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Long-term development in Lake Øyeren studied by paleolimnological method

Langtidsutvikling innsjøen Øyeren studert med limnologiske metoder

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Abstract

Lake Øyeren is a freshwater lake in SE-Norway that is located in the lower part of the river Glomma, having a large drainage area. In the northern part of the lake, river Glomma and two smaller rivers have built up the largest inland delta of Northern Europe.

This study has two major purposes: (1) to reconstruct the long-term development in primary production of Lake Øyeren; (2) to identify inorganic pollution from local and long-range sources based on paleolimnological methods. Additionally, the impact of flooding and water level regulations on sediment transport in the lake was discussed. The sediment cores obtained from the deeper Øyeren basin were analysed to determine pigments and elements (macro- and trace elements) in the lake's sediment.

In the first part of the thesis, the general information about Lake Øyeren and anthropogenic impact on its ecosystem are represented. The data obtained from the sediment cores were systemized and presented. The unusual period with a sharp increase in sedimentation rate and pigment amount was detected. That phenomenon was attributed to an internal movement of surface sediment. The multivariate relations between the sediment parameters were analysed by principal component analysis, while the multivariate relations between the parameters and explanatory variables (weather conditions) were analysed by redundancy analysis. Finally, the obtained results were interpreted in the discussion part with respect to the historical records from the catchment area. Also, the direct comparison of the water quality monitoring data and sediment records was conducted.

The research covers the development study of Lake Øyeren from the 1960s until present. It was concluded that the primary production remains at the same level as at the beginning of the 1960s, despite the high nutrient loading. The major sources of inorganic pollution since the 1970s until present are most probably an anthropogenic atmospheric deposition and upstream mineral particles, while for the 1960s we have observed the effect of point source pollution. Flood events and water level regulations seem to have a minor impact on the sedimentation rate.

Preface

The master thesis was carried out at the Norwegian University of Life Sciences, Faculty of Environmental Sciences and Natural Resource Management. I gratefully acknowledge the financial support from the Vannområde Øyeren, which is an inter-municipal cooperation.

I would like to express my gratitude to my supervisors *Prof. Thomas Rohrlack* and *Prof. Gunnhild Riise* for their guidance, support and important advice. I appreciate their help in all stages of the work – from practical laboratory advises to thesis editing. I also wish to thank *Kristian Moseby* – the project leader of the Vannområde Øyeren. Kristian helped with the sediment cores sampling and provided valuable information about Lake Øyeren. I hope the obtained data and our interpretation will be useful for further studies of Lake Øyeren.

Last, but not least, I wish to thank my family, and especially my wife *Nataliia Sivchenko* for her help and patience.

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1 Introduction

Background

Human activities may both, directly and indirectly, affect the aquatic environment in a negative way. Important main worldwide factors, influencing the aquatic environment, are climate change and nutrient enrichment (Reuss, 2005). Other external factors are acidic deposition, chemical contamination and erosion. All listed drivers could have anthropogenic, natural or combined origin. Along with human-induced changes, other processes occur within ecosystems due to natural causes, and sometimes it is hard to distinguish the real driving forces. An important issue is whether a particular aquatic system shows signs of “stress” due to anthropogenic influence or is in its natural state. The task of water management is to evaluate the degree of anthropogenic alteration and to prevent further deterioration of water bodies. The goals of The Water Framework Directive – main document of water policy in Europe – are to obtain undisturbed (reference) conditions and pressure-response relationships for all water bodies (Hobæk et al., 2012). The aim is a “good ecological status” for all water bodies of inland aquatic systems including surface waters, groundwater and coastal waters (EC (European Commission), 2000).

Lakes are an important part of the inland aquatic environment. They are dynamic ecosystems that respond to external changes and disturbances (Battarbee, 2000). According to the directive, the lakes should be assessed to determine their “good qualitative and quantitative status”. That implies an establishment of pre-impact background conditions based on all available information from monitoring, predictive modelling, historical data and paleoreconstruction. Usually, a reliable long-term monitoring data is missing; there is a lack of the monitoring records or/and they cover only a few decades backwards. Thus, a paleoreconstruction becomes more necessary in environmental assessments. One of the sources of paleoenvironmental data is a lake sediment. Particles with low energy settle and accumulate in lake’s deeper zones (accumulation zones) layer by layer, like in a natural trap. The accumulated material carries a specific information about environmental conditions for a particular time. Thus, an undisturbed sediment profile may form an archive of past events. The information stored in the sediment helps to reconstruct lakes’ past conditions and track a long-term environmental perspective from decades to millennia back. (J. Smol, 2009)

Paleolimnology

Paleolimnology is a multidisciplinary science that studies physical, chemical, and biological information stored in sediments with a purpose to reconstruct the past conditions of inland aquatic systems (J. Smol, 2009). The paleolimnological approach is simple in general. The study consists of sampling of a sediment core from a representative point of the water body with further sectioning into slices suitable for analysis. Another necessary step is a radiometric dating, which provides the temporal resolution of sedimentary sequences. Finally, all collected proxy data are interpreted to resolve the objective of the study. The paleolimnological studies vary from fundamental to applied research (J. P. Smol, Birks, Lotter, & Juggins, 2012). The primary objects of paleolimnological studies are sediment cores from lakes, or they could be sediments from rivers, wetlands and peatlands. Why lakes? Lakes are being considered as indicators of environmental changes (Battarbee, 2000); they collect and preserve in its sediments the long-term signals from the whole catchment area (Carpenter & Cottingham, 1997). Hence, the study of the lake can also tell us something about its catchment area.

The advantage of the paleolimnological approach is a possibility to discover the past events and conditions with high resolution (if needed) for many years back. That provides a context of changes when all noises and short-term or seasonal variations are smoothed. This background shows the broader picture of historical development with a variety of biological indicators. The sedimentation is a continuous process; therefore, the biomarkers preserved in the sediment of the lake represent the averaged information about phototrophic community and production for the whole year. In contrast, monitoring programs usually collect field data during a fixed period of the year when conditions are favourable, which brings some bias into research. Sometimes, the paleolimnological approach is a cheaper and faster method than the long-term monitoring, and in particular cases is the only alternative.

Objectives

This master thesis is a paleolimnological study of the freshwater Lake Øyeren in SE-Norway. The lake is located in the lower part of the river Glomma, having a substantial drainage area that covers a major part of Eastern Norway. In the north of the lake, the river Glomma and two smaller rivers have built up the largest inland delta in Northern Europe that further downstream is followed by a shallow delta platform (<5 m). A southern part of the lake remains, however, deep (the deepest point is 75 m). Lake Øyeren is currently at a good ecological status, but it is still being affected by agriculture, industry and urban emissions (Berge et al., 2002).

Lake Øyeren is an important natural reserve with rich vegetation and high bird and fish biodiversity. Many studies of the lake have been related to water level regulations, biodiversity, water quality and delta development. The similarities between the studies are their focus on the northern part of the lake. This study was the first paleolimnological study of the deeper Øyeren basin where sediment samples have been taken from 65 meters depth.

The aim of the study is to reconstruct the long-term development in:

- lake primary production based on analysis of pigments in the lake sediments;
- inorganic pollution from local and long-range sources based on element analysis (macro- and trace elements) of the sediment;
- impact of flooding and water level regulations on sediment transport.

2 Study site

2.1 General information

Øyeren is a large lake of a glacial origin that is located in the lower part of the Glomma river system (Table 1). A retreating glacier has excavated a long and narrow basin during the last ice age (Berge et al., 2002). There are three main inlet rivers to the lake – Glomma, Nitelva and Leira. The major amount of water comes from Norway's largest river Glomma. In addition, small streams and creeks supply water directly into the lake.

Lake Øyeren consists of two parts with different characteristics. Northern Øyeren is a shallow lake with depth less than 5 m, while a southern part is a narrow deep-basin fjord lake with maximum depth 75 m (Berge et al., 2002). Three rivers deliver waters together with transported material into the lake's northern end. Rivers' particles settle during stagnant lake conditions when the flow and gradient are decreasing. The constant supply of sediment material over the years has developed a large inland delta (56 km^2) and a delta platform (Berge et al., 2002). The study of Bogen & Bønsnes (2002) proposed to divide the Northern Øyeren into following morphological units (Figure 2.1): the actual *delta plain* that is a complex system of distributary channels, lagoons, islands and sandbanks; following *delta platform* that extends 9 km downstream; and the *foreset slope* as a transition to the deep basin of the Southern Øyeren.

The rivers materials include both suspended particles and bed loads. The suspended load consists of fine particles (clay, silt and organic material) remaining in the water column. For a shorter or longer period, the bed load consists of sand and coarser particles that are conveyed in contact with a river bottom (Bogen, Bønsnes, & Elster, 2002). The average suspended load of the Glomma near Bingfoss for 1995-1999 measured by Bogen et al. (2002) is 500,000 tonnes per year. The suspended load dominates the sediment input to Øyeren as the estimated bed load from the Glomma from 75,000 to 150,000 tonnes per year. The estimated suspended loads from the other two rivers Leira and Nitelva are 90,000 and 18,000 tonnes per year respectively (Bogen et al., 2002). The sediment transport pattern varies from year to year. The suspended load measured during the floods in May and June 1995 by Bogen et al. (2002) was 700,000 tonnes, which is 90 % of the year burden. Also, Pedersen (1981) has estimated the sediment transport of Glomma at Fetsund to 210,000 tonnes per year as an average for 1978-1979.

Table 2.1 Hydro-morphological characteristics of Lake Øyeren including Svelle. Data obtained from the Norwegian Water Resources and Energy (NVE Atlas, the 1991 year survey)

Area	85.4 km^2
Mean depth	14 m
Max depth	75.5 m
Volume	1.184 $\times 10^6$ km^3
Catchment	40440 km^2
Glomma*	38873 km^2
Leira*	661 km^2
Nitelva*	522 km^2
Average runoff for 1961-1990 years	682 m^3/s
Theoretical retention time	20 days
Water level	101 m a.s.l.
LRV	98.9 m a.s.l.
HRV	101.3 m a.s.l.

* from Bogen et al. (2002)

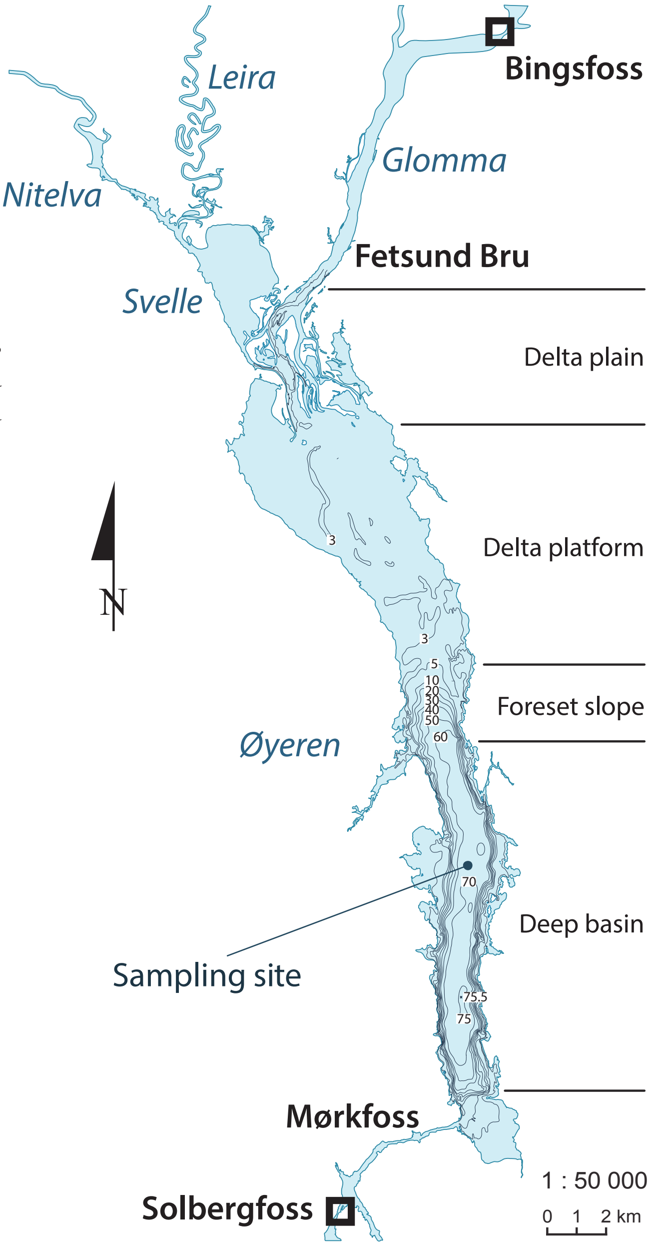

Figure 2.1 Lake Øyeren’s morphology

The difference in morphological and hydrological conditions provides a variety of ecosystems within Lake Øyeren. The Northern Øyeren ecosystem has a mesotrophic productive character. In contrast, the Southern Øyeren has an oligotrophic character (Berge et al., 2002). Three supplying rivers also have its individual flow pattern, water content and water quality. The turbid and relatively warm Nitelva and Leira flow first into Svelle, which is a shallow (average 1-1.5 m) hypertrophic bay of the delta. After Svelle, water merges with colder nutrient-poor waters from Glomma. The water quality of Glomma is better than in Nitelva and Leira, especially regarding turbidity (Martinsen, 2002). The Northern Øyeren shows a river-like behaviour because of a short retention time (1-3 days) and a shallow depth. Berge (2011) proposes to classify the Svelle and Øyeren delta including the delta platform as a river based on regulations of WFD. This approach means to consider Northern Øyeren as Glomma's expansion and Southern Øyeren as an actual lake.

The natural diversity and location of Lake Øyeren make it unique for Norway in terms of biodiversity and amount of species. According to Berge et al. (2002), the lake is inhabited by 25 species of fishes, 260 species of birds and 50 true aquatic plants with 325 species of swamp plants. During postglacial ice melting, Øyeren had a connection to the Baltic Sea area. These migration routes provided the unusually large amount of aquatic species in the lake. Northern Øyeren was preserved as a nature reserve from 1975 (and a Ramsar site from 1985) for the birds nesting and migration in a local and international context. It is important to save such a unique ecosystem, where many species may coexist, under conditions of a good ecological status.

2.2 Anthropogenic impact

Four main aspects of human activity, which affect the Øyeren environment, are water level regulation, agriculture, urban emission and industry (Berge et al., 2002). The water level regulation started in 1862 as an action to prevent flooding and provide a steady flow for navigation and timber transport. The timber transport practised until 1985. The further regulation served for a water accumulation in the lake to generate power. The Mørkfoss dam controlled the outlet flow from 1862 to 1924, and then its function was substituted by hydropower at Solbergfoss. Before the regulation, the lake's natural water level varied with 8 m (up to 14 m) through a year, while now the variation is reduced to 3m. The stabilisation of the water level has changed the lake's morphology and ecosystem function. The shape of the current delta and its platform appears to differ much from the old one before initiation of the regulations comparing with the 1824 maps (Bogen & Bønsnes, 2002). The operation rule is a big issue because it has to satisfy many requirements, which are usually controversial. That are: interests of the local communities, hydroelectric power production and satisfying conditions for all species, which cohabit in the lake.

According to Berge et al. (2002), 2,800 km^2 of agricultural areas lay within the Øyeren catchment. The use of fertilisers, intensive mechanisation and levelling of the ground in 1960-1980s (Bogen & Sandersen, 1991) increased the share of crops growing. This practice boosts the contamination of water bodies with eroded materials and nutrients. Many landslides that were recorded at Romerike in 1970 were attributed to the levelling practice (Bogen, Berg, & Sandersen, 1993).

The total population in the Øyeren catchment area is up to 500,000. The urbanisation and development of the international airport Gardermoen have promoted a constant population growth. The lake receives discharges from more than 20 wastewater treatment plants (WWTPs) with a different capacity. The estimated pollution load on WWTPs is 400,000 population equivalents in total (information from communities provided by Kristian Moseby). Some of the WWTPs do not have a nitrogen removal stage. During extreme precipitation events, the storm water in a mix with municipal wastewater is being discharged directly into a receiving water body without treatment. The largest treatment plant NRA (150,000 p.e.) releases treated water into the Nitelva. Since the 1950s, sewage discharges have been triggering the eutrophication of the lake. A 30-year monitoring program studied by Berge (2011) showed a general improvement in water quality since the 1980s due to the introduction of more advanced WWTPs. However, there are still sites that are not connected to centralised systems and/or do not have appropriate treatment. Also, the lake used to be affected by pollution from Røros mining area in the uppermost part of the Glomma during its active operation. The pulp and paper industry near Lake Mjøsa used to affect downstream Øyeren.

3 Methodology

3.1 Sampling procedure

Three sediment cores, 60-62 cm long, were sampled from 65 m depth in a deep basin part of Lake Øyeren in August 2016 (Figure 2.1). The distance between the sampled cores were not more than 10 m. The sediment site was chosen in order to represent the sediment accumulation for the whole Southern Øyeren. At the same time, it should not be prone to bioturbation and mixing activity. Thus, the sampling site was in the widest part of a flat deep area. An inlet stream with high flow rate occurs along the eastern shore (personal communication with Kristian Moseby). Hence, the sampling site was chosen closer to the western coast. Three sediment cores were collected from a boat with a gravity corer – 75 cm long acrylic tube, 6.0 cm inner diameter and 1 mm wall thickness. All depths were measured with a portable echosounder. The sampled sediment cores were immediately transported to the laboratory, where two out of three (**core A** and **B**) were sectioned through the whole length into 1 cm slices. The slices were placed into polyethylene bags and freeze-dried before further analysis. **Core C** was not sectioned in order to perform a visual observation of the sediment profile.

3.2 Analytical methods

Core A, 62 cm length

To determine the loss on ignition (LOI), 0.5 g of each sub-sample were incinerated at 550 ºC for 4 hours and then the cooled samples were balanced again.

The pigments were extracted from 0.2 g of each sample with 15 ml ethanol (96 % in water) overnight at 4 ºC in the dark (Thrane et al., 2015). The samples were treated with ultrasound to intensify the process of extraction. After the extraction, the samples were centrifuged then the resulting supernatants were analysed by a spectrophotometer. The spectral scans were measured in a range from 400 to 700 nm. The individual concentrations of pigments were derived from spectral scans with a modified Gause-peak spectra (GPS) method (Thrane et al., 2015). The samples storage and all treatment were conducted with an absence of ultraviolet light from natural and artificial sources to avoid pigment degradation.

The trace elements Cu, As, Cd, Cs, Hg and Pb were measured by inductive coupled plasma-mass spectrometry (ICP-MS), while the elements Al, Ca, Fe, K, Mn, Na, P and S were measured by inductive coupled plasma-mass optical emission spectrometry (ICP-OES). The elements C and N were measured on CHN Analyzer.

Core B, 61cm length

All samples were weighed before and after freeze-drying with an aim to determine the water content.

The homogenised dried samples were sent for the radiometric dating at The Environmental Change Research Centre at University College London. According to a received radiometric dating report (Appendix A), the samples were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay using ORTEC HPGe GWL series well-type coaxial low background intrinsic germanium detector. ^{210}Pb was determined via its gamma emissions at 46.5keV and ^{226}Ra by the 295keV and 352keV gamma rays emitted by its daughter isotope ^{214}Pb following three weeks storage in sealed containers to allow radioactive equilibration. ^{137}Cs and ^{241}Am were measured by their emissions at 662keV and 59.5keV (Appleby et al., 1987). The absolute efficiencies of the detector were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self-absorption of low energy gamma rays within the sample (Appleby, Richardson, & Nolan, 1992). Use of the CIC model was precluded by the non-monotonic features in the unsupported ^{210}Pb profile. ^{210}Pb dates were calculated using the CRS model (Appleby, 2001).

3.3 Multivariate data analysis

The principal component analysis (PCA) was performed to extract and display the systematic variation of sediment data, as well as to explore the relationships between variables. PCA is a statistical multivariate data analysis that reduces a dimensionality of data set with the aim to overview and describe the interrelationship among all parameters with a smaller amount of variables – principal components. PCA also helps to reveal outliers, trends and groups of observations – so called structures. The variables were mean centred and standardised prior to PCA with a purpose that all variables make the same contribution to the model (Esbensen et al., 2002). The statistical analysis was carried out in MATLAB, using PLS toolbox.

The dry weight, LOI and concentrations of Chlorophyll a, macro- and trace elements were analysed. The concentrations of Chlorophyll a are a proxy for all photosynthetic algae and higher plants, while the other pigments have an affinity to specific groups of organisms. Also, the PCA with a full variety of pigments showed that they behave coherently with Chlorophyll a. Thus, the other pigments were dropped from further analysis.

The multivariate relations between all obtained parameters (dry weight, LOI and concentrations of Chlorophyll a, macro- and trace elements) and explanatory variables (maximum water flow, maximum water level and weather data – precipitation and temperature) were analysed by redundancy analysis (RDA) in the Microsoft® Excel statistical add-in XLSTAT© (XLSTAT-Ecology, 2017). RDA is a statistical method (van den Wollenberg, 1977), which summarises linear relationships between the components of redundant (response) variables that can be described by a set of explanatory variables.

4 Results

4.1 Visual observation

The colour of the sediment material was grey through the whole length of the column. The surface sediment mud on the top of the core was 1 cm thick and had brownish-grey colour (Figure 4.1). Also at the sediment surface, benthic invertebrates and their activity were detected. At a depth between 35 and 45 cm, from sediment surface, few black coloured patches with a size less than 1 cm were observed. At a depth of 45-55 cm many black coloured patches with a size less than 1 cm were observed. The lamination was not observed for none of the three sediment cores. The grain composition was dominated by fine-grained particles (probably clay), which were uniformly distributed through the whole profile.

Figure 4.1 The sampled sediment cores from Lake Øyeren (photo by K. Moseby)

4.2 Radiometric dating and accumulation rate

The radiometric chronology and sediment accumulation rates of Lake Øyeren are shown in Figure 4.2. Appendix A contains the detailed information about the radiometric dating from The Environmental Change Research Centre at University College London.

Figure 4.3 shows the depth-time profile, where the 62 cm long sediment core represents the time range from the early 1960s until 2016. The axes of sediment depth (the most left on Figure 4.3) have unequal intervals between 16 key depths with certain year given by the radiometric dating. The locations of intermediate observations were distributed evenly between those 16 points. The depth axes were created to visualise the distribution of depths, while the time scale remained conventional. We can observe that 8 cm thick layer of sediment was accumulated within two years 1970-1972, while for other years about 1cm thick sediment represent the one year.

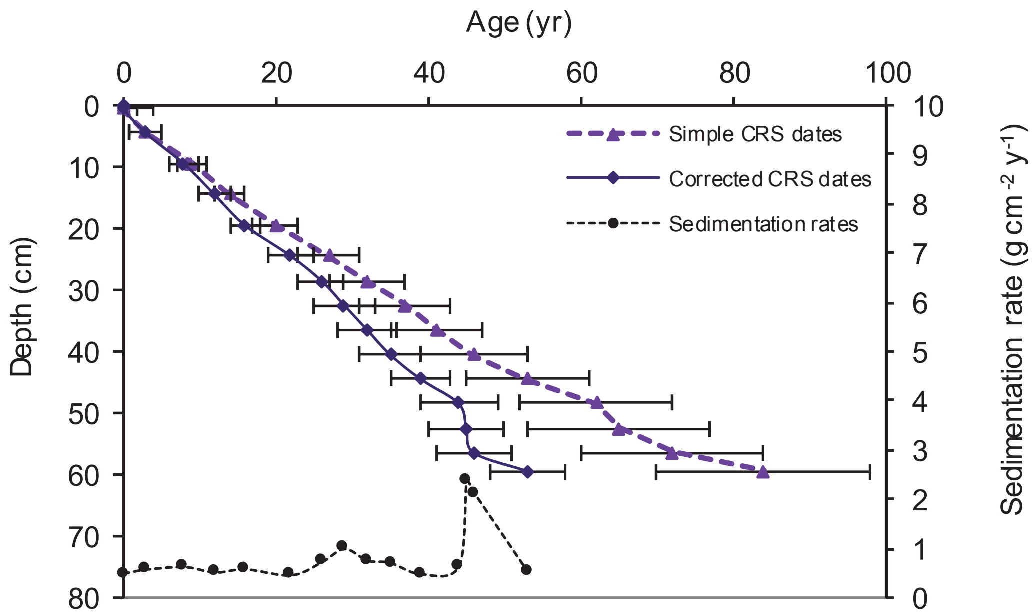

Figure 4.2 Radiometric chronology of the sediment core taken from Lake Øyeren, showing the Constant rate of supply (CRS) model ^{210}Pb dates and sedimentation rates (g cm^{-2} yr^{-1})

The sediment accumulation rate is given for the 16 observations (Figure 4.3). Mostly during the analysed 1961-2016 period, the sedimentation rate is uniform 0.5-0.7 g cm^{-2} yr^{-1} with a gradual increase toward a peak in 1 g cm^{-2} yr^{-1} in the late 1980s. An extreme increase in sedimentation rate occurs around 1970 when the values exceed 2 g cm^{-2} yr^{-1}.

4.3 Water content and organic matter (LOI)

The organic matter (LOI) has a general tendency to increase from 4 % to 6 % during the observed period (Figure 4.3). The LOI values that represent time range from 1968±5 to 1977±4 are characterised by large oscillations up to 2 %. Also, the lowest amounts of organic matter – 3 % occur in this period in 1970. The high value of LOI in 2013 year is most probably an outlier because the observation is not supported by nearby points so it may be the undecomposed fragment of detritus in the sample. The surface sediment, as expected, has the highest level of LOI due to an incomplete process of decomposition, compaction and the activity of benthic organisms.

The dry weight of the sediments provides, to some extent, information about the level of sediment compaction (Håkanson & Jansson, 2002). The dry weight fluctuated around 50 %. The largest dry weight – 57 % is observed for 1967-1970 years, that matches to the great flooding events in 1967 and 1968. The high values of dry weight are followed by a rapid decrease to 48 % in 1970. The organic matter content and the dry weight curves show an inverse symmetric pattern.

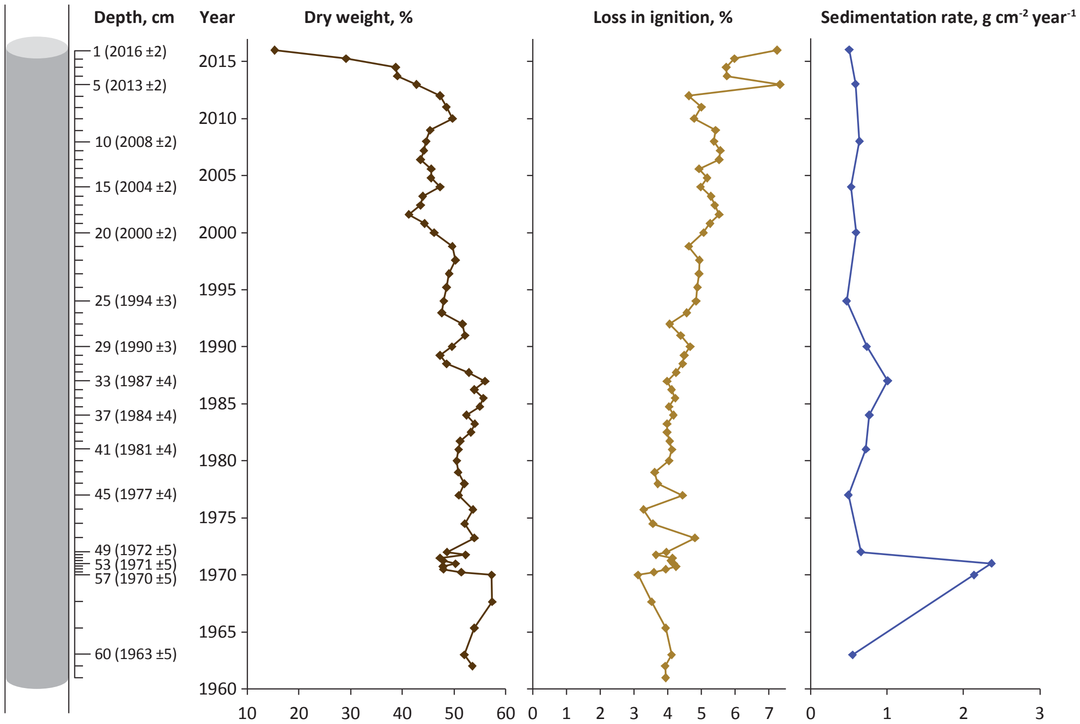

Figure 4.3 Stratigraphy of dry weight (%), organic matter (loss on ignition at 550 ºC, LOI, %) and sedimentation rate (g cm^{-2} yr^{-1}) derived from the sediment cores of Lake Øyeren

4.4 Pigments

The pigment assemblage was determined including the following pigments: *chlorophyll a*, *pheophytin a*, *chlorophyll b*, *pheophytin b*, *chlorophyll c2*, *β-carotene*, *diadinoxanthin*, *diatoxanthin*, *neoxanthin*, *alloxanthin*, *echinenone*, *peridinin*, *myxoxanthophyll* and *violaxanthin*. The concentrations of all pigments are shown in Appendix B. The pigments were quantified as µg per organic matter, where the organic matter equals to LOI, measured in the same sub-sample. The amount of diatoxanthin, neoxanthin, alloxanthin, echinenone and peridinin lay below the detection limit for the most of time. *Canthaxanthin*, *fucoxanthin* and *lutein* were not detected.

In a scope of the study, we focus mostly on the concentration of *chlorophyll a* as biological indicator that is a part of all photosynthetic organisms such as algae and higher water plants. The Total Chlorophyll a and Total Chlorophyll b are defined as the sum of chlorophylls and their stable degradation products – *pheophytin a* and *pheophytin b*, respectively. The concentrations of Total Chlorophyll a, Total Chlorophyll b and Chlorophyll c2 are shown in Figure 4.4. We may observe a rapid increase of Total Chlorophyll a concentration up to

4,500 μg g^{-1} per organic matter in 1970 that is followed by declining to the 1,300 μg g^{-1} per organic matter in the middle of 1980s. After, the Total Chlorophyll a concentration has an overall tendency to increase. The prominent increase of concentrations in 1970 is present for all detected pigments. The derived weights of chlorophylls were recalculated against the sedimentation rate in g cm^{-2} yr^{-1} from the radiometric data dating (Table 3 in Appendix A). That reveals the absolute amount of chlorophylls in the sediment per year. The abundance is expressed in μg of chlorophylls per one square cm of the surface in one year (the right plane of Figure 4.4). Hence, we can see the overall tendency where the most of 16 observations for Total Chlorophyll a lay in a range from 50 to 75 μg cm^{-2} yr^{-1}. After the adjustment of concentrations, the increase in 1970-1972 years became extreme and outstanding. The maximum value reaches 338 μg cm^{-2} yr^{-1}.

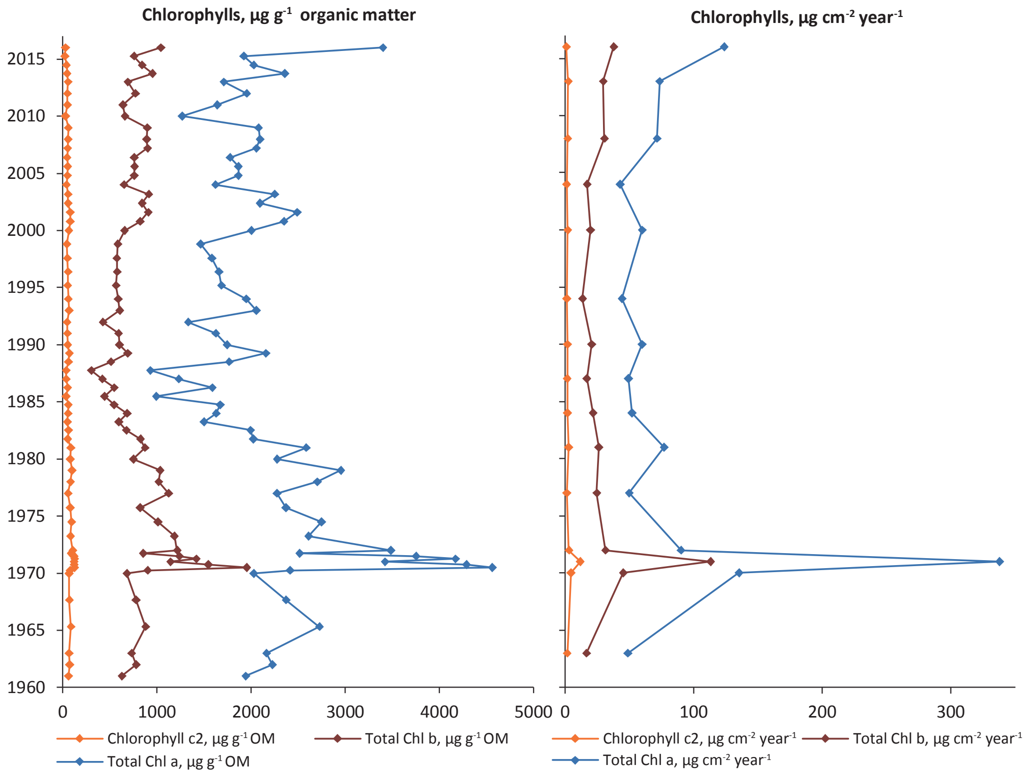

Figure 4.4 Stratigraphy of the chlorophylls (μg g^{-1} organic matter, μg g^{-2} yr^{-1}) in the sediment core from Lake Øyeren

4.5 Macro elements

Concentrations of the macro elements are expressed in g per kg of the dry weight. All measured macro elements are shown in Figure 4.5. The concentration of C has overall tendency to increase from 15 g kg^{-1} to 21 g kg^{-1}. S is characterised by high concentrations up to 3 g kg^{-1} in a period from the early 1960s to 1973 that is followed by period 1973-2016 with a gradual decreasing from 1 g kg^{-1} to 0.5 g kg^{-1}. Other macro elements remain relatively stable through the studied period and do not show high variations.

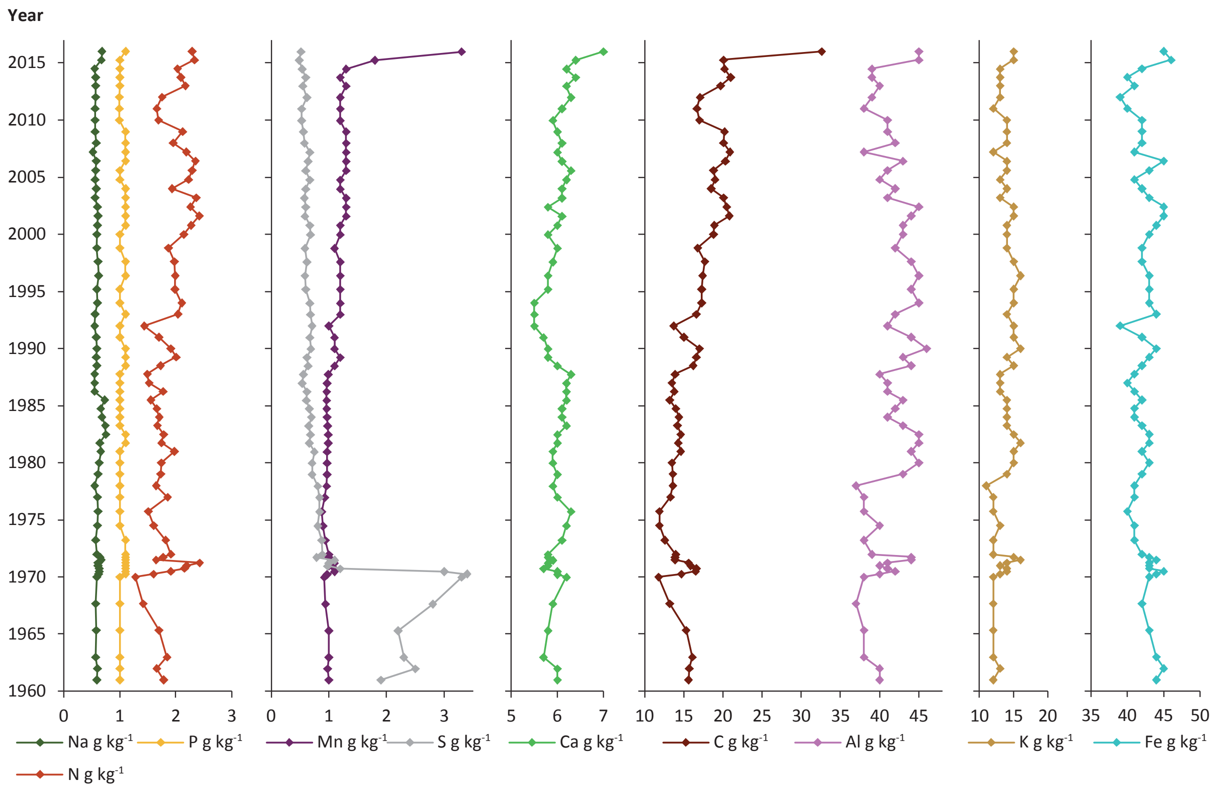

Figure 4.5 Stratigraphy of the macro elements – Na, P, N, Mn, S, Ca, C, Al, K and Fe (g kg^{-1}) – from the sediment core from Lake Øyeren

4.6 Trace elements

Concentrations of trace elements are expressed in mg per kg of the dry weight. The concentration of Cs remains stable through the core most of the time and fluctuates between 3-3.4 mg kg^{-1} (Figure 4.6). The concentration of Hg reaches a maximum of 0.3 mg kg^{-1} 1963 that is followed by a rapid decline to 0.07 mg kg^{-1} in 1973. After that time, the level of Hg is gradually decreasing towards the present value – 0.05 mg kg^{-1}. The concentrations of Cd, As, Cu and Pb have similar patterns. All of the trace elements have high concentrations before 1969 and a small peak on in 1970. After that, there is a fast decline until 1975 year with a further decrease toward the present values. Pb also has an additional peak that coincides with a maximum value of Hg.

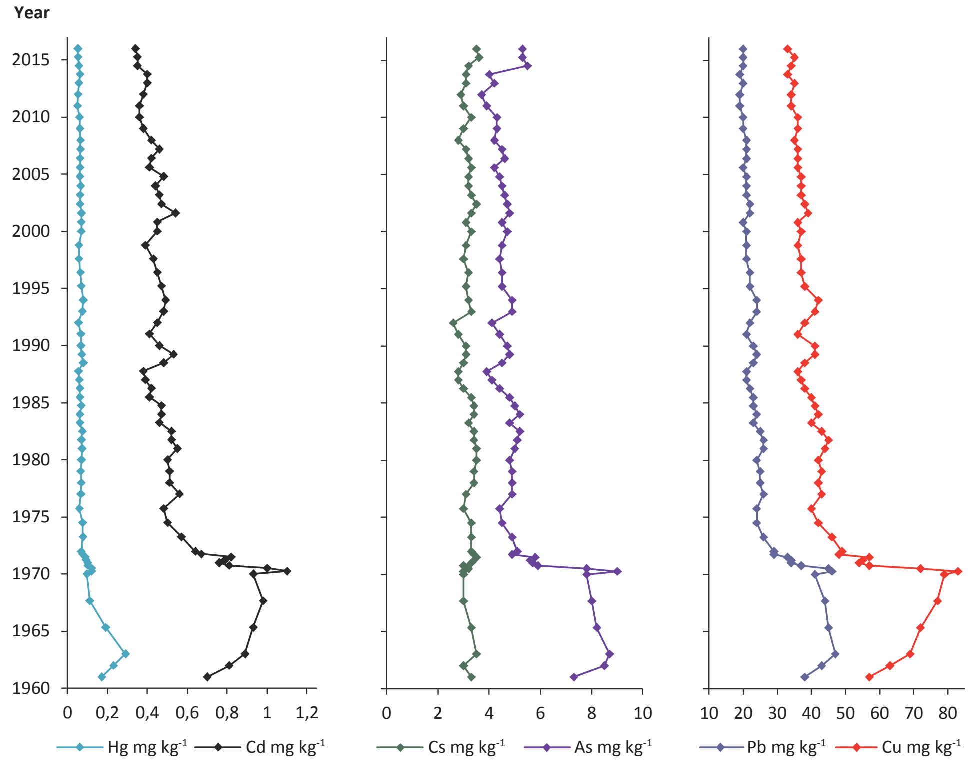

Figure 4.6 Stratigraphy of the trace elements – Hg, Cd, Cs As, Pb and Cu (mg kg^{-1}) – from the sediment core from Lake Øyeren

4.7 Multivariate relationships

Table 4.1a presents the results of PCA for the first six principal components (PCs). With 6 PCs 91.1 % of the variance in the data set was explained.

According to eigenvectors, the first principal component (PC1) shows the covariance between Cu, Pb, Cd, As, Hg and S, and is negatively associated with LOI, Mn and C (the last two are highly correlated). Al and K are also highly correlated and show weak negative associations to PC1, as well as N and Ca. Dry weight and Total Chlorophyll a show weak positive associations to PC1. The second PC is mainly associated to Fe and negatively to dry weight and Ca. The third PC is primarily associated with K, Al and Na, and negatively to C and LOI. With these three PCs, the 74 % of data variation was already explained. PC4 represents a covariation between Ca, Cs and Na, which is negative to P. PC5 is positively associated to Total Chlorophyll a, whereas PC6 represents negative covariation between Ca and Cs. The biplot of PC1 and PC2 is shown in Figure 4.7a.

In order to omit the extreme events in the early 1970s, another PCA was performed. The data excluded samples from 49 to 62 cm depths, which correspond to 1961-1972 years. The results of PCA for the first 4 PCs are shown in Figure 4.7b. With four principal components, 83.4 %

of the variance in the data was explained. The main trends of covariance and negative correlations remained the same as for the data with a whole range of samples (from 1973 to present). However, the loadings on PC1 do not show such high correlation between Cu, Pb, Cd, As, Hg and S as on PC1 for the whole range of samples (Figure 4.7b).

Table 4.1 Principal component analysis (PCA) of the dry weight, LOI and concentrations of Chlorophyll a, macro- and trace elements for two periods 1961-2015 and 1973-2015. Eigenvalues, present variance explained, and eigenvectors are given for the first 6 principal components (PC1-PC6) for whole dataset and 4 principal components (PC1-PC4) for 1-48 cm depths. The parameters were mean centred and standardised prior to analysis

	a. 1961-2015 (1- 62 cm observations)						b. 1973-2015(1- 48 cm observations)			
Parameter	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC1**	**PC2**	**PC3**	**PC4**
Eigenvalue	7,40	4,01	2,65	1,30	1,14	8,11	6,91	4,83	2,43	1,68
Percent	38,97	21,09	13,95	6,86	5,99	427	36,35	25,40	12,80	8,85
Cumulative percent	38,97	60,06	74,01	80,87	86,86	91,13	36,35	61,75	74,55	83,40
Eigenvectors:										
Loss on ignition	-0,28	0,16	-0,25	0,04	-0,11	0,01	-0,31	0,14	-0,15	-0,02
Total Chl a	0,16	0,24	-0,02	-0,10	0,62	0,06	0,12	0,17	-0,47	0,00
Dry weight	0,24	-0,28	0,22	-0,14	-0,05	-0,06	0,28	-0,21	0,20	-0,11
Cu	0,34	0,13	-0,05	0,00	-0,04	0,13	0,35	0,12	-0,04	0,03
As	0,32	0,18	-0,10	0,12	-0,20	0,02	0,17	0,29	-0,03	0,31
Cd	0,33	0,18	-0,04	-0,06	0,07	0,13	0,30	0,18	-0,20	-0,15
Cs	0,02	0,23	0,18	0,48	0,32	-0,49	0,10	0,29	-0,11	0,44
Hg	0,27	0,15	-0,14	0,06	-0,26	-0,33	0,23	0,24	-0,11	-0,23
Pb	0,34	0,16	-0,07	0,00	-0,05	0,02	0,35	0,11	-0,06	0,00
C	-0,23	0,27	-0,27	-0,03	-0,15	0,04	-0,32	0,20	-0,12	-0,09
N	-0,20	0,34	-0,14	-0,03	0,21	-0,14	-0,21	0,31	-0,22	-0,04
P	-0,03	0,29	0,11	-0,41	0,29	0,39	-0,02	0,26	-0,04	-0,38
Al	-0,15	0,20	0,46	-0,04	-0,24	0,06	0,03	0,31	0,43	-0,06
K	-0,14	0,18	0,44	-0,13	-0,24	0,11	0,01	0,27	0,45	-0,12
Na	0,05	0,09	0,45	0,42	0,06	0,22	0,16	0,15	0,28	0,44
Ca	-0,08	-0,15	-0,18	0,58	0,08	0,56	-0,11	-0,15	-0,16	0,50
Mn	-0,25	0,26	-0,20	0,07	-0,16	0,08	-0,32	0,21	-0,05	0,04
Fe	0,06	0,43	0,10	0,11	-0,22	-0,01	-0,06	0,40	0,11	0,04
S	0,32	0,10	-0,14	0,03	-0,19	0,23	0,31	-0,02	-0,27	-0,09

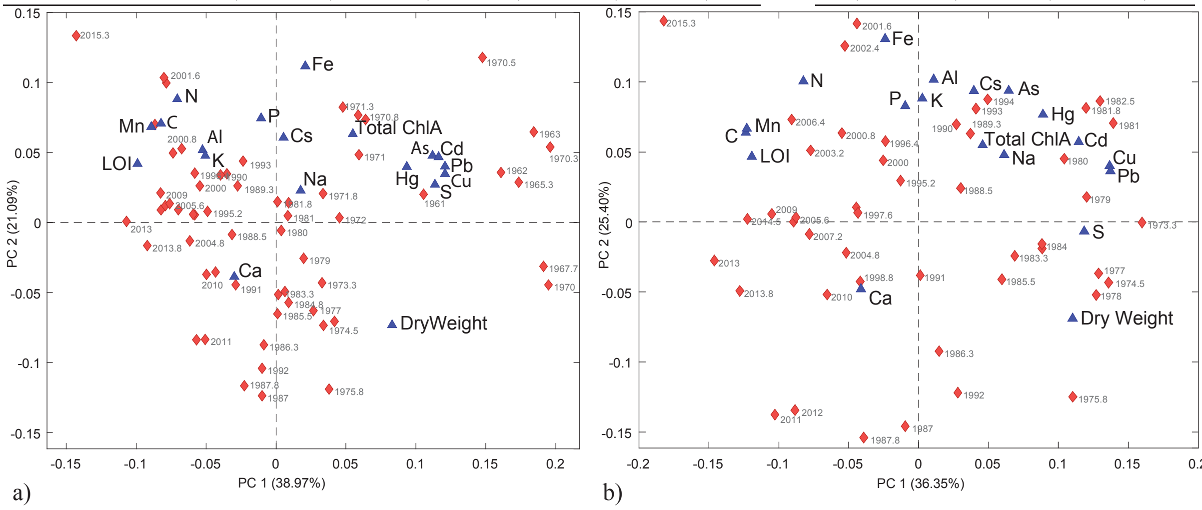

Figure 4.7 Biplots from PCA of dry weight, LOI, Total Chlorophyll a, macro- and trace elements for: a) 1961-2015 and b) 1973-2015. The red rhombuses are scores (observations); the blue triangles are loadings (variables)

The redundancy analysis was performed for the data from 1961 to 2015 years. The redundancy variables included dry weight, LOI and concentrations of Chlorophyll a, macro- and trace elements. The wether explanatory variables were derived from the database of Meteorologisk institutt; that are annual precipitation for the whole Østlandet and annual precipitation nearby Lake Øyeren (4040 and 4050 Enebakk meteroological stations), and anuual temperature the for whole Østlandet and anuual temperature closer to the lake (17850 Ås meteroologicall station). The hydrological explanatory variables are maximum water flow and maximum water level in Lake Øyeren.

Figure 4.8 shows the results of RDA – relationships between two sets of variables. The computed by permutation test p-value = 0.0001, which is lower than the significance level alpha = 0.05, hence, the Y (redundancy) and X (explanatory) variables are linearly related to each other. The first RDA factor (F1) explains 73.3 % of the data variance. Expectedly, the variations of Østlandet temperature and Lake Øyeren temperature are highly correlated. The same tendency is observed for precipitation. Among the explanatory variables, the temperature has a highest negative score on F1, while the maximum flow rate has a highest negative score on F2. F1 indicates a strong positive relationship between temperature and LOI, while dry weight is negatively correlated with temperature, but has a positive relationship to maximum water level. F2 indicates a strong negative relationship between maximum water flow and P, Fe. F2 explains 14.2 % of the variance, while in total F1 and F2 explain about 87% of the data variance.

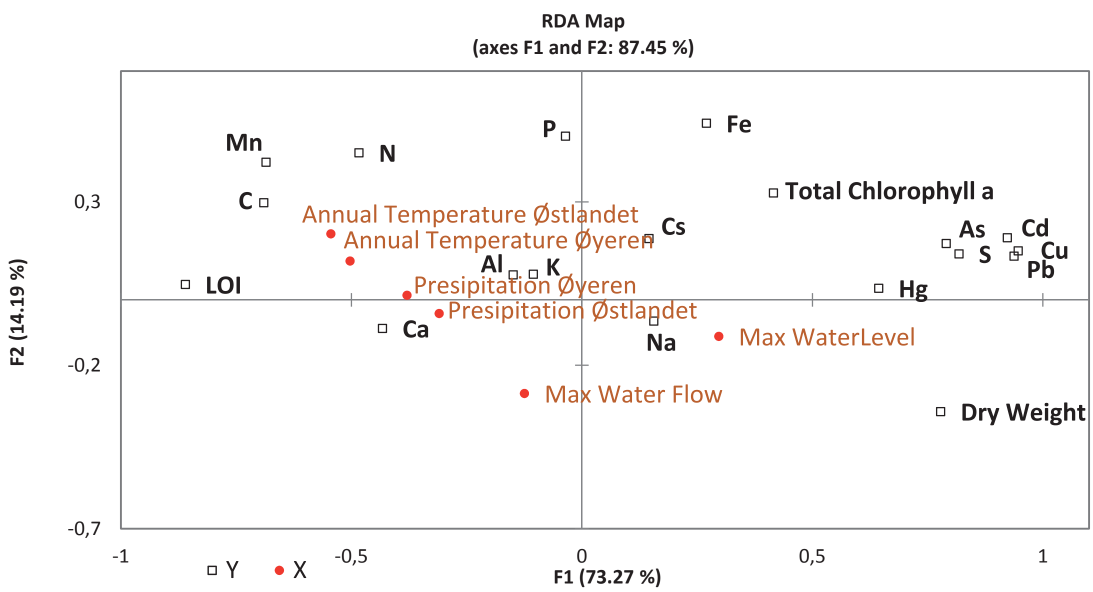

Figure 4.8 Biplots from RDA, where redundancy variables (black squares) are dry weight, LOI, Total Chlorophyll a, macro- and trace elements; explanatory variables (red circles) are weather parameters and lake’s hydrology.

4.8 Comparison of monitoring data and sediment records

Comparison of the water quality monitoring data with sediment records that represent the same period was performed. The water quality data were gathered from the monitoring station Solbergåsen that locates close to our sampling site. Monitoring reports are available by Nicholls (1993) and Berge (2011). The report of Berge (2011) was chosen because it covers longer period – 1980-2000 years. Monitoring data and sediment records with respect to Total P, Total N and Chlorophyll a have similar trends (Figure 4.9), but show quite weak correlations. The correlation between the measured Chlorophyll a in water and preserved in the sediment is r=0.05. The correlation of Total P is r=-0.35and Total N – r=0.38.

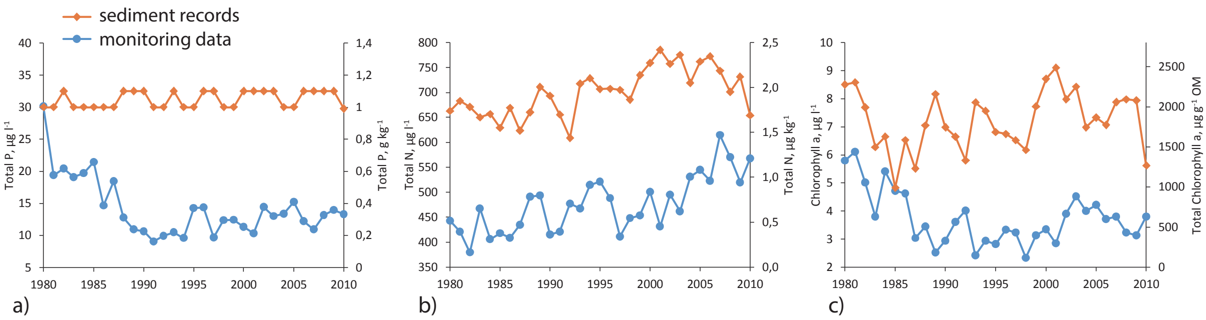

Figure 4.9 Comparison of monitoring data and sediment records over the monitoring period 1980-2000. Panel a) depicts the concentration of Total P in the sediment (orange rhombus) and in the water column (blue circles); panel b) – Total N; panel c) – Chlorophyll a.

5 Discussion

5.1 Long-term development in primary production and sediment transport

The preserved sediment pigments may reflect the primary production within the water body and drivers behind the productivity. Algae and other photosynthetic organisms contain the pigments, and after their death, pigments end up in a lake bottom as fragments of organic detritus that fall through a water column (Leavitt, 1993). The pigment oxidation starts while falling of detritus. The availability of light and oxygen intensify the process of decomposition both in water column and in the bottom of lake. After the sedimentation, pigments are being exposed to oxidation in a sediment surface mud. However, some amount is being preserved and stored as the fossil record. The most of the sedimentary pigments are autochthonous. The detritus that came to the lake from allochthonous sources have passed severe conditions during the transportation. Therefore, organic matter from the watershed is poor on pigments. According to a review of Sanger (1988), the only chlorophyll derivatives can stand the transportation and be present in small concentrations. The major source of pigments in Lake

Øyeren deep basin is an autochthonous phytoplankton. Nevertheless, some amount of allochthonous phytoplankton communities may be carried with the incoming rivers.

The lake sediment can be characterised as poor in organic matter (LOI). The minor difference between LOI of the topmost layer and layers below shows the low decomposition rate that implies good condition for pigment preservation. Based on loadings from PCA (Figure 4.7) LOI, C and N are highly correlated with each other in both PCA runs. The parameters of LOI, C and N create the “organic matter” group that is negatively correlated to Dry weight. Thus, we may consider the left-upper quadrant of the biplots as direction with higher organic matter and the right-bottom quadrant as direction with fine inorganic particles. The coherence of total C and LOI may imply that major contributor of total C is the organic C. The “organic matter” group does not correlate to the Total Chlorophyll a that represents all pigments e.g. accounts for the organic matter of autochthonous origin. Based on the premise that total C and LOI variate incoherently to Total Chlorophyll a, we can conclude that the enrichment of sediment with organic matter is occurring due to allochthonous organic matter from the terrestrial watershed. Hence, the steady increase of LOI and C are not caused by the growth of primary production but resulting by external drivers.

Unusual event in period from 1970±5 to 1972±5

The obtained results revealed the period with a controversial assemblage of measured parameters. Before further explanation of long-term changes, we should clarify the period between 49 and 57 cm depths that reflects the period from 1970±5 and 1972±5 according to the radiometric dating. This period is characterised by a noticeable increase in sedimentation rate along with the prominent increase of concentrations of pigments within a short time (less than a year). This increase was observed in pigments that indicate different groups of organisms such as chlorophylls and their derivatives, *diadinoxanthin* and *violaxanthin*. Then the pigment concentrations return to the previous level after the few oscillations. The event is accompanied by the increase of organic matter and a decrease of the Dry weight.

Sedimentation transport. Why do we think the parameters contradict to each other for 49-57 cm depths? The increase in sedimentation rate in 1970-1972 does not show to be representative for the whole lake. There are many events through 1960-2016, which could have resulted in the higher accumulation rate in the deep basin. However, the accumulation rate remains stable within 0.5-0.7 g cm^{-2} yr^{-1}. Figure 1 in Appendix C is an attempt to summarise the drivers and events that could cause the changes in the sedimentation rate with focus on the 1965-1975 period. There were the great flooding episodes in 1966, 1967 and 1995 that were accompanied with high suspended and bed loads (Bogen et al., 2002). The processes of erosion of the delta and along the shores were recorded, especially after the floods (Bogen et al., 2002). Also, according to Bogen et al. (2002), the flood events triggered the landslides on Øyeren watershed; other landslides in the 1970s were attributed to the ground levelling (Bogen et al., 1993). In period 1965-1980, twelve landslides happened around the lake. The event that could enlarge the suspended and bed load is the constructions of hydropower. Eleven various hydropower stations were constructed and run in Øyeren watershed in period 1965-1980 (Figure 1 in Appendix C). Another parameter that has a direct impact on lake morphology is the water level regulation. There are few periods with different patterns, which match to studied period: 1945-1978, 1978-1995 and 1995-2000.

Thus, we may conclude that the event, which caused the peak of sedimentation rate, happened nearby and might have a local character. Bogen et al. (1993) points out the influence of the creeks and rivers from west and east sides on the deep basin part of Øyeren. The sediment samples were obtained as part of Bogen & Sandersen (1991) study from the Øyeren foreset slope in order to discover the processes of erosion and sediment transport in the watershed of Leira. Their sampling sites were located near the inlet of small river Børterelva (Preståa) that flows to the western shore of Øyeren. The sediment core showed the clear lamination. There is an alternation of the thinner dark layers and the thicker grey or brown layers. The material of sediments was dominated by silt fraction (80-90 %). Bogen & Sandersen (1991) stated that the layers with coarser material and thicker layers indicate the large floods and the water level regulation for Øyeren. In contrast, the sediment cores from our study have the uniform particle size dominated by clay (based on visual observation), without lamination through its whole length. Evidently, the coarse particles with high kinetic energy cannot rich the deep basin plain. Most of the coarse particles settle on the shallower delta platform with the following foreset slope or on the littoral zones. The main input into the sediment accumulation in the deeper part is the suspended particles. The section of sediment cores, which represent the sedimentation peak in 1970-1972 years, consists of the same material as the whole profile with no signs of external intrusion. The higher suspended load, caused by a flood or erosion events, carries more mineral particles and may be reflected in sediment core as a section with the less organic matter, fewer pigments and higher compaction. According to our results and observation, the flood events and different pattern of water level regulations do not play a major role in the sediment accumulation in Øyeren deep basin. The accumulation rate remains relatively stable.

Pigments. As was discussed above, the pigments mostly come into sediment as the fragments of organisms that lived in the water column. Therefore, the sharp peak of Total Chlorophyll a should be explained by the exponential increase in a number of phototrophic organisms. In addition, there is only one prominent peak of pigments for studied period. Such striking event should leave the records, but we did not find the information about such event neither in records or articles nor in the memory of local dwellers. Also, there is no similar pattern in pigments composition which would reflect the well-documented events such as the eutrophication of the lake in the 1980s or eutrophication of Svelle in 1995.

There is no direct correlation between the pigment concentration in sediment and the population growth of aquatic organisms. Some pigments indicate the changes in lake productivity, for example, caused by the increase in nutrient load that leads to the eutrophication. However, an abundance of pigments in sediment reflects the mechanism of sedimentation of particles with pigments as well as the oxidation of pigments in the surface mud. From this perspective, the increase in sedimentation rate may preserve the pigments from the degradation by isolation with the additional sedimentary material (Sanger, 1988). The slumping and focusing of sediment material also may blur the values, both accumulation rate and a number of pigments (Sanger, 1988).

Our main hypothesis, which would explain the extreme event, is the possible slump of sediment material toward the lake bottom that had increased the accumulation rate. By this scenario, the mixture of the surface mud and the below sediment was sealed with the additional material. Thus, the slow post-depositional loss of pigments, which usually occur within years, did not take place. That process promoted the pigment preservation from the decomposition. The narrow flat lake bottom lays between steep slopes from east and west with a gradient of slope from 10 to 65 m depth of the lake. The sampling site is closer to the western slope where the lateral movement may occur. The additional material from the slope most probably had the relatively same characteristics and the radioactive date. Therefore, we may observe the minor increase in organic material and insignificant changes in the concentration of macro elements (except S, which will be discussed later). We are probably dealing with a sediment focusing from the deep zone to the lake bottom.

We cannot reconstruct how the hypothetical slumping occurred: if it was slow or rapid moving of material; was it only once or was it multiple events. The period from 1965 to 1975 is characterised by the high human impact on catchment area when many events coincide in the time. Some of them could trigger the sediment slide or might have a lagged effect on the lake.

The closest hydropower construction in this period was a microhydropower Foss in an upstream of the river Børterelva (Preståa) in 1970. The outlet of the Børterelva (Preståa) locates not so far to the north from the sampling site, so the extreme point increase in the sediment load could induce the morphological changes.

The landslides nearby on watershed may trigger the sediment slide within the lake. After the landslide a mass of clay (and additional nutrients) enter the lake directly. Also after such an event, the outside streams and creeks receive an extra sediment load that can cause a mobilization of near-shore sediments into deeper parts of the lake. The closest landslide to sampling site occurred in 1976 (Halltjern) on western shore of Øyeren, in 1974- 1976 on eastern shore (Trøgstad and Brastad) and two landslide in 1967 (Trøgstad1 and Nordby) to the south form the lake (personal communication with Professor-Emeritus Rolf Sørensen and Kristian Moseby).

General trend of primary production

The unusual event should not be overestimated in a perspective of the general development of primary production for the period 1960-2016. With a purpose to shift a point of view, the obtained shares of chlorophylls were adjusted with respect to the sedimentation rate. Figure 4.4 shows the development of the chlorophylls abundance, which has been fallen on one square centimetre of sediment surface in one year regardless of the sedimentation rate and organic matter. The resulting patterns are the same for all chlorophylls including the value of Total Chlorophyll a. First of all, we may notice how the peaks are isolated and abrupt regarding the overall trend. The pigments base level before the peak restored within the two years to the same degree. The second and more important observation is that the abundance of chlorophylls remains stable through the given period if to drop the extreme peak. The short-term oscillations were smoothed, and we can say that the general trend of preserved in sediment chlorophylls is linear. Total Chlorophyll a abundance lays within 50-75 µg cm^{-2} yr^{-1} (Figure 4.4). After each increase in concentration, the value of Total Chlorophyll a returns to the level of 50 µg cm^{-2} yr^{-1} that seems to be a normal representative level for the lake in period 1960-2016. The concentrations after 2005 year are higher, but it could be due to unfinished processes of slow decomposition within the buried sediment. Because the oxidation of sediment material occurs during 5-10 years after the burial in a higher rate than the material bellow (Leavitt, 1993). Therefore, data from the upper layers could be out of the trend.

The RDA showed that a shift toward the warmer and wetter weather promote the increase of organic matter in the sediment. This relation fits to the overall increase of organic matter in surface waters in boreal and hemiboreal regions. According to RDA, the weather changes have a negative effect on the autochthonous primary production indicated by pigments in the sediment. That may demonstrate not a negative correlation between temperature and primary production in the lake, but likely to be complex mechanism of phytoplankton growth in Øyeren as a response to the climate changes. The primary production occurs also outside of the summer period. Warming of epilimnion and warmer winters, which mean a shorter period of lake's ice-cover, provide the longer growth season conditions. The phytoplankton growth, which may be dominated by diatoms, occurs during the circulation periods and partly during the winter. The long productive period within the lake may explain the weak correlation of Total Chlorophyl a in the sediment with the monitored Chlorophyll a in a water column. The samples for monitoring were obtained during summer, but the pigments in sediment represent the whole year productivity. Therefore, the trends are similar but not identical. The pigments in the sediment do not reflect the nutrient load of a water body; they reflect how nutrients are used.

The light availability is an environmental parameter that may control the phytoplankton growth in Lake Øyeren. The light limitation is induced by suspended particles, which adsorbs and scatter sun radiation. For example, in Northern Øyeren an increase of water level causes a poor development of vegetation and may cause an increase of mortality because light must penetrate much water to reach the higher water plants (Berge et al., 2002). The other important factor is a short water retention time of the lake. The retention time 20 days was calculated from a water flow (Table 2.1). The fast moving of nutrients and organic matter may limit the autochthonous primary production.

5.2 Inorganic pollution

Trace elements and S

The trace elements Pb, As, Cu, Hg and Cd have the similar patterns for the given time range (Figure 4.6). They form the distinct and coherent group in PCA, with strong loadings on the first component – PC1. The group of trace elements has the positive correlation with Dry weight and the high negative correlation with LOI on the PC1. The trace elements form the complexes with organic compounds, mostly with humic substances. The complexation provides a mobilisation and further transportation of trace elements in the aquatic ecosystem. The PCA demonstrate that the organic matter, which, as we decided, consists mostly of the allochthonous humic substances, does not play a major role in the transportation of trace elements into the lake water and sediment. That is not typical for lakes in the context of Nordic countries where, as has been shown by Skjelkvåle et al. (2001), the concentration of total organic carbon (TOC), which represent organic matter, have a strong positive correlation to trace elements and metals. We may observe only the strong association between LOI and Mn, while Fe does not show the correlation to LOI. The transportation of trace elements is more associated with the fine inorganic particles, based on the group's positive correlation to the Dry weight. The RDA showed that the variations of the weather parameters could not explain the variation of the trace element group. Also, water flow showed negative correlation to trace elements. Thus, trace elements and S since the 1970s until present are most likely originating from direct deposition from air pollution and upstream mineral particles. The high concentrations of trace elements in the sediment in the period 1960-1970 may indicate the point local sources of pollution, which may be associated with the mining in Røros area. The local pollutions could be boosted by the industrial emissions and smelting activities in a local and international context.

Element S, unlike the other macro elements, behaves in the same way as the trace elements. The concentration of S varies incoherently to Fe and Mn (Figure 4.5); according to PCA, S has a weak relation to Fe and negative correlation to Mn. Thus, the high concentration of S from the early 1960s to 1973 is not a sign of anoxia. The PCA placed S in one group with trace elements that imply the strong negative correlation to the LOI. The trace elements and S might have similar origin and pathways. The primary source of S is most probably an atmospheric deposition. The high concentration of S in the 1960-1970s and its further stable declining happened together with a gradual growth of LOI and C. That matches to the phenomenon of increase in organic matter concentration in surface waters, which had been started to be monitored from the 1970s until now in North-West Europe and North America (Kritzberg & Ekström, 2012). This process is also called a brownification due to changes in a colour of water. That time matches to significantly reduced anthropogenic S emission in Europe.

The peak of Hg concentration in 1963 that is followed by a decreasing has a similarity with the Hg contamination of Lake Mjøsa (Figure 4.5). The comprehensive study of Hg depositions in Lake Mjøsa sediment showed the high level of Hg from 1945 with a peak in a middle of 1960s that is followed by further decreasing (Rognerud, 1985). The half of the deposition were attributed for the factory that produced a carton "Mesna kartongfabrikk" in Lillehammer area. The ban on a usage of Hg in a wood processing industry provided the decrease of Hg load to

Lake Mjøsa. Since the two lakes are connected by rivers Vorma and Glomma, the point source of contamination of Lake Mjøsa could affect the Lake Øyeren as well. After 1970s, the major source of Hg contamination most likely was an anthropogenic atmospheric deposition. Also, there is the minor peak of concentrations in 1963 for S, As and Pb that coincide with the Hg peak. The increase of S, As and Pb concentrations also could have been caused by the pulp and paper industry production on the catchment area.

6 Conclusions

Based on radiometric dating the studied sediment cores from Lake Øyeren represent a time period from the 1960s until present. The sediment accumulation rate in deep basin of Lake Øyeren was estimated to 0.5–0.7 g cm^{-2} yr^{-1} for most of the time-period. Flood events and water level regulations seem to have minor impact on the sedimentation rate. In addition, the sediment cores seem to be intact and undisturbed. That makes sediment cores from the deeper basin suitable for reconstruction of long-term development. Hence, reference conditions for the lake can be obtained by analysing deep layers of sediment cores.

The primary production, estimated from preserved carotenoids and chlorophylls in the lake sediment, has a stable development through the studied period. Based on the amount of *chlorophyll a* and its stable degradation products *pheophytin a* in the sediment, the primary production remains at the same level as in the beginning of the 1960s, despite the high nutrient loading from the municipal savage systems and agricultural activity in the catchment area. The productivity within Øyeren is most likely being controlled by particle induced light limitation and short water retention time (high flow).

The sharp increase in sedimentation rate and pigment amount in 1970-1972 is a temporary and spatially isolated event. Internal movement of surface sediments seems to be the most probable explanation, where steep slope sediments have slipped and buried undecomposed surface mud in the deeper basin. That has provided a good preservation of the pigments and increased the accumulation rate. The unusual event does not indicate important changes in the lake ecosystem.

Overall, there is a decreasing trend in trace elements (Hg, Cd, Cu, Pb and As) and S concentrations in the sediments since the 1960s. A period with significantly higher concentrations of the trace elements in 1961-1972 coincides with the unusual event. According to statistical analysis (PCA) the transportation of trace elements are not associated with humic substances. The trace elements and S are most likely originating from anthropogenic atmospheric deposition and upstream mineral particles. The high concentrations of trace elements in the 1960-1970s coincide with the industrial emissions and smelting activities in a local and international context. The possible local point source of Hg contamination of Lake Øyeren in the middle of the 1960s is the carton factory in Lillehammer area.

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Appendix A: Report on the Radiometric Dating of Sediment Core from Lake Øyeren, Norway

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Rationale and methodology

Lead-210 (half-life is 22.3 year) is a naturally-produced radionuclide, derived from atmospheric fallout (termed unsupported ^{210}Pb). Cesium-137 (half-life is 30 years) and ^{241}Am are artificially produced radionuclides, introduced to the study area by atmospheric fallout from nuclear weapons testing and nuclear reactor accidents. They have been extensively used in the dating of recent sediments. Dried sediment samples from core OYERE taken from Lake Øyeren, Norway, were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay in the Environmental Radiometric Facility at University College London, using ORTEC HPGe GWL series well-type coaxial low background intrinsic germanium detector. Lead-210 was determined via its gamma emissions at 46.5keV, and ^{226}Ra by the 295keV and 352keV gamma rays emitted by its daughter isotope ^{214}Pb following 3 weeks storage in sealed containers to allow radioactive equilibration. Cesium-137 and ^{241}Am were measured by their emissions at 662kev and 59.5kev (Appleby et al, 1986). The absolute efficiencies of the detector were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self absorption of low energy gamma rays within the sample (Appleby et al, 1992).

Results

Lead-210 Activity. Given the counting error at 60.5 cm, total ^{210}Pb activity may reach equilibrium with supporting ^{210}Pb at the base of the core (Table 1, Figure 1a). Unsupported ^{210}Pb activities, calculated by subtracting supporting ^{210}Pb activity from total ^{210}Pb activity, decline irregularly with depth (Figure 1b). In the top 25 cm, unsupported ^{210}Pb decline more or less exponentially with depth, indicating relatively uniform sediment accumulation rates. Dips at 32.5 and 52.5-56.5 cm in unsupported ^{210}Pb activities suggest increased accumulation rates at the time that diluted the activities.

Artificial Fallout Radionuclides. The ^{137}Cs activity versus depth profile (Figure 1c) has a sharp peak with an enormously high ^{137}Cs activity at 36.5 cm, which was derived certainly from the fallout of the 1986 Chernobyl accident. A ^{137}Cs peak at 59.5 cm was derived from the 1963 fallout maximum from the atmospheric testing of nuclear weapons. Detected ^{241}Am activities around this depth also suggested nuclear weapon testing.

Core Chronology

Use of the CIC model was precluded by the non-monotonic features in the unsupported ^{210}Pb profile. ^{210}Pb dates were calculated using the CRS model (Appleby, 2001). The simple CRS dating model places 1963 and 1986 at c. 44.5 and 26 cm, respectively. They are considerably shallower than the corresponding depths suggested by the ^{137}Cs profile of the core. The final chronologies and sediment accumulation rates were corrected by the CRS model and referring the sediments at 59.5 cm as formed in 1963. The results are given in Table 3 and shown in Figure 2. This correction puts 1986 in between 32.5 – 36.5 cm, in agreement with the ^{137}Cs record. Most time sediment accumulation rates in the core are in 0.5 – 0.7 g cm^{-2} yr^{-1}, the rates increased in around 1970, excessing 2 g cm^{-2} yr^{-1}, and in the middle of the 1980s, reaching 1 g cm^{-2} yr^{-1}.

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Table 1. ^{210}Pb concentrations in core OYERE taken from Lake Øyeren, Norway.

Depth	Dry Mass	Pb-210						Cum Unsupported	
		Total		Supported		Unsupp		Pb-210	
cm	g cm^{-2}	Bq Kg^{-1}	±	Bq Kg^{-1}	±	Bq Kg^{-1}	±	Bq m^{-2}	±
0.5	0.032	136.74	11.74	60.2	2.82	76.54	12.07	24.5	3
4.5	1.5325	113.16	10.08	52.97	2.32	60.19	10.34	1045.4	131.2
9.5	4.541	108.71	9.26	61.21	2.41	47.5	9.57	2657.8	304.7
14.5	6.9825	108.97	9.71	58.69	2.48	50.28	10.02	3851.2	398.3
19.5	9.412	102.71	9.54	63.53	2.35	39.18	9.83	4932.3	469.5
24.5	12.2015	105.22	12.55	63.4	2.86	41.82	12.87	6061.6	554.4
28.5	14.6075	89.09	5.84	65.58	1.53	23.51	6.04	6826.5	627.5
32.5	17.3755	74.92	8.75	59.38	2.27	15.54	9.04	7359.4	655.2
36.5	19.608	78.34	9.85	59.54	2.49	18.8	10.16	7741.5	691.3
40.5	22.035	82.24	11.04	64.21	2.69	18.03	11.36	8188.4	735.3
44.5	24.5845	82.78	11.27	59.69	2.76	23.09	11.6	8709.9	790
48.5	27.4505	79.74	6.39	64.87	1.65	14.87	6.6	9245.3	843
52.5	30.0325	73.54	10.79	64.12	2.62	9.42	11.1	9553.5	868.8
56.5	32.5835	65.11	10.48	57.23	2.35	7.88	10.74	9773.6	913.4
59.5	34.6866	83.16	6.74	69.62	1.66	13.54	6.94	9993.5	939.9
60.5	35.394	71.77	9.28	62.71	2.45	9.06	9.6	10072.4	942.8

Table 2. Artificial fallout radionuclide concentrations in core OYERE.

Depth	Cs-137		Am-241	
cm	Bq Kg^{-1}	±	Bq Kg^{-1}	±
0.5	54.17	2.16	0	0
4.5	52.58	2.01	0	0
9.5	69.87	2.03	0	0
14.5	70.37	2.27	0	0
19.5	80.5	2.15	0	0
24.5	103.21	2.97	0	0
28.5	131.71	1.62	0	0
32.5	192.2	3	1.62	0.89
36.5	979.95	6.47	0	0
40.5	54.71	2.25	0	0
44.5	19.63	1.73	0	0
48.5	25.47	1.07	0	0
52.5	29.67	1.78	0	0
56.5	33.32	1.8	3.3	0.94
59.5	83.58	1.59	0	0
60.5	79.02	2.38	1.95	0.97

Table 3. ^{210}Pb chronology of core OYERE taken from Lake Øyeren, Norway.

Depth	Drymass	Chronology			Sedimentation Rate		
		Date	Age				
cm	g cm^{-2}	AD	yr	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± %
0	0	2016	0				
0.5	0.032	2016	0	2	0.5022	1.475	17.5
4.5	1.5325	2013	3	2	0.5858	1.169	19
9.5	4.541	2008	8	2	0.6365	1.168	22.1
14.5	6.9825	2004	12	2	0.5274	1.083	22.2
19.5	9.412	2000	16	2	0.591	1.132	27.3
24.5	12.2015	1994	22	3	0.4696	0.813	32.8
28.5	14.6075	1990	26	3	0.734	1.135	28.7
32.5	17.3755	1987	29	4	1.0036	1.606	59.6
36.5	19.608	1984	32	4	0.7663	1.316	55.6
40.5	22.035	1981	35	4	0.7218	1.16	64.3
44.5	24.5845	1977	39	4	0.4933	0.729	51.7
48.5	27.4505	1972	44	5	0.6539	0.96	46.5
52.5	30.0325	1971	45	5	2.3641	3.684	42.5
56.5	32.5835	1970	46	5	2.1386	3.217	35.8
59.5	34.6866	1963	53	5	0.5461	0.777	31.7

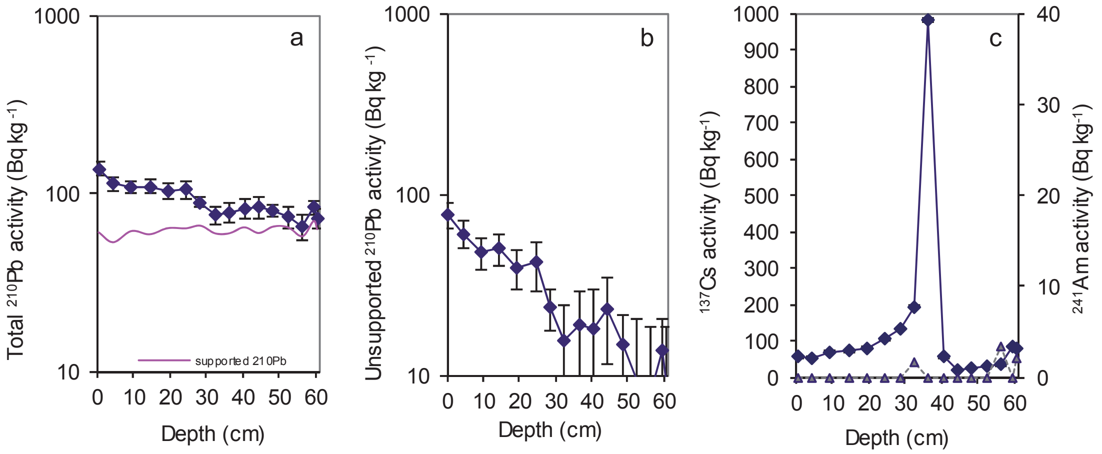


Figure 1. Fallout radionuclide concentrations in core OYERE taken from Lake Øyeren, Norway, showing (a) total ^{210}Pb, (b) unsupported ^{210}Pb, and (c) ^{137}Cs and ^{241}Am concentrations versus depth.

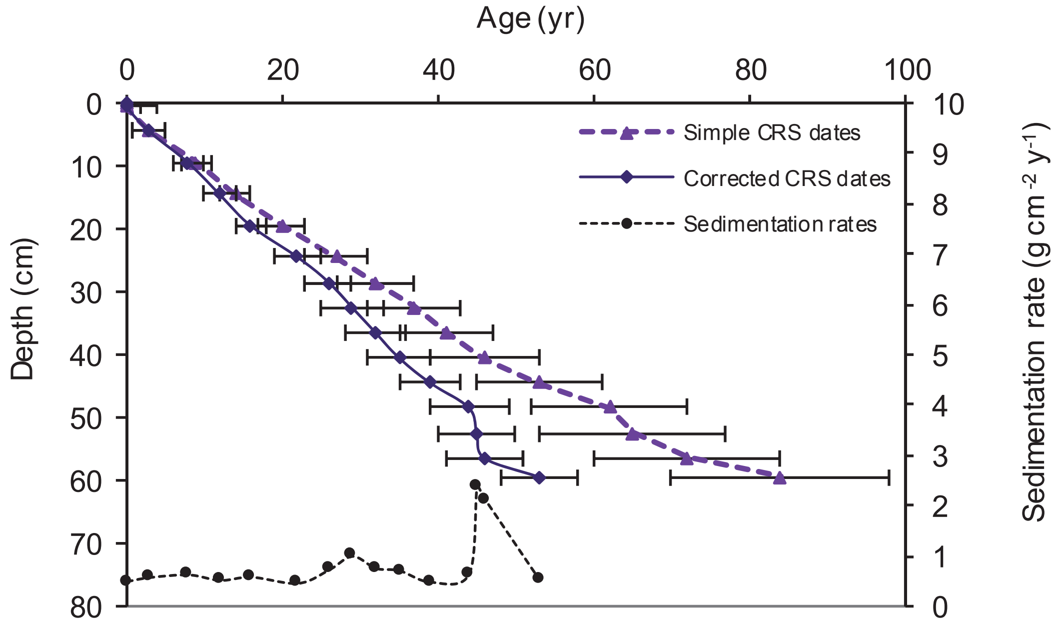
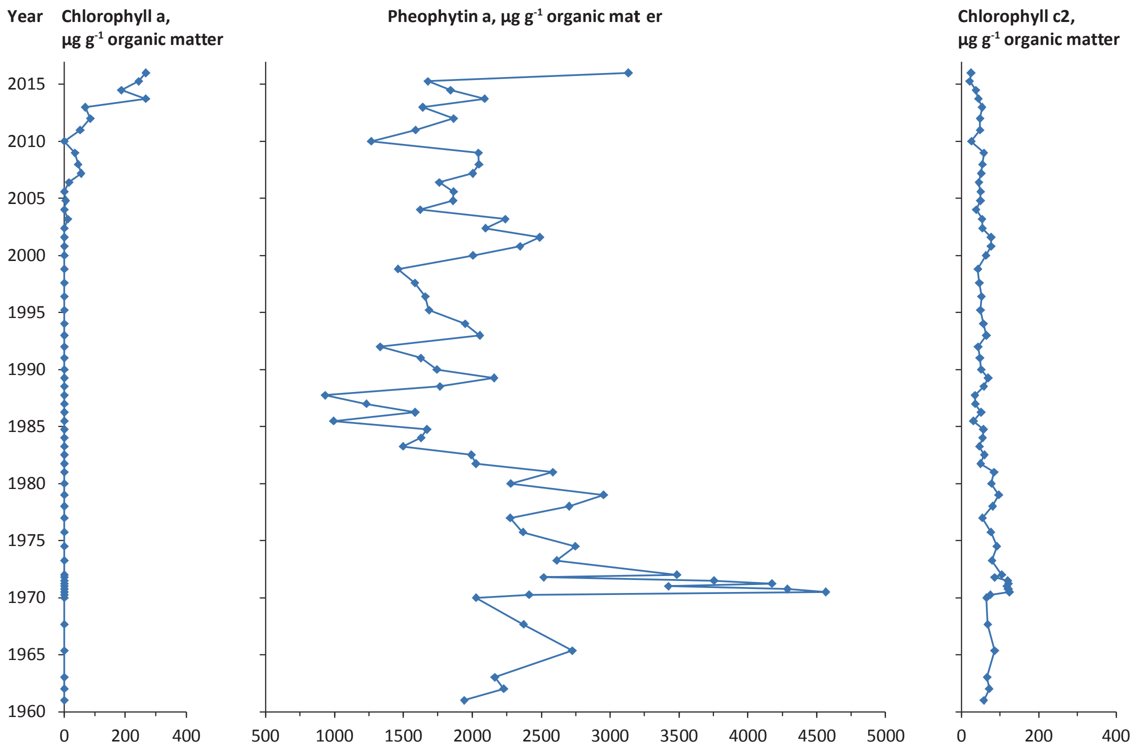
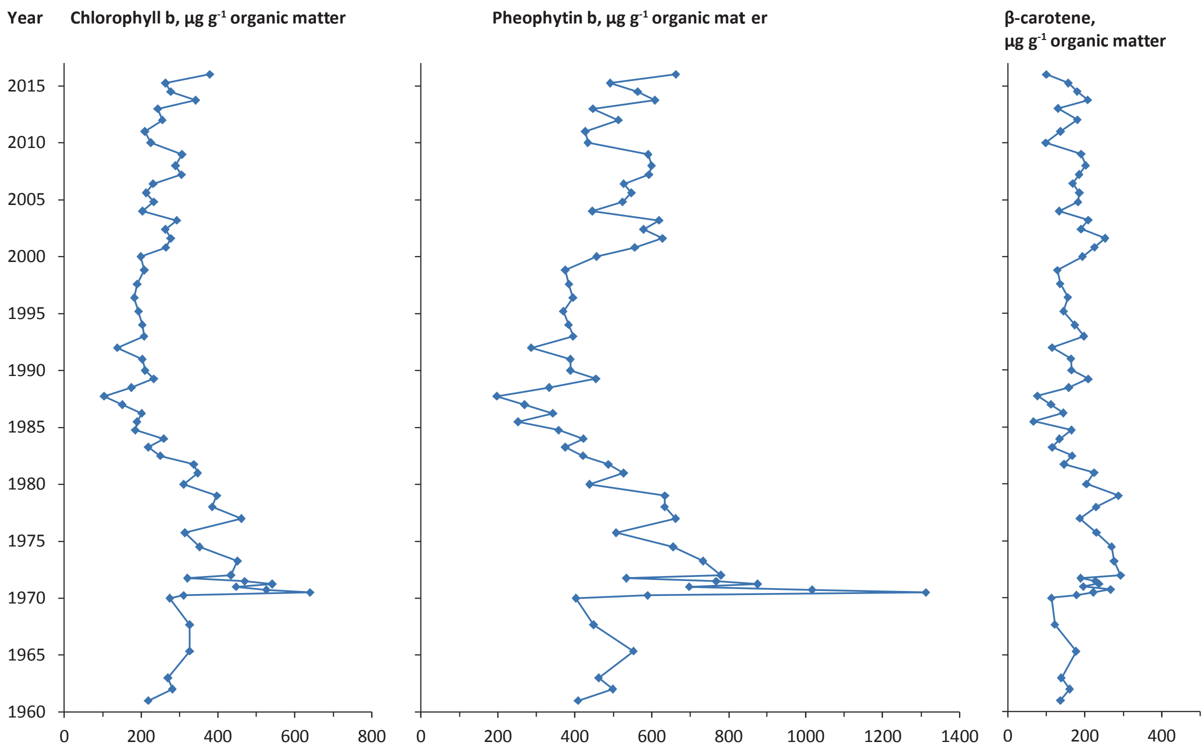
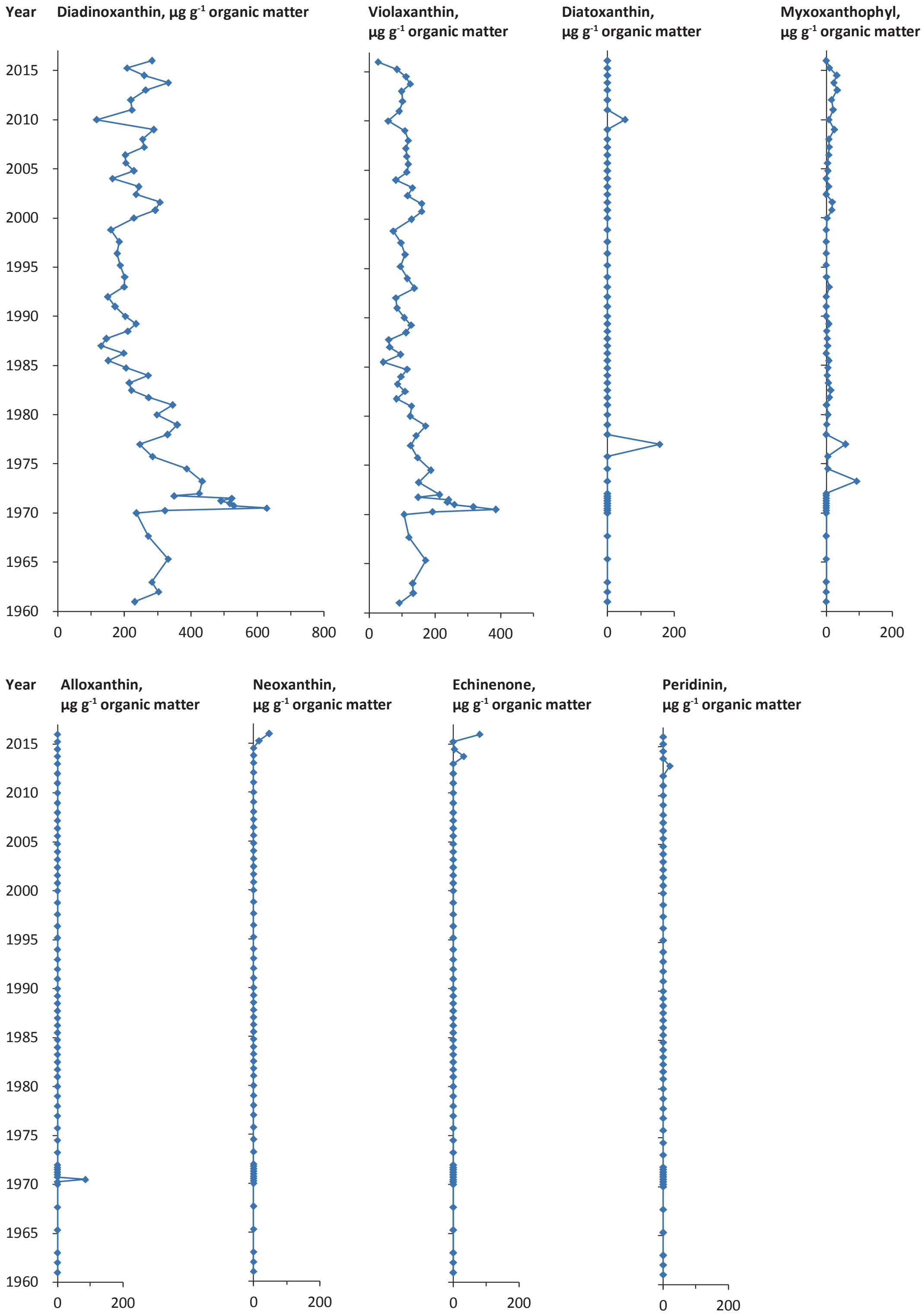


Figure 2. Radiometric chronology of core OYERE taken from Lake Øyeren, Norway, showing the CRS model ^{210}Pb dates and sedimentation rates.

Appendix B: Stratigraphy of pigments






Year
Diadinoxanthin, µg g-1 organic matter
Violaxanthin, µg g-1 organic matter
Diatoxanthin, µg g-1 organic matter
Myxoxanthophyl, µg g-1 organic matter
2015
2010
2005
2000
1995
1990
1985
1980
1975
1970
1965
1960
0
200
400
600
800
Year
Alloxanthin, µg g-1 organic matter
Neoxanthin, µg g-1 organic matter
Echinenone, µg g-1 organic matter
Peridinin, µg g-1 organic matter

Appendix C: Stratigraphy of chlorophylls and sedimentation rate, and events that happened in the catchment area

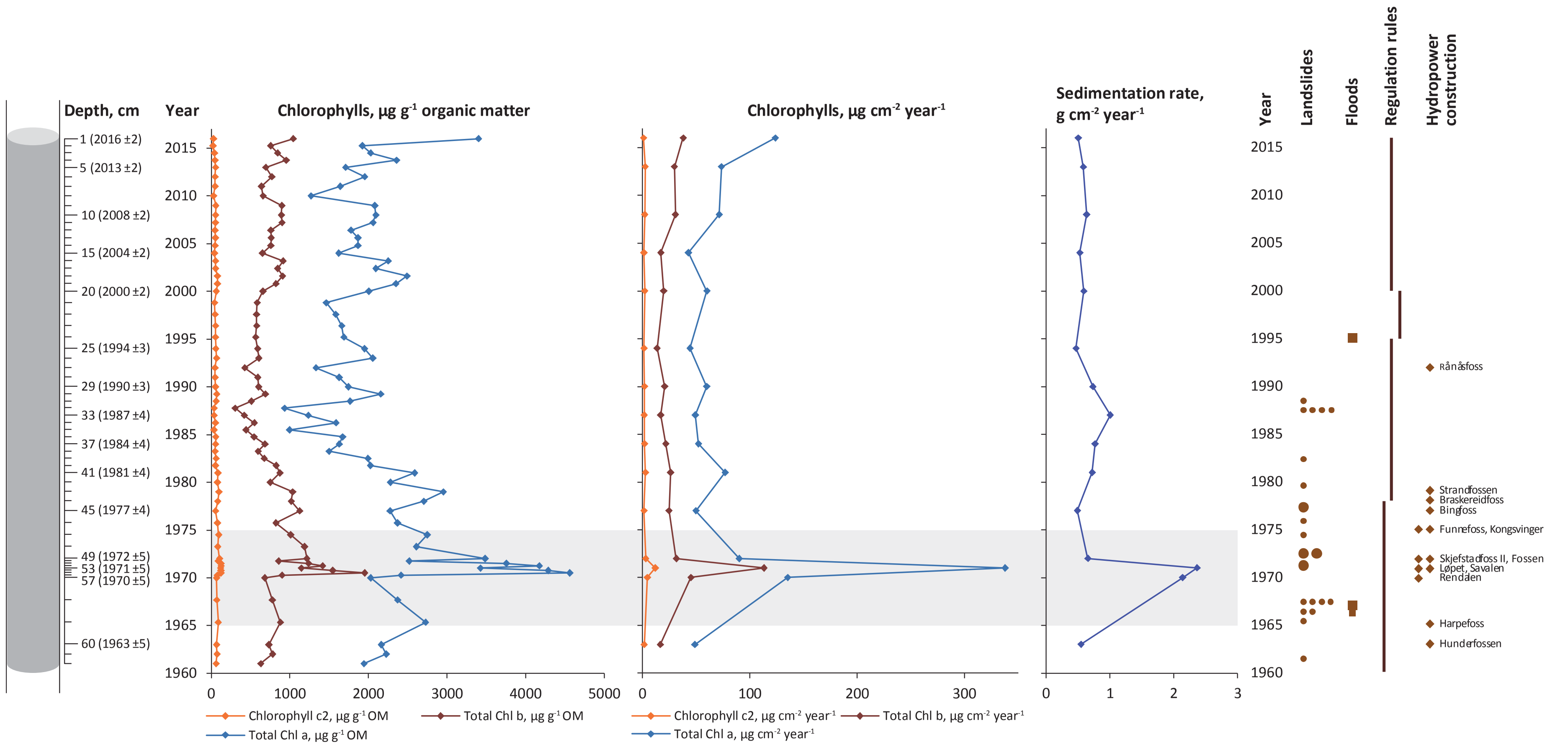


Figure 1 Stratigraphy of the chlorophylls (µg g^{-1} organic matter, µg g^{-2} yr^{-1}) and sedimentation rate (g cm^{-2} yr^{-1}) from the sediment core of Lake Øyeren together with events that happened in the catchment area (main focus on period from 1960-1980). Larger circles and squares depict larger landslides and flooding events, respectively.

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