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Development of water quality in Lake Brønnerødtjern – studied by

paleolimnological methods, with special focus on heavy metals

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Master in Ecology

Abstract

Lake Brønnerødtjern is a freshwater lake located in Våler municipality in Viken county, city of Moss. It belongs to the Mossevassdraget water courses which is a part of the Vansjø watershed.

This thesis aims to reconstruct the long-term development of heavy metals in Lake Brønnerødtjern, based on paleolimnological methods by evaluating natural and anthropogenic sources of heavy metals, the level of heavy metals in the lake sediment and impact of climate change and land use changes on the transport of heavy metals.

In the first part of the thesis the general information about the lake Brønnerødtjern is represented with natural and anthropogenic effect in the watershed. The two sediment cores collected from the lake are analysed to obtain concentration of different chemical constituents (P, Cr, Mn, Co, Cu, Zn, C, S, Fe, Hg, Cd, Pb and N). The period with high sedimentation rate and concentration of the elements mentioned above was detected. Then, the results obtained were interpreted with respect to the available information from the lake.

The research covers the development study of Lake Brønnerødtjern for last 164 years. The most probable primary sources of the inorganic pollution since 1853 until present are considered as the long-distance atmospheric deposition and industrial emission. Moreover, geochemical processes and the bedrock composition of the catchment area also influenced concentration of some metals. The small tunnels made in the surrounding of the catchment during peat extraction in the past have impacted the sedimentation rate. This study is anticipated to curtail the research gap in the lake Brønnerødtjern, with a special focus on the presence of the heavy metals using different methods.

Acknowledgements

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Lake Brønnerødtjern
Photo: Evy KS Eliassen
https://s3-eu-west-1.amazonaws.com/turistforeningen/images/GE/2V/JE-940.jpeg

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1 Introduction

1.1 Background

The aquatic environment is highly influenced by two main important factors, change in the climate and anthropogenic activities. (Reuss, 2005). Humans can be considered as the main drivers of the change in the environment after the beginning of the Industrial Revolution in the late eighteenth century (Rockstro¨m et al. 2009; Catalan et al. 2013). After the beginning of the industrial age, metal concentration in aquatic system has increased noticeably. Metal industries, transport, sewage management and chemical fertilizers are major anthropogenic sources (Steinnes *et al.* 1989; Szyczewski *et al.* 2009; Zambon, 2010). Besides anthropogenic, other factors like acidic deposition, chemical contamination, erosion etc. may also affect the aquatic environment. Along with the human-induced changes, other processes occur within ecosystems due to natural causes and sometimes it is hard to distinguish the real driving forces; the drivers may have combined origin (Hobæk et al., 2012; Shyika, 2017).

As lakes are the important parts of the inland aquatic environment, they are dynamic ecosystems that respond to external changes and disturbances (Battarbee, 2000). The lakes should be regularly assessed to determine its status which can be done by monitoring, comparing historical data and paleoreconstruction. The particles slowly settle and accumulate in the accumulation zones of the lake by forming different layers on layers. These materials carry much information about the lake within different time. Hence, the information stored in the undisturbed sediment profile helps to reconstruct lakes past conditions and track a long-term environmental perspective from decades to millennia back.(J. Smol, 2009).

The thesis represents the analysis of the chemical indicators which is retrieved from sediment cores from the lake Brønnerødtjern. It helps to investigate the physical environment of the lake at the time of sedimentation. The analyses gave the amount of different chemical present in the different layers of the sediments during the process (P, Cr, Mn, Co, Cu, Zn, C, S, Fe, Hg, Cd, Pb and N). The thesis will rely on the data collected from the core sediment deposited over last 164 years and will use the paleolimnological approach. It will aim to bridge the research gap in the lake Brønnerødtjern, with a special focus on the presence of the heavy metals using different methods.

The remote lakes, like Brønnerødjtern are mainly influenced by the change in the natural factors such as temperature, hydrology, wind regimes, and geomorphology in the catchment area (Batterbee et al. 2002). These factors altogether have a great influence in the internal process of the lake and also in the transportation of the chemicals to the lake. Moreover, the remote lakes are also reservoir of the long-distance transported pollutants like Hg, Pb and Cd. Some trace metals are found naturally in the mineral composition of the bedrock. Even though the lake, Brønnerødtjern is not much affected by human activities there may be little change in the deposition of the metals by peat extraction in the past.

1.2 Paleolimnology

Paleolimnology is a multidisciplinary science that studies physical, chemical, and biological information stored in the sediments with a purpose to reconstruct the past conditions of inland aquatic systems (Smol, 2009). It is a simple approach which consists of sampling of the sediment core from a definite point of the lake, which is then further sectioned into many slices for the analysis. This is followed by a radiometric dating, which provides the temporal resolution of the sedimentary slices. Eventually all the data is interpreted to resolve the objective of the study. The paleolimnological studies vary from basic to applied research (Smol, Birks, Lotter and Juggins, 2012). Lakes are the indicators of the environmental changes. Thus, the sediment cores from lakes are used for the limnological studies (Battarbee, 2000). Lakes collect and preserve the long-term signals from the whole catchment area (Carpenter & Cottingham, 1997). The study of a lake can be used to obtain a lot of information of its catchment area. Paleolimnology has shown that the pristine water bodies have been not only impacted by human activities slowly but even the remote ecosystems are also changing (J. Smol, 2009).

The paleolimnological approach is a method to discover the past events and conditions. It also helps to capture the historical development of different biological indicators and chemical indicators such as pigments, organic matters, pollen, ions and pollutants (Smol 2009; Leavitt et. al. 1997; Vrålstad, 2017). A lake system is a natural reservoir of chemical and biological material. Materials produced within the lake (autochthonous) or get into the

lake externally (allochthonous), will finally precipitates to the bottom of the lake (Cronin 2009).

As sedimentation is a continuous process the biomarkers preserved in the sediments inform the autotrophic community and the production of the lake for a whole year. Monitoring programs collect the data when the conditions are favorable and in the fixed time of the year whereas paleolimnological method is cheaper and faster method than long term monitoring and in particular cases it is the only alternative (Shyika, 2017). It is the powerful approach to collect the information of the whole water body. The recent studies have showed that when sediment cores are collected and interpreted, can provide the accurate reconstructions of the past environmental activities. This should be done with a proper volume of quality assurance and quality control data (J. Smol, 2009). Sediment analysis is able to answer the state, pattern and changes even though it is both cost and time effective (Håkanson&Jansson, 1983).

1.3 Inorganic Constituents

Trace metals are the metals found in relatively low concentration in the nature (Pierzynski *et al.* 2000). Some of these metals like Fe, Cu and Zn are toxic if present in high concentration but important for the physiological process in the lake to some extent. Others like Hg, Pb and Cd are highly toxic in their low concentration. They are capable of binding with organic matters and with run off they enter the catchment area. They are essential to study about the geochemical composition of the bedrock and anthropogenic effect in the lake (Håkanson & Jansson, 1983).

Metals enter to the aquatic systems through runoff and groundwater inflow, which are emitted to the atmosphere during weathering and other geochemical processes. A number of metals with inorganic constituents are collected in the lake to form sediment profiles (Smol, 2009). In addition, many trace metals are added to the lake system by long-distance transportation which also finally end up forming sediment profile (Rognerud & Fjeld 2001). The concentrarion of chemicals in the Norwegian lakes are highly affected by long-range transportation (Steinnes, 2001). The accumulation of metals in the sediments is much higher than in the overlying water (Rognerud&Fjeld, 2001; Zambon, 2010). Illustrating the concentration of the heavy and trace metals (Cd, Cr, Co, Cu, Hg, Fe, Mn, Zn and Pb) can give imperative information of the geochemical composition of the bedrock and about the sources from where those metals get into the aquatic environment (Zambon, 2010). However,

studying concentration of trace metals present in the accumulation is complicated which can be affected by several other reasons (Fjeld et al. 1994). We use lake sediment as the source of the paleoenvironmental data

1.4 Objectives of the study

This master thesis is a paleolimnological study of the freshwater Lake Brønnerødtjern, Norway. The major aim of the study is to reconstruct the long-term development of heavy metals in a humic lake based on paleolimnological methods, with the following sub goals.

- Evaluate natural and anthropogenic sources of heavy metals in Lake Brønnerødtjern.
- Evaluate the importance of organic matter for the level of heavy metals in the lake sediments.
- Evaluate the impact of climate change and land use changes on the transport of heavy metals.

2 Study Site

2.1 General information

Lake Bønnerødtjern is located in Våler municipality in Viken county, city of Moss at Sperrebotn. It belongs to the Mossevassdraget water courses which is a part of the Vansjø watershed. The total area of the lake is 1.73 km^2 located on 32 m. o. h and deepest point is 4.2 meters. It is lightly acidic lake with p$_H$ 6. The lake receives its water from forest found around it through several small streams and to some extent from wetlands (nevina.nve.no/ Appendix A).
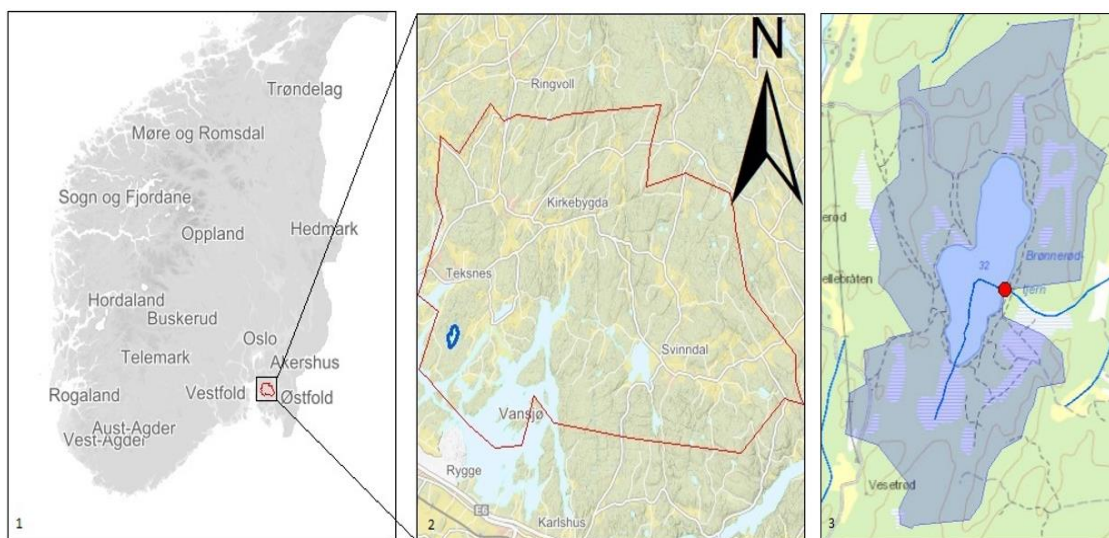
Figure 1: Left: Southern Norway. Middle: Våler municipality. Right: Brønnerødtjern with precipitation field taken from http://nevina.nve.no/ (Appendix A).

The lake is all surrounded by woods which is unaffected by agriculture or any type of urbanization. It is famous for recreation. People enjoy hiking to the lake, observe its captivating beauty and some enjoy fishing. The lake is considered as a dystrophic lake characterised by the low concentrations of nutrients, low light penetration and high content of organic material (Jansson et al., 1996). The high amount of organic matters gets in the lake during high flow periods, which is probably influenced by the peat extraction which was done in the lake many years ago.

3 Methodology

The sediment cores were taken and sliced at site on 24. July 2018 by Camilla Hagman and Thomas Rohrlack. The samples were put into plastic bags and frozen until further analyses. The sediment data after analysis was provided by the MINA faculty which is elucidated by me below:

3.1 Sampling and slicing of the sediment cores

The sediment core (two samples) 51 cm long were taken from the deep, flat, central areas of the lake with an Uwitec sediment sampler. The deepest parts of the lake accumulate the smaller size fractions. To find the deepest point a depth gauge was used. After the visual observation, the sediment cores (6 cm diameter) were divided into layers of 1 cm in thickness (51 sub sediment samples) immediately on site and then transferred into polythene bags and then freeze-dried before further analysis after they were taken in the laboratory. The bottom 50 sub sediment layers (from 2cm to 51 cm depth) were only reported. The first sub sediment layer was avoided to avoid the uncertainties due to high water content in it.

3.2 Analytical methods

First Core

The freeze-dried samples from the first sediment core were used for the analyses of loss on ignition (LOI), S and Dissolved Organic Matters (DOM). For the determination of LOI, gravity analyses were performed based on difference in weight from dried sediment material (105 ^{o} C for 24 hours) in which each sub samples were incinerated at 550 ^{o} C for 2 hours (Xiao et al., 2020). The relationship between LOI and OC, where carbon is assumed as 50% is used to estimate sediment OC (Dean, 1974; Håkanson and Jansson, 1983; Heiri et al., 2001; Xiao et al., 2020).

The trace elements Cu, Cd, Cs, Hg, Pb, Co and Cr were measured by inductive coupled plasma spectrometry (ICP-MS) by the laboratory technical staff at the Soil- and Water laboratory, NMBU. The Agilent 8800 ICP-QQQ is the ICP-MS with a quadrupole(Q_1), a reaction collision cell and a second quadrupole(Q_2) before the detector, which operates as unit mass filter reducing most of the interferences (Agilent,2014; Abiyos, 2017). Helium was

used when collision was useful and Oxygen when a reaction with the element of interest or with an interfering element was option to reduce interference. (Abiyos, 2017). Whereas, the other elements Zn, Fe, Mn, and P were measured with Inductive Coupled Plasma-mass Optical Emission Spectrometry (ICP-OES).Simultaneous CNS analysis was performed at NMBU, Animal and Aquacultural Sciences laboratories and based on the classical Pregl-Dumas method. 5 mg of freeze-dried sediment samples were combusted at 1150°C in an oxygen-rich environment and then lead through a Helium (g) reduction tube at 850°C, before they separated on three columns. C, N and S were measured as CO_2, N_2 and SO_2 respectively using a Vario El Cube element-analyzer (Elementar Analysensysteme GmbH, Hanau, Germany).

Second Core

The freeze- dried subsamples from the second sediment were sent to The University College of London (England) for the depth time chronology analysis. For the estimation of the total annual deposition of the radioactive Cesium (^{137}Cs) and Americium (^{241}Am) were analyzed by direct gamma assay measurements at their emissions at 662keV and 59.5keV (Appleby, 2002; Appleby et al., 1986; Xiao et al., 2020). This method finds two peaks representing the Chernobyl accident (1986) and the latest in the atmosphere (1962/1963), respectively. Furthermore, radioactive lead (^{210}Pb) was analyzed, using the CRS model. The results were used to generate a mathematical model that converts the distance from the sediment surface to time when the sediments were deposited (Appleby, 2002; Appleby and Oldfield, 1978; Xiao et al., 2020).

4 Statistical analysis

The raw data processing was done with Microsoft Office Excel (2020). Descriptive statistic was used to illustrate the limit of quantification (LOQ) in number. The concentration of elements measured by ICP-MS had values under the detection limits and the quantification limits. The non-noticeable values were substituted by one-half the detection limit and quantification limit (LOD/2 and LOQ/2). This is the most commonly used technique in environmental chemistry (Helsel, 2006; Abiyos, 2017).

5 Results

5.1 Visual observation

The sediment core was visible homogeneous and unlayered through the whole length of the column. It was indicated by a dark colour that signifies the high amount of organic matter content with some light and dark areas. The composition of the matter was mostly fine-grained clay throughout the whole profile. The sediment of the lower cores was more compressed and held little water in contrast to the upper layers (Camilla Hagman and Thomas Rohrlack).

5.2 Sedimentation rate

The sediment accumulation rates of Lake Brønnerødtjern in g cm^{-2} year^{-1} from 1853 to 2017 are shown in Figure 2. The detailed information about the radiometric dating from The Environmental Change Research Centre at University College London is given in Appendix B.

Sedimentation rate was uniform for almost 50 years from 1950 to 1900 about 0.2gm cm^{-2} yr^{-1} but started to raise from1925. The highest peak in the sedimentation rate was observed during 1939-1940. The highest increase in the accumulation rate was seen between 1935 and 1941. The minimum sedimentation rate was found between 1853 and 1900. Sedimentation rate has been continuously increasing from 1960 throughout the study period.
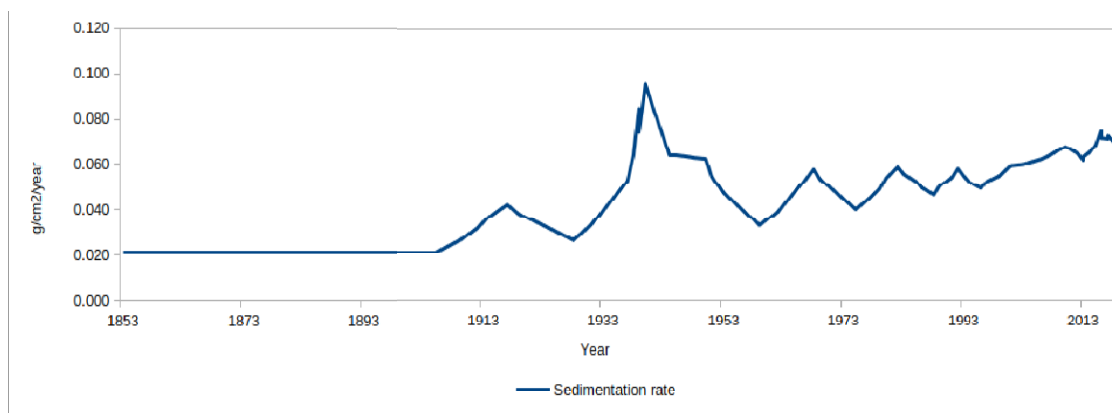
Figure 2: Sedimentation rates (g cm-2 y-1) taken from Lake Brønnerødtjern

5.3 Macro elements
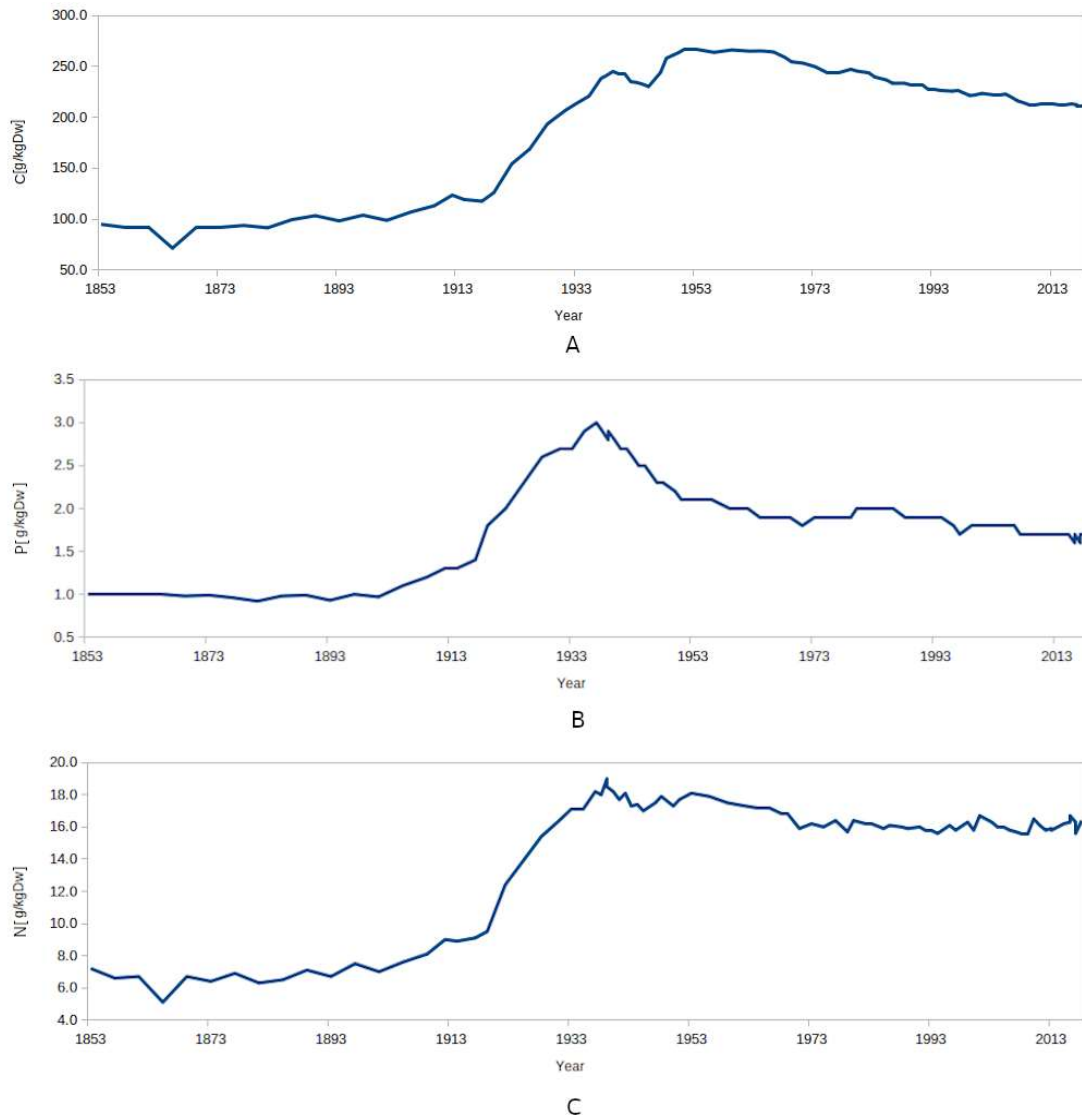
Figure 3: Concentrations of carbon (A), phosphorus (B), and nitrogen (N) in g kg-1 from top to bottom of the sediment core.
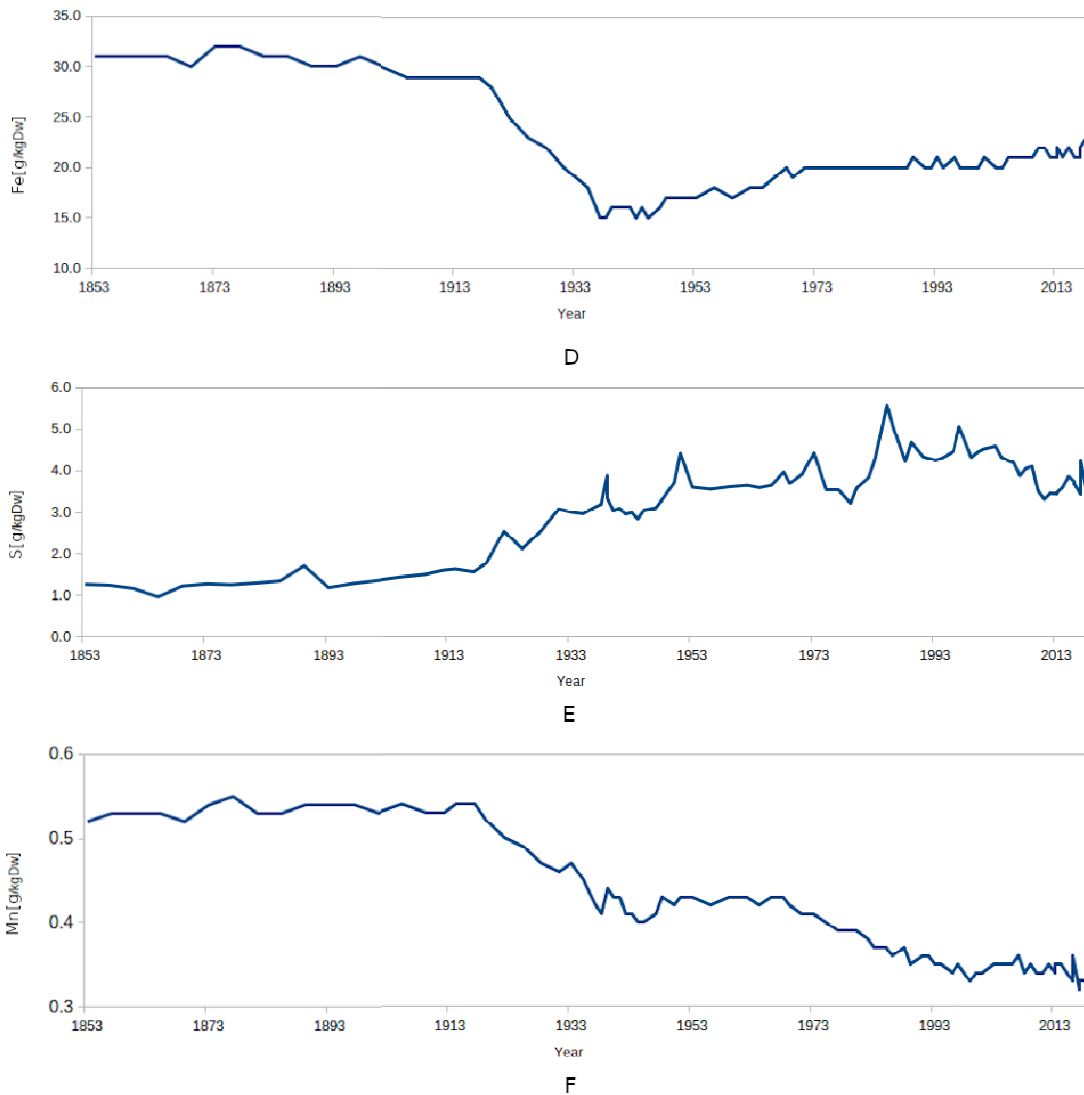
Figure 4: Concentrations of iron (D), sulphur (E), and manganese (F) in g kg-1 from top to bottom of the sediment core.

Concentrations of the macro elements are expressed in g per kg of the dry weight. All measured macro elements are shown in the Figure 3 and 4. The concentration of the element Carbon(C) shows tremendous increase. It was 94.8g kg^{-1} in 1853 which reached the highest peak in 1953 which is 266.9 g kg^{-1}. It has shown gradual decrease in the concentration of carbon but still is very high 211 g kg^{-1} in 2017. Nitrogen and phosphorus have shown the similar trend they were found less in the past but rapidly increased in their amount with high variations over the years through the studied period. Concentrations of both the elements increased from 1930, peaked in about 1936-1938 and is stable then. Concentration of Fe has shown totally different trend than any other macro elements. Concentration was very high

about 30 g/kg in 1853 which decreased to 15 g/kg in 1957 and is increasing slowly over the years. Concentration of the element S has also shown the increasing trend. The concentration of Sulphur has increased more than 3 times from 1853 to 2017 with several variations through the period. Mn is the only element, which has shown the decreasing trend. The concentration of Mn is decreased more than half over the studied period.

5.4 Trace elements
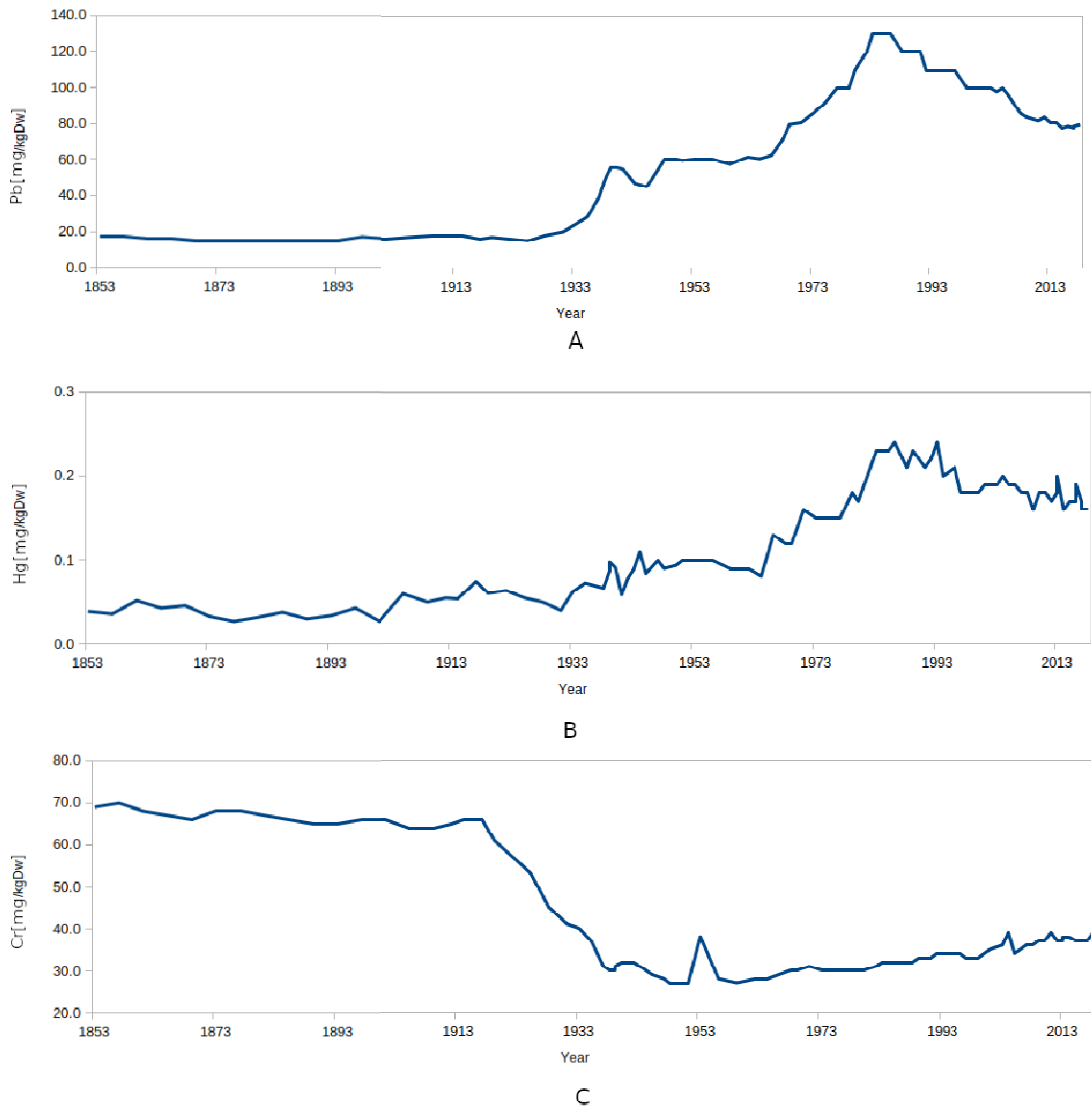
Figure 5: Concentrations of lead (A), mercury (B), and chromium (C) in g kg-1 from top to bottom of the sediment core.
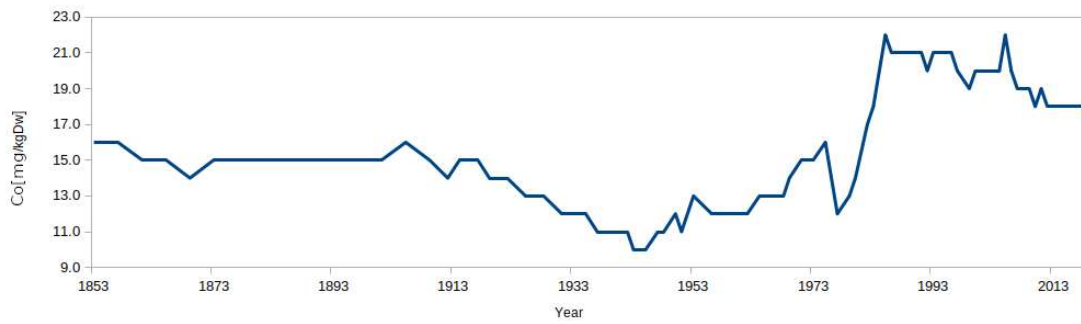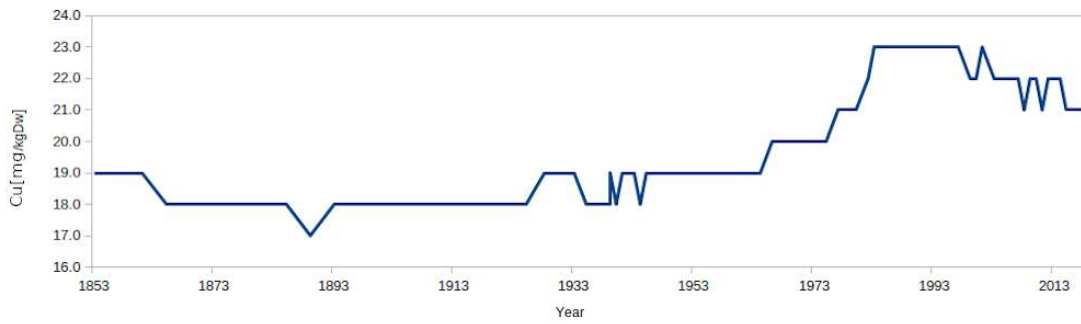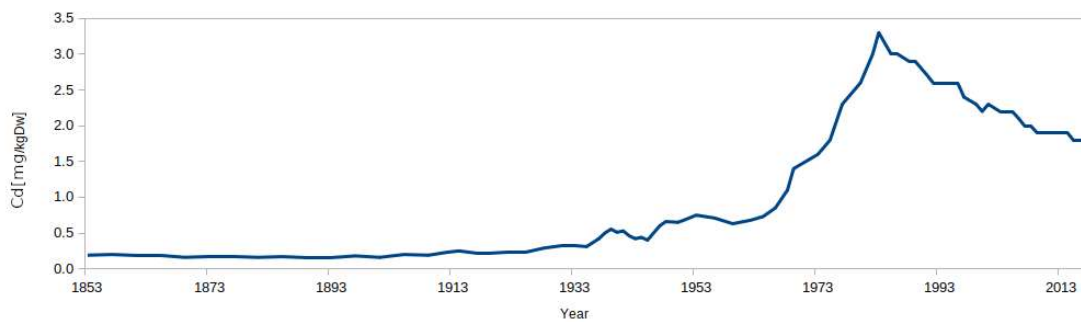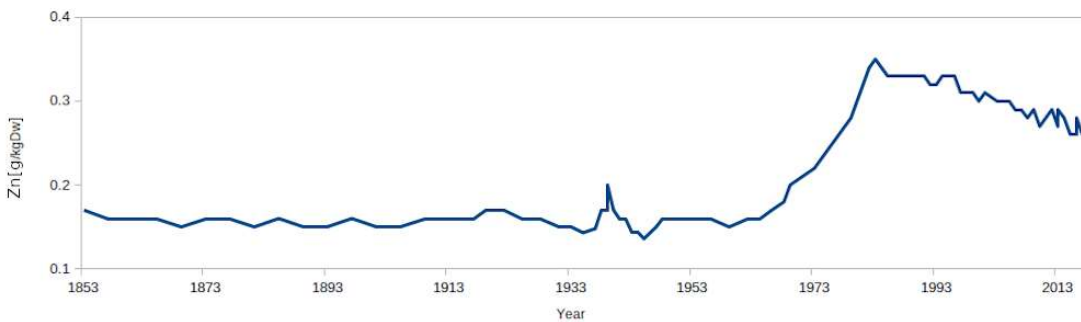
Figure 6: Concentrations of cobalt (D), copper (E), cadmium (F), and zinc (G) in g kg-1 from top to bottom of the sediment core.

Concentrations of trace elements are expressed in mg per kg of the dry weight.

The concentration of Pb reaches a maximum of 130 mg/kg in 1985 that is followed by a slow and steady decline. The concentration of Hg started to elevate from 1900 and peaked twice in 1986 and 1993 with its 0.24 mg/kg. It is also showing up gradual decrease through the studied period. The concentrations of Pb and Hg have almost similar patterns. The concentration of Cr is in contrast with other elements, it was very high in 1853 which was almost 70 mg/kg but started declining from 1917 to half with some fluctuations in different years. The concentration of Co has increased with variations over the years. The highest concentration of Cu was seen through the period between 1985 to 1997 with variations in the concentrations and increasing trend. Concentration of Cd was very low until 1964 which is below 1 mg/kg with sudden rise to 3.3 mg/kg in 1983 and again the pattern is showing decreasing trend gradually. Zn is characterized by the high concentration up to 0.3g kg^{-1} in 1983 with increase in concentration of 0.1 g kg^{-1} and relatively stable after 1983 through the study period.

6 Discussion

6.1 Climate change and Sediment transport

Sediment transport, composition and patterns of a catchment change with time, also response to different climatic factors (Bogen, 1983; Kennie, 2012). The flooding brought due to the climate change can affect the distribution of the sediments in the lake, the amount of organic matter as well as mineral composition of the sediment particles (Tremblay *et al.,* 2003; Bogen, 2009; Kennie, 2012). The increase in the number of precipitation events and different weather events in Norway advises the shift in weather condition. The repetition of flood events in last 100 years, also indicated high run off and erosion rates (Bogen, 2009).

There can be seen small tunnels formed to the lake from surrounding areas in the past for the peat extraction. This can be also a reason for the high rate of sedimentation in the lake

6.2. Distribution of inorganic constituent

The trace elements Pb, Hg, and Cd as well as the macro element Zn have almost similar patterns for the given time range (Figure 3 and 4). These trace elements form colloids or complexes with organic substances, usually with humic substances. After formation of colloids it is easy for further transportation of these substances in the aquatic system. The elements Cd and Pb both are observed with high concentrations in the pre-industrial times. Pb, Cd, Zn and Hg are the group of elements that are largely dominated by long-range transport of atmospheric deposition (Skjelkvåle et al., 2001; Shyika, 2017; Vrålstad, 1017). The result shows a decreasing trend in the concentrations of the elements Pb, Cd, Hg and Zn in the recent years.

The high amount of trace elements in the sediment in between 1950 to 1990 indicates the pollution from local sources. The peat extraction in the local area and mining can be the major cause of local pollution. The local pollution could be boosted by the emissions from industries and smelting activities in the local and international context (Shyika, 2017). In addition, the trace elements are highly impacted by anthropogenic activity, but it is usually focused on increase after the industrial revolution (Skjelkvåle et al., 2001; Vrålstad, 1017). Indicating the numerous aspects that influence the composition of chemical constituents in

Lake Brønnerødtjern, the remaining constituents indicate different behavior. The constituents are discussed in more details below.

Mercury (Hg) and Lead (Pb)

Concentrations of Hg (Figure 4) show a general increase from 1853 until present. Hg comes in several forms organic and inorganic and easily transported over long distances (Smol, 2008). There are several sources, both natural and anthropogenic, which can release Hg into the surrounding. In some places concentration of Hg is affected by weathering of the rocks or volcanic eruptions. Hg usually not perceived as natural constituent in the mineral composition, which signals some source of release. Due to its extreme volatile nature, it handily enters the atmosphere and several Arctic areas have become a dominant center for Hg accumulation (Perry et al. 2005; Vrålstad, 2017). Nevertheless, transmission of Hg is complicated process. To calculate the amount of man-made influence on Hg concentrations, it is necessary to gain a more comprehensive knowledge on the natural background levels (Martinez-Cortizas et al. 1999). However, human activities have accelerated the mercury release in the environment. It is recorded in 20th century that anthropogenic activities are more responsible for Hg release than weathering (Moore & Ramamoorthay, 1984; Smol, 2008). Besides burning of fossil fuels, alkali and metal processing industries, incineration of hospital wastes, pulp and paper industry mining and peat extraction are major sources of Mercury (Smol, 2008).

The concentration of lead starts to increase from 1933, reached highest and flattened from 1983-1986 and shows gradual fall until now. Pb is the one of the primary metal men started to exploit (Nriagu, 1983; Bränvall et al., 2001; Vrålstad, 2017). The manufacture of this metal never stopped as once it started, which can be the reason why concentration of Pb is still high than the past (Bränvall et al., 2001; Vrålstad, 2017). The use of leaded petroleum also helped in the addition of Pb in the atmospheric air before 1980 (Renberg et al. 2001). Concentration of Pb shows decrease after using unleaded gasoline however, concentration is still high and shows increase in recent years (Wan et al 2020). Studies in the past on heavy metals suggest that there is negative effect of catchment to the ratio of lake area in terms of Pb concentrations. It can directly enter the lake being highly absorbable with humic substances in the soil. Similar characteristic is expressed by other trace metals like Hg and Cu. An extensive study on the lake conducted in metal concentrations and it´s sources in approximately 3000 Nordic lakes suggests that bedrock composition as the main cause for the

release of Cu and Cr though Pb, Cd and Zn were affected by long range atmospheric deposition (Skjelkvåle et. al, 2006; Vrålstad, 2017).

Cadmium (Cd) and Zinc (Zn)

Cd and Zn both trace metals follow the similar pathway of long-range atmospheric deposition like other trace metals. Cd is not a natural portion of the bedrock composition (Skjelkvåle, 2001). It is seen in the figure the level peaked to 3.3mg/kg in 1983 and still very high. Cd is not a part of crustal rocks in Scandinavian lakes (Fjeld et. al., 1994). The unexpected increase can be only because of the long-distance transportation of Cd in a similar way as Pb, Hg, Zn and S.

Copper (Cu) and Chromium (Cr)

Concentration of Cu is increased yet it shows much fluctuation than other metals. Cu is not highly influenced by long-distance transport of atmospheric deposition though some parts of Norway near to Russian smelters and smelters in the southern part of Norway are express different trend (Rognerud & Fjeld, 2001). During 1873-1893 there was fall in the concentration of the Cu then it there was little increase in 1897 and then it plateaued for several years. Again, it showed increase which continued until now with several rise and fall. Concentration of Cu can be strongly influenced by the pollution emitted from local industries (Rühling et al., 1992). In contrary, Cr shows tremendous decrease in the recent years with exception of contributions in the north from Russian smelters. The main source can be long range atmospheric transport for Cr (Steinnes, 2001). Cr and Cu can be also the constituent of the bedrock.

Phosphorus (P), Iron (Fe) and Manganese (Mn)

P, Fe and Mn are linked to co-precipitation in a well oxygenated lake (Mackereth 1966: Kloster & Hongve, 1978; Vrålstad, 2017). The source of phosphorus in the sediments is the decomposition of the algae within the lake (Kloster & Hongve, 1978; Vrålstad, 2017). P can be also released in the water by weathering of the bedrocks. Also, the transported sediments in the lake carry P in it. Increase in the concentration of P in between 1930 to 1940 can be due to periodic flooding in the local area due to peat extraction process.

Fe is the important portion of the bedrock. The concentration of Fe is constant from 1971 until now with little rise. Concentration of Manganese is affected by Total Organic Carbon

(TOC) (Skjelkvåle et al., 2006). Mn is soluble in anoxic condition. During anoxic condition, mineralization of the organic matter (OM) occurs in the lake, consuming Oxygen present in the water in the presence of light. It results in the release of Fe and Mn (Naeher et. al., 2013). Fall in the concentration of Mn continuously is observed in the sediment sample analysis. Fe and Mn also help in the transport of other trace elements (Davison W., 1993).

Carbon (C) and Nitrogen (N) and Sulfur (S)

Rise in the concentration of carbon and Nitrogen indicates the high amount of organic matter present in the sediment sample. The sediments collected in the lake are influenced with the allochthonous and autochthonous matters

Concentration of S is regularly rising. The most probable cause is acidic precipitation. S found naturally in the organic matter helps in the addition concentration of S in the sediments (Wetzel 2001). S is important constituent minerals. However, it is highly affected by long-range transport of atmospheric deposition. S also forms sulfides with iron under anoxic conditions and remains in insoluble form in the sediments (Smol, J., 2008).

6.3 Data uncertainty

The techniques used in the paleolimnological studies may include sources of error and uncertainty. The sediments can even undergo further oxidation after sampling due to exposure to light and air. It may affect the results, as the chemical constituents are sensitive to light, temperature and oxygen. The risk of contamination of samples due to light increases when the time between sampling the core sediment, slicing them and preserving increases. When sediment cores are analysed, a constant accumulation rate is assumed. In fact, sediments in the lake cannot be always considered as the representative of the historical sedimentation occurring in the lake. There may be alteration due to climatic condition, as well as both allochthonous and autochthonous intake in the lake. Several factors like land, morphometry and lake movements like waves and wind also affect the sedimentation rate and the results (Vrålstad, 2017). According to the trend of lake morphometry, the heavier particles settle close to the shoreline and fine particles reaches to the deeper parts of the lake (Wetzel, 2001). In this study, the sample cores were taken from the flat and deep part of the lake and the sediments were fine grained.

The process of dating sediment cores may also be the source of ambiguity in the results. As it is specified already, a constant rate of accumulation is expected to date the sample sediment. There may be many uncertainties involved in the dating method although the study is only aimed upon the primary trends of the sediment core. The age of the sediment was determined by the dating process in this thesis which is done by comparing the results of this study with the previous study of the lake sediments from the same lake. Even though this method has ambiguity, still the study focuses on only main trends so exact data for definite years was not essential. The method was chosen with consideration of the basis that, the lower and older sediments are compact which decreases the efficiency rate of dating the sediment sample (Cohen, 2003; Vrålstad, 2017).

Despite the field and lab work and all procedure of data analysis were succeed delicately, the probability of instrumental and human errors is unavoidable.

7 Conclusion

On the basis of the radiometric dating of the sediment cores from the lake Brønnerodtjern from 1853 to 2018 the sedimentation rate was estimated to 0.3 to 0.6 g cm^{-2} yr^{-1} for most of the studied period. Flood events due to the peat extraction occurred long time ago probably has minor impact on the sedimentation rate. The sediment cores seem intact and smooth. This helped in reconstruction of long-term development from the sediment cores obtained from the deep lake and also reference conditions attained.

The distribution of inorganic constituents from the obtained sediment core from the lake Bønnerødtjern shows the impact of anthropogenic activity in the study period. Several of the heavy metals (Zn, Pb, Hg, Co, Cu and Cd) and S showed substantial increase until the recent times. However, these elements are not considered as the natural component of the bedrock composition of the catchment area, thus long-range transport of atmospheric deposition can be the primary reason. Increase in the concentration of these elements in 1970´s can be explained by the smelting activities and the emission from industries in the international context rather than local.

The reason for the presence of remaining constituents beside above mentioned is probably geochemical processes and the bedrock composition of the catchment area. Moreover, periodic flooding from the surrounding also can be source for elements like phosphorus. Rise is C concentration can be justified by the allochthonous and autochthonous input to the lake.

The long-term study of the lake helps to retrieve a detail view of the previous conditions of the lake. In addition, it also provides the detailed information of the remote lakes.

 The lake Brønnerødtjern is an important lake for study in future, as very less research is carried out about the lake until now. The long-term studies are also very important to understand the change in climate, as lakes are very sensitive to changes. Moreover, paleolimnological studies are helpful to reconnect the past and understand the upcoming days.

To sum up, the findings in this thesis open different ways for the similar study in the future.

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February 2020

Appendix A: Map of Lake Brønnerødtjern

Lavvannskart

Vassdragsnr.:	003.B4	
Kommune:	Våler	
Fylke:	Viken	
Vassdrag:	Mossevassdraget	

Vannføringsindeks, se merknader

Middelvannføring (61-90)	15,0	l/(s*km²)
Alminnelig lavvannføring		l/(s*km²)
5-persentil (hele året)		l/(s*km²)
5-persentil (1/5-30/9)		l/(s*km²)
5-persentil (1/10-30/4)		l/(s*km²)
Base flow	0,0	l/(s*km²)
BFI		

Klima

Klimaregion		Ost
Årsnedbør	843	mm
Sommernedbør	381	mm
Vinternedbør	461	mm
Årstemperatur	5,9	°C
Sommertemperatur	13,5	°C
Vintertemperatur	0,5	°C
Temperatur Juli	16,2	°C
Temperatur August	15,2	°C

Feltparametere

Areal (A)	1,7 km²
Effektiv sjø (S_{eff})	13,3 %
Elvelengde (E_L)	0,7 km
Elvegradient (E_G)	5,8 m/km
Elvegradient$_{1085}$ (G_{1085})	5,5 m/km
Feltlengde(F_L)	1,2 km
H_{min}	32 moh.
H_{10}	32 moh.
H_{20}	33 moh.
H_{30}	35 moh.
H_{40}	36 moh.
H_{50}	37 moh.
H_{60}	38 moh.
H_{70}	40 moh.
H_{80}	moh.
H_{90}	44 moh.
H_{max}	61 moh.
Bre	0,0 %
Dyrket mark	0,0 %
Myr	11,5 %
Sjø	12,3 %
Skog	76,3 %
Snaufjell	0,0 %
Urban	0,0 %

1) Verdien er editert

Kartbakgrunn:	Statens Kartverk
Kartdatum:	EUREF89 WGS84
Projeksjon:	UTM 33N

Nedbørfeltgrenser, feltparametere og vannføringsindekser er automatisk generert og kan inneholde feil. Resultatene må kvalitetssikres.

Det er generelt stor usikkerhet i beregninger av lavvannsindekser. Resultatene bør verifiseres mot egne observasjoner eller sammenlignbare målestasjoner.

I nedbørfelt med høy breprosent eller stor innsjøprosent vil tørrværsavrenning (baseflow) ha store bidrag fra disse lagringsmagasinene.

02.07.2020 13:23:12 © nevina.nve.no

Appendix B: Historic map of Brønnerødtjern

https://kart.finn.no/?lng=10.80520&lat=59.43328&tab=feedback&zoom=15&mapType=historicalm-Moss-Rygge-1972%40h&activetab=feedback

https://kart.finn.no/?lng=10.80520&lat=59.43328&tab=feedback&zoom=15&mapType=historicalm-Ostfold-skraafoto-2017%40h&activetab=feedback

Appendix C: Report on the Radiometric Dating of Lake Sediment Cores KROK8-2 and BRON9-2 Taken from Norwegian Lakes

Handong Yang

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University College London

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 KROK8-2 and BRON9-2 taken from Norwegian lakes 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

BRON9-2 from Brønnerødtjern

Lead-210 Activity

Total ^{210}Pb activities have not reached equilibrium depth with the supported ^{210}Pb activities in the core (Figure 3a). Unsupported ^{210}Pb activities decline more or less exponentially with depth in the top about 40 cm (Figure 3b), suggesting relatively uniform sedimentation rates. However, there is a considerable dip in unsupported ^{210}Pb activities in around 57.5 cm, implying increased sedimentation rates at the depths.

Artificial Fallout Radionuclides

The ^{137}Cs activity versus depth (Figure 3c) shows a peak between 29.5 and 33.5 cm. It is almost certain that the high ^{137}Cs activity peak was derived from the 1986 Chernobyl accident.

Core Chronology

Because of the irregular decline in unsupported ^{210}Pb activities, chronologies of the core were calculated by using the CRS dating model. The CRS model places the 1986 depth just between 29.5 and 33.5 cm, in agreement with the ^{137}Cs record. The model places the 1963 depth between 41.5 and 45.5 cm, suggesting that the 1986 ^{137}Cs fallout has obscured the fallout peak derived from the nuclear bomb testing peaked in 1963. The sedimentation rate profile of the core shows that the rates were relatively stable with a slight increase trend in the last hundred years or so, except an increased peak in around 1940.

Unsupported ^{210}Pb inventories in cores KROK8-2 and BRON9-2 worked out the unsupported ^{210}Pb fluxes to the cores are 11.1 and 272.7 Bq m^{-2} yr^{-1}, respectively. This suggests that sediment might focussed to the BRON9-2 coring location, while sediments have been moved away from the KROK8-2 coring location by sediment focussing process.

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Appendix D: Primary data

483-2019				ICP-MS			
11/10/2019							
Limit of detection, LOD in (w/w)			0,000278	0,066668	1,37E-05	0,001087	0,003193
Limit of quantification, LOQ in (w/w)			0,000928	0,222227	4,56E-05	0,003622	0,010642
Sample		Sedimentation rate	P	Cr	Mn	Fe	Co
	Year	g/cm2/year	g/kg	mg/kg	g/kg	g/kg	mg/kg
Blank			<0,0009	<LOD	<LOD	<0,004	<LOD
Blank			<0,0009	<LOD	<LOD	<LOD	<LOD
Blank			<0,0009	<LOD	<LOD	<LOD	<LOD
Blank			<0,0009	<LOD	<LOD	<LOD	<LOD
1	2018	0,070	1,7	39	0,28	23	18
2	2017	0,071	1,6	37	0,27	21	18
3	2017	0,073	1,7	37	0,28	22	18
4	2016	0,075	1,6	37	0,28	21	18
5	2016	0,072	1,7	37	0,31	21	18
6	2015	0,068	1,7	37	0,29	22	18
7	2014	0,065	1,7	38	0,30	21	18
8	2013	0,062	1,7	37	0,29	21	18
9	2013	0,063	1,7	38	0,30	22	18
10	2012	0,065	1,7	37	0,30	21	18
11	2011	0,066	1,7	39	0,29	22	19
12	2010	0,068	1,7	37	0,29	22	18
13	2009	0,066	1,7	37	0,30	21	19
14	2008	0,065	1,7	36	0,29	21	19
15	2007	0,063	1,7	36	0,31	21	19
16	2006	0,062	1,8	35	0,30	21	20
17	2005	0,061	1,8	34	0,30	21	22
18	2004	0,061	1,8	39	0,30	20	20
19	2003	0,060	1,8	36	0,30	20	20
20	2001	0,059	1,8	35	0,29	21	20
21	2000	0,057	1,8	34	0,29	20	20
22	1999	0,055	1,8	33	0,28	20	19
23	1997	0,053	1,7	33	0,30	20	20
24	1996	0,050	1,8	34	0,29	21	21
25	1994	0,052	1,9	34	0,30	20	21

Cu mg/kg	Zn g/kg	Cd mg/kg	Hg mg/kg	Pb mg/kg	N g/kg	C g/kg	S g/kg
0,01137	1,26E-05	0,000858	0,004613	0,000672			
0,03791	4,19E-05	0,002859	0,015377	0,002238			
Cu mg/kg	**Zn** g/kg	**Cd** mg/kg	**Hg** mg/kg	**Pb** mg/kg	**N** g/kg	**C** g/kg	**S** g/kg
<LOD	<LOD	<LOD	<LOD	<LOD			
<LOD	<LOD	<LOD	<LOD	<LOD			
<LOD	<LOD	<LOD	<LOD	<LOD			
<LOD	<LOD	<LOD	<LOD	<LOD			
21	0,21	1,8	0,16	80	16,4	211,1	3,51
21	0,21	1,8	0,17	78	16,3	212,4	3,42
21	0,21	1,8	0,16	79	15,6	211	4,26
21	0,21	1,8	0,17	79	16,3	213,2	3,74
21	0,23	1,8	0,19	79	16,7	212,8	3,68
21	0,21	1,8	0,17	78	16,2	212,2	3,86
22	0,23	1,9	0,16	81	16	212,5	3,58
22	0,22	1,9	0,18	81	15,9	213,3	3,43
22	0,24	1,9	0,20	81	15,8	213,4	3,45
22	0,24	1,9	0,17	84	15,8	212,8	3,44
21	0,23	1,9	0,18	82	16,1	213	3,3
22	0,22	1,9	0,18	83	16,5	212,4	3,5
22	0,24	1,9	0,16	84	15,6	212,5	4,11
21	0,23	2,0	0,18	86	15,6	214,4	4,06
22	0,24	2,0	0,18	91	15,7	216,2	3,88
22	0,24	2,1	0,19	96	15,8	219,7	4,2
22	0,25	2,2	0,19	100	16	222,9	4,26
22	0,25	2,2	0,20	98	16	222,1	4,33
22	0,25	2,2	0,19	100	16,3	222,1	4,6
23	0,26	2,3	0,19	100	16,7	223,6	4,53
22	0,25	2,2	0,18	100	15,8	222,2	4,45
22	0,26	2,3	0,18	100	16,3	221,4	4,33
23	0,26	2,4	0,18	110	15,8	226,4	5,07
23	0,28	2,6	0,21	110	16,1	225,8	4,48
23	0,28	2,6	0,20	110	15,6	226,5	4,31

26	1993	0,055	1,9	34	0,30	21	21
27	1992	0,058	1,9	34	0,31	20	20
28	1991	0,054	1,9	33	0,31	20	21
29	1989	0,051	1,9	33	0,30	21	21
30	1988	0,047	1,9	32	0,32	20	21
31	1986	0,050	2,0	32	0,31	20	21
32	1985	0,053	2,0	32	0,32	20	22
33	1983	0,056	2,0	32	0,32	20	18
34	1982	0,059	2,0	31	0,33	20	17
35	1980	0,054	2,0	30	0,34	20	14
36	1979	0,049	1,9	30	0,34	20	13
37	1977	0,044	1,9	30	0,34	20	12
38	1975	0,040	1,9	30	0,35	20	16
39	1973	0,045	1,9	30	0,36	20	15
40	1971	0,049	1,8	31	0,36	20	15
41	1969	0,054	1,9	30	0,37	19	14
42	1968	0,058	1,9	30	0,38	20	13
43	1966	0,051	1,9	29	0,38	19	13
44	1964	0,045	1,9	28	0,37	18	13
45	1962	0,039	2,0	28	0,38	18	12
46	1959	0,033	2,0	27	0,38	17	12
47	1956	0,040	2,1	28	0,37	18	12
48	1953	0,048	2,1	38	0,38	17	13
49	1951	0,055	2,1	27	0,38	17	11
50	1950	0,062	2,2	27	0,37	17	12
51	1948	0,063	2,3	27	0,38	17	11
52	1947	0,063	2,3	28	0,36	16	11
53	1945	0,064	2,5	29	0,35	15	10
54	1944	0,064	2,5	30	0,35	16	10
55	1943	0,072	2,6	31	0,36	15	10
56	1942	0,080	2,7	32	0,36	16	11
57	1941	0,087	2,7	32	0,38	16	11
58	1940	0,095	2,8	32	0,38	16	11
59	1939	0,085	2,8	30	0,39	16	11
60	1939	0,074	2,9	31	0,39	16	11
61	1938	0,064	2,9	30	0,36	15	11
62	1937	0,053	3,0	31	0,37	15	11
63	1935	0,046	2,9	37	0,40	18	12
64	1933	0,040	2,7	40	0,42	19	12
65	1931	0,033	2,7	41	0,41	20	12

23	0,27	2,6	0,24	110	15,8	227	4,26
23	0,27	2,6	0,22	110	15,8	228	4,3
23	0,28	2,7	0,21	120	16	232	4,34
23	0,28	2,9	0,23	120	15,9	232,4	4,69
23	0,28	2,9	0,21	120	16	233,6	4,24
23	0,28	3,0	0,24	130	16,1	233,5	5,06
23	0,28	3,0	0,23	130	15,9	236,7	5,58
23	0,30	3,3	0,23	130	16,2	239,7	4,28
22	0,29	3,0	0,21	120	16,2	243,8	3,84
21	0,25	2,6	0,17	110	16,4	245,5	3,57
21	0,23	2,5	0,18	100	15,7	247,3	3,21
21	0,21	2,3	0,15	100	16,4	244,2	3,53
20	0,19	1,8	0,15	92	16	244,3	3,52
20	0,17	1,6	0,15	86	16,2	249,8	4,44
20	0,16	1,5	0,16	81	15,9	253,3	3,91
20	0,15	1,4	0,12	80	16,8	254,6	3,69
20	0,13	1,1	0,12	72	16,8	258,7	3,97
20	0,12	0,85	0,13	63	17,2	264,3	3,64
19	0,11	0,73	0,081	61	17,2	265,3	3,58
19	0,11	0,68	0,090	62	17,3	265,1	3,64
19	0,10	0,63	0,090	58	17,5	266,3	3,6
19	0,11	0,71	0,10	61	17,9	263,9	3,54
19	0,11	0,75	0,10	61	18,1	266,9	3,59
19	0,11	0,68	0,10	60	17,7	266,4	4,43
19	0,11	0,65	0,094	61	17,3	263,5	3,7
19	0,11	0,66	0,090	61	17,9	258,2	3,29
19	0,10	0,60	0,10	55	17,5	244	3,09
19	0,086	0,40	0,084	45	17	230,3	3,03
18	0,093	0,44	0,11	46	17,4	232,6	2,82
19	0,094	0,42	0,089	47	17,3	234,3	2,98
19	0,11	0,46	0,078	51	18,1	235,1	2,94
19	0,11	0,53	0,059	55	17,7	243,1	3,08
18	0,12	0,51	0,091	56	18,2	243,3	3,02
18	0,12	0,56	0,087	56	19	245,1	3,88
19	0,15	0,55	0,098	56	18,5	245,2	3,33
18	0,12	0,50	0,067	49	18	241,4	3,18
18	0,098	0,42	0,069	39	18,2	238,2	3,11
18	0,093	0,31	0,073	28	17,1	220,9	2,95
19	0,10	0,32	0,063	24	17,1	214,1	2,99
19	0,10	0,32	0,040	20	16,4	206,8	3,06

66	1928	0,027	2,6	45	0,42	22	13
67	1925	0,030	2,3	53	0,44	23	13
68	1922	0,034	2,0	57	0,45	25	14
69	1919	0,038	1,8	61	0,47	28	14
70	1917	0,042	1,4	66	0,49	29	15
71	1914	0,037	1,3	66	0,49	29	15
72	1912	0,032	1,3	65	0,48	29	14
73	1909	0,026	1,2	64	0,48	29	15
74	1905	0,021	1,1	64	0,49	29	16
75	1901	0,021	0,97	66	0,48	30	15
76	1897	0,021	1,0	66	0,49	31	15
77	1893	0,021	0,93	65	0,49	30	15
78	1889	0,021	0,99	65	0,49	30	15
79	1885	0,021	0,98	66	0,48	31	15
80	1881	0,021	0,92	67	0,48	31	15
81	1877	0,021	0,96	68	0,50	32	15
82	1873	0,021	0,99	68	0,49	32	15
83	1869	0,021	0,98	66	0,47	30	14
84	1865	0,021	1,0	67	0,48	31	15
85	1861	0,021	1,0	68	0,48	31	15
86	1857	0,021	1,0	70	0,48	31	16
87	1853	0,021	1,0	69	0,47	31	16
CRM 1646			0,51	68	0,27	28	8,6
CRM 2702				1,3	320	1,7	24

19	0,11	0,29	0,050	18	15,4	193,6	2,53
18	0,11	0,24	0,055	15	13,9	168,8	2,11
18	0,12	0,23	0,064	16	12,4	154,2	2,53
18	0,12	0,21	0,061	17	9,5	126	1,75
18	0,11	0,22	0,075	16	9,1	117,5	1,55
18	0,11	0,25	0,054	18	8,9	119,2	1,62
18	0,11	0,23	0,055	18	9	123,5	1,59
18	0,11	0,19	0,050	18	8,1	113,1	1,49
18	0,10	0,20	0,060	17	7,6	106,8	1,43
18	0,10	0,16	0,027	16	7	98,7	1,35
18	0,11	0,18	0,043	17	7,5	103,8	1,28
18	0,10	0,16	0,034	15	6,7	98,2	1,18
17	0,10	0,16	0,030	15	7,1	103,3	1,71
18	0,11	0,17	0,038	15	6,5	99,3	1,34
18	0,10	0,16	0,032	15	6,3	91,4	1,29
18	0,11	0,17	0,027	15	6,9	93,7	1,25
18	0,11	0,17	0,033	15	6,4	92,2	1,27
18	0,10	0,16	0,046	15	6,7	91,9	1,22
18	0,11	0,18	0,043	16	5,1	71,4	0,96
19	0,11	0,18	0,052	16	6,7	91,6	1,16
19	0,11	0,20	0,036	17	6,6	91,6	1,24
19	0,12	0,19	0,039	17	7,2	94,8	1,26
15	0,12	0,31	0,088	21			
110	0,48	0,7	0,43	120			