Norwegian University
of Life Sciences

Master's Thesis 2017 60 Credits
Faculty of Environmental Science and Natural Resource Management

Paleolimnological Investigation in Øvre Heimdalsvatn - Natural and Anthropogenic Influences During the Late Holocene

Åse Helene Vrålstad
Environment and Natural Resources

Acknowledgements

This is the final thesis for my master's degree in Environment and natural resources, with a specialization in limnology and freshwater resources at Norwegian University of Life Science (NMBU).

First and foremost; I would like to express my gratitude toward my supervisors Thomas Rohrlack, Gunnhild Riise and Ståle Haaland for interesting thesis, good assistance, and encouragement. This thesis would not be possible without your help, support and knowledge, and I am thankful for your willingness and enthusiasm to share your knowledge. I also like to thank the staff at IMV laboratory for assistance and help with the analyses.

Thanks to my friends and fellow students for valuable discussions, helpful tips, proofreading of thesis, and motivation during the process. Special thanks goes to my dear friend, Andrea N. Østvik. The time here at NMBU would not have been the same without you around, and I am grateful for all the memories we share. Let`s hope there will be plenty more in the future!

A big thanks to my family and Stian for always giving me good support, motivation, and in general just believing in what I do. Last but not least, my beloved dog and true friend during the last 12 years, who unfortunately passed away some weeks ago.

Åse Helene Vrålstad 09.05.2017

Øvre Heimdalsvatn

© Photo: Åse Helene Vrålstad, 2016

Abstract

Knowledge-based water management requires a thorough understanding of previous lake conditions. Paleolimnological methods utilizes lake sediments as an important tool to obtain this knowledge. To gain a realistic view of previous conditions in lakes, the Water Framework Directive (WFD) require lake sediments to be retrieved from a lake unaffected by anthropogenic activity or classified as a reference lake. This thesis is based on the analysis of two sediment core records collected from Øvre Heimdalsvatn in September 2016, located in Øystre Slidre, Oppland County. The lake is classified as a reference lake for other sub-alpine lakes in Norway, and has served as an important research site in several fields, related to e.g. lake ecosystems during the last 50 years. The two sediment cores have been analyzed for nineteen different chemical constituents (*Fe, Al, Ca, Mg, K, P, S, Na, Mn, Cu, V, Zn, Cr, Pb, As, Cs, Cd, Hg, Ni, Pb, As, Cs, Cd, Hg)*, and sixteen pigments included degradation products. Simultaneously, analyses of dry weight, total carbon, and total nitrogen have been carried out. By using these parameters, the thesis aims to examine late Holocene environmental history in Øvre Heimdalsvatn, and look at the major trends in distribution of inorganic constituents and pigments during the last ca 2000 years. A principal component analysis (PCA) was used to emphasize variation and correlation among the parameters. The results from PCA indicated a positive correlation between the trace metals *(Zn, Hg, Cd, As, Pb)* and *S.* Since 950 CE until present, there is a generally increasing trend, with a decline in *Pb, Cd* and *Zn* in recent times. These trace metals are not considered a natural part of the bedrock composition in the area, and are assumed to be a result of long-range transport of atmospheric pollution. The remaining constituents show a more constant pattern throughout the sediment core, with minor variations. Based on the geomorphology in the area these constituents are a part of the bedrock composition, and the occurrence is most probably a result of natural background levels. The PCA indicated a positive correlation between chlorophyll a and -b (included degradation products) as they orient in the same direction. This was to be expected. Some pigments were excluded from the thesis, as they were not found or had very low concentrations. The remaining pigments indicated an overall similar trend, but occurred at different concentration levels. A change in pigment assemblage indicate a change in phytoplankton community in the lake. The major trends in pigment variations coincide well with the estimated temperature reconstruction in Northern Europe during the last millennium. The algae assemblage in a lake is largely influenced by changes in climatic conditions, which is well reflected in the pigment analyses.

Sammendrag

Paleolimnologisk undersøkelse i Øvre Heimdalsvatn – naturlige og antropogene påvirkninger i siste del av den Holocene tidsepoke

God kunnskapsbasert vannforvaltning krever innsikt i innsjøers tidligere tilstand. Paleolimnologi er en metode som bruker innsjøsedimenter som et viktig redskap for å tilegne seg nettopp denne kunnskapen. For at metoden skal gi en så realistisk fremstilling som mulig, krever Vanndirektivet at prøvene skal tas fra en referanseinnsjø eller innsjøer som er upåvirket av antropogen aktivitet. Denne oppgaven er basert på analyser av to sedimentkjerner hentet fra Øvre Heimdalsvatn i september 2016, som ligger i Øystre Slidre, Oppland fylke. Den er klassifisert som en referanseinnsjø for subalpine innsjøer i Norge og har gjennom de siste 50 år vært svært viktig for en rekke studier innen e.g. akvatiske økosystemer. Sedimentsøylene ble analysert for nitten ulike grunnstoffer (*Fe, Al, Ca, Mg, K, P, S, Na, Mn, Cu, V, Zn, Cr, Pb, As, Cs, Cd, Hg, Ni, Pb, As, Cs, Cd, Hg)*, og seksten forskjellige pigmenter, inkludert nedbrytningsproduktene. Samtidig er det utført analyser på tørrvekt, total karbon og total nitrogen. Formålet med oppgaven er å bruke disse parameterene til å undersøke klimahistorie gjennom siste del av den Holocene tidsperioden, samtidig se på de store trender i utvalgte grunnstoffer og pigmenter gjennom de siste ca 2000 år. For å fremheve variasjon og korrelasjon i variablene, ble det gjennomført en prinsipial komponent analyse (PCA). Resultatene fra PCA indikerer en sammenheng mellom de fleste spormetallene *(Zn, Hg, Cd, As, Pb)* og *S.* Fra år 950 evt. er det generelt en økende trend blant alle spormetallene, med en avtakende konsentrasjon av *Pb, Cd* og *Zn* mot nyere tid. Disse spormetallene er ikke en naturlig del av berggrunnen i området og antas å være et resultat fra langtransporterte luftforurensinger. De resterende grunnstoffene viser en noe varierende, men jevn konsentrasjon i sedimentene. Det antas at dette er konsentrasjoner som skyldes naturlige bakgrunnsverdier fra bergrunnen. Som forventet er det en positiv korrelasjon mellom klorofyll a og -b (inkludert nedbrytningsproduktene), da disse orienterer seg i samme retning i PCA. Enkelte pigmenter ble ikke funnet, samt noen med svært lave verdier og er derfor utelatt i oppgaven. De resterende pigmenter som er tatt med i oppgaven følger hverandre tett, med noen unntak. Endringer i pigmentsammensetning kan tyde på et endret fytoplanktonsammfunn i innsjøen. Videre tyder det på at pigmenter i stor grad er styrt av temperatur, da variasjon i pigment følger i stor grad estimerte temperatursvingninger de siste 1000 år. Variasjon i pigmenter sammenfaller med estimerte temperaturrekonstruksjoner gjennom de siste 1000 år. Algesammensetningen i innsjøen ser ut til å være særlig styrt av klimatiske forhold, som kommer tydelig frem av pigmentanalysene.

Contents

Description of terminology

Allochtonous	Input to a lake from outside the aquatic system
Autochthonous	Input by the photosynthesis of larger plants and algae within a lake
Bathymetry	Topography beneath the water surface
Geomorphology	Physical features of land surfaces in relation to geological structures
Pigment	Molecules absorbing energy in the visible spectra
Trace metal	Metals normally found in small, but measurable quantities

Figures

Tables

1 Introduction

High-latitude lake ecosystems are assumed to be sensitive to changes in climatic conditions, and lakes of similar character are expected to respond similarly to these changes (Battarbee et al. 2002). Studies of lake sediments can provide a compelling story about past conditions in terms of "*changes in chemical and biological indicators*" (Reuss 2005, p.9). To estimate previous conditions, measures must be taken under the regulation of the Water Framework Directive (hereafter WFD) from a lake considered undisturbed by anthropogenic activities, or from a reference lake (Reuss 2005). Long-term records are necessary to monitor reference conditions in lakes, as these provide information before humans started to influence to a great extent. Anthropogenic influence upon lake ecosystems are a challenge in paleolimnological research, hence choosing a remote mountain lake may provide more accurate information on previous conditions.

This thesis represents the analyses of chemical and biological indicators, retrieved from two sediment cores from Øvre Heimdalsvatn. The method is accepted as a useful way to examine the physical environment at the time of sedimentation. The analyses carried out provide information on chemical constituents *(Fe, Al, Ca, Mg, K, P, S, Na, Mn, Cu, V, Zn, Cr, Pb, As, Cs, Cd, Hg, Ni)*, sixteen pigments included degradation products, and organic matter.

Remote mountain lakes, like Øvre Heimdalsvatn, are mainly influenced by changes in natural factors, such as: temperature, hydrology, wind regimes, and geomorphology in the catchment area (Battarbee et al. 2002). These factors all influence transport of chemical constituents to the lake, and internal lake processes. Additionally, high-latitude ecosystems are recognized as important archives for many long-transported pollutants. Øvre Heimdalsvatn is an undisturbed lake system, and classified as in good conditions in the Norwegian WFD (Vann-nett n.d.). Due to little human activity, this lake may be a suitable reference lake for investigating natural changes in a lake ecosystem, as well as external influences from atmospheric pollution. In Øvre Heimdalsvatn there are no known point sources, hence long-range atmospheric transport and deposition is likely to be the main contributor of certain trace metals to the lake and catchment area. On the other hand, it is important to look at the geomorphology in the area, as some trace metals are considered a natural part of the mineral composition in the bedrock.

Sediment cores from relatively remote and undisturbed lakes are suitable to reflect changes in environmental conditions by looking at long-term biotic variations. However, the interactions between chemical and biological indicators are often overlooked, because such proxies are challenging to interpret. In this study, several parameters are used, which makes it possible to examine the correlation of one parameter with the information from a second parameter (Velle et al. 2010). Information obtained from several parameters may give a more comprehensive picture of past conditions in the lake (Velle et al. 2005).

1.1 Paleolimnology

"The past is the key to the future", is a well-known assertion in paleo-science and represents the basis of paleolimnology. This method studies lake sediments as historical archives. It was established to gain knowledge about previous lake conditions, as the sediments provide information on a variety of different chemical and biological indicators, such as: pigments, organic matter, pollen, ions, and pollutants (Smol 2008; Leavitt et al. 1997).

A lake system serve as a natural trap for chemical and biological material, which constitute the sediments. Additionally, a lake is "*located at the receiving, downgrading end of a drainage basin"*(Wetzel 2001, p.785). Thus, a large portion of material will enter a lake system. Materials produced within the lake (autochthonous) or enters the lake externally (allochtonous) will eventually settle to the bottom of the lake (Cronin 2009). However, the sedimentation is influenced by a variety of different factors such as bathymetry, oxygen, and light irradiation (Westerås 2016). These factors determine to a large degree the portion and composition of materials that actually deposit and constitute the sediments.

Lakes have in general an insufficient transport of materials out of the basin, and the sediments serve as an archive for studying past conditions (Wetzel 2001). Sediments in freshwater lakes serve as archives for pollution both from natural and anthropogenic sources (Kainz & Lucotte 2006). Plant and animal remains are often well preserved, hence information on environmental conditions at the time of depositions can be retrieved (Velle et al. 2010). Remote ake sediments are fairly undisturbed by humans, and can provide information on long-term changes that reflects environmental variability (Velle et al. 2010).

1.2 Organic Matter

Organic matter (hereafter OM) are recognized as one of the most important and basic components that constitute lake sediments. It provides useful information on past deposition, lake productivity and changes in climatic conditions (Avramidis et al. 2015; Wang et al. 2012). In order to determine sources of OM in lakes, analyses of Total carbon (hereafter TC) and total nitrogen (hereafter TN) are useful parameters. TC consists of both total inorganic carbon (hereafter TIC) and total organic carbon (hereafter TOC). Most analytical measures of OM in water determines the amount of carbon, however in this method it is necessary to distinguish between the organic and inorganic forms of carbon (vanLoon & Duffy 2011). In order to separate the amount of TIC to TOC, there are different ways to perform this; *"Measure TOC, either as the difference between TC and TIC, or as the carbon content remaining after carbonate carbon has been removed"* (Meyers and Teranes 2001: Wang et al. 2012, p. 49). The inorganic carbon in sediments are mainly related to calcium carbonate ($CaCO_3$)(Wang et al. 2012).

TOC and TN originate from allochtonous and autochthonous inputs and are often a result of decomposition of animals, plants, plankton or anthropogenic activity. TOC is sensitive to changes in climatic conditions, as increased temperatures have shown to increase the transport of OM (Schindler et al. 1996). As temperature increases, the growth period will be extended and production of OM will increase (Økland & Økland 2006). OM and TN has also been used as biomarkers to estimate climate variability of the past (Avramidis et al. 2015). By looking at the ratio between carbon and nitrogen (hereafter C:N), it is possible to obtain information about the amount of carbon vs nitrogen in lake sediments. Remote mountain lakes with sparse vegetation often have a low C:N ratio, which is often seen in unproductive lakes (Battarbee et al. 2002).

1.3 Biological parameters - Pigments

Pigments are produced by photosynthesizing organisms and algae, and by studying pigment composition in lake sediments it is possible to reconstruct the internal lake production and phototrophic communities from the past (Reuss 2005). Pigments are used to determine the taxonomic groups of photosynthesizing organisms in the lake sediments (Zuur 2014). All photosynthetic organisms contain pigments and can serve as biomarkers and provide information on sources and composition of primary producers in the lake and its catchment area (Battarbee et al. 2002, Reuss 2005).

Some pigments, such as *Chlorophyll a* and its degradation product, *pheophytin a* (hereafter *total chlorophyll a*) is found in more or less all autotrophic organisms, hence it is a good measure for internal lake production from the past (Leavitt & Hodgson 2001). This is also the case for β-carotene, which occurs in most algae plants. Due to the high abundance of chlorophyll a, pheophytin a, and β-carotene, they provide useful information on algae abundance in a lake. Pigments such as violaxanthin, a carotenoid, is found in cyanobacteria and can be useful when studying variation in algae classes or functional groups (Leavitt & Hodgson 2001). Other pigments are more specific to different algae groups (Reuss 2005) (Table 1). As pigments are mainly autochthonous, they are suitable for studying primary production within a lake ecosystem.

Degradation of pigments mostly occurs in the water phase as they settle (Leavitt 1993). Pigment degradation in sediments is relatively low, compared to degradation in the water column, especially under anoxic conditions (Buchaca & Catalan 2007). Factors such as oxygen and bathymetry are crucial in the degradation process and determines what material is deposited at the bottom (Cuddington & Leavitt 1999). Pigments are a relatively stable component of an organism and are well-preserved in sediments, even so different pigments appear at different stabilities (see Table 1) (Wetzel 2001).

Table 1: Overview of pigments with their taxonomic affinity and stability. Some of the pigments are discussed further in this thesis. Stability represents most stable (1) to least stable (4).Table modified from Leavitt and Hodgson (2001)

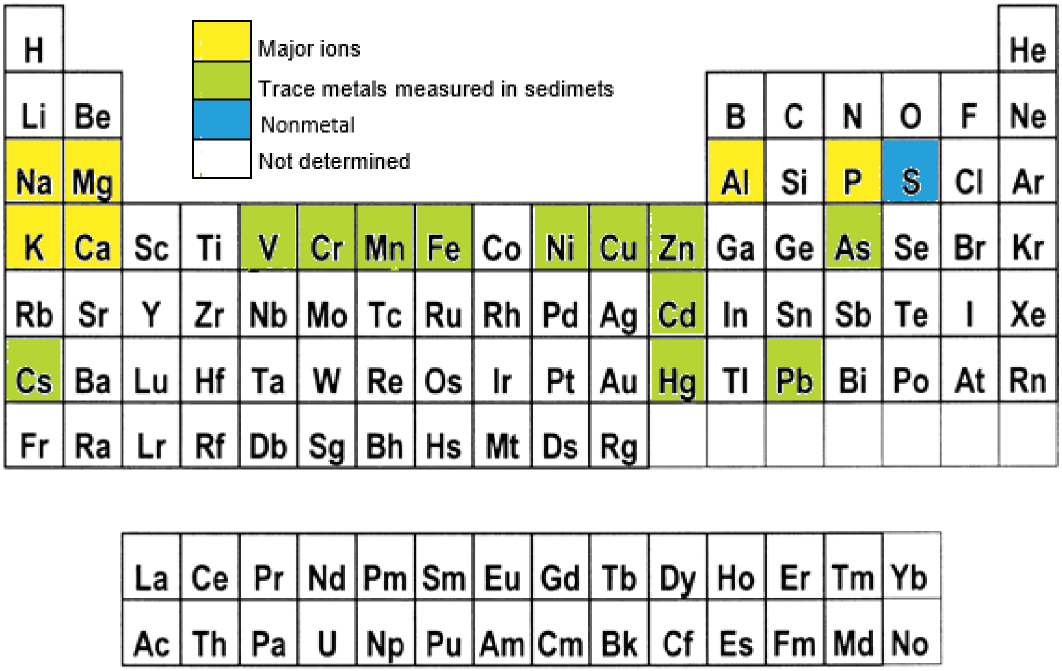
Pigment	Affinity (major groups or processes)	Stability
Chlorophylls		
Chl a	All photosynthetic algae, higher plants	3
Chl b	Green algae, higher plants	2
Chlorophylls degradation products		
Pheophytin a	Chl a derivative (general)	1
Pheophytin b	Chl b derivative (general)	2
Carotenoids		
β-carotene	Most algae plants	1
Alloxanthin	Cryptophytes	1
Diadinoxanthin	Diatoms, dinoflagellates	3
Diatoxanthin	Diatoms, dinoflagelates, crysophytes	2
Violaxanthin	Green algae, Euglenophytes, higher plants	4
Lutein	Green algae, euglenophytes, higher plants	1
Myxoxanthophyll	Colonial cyanobacteria	

1.4 Chemical parameters – Inorganic Constituents

The composition of lake sediments is highly influenced by the geomorphology in the catchment area (Wetzel 2001). Geochemical processes release several trace metals and inorganic constituents, and a large portion ends up in the sediments. Additionally, lake systems are to a large extent influenced by long-range atmospheric deposition of several trace metals (Rognerud & Fjeld 2001). Deposition of metals to lake surfaces and catchment areas are likely to be transported by particles and eventually end up in the sediments (Rognerud & Fjeld 2001). By studying the chemical composition, it is possible to examine different factors that influence variation in sediment composition of a lake, such as changes in climatic conditions and limnological activities (Ma et al. 2016; Wetzel 2001). Moreover, several inorganic constituents appears to contain good temporal records within lake sediments, as they often contain much higher concentrations compared to overlying waters (Rognerud & Fjeld 2001). Metals are absorbed by fine-grained particles and will eventually deposit at the lake bottom, which makes sediments a useful way to estimate past deposition of metals (Fjeld et al. 1994).

Studies of trace metals in sediment are however complex, as many factors influence the concentrations (Fjeld et al. 1994). An overview of the selected constituents analyzed in this thesis is found in Table 2, in the flowing section a more detailed background description is given for *Hg*.

Table 2: Periodic table representing the constituents included in the thesis. Modified from Skjelkvåle et al. (2006)



🟨 Major ions
🟩 Trace metals measured in sedimets
🟦 Nonmetal
⬜ Not determined

H																	He
Li	Be											B	C	N	O	F	Ne
🟨 Na	🟨 Mg											🟨 Al	Si	🟨 P	🟦 S	Cl	Ar
🟨 K	🟨 Ca	Sc	Ti	🟩 V	🟩 Cr	🟩 Mn	🟩 Fe	Co	🟩 Ni	🟩 Cu	🟩 Zn	Ga	Ge	🟩 As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	🟩 Cd	In	Sn	Sb	Te	I	Xe
🟩 Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	🟩 Hg	Tl	🟩 Pb	Bi	Po	At	Rn
Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg							

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No

Mercury (hereafter *Hg*), is a contaminant of great importance in many remote lakes, especially in Arctic- and high latitude ecosystems. Since the first big discovery of *Hg* toxicity in Minamata Bay, Japan, in 1956, awareness of *Hg* has led to more attention towards understanding the influence it has in the environment.

Hg is a metal found naturally in the Earth`s crust in many parts of the world, but rarely occurs as a free metal in nature (UNEP 2013). It is present in many minerals, but most commonly found as a complex with Sulphur (HgS) in cinnabar ores (UNEP 2013). *Hg* is released into the environment both by natural and anthropogenic activities, were the latter is recognized as the largest contributor, in terms of: combustion of coal, natural gas, industrial and household waste. Natural sources of *Hg* are related to weathering of rocks or volcanic eruptions (UNEP 2013). *Hg* in the environment is mobilized from deep in the Earth`s crust (Selin 2009), and due to the high volatility of *Hg*, it easily enters ocean and atmosphere after release (Bindler et al. 2001). *Hg* is extracted through heating, and emitted to the atmosphere both by natural and anthropogenic processes as the elemental form Hg^0 (Selin 2009). The main sink of Hg^0 in the atmosphere is the oxidation to the inorganic form Hg^{2+}, and is deposited on land surfaces, mainly through wet deposition (Selin 2009). Once deposited on land surfaces, *Hg* is most commonly found as Hg^{2+} in lakes, waters, streams, and a large portion of this are eventually stored in sediments

(AMAP 2011). A large part of *Hg* is released from regions outside of Arctic- and high latitude lake ecosystems, but is a subject to the process of global distillation (more commonly referred to as the grasshopper effect). Global distillation is a phenomenon that refers to e.g. volatile, environmental pollutants such as *Hg* (Wania & Mackay 1997) These compounds are emitted to the atmosphere in gaseous forms, often in temperate and lower latitude regions, and when exposed to colder air in higher latitude regions they tend to slow down and deposit (Wania & Mackay 1997).

1.5 Climate variability in the late Holocene

The Holocene or post-glacial epoch is the most recent stratigraphic unit within the geological records, and covers the interval from approximately 10,000 years before common era (hereafter BCE) until present day (Walker et al. 2012). The epoch belongs to the Quaternary period and is divided into three intervals; early, mid- and late Holocene, based on e.g. climatic conditions. The retrieved sediment cores used in this thesis represents the last 2000 years, which belongs to the Late Holocene. The climate in Holocene is characterized by fluctuations, which led to a disappearance of ice ages and caused warm interglacial periods (Eronen & Zetterberg 1996). The late Holocene however, is characterized as a period with relatively stable climate, even though evidence indicates the contrary (Bradley et al. 2003). Previous studies provide evidence of warmer summer temperatures in northern Europe, southern Greenland and Iceland from 900-1000 common era (hereafter CE) to 1200-1300 CE (Hughes & Diaz 1994). This period is often referred to as the Medieval Warm period (MWP) or the Holocene Climate Optimum (HCO) and is said to match the temperatures of past decades in some regions, but is below global levels in recent times (Mann et al. 2009). The time interval between 100-1200 CE has also been characterized as a period dominated by high levels of volcanisms, which caused warmer winters in the northern part of Europe (Bradley et. Al 2003).

After the HCO, a climatic instability followed, also known as the Little Ice Age (LIA) dated to 1600 CE to 1800-1900 CE (Benito et al. 1998). However, the coldest temperatures in the Northern Hemisphere occurred in the interval between 830-1000 CE and 1400-1700 CE (Mann et al. 2009). Another study suggests evidence of a transition to a colder climate between 1200-1500 CE in Europe, Asia and the Arctic (Consortium 2013).

Mann et al. (2009) reconstructed the mean annual temperature for the Northern Hemisphere during the last 1000 years (Figure 1). This major temperature reconstruction was based on a multiproxy network, consisting of more than thousand records from sediments, ice cores, tree ring, corals etc. The records were taken from ocean and land from both the Northern and- Southern Hemisphere.

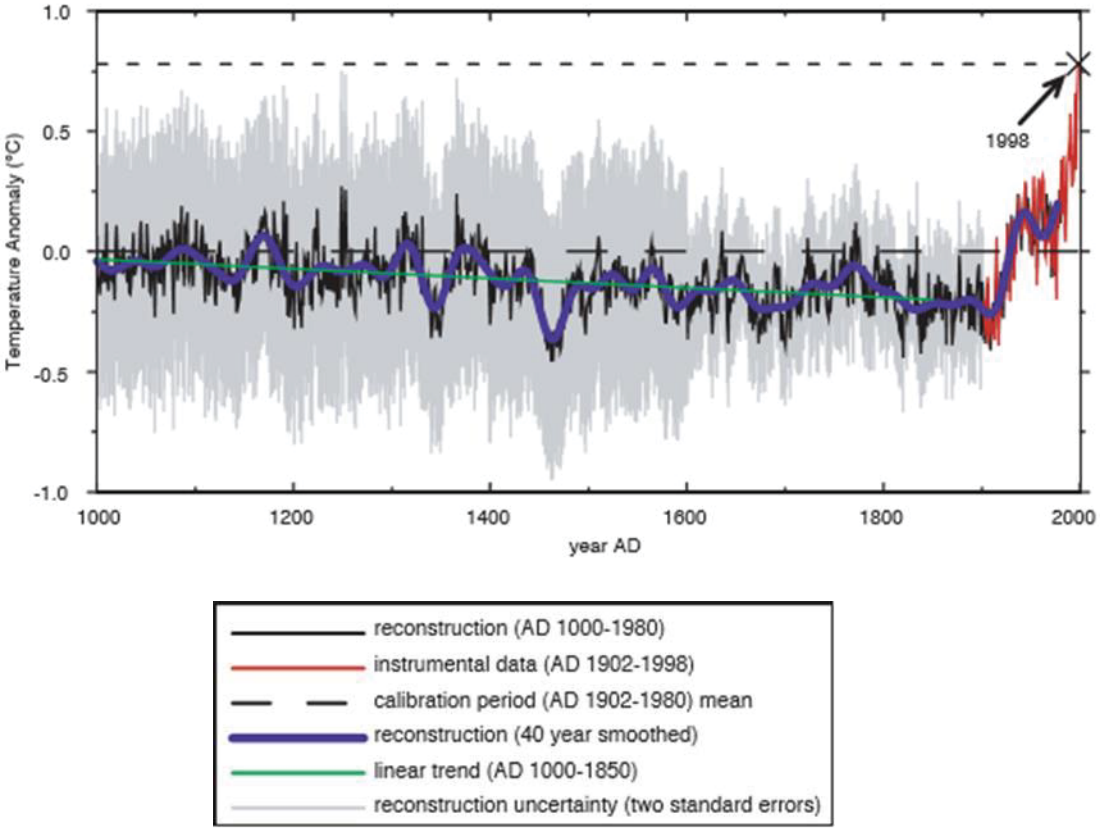


Figure 1: Reconstruction of mean annual temperature in the Northern Hemisphere for the last 1000 years, showing temperature disparities (Mann et al. 1999)

Despite difficulties in obtaining accurate temperature data for long-term temperature variations, several proxies have shown to be valuable in estimating pattern of climate conditions in the past. Consequently, the temperature variations are not uniform among regions and large regional fluctuations most probably occurred.

1.6 Thesis statement

The thesis aims to reconstruct the Late Holocene environmental history in Øvre Heimdalsvatn, based on the analyses of two sediment cores retrieved from the lake. The analyses provide information on the chemical composition of constituents, pigments, TC, TN and dry weight, from approximately 100 BCE to 2016 CE.

Thus, the primary objectives of this thesis is to examine the main factors that have influenced the lake ecosystem, in terms of:

1. *Distribution of pigments*
2. *Distribution of chemical constituents*

Analysis of OM are used as a tool to determine the amount of allochtonous and autochthonous material in the lake and its catchment, whereas total *chlorophyll a* is mainly used as a tool to represent the internal lake production.

Further, the thesis highlights the importance of using paleolimnology as a method, to better understand long-term climatic variations, and evaluate these factors as indicators for anthropogenic and natural influences. The analyses provide data from biological and chemical parameters, which can give valuable information on lake development and historic loading of long-range transport of atmospheric pollutants to remote ecosystems. Paleolimnology may be a suitable method to establish future predictions in lake responses to climate change.

2 Description of area

2.1 Study site description of Øvre Heimdalsvatn and the catchment area

Øvre Heimdalsvatn is a subalpine lake (Figure 2) located 1,088 m a.s.l, in Øystre Slidre municipality, Oppland County (Figure 3). The lake belongs to the Mjøsa water area, which is in the Glomma water region (division within the WFD). The total lake area is 0,78 km^2, with a maximum depth of 13 m (see Table 3 for morphometric values) and a relatively large catchment area of 23,6 km^2 (Brittain & Borgstrøm 2010). The lake is fed by a number of fast-flowing streams, where Brurskardsbekken in the west end of the lake is the largest inflow stream (Larsson et al. 1978; Kvambekk & Melvold 2010).

Figure 2: Øvre Heimdalsvatn, early September 2016, looking eastward. © Photo: Åse Helene Vrålstad

During winter season the lake is typically ice-covered from the end of October until the beginning of June (Brittain & Borgstrøm 2010). The climate in this region is recognized by cold winters with long periods of ice-cover, but relatively warm summer seasons, and precipitation is considered moderate (Kvambekk & Melvold 2010). Øvre Heimdalsvatn is a shallow and nutrient poor lake and the sparse vegetation cover in the region, makes the lake highly exposed to wind (Brittain & Borgstrøm 2015). The lake is not thermally stratified during summer season (Økland & Økland 2006). The theoretical retention time in Øvre Heimdalsvatn varies considerably, depending on the time of year. In the winter the renewal time may be over 400 days, compared to only a few days in the spring (Vik 1978).

The lake sediments in Øvre Heimdalsvatn is mainly dominated by allochtonous material being transported from the catchment, and it is estimated that approximately 50% of the OM originates from allochtonous plant material from the catchment area (Brittain & Borgstrøm 2015). Further, terrestrial plant material from the catchment area plays a major role in the transport of OM (Larsson et al. 1978).

The sedimentation layer in Øvre Heimdalsvatn is about 2 meters (in the middle of the lake) which is a result of approximately 8000 years of sedimentation (Larsson et al. 1978). The exact sedimentation rate is difficult to estimate, due to large bathymetric variations in the lake (Larsson et al. 1978). Overall, the sedimentation rate is relatively low, which is typical for a unproductive lake (Battarbee et al. 2002).

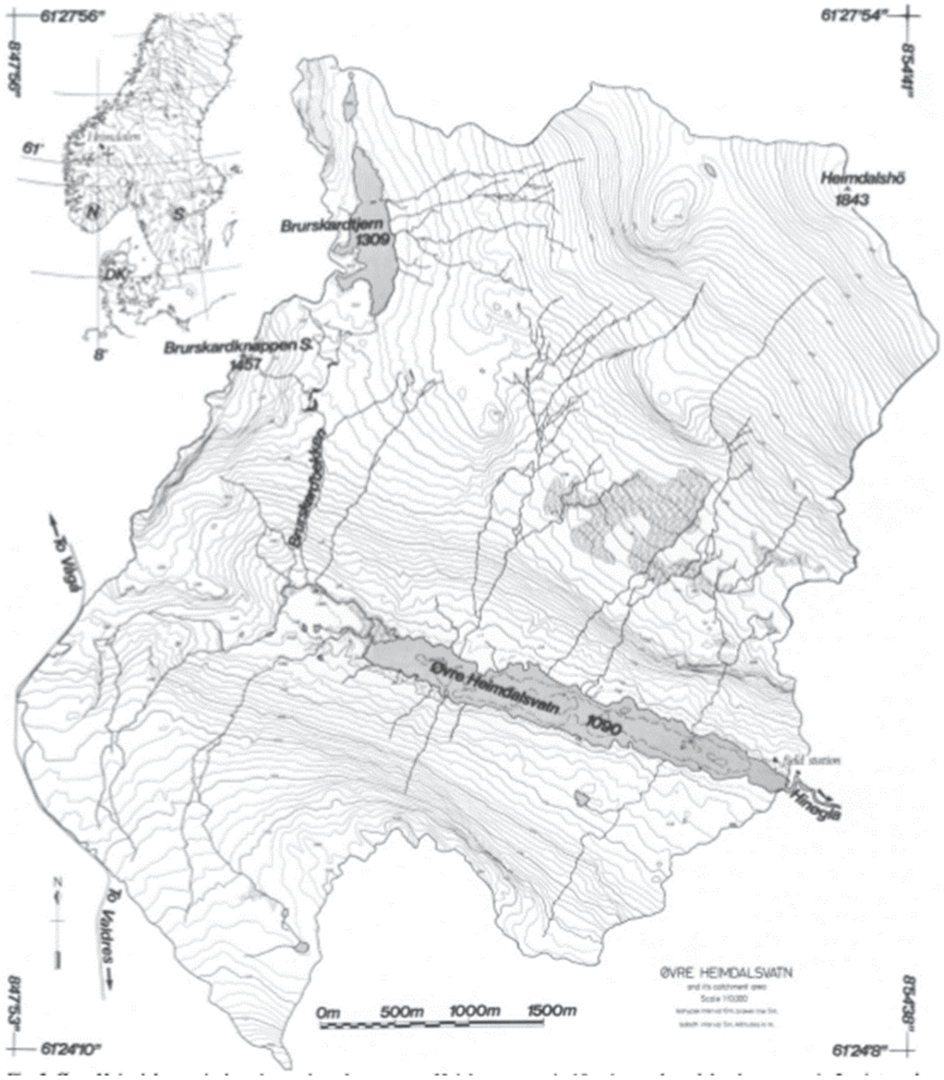
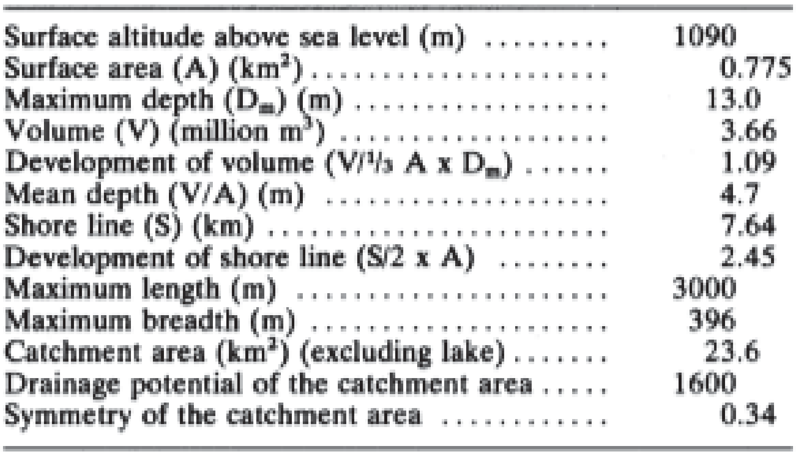


Figure 3: Location of the lake in south-central Norway and catchment area with inflow streams, figure from Vik (1978)

Throughout the years, Heimdalen valley has been important for activities such as hunting and fishing. Further, the valley has been used for grazing, but in recent years this has been limited. In later years, there have mostly been grazing by some domesticated reindeer in spring and autumn (Brittain & Borgstrøm 2010).

During the last 50 years the lake and its catchment have been an important area of ecosystem studies (Brittain & Borgstrøm 2010). In the 1950s the main purpose of these studies was related to fishing strategies. Later on these studies included the whole lake ecosystem, as a part of the *"Norwegian contribution to the freshwater section of the International Biological Programme (IBP)"* from 1968 to 1974 (Brittain & Borgstrøm 2010, p. 8). During the IBP period a major finding was the importance of allochtonous inputs being transported to the lake, as one of the major sources of primary production (Brittain & Borgstrøm 2010). Due to the extensive studies carried out, Øvre Heimdalsvatn serves as a reference lake to other Norwegian sub-alpine lake-ecosystems. Another important field of study has focused on inputs of radioactive ^{137}Cs. By the end of April 1986, the lake received a lot of radioactive ^{137}Cesium fallout because of the Chernobyl accident. In June, the same year, the ^{137}Cesium concentration in the lake water was measured to 5.5 kBq m^{-3}, right after the ice break up (Dahlgaard 1994). A major part of the ^{137}Cs was transported to the lake, as a result of contaminated plant material from the catchment area (Brittain & Bjørnstad 2010).

Table 3: Overview of morphometric values in Øvre Heimdalsvatn (Grøterud 1972: Grøterud & Kloster 1978)



Surface altitude above sea level (m)	1090
Surface area (A) (km^2)	0.775
Maximum depth (D_m) (m)	13.0
Volume (V) (million m^3)	3.66
Development of volume ($V/{}^1/_3\ A \times D_m$)	1.09
Mean depth (V/A) (m)	4.7
Shore line (S) (km)	7.64
Development of shore line (S/2 x A)	2.45
Maximum length (m)	3000
Maximum breadth (m)	396
Catchment area (km^2) (excluding lake)	23.6
Drainage potential of the catchment area	1600
Symmetry of the catchment area	0.34

Most of the mountain range is a part of the alpine zone, above the "*altitudinal birch tree line at approximately 1000 m*" (Nesje et al. 2004, p. 2186). Vegetation in the area ranges from subalpine birch forest with mountain pasture to high alpine vegetation above 1600 m (Dahlgaard 1994). On the south-facing slope north of Øvre Heimdalsvatn there is a small patch of subalpine birch forest (Østhagen & Egelie 1978). Previous studies from Øvre Heimdalen indicates a pine tree (*Pinus silvestris*) forest up to 1300 m a.s.l at around 9000 years BCE (Brittain & Borgstrøm 2010, Faarlund & Aas 1991). Since 5000 years BCE there has been a decline in the tree line, which caused a more open landscape (Velle et al. 2010).

Øvre Heimdalsvatn is situated on the eastern edge of Jotunheimen Mountains, south central Norway (Figure 3). This mountain range is the highest in northern Europe, and "*contain approximately 300 glaciers*" (Østrem et al. 1998: Nesje et al. 2004, p. 2186). Several geological conditions have influenced Øvre Heimdalsvatn and like most lakes today they are a direct result of the last glaciation period (Wetzel 2001). Heimdalen valley and its catchment is a result of two periods with ice erosion (Skjeseth & Kloster 1978). "*Heimdalen valley and the lake are cut down deep into the thrust plane of basic Precambrian rocks. The lake is influenced by the thick Quaternary deposits from the ice age and the period of ice retreat*" (Skjeseth & Kloster 1978, p. 89). The south and north side of the lake show different deposition patterns (Skjeseth & Kloster 1978). The south side shows clear evidence of greater deposition than the north side, with thick ablation moraines. On the north side cliffs are more dominating, with screes, gravel fans and streams courses (Skjeseth & Kloster 1978). The bedrock in the area consists almost entirely of basic Precambrian rocks which is a part of the large Caledonian thrust complex known as the "Jotundekkene" (Skjeseth & Kloster 1978). A large part of the catchment area is dominated by gabbro, sandstone and pyroxene-granulite (see Appendix A for an overview of bedrock composition)(Lie et al. 2004; Velle et al. 2010) and the lake basin is largely influenced by the bedrock composition. Due to the geology in the surrounding area, and calcium poor ground, the electrical conductivity in the lake is fairly low (Økland & Økland 2006).

3 Materials and Methods

3.1 Sampling and slicing of sediment cores

Sediment sampling from Øvre Heimdalsvatnet took place on the 07.09.2016. The sediment cores were retrieved from a boat, using UWITEC gravity corer with a diameter of 60 mm. Two sediment cores (Figure 4) were sampled near the deepest point (Figure 5), in the lake (11,6m and 12,3m respectively). It was crucial to retrieve the sediment cores from (nearly) the deepest point in the lake, as this is the accumulation area for smaller size fractions. To find the deepest point, a depth chart (Appendix B), map of water current stations (fig. 6), and a depth gauge were used. Strong wind in the area, made it challenging to keep the boat in the right position. To make sure enough test material was collected, two cores were taken out. Due to low sedimentation rate in the lake and in general slow processes in the lake and drainage basin, one can assume the cores to be almost identical. The core sampler was dropped from a certain distance above the bottom, in close distance to each other within the sediment accumulation area. Core number 1 (at 11,6 m) was 42 cm long and core number 2 (at 12,5 m) was 54,2 cm long.

Slicing of cores took place in field. The first 10 cm of each core were sliced in 0,5 cm intervals, while the remaining cores were sliced in 1 cm intervals. All sub-samples were sealed in zip lock bags and immediately stored in a cooling container, with no access to light. Between each sub-sample, the sediment slicer was dried off with paper towels, to minimize the risk of contamination. Immediately after arrival at the Soil building laboratory (Norwegian University of Life Science), the samples were stored in a freezer with a temperature at -20 degrees Celsius. This was executed at the same day (evening time) as the cores were collected.

Figure 4: The two sediment cores collected (left) and the top layer of sediment core number 1 (right), from Øvre Heimdalsvatnet. © Photo: Åse Helene Vrålstad

Figure 5: Red marks showing sampling sites in Øvre Heimdalsvatn, where the two sediment cores were retrieved. © Norge i bilder, downloaded 06.10.2016

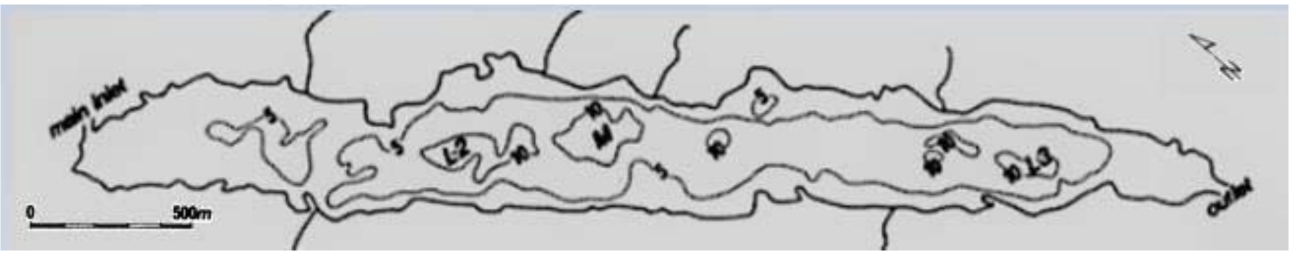


Figure 6: Bathygraphical map of Øvre Heimdalsvatn. Shows depth in meters and water current stations. Modified from (Grøterud & Kloster 1978)

3.1.1 Sediment core 1

The sediment core was sliced in field and each sub-sample was marked with a number (1-1, 1-2 etc.), placed in zip lock bags and immediately stored in a cooler. In total, there were 50 sub-samples, but due to small amounts of test-material in sample 1-1 and 1-2 they were merged. In total 49 sub-samples were used for further analysis of inorganic constituents and dry weight.

3.1.2 Sediment core 2

The sediment core was sliced in field and each sub-sample was marked with a number (2-1, 2-2 etc.), placed in zip lock bags and immediately stored in a cooler. 66 sub-samples were counted in field. After freeze drying two sub-samples were missing. In total 64 sub-samples were used for further analysis of pigments and TC and TN.

3.2 Analyses of sediment cores in laboratory

3.2.1 Dry weight

The dry weight of the sediment samples establishes the basis to further analyses of pigments and OM. Dry weight is measured based on loss in water content. The water content in the samples varies in different parts of the sediments, and may influence further analyses of OM, pigments and constituents (Cohen 2003). For analysis of dry weight, sediment core number 1 was used. The sub-samples were weighed after 1 night in freezer, and then weighed again after 4 days of dry freezing to estimate loss of water content (see Appendix B for primary data). The process of freeze drying is the first step for further analytical investigation. When placed in the freeze drier, the samples need to be completely frozen in advance. All the samples were stored in zip lock bags and opened to air before placed in the freeze drier, this is important for vapor to escape.

The sub samples contained a lot of water, especially the first 5-10 cm of the core. The more water in the samples, the longer they need to be stored in the freeze drier.

3.2.2 Dating

Radio carbon (C-14) based on a previous study of lake sediments in Øvre Heimdalsvatn was used to age determination of the sediments. The study conducted by Kloster and Hongve (1978) analyzed for several constituents, such as *Mn, P, K, Na, Mg, Ca*, *Fe*, and water content. By comparing sediment characteristics versus depth, and length of sediment cores it was possible to find similar trends, which made it possible to obtain an age estimate of the two sediment cores.

3.2.3 ICP-analysis

Concentrations of *V, Cr, Ni, Cu, Zn, As, Cd, Cs, Hg, Pb* were analyzed by Inductively coupled plasma mass spectrometry (ICP-MS, from Perkin Elmer Corporation, USA), whereas *Al, Ca, Fe, K, Mg, Mn, Na, P, S* were analyzed by Inductively coupled plasma optical emission spectroscopy (ICP-OES, Optima 5300 PV). For preparation of samples to ICP analysis, approximately 0,25-0,30 g sediment from each sub-sample was weighed and placed in a test tube. To each sample 5ml of double distilled nitric acid (HNO_3) was added.

After decomposition, each sample were added hydrogen chloride (HCL) and diluted to 50 ml. The samples were decomposed on Ultraclave. Subsequently, the samples were analyzed on ICP-MS and ICP-OES for an hour, with a temperature at 260 degrees gradually increasing. The staff at IMV laboratory, NMBU, carried out the chemical analyses.

The analysis on ICP-MS and ICP-OES was calibrated against standard reference sediments; marine sediment, estuarine sediment, and river sediments

An overview of the elements detected by ICP-MS and ICP-OES, including detection limits and limit of quantification can be found in Appendix D. Detection limit is the lowest measured concentration of each element, which can be proven with certainty.

3.2.4 Total Carbon and Total Nitrogen

Sediment core number 2 were used for analyses of TC and TN. Due to fine-grained test material, it was not necessary to grind the sub-samples. In total 64 sub-samples were analyzed for TC and TN (Appendix E). Approximately two spatulas from each sub-sample were placed in a plastic test-tube, without a lid.

Dry combustion is a common method for analysis of TC (Nelson & Sommers 1982: Sørli 2015). The concentration of TC was measured with Leco TrueSpec CHN analyzer at IMV laboratory. Analyses of TC gives an estimate of both organic and inorganic carbon present in the sediment sample. For determination of TC, freeze-dried sediments were used. At a temperature of 1050 degrees, the samples were incinerated to oxidize carbon to CO2 gas. The total amount of CO2 gas is then measured by an IR-cell.

For analysis of total TN content, the dumas method was utilized (McGill & Figueiredo 1993) and analyzed with Leco TrueSpec. All nitrogen compounds are reduced to nitrogen gas (N_2) (by using cobber). The total concentration of nitrogen gas is measured by thermic conductivity in the same device.

3.2.5 Pigment analysis

Pigments were analyzed from sediment core number 2, at IMV laboratory, Norwegian University of Life Science. For preparation of pigment analysis, the sub-samples were freeze dried.

Approximately 0,2 grams of each sub-sample were weighed in and stored in a centrifuge tube. A further 5 ml of pure alcohol were added to each sub-sample and shaken by hand, to make sure the ethanol and pigments were well-mixed, before stored in a fridge overnight. The alcohol is added to extract the pigments, and most pigments are being extracted immediately. However, some pigments are extracted in a slower phase, hence all sub-samples are stored overnight to make sure all pigments are entirely extracted (Figure 7).

After extraction, the sub-samples were centrifuged in VWR Mega Star 1.6 for 15 minutes, with 1900 revolutions per min. This is a crucial step in the pigment analysis in order to separate the particles from the analytical solution. The separation reduces disturbance from particles during the absorption measurements. Proceeding from this, 2ml of each sample were extracted and placed in a quartz cuvette in UH5300 Hitachi, Spectrophotometer. None of the sub-samples were diluted. If some samples exceed absorption above 750 nm (which exceeds the interval used to analyze the pigments), the samples are diluted to stay within the linear area (Kvam

2015). During pigment analysis, the samples were kept in a dark room or in a plastic container with reduced light access.

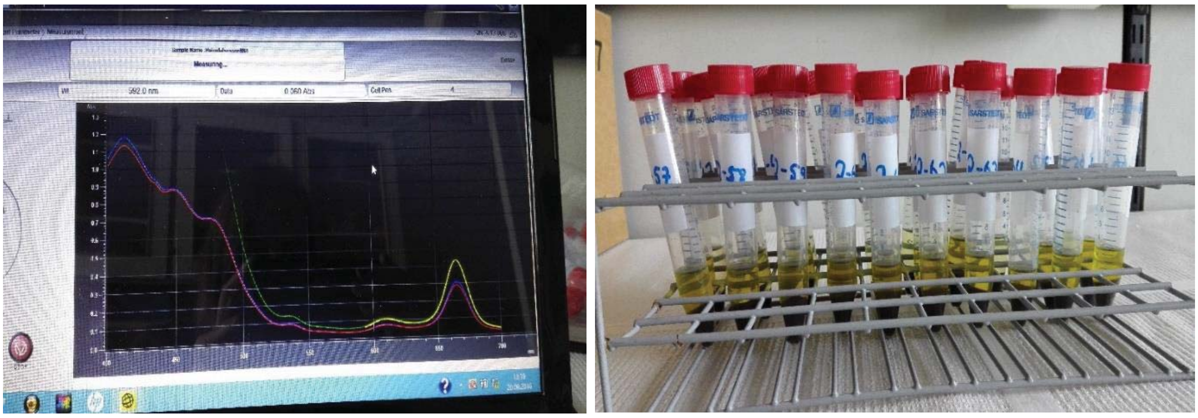


Figure 7: Pigments absorbed at different wave lengths (left). Test tubes after pigment extraction (right). © Photo: Åse Helene Vrålstad

The pigments are estimated based on different absorptions spectra (from 400 to 700 nm) in a Spectrophotometer. For each round in the Spectrophotometer two blank samples and five sub-samples were analyzed. Since pigments absorb at different wavelengths, there will be a variation in the pattern of absorption (Figure 7) referred to as an absorption spectrum (Raven et al. 2005; Kvam 2015). For example, chlorophyll a is the only pigment absorbed at a wavelength between 650 and 700 nm (red light). Other wavelength peaks, represent other pigments.

3.3 Statistical analysis

For organizing and presenting data Microsoft Excel has been used. The statistical analysis was done with a Principal Component Analysis (PCA).

3.3.1 PCA Analysis

Principal Component Analysis (PCA) is a multivariate statistical method used to look for correlation in the data material, hence to categorize variables with similar behavior. A PCA favors those data who explain most of the variation in the data set. The main purpose of using PCA is to "*find a minimum number of principal components that explains most of the variance in the data set*" (Skjelkvåle 2001, p. 3). A PCA will provide several principal components, were the first one explains the largest variation in the dataset, the next principal component explains the second largest variation etc. (Sørli 2015). There will be equal number of principal components as there are variables, but the first components will explain most of the variation (Sørli 2015).

All the data were normally distributed before the analysis by using the formula $X_y - X_{min} / X_{max} - X_{min} = NX$ (Mohamad & Usman 2013, p. 3300; Kvam 2015). NX represents the normallt distributed values and helps to compare variations in the dataset independent of a value or a unit (Kvam 2015).

4 Results

4.1 Analyses of sediment cores

4.1.1 Sediment Characteristics

The cores were retrieved within the water station L-2 (Figure 6). This station is located in the deepest part of the lake, and is not influenced directly by the inlet streams (Kloster & Hongve 1978). The content was characterized as a mixture of fine grained inorganic particles and OM. Pieces of leaves were found throughout the cores, and they were both brown in color and had a homogenous appearance. Further down in the cores the sediments were more compressed and contained less water than the top layer.

4.1.2 Dating of cores

The analysis of post-glacial sediments from Øvre Heimdalsvatn, executed by Kloster and Hongve (1978) performed C-14 for age determination of the sediment cores. The sediment core used for analysis of chemical constituents in that study were 268 cm long. The retrieved sediment cores in this study were 42 and 54,2 cm (respectively), hence it is the upper 50 cm of the results in Kloster and Hongve (1978) that have been of interest. Seen from Figure 9, the depth stratification indicates the first 50 cm of the cores to represent the last ca 2000 years. Based on these result and estimated rate of sedimentation in Øvre Heimdalsvatn (2mm year^{-1}), it was possible to estimate approximate time intervals.

The constituents *K, Na,* and *Fe* in the first 25-30 cm of the sediments cores in Kloster and Hongve (1978) show similar trends to *K, Na,* and *Fe* presented in this thesis.

Looking at *Fe* (Figure 9) in the first 10 cm of the core, it shows a similar trend compared to *Fe* from the cores used in this thesis (Figure 16). For *K*, especially the first 25 cm (estimated time scale at 25 cm is year 1000 CE), the concentration increase around 25 cm, followed by a decrease. In the first 10 cm, the concentration increases again. This is also reflected in *K* (Figure 16) from this thesis. Additionally, analysis of dry weight, representing water content, is also used to compare with the results in this study. Analysis of water content in Kloster and Hongve (1978) indicate similar trends, especially the two minima in the first 50 cm of the core (Figure 10) in comparison with the analysis of dry weight executed in this thesis. Based on these results and the sedimentation rate it was possible to obtain an age estimate of the sediment cores.

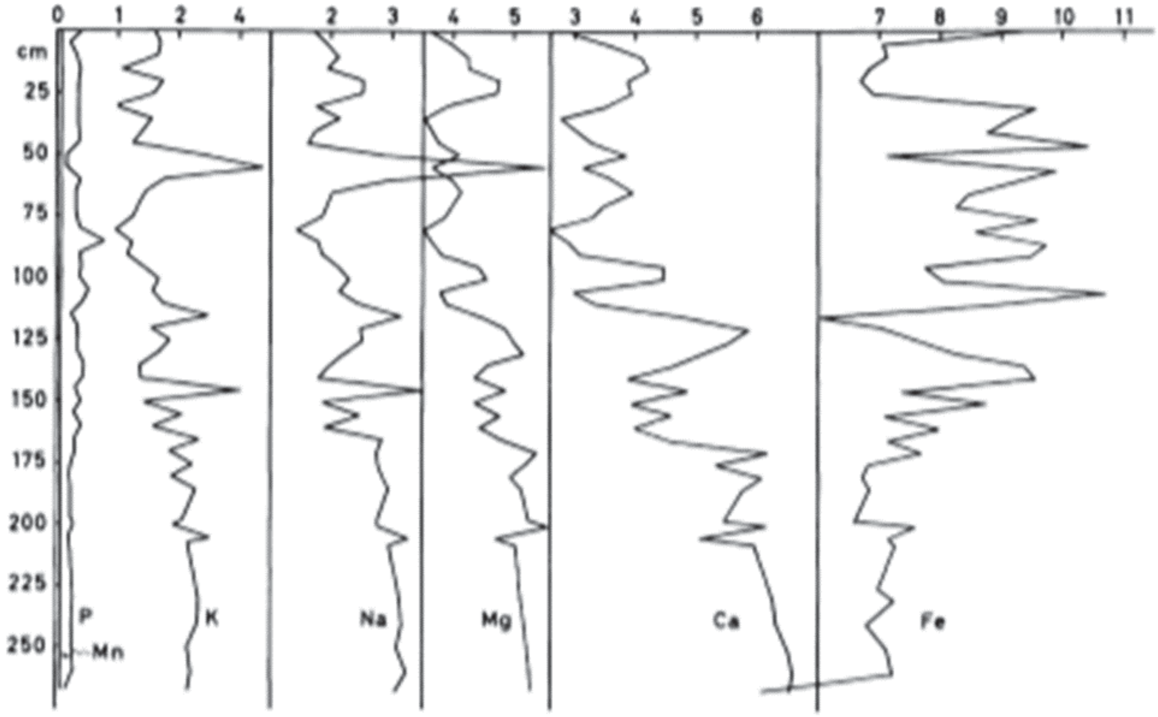


Figure 8: Depth stratification of inorganic constituents from the study executed by Kloster and Hongve (1978), used to age determination in this study. The values are given as percentage of dry weight

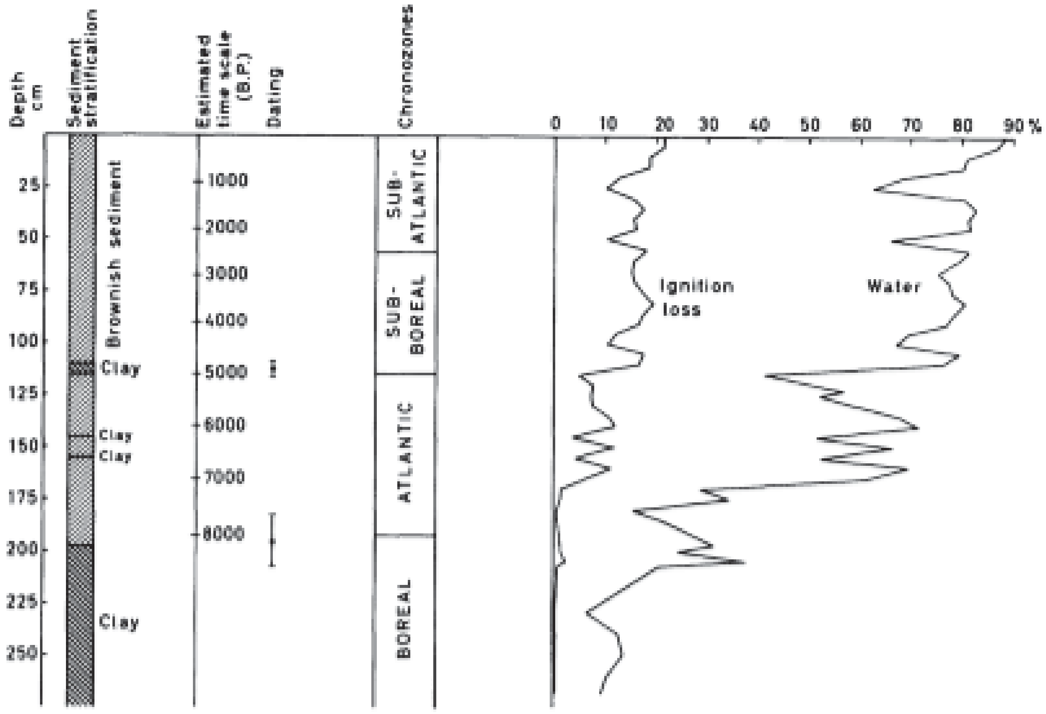


Figure 9: Depth stratification of water content and estimated time scale from Kloster and Hongve (1978)

4.1.3 Median concentrations of constituents and bedrock composition

The inorganic constituents show a varying concentration in the sediment core. The mean concentration of the constituents in g/kg are given in Table 4.

Fe and *Al* appear as the most abundant constituents in the sediment core, with a mean concentration of 39,89 and 35,61 g/kg (respectively). Followed by *Ca* and *Mg*.

K, P, Pb and *S* also appear at concentrations ranging between 1 and 4 g/kg, while the remaining constituents appear at concentrations below 1 g/kg.

Table 4: Mean value of the constituents throughout the core in g/kg, ranging from most to least in concentrations

Fe	39,89 g/kg
Al	35,51 g/kg
Ca	19,21 g/kg
Mg	11,30 g/kg
K	3,80 g/kg
P	2,60 g/kg
Pb	2,307 g/kg
S	1,4 g/kg
Na	0,79 g/kg
Mn	0,47 g/kg
Cu	0,19 g/kg
As	0,144 g/kg
V	0,12 g/kg
Zn	0,085 g/kg
Cs	0,065 g/kg
Cd	0,026 g/kg
Hg	0,01 g/kg
Cr	0,007 g/kg
Ni	0,0026 g/kg

The catchment area in Øvre Heimdalsvatn is dominated by gabbro and sandstones, but also biotite gneiss, pyroxene-granulite and the minerals; chlorite, sericite, uralite. Table 5 presents an overview of the most common constituents found in these rocks and minerals. Bold text indicates constituents found in largest quantities, while italics represents those constituents found in less quantities in the bedrock composition. Area 1-3 represents where in the catchment the different rocks and minerals occurs (see Appendix A).

Table 5: Overview of the bedrock composition in the catchment area, with chemical constituents (italics indicate constituents that does not occur in large quantities in the different rocks and minerals) (M Heim 2017, personal communication, April 2017)

Bedrock	Area (1, 2, 3)	Constituents
Biotite gneiss (rock)	1	**Mg, K, Fe** *(Na, Ca, Al)*
Chlorite (mineral)	1	**Mg, Al, Fe**
Sericite (mineral)	1	**Al, K**
Meta-arkose (sandstone)	2	**Al, K** *(Na, Ca)*
Monzodiorite (rock) - Gabbro (rock) - Uralite (mineral) - Saussurittgabbro - Amphibolite (rock)	3	**Mg, Fe, Ca** (Ni, V, Al, Cr, P, K, Na, Cr, Ni, Cs, Cu)
Pyroxene granulite (rock)	3	**Ca, Mg, Fe**

4.1.4 Dry weight and Total Carbon

The concentration of TC represents both organic and inorganic carbon. However, in this thesis the following sections will only focus on TOC. As Øvre Heimdalsvatn is surrounded by a calcium poor ground, the amount of $CaCO_3$ is very low. In other words, the presence of TIC in the sediments are low.

Results from dry weight and TOC in percent, are shown in Figure 10. Dry weight shows a varying trend, with three minima at CE 350-500, 900-1000, and 1300-1400. The figure also shows two maxima in dry weight at 650- and 1200 CE. The concentration of dry weight shows major variations, ranging from 24%, down to almost 0% in recent times.

TOC shows minor variation throughout the core. From approximately 350-1100 CE the concentration is slightly decreasing, followed by a minor increase from 1100-1300 CE. The concentration of TOC is relatively stable at 8 % throughout the core.

4.1.5 Total chlorophyll a and C:N ratio

Total chlorophyll a and C:N ratio are shown in Figure 10 (left).

Total chlorophyll a ranging around 100µ/g dry weight from the year 100 BCE to 400 CE, before it decreases to a minimum and stabilizes at almost 0 µg/g dry weight until 1000 CE. Further, total chlorophyll increases from 1100-1250 CE, followed by a decrease. The concentration keeps increasing toward 1850 CE, before the concentration drops again.

The C:N ratio show an even concentration, with minor variations. Throughout the core it stays within the area between 8 and 10. Shows less variation than TOC alone.

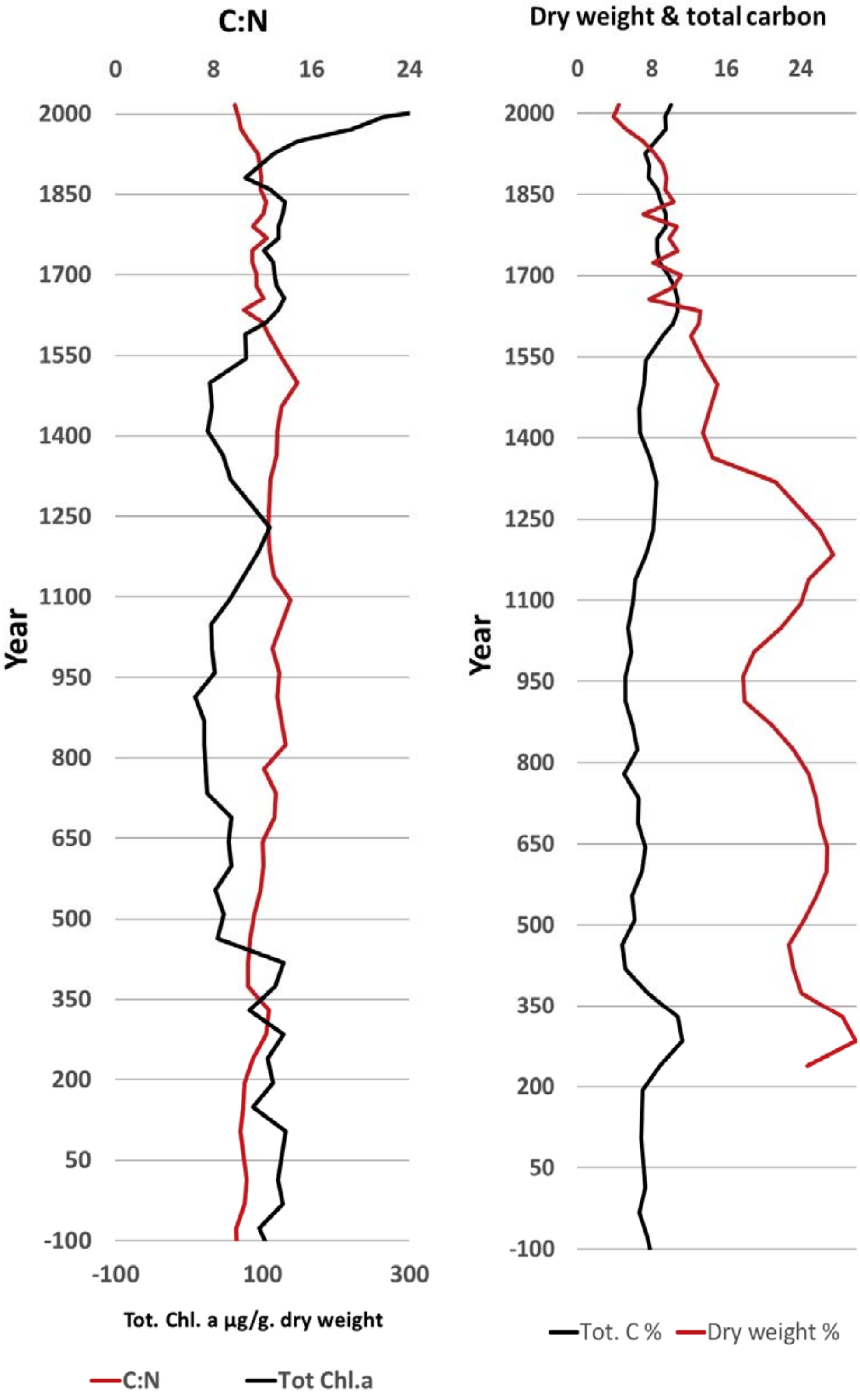


Figure 10: Correlation between dry weight and total carbon in % (left) and total chlorophyll a and total carbon/nitrogen (right)

4.2 Biological and chemical parameters

4.2.1 Biological parameters – analysis of pigments

In total 19 pigments were analyzed, where two of them are degradation products (pheophytin a & b). Five pigments were not found (peridinin, fucoxanthin, echinenenone, chlorophyll c1, canthaxanthin) and six pigments had values under limit of detection or sporadic values (c.neo, dino, diatoxanthin, myxoxanthophyll, lutein, chlorophyll c2). These are not considered important for the results and are not discussed further (see Appendix F for algae groups). The remaining eight pigments (Chlorophyll a & b, Pheophytin a & b, β-Carotene, Diadino, Violaxanthin, Alloxanthin) were all represented in the sediment core and are discussed further.

The oldest part of the sediments are represented at year 100 BCE, while the top layer of the core represents ca year 2016.

In general, the pigments indicate a relatively similar trend throughout the core (Figures 11, 12, 13). The first time interval of the core (100 BCE – 400 CE) shows a relatively high concentration among most of the pigments, compared to the next 500 years.

In the time interval between 500-900 CE the pigment concentrations decrease almost to 0 µg/g dry weight. Further, the results show an increase in pigment concentrations from approximately 900-1250 CE, followed by a decrease until 1400 CE.

From 1400 CE until recent times, the pigment concentrations show a general increase with minor variations. At 1850 CE there is a quite rapid decrease in pigment concentrations, except β-carotene and violaxanthin. The same trend is seen from 1850 CE (after the rapid increase), where the pigments have increased gradually, except β-carotene and violaxanthin, which decreases in more recent times.

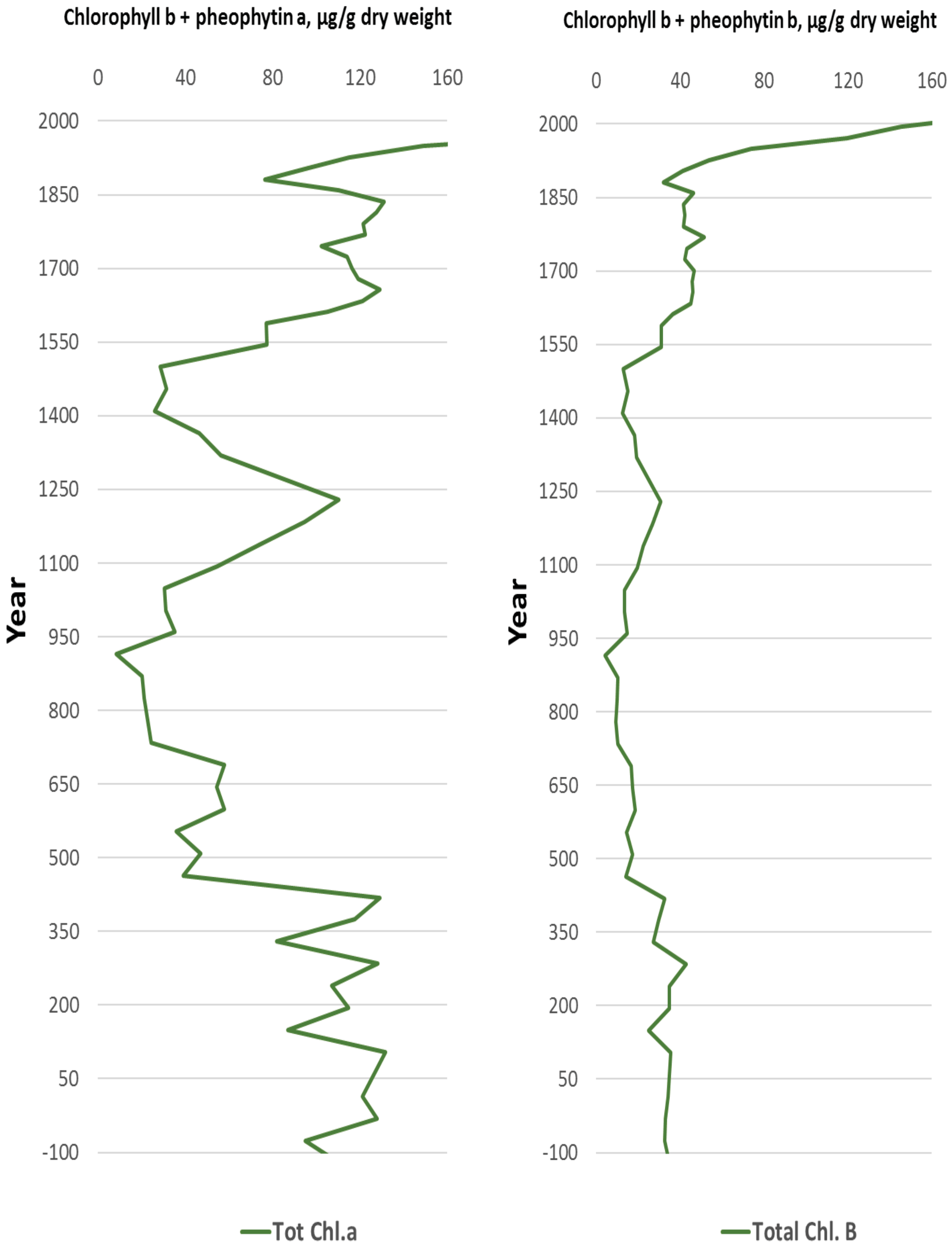


Figure 11: Chlorophyll a and pheophytin a (µg/g. dry weight) represents all photosynthetic algae and vascular plants, whereas chlorophyll b and pheophytin b (µg/g. dry weight) represents green algae and vascular plants (Reuss 2005)

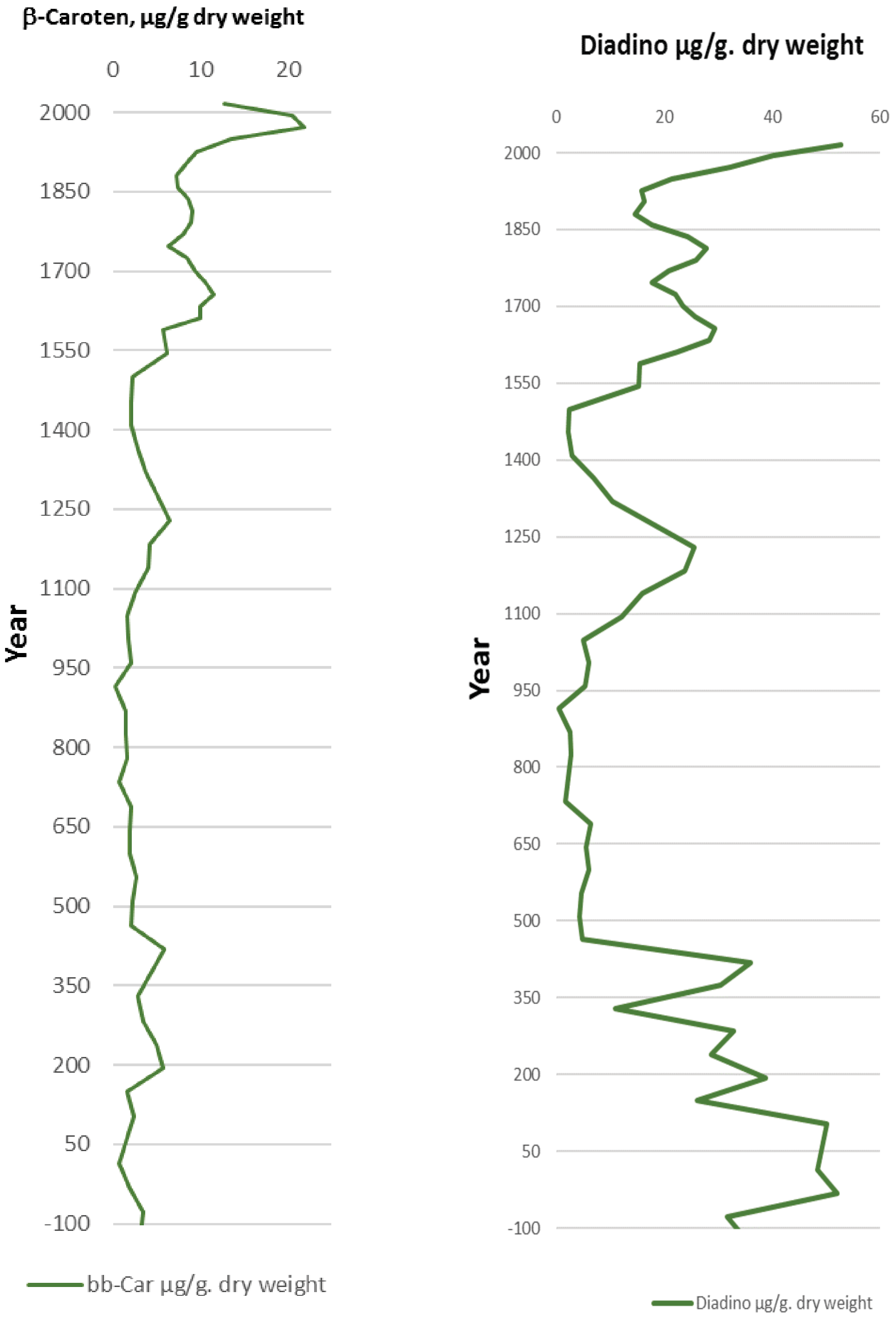


Figure 12: β-Caroten (µg/g. dry weight) represents most algae and vascular plants (left), whereas Diadinoxanthin (µg/g. dry weight) represents diatoms, dinoflaggellates, prymneophytes, crysophytes, raphidophytes, and euglenophyes (Reuss 2005)

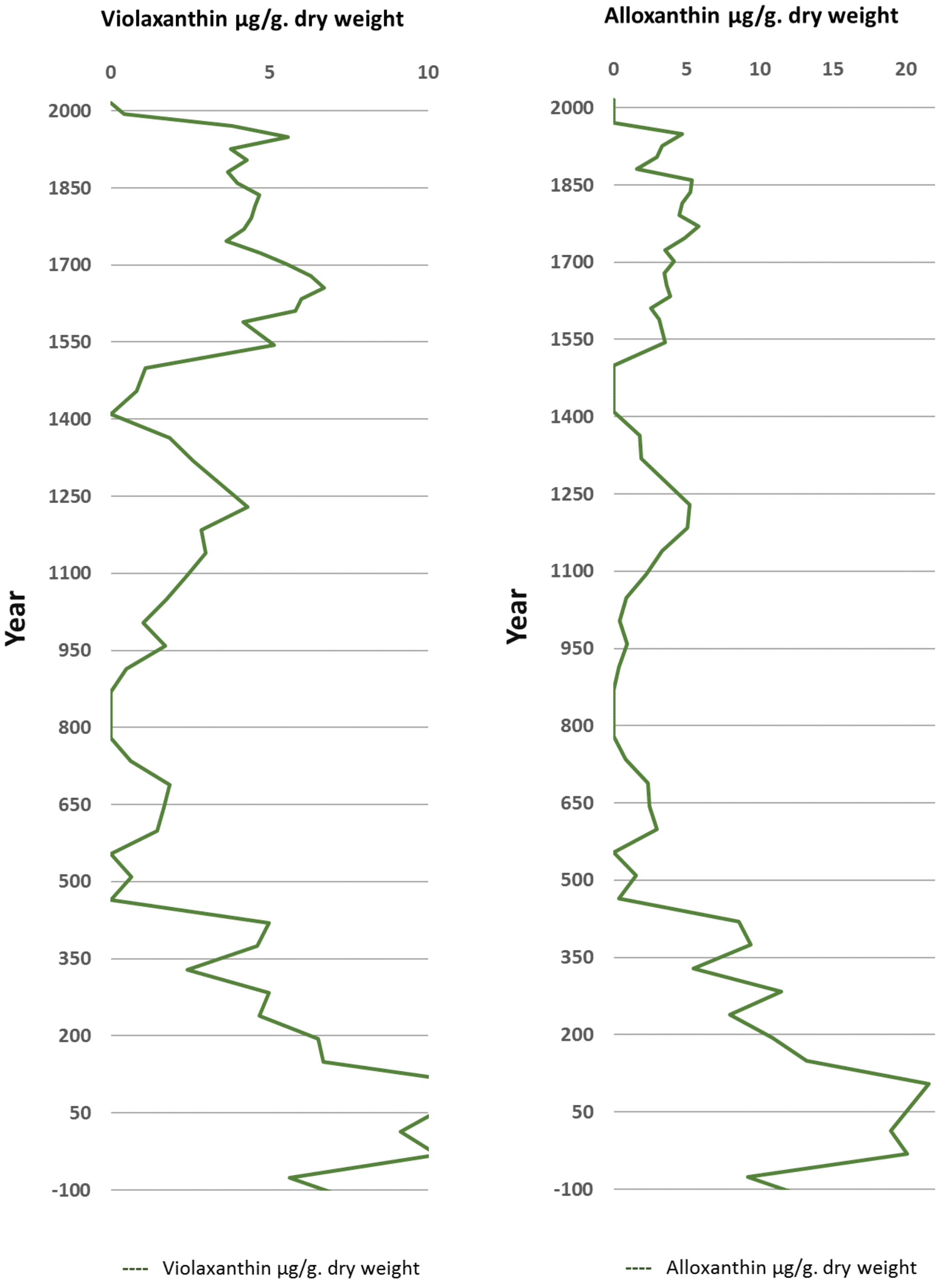


Figure 13: Violaxanthin (µg/g. dry weight) represents green algae and vascular plants (left), whereas Alloxanthin (µg/g. dry weight) represents cryptophytes (right)

4.3.2 Chemical parameters – analysis of constituents

In total 19 constituents, have been analyzed and represent approximately the last 2000 years. Although several of the constituents show minor variations, several of them indicate similar behavior and are therefore grouped.

Most of the trace metals *Hg, Zn Cd* and *As, S* (Figure 14) and *Pb* (Figure 16) show similar patterns with some minor differences. In general, there is an increasing trend among these constituents from 950 CE. Furthermore, *Cd, Zn, Pb* and *Cu* decrease in recent times, in contrast with *As*, *Hg* and *S*.

The concentration of *Hg* is generally stable at 0,05 mg/kg the first 1000 years, except a drastic increase right after 500 CE, before it drops back to 0,05 mg/kg. From 900 CE the concentration has been steadily increasing until recent times. The present concentration is approximately at 0,15 mg/kg. *Cd* and *Zn* show even concentrations the first 1000 years, where *Cd* is quite stable at ca 0,15 mg/kg, and *Zn* at ca 0,08 g/kg.

For *Cr, Ni, V* and *Al, Mg, P* (Figure 15) there are less major variations in the pattern, but large variation in concentrations. At 1850 CE all the constituents show a quite rapid decrease in concentrations, followed by an increase, right after 1850 CE until recent times. The only exception is for *Na* (Figure 17), which differentiate from the other constituents. At around 1850 the concentration of *Na* is increasing.

Fe and *Mn* (Figure 16) indicate a similar trend throughout the core, with less major variations, except an increasing trend toward recent times. *Cs* and *K* (Figure 6) follow a similar pattern, where the concentration of *Cs* ranges between 0,6 and 0,9 mg/kg. *K* appears at much higher concentration, and ranges between 2,0 and 4,0 g/kg.

Cu is relatively even throughout the core, and indicate a minor decline since 1000 CE, and ranges between 0,1 and 0,25 g/kg.

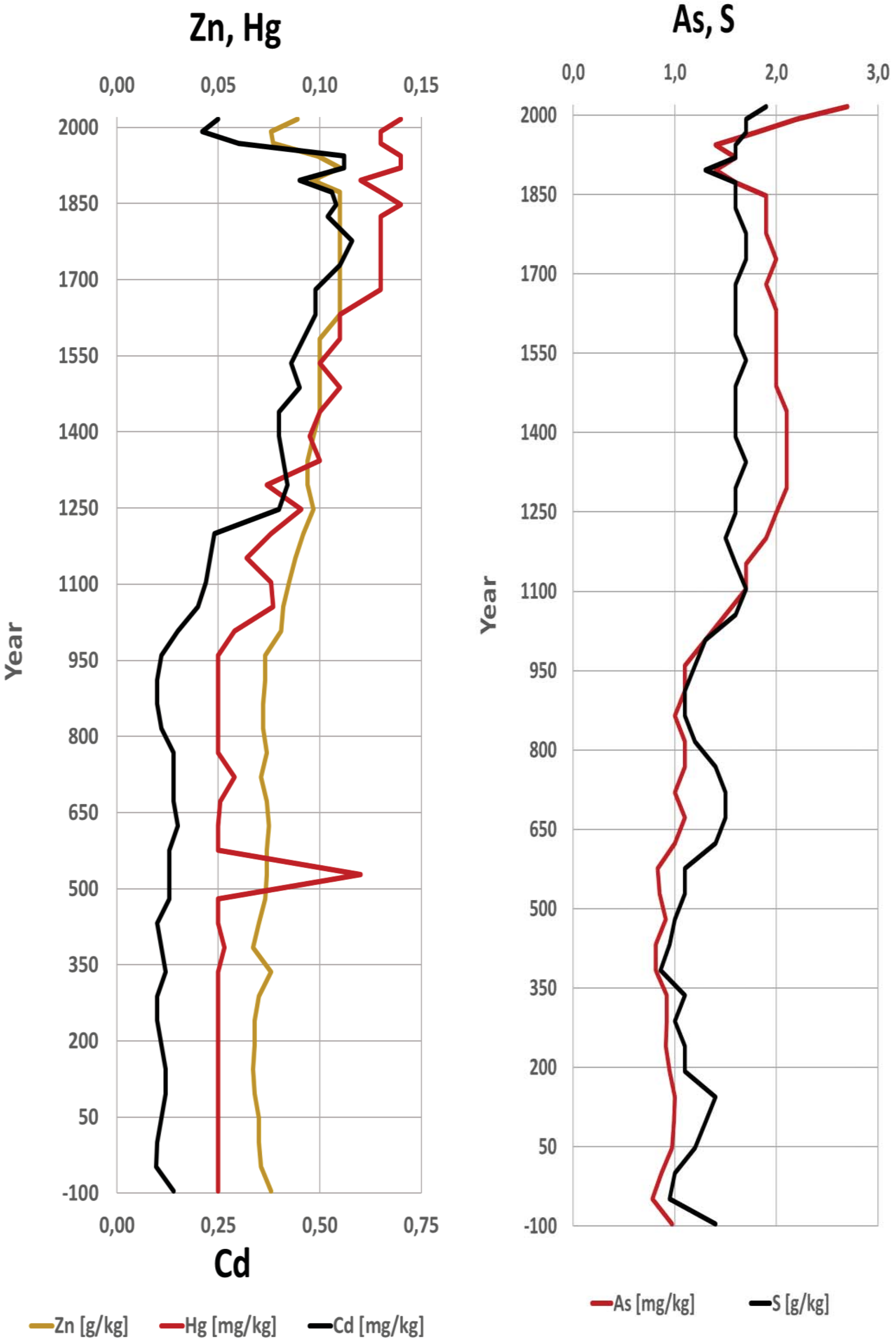


Figure 14: Concentrations of Cd, Hg in mg/kg and Zn in g/kg (left). Concentrations of As in mg/kg and S in g/kg (right)

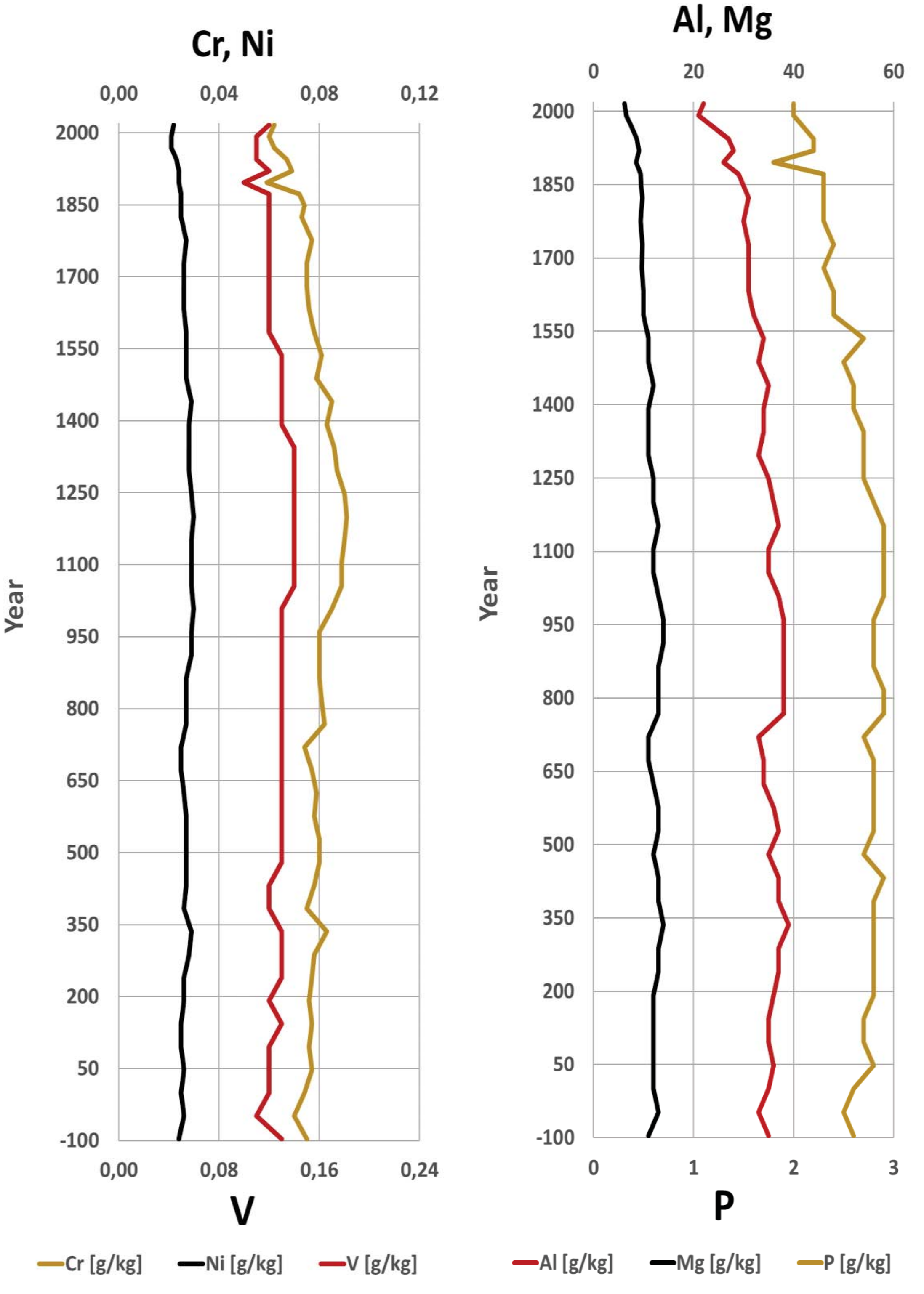


Figure 15: Concentrations of V, Ni *and* Cr *in g/kg (left). Concentrations of* Al, Mg *and* P *in g/kg (right).*

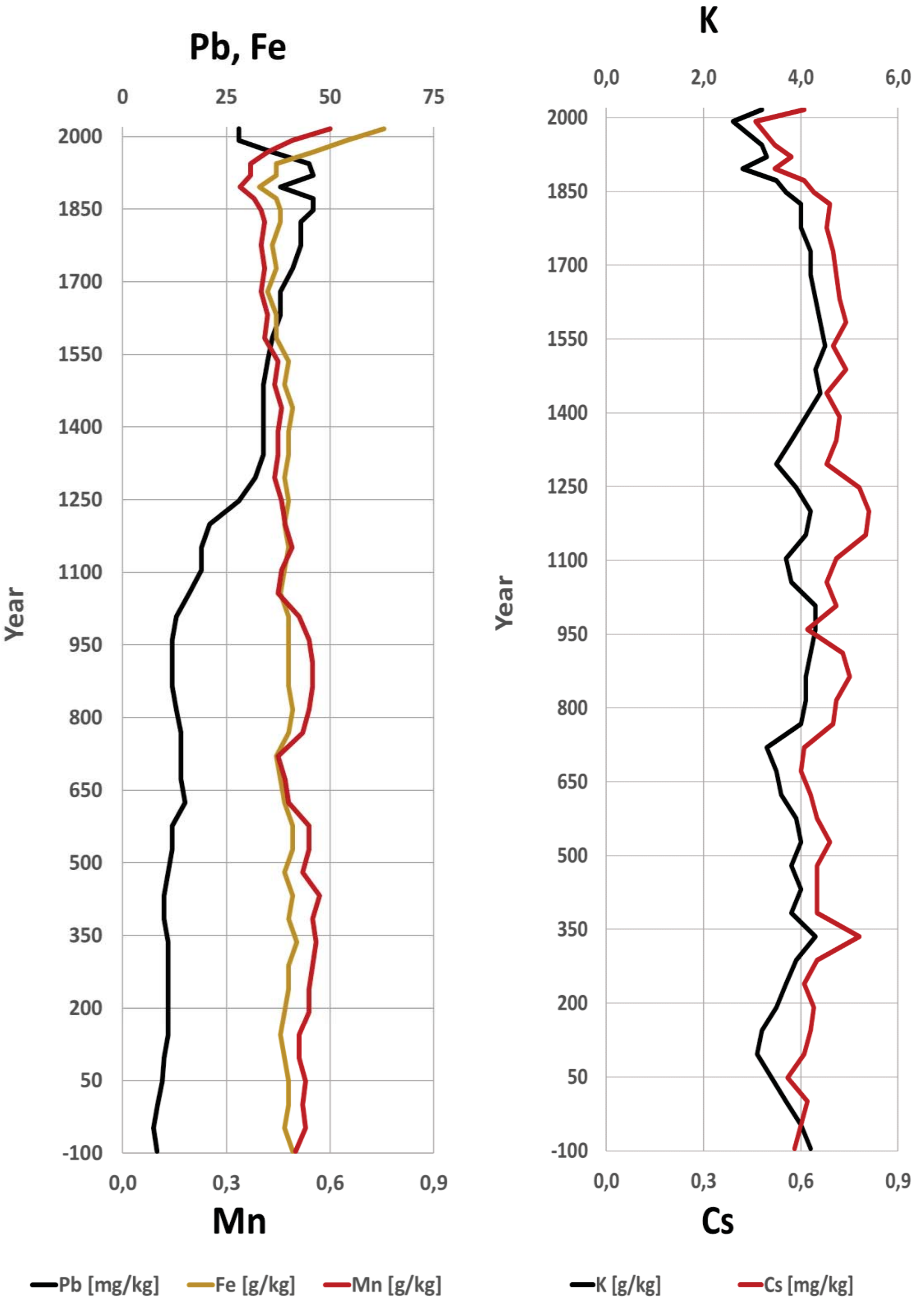


Figure 16: Concentrations of V, Ni and Cr in g/kg (left). Concentrations of Al, Mg and P in g/kg (right).

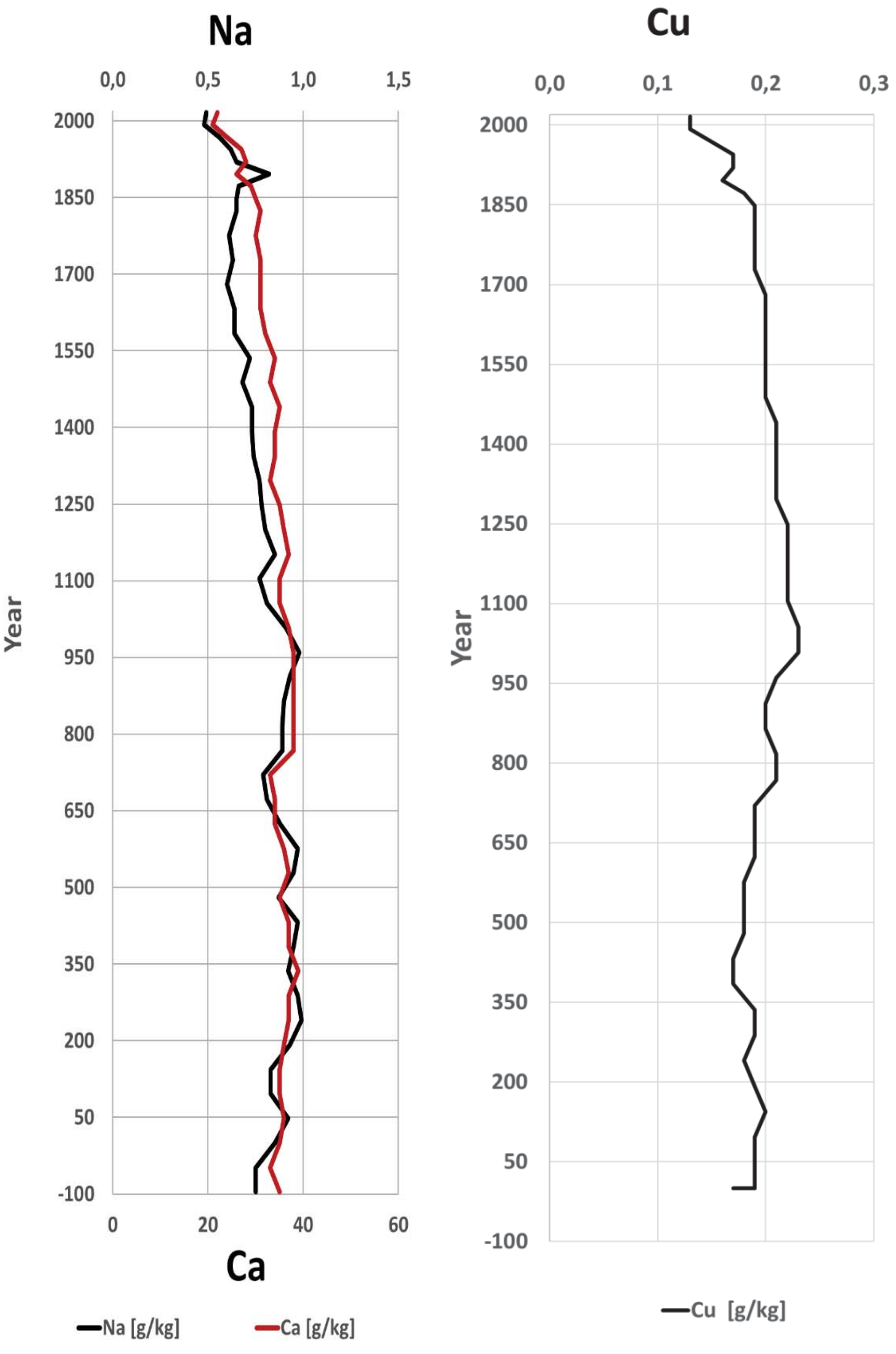


Figure 17: Concentrations of Na and Ca in g/kg (left). Concentrations of Cu in g/kg (right).

4.3 Statistical Analysis

4.3.1 Principal Component Analysis

The principal components PC1 and PC2 explain together 63,7 % of the variations in the dataset (Figure 18), with eigenvalues at 4,31 and 2,06 (Appendix G). All 38 variables from analyses of chemical constituents and pigments are represented in the PCA. As mentioned previously not all the variables are discussed further, only those variables considered to be of major relevance. The variables that orient in the same direction indicate a positive correlation, while those variables pointing in different directions indicate a negative correlation. Perpendicular variables indicate a lack of correlation. β-carotene is almost perpendicular to *Mg, Al* and *P*. The PCA indicate a grouping trend between some of the constituents and some of the pigments. Most of the trace metals and sulfur (*Zn, Cd, Pb, Hg, As, S*) indicate a positive correlation. Chlorophyll a and b with its degradation products are oriented in the same direction, indicating a positive correlation. *Cs, K, Cu, Ni, V* and *Cr* are oriented in the same direction, indicating a positive correlation and probably influenced by many of the same factors.

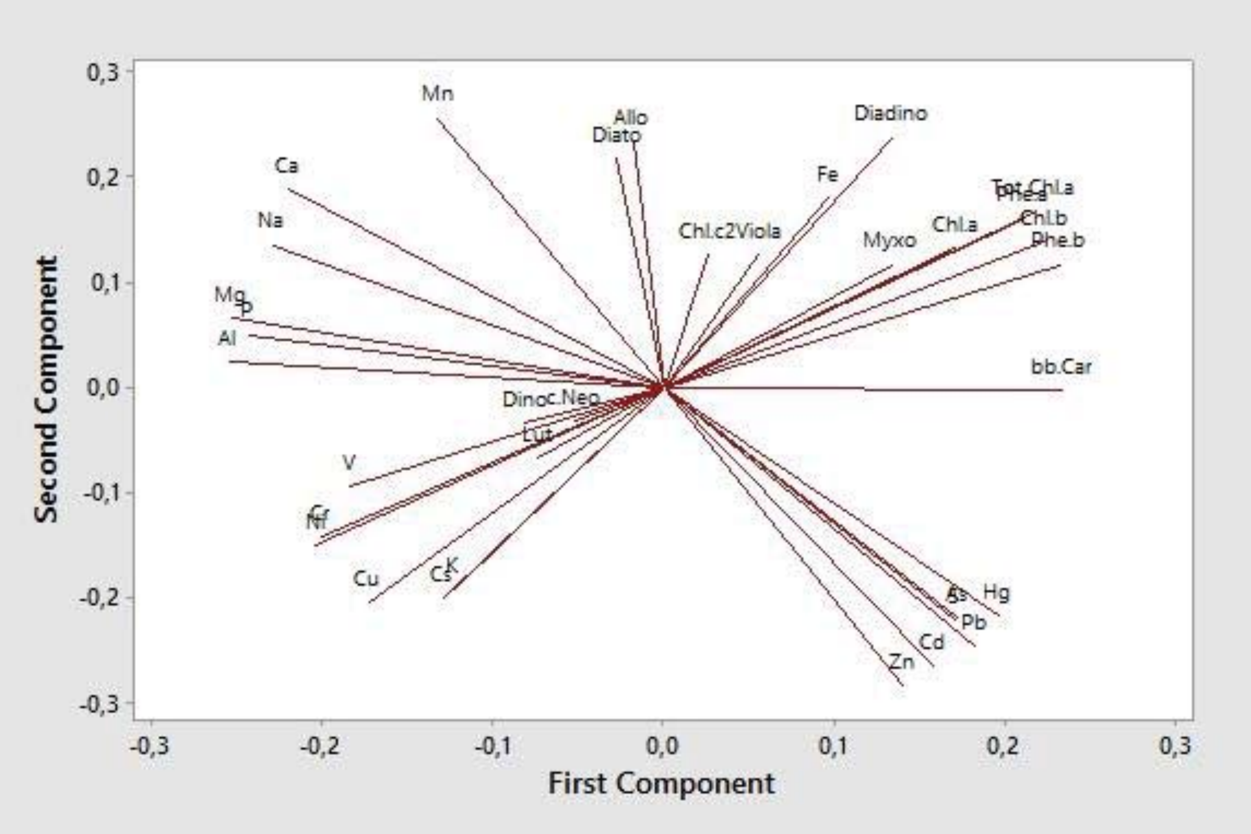


Figure 18: Principal Component Analysis (PCA) for Øvre Heimdalsvatn. showing the correlation between pigments and the chemical constituents.

5 Discussion

5.1 Data uncertainty

Many of the techniques used in paleolimnology include sources of error and uncertainty. Sampled sediments can undergo photo- and chemical oxidation when exposed to air and light, which could influence the results. Pigments and chemical constituents are sensitive to light, temperature, and oxygen. During the process of pigment analysis, reduced lighting conditions were used as much as possible. As the cores were sliced in field within 1-2 hours after collection, the risk of contaminated samples due to light is assumed to be low. According to Leavitt and Hodgson (2001) freezing of pigments for more than a month should be avoided, as oxidation and dehydration of the pigments may occur. In this thesis the pigment analysis were conducted within the same week, and the process of freeze drying is assumed to have little negative influence of the results. The technique of pigment identification is also questionable, as a spectrophotometer has its limitation due to quantification and identification of multiple pigments (Millie et al. 1993: Reuss 2005).

It is important to consider that *"The extent of preservation is not always uniform in inorganic compounds"* (Wetzel 2001). Results from the sediment cores do not always reflect the actual conditions in the water phase. In the analysis of the cores, a constant sedimentation rate is assumed. Consequently, lake sediments are not always representative of the chronological sedimentation occurring in a lake. There may have been variations in both allochtonous and autochthonous inputs to the lake, as well as changes in climatic conditions. As the sedimentation in a lake is influenced by a variety of different factors; topography, morphometry, and lake movements such as wind and waves, it may resuspend and sort particles after size and density. Consequently, such factors could influence the results. According to Wetzel (2001) there is a general trend in the lakes morphometry, that coarse particles settle closer to the shoreline, while fine particles tend to accumulate in deeper parts of the lake. In this study the cores were taken from the deepest part of the lake, and the sediments were fine-grained.

Dating of sediment cores is another process in this study that includes sources uncertainty. As mentioned above, a constant sedimentation rate is assumed to date the cores. The results in this study are compared to a previous study of lake sediments from the same lake. By comparing trends between these results, this was the basis of dating. There can be many uncertainties involved in this method, but as this thesis focuses upon the major trends throughout the core. Comparing trends between these results made up the basis of the age determination of sediment cores in this thesis. Such a method can involve many uncertainties, but as the thesis focuses upon the major trends throughout the cores, accurate data for specific years was not considered necessary. The considered time intervals were 50 years (+/-). This approach was taken in light of the fact that; as the sediments get older, they tend to be more compressed and the accuracy of dating the cores may decrease (Cohen 2003).

All large-scale reconstructions of past temperatures suffer from difficulties in representative data, and there will always be uncertainties in relation to past climate reconstructions. The estimated temperature reconstruction used as a tool to discuss variation in different parameters in this thesis, may not provide accurate data on regions. Thus, it can provide a minor indication of temperature variations in the past.

During field- and laboratory work, procedures for collection, slicing, and preparation of samples to analyze were followed carefully. However, the possibility of instrumental and human errors cannot be excluded.

5.2 Variation in organic material

By comparing *total chlorophyll a* to OM, one can obtain information on whether the changes in organic matter is a result of internal or external lake processes (Sørli 2015).

Variation in TOC and dry weight and C:N and *total chlorophyll a* indicate some correlation (fig. 10), where especially some trends point out. Although C:N ratio is low as expected, it is challenging to comment on a clear variation between C:N and *total chlorophyll a.* Moreover, TOC show a little more variation and seems to follow the variation in *total chlorophyll a.* This indicates that organic material in Øvre Heimdalsvatn is both influenced by primary production within the lake, as well as allochtonous inputs. TOC show minor variations and is generally low, which is to be expected for a lake of this character, however it provides a minor indication of changes in allochtonous material. Between 950 CE and 1400 CE, *total chlorophyll a,* dry weight and to a less degree TOC indicate a similar trend. This time interval is referred to as the Holocene Climate Optimum (HCO), followed by the Little Ice Age (LIA) and seems to have influenced the transport of both allochtonous and autochthonous material in the lake. An increase in temperature has shown to increase the transport of organic material, contrary a decrease will influence transport of organic material in the opposite direction (Schindler et al. 1996).

The sediments in Øvre Heimdalsvatn has been characterized as mainly influenced by allochtonous material from the catchment, while primary production in the lake has been referred to as low, due to a high rate of flowing through rate in the lake (Kloster & Hongve 1978). Although allochtonous material is the main source of primary production in the lake, the results of total *chlorophyll a* give a much better indication of lake production. *Chlorophyll a* is also recognized as a major part of most autotrophic organisms, hence it serves as a suitable measure for primary production (Leavitt & Hodgson 2001).

A large amount of TOC in subalpine lakes are associated with allochtonous humic substances, and are known to be efficient "*Metal complexing agents and play an important role in transport of certain metals and trace metals to lakes and sediments*" (Rognerud & Fjeld 2001, p. 17).

The study conducted by (Kloster & Hongve 1978) in Øvre Heimdalsvatn measured Loss On Ignition (LOI) and water content (fig 9) and the latter was well correlated to LOI. The correlation is probably related to the water content`s ability to absorb to organic fractions. Hence, the variations in water content is likely caused by OM. Figure 10 indicate a relatively similar trend between both TOC and water content throughout the core, which strengthens this argument.

The variations in OM and *total chlorophyll a* are used as valuable information in order to discuss the following part: distribution of pigments and chemical constituents.

5.3 Distribution of pigments

The pigments indicate relatively similar patterns throughout the core (Figures 10, 11, 12, 13). This implies that the algae assemblage in Øvre Heimdalsvatn is largely influenced by many of the same forcing mechanism. The pigments discussed below indicates a generally positive correlation in the PCA (Figure 18), as several of them orient in the same direction. Some indicates a better correlation than others, for instance *chlorophyll a & b*, with its degradation products. This was expected for *chlorophyll a and pheophytin a*, as this pigment is found in all phytoplankton groups and vascular plants, whereas other pigments are more specific to certain algae groups (Reuss 2005) (table 1). *Alloxanthin* and *Violaxanthin* orients in the same direction, and may be influenced by different forcing factors than the chlorophylls. Both *β-Carotene* and *diadino* indicates less positive correlation to the other pigments, but the PCA it shows most correlation to the chlorophylls. What separates them the most is the concentration among the pigments. Especially *β-Carotene* and *diadino* occurs in lower concentrations compared to the remaining pigments. This is however, related to the occurrence of pigments in different phytoplankton groups. *β-Carotene* for instance is found in most algae plants, whereas *diadino* occurs in diatoms and dinoflagellates (Leavitt & Hodgson 2001). The major trends in distribution of pigments throughout the sediment record are discussed in more details below.

Variation in pigment concentration 100 BCE-500 CE. The pigment assemblage in the time interval between 100 BCE – 500 CE indicate minor variations, without any significant changes. However, the pigment concentrations are slightly higher compared to the next 500 years. Major influences by human activity in this period is not likely to have been a large contributor, hence other natural forcing mechanisms must be considered. The time interval between 100-1200 CE has been characterized by a high rate of volcanic activity that led to warmer winters in the northern part of Europe (Bradley et al. 2003). An increase in temperature may have led to increased production and transport of allochtonous material to the lake or increased production within the lake.

Variation in pigment concentration 500-1000 CE. Between 500-1000 CE there is a general decrease in all the pigment concentrations. Each pigment reached a low in this period at almost 0 µg/g dry weight. At the same time, there is a slight decline in the percentage of TOC (Figure 10), which is consistent with the decline in plant and plankton populations (Zuur 2014). Further, the temperature reconstruction conducted by Mann et al. (2009), indicate a cooling trend in this time interval (Figure 1). The coldest temperatures observed in the Northern Hemisphere occurred between 800-1000 CE. It is likely to assume that the decline in pigments are a result of a period with cooling conditions. Decline in temperature may cause a decline in production, as temperature is an important driver for production in terrestrial and aquatic environments (Wetzel 2001).

Variation in pigment concentrations 1000-1400 CE. The time interval between 1000-1250 CE is characterized by a maximum in pigment concentrations, positively correlated with dry weight and a minor increase in TOC. Estimated temperature data for the Northern Hemisphere indicate a period characterized by higher temperatures, and falls into the period defined as the Holocene Climate Optimum. A warmer climate, contrary to the time interval described above may have caused an increase in plant and plankton population. This trend is followed by an apparent decline in pigment concentrations, which coincides with the period defined as The Little Ice Age.

Variation in pigment concentrations 1400 CE -present. Each pigment (except *β-carotene*) show a general increase from ca 1850 CE until present. The elevated concentrations of *chlorophyll a & b* may be explained by the time it takes for *chlorophyll a & b* to degrade to its degradation products. This transformation is oxygen dependent, and might imply a period with less oxygen in the lake (Reuss 2005), since anoxic conditions influence pigment composition in the sediments. When the algae cells die, the degradation from *chlorophyll a & b* to *pheophytin a & b* starts, and this process continues in the sediment until the *chlorophyll a & b* is completely converted to its degradation product (Rohrlack & Haaland 2017). Contrary, the rate of degradation increases with access to oxygen at the lake bottom (Rohrlack & Haaland 2017). Furthermore, the oxygen level at the lake bottom is influenced by the internal production in the lake, hence it can be challenging to distinguish if the increased pigment concentrations are a result of more production or preservation conditions in the sediments (Reuss 2005). *β-carotene* differentiate form the rest of the pigments toward recent times (fig. 12), as the concentration indicate a decline. A change in pigment assemblage signify a change in phytoplankton composition in the lake, especially since *β-carotene* is present in most vascular plants and algae (Reuss 2005).

To summarize some of the major findings in distribution of pigments, it seems like there is an overall similar trend. The algae assemblage in Øvre Heimdalsvatn is highly sensitive to changes in temperature (Broderesen & Anderson 2002;Velle et al. 2010), which is well reflected in the pigment concentrations. It is likely to assume that climatic conditions during the Late Holocene have been an important controlling factor for pigment variations in the lake. The result of *total* *chlorophyll a* show larger variation throughout the sediment core, compared to C:N. Contrary to previous studies, it might imply that internal lake production in Øvre Heimdalsvatn plays a greater role than first expected. Additionally, the lake itself may be sensitive to changes in climatic conditions. Since Øvre Heimdalsvatn represents several high-latitude lake ecosystems in Norway, it may be an indication that similar lake systems are sensitive for changes in climatic conditions. These changes may as well be reflected in chemical parameters. The distribution of inorganic constituents analyzed in the sediments will be discussed in the next section.

5.4 Distribution of inorganic constituents

Results from the analyses of chemical constituents in Øvre Heimdalsvatn clearly fall into different groups, where some of the constituents show better correlation than others. Based on the results and the PCA there is a clear trend among *Hg, Cd, Zn, Pb* and *S,* since 950 CE (Figures 14 and 16). These constituents formed a coherent group in the PCA, indicating a positive correlation as they orient in the same direction. Both *Pb* and *Cd* showed generally higher concentrations in pre-industrial times. *Pb, Cd, As, Zn* and *Hg* are a group of elements that are largely dominated by long-range transport of atmospheric deposition (Skjelkvåle 2001). From the results, there is a decreasing trend in concentrations for *Pb, Zn, Cu* and *Cd* in recent times. These trace metals are today recognized as highly influenced by human activity, but it is often focused on the increase after the industrial revolution (Skjelkvåle 2001). Analysis of these trace metals indicates a trend were anthropogenic activity may already have altered the global emission of trace metals, as early as 950 CE. The remaining constituents indicate different behavior compared to those mention above, indicating that multiple factors influence the distribution of chemical constituents in Øvre Heimdalsvatn. The constituents are discussed in more details below.

Mercury (Hg), Lead (Pb), Sulfur (S), Cadmium (Cd), Zink (Zn), Arsenic (As)

Concentrations of *Hg* (Figure 15) show a general increase from 900 CE until present. There are several sources, both natural and anthropogenic, which can release *Hg* into the environment. The latter is clearly the largest contributor at present, but in some areas *Hg* concentrations may be altered by weathering of rocks or volcanic eruptions. The early increase in *Hg* concentrations in Øvre Heimdalsvatn is less likely to be a result of the geomorphology in the catchment area. Seen from the bedrock geology (Table 4) *Hg* is not recognized as a natural constituent in the mineral composition, which indicates other sources of release. Due to the high vapor pressure of *Hg*, it easily enters the atmosphere and many Arctic regions has become a major gathering point for *Hg* release (Perry et al. 2005). However, emissions of *Hg* are complicated and to estimate the load of anthropogenic influence on *Hg* concentrations, it is crucial to gain a more comprehensive knowledge on the natural background levels (Martínez-Cortizas et al. 1999).

The drastic change in *Hg* concentrations around 500 CE could be a result of contaminated samples or error during the analysis. Further, the peak in *Hg* at around 500 CE is only represented by one sample. To say anything with certainty about the sudden increase/decrease, parallel analysis should be carried out. Nonetheless, the literature refers to this specific increase in *Hg* in previous studies, hence it is included in the discussion below. Summer temperatures dropped in the Northern Hemisphere around 500 CE and tree ring constructions indicate an exceptionally cold period in the Northern Hemisphere (Sigl et al. 2015). Climate anomalies from the period 536-550 CE observed what is called "the mystery cloud" in 536 CE, which is argued to be a result of an unknown tropical volcanic eruptions in the same period (Sigl et al. 2015). Volcanic activity is a known natural source to release of *Hg* in the atmosphere (Smol 2008). Ice cores from Greenland indicates another volcanic episode in 539 CE, which led to increased aerosol loading (Sigl et al. 2015). Post-volcanic cooling based on tree-ring records and temperature variability have been able to demonstrate that large volcanic eruptions were important drivers for the temperature variability in the Northern Hemisphere (Sigl et al. 2015).. However, *total chlorophyll a* (Figure 10) indicates a period with less lake productivity around 500 CE. Pigments are in general sensitive to changes in temperature, and may be caused by the cold period in the Northern Hemisphere at the same time. In the period between 100-1300 CE there is an increase in sulfur levels. This period is characterized by high levels of volcanism, and previous studies have shown that such volcanic events have led to warmer winters (Bradley et al. 2003).

Lead (*Pb)* concentration starts to increase around 1200 CE and is generally increasing until recent times (Figure 16). This steady increase falls into the history of metal production in Europe (Bränvall et al. 2001). Historical sources have shown *Pb* to be among the first metals that humans started to exploit (Nriagu 1983: Bränvall et al. 2001). The fall of the Roman empire led to less metal production, followed by the Middle Ages in Europe, where *Pb* production started to increase again. However, the production never stopped completely, which could explain why the *Pb* concentrations did not return to background levels (Bränvall et al. 2001). These changes in *Pb* concentrations reflects, to a certain degree, the history of metal production in Europe (Bränvall et al. 2001). Despite the decline in *Pb* concentrations in recent times, *Pb* still occurs in relatively high concentrations, with a mean value at 2,307 g/kg (Table 4). The results show a relatively large decline and the present concentration in the sediments from Øvre Heimdalsvatn, has dropped below the levels from the Middle Ages in Europe. The declining concentrations of *Pb* is a result of more regulation and control "*And provides a positive example of how pollution regulations can lead to improvements in the environment*" (Bränvall et al. 2001, p. 433). Especially the regulation on leaded gasoline, seems to have had a positive effect on atmospheric deposition of *Pb* (Renberg et al. 2001). Previous studies carried out on trace metals in Norwegian lake sediments found a negative effect of catchment to lake area ratio in

Pb-concentrations. Indicating that *Pb* easily adsorb to humic substances in the soil, leaving direct deposition to be one of the main pathways for *Pb* to enter lakes (Skjelkvåle et al. 2006). The same is seen for several other trace metals, such as *Hg, Cu* and *As*. A large-scale lake study conducted in Nordic countries in 1995, investigated metal concentrations and sources in almost 3000 lakes. The results indicated that bedrock composition is the major source of release for *Cu, Ni, As, Cr* and *V*, whereas *Pb, Cd* and *Zn* were mainly influenced by long-range atmospheric deposition (Skjelkvåle et al. 2006).

Sulfur (*S)* shows an increase from ca 950 CE (Figure 14). Increased *S* in sediment can be a result of several factors, but in general *S* is a natural part of organic material, hence organic material is one explanation for the concentration of *S* in sediments (Wetzel 2001). *S* is also found in minerals. However, seen from the bedrock composition in Øvre Heimdalsvatn, it is less likely that the geomorphology is the major source of *S* to the sediment. Even so *S* does follow the same trends as the trace metals described above. Consequently, long-range transport of atmospheric deposition seems to be the major source of *S* to the lake sediment in Øvre Heimdalsvatn. Other possible explanations beside atmospheric deposition is bonding of iron-sulfide in sediments under anoxic conditions (Smol 2008). Compared to the pigment analysis, there is a negative correlation between *S* and *total chlorophyll a*. This might imply that *S* deposition in Øvre Heimdalsvatn is not a result of iron-sulfide. With an increase in pigment assemblage the oxygen level at the lake bottom is likely to decrease, and as the lake bottom is moving toward anoxic conditions more *S* would probably be released. This strengthens the argument that *S* in Øvre Heimdalsvatn is influenced by atmospheric deposition.

Cadmium (*Cd)* (Figure 14) is a metal rarely found in crustal rocks in Scandinavian waters, therefore the geochemical contribution of *Cd* is likely of minor importance (Fjeld et al. 1994). Seen from Table 4, *Cd* is not recognized as a natural constituent of the bedrock composition. Both *Cd* and *Zn* follow the same pattern as the other trace metals and *S*. Therefore, it is likely that both *Cd* and *Zn* are largely influenced by long-range transport of atmospheric deposition (Skjelkvåle 2001).

Distribution of *As*-concentrations (Figure 14) in the sediment cores show similar patterns as the constituents mentioned above, with an increase since 950 CE. Further, *As* increases in recent times and shows a trend similar to *Hg* and *S*.

The results indicate a similar trend between *Hg, Pb, Cd, Zn, As* and *S* from ca 950 CE and the PCA indicates a positive correlation between these constituents. It is likely that this group of trace metals are influenced by many of the same factors. In addition, none of these constituents are contained within the natural bedrock, which leaves long-range transport through atmospheric deposition as the most probable source. The result does however indicate an early incidence of these trace metals.

Vanadium (V), Nickel (Ni), Chromium (Cr), Cobber (Cu), Aluminum (Al), Magnesium (Mg)

Vanadium (*V*) is a heavy metal that characterized to be influenced by atmospheric deposition, as a consequence of oil combustion and metal manufacturing industry (Rühling et al. 1992). *V* concentrations usually seem to increase in areas close to industry and mining activities. The local industry in Årdal, which is bordering the Jotunheimen National Park, has previously shown to emit *V* to the northern coastlines and mountains in Norway (Rühling et al. 1992). This could be an explanation of the recent increase in *V*, but the precipitation pattern for the region does not favor Øvre Heimdalsvatn as a typical site for fallout (Heim, M. personal communication 2017). Soil surveys of *V* concentration conducted in several parts of Norway concluded that *V* was heavily influenced by two processes; long-range transport and mobilization along with *Fe* (Skjelkvåle et al. 2006). The PCA indicate a negative correlation between *Fe* and *V*, which makes this less likely to be the cause. Furthermore, the PCA indicate a negative between *V* and *Hg, Cd, Zn, Pb, As* and *S*. as latter constituents are explained by atmospheric deposition, there must be other plausible explanations for the occurrence of *V*.

Nickel (*Ni)* shows a steady concentration throughout the core. Previous studies of sediments in Norwegian lakes show no sign of elevated concentrations of *Ni*, which are linked to atmospheric deposition (Fjeld et al. 1994). Emission of *Ni* is mainly associated with industry, where larger particles are deposited close to the smelters (Rognerud & Fjeld 1993; Rognerud et al. 1993: Fjeld et al. 1994). The occurrence of *Ni* in the sediments from Øvre Heimdalsvatn is likely a result of weathering processes from the catchment area.

Copper (*Cu)* is not strongly associated with long-range transport of atmospheric deposition, except some regions in Norway close to Russian smelters on the Kola Peninsula and smelters in the southern part of Norway (Rognerud & Fjeld 2001). The results for *Cu* (Figure 17) does not provide the same trend, as the other constituents assumed to be a result of geochemical influence. The concentration of *Cu* shows a general increase from CE 350 to 1000, from which point a steady decrease until recent times. It is likely to think that *Cu* is more related to local anthropogenic pollution from industry in the nearby area, as local point sources is of great importance of *Cu* emission (Rühling et al. 1992). However, as the concentration is decreasing from 1000 CE, this argument is weak. The PCA however indicates a positive correlation with *Cs, K*, as *Cu* orients in the same direction.

The occurrence of *V, Ni, Cr, Cu* and *Al* in sediments are likely to be a direct result of the geomorphology in the catchment area. Especially as a large part of the bedrock in the catchment area contains gabbro (Table 4), which is comprised of constituents such as *V, Ni, Cr* and *Cu*. The occurrence of *Al* is likely a result of weathering processes of meta-arkose (sandstone), and the minerals chlorite and sericite, which all comprise of *Al*.

The distribution of *V, Ni, Cr, Cu, Al* and *Mg* indicate similar pattern throughout the core, with some minor variations. There seems to be a little correlation between these constituents and *total chlorophyll a* and analysis of dry weight (Figure 10). It is possible that temperature and climate fluctuations have not influenced the concentration of these constituents to any large extent, except for the sudden drop at 1850 CE. This coincides with the estimated temperature data, and the decline in most of the analyzed parameters indicate a period characterized by cold temperatures which could have influenced transport of material from the catchment as well as lake production. Moreover the analysis of dry weight and C:N does not follow the same pattern. If the lake and catchment at this point was characterized by longer period of ice cover and frozen ground, one should expect allochtonous material to decline as well.

Phosphorous (P), Iron (Fe), Manganese (Mn)

P in well-oxygenated lakes is often related to co-precipitation with *Fe* and *Mn* (Mackereth 1966; Kloster & Hongve 1978). As *Mn* occurs in low concentrations and vice versa for *Fe*, it seems like co-precipitation with *Fe* is more important for precipitation of *P* in Øvre Heimdalsvatn (Kloster & Hongve 1978). Figures 15 and 16 does not show any specific dissimilarities between *P, Fe* and *Mn.* Although, the PCA indicate little positive correlation (fig 18). Due to the low primary production in Øvre Heimdalsvatn, it is less likely that *P* is a result of sedimentation with autochthonous algae material (Kloster & Hongve 1978). Other explanations for the *P* concentrations is related to the geomorphology in the area. Seen from Table 4, area 3 is likely to contain amounts of *P*, and may be released by weathering in the catchment area. Additionally, Øvre Heimdalsvatn has a large catchment area compared to lake size, hence concentration of transported material from the catchment area is relatively high.

Fe appears as the most abundant of all the analyzed elements (Table 4). The high concentration of *Fe* in recent times may be due to *Fe*-rich groundwater in the area. A ground water sample taken from a boring showed high levels of *Fe*, and is likely to be the main source of *Fe* found in these sediments (Kloster & Hongve 1978). Furthermore, *Fe* is a dominant part of the geomorphology in the catchment area, and is found in nearly all parts the bedrock. In general, the *Fe* concentrations remains quite constant throughout the core. The same patterns are observed for *Mn* (Figure 17). Except that *Mn* occurs in low concentrations throughout the core, and probably reflects the concentration of *Mn* in the bedrock composition (Kloster & Hongve 1978). It is likely that *Fe* and *Mn* are influenced by many of the same processes.

Mn found in sediments is probably influenced by TOC (Njåstad et al. 1994, Nygård 2000; Skjelkvåle et al. 2006). During periods of anoxic conditions, *Mn* goes into solution. Anoxic conditions are the result of increased O_2 consumption during organic matter (OM) mineralization in the lake, which influence the release of *Fe* and *Mn* (Naeher et al. 2013). After the drop in *Fe* and *Mn* concentrations after 1850 CE, there has been a steady increase which could indicate a period with more OM being transported into the lake. The results of TOC and TN can give an indication of periods when the lake was dominated by anoxic conditions (Avramidis et al. 2015). However, as the C:N ratio is very low, it is challenging to say with certainty that this is the main contributing factor for the increase observed in recent times.

Calcium (Ca), Sodium (Na)

The concentration of *Ca* and *Na* are "*probably determined solely by the composition of the sedimented mineral particles and their degree of dilution by mixing with organic matter*" (Kloster & Hongve 1978, p. 126). *Ca* and *Na* appear as natural constituents in the catchment area (Table 4) and they indicate a positive correlation in the PCA. Hence, it is likely that *Ca* and *Na* are both influenced by many of the same processes. The minor differences between *Ca* and *Na* may be explained by what parts of the catchment area contain highest concentrations of *Ca* and *Na* and where "*erosion has been most intensive*" (Kloster & Hongve 1978, p.126). These clastic minerals provide information on soil erosion intensity (Wetzel 2001) and are largely influenced by hydrological processes within the catchment area, as well as being highly soluble in water. Temperature during the Late Holocene might have been an important controlling factor, as weathering processes may increase with increased temperature. This, the minor differences seen in *Ca* and *Na* does not indicate a similar trend to the estimated temperature reconstruction. A small amount of *Ca* may be related to precipitation, but is not considered to be a large contributor (Økland & Økland 2006).

At around 1850 CE *Na* shows a different trend from the rest of the results, as the concentration increased. *Na* is a marine component and can be transported by wind, which may influence the concentration of *Na* in lakes. Despite this, Øvre Heimdalsvatn is far from the coast line and is probably not influenced by sea salt episodes. Another possible explanation could be that *Na* is considered a water level indicator (Ma et al. 2016). As lake levels drops, salinity in sediments may increase. If this period was dominated by cooling conditions, with longer ice cover, it may have influenced the lake level. However, these explanations are not to be confirmed and the increase in *Na* may also be a result of an error in the analysis.

Cesium (Cs), Potassium (K)

Cs and *K* indicate a positive correlation in the PCA (fig. 18). The show a similar pattern with varying trends throughout the core (fig. 16), but does not follow a pattern similar to the constituents described above. This implies that *Cs* and *K* may be influenced by different factors.

Concentration of both *Cs* and *K* indicates periods with increased deposition, and vice versa. Especially three maxima are worth mentioning; CE 350, 650-950, and 950-1400. Compared to analysis of dry weight, the latter time interval coincides with the variation in dry weight. These peaks in *Cs* and *K* could be a result of increased allochtonous material from the catchment. *Cs* and *K* are both strongly influenced by clay particles, and the clay found in the sediment cores from Øvre Heimdalsvatn is a result of the last deglaciation (Kloster & Hongve 1978). During this time, which most likely took place in Boreal times, clay was deposited all over the catchment area. Moreover, clay particles easily bond water, when the catchment area was exposed to increased meltwater and precipitation, the transport of silt and clay to the lake must have been quite substantial (Kloster & Hongve 1978). The estimated temperature reconstruction (Figure 1) indicates a time interval with increased temperatures in the Northern Hemisphere during the late Holocene, between 900-1200 CE (Hughes & Diaz 1994). This seems to coincide with the variations in *Cs* and *K*. The pigment analysis show an increase in concentrations at the same time. Consequently, as pigments are temperature sensitive it strengthens the argument that both *Cs* and *K* were influenced by increased temperature that led to more leaching of *Cs* and *K* to the lake. *Cs* and *K* are also found to be a natural part of the bedrock composition, and may be a result of weathering of rocks and minerals. During warmer periods, it is likely that *Cs* and *K* are influence by weathering processes in the catchment area. A previous study conducted on tree growth in Gudbransdalen found trends of cooling conditions from the beginning of the 1700s to the mid-1800s (Matthews 1976, 1977; Nesje et al. 1991). Both *Cs* and *K* concentrations indicate a slight decrease in this time interval, which strengthens the argument that *Cs* and *K* in Øvre Heimdalsvatn is largely influenced by the erosion of clay particles and water content in the sediments. As a consequence of the Chernobyl accident 1986 that led to large amount of *Cs* fallout to Øvre Heimdalsvatn and its catchment, the concentration of *Cs* was expected to increase in recent times. The figure indicates an increase in *Cs* concentration, but due to low sedimentation rate in the lake, time resolution in the top layer of the sediments are crucial. Consequently, as this part of the sediment record is only represented by two sub samples, it is difficult to interpret these data with certainty.

There are several topics that could have received more attention and would be interesting to look into, but was beyond the scope of this thesis. However, here are a few things that could have been improved:

- To better examine the correlation between pigments, chemical constituents and OM, the latter should have been included in the PCA.
- To obtain a more comprehensive picture of the correlation between the parameters, correlation analysis between parameters that indicated positive correlation could have been performed.
- To strengthen the results in this thesis, similar studies from Øvre Heimdalsvatn should be conducted, and compared.
- In paleo science, single environmental proxies are often utilized, however to obtain a more comprehensive picture of past conditions, several proxies should be included.

6 Conclusion

The findings in this thesis illustrate that sediments from remote lake ecosystem are suitable for studying natural and anthropogenic changes from the past, which is well reflected in the results.

The distribution of inorganic constituents, pigments, and OM from the two sediment cores retrieved in Øvre Heimdalsvatn; clearly indicate that the lake has been influenced by a variety of different factors during the late Holocene. Several of the trace metals (*Hg, Pb, Cd, Zn, As*) and *S* showed a substantial increase form 950 CE until recent times. As these constituents are not considered a natural part of the bedrock composition in the catchment area, long-range transport of atmospheric deposition is likely a possible explanation. This might illustrate that anthropogenic activity started to influence the global transport of certain heavy metals as early as 950 CE.

The remaining constituents differentiate from those mentioned above, which indicate other sources of release. As many of these comprise the bedrock composition in the catchment area, geochemical processes are probably the main source of release.

Øvre Heimdalsvatn seems to be mostly dominated by allochtonous inputs, as the main source of primary produced material to the lake. Nevertheless, seen from this study the concentration of pigments clearly indicate periods with increased production within the lake, which coincides with the estimated temperature reconstruction in the Northern Hemisphere, during the last millennium. This reflect the impact temperature and climate have on the algae assemblage in Øvre Heimdalsvatn. Contrary to previous studies, autochthonous inputs in Øvre Heimdalsvatn may be a larger contributor than expected.

Long-term studies of remote lake sediments serve as useful tools to obtain a more comprehensive view of previous lake conditions. Furthermore, to obtain valuable information of reference conditions in lakes, long-term studies from remote lakes provide more accurate information, as these are less influenced by anthropogenic activities.

Øvre Heimdalsvatn serves as an important lake for future studies, especially due to the amount of research carried out during the last 50 years. These long-term studies are crucial and important tools for future managers in terms of understanding lake responsiveness to changes in climatic conditions. as remote lakes are seen to be sensitive to these changes, lakes of similar character may respond similarly to such changes and serve as important research site for future managers. In order to understand future lake responses, understanding the past can steer us in the right direction.

It is important to keep in mind the complexity of discussing changes in climate both from the past and in the future. However, paleolimnology is a method that must be considered and used to obtain valuable information about past conditions.

Finally, the findings in this thesis clearly illustrates that this study is a preliminary approach and opens many paths for future research.

7 References

AMAP. (2011). AMAP Assessment 2011: Mercury in the Arctic. Arctic Monitoring and Asessment Programme (AMAP). Oslo, Norway. xiv + 193 pp.

Avramidis, P., Nikolaou, K. & Bekiari, V. (2015). Total Organic Carbon and Total Nitrogen in Sediments and Soils: A Comparison of the Wet Oxidation – Titration Method with the Combustion-infrared Method. *Agriculture and Agricultural Science Procedia*, 4: 425-430.

Battarbee, R. W., Grytnes, J.-A., Thompson, R., Appleby, P. G., Catalan, J., Korhola, A., Birks, H. J. B., Heegaard, E. & Lami, A. (2002). Comparing palaeolimnological and instrumental evidence of climate change for remote mountain lakes over the last 200 years. *Journal of Paleolimnology*, 28 (1): 161-179.

Benito, G., Baker, V. R. & Gregory, K. J. (1998). *Paleohydrology and Environmental Change*: John Wiley & Sons Ltd.

Bindler, R., Renberg, I., Appleby, P. G., Anderson, J. N. & Rose, N. L. (2001). Mercury Accumulation Rates and Spatial Patterns in Lake Sediments from West Greenland: A Coast to Ice Margin Transect. 35 (9): 1736-1741.

Bradley, R. S., Hughes, M. K. & Diaz, H. F. (2003). Climate in Medieval Time. *Science*, 302 (5644): 404-405.

Brittain, J. E. & Bjørnstad, H. E. (2010). A long-term study of catchment inputd of ^{137}Cs to a subalpine lake in the form of allochtonous terrstrial plant material. *Hydrobiologia*, 642 (1): 101-106.

Brittain, J. E. & Borgstrøm, R. (2010). The Norwegian reference lake ecosystem, Øvre Heimdalsvatn. *Hydrobiologia*, 642 (1): 5-12.

Brittain, J. E. & Borgstrøm, R. (2015). *Naturlige variasjoner versus menneskeskapte miljøendringer - hva viser lange tidsserier fra referansevannet Øvre Heimdalsvatn?* Fagtreff Norsk vannforening.

Bränvall, M.-L., Bindler, R., Emteryd, O. & Renberg, I. (2001). Four thousand years of atmospheric lead pollution in northern Europe: a summary from Swedish lake sediments. *Journal of Paleolimnology*, 25 (4): 421-435.

Buchaca, T. & Catalan, J. (2007). Factors influencing the variability of pigments in the surface sediments of mountain lakes. *Freshwater Biology*, 52 (7): 1365-1379.

Cohen, A. S. (2003). *Paleolimnology: the history and evolution of lake systems*: Oxford University Press, USA.

Consortium, P. k. (2013). Continental-scale temperature variability during the past two millennia. *Nature Geosci*, 6 (5): 339-346.

Cronin, T. M. (2009). *Paleoclimates: understanding climate change past and present*: Columbia University Press.

Cuddington, K. & Leavitt, P. R. (1999). An individual-based model of pigment flux in lakes: implications for organic biogeochemistry and paleoecology. *Canadian Journal of Fisheries and Aquatic Sciences*, 56 (10): 1964-1977.

Dahlgaard, H. (1994). *Nordic Radioecology: The Transfer of Radionuclides through Nordic Ecosystems To Main*. Amsterdam, The Netherlands: Elsevier Science.

Eronen, M. & Zetterberg, P. (1996). Climatic Changes in Northern Europe Since Late Glacial Times, with special reference to dendroclimatological studies in northern Finnish Lapland. *Geophysica* 32 ((1-2)): 35-60.

Faarlund, T. & Aas, B. (1991). Sør-Norges fjellskoger gjennom etteristiden. *Viking*, 54: 113-137.

Fjeld, E., Rognerud, S. & Steinnes, E. (1994). Influence of Environmental Factors on Heavy Metal Concentration in Lake Sediments in Southern Norway Indicated by Path Analysis. *Canadian Journal of Fisheries and Aquatic Sciences*, 51 (8): 1708-1720.

Grøterud, O. & Kloster, A. E. (1978). Hypsography, Meteorology and Hydrology of the Øvre Heimdalen Catchment. *Holarctic Ecology*, 1 (2/3): 11-116.

Hughes, M. K. & Diaz, H. F. (1994). Was there a 'medieval warm period', and if so, where and when? *Climatic Change*, 26 (2): 109-142.

Kainz, M. & Lucotte, M. (2006). Mercury Concentrations in Lake Sediments – Revisiting the Predictive Power of Catchment Morphometry and Organic Matter Composition. *Water, Air, and Soil Pollution*, 170 (1-4): 173-189.

Kloster, A. E. & Hongve, D. (1978). The Post-Glacial Sediments of Øvre Heimdalsvatn. *Holarctic Ecology*, 1 (2/3): 124-127.

Kvam, A. (2015b). *Langtidsutvikling og drivkrefter til variasjon i vannkvalitet i en eutrof innsjø - Innsjøsedimenter som arkiv for autotrof produksjon og alloktone tilførsler av organisk materiale, med eksempel fra Helgetjern.* : Norwegian University of Life Science.

Kvambekk, Å., S & Melvold, K. (2010). Long-term trends in water temperature and ice cover in the subalpine lake, Øvre Heimdalsvatn, and nearby lakes and rivers. *Hydrobiologia*.

Larsson, P., Brittain, J. E., Lien, L., Lillehammer, A. & Tangen, K. (1978). The Lake Ecosystems of Øvre Heimdalsvatn. *Holarctic Ecology*, 1: 304-320.

Leavitt, P. R. (1993). A review of factors that regulate carotenoid and chlorophyll deposition and fossil pigment abundance. *Journal of Paleolimnology*, 9: 109-127.

Leavitt, P. R., Vinebrooke, R. D., Donald, D. B., Smol, J. P. & Schindler, D. W. (1997). Past ultraviolet radiation environments in lakes derived from fossil pigments. *Nature*, 388 (6641): 457-459.

Leavitt, P. R. & Hodgson, D. A. (2001). Sedimentary Pigments. In Smol, J. P., Birks, H. J. B., Last, W. M., Bradley, R. S. & Alverson, K. (eds) *Tracking Environmental Change Using Lake Sediments: Terrestrial, Algal, and Siliceous Indicators*, pp. 295-325. Dordrecht: Springer Netherlands.

Ma, L., Wu, J., Abuduwaili, J. & Liu, W. (2016). Geochemical Responses to Anthropogenic and Natural Influences in Ebinur Lake Sediments of Arid Northwest China. *PLoS ONE*, 11 (5): e0155819.

Mann, M. E., Bradley, R. S. & Hughes, M. K. (1999). Northern hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophysical Research Letters*, 26 (6): 759-762.

Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R. S., Hughes, M. K., Shindell, D., Ammann, C., Faluvegi, G. & Ni, F. (2009). Global Signatures and Dynamical Origins of the Little Ice Age and Medieval Climate Anomaly. *Science*, 326 (5957): 1256-1260.

Martínez-Cortizas, A., Pontevedra-Pombal, X., García-Rodeja, E., Nóvoa-Muñoz, J. C. & Shotyk, W. (1999). Mercury in a Spanish Peat Bog: Archive of Climate Change and Atmospheric Metal Deposition. *Science*, 284 (5416): 939-942.

McGill, W. & Figueiredo, C. (1993). Total nitrogen. *Soil sampling and methods of analysis. Lewis Publ., Boca Raton, FL*: 201-211.

Naeher, S., Gilli, A., North, R. P., Hamann, Y. & Schubert, C. J. (2013). Tracing bottom water oxygenation with sedimentary Mn/Fe ratios in Lake Zurich, Switzerland. *Chemical Geology*, 352: 125-133.

Nesje, A., Kvamme, M., Rye, N. & Løvlie, R. (1991). Holocene Glacial and Climate History Of The Jostedalsbreen Region, Western Norway; Evidence From Lake Sediments. *Quaternary Science Reviews*, 10: 87-114.

Nesje, A., Olaf Dahl, S. & Lie, Ø. (2004). Holocene millennial-scale summer temperature variability inferred from sediment parameters in a non-glacial mountain lake: Danntjørn, Jotunheimen, central southern Norway. *Quaternary Science Reviews*, 23 (20–22): 2183-2205.

Perry, E., Norton, S. A., Kamman, N. C., Lorey, P. M. & Driscoll, C. T. (2005). Deconstruction of Historic Mercury Accumulation in Lake Sediments, Northeastern United States. *Ecotoxicology*, 14 (1): 85-99.

Renberg, I., Bindler, R. & Brännvall, M.-L. (2001). Using the historical atmospheric lead-deposition record as a chronological marker in sediment deposits in Europe. *The Holocene*, 11 (5): 511-516.

Reuss, N. (2005). *Sediment pigments as biomarkers of environmental change*. Roskilde, Denmark, National Environmental Research Institute.

Rognerud, S. & Fjeld, E. (2001). Trace Element Contamination of Norwegian Lake Sediments. *AMBIO: A Journal of the Human Environment*, 30 (1): 11-19.

Rohrlack, T. & Haaland, S. (2017). Paleolimnologiske undersøkelser av Hersjøen (002-4158-L). *MINA fagrapport 39* (21).

Rühling, Å., Brumelis, G., Goltsova, N., Kubin, E., Liiv, S., Magnússon, S., Mäkinen, A., Pilegaard, K., Rasmussen, L. & Sander, E. (1992). *Atmospheric heavy metal deposition in northern Europe 1990*: Nordic Council of Ministers.

Schindler, D. W., Bayley, S. E., Parker, B. R., Beaty, K. G., Cruikshank, D. R., Fee, E. J., Schindler, E. U. & Stainton, M. P. (1996). The effects of climatic warming on the properties of boreal lakes and streams at the Experimental Lakes Area, northwestern Ontario. *Limnology and Oceanography*, 41 (5): 1004-1017.

Selin, N. E. (2009). Global Biogeochemical Cycling of Mercury: A Review. *Annual Review of Environment and Resources*, 34 (1): 43-63.

Sigl, M., Winstrup, M., McConnell, J. R., Welten, K. C., Plunkett, G., Ludlow, F., Buntgen, U., Caffee, M., Chellman, N., Dahl-Jensen, D., et al. (2015). Timing and climate forcing of volcanic eruptions for the past 2,500 years. *Nature*, 523 (7562): 543-549.

Skjelkvåle, B., Steinnes, E., Rognerud, S., Fjeld, E., Berg, T. & Røyset, O. (2006). Trace metals in Norwegian surface waters, soils, and lake sediments - relation to atmospheric deposition.: Norwegian institute for Water Research.

Skjelkvåle, B. L., Andersen, T., Fjeld, E., Mannio, J., Wilander, A., Johansson, K., Jensen, J.P., Moiseenko, T. (2001). Heavy Metal Surveys in Nordic Lakes; Concentrations, Geographic Patterns and Relation to Critical Limits. 10 pp.

Skjeseth, S. & Kloster, A. E. (1978). The Geology of the Øvre Heimdalen Valley. *Holarctic Ecology*, 1 (2/3): 89-92.

Smol, J. P. (2008). *Pollution of lakes and river: a paleoenvironmental perspective*. 2nd ed. Oxford: Blackwell Publ.

Sørli, M. (2015). *Utvikling av vannkvalitet i en innsjø med ulike påvirkningsfaktorer studert ved sedimentanalyser - med eksempel fra Jarenvatnet med hovedfokus på biologiske analyser*: Norges miljø- og biovitenskapelige universitet, Institutt for miljøvitenskap. 72 pp.

UNEP. (2013). *Global Mercury Assessment 2013: Sources, Emission, Releases and Environmental Transport*. UNEP Chemicals Branch, Geneva, Switzerland.

vanLoon, G. W. & Duffy, S. J. (2011). *Environmental chemistry, a global perspective*. 3 ed. United States, New York: Oxford University press Inc.

Vann-nett. (n.d.). *Faktaark Øvre Heimdalsvatn* [Applikasjon]. Vann-nett. (Accessed 10.05.2017). Available at: http://vann-nett.no/portal/Water?WaterbodyID=002-272-L

Velle, G., Larsen, J., Eide, W., Peglar, S. M., John, H. & Birks, B. (2005). Holocene environmental history and climate of Råtåsjøen, a low-alpine lake in south-central Norway. *J Paleolimnol*, 33: 129-153.

Velle, G., Bjune, A. E., Larsen, J. & Birks, H. J. B. (2010). Holocene climate and environmental history of Brurskardstjørni, a lake in the catchment of Øvre Heimdalsvatn, south-central Norway. *Hydrobiologia*, 642 (1): 13-34.

Vik, R. (1978). The Lake Øvre Heimdalsvatn: A Subalpine Freshwater Ecosystem: Introduction. *Holarctic Ecology*, 1 (2/3): 84-88.

Wang, J., Zhu, L., Wang, Y., Gao, S. & Daut, G. (2012). A comparison of different methods for determining the organic and inorganic carbon content of lake sediment from two lakes on the Tibetan Plateau. *Quaternary International*, 250: 49-54.

Wania, F. & Mackay, D. (1997). Global distillation. *Our Planet*, 8.6.

Westerås, A. C. (2016). *Rekonstruering av cyanobakterien Planktothrix sine forekomster i Hålandsvatnet fra 1980 fram til 2014 under påvirkning av den vertsspesifikke parasitten Chytridiomycota*: Norges Miljø- og Biovitenskapelige Universitet, Institutt for miljøvitenskap. 78 pp.

Wetzel, R. G. (2001). *Limnology, Lake and River Ecosystems*. 3 ed. San Diego: Elsevier.

Zuur, A. F. (2014). *Chronicling the rise and fall of the invasive species Elodea canadensis in a eutrophic lake using paleolimnological methods*: Norwegian University of Life Science.

Økland, J. & Økland, K. A. (2006). *Vann og Vassdrag 3. Kjemi, fysikk og miljø*. Norway: Forlaget Vett & Viten AS.

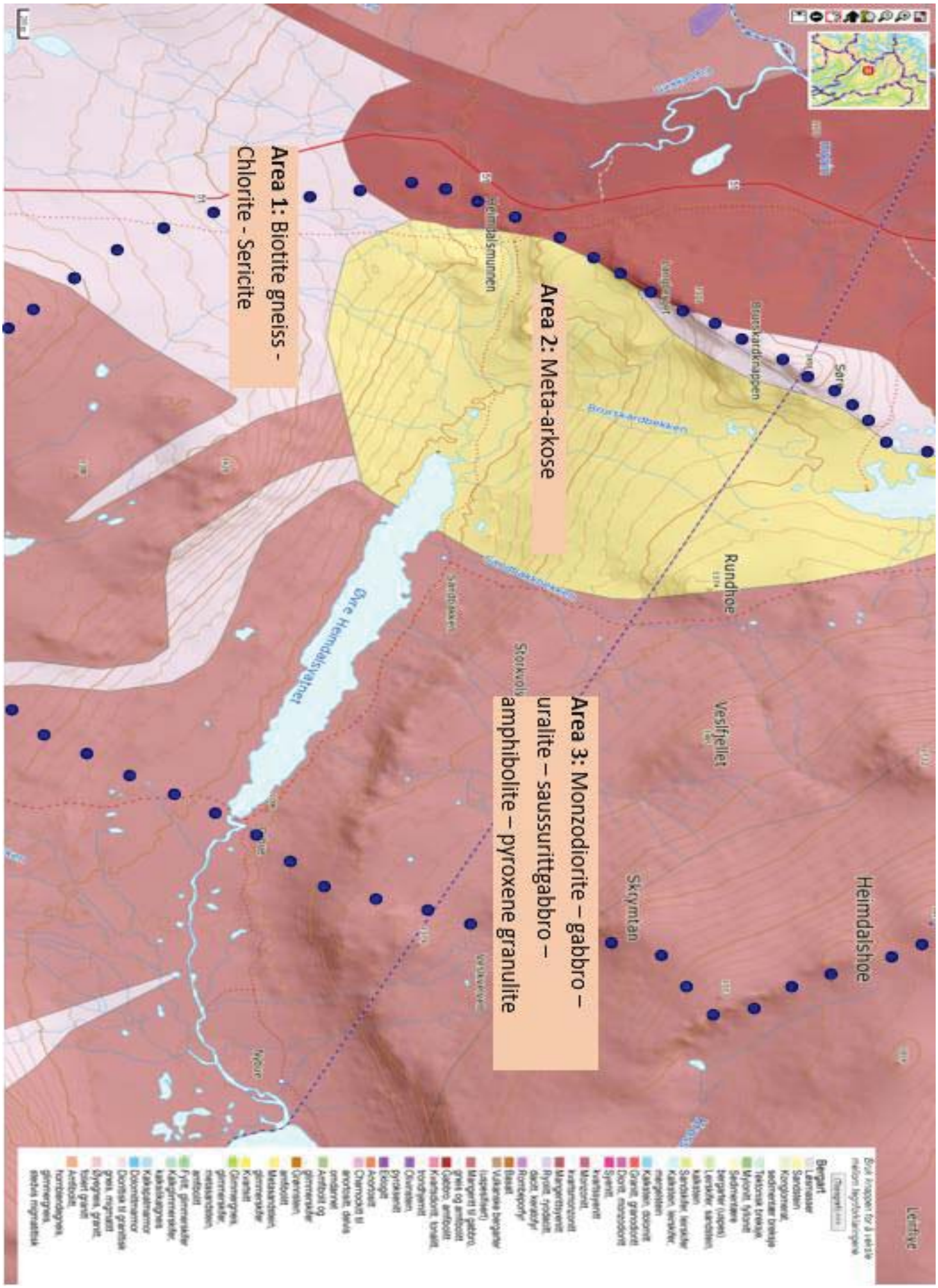
Østhagen, H. & Egelie, K. (1978). The Vegetation of the Øvre Heimdalen Valley. *Holarctic Ecology*, 1 (2/3): 103-106.

7.1 Personal Communication

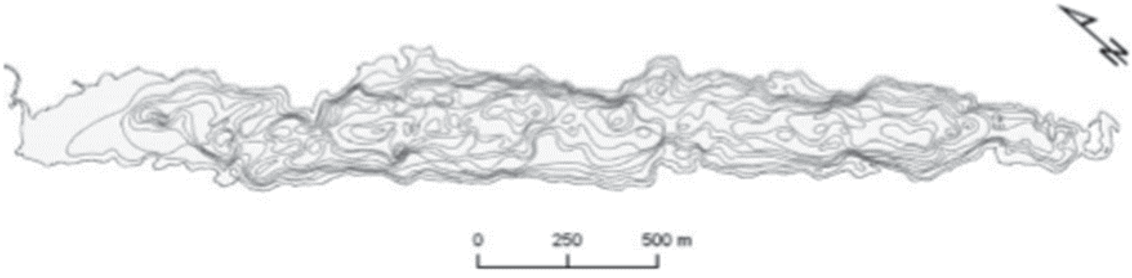
Heim, M.: Associate professor in geology. Norwegian University of Life Science.
Personal communitation April 2017.

8 Appendices

Appendix A: Bedrock Geology in Øvre Heimdalsvatn



Appendix B: Depth chart used during field work, with 1 m contour intervals.
Source: (Brittain & Borgstrøm 2010).



Appendix C: Primary data for dry weight analysis (wet weight and dry weight).
Core number 1.

Location	Sample nr.	Wet weight (gram)	Dry weight (gram)
Heimdalsvatn	1-1.	5,37	0,17
Heimdalsvatn	1-2.	3,83	0,17
Heimdalsvatn	1-3.	8,75	0,34
Heimdalsvatn	1-4.	8,08	0,42
Heimdalsvatn	1-5.	10,81	0,76
Heimdalsvatn	1-6.	8,81	0,73
Heimdalsvatn	1-7.	8,81	0,81
Heimdalsvatn	1-8.	12,58	1,2
Heimdalsvatn	1-9.	11,35	1,07
Heimdalsvatn	1-10.	11,02	1,14
Heimdalsvatn	1-11.	3,12	0,22
Heimdalsvatn	1-12.	6,25	0,67
Heimdalsvatn	1-13.	6,7	0,66
Heimdalsvatn	1-14.	6,79	0,73
Heimdalsvatn	1-15.	3,93	0,32
Heimdalsvatn	1-16.	8,54	0,95
Heimdalsvatn	1-17.	6,47	0,67
Heimdalsvatn	1-18.	4,01	0,31
Heimdalsvatn	1-19.	12,36	1,63
Heimdalsvatn	1-20.	11,16	1,46
Heimdalsvatn	1-21.	15,28	1,86
Heimdalsvatn	1-22.	21,88	2,95
Heimdalsvatn	1-23.	21,98	3,3
Heimdalsvatn	1-24.	24,09	3,44

Heimdalsvatn	1-25.	18,85	2,54
Heimdalsvatn	1-26.	23,85	3,47
Heimdalsvatn	1-27.	25,59	5,45
Heimdalsvatn	1-28.	27,88	7,27
Heimdalsvatn	1-29.	26,8	7,36
Heimdalsvatn	1-30.	15,87	3,95
Heimdalsvatn	1-31.	24,56	5,9
Heimdalsvatn	1-32.	28,48	6,23
Heimdalsvatn	1-33.	23,96	4,55
Heimdalsvatn	1-34.	23,76	4,24
Heimdalsvatn	1-35.	35,11	6,3
Heimdalsvatn	1-36.	26,77	5,61
Heimdalsvatn	1-37.	28,26	6,57
Heimdalsvatn	1-38.	24,32	6,05
Heimdalsvatn	1-39.	24,6	6,31
Heimdalsvatn	1-40.	29,6	7,71
Heimdalsvatn	1-41.	28,65	7,69
Heimdalsvatn	1-42.	26,63	7,14
Heimdalsvatn	1-43.	28,24	7,27
Heimdalsvatn	1-44.	24,06	5,87
Heimdalsvatn	1-45.	29,02	6,6
Heimdalsvatn	1-46.	27,74	6,45
Heimdalsvatn	1-47.	30,37	7,32
Heimdalsvatn	1-48.	29,5	8,41
Heimdalsvatn	1-49.	28,28	8,45
Heimdalsvatn	1-50.	31,39	7,77

Appendix D: Elements detected by ICP-MS and ICP-OES. Limits of detection (LOD) and Limit of quantification (LOQ) are included.

	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS
LOD in (w/w)	3,8032E-06	6,4036E-05	7,31552E-05	4,71E-06	2,5875E-05	0,01161504	0	0,00930115	0,014509406	0,00373707
LOQ (w/w)	1,2677E-05	0,00021345	0,000243851	1,57E-05	8,6251E-05	0,0387168	0	0,03100383	0,048364685	0,01245692
	V	Cr	Ni	Cu	Zn	As	Cd	Cs	Hg	Pb
	g/kg	g/kg	g/kg	g/kg	g/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
	0,12	0,062	0,022	0,13	0,089	2,7	0,25	0,61	0,14	28
	0,11	0,06	0,021	0,13	0,076	2,2	0,21	0,46	0,13	28
	0,11	0,062	0,021	0,15	0,077	1,8	0,30	0,49	0,13	36
	0,11	0,067	0,023	0,17	0,099	1,4	0,56	0,52	0,14	45
	0,12	0,069	0,024	0,17	0,11	1,6	0,56	0,57	0,14	46
	0,10	0,059	0,024	0,16	0,096	1,4	0,45	0,52	0,12	38
	0,12	0,072	0,025	0,18	0,11	1,6	0,53	0,61	0,13	46
	0,12	0,074	0,025	0,19	0,11	1,9	0,54	0,64	0,14	46
	0,12	0,073	0,025	0,19	0,11	1,9	0,52	0,69	0,13	43
	0,12	0,077	0,027	0,19	0,11	1,9	0,58	0,68	0,13	43
	0,12	0,075	0,026	0,19	0,11	2	0,55	0,70	0,13	41
	0,12	0,075	0,026	0,20	0,11	1,9	0,49	0,71	0,13	38
	0,12	0,076	0,026	0,20	0,11	2,0	0,49	0,72	0,11	38
	0,12	0,078	0,027	0,20	0,10	2,0	0,46	0,74	0,11	36
	0,13	0,081	0,027	0,20	0,10	2,0	0,43	0,7	0,1	35
	0,13	0,079	0,027	0,20	0,10	2,0	0,45	0,74	0,11	34
	0,13	0,085	0,029	0,21	0,10	2,1	0,40	0,68	0,10	34
	0,13	0,083	0,028	0,21	0,097	2,1	0,40	0,72	0,095	34
	0,14	0,086	0,028	0,21	0,094	2,1	0,41	0,71	0,10	34
	0,14	0,087	0,028	0,21	0,094	2,1	0,42	0,68	0,074	32
	0,14	0,09	0,029	0,22	0,097	2,0	0,40	0,78	0,091	28
	0,14	0,091	0,03	0,22	0,092	1,9	0,24	0,81	0,076	21
	0,14	0,09	0,029	0,22	0,088	1,7	0,23	0,80	0,064	19
	0,14	0,089	0,029	0,22	0,085	1,7	0,22	0,71	0,076	19
	0,14	0,089	0,029	0,23	0,082	1,5	0,20	0,68	0,077	16
	0,13	0,085	0,03	0,23	0,081	1,3	0,15	0,71	0,058	13
	0,13	0,08	0,029	0,21	0,073	1,1	0,11	0,62	<0,05	12
	0,13	0,08	0,029	0,20	0,073	1,1	0,10	0,73	<0,04	12
	0,13	0,08	0,027	0,20	0,072	1,0	0,099	0,75	<0,05	12
	0,13	0,081	0,027	0,21	0,072	1,1	0,11	0,71	<0,05	13
	0,13	0,082	0,027	0,21	0,074	1,1	0,14	0,70	<0,05	14
	0,13	0,074	0,025	0,19	0,071	1,0	0,14	0,61	0,058	14
	0,13	0,077	0,025	0,19	0,074	1,1	0,14	0,60	0,051	14
	0,13	0,079	0,026	0,19	0,075	1,0	0,15	0,63	<0,05	15
	0,13	0,078	0,027	0,18	0,074	0,83	0,13	0,65	<0,05	12
	0,13	0,08	0,027	0,18	0,074	0,85	0,13	0,69	0,12	12
	0,13	0,08	0,027	0,18	0,073	0,91	0,13	0,65	<0,05	11
	0,12	0,078	0,027	0,17	0,07	0,81	0,099	0,65	<0,05	10
	0,12	0,075	0,026	0,17	0,067	0,81	0,11	0,65	0,053	10
	0,13	0,083	0,029	0,19	0,076	0,92	0,12	0,78	<0,05	11
	0,13	0,078	0,028	0,19	0,070	0,92	0,10	0,65	<LOD	11
	0,13	0,077	0,026	0,18	0,068	0,91	0,10	0,61	<LOD	11
	0,12	0,076	0,026	0,19	0,068	0,95	0,11	0,64	<0,05	11
	0,13	0,077	0,025	0,20	0,067	1,0	0,12	0,63	<0,04	11
	0,12	0,076	0,025	0,19	0,068	0,99	0,12	0,61	<0,04	10
	0,12	0,077	0,026	0,19	0,070	0,97	0,11	0,56	<LOD	9,6
	0,12	0,074	0,025	0,19	0,070	0,87	0,10	0,62	<LOD	8,4
	0,11	0,07	0,026	0,17	0,071	0,78	0,097	0,60	<LOD	7,4
	0,13	0,075	0,024	0,18	0,076	0,97	0,14	0,58	<0,05	8,3

	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES
LOD in (w/w)	0,001669	0,00903839	0,00144415	0,01243898	0,0022866	0,00064967	0,00212926	0,01247247	0,02953695
LOQ (w/w)	0,00556333	0,03012797	0,00481383	0,04146325	0,00762201	0,00216555	0,00709752	0,04157489	0,0984565
	Al	Ca	Fe	K	Mg	Mn	Na	P	S
	g/kg	g/kg	g/kg	g/kg	g/kg	g/kg	g/kg	g/kg	g/kg
	22	9,5	63	3,2	6,2	0,6	0,49	2	1,9
	21	9,9	54	2,6	6,5	0,49	0,48	2	1,7
	24	12	46	2,9	7,6	0,42	0,56	2,1	1,7
	27	13	37	3,2	8,6	0,37	0,62	2,2	1,6
	28	13	37	3,3	9,1	0,37	0,65	2,2	1,6
	26	15	33	2,8	8,5	0,34	0,82	1,8	1,3
	29	14	37	3,5	9,4	0,38	0,66	2,3	1,6
	30	14	38	3,7	9,5	0,40	0,65	2,3	1,6
	31	14	38	4,0	9,8	0,41	0,65	2,3	1,6
	30	13	36	4,0	9,4	0,4	0,61	2,3	1,7
	31	14	37	4,2	9,8	0,41	0,63	2,4	1,7
	31	14	35	4,2	9,6	0,4	0,60	2,3	1,6
	31	15	37	4,3	10	0,42	0,64	2,4	1,6
	32	14	37	4,4	10	0,41	0,64	2,4	1,6
	34	16	40	4,5	11	0,45	0,72	2,7	1,7
	33	16	39	4,3	11	0,44	0,68	2,5	1,6
	35	17	41	4,4	12	0,46	0,73	2,6	1,6
	34	16	40	4,1	11	0,45	0,73	2,6	1,6
	34	17	40	3,8	11	0,45	0,74	2,7	1,7
	33	17	39	3,5	11	0,44	0,77	2,7	1,6
	35	17	40	3,9	12	0,46	0,78	2,7	1,6
	36	19	39	4,2	12	0,47	0,80	2,8	1,5
	37	19	40	4,1	13	0,49	0,85	2,9	1,6
	35	18	39	3,7	12	0,46	0,77	2,9	1,7
	35	18	38	3,8	12	0,45	0,81	2,9	1,6
	37	21	40	4,3	13	0,51	0,91	2,9	1,3
	38	25	40	4,3	14	0,54	0,98	2,8	1,2
	38	25	40	4,2	14	0,55	0,93	2,8	1,1
	38	25	40	4,1	13	0,55	0,9	2,8	1,1
	38	24	41	4,1	13	0,54	0,89	2,9	1,2
	38	23	40	4,0	13	0,52	0,89	2,9	1,4
	33	19	37	3,3	11	0,45	0,79	2,7	1,5
	34	20	38	3,5	11	0,47	0,81	2,8	1,5
	34	20	39	3,6	12	0,48	0,88	2,8	1,4
	36	24	41	3,9	13	0,54	0,97	2,8	1,1
	37	24	41	4,0	13	0,54	0,95	2,8	1,1
	35	24	39	3,8	12	0,52	0,87	2,7	1,0
	37	27	41	4,0	13	0,57	0,97	2,9	0,95
	37	27	40	3,8	13	0,55	0,95	2,8	0,86
	39	25	42	4,3	14	0,56	0,92	2,8	1,1
	37	26	40	3,9	13	0,55	0,97	2,8	1,0
	37	26	40	3,7	13	0,54	0,99	2,8	1,1
	36	26	39	3,5	12	0,54	0,93	2,8	1,1
	35	23	38	3,2	12	0,51	0,83	2,7	1,4
	35	23	39	3,1	12	0,51	0,83	2,7	1,3
	36	24	40	3,4	12	0,53	0,92	2,8	1,2
	35	24	40	3,7	12	0,52	0,85	2,6	1,0
	33	22	39	4,0	13	0,53	0,75	2,5	0,95
	35	20	41	4,2	11	0,5	0,75	2,6	1,4

Appendix E: Primary data, total carbon and total nitrogen analysis

Lake	Tot. C %	Tot. N %	C:N
Heimdalsvatn1	10,10	1,04	9,720885467
Heimdalsvatn2	9,45	0,94	10,02227171
Heimdalsvatn3	9,50	0,93	10,26139555
Heimdalsvatn4	8,46	0,78	10,88102894
Heimdalsvatn5	7,32	0,63	11,63197203
Heimdalsvatn6	7,75	0,66	11,81762733
Heimdalsvatn7	7,68	0,65	11,8922267
Heimdalsvatn8	8,60	0,73	11,83106342
Heimdalsvatn9	8,99	0,73	12,3268888
Heimdalsvatn10	9,50	0,79	12,09112893
Heimdalsvatn11	9,47	0,84	11,22836139
Heimdalsvatn12	8,57	0,69	12,37187816
Heimdalsvatn13	8,56	0,77	11,17785323
Heimdalsvatn14	8,86	0,79	11,17417077
Heimdalsvatn15	9,79	0,85	11,48252404
Heimdalsvatn16	10,40	0,91	11,47776184
Heimdalsvatn17	10,80	0,90	12,04550524
Heimdalsvatn18	10,80	1,03	10,46511628
Heimdalsvatn19	10,30	0,86	12,02989956
Heimdalsvatn20	9,11	0,73	12,48287202
Heimdalsvatn21	7,37	0,54	13,62040288
Heimdalsvatn22	7,15	0,48	14,82787225
Heimdalsvatn23	6,62	0,49	13,56835417
Heimdalsvatn24	6,72	0,51	13,19199058
Heimdalsvatn25	7,78	0,59	13,12858589
Heimdalsvatn26	8,53	0,67	12,65203204
Heimdalsvatn27	8,16	0,66	12,45801527
Heimdalsvatn28	7,36	0,58	12,60705721
Heimdalsvatn29	6,26	0,48	12,94190614
Heimdalsvatn30	5,96	0,42	14,29599424
Heimdalsvatn31	5,47	0,40	13,56646825
Heimdalsvatn32	5,78	0,45	12,81312348
Heimdalsvatn33	5,19	0,39	13,40392562
Heimdalsvatn34	5,16	0,39	13,19355664
Heimdalsvatn35	5,92	0,44	13,55932203
Heimdalsvatn36	6,43	0,46	13,89068913
Heimdalsvatn37	5,05	0,42	12,14526215
Heimdalsvatn38	6,59	0,50	13,09358236
Heimdalsvatn39	6,48	0,50	12,9703763
Heimdalsvatn40	7,30	0,61	12,01646091
Heimdalsvatn41	6,93	0,57	12,06686401
Heimdalsvatn42	5,87	0,50	11,84422922
Heimdalsvatn43	6,15	0,54	11,35734072
Heimdalsvatn44	4,78	0,43	10,99861942
Heimdalsvatn45	5,17	0,48	10,847671
Heimdalsvatn46	7,55	0,70	10,83991385
Heimdalsvatn47	10,80	0,86	12,50868659
Heimdalsvatn48	11,30	0,92	12,297312

Heimdalsvatn49	8,89	0,79	11,19365399
Heimdalsvatn50	6,98	0,66	10,56135573
Heimdalsvatn51	6,93	0,67	10,40540541
Heimdalsvatn52	6,86	0,67	10,18106263
Heimdalsvatn53	7,30	0,68	10,71166544
Heimdalsvatn54	6,62	0,63	10,54308011
Heimdalsvatn55	7,50	0,76	9,858044164
Heimdalsvatn56	8,08	0,82	9,891051536
Heimdalsvatn57	7,38	0,72	10,30150754
Heimdalsvatn58	7,86	0,80	9,881820468
Heimdalsvatn59	7,99	0,80	9,986251719
Heimdalsvatn60	7,67	0,79	9,679454821
Heimdalsvatn61	7,30	0,70	10,47496054
Heimdalsvatn62	7,29	0,75	9,745989305
Heimdalsvatn63	5,81	0,58	9,975961538
Heimdalsvatn64	6,83	0,67	10,15462385

Appendix E: Primary data pigments

lake	year	Allo	bb.Car	c.Neo	Cantha	Chl.a	Chl.b	Chl.c1	Chl.c2
Heimdalsv	2016	0	12,78855	0	0	129,3588	78,89667	0	0
Heimdalsv	1994	0	20,52996	0	0	60,27551	60,11601	0	0
Heimdalsv	1971	0	21,90451	0	0	41,54385	48,97792	0	0
Heimdalsv	1949	4,67661	13,49699	0	0	7,71285	28,09675	0	2,078171
Heimdalsv	1926	3,283391	9,622661	0	0	9,213754	21,67075	0	1,533171
Heimdalsv	1904	2,939638	8,566984	0	0	0	14,49802	0	2,571355
Heimdalsv	1881	1,579857	7,349386	0	0	0	11,25269	0	2,42218
Heimdalsv	1859	5,34815	7,394182	0	0	1,178763	17,05757	0	2,710895
Heimdalsv	1836	5,232229	8,620379	0	0	0	16,09584	0	4,118763
Heimdalsv	1814	4,668263	9,113397	0	0	0	15,8005	0	4,43569
Heimdalsv	1791	4,463479	8,890914	0	0	0	15,11565	0	3,95086
Heimdalsv	1769	5,78173	8,076068	0	0	1,345885	17,99001	0	2,55698
Heimdalsv	1746	4,838339	6,445451	0	0	1,817049	15,1793	0	2,17167
Heimdalsv	1724	3,530187	8,572018	0	0	0	14,39137	0	3,148591
Heimdalsv	1701	4,132904	9,48007	0	0	0	15,40493	0	3,300834
Heimdalsv	1679	3,466866	10,63695	0	0	0	13,83091	0	3,782762
Heimdalsv	1656	3,601185	11,57713	0	0	0	15,46359	0	4,418696
Heimdalsv	1634	3,851132	10,10169	0	0	0	16,19911	0	4,090219
Heimdalsv	1611	2,513784	10,07793	0	0	0	11,95185	0	3,248625
Heimdalsv	1589	3,101045	5,816349	0	0	0	10,13701	0	2,074122
Heimdalsv	1544	3,512443	6,25824	0	0	0	9,302224	0	1,982879
Heimdalsv	1499	0	2,209931	0	0	0	3,284594	0	0,181867
Heimdalsv	1454	0	2,058431	0	0	0	3,804514	0	0,126569
Heimdalsv	1409	0	2,147662	0	0	0	3,18851	0	0
Heimdalsv	1364	1,76549	2,827141	0	0	0	6,031251	0	0,583754
Heimdalsv	1319	1,860076	3,81549	0	0	0	6,011576	0	1,235176
Heimdalsv	1229	5,18934	6,472209	0	0	0	12,01047	0	4,094044
Heimdalsv	1184	5,02786	4,31689	0	0	0	11,98118	0	3,775695
Heimdalsv	1139	3,280832	4,026664	0	0	0	8,277884	0	2,59631
Heimdalsv	1094	2,220713	2,560029	0	0	0	7,024001	0	1,892927
Heimdalsv	1049	0,86111	1,678866	0,332139	0	0	3,793199	0	0,679182
Heimdalsv	1004	0,372422	1,842852	0,947374	0	0	3,47513	0	0,739419
Heimdalsv	959	0,906583	2,073135	0,032473	0	0	3,98532	0	0,925001
Heimdalsv	914	0,322281	0,267242	0	0	0	1,274874	0	0,078519
Heimdalsv	869	0	1,546825	0	0	0	2,204009	0	0
Heimdalsv	824	0	1,566651	0	0	0	2,184745	0	0
Heimdalsv	779	0	1,67569	0	0	0	2,335654	0	0
Heimdalsv	734	0,786566	0,698522	0	0	0	3,145846	0	0
Heimdalsv	689	2,342833	2,123907	0	0	0	6,233649	0	1,018344
Heimdalsv	644	2,444368	1,970013	0	0	0	6,284956	0	0,725374
Heimdalsv	599	2,939724	1,964982	0	0	0	6,656414	0	0,492185
Heimdalsv	554	0	2,790912	0	0	0	3,952474	0	0
Heimdalsv	509	1,518259	2,322273	0	0	0	5,578123	0	0
Heimdalsv	464	0,326038	2,19865	0	0	0	4,193426	0	0,115816
Heimdalsv	419	8,576133	5,951049	0	0	0	12,45907	0	5,2059
Heimdalsv	374	9,374074	4,439959	0	0	0	11,01526	0	4,096628
Heimdalsv	329	5,426842	2,854996	0	0	0	9,805447	0	0,73679
Heimdalsv	284	11,4578	3,557613	0	0	0	16,64767	0	3,658882
Heimdalsv	239	7,956192	4,941456	0	0	0	12,36607	0	3,207375
Heimdalsv	194	10,85435	5,844231	0	0	0	12,76448	0	4,97967
Heimdalsv	149	13,18467	1,637691	0	0	0	8,568422	0	3,559154
Heimdalsv	104	21,57358	2,424146	0	0	0	13,13087	0	7,417631
Heimdalsv	14	18,95088	0,8263	0	0	0	13,45349	0	6,826632
Heimdalsv	-32	20,06934	1,995533	0	0	0	13,65937	0	7,095806
Heimdalsv	-77	9,17736	3,532583	0	0	0	11,95296	0	3,531525
Heimdalsv	-122	13,91009	3,24331	0	0	0	12,1607	0	4,228833
Heimdalsv	-167	14,72011	1,713134	0	0	0	12,55465	0	4,514214
Heimdalsv	-212	21,28752	0	0	0	0	17,78431	0	7,698046
Heimdalsv	-257	25,76974	0	0	0	0	17,68854	0	8,39683
Heimdalsv	-302	21,16314	0	0	0	0	15,23559	0	6,96048
Heimdalsv	-347	19,55222	0	0	0	0	14,55114	0	6,484672
Heimdalsv	-392	21,23412	0	0	0	0	16,26489	0	6,509475
Heimdalsv	-437	13,99187	0	0	0	0	13,12087	0	4,508681
Heimdalsv	-482	20,01825	0	0	0	0	16,39339	0	5,674942

lake	year	Diadino	Diato	Dino	Echin	Fuco	Lut	Myxo	Peri
Heimdalsv	2016	52,74719	0	0	0	0	0	7,357105	0
Heimdalsv	1994	40,26571	0	0	0	0	0	1,578126	0
Heimdalsv	1971	32,28701	0	0	0	0	0	0	0
Heimdalsv	1949	21,45002	0	0	0	0	0	0	0
Heimdalsv	1926	15,77878	0	0	0	0	0	0	0
Heimdalsv	1904	16,42382	0	0	0	0	0	0	0
Heimdalsv	1881	14,58952	0	0	0	0	0	0	0
Heimdalsv	1859	17,68996	0	0	0	0	0	0	0
Heimdalsv	1836	24,39455	0	0	0	0	0	0	0
Heimdalsv	1814	27,88589	0	0	0	0	0	0	0
Heimdalsv	1791	25,99295	0	0	0	0	0	0	0
Heimdalsv	1769	20,90821	0	0	0	0	0	0	0
Heimdalsv	1746	17,83788	0	0	0	0	0	0	0
Heimdalsv	1724	22,09617	0	0	0	0	0	0	0
Heimdalsv	1701	23,51056	0	0	0	0	0	0	0
Heimdalsv	1679	25,85664	0	0	0	0	0	0	0
Heimdalsv	1656	29,4729	0	0	0	0	0	0	0
Heimdalsv	1634	28,31731	0	0	0	0	0	0	0
Heimdalsv	1611	22,50468	0	0	0	0	0	0	0
Heimdalsv	1589	15,50362	0	0	0	0	0	0	0
Heimdalsv	1544	15,39767	1,51807	0	0	0	0	0	0
Heimdalsv	1499	2,49501	0,345731	0	0	0	2,837104	0	0
Heimdalsv	1454	2,288112	0	0	0	0	3,954508	0	0
Heimdalsv	1409	2,867328	0,34675	1,00905	0	0	2,163729	0	0
Heimdalsv	1364	7,019401	0	0	0	0	0	0	0
Heimdalsv	1319	10,37811	0,312427	0	0	0	0	0	0
Heimdalsv	1229	25,62908	0	0	0	0	0	0	0
Heimdalsv	1184	23,79021	0	0	0	0	0	0	0
Heimdalsv	1139	16,0791	0	0	0	0	0	0	0
Heimdalsv	1094	12,1778	0	0	0	0	0	0	0
Heimdalsv	1049	5,041245	1,897342	0	0	0	0	0	0
Heimdalsv	1004	6,162122	0	0	0	0	0	0	0
Heimdalsv	959	5,350536	0,350398	0	0	0	0,081355	0	0
Heimdalsv	914	0,555097	1,113734	0	0	0	0	0	0
Heimdalsv	869	2,56717	0,492451	1,049869	0	0	1,116173	0	0
Heimdalsv	824	2,766666	0,262691	1,043372	0	0	1,03432	0	0
Heimdalsv	779	2,191585	0	0,588276	0	0	0,819232	0	0
Heimdalsv	734	1,773468	0	0,010593	0	0	1,356895	0	0
Heimdalsv	689	6,392078	0	0	0	0	0	0	0
Heimdalsv	644	5,632971	0	0	0	0	0	0	0
Heimdalsv	599	6,12477	0	0	0	0	0	0	0
Heimdalsv	554	4,615536	0	0,838625	0	0	1,062358	0	0
Heimdalsv	509	4,330807	0	0	0	0	2,535972	0	0
Heimdalsv	464	4,834048	0,13901	0	0	0	5,236593	0	0
Heimdalsv	419	36,04228	0	0	0	0	0	0	0
Heimdalsv	374	30,42757	0	0	0	0	0	0	0
Heimdalsv	329	10,93401	0	0	0	0	0	0	0
Heimdalsv	284	32,98522	0	0	0	0	0	0	0
Heimdalsv	239	28,74258	0	0	0	0	0	0	0
Heimdalsv	194	38,88946	6,792886	0	0	0	0	0	0
Heimdalsv	149	26,10939	18,50994	0	0	0	0	0	0
Heimdalsv	104	50,13193	29,57643	0	0	0	0	0	0
Heimdalsv	14	48,42816	20,91201	0	0	0	0	0	0
Heimdalsv	-32	52,04766	19,90094	0	0	0	0	0	0
Heimdalsv	-77	31,66537	4,836491	0	0	0	0	0	0
Heimdalsv	-122	35,13978	14,66075	0	0	0	0	0	0
Heimdalsv	-167	36,45829	15,86729	0	0	0	0	0	0
Heimdalsv	-212	64,48156	18,56509	0	0	0	3,152542	0	0
Heimdalsv	-257	64,26292	23,08245	0	0	0	0	0	0
Heimdalsv	-302	52,06818	23,2669	0	0	0	0	0	0
Heimdalsv	-347	49,1028	23,16328	0	0	0	0	0	0
Heimdalsv	-392	52,86911	23,53834	0	0	0	0	0	0
Heimdalsv	-437	38,21913	21,29937	0	0	0	5,396363	0	0
Heimdalsv	-482	49,85585	15,51885	0	0	0	0	0	0

lake	year	Phe.a	Phe.b	Viola	Total Kloro
Heimdalsv	2016	250,6475	109,412	0	380,0063
Heimdalsv	1994	204,7826	85,25884	0,410343	265,0581
Heimdalsv	1971	180,1514	70,52062	3,821518	221,6953
Heimdalsv	1949	141,0869	45,64898	5,577261	148,7998
Heimdalsv	1926	105,8674	32,04241	3,767519	115,0812
Heimdalsv	1904	96,21815	26,79024	4,293545	96,21815
Heimdalsv	1881	76,43909	20,84062	3,679863	76,43909
Heimdalsv	1859	109,2171	29,23746	3,971133	110,3958
Heimdalsv	1836	130,9462	25,602	4,687593	130,9462
Heimdalsv	1814	127,5993	26,59813	4,544847	127,5993
Heimdalsv	1791	121,5541	26,59608	4,417625	121,5541
Heimdalsv	1769	121,0982	33,62184	4,183978	122,4441
Heimdalsv	1746	100,5462	27,9598	3,63953	102,3632
Heimdalsv	1724	114,0541	27,73559	4,710979	114,0541
Heimdalsv	1701	116,3198	31,3396	5,524923	116,3198
Heimdalsv	1679	119,1395	31,96147	6,306971	119,1395
Heimdalsv	1656	129,1236	30,50387	6,717665	129,1236
Heimdalsv	1634	120,9948	29,02003	5,99217	120,9948
Heimdalsv	1611	105,1537	24,48987	5,81779	105,1537
Heimdalsv	1589	76,98689	20,88443	4,17709	76,98689
Heimdalsv	1544	77,30441	21,8616	5,130985	77,30441
Heimdalsv	1499	28,43864	9,543626	1,088282	28,43864
Heimdalsv	1454	31,31254	11,33941	0,796969	31,31254
Heimdalsv	1409	25,90389	9,306478	0	25,90389
Heimdalsv	1364	46,52302	12,35886	1,84834	46,52302
Heimdalsv	1319	56,31661	13,26953	2,592176	56,31661
Heimdalsv	1229	110,1935	18,85342	4,314121	110,1935
Heimdalsv	1184	94,60637	14,99127	2,849779	94,60637
Heimdalsv	1139	74,42087	14,10343	2,996275	74,42087
Heimdalsv	1094	54,71565	12,50526	2,374175	54,71565
Heimdalsv	1049	30,40028	9,863401	1,72804	30,40028
Heimdalsv	1004	31,03778	10,1224	1,026139	31,03778
Heimdalsv	959	35,12064	10,92713	1,709539	35,12064
Heimdalsv	914	8,425036	2,968845	0,489335	8,425036
Heimdalsv	869	20,40805	8,110125	0	20,40805
Heimdalsv	824	21,16692	7,885558	0	21,16692
Heimdalsv	779	22,91553	6,96161	0	22,91553
Heimdalsv	734	24,49146	7,276906	0,625868	24,49146
Heimdalsv	689	57,79672	10,5734	1,845053	57,79672
Heimdalsv	644	54,39222	11,19511	1,656772	54,39222
Heimdalsv	599	57,94434	12,04508	1,456465	57,94434
Heimdalsv	554	35,74838	10,5325	0	35,74838
Heimdalsv	509	47,0151	11,76346	0,642627	47,0151
Heimdalsv	464	39,1364	10,00686	0	39,1364
Heimdalsv	419	129,0423	20,32707	4,967276	129,0423
Heimdalsv	374	117,7245	18,88478	4,599711	117,7245
Heimdalsv	329	81,95459	17,42998	2,394803	81,95459
Heimdalsv	284	128,2529	26,1558	4,975878	128,2529
Heimdalsv	239	107,138	22,47823	4,673775	107,138
Heimdalsv	194	114,9215	22,14321	6,537377	114,9215
Heimdalsv	149	87,06485	16,62011	6,696376	87,06485
Heimdalsv	104	131,6671	22,5076	11,80166	131,6671
Heimdalsv	14	121,0991	20,97041	9,126132	121,0991
Heimdalsv	-32	127,9908	19,45182	10,27712	127,9908
Heimdalsv	-77	95,11292	20,8253	5,618053	95,11292
Heimdalsv	-122	110,7514	22,78456	7,773758	110,7514
Heimdalsv	-167	107,0905	21,80071	8,244658	107,0905
Heimdalsv	-212	133,5939	26,98869	8,712833	133,5939
Heimdalsv	-257	149,9035	24,63086	12,29806	149,9035
Heimdalsv	-302	123,5587	23,04568	10,44152	123,5587
Heimdalsv	-347	120,0852	23,69386	9,991026	120,0852
Heimdalsv	-392	122,8301	27,10386	9,851415	122,8301
Heimdalsv	-437	102,3489	25,25557	5,652601	102,3489
Heimdalsv	-482	122,3614	24,7758	8,268316	122,3614

Appendix F: Primary data PCA

PCA loadings:	V	Cr	Ni	Cu	Zn	As	Cd	Cs	Hg	Pb	Al	Ca	Fe	K	Mg	Mn	Na	P	S
PC 1	-0,18	-0,20	-0,20	-0,17	0,14	0,17	0,16	-0,13	0,20	0,18	-0,25	-0,22	0,10	-0,12	-0,25	-0,13	-0,23	-0,24	0,17
PC 2	0,09	0,14	0,15	0,21	0,28	0,22	0,27	0,20	0,22	0,25	-0,02	-0,19	-0,18	0,19	-0,07	-0,26	-0,14	-0,05	0,22
PC 3	0,13	0,00	-0,01	-0,10	-0,13	0,04	-0,15	-0,02	0,02	-0,09	-0,03	0,00	0,33	-0,04	-0,01	0,20	0,03	0,04	0,02
PC 4	0,27	0,28	0,25	0,22	0,07	0,25	-0,01	0,36	-0,05	-0,04	0,09	-0,04	0,20	0,23	0,05	0,16	-0,06	0,13	0,16
PC 5	0,08	0,03	0,03	0,14	-0,10	-0,06	-0,08	-0,24	-0,02	-0,06	-0,07	-0,07	-0,04	-0,26	-0,03	-0,12	0,06	0,06	0,12
PC 6	-0,25	-0,12	0,10	-0,16	0,08	-0,13	0,03	0,14	-0,02	0,03	0,08	0,14	-0,07	0,39	0,10	0,09	0,13	-0,05	-0,33
PC 7	0,30	0,12	-0,02	-0,06	-0,08	-0,02	-0,04	-0,03	-0,07	-0,01	0,01	0,02	-0,04	-0,24	0,02	-0,06	0,09	0,12	0,11
PC 8	-0,01	0,01	0,09	-0,13	0,05	0,01	0,04	-0,04	-0,01	-0,01	-0,02	0,02	0,01	0,11	0,01	0,02	-0,01	-0,04	-0,08
PC 9	0,11	0,24	0,01	0,10	-0,17	0,11	-0,11	-0,05	0,01	-0,05	0,00	0,00	0,10	-0,11	-0,01	-0,01	-0,08	0,16	0,04
PC 10	-0,16	-0,15	-0,17	0,06	-0,18	0,04	-0,19	0,03	-0,21	-0,18	-0,01	-0,13	0,10	0,51	0,02	0,06	-0,36	-0,01	0,18

PCA loadings:	Allo	bb.Car	c.Neo	Chl.a	Chl.b	Chl.c2	Diadino	Diato	Dino	Lut	Myxo	Phe.a	Phe.b	Viola	Tot kla
PC 1	-0,02	0,23	-0,05	0,17	0,22	0,03	0,13	-0,03	-0,08	-0,07	0,13	0,21	0,23	0,06	0,22
PC 2	-0,23	0,00	0,03	-0,13	-0,14	-0,13	-0,24	-0,22	0,04	0,07	-0,12	-0,16	-0,12	-0,13	-0,17
PC 3	-0,34	0,01	0,05	0,27	0,13	-0,40	-0,20	-0,24	0,17	0,18	0,25	-0,09	0,11	-0,41	0,02
PC 4	0,10	-0,02	0,11	0,18	0,13	0,17	0,23	0,05	-0,11	-0,18	0,27	0,17	0,12	0,09	0,19
PC 5	-0,07	0,03	0,67	-0,01	0,02	-0,09	-0,09	-0,04	-0,39	-0,38	-0,08	-0,05	0,00	-0,03	-0,04
PC 6	-0,15	0,26	0,16	-0,08	0,04	0,06	0,05	-0,53	-0,07	-0,21	-0,08	0,17	0,08	-0,03	0,11
PC 7	-0,07	0,09	-0,64	-0,06	0,03	-0,04	-0,06	-0,31	-0,36	-0,31	-0,11	0,08	-0,01	-0,05	0,04
PC 8	0,03	-0,10	0,03	0,02	-0,01	0,00	0,00	-0,02	-0,74	0,62	0,07	0,01	-0,02	0,00	0,01
PC 9	-0,05	0,50	0,10	-0,15	0,10	0,04	0,14	-0,05	0,15	0,39	-0,52	0,16	0,11	0,05	0,08
PC 10	-0,07	0,11	-0,13	-0,01	0,00	-0,27	-0,10	0,20	-0,19	-0,18	-0,21	-0,15	0,04	0,13	-0,12

EXPLAINED VARIANCE:										
	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8	PC 9	PC 10
	43,10 %	20,60 %	13,60 %	7,30 %	3,50 %	2,90 %	2,40 %	2,20 %	1,20 %	0,80 %

Norges miljø- og biovitenskapelig universitet
Noregs miljø- og biovitskapelege universitet
Norwegian University of Life Sciences

Postboks 5003
NO-1432 Ås
Norway