during the recent years. According to Williams and Mayer (1972) it is difficult to relate higher total phosphorus values in the top of sediment cores to recent increased phosphorus loading of a lake because diagenetic processes may account for vertical variation in total phosphorus in a sediment core. The existence of not yet decomposed organic phosphorus compounds in the uppermost ca. 5 cm of the sediment core under the prevailing redox conditions seems reasonable.

The vertical distribution of phosphorus may be highly dependent on the distribution of iron and manganese. When consulting the papers of Tessenow (1973a, 1973b, 1974, 1975) it seems likely that the accumulation of these elements in the uppermost layers of the sediment core to some extent may be results of lateral concentration transfer from the surrounding sediment areas as well as vertical concentration transfer within the sediment itself. The sediment cores discussed in this paper are sampled from the anaerobic zone in the area of maximum depth of the lake. In order to elucidate the importance of the referred lateral and vertical concentration transfers more data, at least sediment cores from the transition zone between the anaerobic and aerobic zones and from the aerobic profundal zone should have been available.

Among the heavy metals copper, zinc and lead, only zinc has an significant increase in the uppermost ca. 25 cm.

It is not possible to decide the source of this increase in zinc, but the following interpretations can be suggested: The increase may be caused by a higher content of zinc in the clay. It may also be due to diagenetic processes. Further, it may be a result of the activity in the drainage area during the eutrophication period. Lastly, it may be explained by the lowered pH in the precipitation during the last years (Odén 1968, Odén and Ahl 1970), which would have increased the corrosion of zinc materials in the drainage area.

The weight ratio Fe: Mn

The weight ratio Fe: Mn (total amounts) in the sediment core are illustrated in Fig.7. This ratio was used by Mackereth (1966) to deduce information on redox conditions

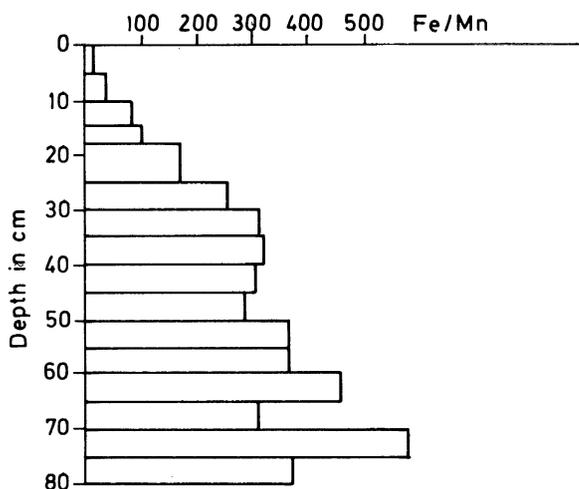


Fig. 7. Distribution in depth of the Fe:Mn ratio (on dry weight basis) in a hypolimnetic sediment core from Lake Gjersjøen.

in the soil in the drainage area and in the lake itself in a number of lakes in English Lake District. Kjensmo (1968) concluded on the basis of the Fe: Mn ratio that an increased supply of iron to the deep part of Lake Svinsjøen occurring ca. 2000 years ago seems to have been of the greatest importance for the initiation of the meromictic stability in this lake. For the reason for using this ratio it suffices to refer to the literature cited above. In this study it has not been possible by means of the Fe: Mn ratio to deduce the changes in redox conditions in the lake or its drainage area, but it probably reflects that profound changes have taken place.

Extractable amounts of cations (Fig.8).

The vertical variation of extractable calcium is insignificant, but there is a minimum in the upper 5 cm. On the other hand, the distribution of magnesium shows an approximately tenfold increase with depth in the sediment core. The extractable amounts of sodium and potassium varies considerably but there is a tendency to increase with depth in the sediment core.

The order of concentration of major cations in the lake water (Table 2.) and in the sediment (layer 0-5 cm) is the same: $Ca > Na > Mg > K$. According to Digerfeldt (1972) the concentration of these cations in the sediment (e.g.the extractable fraction) is largely determined by the ionic equilibrium between the concentration of dissolved ions in the lake water and the concentration of ions bound in colloidal systems in the sediment. However, the suggested influx of saline groundwater (see discussion on the interstitial water) may strongly affect the concentrations and vertical distribution of these cations in the sediment (i.e. the extractable fraction).

Copper has a significant increase in the upper 25 cm in the sediment but there is no significant variation in the extractable amounts of zinc and lead. The explanation for the increase in extractable amount of copper may be the same as for the distribution of total amounts of zinc.

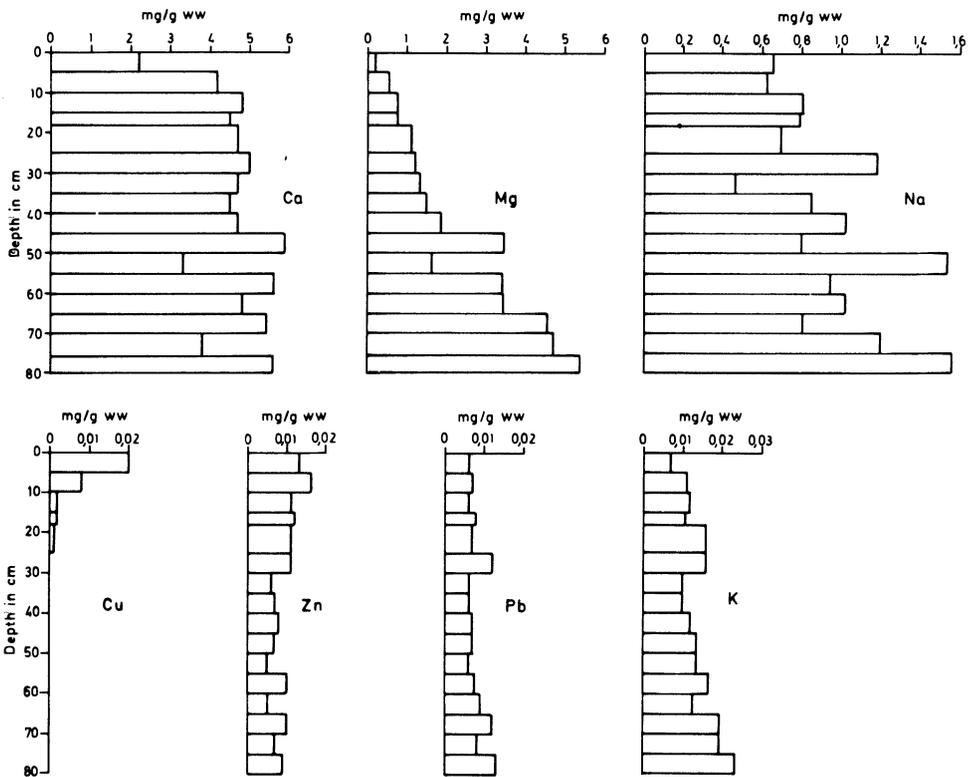


Fig. 8. Distribution in depth of extractable amounts(mg/g wet weight) of calcium, magnesium, sodium, potassium, copper, zinc, and lead in a hypolimnetic sediment core from Lake Gjørsjøen.

Interstitial Water (Fig.9.)

There is some vertical variation of calcium, but no clear pattern. Magnesium, potassium, sodium, and chloride all exhibit a marked linear increase with depth in the sediment. This increase may be interpreted as an influx of saline groundwater. In Fig. 10 the linear regression diagrams for chloride and sodium, chloride and potassium, and chloride and magnesium are given. The linear correlation coefficients are all very close to + 1.000 and they are all significant at 0.1% level. This clearly indicates the saline quality of the influx of groundwater. Nothing is known about the regional distribution within the lake basin of such groundwater influx. Even if this is a general property, at least in the central, deepest region, one may assume that groundwater will only contribute to the lake water composition to a minor extent.

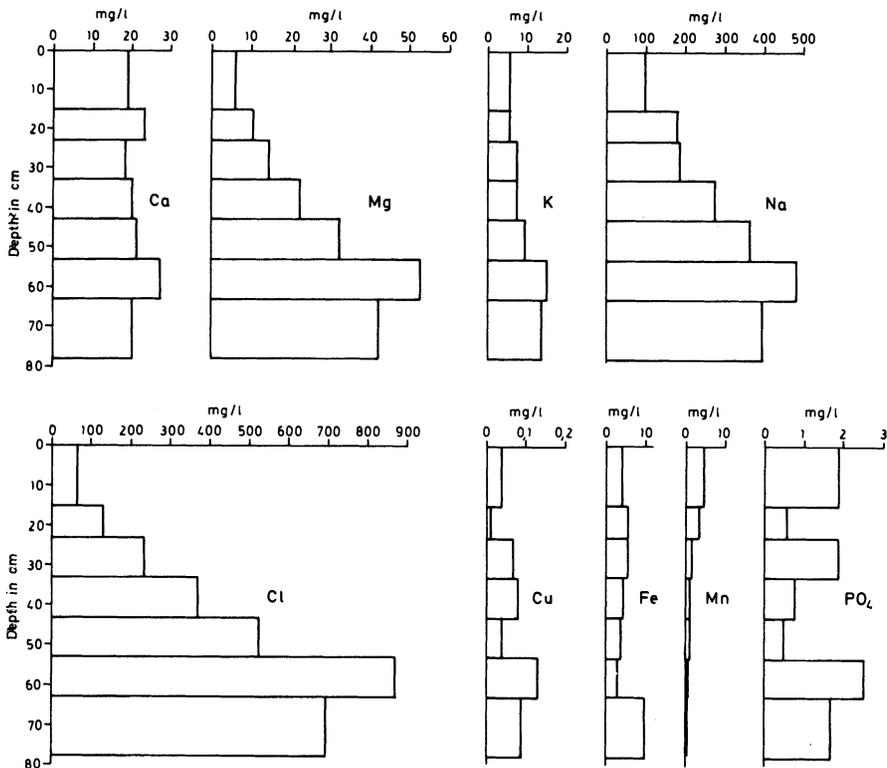


Fig. 9. Distribution in depth of calcium, magnesium, sodium, potassium, iron, manganese, ortho-phosphate, chloride/ and copper (mg/l) in the interstitial water in a sediment core from Lake Gjersjøen.

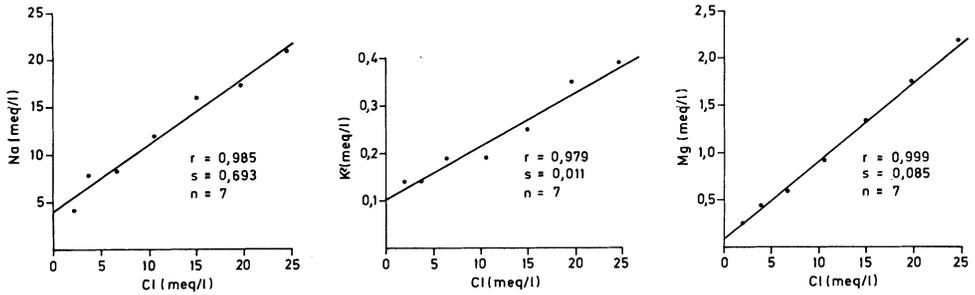


Fig. 10. Linear regression diagrams for Cl and Na, Cl and K, and Cl and Mg in the interstitial water in a sediment core from Lake Gjersjøen. The estimated linear regression lines are drawn (r = coefficient of correlation, s = slope for regression line, n = number of observations).

However, under conditions favourable for the origin of a meromictic stability, influx of saline groundwater might be expected to play an important role in rendering the lake meromictic. Studies on interstitial water from monimolimnetic sediments of Green Lake have demonstrated a possible influx of saline groundwater to the monimolimnion (Brunskill and Harriss 1969). These authors stated that this influx had been an important factor contributing to the origin and persistence of meromixis in Green Lake.

No estimations on the water balance or the chloride balance of the lake system, that might have supported the theory on influx of saline groundwater are available.

There is a regular increase in manganese upwards in the sediment. The concentration in the uppermost layer is ca. 4.4 mg Mn/l, which is of the same order as the concentration in the lower part of the hypolimnetic water.

There is a covariation of total amounts of manganese and manganese in the interstitial water.

The concentration of iron varies somewhat and the highest concentration is in the lowest part of the sediment core. However, this vertical distribution cannot be related directly to the influx of saline groundwater. pH in the interstitial water varied between 7.19 and 7.81 but did not show any regular pattern. These pH measurements may be regarded as rather uncertain because of disturbances of equilibria when centrifuging the sediment, and filtering the interstitial water may strongly affect pH. The vertical distribution of ortho-phosphate showed an irregular pattern. It has been shown by Weiler (1973) that ortho-phosphate concentration in the interstitial water is highly dependent on the volume of the interstitial water produced by squeezing. The interstitial water in the present study was obtained by centrifugation and the same error may be expected to be involved. The vertical variation of ortho-

phosphate therefore probably does not reflect real variations. The ortho-phosphate concentration in the uppermost layer of the sediment was ca. 5 times greater than in the lake water near the sediment surface.

Only copper could be detected among the heavy metals copper, zinc, and lead. The concentration was highest in the lower part of the sediment core, but the relationship to the influx of ground water suggested above seems uncertain.

Summary

Two hypolimnetic sediment cores (ca. 80 cm long) from the eutrophicated Lake Gjersjøen have been examined. A brief introduction to the limnological development and present state is given. On the basis of very distinct layers of FeS in the upper 15 cm of the sediment the following average rates of deposition of the recent sediments have been calculated:

2-8 cm layer: 4-6 mm/year

8-15 cm layer: 2-4 mm/year

A very distinct layer of homogeneous clay in the layer 15-18 cm below the sediment surface indicates a drastic, but unidentified, change within the lake or its drainage area. During the period represented by the upper 0-30 cm of the sediment a gradual increase in the deposition of clay has taken place and simultaneously there has been a development towards anaerobic conditions in the lower part of the hypolimnion that has allowed precipitation of FeS. It has not been successful by means of the Fe:Mn ratio to deduce information on change in the redox conditions in the lake or the drainage area during the eutrophication.

The vertical distribution of total amounts of iron probably reflects an onset of reducing conditions in the lower part of the hypolimnion and conditions favourable for precipitation of FeS. The very marked increase of manganese in the uppermost layers of the sediment core may be due to diagenetic accumulation and precipitation of manganese as $MnCO_3$. The very pronounced increase in total amounts of phosphorus in the uppermost ca. 5 cm of the sediment core cannot be related directly to the increased loading of phosphorus during the cultural eutrophication. Not yet decomposed organic phosphorus compounds and diagenetic processes may account for the vertical variation in total amount of phosphorus. The accumulation of iron, manganese, and phosphorus in the uppermost layers of the sediment may to some extent be results of lateral and vertical concentration transfers.

Variation in ignition loss, when calculated on dry weight basis, does not reflect the increase in primary production during the course of eutrophication but merely the increase in deposition of clay. Sedimentary chlorophyll, when calculated on ignition loss basis, plainly shows the increase in primary production during eutrophication.

An influx of saline groundwater is suggested because of an approximately tenfold linear increase with depth in the sediment of chloride, sodium, potassium, and magnesium. Under the assumption that influx of saline groundwater is a general property of the central and deepest part of the lake basin it is suggested that this phenomenon will under favourable conditions play an important role in rendering the lake meromictic.

The increase in total amounts of zinc and extractable amount of copper in the sediment deposited during the period of eutrophication may be a result of chemical properties of the clay, general increase due to human activities, diagenetic processes or increased corrosion of materials containing zinc and copper in the drainage area because of lowered pH in the precipitation during the last years.

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References

- American Public Health Association (1962) Standard Methods for examination of water and wastewater. New York, 1-626.
- Brunskill, G.J., and Harriss, R.C. (1969) Fayetteville Green Lake, New York. IV. Interstitial water chemistry of the sediments. *Limnol. Oceanogr.* 14, 858-861.
- Digerfeldt, G. (1972) The post-glacial development of Lake Trummen. *Folia limnol. scand.* 16. Lund.
- Edmondson, W.T. (1969) Cultural eutrophication with special reference to Lake Washington. *Mitt. Internat. Verein. Limnol.* 17, 19-32.
- Golterman, H. L. (1969) Methods for chemical analysis of fresh waters. IBP Handbook No. 8, 1-172.
- Gorham, E. (1960) Chlorophyll derivatives in surface muds from the English Lakes. *Limnol. Oceanogr.* 5, 29-33.
- Holtan, H. (1972) Gjersjøen - a eutrophic lake in Norway. *Verh. Internat. Verein. Limnol.* 18, 349-354.
- Holtan, H. (1973) Loading estimations and nutrient budget. Rapport från ett nordiskt symposium. Norr Malma 16-18 oktober 1973. Nordforsk. Miljövärdsssekretariatet.
- Hongve, D. (1974) Hydrographical features of Nordbytjernet, a manganese-rich meromictic lake in SE Norway. *Arch. Hydrobiol.* 74, 227-246.

- Johansen, K., Stene (1955) En limnologisk undersøkelse av Gjersjøen. Unpublished graduation paper at the University of Oslo.
- Kjensmo, J. (1966) Electrolytes in Norwegian lakes. *Schweiz. Z. Hydrol.* 28, 29-42.
- Kjensmo, J. (1968) Late and Post-glacial Sediments in the small Meromictic Lake Svinsjøen. *Arch. Hydrobiol.* 65, 125-141.
- Lillevold, L. (1975) Gjersjøen 1972-1973. En limnologisk undersøkelse med hovedvekt på fytoplankton og fosfor - og nitrogenomsetning. Unpublished graduation paper at the University of Oslo.
- Lynn, D.G., and Bonatti, E. (1965) Mobility of manganese in diagenesis of deep-sea sediments. *Marine Geol.* 3, 457-475.
- Mackereth, F.J. H. (1963) Water Analysis for Limnologists. *Freshw. Biol. Ass. sci. Publ.* 21, 1-70.
- Mackereth, F.J. H. (1966) Some chemical observations on postglacial lake sediments. *Phil. Trans. Roy. Soc. London* 250, 165-213.
- Mannheim, F.T. (1961) Geochemical Profile in the Baltic Sea. *Geochim. Cosmochim. Acta.* 25, 52-70.
- Norwegian Institute for Water Research (1969) Limnologisk undersøkelse av Gjersjøen 1968-1969. Foreløpig rapport. Oslo.
- Norwegian Institute for Water-Research (1972) Limnologisk undersøkelse av Gjersjøen 1970-1971. Fremdriftsrapport nr. 1. Oslo.
- Odén, S. (1968) Nedbördens och luftens försurning - dess orsaker, förlopp och verkan i olika miljöer. Ekologikomiteen, Bull. Nr. 1, Stockholm, Statens Naturvetenskapliga Forskningsråd. 1-86.
- Odén, S., and Ahl, T. (1970) Försurningen av skandinaviska vatten. *Årsbok Ymer* 90. 103-120.
- Skulberg, O.M. (1968) Studies on eutrophication of some Norwegian inland waters. *Mitt. Internat. Verein. Limnol.* 14, 187-200.
- Tessenow, U. (1973a) Lösungs-, Diffusions- und Sorptionsprozesse in der Oberschicht von Seesedimenten. II. Rezente Akkumulation von Eisen (II) phosphat (Vivianit) im Sediment eines meromiktischen Moorees (Ursee, Hochschwarzwald durch postsedimentäre Verlagerung. *Arch. Hydrobiol. Suppl.* 42, 143-189.
- Tessenow, U., (1973b) III. Die chemischen und physikalischen Bedingungen im Sediment-Wasser-Übergangsbereich eines meromiktischen Moorees (Ursee) als Voraussetzung zur Viviantakkumulation. *Arch. Hydrobiol. Suppl.* 42, 273-339.
- Tessenow, U. (1974) IV. Reaktionsmechanismen und Gleichgewichte im System Eisen-Mangan-Phosphat im Hinblick auf die Vivianitakkumulation im Ursee. *Arch. Hydrobiol. Suppl.* 47, 1-79.
- Tessenow, U. (1975) V. Die Differenzierung der Profundalsedimente eines oligotrophen Bergsees (Feldsee, Hochschwarzwald) durch Sediment-Wasser-Wechselwirkungen. *Arch. Hydrobiol. Suppl.* 47, 325-412.
- Vallentyne, J. R. (1955) Sedimentary Chlorophyll determination as a paleobotanical method. *Can J. Bot.* 33, 304-313.
- Weiler, R. R. (1973) The interstitial water composition in the sediments of The Great Lakes. I. Western Lake Ontario. *Limnol Oceanogr.* 18: 918-931.
- Wetzel, R.G. (1970) Recent an postglacial production rates of a marl lake. *Limnol. Oceanogr.* 15, 491-503.

- Williams, J. D. H., and Mayer, T. (1972) Effects of sediment diagenesis and regeneration of phosphorus with special reference to lakes Erie and Ontario. pp. 281-315 in Alleen, H. E., and Kramer, J. R. (1972) Nutrients in natural waters. John Wiley and Sons, Inc., New York.
- Züllig, H. (1956) Sedimente als Ausdruck des Zustandes eines Gewässers. *Schweiz. Z. Hydrol.* 18, 5-143.

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