SEDIMENTATION PATTERNS IN A NORWEGIAN GLACIAL LAKE WITH FOCUS ON CLIMATE-RELATED HYDROLOGICAL PROCESSES

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Department of plant and environmental science
Master Thesis 30 credits 2012

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Preface and acknowledgements

The following is a thesis for my Masters of Science Degree in the program Environment and Natural Resources, specialising in Water Resources and Limnology within the Institute of Plant and Environmental Science (IPM) at the Norwegian University of Life Sciences (UMB) in Ås, Norway. It is part of a research and development project on the effect of variations in climate on sediment transport and erosion processes for the Norwegian Water Resources and Energy Directorate (NVE) in Oslo, Norway, within the Section for Sediment and Erosion of the Hydrology Department where I have been a full time employee since 2009. The topic of this thesis is of great interest to myself and appropriate for my current position at NVE and goal of becoming an expert in sediment transport, and it is well-suited to my background in and interest for physics, chemistry and ecology as well as the effects of various impacts on the environment.

I would like to thank everyone who has assisted me with my research and in completing this thesis, especially my main supervisor Jim Bogen, section leader for the Sediment and Erosion section at NVE, who created the idea for this project, funded my employment, allowed me to use the data and sediment cores from Nigardsvatn, has been a mentor for me with regards to my work and studies with sediment transport and sedimentation and inspired me to obtain a masters degree and potential future PhD in the subject area. I would also like to thank my other supervisors, Nils-Otto Kitterød and Gunnhild Riise at the Norwegian University of Life Science for helping me with various other aspects of this thesis within their own areas of expertise. I would also like to thank the various other people who have assisted with this project, Kristen Åsen who has helped with the field work for the sediment traps and been a field station monitor for NVE for many years, Kjell Holmgren who created the computer program which is used to determine the thicknesses of the sediment layers in the sediment cores, and my many other colleagues at NVE in the section for sediment and erosion who have done field work, analysed samples and data and provided information and data on sediment transport and sedimentation for the study area (Hans Christian Olsen, Truls Erik Bønsnes, Nils Haakensen, Halfdan Benjaminsen, Fred Wenger, Margrethe Elster). I am also thankful to Bjørn Lytskjold of NVE for helping with the geoinformation systems, John Brittain of NVE/UiO/UMB for giving advice about the ecological implications, and the section for geochemistry at NGU (Rolf Tore Ottesen, Tor Erik Finne and Malin Andresson) for providing me with the data on other chemical analyses performed on flood sediments in Jostedal, as well as the others who helped me obtain references, and those who conduct research in similar fields. I am also thankful to my friends and family, for encouragement and support, as well as much needed breaks. This thesis is a continuation of the previous NVE investigations into the sediments which melt out of Nigardsbreen glacier and are transported to Nigardsvatn lake, including my own publication “Estimating long term sediment yields from sediment core analysis” (Kennie *et al.* 2010) which was presented at the 2010 ICCE-IAHS conference in Warsaw, Poland and received a prize for best poster. Part of this thesis has been used in a separate publication entitled “Sedimentation patterns and sediment composition in a Norwegian glacial lake during a large magnitude flood” (Kennie & Bogen, 2012) which has been accepted for publication in the IAHS redbook “Erosion and sediment yields in the changing environment”, as well as oral presentation at the ICCE-IAHS 2012 conference in Chengdu, China.

Abstract

Sedimentation patterns in a Norwegian glacial lake were investigated with focus on climate-related hydrological processes. Three different years with extreme climatic situations were chosen. 1979 had a large magnitude flood with a culmination around $90m^3/s$ and a recurrence interval estimated at 100 years. 2002 had the highest summer temperatures since 1876 and extensive glacial melting. The summer of 2011 had long lasting relatively high rainfall resulting in a long period of high water discharge. These years were compared to a year with extremely low water discharge, 1993, which occurred due to a cold summer and low glacial melt rate.

It was found that large floods and years with long-lasting high water discharge can be recognized by thicker sediment deposits. 1979 had an average thickness of 6.3 mm and 2002 had an average sedimentation of 5 mm whereas 1993 had a thickness of only 2.2 mm. More organic sediments were found in the flood layers, around double of the concentrations found in the sediments deposited in the years before and after. The organic material is washed out from the non-glacial part of the catchment area during rainfall-induced floods. The flood layers contain somewhat larger grain sizes and the sand fraction is deposited especially at distances near the delta front. Throughout the entire lake, it was found that the 1979 layer in four of the cores contained 10-30% more material larger than 31 micron than the 1993 layer. Chemical analyses revealed that the 1979 flood layer contained more Al, Ca, Cu, Fe, K, Mg, Mn, P, S and Zn than the other years, and the higher levels are believed to be caused by the higher surface runoff during the flood. Iron oxides are especially visible when Fe is contained in higher concentrations, and this is a reason why this layer is distinguishable. The sediment trap studies from the period of high transport in 2011 showed lower concentrations of several chemical elements (Al, Cu, Fe, K, Mg, Mn and Na) and more clay and organic material than the cores. This is because many elements are associated with the clay and organic fractions of sediment, and they take a longer time to settle out of suspension, later in the season. The implications for ecology and the use of sediment cores to study changes in climate are discussed.

Sammendrag

Sedimentasjonsmønstre i en glasial innsjø i Norge ble undersøkt med fokus på klimarelaterte hydrologiske prosesser. Tre forskjellige år med ekstreme klimatiske situasjoner ble utvalgt for nærmere undersøkelser. I 1979 inntraff en stor flom som kulminerte på 90m^3/s og hadde et estimert gjentaksintervall på 100 år. I året 2002 ble det registrert de høyeste sommertemperaturer siden 1876 og omfattende smelting av breen. Sommeren 2011 hadde langvarig relativt mye regn. Disse tre årene ble sammenlignet med et år med ekstremt lav vannføring, 1993, som hadde sammenheng med en kald sommer med lite bresmelting.

Det ble påvist at år med store flommer og år med langvarig høy vannføring kan gjenkjennes som tykkere sedimentavsetninger. 1979 hadde en gjennomsnittelig tykkelse på 6,3 mm, 2002 hadde gjennomsnittelig sedimentasjon på 5 mm og 1993 hadde en tykkelse på bare 2,2 mm. Det ble påvist mer organiske sedimenter i flomlagene, rundt dobbelt så mye som konsentrasjonene i sedimentene avsatt i årene før og etter. Det organiske materialet ble skylt ut fra den brefrie delen av nedbørfeltet under regnflommene. Flomlagene innholder noe grovere kornstørrelser. Spesielt på avstander nære deltafronten er det avsatt sand. Over hele innsjøen ble det påvist at 1979-laget innholdt 10-30% mer materiale enn 1993-laget i fraksjonene større enn 31 mikron. Kjemiske analyser påviste at 1979 flomlaget innholdt mer Al, Ca, Cu, Fe, K, Mg, Mn, P, S og Zn enn årene med lav vannføring. Dette har sannsynligvis sammenheng med høy overflateavrenning under flommen. Jernoksid er spesielt synlig når Fe forekommer i høyre konsentrasjoner, og dette er grunnen til at dette laget kan skilles ut. Sedimentfelleundersøkelsene fra perioden med høy transport i 2011 viste lavere konsentrasjoner av flere kjemiske elementer (Al, Cu, Fe, K, Mg, Mn og Na), leire og organiske materiale enn kjernene. Dette har sammenheng med at mange elementer er assosierte med leire og organiske fraksjoner i sedimentet, og de tar lengre tid å sedimentere. Dette skjer senere i sesongen. Implikasjonene for økologi og bruk av sedimentkjerner til å undersøke klimaendringer er diskutert.

1 INTRODUCTION

1.1 Background and issue to be addressed

Sediments deposited in glacial lakes during varying climatic and hydrological conditions can differ from those deposited in more average conditions, and therefore act as important indicators which can be used in dating of sedimentary sequences. These sediments can also be used to study historical climate, or to predict the future effects of climate change on glacial and aquatic systems. The information obtained from studying these sediments is of great significance in the study of how climatic and hydrological variables can affect processes of sediment transport and sedimentation.

Sediment transport, sediment composition and sedimentation patterns in a specific lake and river system vary with time, in response to various external factors. Differences in glacial melt rate due to temperature as well as variations in rainfall are metrological processes related to climate change which can lead to different effects on the hydrology in a catchment and result in different characteristic patterns of sediment transport and sedimentation. Intrinsic factors characteristic to the individual lake such as physical geography and geomorphology also play a role in determining sedimentary processes (Bogen, 1983).

Annual sediment layers reflecting a shift between thick, light, coarser layers deposited during the summer and the thin, dark layer of mica (biotite) in the fine clay fraction which settles in the winter are called varves, and are used to study variations in sediment transport and sedimentation (Kennie *et al.*, 2010; Zolitschka, 1997). It has been shown in earlier studies (Østrem, 2005) that the rhythmic sequences in lake Nigardsvatn are due to annual changes in grain size and mineral composition. In lakes, sediments deposited during floods may be incorporated into layers that are deposited during periods subject to more moderate flow conditions. Sediments deposited in floods may often be visible as distinct layers discernible to the naked eye or distinguishable through laboratory analyses. This may be due to high deposition rates of coarse grain sizes, a lower percentage of organic material, differences in mineral composition and orientation of particles. Such differences are due to changes in sediment supply and availability during differing flow conditions as well as changes in the pattern of sedimentation because of higher flow velocities combined with lake morphology.

The aim of this thesis is to analyze the sediments deposited in a Norwegian glacial fed lake during large magnitude floods caused by high intensity rainfall or a large glacial melt rate in order to quantify and make a basis for their identification in relation to material deposited during lower water discharges. Chemical elements associated with particles move with the sediment and their distribution is affected by the processes of transport and deposition. It is thus also of interest to analyze these parameters to determine how the distribution and composition of sediments is affected during different periods subject to varying hydrological conditions. Organic material plays a special role as its settling velocity differs from that of minerogenic material, and comes from different sources. Large amounts of organic material may be seen as distinct layers in sedimentary deposits and thus help to establish a chronology. It is also of decisive importance for biological life.

1.2 Earlier research

Some of the most extreme erosion processes and episodes of high sediment transport are associated with large magnitude floods (Bogen, 2006; 2009). During large floods, the erosion processes intensify and the number of active sediment sources increases. Riverbanks and floodplains are often inundated only during flood periods, depositing sediments. These settle in a series of flood layers and can be used to obtain information about the extent of previous floods, and composition of sediments transported in historical periods (Bogen & Ottesen, 2006). In lakes the sediments transported during floods can be interbedded amongst sediments deposited during more moderate conditions. Flood layers can often be clearly identified and measured in sediment cores, due to the fact that they form distinctive layers which can be visually distinguished (Kennie *et al.*, 2010; Østrem & Olsen, 1987). The difference between sediments deposited in flood and non-flood conditions can be related to factors such as the amount of material, grain size distribution of the sediments, fraction of organic material, geochemical elements, density and porosity, as well as the mineralogical composition and orientation of the particles. The distinguishing features of flood sediments can be attributed to the changes in the supply and sources of the sediments (Tremblay *et al.,* 2003; Bogen, 2009), changes in the sedimentation patterns in the lake due to the increased water discharge and velocity (Bogen, 1985), and the residence time of water in the lake (Pharo *et al*., 1979). These factors are dependent on the depositional processes in the lake (Gyr & Hoyer, 2006) as well as the geology and morphology of the catchment area, river, delta and lake basin (Bogen, 1983; 1988).

Analysis of sediment cores can be used to reconstruct climatic and hydrologic history of a catchment area including information about the glaciers former position, or meterological factors such as temperature and precipitation (Leemann & Niessen, 1994; Nesje *et al*., 2008; Shakesby *et al*., 2007; Hodder *et al.*, 2007). Østrem & Olsen (1987) used the thickest varves from long sediment cores to estimate the size of extreme flood events. Increased water discharge causes an increase in the stream velocity, thus keeping sediment particles in suspension further downstream. This changes the sedimentation patterns in the lake, with regards to the location, amount and grain size composition of the deposited sediments. Floods can change the supply of the sediments, washing in sediments and bound chemical elements from further away, or from areas which are normally dry. This is especially true for glacial lakes and streams, where material is carried in from the unglaciated parts of the catchment area only during high rainfall (Bogen, 1995). While most of the sediment supply comes from glacial erosion carried through the englacial, subglacial, and proglacial drainage by glacial meltwater, during high rainfall or snowmelt more material is transported into from the ice-free mountain slopes by the high surface runoff. Due to the fact that that the number of sediment sources increases during large magnitude floods and sediments are derived from a larger part of the whole catchment area, overbank sediments have been found to be useful as sampling media for regional geochemical analyses and mapping (Ottesen *et al.*, 1989).

It is of great interest to obtain a better understanding of how sediment sequences deposited during floods of varying intensity compare to layers deposited during years with average or low water discharge. Several researchers have published articles in this area of research (Macklin & Lewin, 2003; Østrem & Olsen, 1975; Nesje *et al*., 2001; Gilli *et al*., 2002; Gilbert *et al*., 2006) but few have connected their sediment core analyses to a long-term monitoring period of sediment transport measurements from the same catchment area.

Flood layers offer special possibilities for dating of recent sediments. It is the aim of this thesis to establish an objective characterization of flood layers, where they can be recognized and distinguished from layers deposited in years with average water discharge through analytical techniques. We also hope to determine other quantitative differences in flood layers, such as differences in the fraction of organic material or associated chemical elements.

1.3 Choice of lake

Nigardsvatn lake was chosen for this thesis as it is an ideal site to study processes of glacial-fluvial sediment transport and considered a reference catchment area. In addition, several sediment cores were taken up for analysis in 2006 which can be analysed for this project and considerable data from a long monitoring series are available on the historic water discharge, sediment concentrations, and sedimentation in the delta. Another quality of this lake is that being a glacial lake, sediments settle as a series of laminated annual layers called varves, which are easily distinguishable as they are deposited in alternating light summer and dark winter layers, due to particle size of the sediments, minerogenic components, particle orientation, and settling time (Østrem, 2005). Nigardsvatn has also experienced large magnitude floods, which makes it ideal for studying flood processes. In the summer of 1979 this area suffered a great flood estimated at a 100-year reoccurrence interval, which deposited an easily identifiable sediment layer for analysis (Gjessing & Wold, 1980; Kennie *et al.*, 2010).

This lake has not been artificially regulated, so therefore the cycle of summer melt and winter freezing typical of a Norwegian mountain climate has not been interrupted, nor has the natural hydrology and sediment transport. In regulated watercourses, water can be stored during the summer and released during the winter, sediments are held back by dams and weirs, and the natural water flow, velocity, sediment carrying capacity and sedimentation regime is affected. In regulated rivers and lakes, the sediment transport and sedimentation measured downstream of the infrastructure does not reflect the natural variation, precipitation, glacial melting and general hydrology of the region. Nigardsvatn is located in a small catchment area and is a nearly pristine environment protected as a national park so it is free of most human interference such as physical developments, agriculture and industrial pollution. Therefore this is an ideal study area for natural processes, completely independent of human influence.

1.4 Conceptual sedimentation model of Nigardsvatn lake

The physical sedimentation system can be described in terms of a conceptual model in order to clarify the processes and the importance of the different variables. Since the lake appeared in the 1960s after melt back of the glacier, it has been slowly filling in with sediments. The sedimentation is higher in the delta area, proximal to the inflowing river, so that the delta is prograding into the basin during the melting seasons. The river expands across the delta platform and some of the bedload is deposited on the topset and some is carried downstream to the delta front. Early and late in the season during lower water levels a braided river system exists on the delta platform. Throughout the melting season the water level rises and the delta platform is submerged. This rise in water level has important implications for the sedimentation system. During summer melting when the lake level is high, some of the sand is also deposited on the delta platform. At the delta front, a three dimensional expansion takes place and the sediment particles are deposited in the lake. A sorting of sediments takes place, where the coarser fractions are deposited closest to the delta front and the finest are carried in suspension further out into the lake where they are then deposited. Deposition of bedload has caused the delta to grow from 1968 to the present position and NVE has surveyed this development (Kennie *et al*, 2009; Østrem, *et al.* 2005). This paper focuses on the sedimentation processes of the suspended material that take place in the lake basin beyond the present delta front.

The material of the inner part of the delta consists primarily of bedload, but during the water level rise, the suspended sediments also settle in this area. It has been found that from 6-90% and an average of 42.6% percent of the material in the delta is less than the grain size of 0.5 mm (Olsen, 2008). A dominant amount of the suspended material is deposited in the area where the delta turns into a deeper lake basin.

The river jet flows across the delta and then expands when it reaches the wider and deeper lake basin, introducing the sediment particles into the lake. This leads to a decrease in flow velocity with distance from the delta front. The processes which control the deposition of sediments can be divided into three types; the three-dimensional flow that takes place at the delta front, the two dimensional flow across the delta platform, and the depositional processes in the river channel (Bogen, 1988). The grain size distribution of the sediments entering the system is important as well as the hydraulics of the system when determining sedimentation patterns.

Important factors determining the amount and diameter of the sediments deposited at various locations in the lake include the distance from the glacier to the basin of sedimentation, the hydrological regime of the catchment area, and sorting of sediments during transport. The sedimentation process can be analyzed in terms of a conceptual model. High flow velocities transport particles longer distances than low flow. The sedimentation system and the essential variables are shown in Fig. 1. *Vo* is the velocity at the river mouth and *Vx* is the stream velocity at a distance *x*. Flow velocity in the lake is a function of distance from the inflowing river and initial stream velocity, and depends on the lakes morphology. Larger water discharge due to high glacial melting or rainfall will lead to a higher stream velocity in the inflowing river meaning there will also be a higher flow velocity further out into the lake. *Co* is sediment concentration at the river mouth and *Cx* is sediment concentration at distance *x*. The particle settling velocity *Vs* is dependant of grain size and fine fractions are carried further away from the river mouth. The thickness or weight per unit area of a sedimentary layer (Δd or ΔM) at a distance x from the river mouth is dependant on the concentration and flux of particles at that distance.

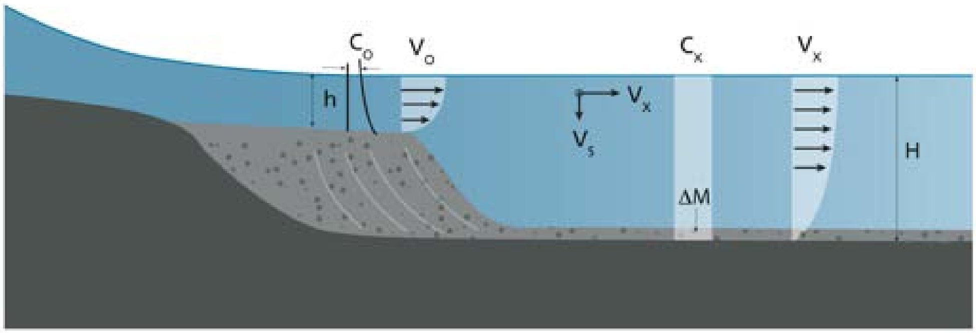


Fig. 5: Sedimentation system of Nigardsvatn delta and lake. Vo is velocity at the delta front and Vx is velocity after the river jet has expanded, at distance x from the delta front. Vs is sedimentation velocity. ΔM is sedimentation rate.

The theoretical settling velocity of particles in suspension is described by Stokes' law (Lamb, 1994; Batchelor, 1967) and Oseen's law (Oseen, 1910), which is valid for larger sand particles. Rubey's formula (Rubey, 1933) combines both Oseen's and Stokes' law to give the fall velocity for sediment particles in a wider particle range. Stokes' law consists of the following equation:

1) $Vs=(2(\rho_p-\rho_f)/9\mu)gR^2$

where V_s is the particles' settling velocity (m/s), g is the gravitational acceleration (m/s^2), R is the reynolds number, ρ_p is the mass density of the particles (kg/m^3), and ρ_f is the mass density of the fluid (kg/m^3), and μ is viscocity (Ns/m2).

The flow field in a lake in the vicinity of the river inlet is a very important factor in the process of sedimentation. Bates (1953) was the first to show that the flow field of the river mouth resembled that of a jet. Bogen (1983; 1987) carried out current measurements in various lakes and found that the flow field in the river mouth of fjord valley lakes can be described by the theory of sediment laden jets close to river mouths. He showed that the velocity decayed along the axis of a jet expansion, and the relation can be expressed as:

2) $Vx/Vo = a(X/2h)^{-b}$

where a and b are parameters which must be determined through experiments, h equals the river depth. Measurements in lake Tunsbergdalsvatn at high water discharges gave us a result that a was 54 and b was 1.51. The conditions of

Nigardsvatn resemble those in Tunsbergdalsvatn. However, since the area in front of the delta in Nigardsvatn is more shallow, this probably leads to a slightly higher value for *a* and lower value for *b,* possibly as low as 0.5 which is the value for a 2-dimensional free jet, as described by Bogen (1987). This means that the velocity does not decrease as rapidly with distance out into the lake as in a very deep basin. A large difference between the two is that the Nigardsbreelv river moves across the delta platform which is submerged at high discharges leading to high water levels in the lake. However beyond the delta rim it is likely that the mean features of the flow may be described by equation 1 along the axis of flow.

Density also plays an important role in determining stream currents and sedimentation in glacial lakes (Gilbert, 1973a,b). Rao & Carstens (1971) discovered that submerged sediment laden horizontal jets behave differently from those which consist of pure water. Many glacial lakes are characterized by underflow currents, due partially to the lakes morphology, temperature strata, and higher concentrations of sediment which affect the density of the inflowing water, since the density of sediment particles is higher than the density of water. Nigardsvatn is cold and the temperature is estimated at near zero, although the temperature varies with season and depth in the lake. Since sediments are much heavier than water, with a density of 2.7 for quartz as opposed to around 1.0 for water, water from the inflowing river is heavier than that in the lake due to a higher concentration of sediments and will therefore behave differently than the surrounding water mass. Sedimentation regimes can also be affected by sediment concentrations. High inflowing sediment concentrations can result in underflows, where bottom topography is the strongest factor controlling transport and deposition. During low sediment concentrations, the inflowing water is less dense than the hypolimnic water and therefore enters the lake as overflows (Smith *et al.* 1982). Therefore different sedimentation patterns can occur due to the differences in hydraulic flow fields during different discharges, sediment concentrations, and water temperatures.

1.5 Reasons for study

A specialized study of this type into the characterisation of flood sediments is of great interest to the more generalized field of sediment core analysis and sediment transport. The most important outcome is to achieve a better understanding of the composition of sediment transported and deposited in floods and the physical processes and mechanisms which lie behind. These results will give a better understanding of how sediment transport and sedimentation during various hydrological conditions influenced by climate change varies from that which occurs under more average conditions. This can also help in the identification of sediment layers from periods with large floods and the role of sedimentary deposits in interpretation and estimation of hydrological parameters during the period in which these layers were deposited.

The most relevant application of the results of this study of the components and structure of flood layers will be their use in sediment core dating. Flood layers serve as a reference marker for years with known floods and this information can therefore be used to assist in dating the remaining layers in sediment cores. Although data on water discharge can be limited as measurements are not taken in every river, and the time series are often short or incomplete, there are often records of large magnitude floods dating back to thousands of years (Roald, 2012). In addition, data on sediment transport is even scarcer, as sediment concentrations and sediment yields are rarely monitored even in the catchments or rivers which monitor water discharge. Therefore flood layers can act as a convenient reference point when analysing sediment cores which span over both short and long time series. Kennie *et al.* (2010) showed that long term sediment yields can be reliably estimated through analyzing varves of sediment cores, while using flood layers to assist in dating. This dating method can also be used in connection with other sediment core analysis techniques to aid in the interpretation of varves such as radionuclide dating. Flood layers and their characteristics can also be used in paleolimnological studies, or in connection with ecological studies.

The identification and examination of flood layers is also of interest to the study of climate change, with future floods predicted for Norway and other parts of the world (Roald *et al*, 2002, 2006; RegiClim, 2005). Through this study, it will be easier to identify historical flood layers in sediment cores where the climatic history is not fully known, or there is some uncertainty in the dating of sediment cores. Historical climatic variables can also be interpreted from layers in sediment cores, for example, sedimentation thickness, grain size or other characteristics can correspond to years with floods of a certain magnitude, cold summers with low glacial melt, or extremely warm summers with high melting of the glacier. Another important result is the ability to apply this knowledge to the study of climate related changes regarding the occurrence and magnitude of floods in earlier years, or glacial melt rate. This study is especially important with projected changes to climate and the hydrological cycle in Norway and the rest of the world, since changes in flood frequency and magnitude will have effects on erosion, sediment transport and sedimentation (Bogen, 2009).

It is also important to study the effect of climate change on the sedimentary environment to understand effects on the ecosystem, as the majority of aquatic and benthic organisms are affected in some way by changes in sediment concentration and sedimentation along with grain size distribution, amount of organic material and associated chemical elements of the sediments.

2 MATERIALS AND METHODS

2.1 Study area

A series of studies investigating sediment transport and sedimentation patterns were undertaken in Nigardsvatn, a proglacial glacial lake in western Norway. It is also called Nigardsbrevannet, Nigardsbresøen or Nigardsvann and is located in the Jostedøla valley, which lies in the community of Luster, in the county Sogn and Fjordane (Fig. 2). The melting water from the Nigardsbreen glacier flows into the lake below through a meltwater river called Nigardselv or Nigardsbreelv and delivers sediment. This is the only source of water flow into the lake, except for during periods of high rainfall and snowmelt when water comes into the meltwater river and lake from the mountain sides, often in the form of several smaller ravines, shown in Fig. 2 and 3a. Landslides have also been known to occur from the mountain sides and deliver material into the lake, especially during periods of high rainfall. This lake is a glacial trough, carved out from the last ice age. The lake is relatively new, as the glacier was historically larger and only began to melt back across the lake surface in 1937 (Bogen, 1989). It probably existed as a lake in earlier times before the last ice age until the glacier expanded again. Since the little ice age in the 1700s when the glacial front was nearly a kilometre longer, the glacier has been melting back. The glacial previously covered the entire surface area of the lake, but melted back over the length of the lake during the years 1937-1967 (Bogen, 1995). It was not until the end of the 1960s that the entire area of the lake was visible as the glacier area had decreased so much. The hydrologic and geographic information on Nigardsvatn lake is given in Table 1. A depth contour map is given in Fig. 4, Fig. 5a and 5b show the catchment areas for both the inlet and outlet of the lake, and Table 2 and 3 list the respective climatic and geographical data of these two catchment areas. The catchment area to the glacial melt water river is smaller than that which includes all water flowing into all areas of the lake, and the latter differs as it is covered by a proportionally lower glaciated area, and a higher amount of vegetation. The hydrology of the glacial river is controlled mostly by glacial melt, but rainfall can contribute to the discharge, whereas the unglaciated part of the catchment in Fig 5b. receives runoff only during times of rainfall and snowmelt.

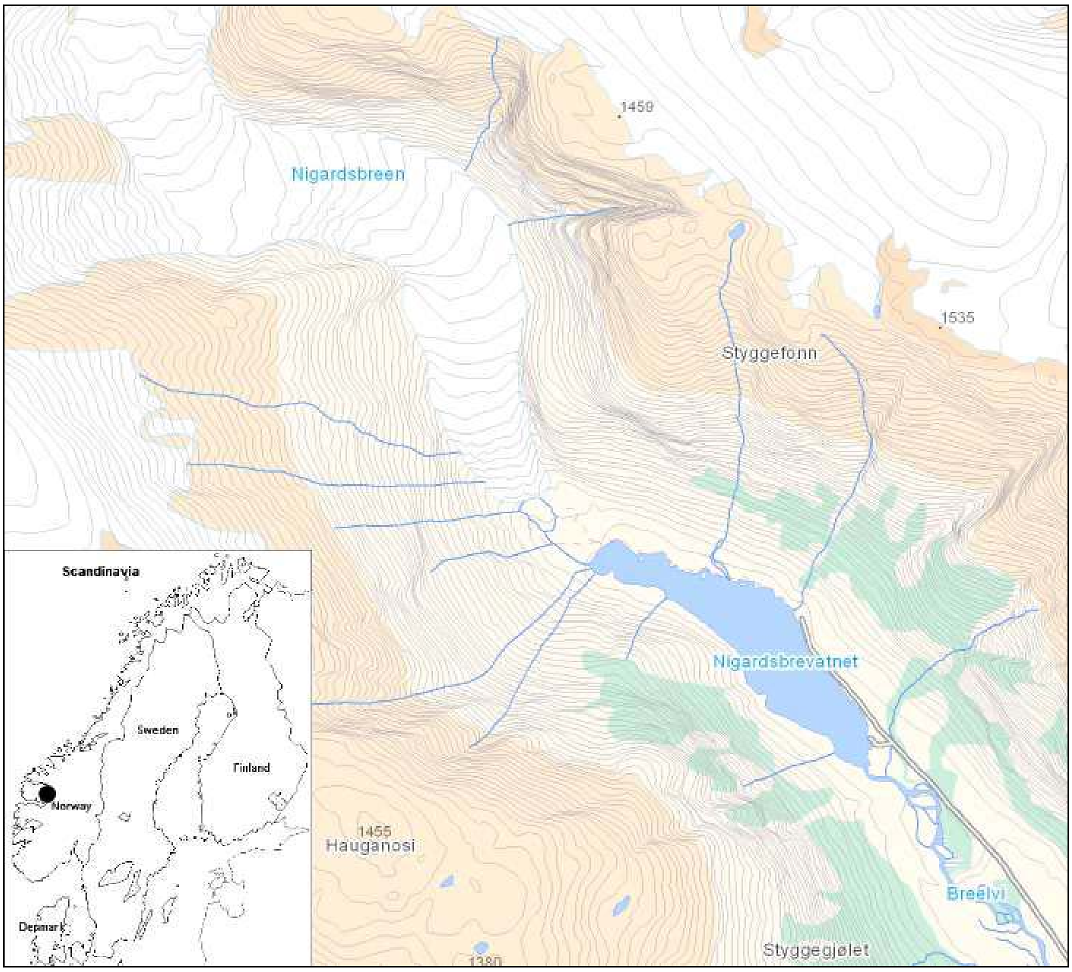


Fig. 2: Map showing the position of the Nigardsbreen glacier and Nigardsvatn lake, with a map of Scandinavia on the side. The black circle indicates the position of the study site. White indicates the glacier, blue indicates water, and green indicates vegetated areas.

Fig. 3a,b: Photo of Nigardsbreen glacier and Nigardsvatn lake in June immediately after heavy rainfall with both runoff and snow melting down the mountain sides (June 2011), and photo of Nigardsbreen glacier and Nigardsvatn lake during dry conditions (August 2011)

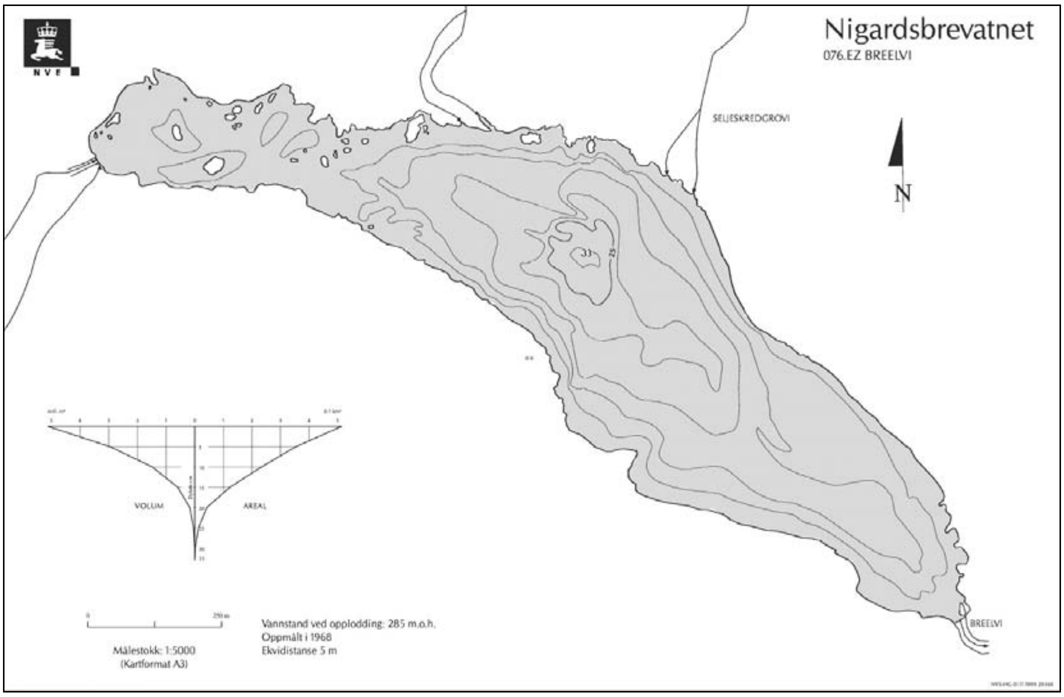


Fig. 4: Depth contour map of Nigardsbreen lake (from NVE Atlas database)

Tabel 1: Data for Nigardsvatn lake

Nigardsvatn lake	
Meters above sea level	285
Surface area (km^2)	65.73
Volume (m^3)	5.13 million
Mean depth (m)	10
Maximum depth (m)	33
Length (km)	2
Retention time (years)	0.03

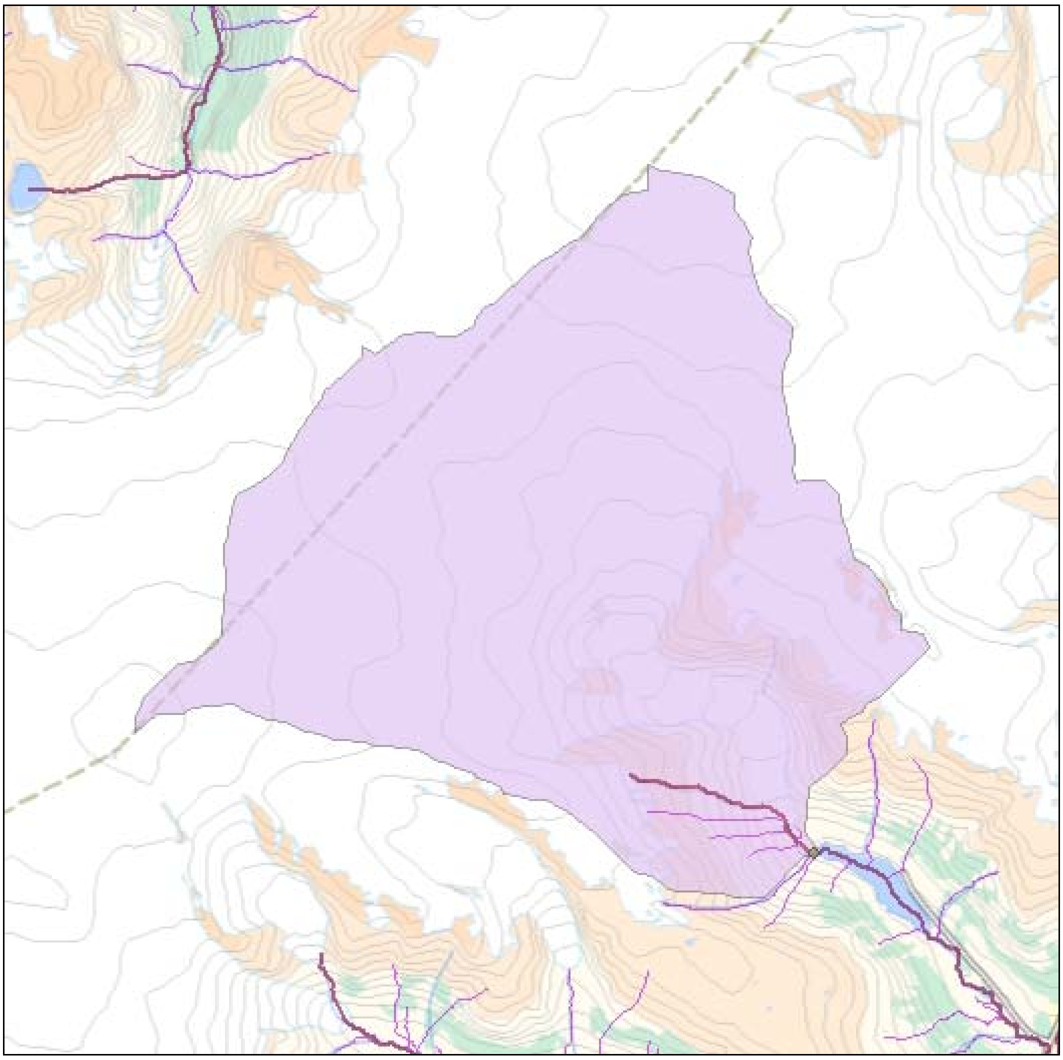


Fig. 5a: Catchment area for the inlet of Nigardsvatn lake. The catchment area is in pink and the lake is in blue. The coloured lines indicate the main streams of water entering into the lake. This is the catchment area in which water and sediments enter the lake through the melt water river running from Nigardsbreen glacier to the lake.

Table 2: Climatic, geographic and hydrological data for the catchment area of Nigardsvatn inlet (Nigardsbreelv). This area is the source of the sediments sampled at the inflowing river.

Catchment area: Nigardsvatn inlet	
Area (km^2)	54.1
Length (km	9.4
Meters over sea level (avg)	1588
M.O.S.L. (min)	285
M.O.S.L. (max)	1946
Percent glacier	84.9
Percent mountain	13.5
Percent forest	0
Percent agricultural	0
Percent urban	0
Average discharge ($L/s/km^2$)	98.5
Annual precipitation (mm)	2075
Summer precipitation- May-Sept (mm)	744
Winter precipitation- Oct-April (mm)	1330
Avg annual temperature	-1.9
Avg summer temperature	2.6
Avg winter temperature	-5.1
Temperature July	4.3
Temperature August	5.7

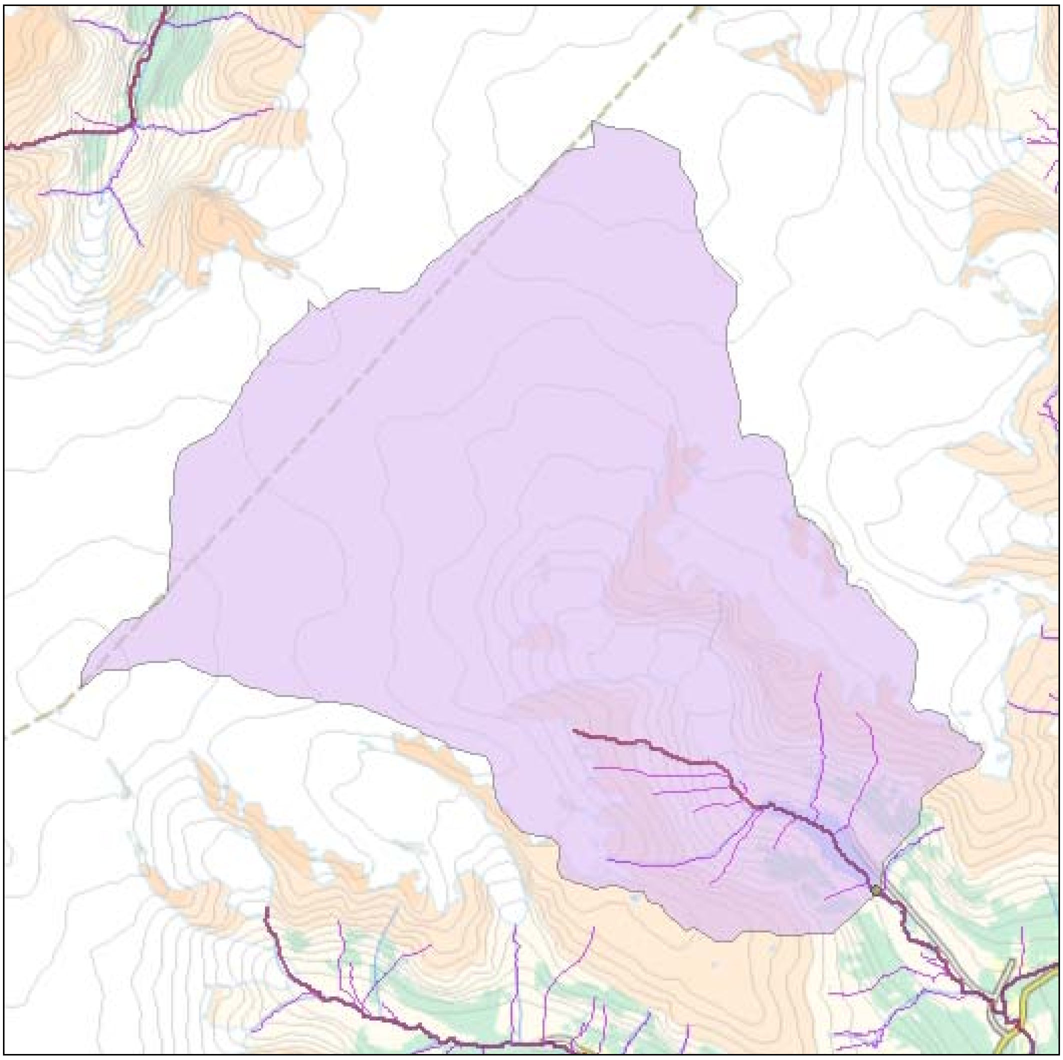


Fig. 5b: Catchment area for the outlet of Nigardsvatn lake. This is the catchment area in which water and sediments enter the entire area of the lake and lake outlet, including runoff from the mountain sides.

Table 3: Climatic, geographic and hydrological data for the catchment area of Nigardsvatn outlet (Breelvi). This area is the source of all sediments carried into the lake.

Catchment area: Nigardsvatn outlet	
Area (km^2)	64.7
Length (km	10.9
Meters over sea level (avg)	1538
M.O.S.L. (min)	285
M.O.S.L. (max)	1946
Percent glacier	74
Percent mountain	19.6
Percent forest	1.4
Percent agricultural	0
Percent urban	0
Average discharge ($L/s/km^2$)	93.6
Annual precipitation (mm)	1993
Summer precipitation- May-Sept (mm)	709
Winter precipitation- Oct-April (mm)	1284
Avg annual temperature	-1.7
Avg summer temperature	3
Avg winter temperature	-4.9
Temperature July	4.6
Temperature August	6

2.2 Program for analysis

The study of lake sedimentation includes systematic laboratory analysis for grain size distribution and total volume or weight of sediments carried in suspension and deposited on the lake bottom. Three types of sediment samples were used for this study; sediments sampled from cores, material collected in sediment traps and sediments carried in suspension sampled from the monitoring station. In addition, data on water discharge and sedimentation in the delta are also discussed. Four years were focused on: 1979 with a very large magnitude flood, 1993 with very low glacial melt, 2002 with very high glacial melt, and 2011 with extremely high discharge and several flood events. The program of analysis for this project includes the following;

- A total of 7 sediment cores taken in 2006 were chosen for analysis along the line of stream flow through Nigardsvatn lake from the glacial river inlet which flows from Nigardsbreen glacier into Nigardsvatn lake through Nigardsbreelv river and thereafter to the out-flowing river, Breelvi. Sediments from particular annual layers were analysed for thickness, grain size distribution, organic material and chemistry in order to distinguish the differences between sediments deposited during high magnitude floods due to rainfall from periods of both high and low glacial melting due to summer temperatures. The years of focus were 1979 (large flood), 1993 (cold temperatures and low glacial melt) and 2002 (very high temperatures and high glacial melt). The results were compared in relation to hydrological and meteorological variables.
- Sediment traps are also used to study sedimentation in shorter periods, where 5 traps were set out along the line of stream flow during three periods of the melting season of 2011. The first two periods had large magnitude floods, estimated in the order of magnitude of 5 and 10 year floods. These sediments were also analysed for total dry weight, grain size distribution, organic material, chemical elements and density. These results were also discussed in the context of hydrology and changes in climate.

- These results are compared to data on water discharge, concentration, percent organic and grain size distribution of suspended sediment sampled at a hydrological monitoring station, and sedimentation in the delta area with focus on the particular periods of interest.

2.3 Field methods

The field methods include the obtainment of data from suspended sediment sampling and water discharge monitoring over the past several decades, as well as the sampling of sediment cores from the lake bottom in 2006 and setting out sediment traps in the lake in 2011.

2.3.1 Suspended sediment sampling

Suspended sediments were sampled starting in 1967 from the glacial meltwater stream running from Nigardsbreen glacier to Nigardsvatn glacial lake. The sampling procedure is described by Bogen (1996). At first the samples were taken manually at both the inlet and outlet of the lake. In 1982 a monitoring station including an ISCO automatic water sampler was established. This device has 24 chambers for special sampling bottles made of plastic. It can be programmed to take samples at certain intervals, for this station samples were taken at 12 or 6 hour intervals throughout each melting season of the entire monitoring period. In 2002 a glacier advance combined with a warm summer and large melting of the glacier lead to a change in the subglacial channel system and caused water to flow out a second outlet. The temperatures during this year were higher than those recorded up to that point since 1876 (Andreasson & Oerlemans, 2009), and the mean summer temperature was 2.1° warmer than the mean from 1961-1990 (Nesje *et al.*, 2008). During this melting season a second monitoring station was built. The location of the sediment monitoring station is shown in Fig. 6a, and Fig. 6b shows the location of both monitoring stations for suspended sediments (adapted from Kennie *et al.* 2010). In addition to the sampling of water for suspended sediments, two water samples were taken at the peak of a large magnitude flood on the 29th of June, 2011 for analysis of conductivity, pH and turbidity; one at the inlet to the lake and one at the outlet.

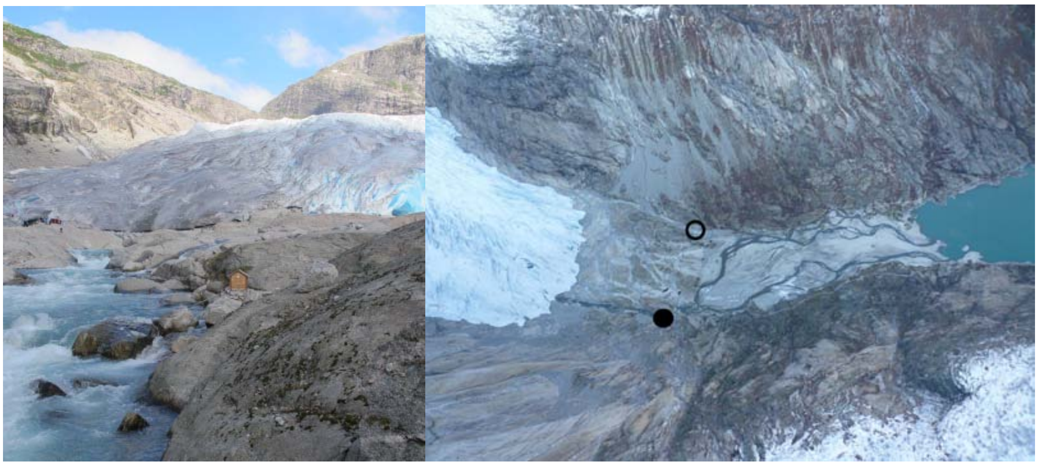


Fig. 6a,b: The sediment monitoring station at the Nigardsbreelv river, and aerial shot of Nigardsbreen glacier and Nigardsvatn lake and delta topset. The solid circle indicates the position of the main ISCO sediment monitoring station and the ring indicates the location where the supplementary station was placed for the second river channel after the glacial advance of 1999-2006.

2.3.2 Sediment coring

In 2006, sediment cores were taken up at 24 locations in Nigardsvatn lake, using a percussion corer of the type described by Reasoner (1993) and Gilbert (1985). All cores used were taken from the ice in April. The location of all the cores is shown in Fig. 7, along with the location of the sediment traps used in the experiment.

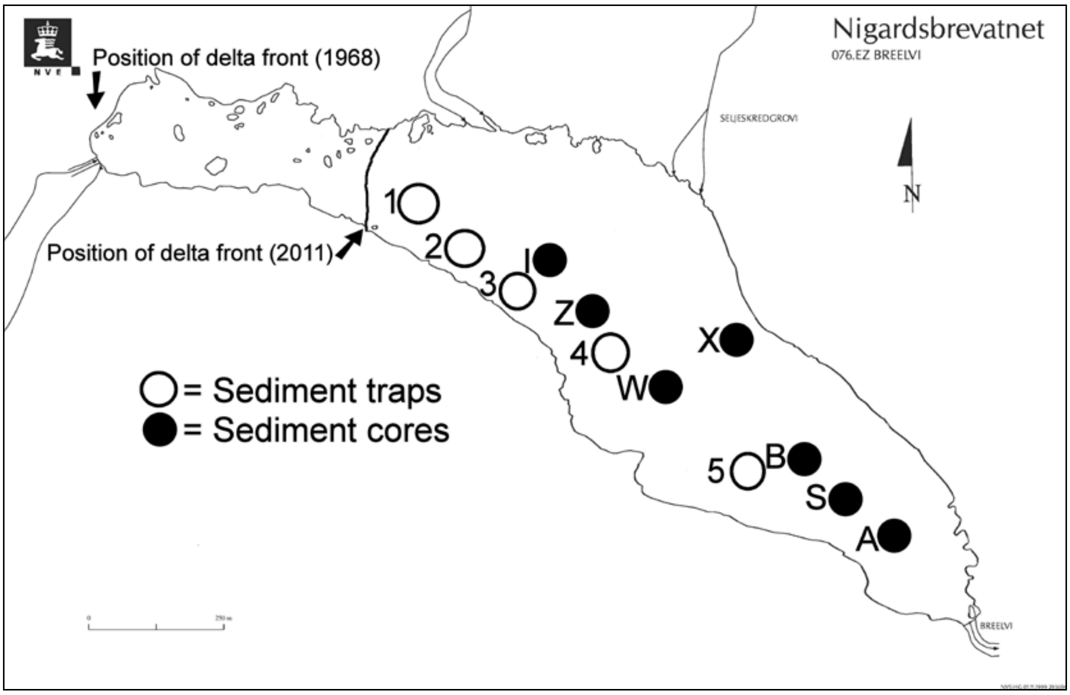


Fig. 7: Map of Nigardsvatn lake, and the locations of the sediment cores and sediment traps used in this experiment. The current and former positions of the delta front are shown.

2.3.3 Sediment traps

Five sediment traps of the type described by Håkansson (1976) were set up along the line of stream flow on Nigardsvatn lake bottom in order to determine the seasonal variation in sedimentation patterns. The bottom traps (Fig. 8a,b), were made from large buckets which were cut off 8 cm from the bottom. Of the 5 traps, two were 29.5 cm in diameter and 3 were 35 cm in diameter, due to the stores' availability of only these small amounts of the certain types. A hole was drilled in the bottom of each and a metal pipe of approximately 1 cm diameter was attached through the hole, to a lead weight underneath. Flag rope with a diameter of 0.6 mm was knotted at the bottom of each trap under the weight, and the string was led through the pipe in the trap. The traps were placed at 5 locations on the bottom of Nigardsvatn and the ropes attached to the traps stretched up to the surface where it was attached to a buoy, in order to collect sediments which would otherwise settle on the lake bed. The locations of the traps are displayed in Fig. 7.

Each series of traps was set out for approximately 5 weeks each, or from 33-35 days over a large part of the summer glacier melt period of 2011, from late

June to early October. This season had one of the highest annual water discharges measured at the hydrological monitoring station registered since the 1930s. Each series was set up during a different period of time, with different seasonal processes controlling hydrology and sediment supply. The first traps were set up June 28th 2011, and taken up again on August 1st and 2nd. These first traps were set up during the course of a flood in the area, with heavy rains. The highest water discharge during this period cumulated on June 29th, at 52 m^3/s, which corresponds to a flood with a recurrence interval of 5 years. The recurrence intervals are based on a frequency analysis of the highest flood tops each year over a long period of time. Culmination values are used instead of the daily average, as this is a more correct analysis. New traps were set out at the same time as the first traps were taken up, and stood out from August 1st and 2nd until September 5th, which was approximately 35 days. This second series was during the period of high glacial melting due to warmer temperatures combined with heavy rainfall. There was an even larger flood during this second period, with a top on August 28th at 60 m^3/s, which corresponds to a flood with a recurrence interval of 10 years. The third and final round of traps was set out from September 5th and 6th and taken up again on October 10th, after 33 days. This third period was a cooler period, when the temperatures were lower and the glacial melting decreased. Ice was already starting to form over the lake in early-mid October when the traps were taken up. After each individual sediment trap was hoisted up, the sediments were washed into wide-mouth bottles or jugs where they were left to sedimentation. They stood still for several weeks, until all the sediments including the finer clay fraction had settled, and then the excess water was decanted off. They were left open to dry.

Fig. 8a,b: In the field, setting out sediment traps, shown on the right.

2.3.4 Delta leveling

The sedimentation on the delta topset of Nigardsvatn lake has been carried out each fall since 1968, using surveying equipment. The field methods are described by Østrem *et al*. (2005) and Kennie *et al.* (2010). The procedure involved stretching wire across the delta area in up to 41 combinations to 20 bolts fastened to the mountain sides stretching along the length of the lake. Previously surveying binoculars and a meter stick were used to measure the topography, but recently a laser scanner has replaced this method. The height of the delta is measured at approximately 1000 single points, and from this data the total annual sedimentation can be calculated from data obtained in previous years.

2.4 Laboratory methods

The laboratory methods consist of analysis of suspended sediments collected at the monitoring station, sediments from sediment cores, and sediments collected in sediment traps. They were all analyzed for total amount, grain size distribution and organic carbon. Some types of sediments were analyzed for pH and chemical elements.

2.4.1 Sediment transport/sedimentation

Sedimentation rate was studied through analysis of sediments sampled from the monitoring station, sediment cores, and sediment traps.

The sediment transport determined by sediment sampling and water discharge methods was determined in the laboratory by first filtering onto Whatman glass fibre filters that were previously dried with an exicator and weighed, recording the volume of the sample, drying the filters in a drying cabinet heated to 60 degrees, and weighing them after. The total sediment mass is then the filter mass after filtration minus the filter mass before filtration. The filters are then warmed in an oven at 480 degrees in order to convert all organic carbon into carbon dioxide. This process is called Losson Ignition (LOI). The laboratory process for the filtering and weighing processes are shown in Fig. 9a and b. The weight after heating minus the filter weight is therefore the mass of inorganic sediment, and the mass of organic sediment can be calculated by the filter weight before ignition minus the filter weight after. The equations used are below (3-8), where Mt= total sediment mass, $M1$= gross mass of filter and sediments after drying, Mf= mass of dry filter, $M2$= gross mass of filter and sediments after ignition, Min= mass of the inorganic constituents of the sediments, Mo= mass of organic carbon.

2) $Mt=M1-Mf$

3) $Min=M2-Mf$

4) $Mo=Mt-Min=M1-M2$

Since organic material contains approximately 60% carbon, the weight of the organic material can be corrected for with the following equation, where Mo* is the corrected mass of organic material (van Bemmelen 1980).

5) $Mo^*=Mo*1.724$

The total sediment concentrations as well as those of organic vs. inorganic material are then calculated by dividing the sediment mass on the filters by the volume of the samples. The total transport in units of mass over time is then calculated from the data on water discharge. The following equations are used where C= sediment concentration, M= sediment mass, V= volume of sample, Q= water discharge, and Gs=sediment transport per unit time.

6) $C=M/V$

7) $Gs=Q*C$

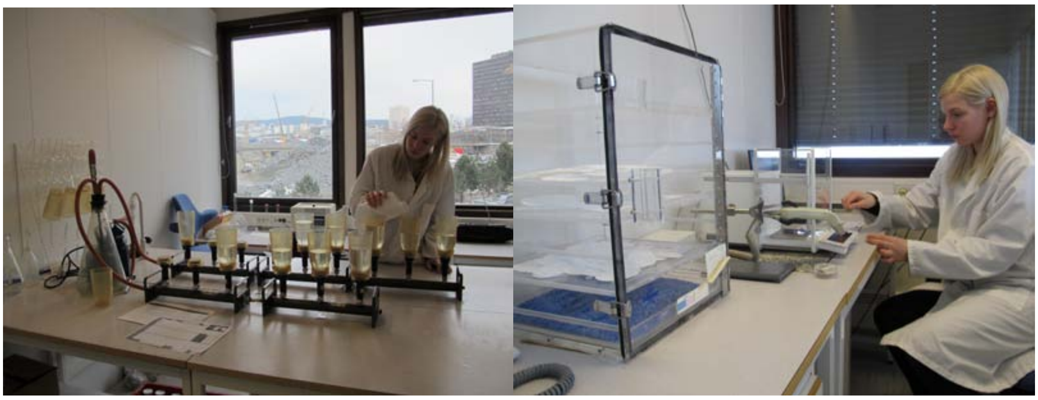


Fig. 9a,b: Filtering the suspended sediment samples in the laboratory and conducting weighing operations of the filtered and dried suspended sediment samples in the laboratory

Sedimentation on Nigardsvatn lake bottom was determined through sediment core analysis by Kennie *et al*. (2010). The sediment cores were sawed in half with a band saw and prepared using a knife and scraped so that the surfaces are flat and no loose sediments are interfering with the appearance of the varves. They were sometimes moistened with a fine mist using a spray bottle as this can often make the varves more visible. Some of the cores, mostly those close to the delta, could not be used because either they did not have varves due to the presence of coarser material and the sloping gradient, or they were distorted, possibly due to underwater landslides. A total of 7 sediment cores (I, Z, W, X-1, B, S and A) were used for the determination of sedimentation in this project. They were chosen for analysis as they were taken along the line of stream flow through Nigardsvatn lake from the glacial river inlet which flows from Nigardsbreen glacier into Nigardsvatn lake to the out-flowing river, Breelvi. The sediment core analysis to determine the thickness of each annual varve was done with the assistance of the JPEG editior program described by Kennie *et al.* (2010), created by NVE with the goal of creating an objective method to estimate varve thickness, which analyses high-quality pictures of split and prepared sediment cores. This program analyses the difference between dark and light pixels and creates a strip with white and black bars of the same thickness of the summer and winter varves. Fig. 10a shows an example of a sediment core "S" which has been analysed with this program, adapted from Kennie *et al.* (2010). Fig. 10b-g shows the other 6 sediment cores analyzed for this thesis. This strip created by JPEG editor usually has to be corrected by photoshop, which makes it somewhat subjective, due to the presence of pseudovarves and the difference in colour of the individual sediment grains. This strip is then run through another feature of the same program, which when core length is written in, gives the result of the thickness of each summer and winter varve. Variation in the thicknesses of the layers from the selected years 1979, 1993 and 2002 were plotted against distance from the inlet, as well as average annual sedimentation from the period 1979-2005.

After transfer to a large container, a sedimentation period, decantation of the water, and being allowed to dry, the sediments collected from the traps were transferred into pre-weighed metal forms, where they were set into a drying oven at 60 degrees for several days to eliminate all residual moisture. They were then weighed, and the tare weight was subtracted in order to find the total sediment weight. The dry weight of sediments from each of the 15 traps (5 traps each from 3 different series) was divided by the bottom surface area of each sediment trap in order to obtain the sedimentation in grams per cm^2. This value was then divided by the amount of days the trap was stood out for, in order to determine the average daily sedimentation by weight, per cubic centimetre. Figures and equations of the data were created using excel, relating the total sediment weight to the distance from the delta foreset.

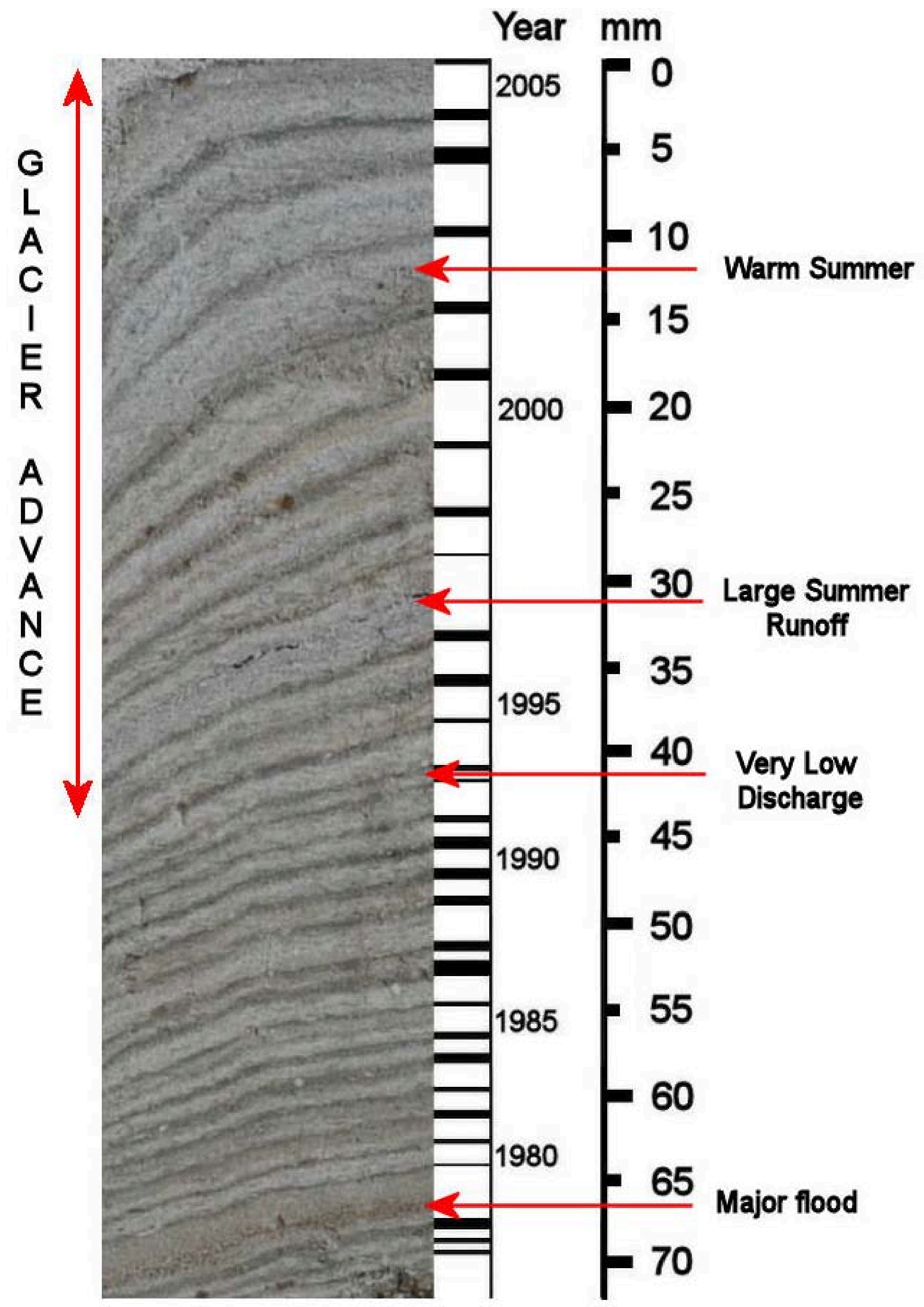
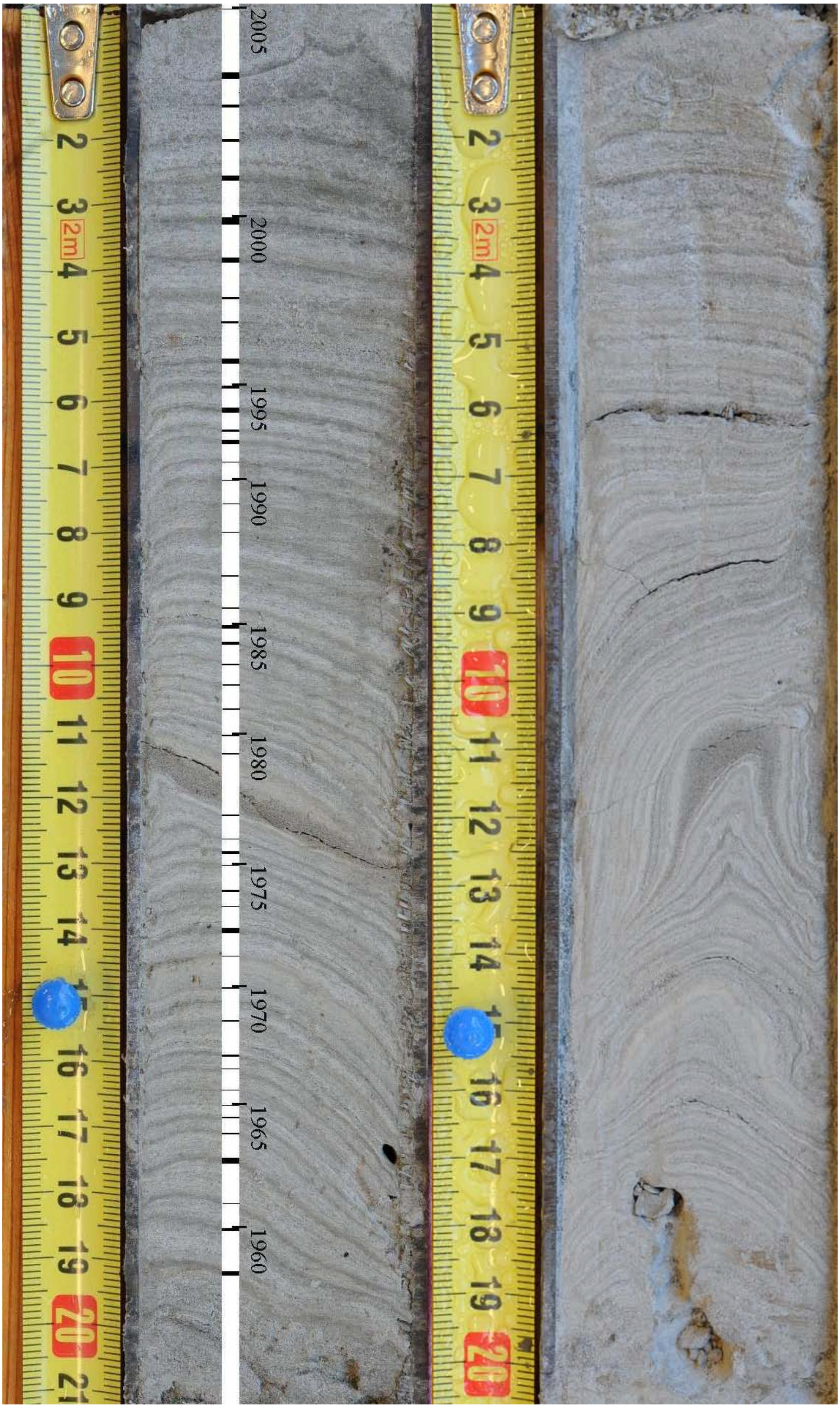


Fig. 10a: Sediment core "S", adapted from Kennie *et al.* (2010). The selected years chosen for analysis are shown; 1979 (major flood), 1993 (very low discharge), and 2002 (warm summer, during the period of a glacial advance). The differences in hydrology and climate between the years are apparent by differences in thickness and appearance of these selected layers.


2005
2000
1995
1990
1985
1980
1975
1970
1965
1960

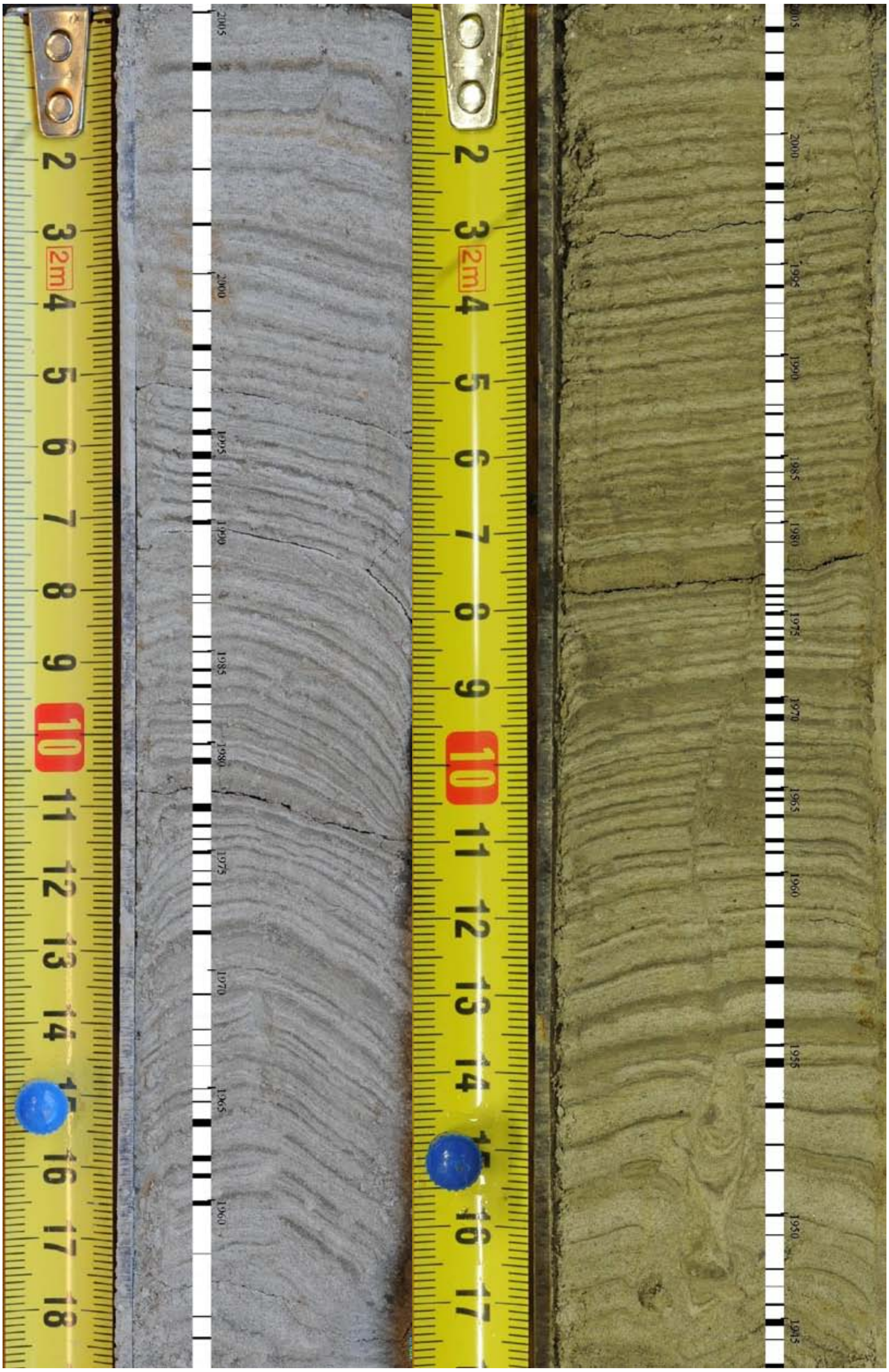


Fig. 10a,b,c,d,e,f: Sediment cores I, Z, W, X, B, A in order of decreasing distance from the inflowing river. The years are not calculated on core Z due to distortion.

2.4.2 Grain size distribution

Suspended sediments from the monitoring station, sediments from cores, and sediment traps were all analyses for grain size distribution.

The suspended sediment samples were filtered onto cellulose filters and then transferred into small, labelled laboratory beakers, where hydrogen peroxide was added in order to eliminate organic material as is standard procedure in the NVE laboratory for preparation of samples to be analysed for grain size distribution. The hydrogen peroxide reacts with the organic material, creating gasses. This is to eliminate the presence of aggregates as the organic material can flocculate and interfere with the grain size distribution curve, as well as to obtain a grain size distribution curve for purely minerogenic sediments. After several days they were filtered onto a cellulose filter while being rinsed with water to wash excess traces of hydrogen peroxide away. The samples were then added to a beaker with a small amount of water and sonicated for 2 minutes in order to break up aggregates. The samples were then analysed using a Coulter Laser Diffraction Particle Size Analyser (model Ls 13 320, shown in Fig. 11), in order to obtain the grain size distribution. The laser coulter sizer uses the principles of light reflection and refraction to determine the grain size distribution of small samples, and curves can be created using another feature of the corresponding computer program. Using the corresponding program, data could be taken out for graphical analysis.

Fig. 11: Grain size distribution analysis with the Coulter laser diffraction particle size analyser

Grain size distribution was conducted on the seven cores labelled I, Z, W, X-1, B, S and A. The year 1979 was chosen as it had a large magnitude flood with a 100-year recurrence interval, and the varves deposited during this year are thicker and visibly distinguishable from the other layers. The same analysis is done for 2002, as it is distinguished by high summer temperatures, large melting of the glacier, high sediment transport, as well as distinct channel changes due to the sub-glacial meltwater channels. 1993 was also chosen, which was a year with very little water discharge and little sediment transport. All three of these varves are relatively easily to distinguish in all the cores so there is little uncertainty as to taking out the wrong annual layer.

Small samples were taken out of the material collected in each of the 15 sediment traps for grain size distribution analysis. The same procedure was followed for analysis of particle size for all of the sediment traps as for the samples from the sediment core layers.

Sediments from the delta area were analyzed for grain size distribution by sifting, in order to obtain the percentage in the suspended fraction.

2.4.3 Determination of organic fraction

Suspended sediments sampled at the monitoring station, sediment from cores, and sediment from traps were all analyzed for organic carbon using the loss on ignition (LOI) method. The latter two types of sediment were also analyzed using a carbon analyzer.

The suspended sediment samples were analysed for organic carbon and total organic material using the method listed in section 2.4.1, involving loss on ignition.

Small samples were taken out of the core layers as well as other layers to analyse organic carbon. Samples were taken out of the 1979 layer for cores Z and I combined since they were so near each other and had such small amounts of material. A sample from the 1979 flood layer was also taken out for core X. Samples from the period 1968-1978 as well as the period 2000-2005 were taken out from the three cores Z, X and A. It was not possible to take samples out for individual years besides 1979, due to the small amounts of material. The samples were first dried in the drying cabinet at 60 degrees, weighed with a ceramic vessel of predetermined weight, and thereafter set into the ignition oven at 480 °C for two hours. This process converts the organic carbon into CO_2. The sample in the ceramic vessel is then weighed again. The difference between the weights before and after ignition with the LOI method is a proxy for amount of organic material. The weight of the sediments minus the weight of the vessel after ignition is the weight of inorganic material. The percentage of organic and inorganic fractions can then be found by dividing the individual weights of organic and inorganic sediments by the total weight of the sediments in the vessel before ignition.

The samples were also analysed for carbon at the University of Ås earth sciences building with a LECO carbon analyser CHN-1000 (EC12), as well as nitrogen. The material is first crushed, weighed in a Whatman glass fiber filter and rinsed 5-6 times with 1M HCL and a glass pipette to eliminate the carbonate from the material. The samples are then rinsed with distilled/deionised water to eliminate traces of Cl. The samples are dried in the drying oven at 70 degrees, and then packed into a porcelain container.

The same procedure was followed for analysis of organic material for all 15 of the sediment traps as for the samples from the sediment core layers.

2.4.4 Determination of chemistry

Water samples collected during the flood peak were analyzed for pH, conductivity, and turbidity, sediment from cores and traps was analyzed for chemical elements, and the sediment from the traps were also analyzed for pH.

Two water samples taken at the peak of the flood on the 29th of June, 2011 were analyzed for two different chemical parameters. One was taken at the inlet and one was taken at the outlet. They were analyzed for conductivity with a Radiometer Copenhagen- CDM 80 conductivity meter, for turbidity with a HAch 2100 AN IS Turbidimeter, and for pH with a PHM210 standard pH meter (Meterlab, Radiometer Copenhagen).

Small samples of sediments were taken from the same layers in the sediment cores for chemical analysis as were taken out for the analyses of organic carbon (described in 2.4.3). These samples were analyzed for the following chemical elements with an ICP perkin-Elmer 5000 DV ICP OES (optical emission spectroscope), after digestion with acid; Ca, Mg, Na, K, Fe, Mn, K, Al, P, S, Zn, Pb and Cu. pH analysis was not conducted on these samples since the material could have reacted with atmospheric constituents in order to acidify the sample.

Material from all 15 sediment traps was analyzed for chemical elements in the same method as the material from the sediment cores above. In addition, water was extracted from above the material collected in each of the traps for pH analysis with an Orion SA 720 pH meter.

2.4.5 Estimation of density

Density is estimated for suspended sediments, cores and traps.

The density of suspended sediments was not analyzed in the lab, it was taken from known densities of the rock species in the area, gneiss, and the important minerals (quartz, feldspar and mica, from Olson & Ziegler, 1987).

Sediment density from cores was not analyzed in the lab, it was taken from that which previous studies of Nigardsvatn and other glacial lakes had found.

The analysis for density of the material in the sediment traps was achieved by calculating the volume of the samples by measuring the diameter of cylindrical container in which the wet samples were kept in, and the height of the sediments. They were assumed to have settled naturally as they do in nature. The mass was then taken out of the cylinder and weighed, and the density was calculated by dividing the weight by the volume. This was done for two samples; Sample 1 from Series 1, and Sample 5 from Series 3.

The bulk density of the material deposited in the delta area was not measured for this project, it was taken from previous studies and known bulk density of material in glacial deltas.

2.5 Data analysis

A program created by NVE called JPEG editor was used to analyze the thickness of the varves in the sediment cores. The NVE Hydra database was used in order to obtain data and create some of the curves for water discharge. A GIS program along with Corel Paintshop were used to plot the GPS points of locations of the sediment cores and traps as well as the delta front on the map and calculate distances. The program for the laser coulter sizer called ls13320 along with excel were used in order to calculate the data and create the graphs and equations. The grain-size distribution curves as well as sedimentation at specific locations during the different periods were analyzed in comparison to the distance from the inflowing river in which the bed sediments were deposited, as well as in the context of their characteristic periods or years, such as high precipitation and floods, or either low- or high glacier melting.

3 RESULTS

The results of the analyses for sediment transport, sedimentation, grain size distribution, organic carbon and sediment chemistry are listed below.

3.1 Sediment transport and sedimentation

Sediment transport and sedimentation were calculated in various ways from sediments collected at the monitoring station along with water discharge measurements, sediment in the cores and sediment collected in traps.

3.1.1 Sediment concentrations, water discharge, and delta sedimentation

Large seasonal and year-to year fluctuations in sediment transport delivered to the lake were observed, through the analyses of the water sampled at the monitoring station and discharge measurements. The most extreme levels of sediment and water discharge were measured in 1979, during a large magnitude flood with a recurrence interval estimated at 100 years (Gjessing & Wold, 1980; Hegge & Krog 1981). The flood in August of 1979 lead to a very high but short lived water discharge and the highest suspended sediment concentrations recorded during the entire monitoring period since sampling started in 1968. The flood peaked at over 80 m^3/s on the night of August 14-15 with concentrations over 3000 g/L, see Fig. 12(a). This flood was of a very large magnitude with extremely high water discharges and was responsible for the transport of large amounts of suspended sediment, but it was short and intense only over two days. The rest of the 1979 season did not experience especially high water discharges or sediment transport. The total water discharge over the year was 191 millions of m^3, and suspended sediment transport was 18,400 tons. This year is an example of a very high water discharge which lasted a very short time and caused very high sediment concentrations.

The year 1993 is included because it is an example of a year with low water discharge and low suspended sediment transport and thin sedimentation in the lake. This year had much lower water discharge and sediment transport than the other years in the study and was one of the lowest years on record. The total discharge was 95 millions of m^3 and the suspended sediment transport throughout the year was 4,600 tons. Maximal concentrations reached only under 80 mg/L during the water discharge 24-27 m^3/s. During large parts of the season the water discharge was less than 10 m^3/s, see Fig. 12(b).

The year 2002 is an example of a season with relatively high water discharges lasting over a large portion of the melting season. This year had maximum water discharges between 30 and 40 m^3/s. During two months from around July 8^{th} to September 8^{th} water discharge was mostly above 20 m^3/s measured at the main monitoring station. Over almost 10 days at the end of August the concentrations were over 500 mg/L. This year, like 1979, also experienced a short lived pulse with relatively high sediment concentrations in August, where maximum concentrations reached 1900 mg/l, see Fig. 12(c). The high water discharge came from glacial melting due to high summer temperatures, one of the warmest summers observed in Norway since measurements started in 1876. Total transport in 2002 is slightly larger than the total transport in 1979, and had the second highest water discharge and sediment transport recorded since the monitoring started, after the year 2011. Total water discharge over the season is measured at 255 millions of m^3 and the total suspended load is measured at 20,000 tons but there is some uncertainty in these measurements due to the difficulties in monitoring these parameters, due to the establishment of new meltwater channels from the glacier, so these values are probably underestimated.

The 2011 season had the highest total discharge on record since the monitoring started in 1968. The total discharge over the season was 259 million m^3/s and the total suspended sediment transport was 34,000 tons. This is higher than all the other years on record. Maximum sediment concentrations were around 1200 mg/L. This year experienced two large magnitude floods. The first culminated on the 19th of June at 52 m^3/s, with a recurrence interval of 5 years. The second had a recurrence interval of 10 years, and culminated at 60 m^3/s the 28th of August. This second flood experienced sediment concentrations of over 30 mg/l, but later in the season there were higher sediment concentrations at over 50 mg/l, see Fig. 12(d).

The water samples taken at the inlet and outlet of the lake during the peak of the June flood of 2001 showed a turbidity of 20 NTU at the inlet and 15 at the outlet.

The amount of sediment deposited in the delta during the melt season of 1979 was 16900 tons. 10100 tons were accumulated in 1993, 22900 tons in 2002 and 12400 tons in 2011. The years 1979, 2002 and 2011 were above the average value of 11850 tons, while the year 1993 was below average (Fig. 13, Appendix 1).

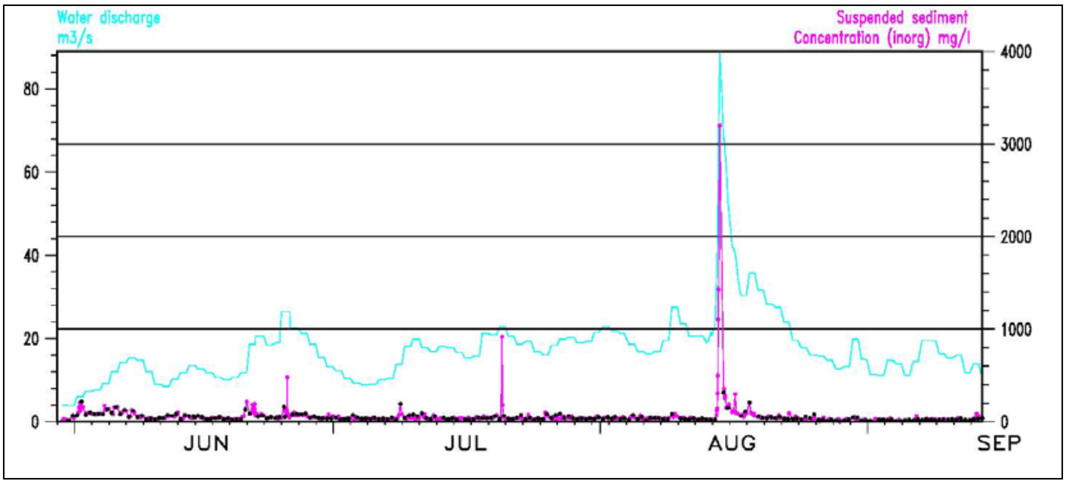


Fig. 12a: Data for water discharge and suspended sediment concentrations for the river Nigardsbreelv, 1979. The peak in water discharge and suspended sediment concentrations occurred during the large magnitude flood of August 14-15.

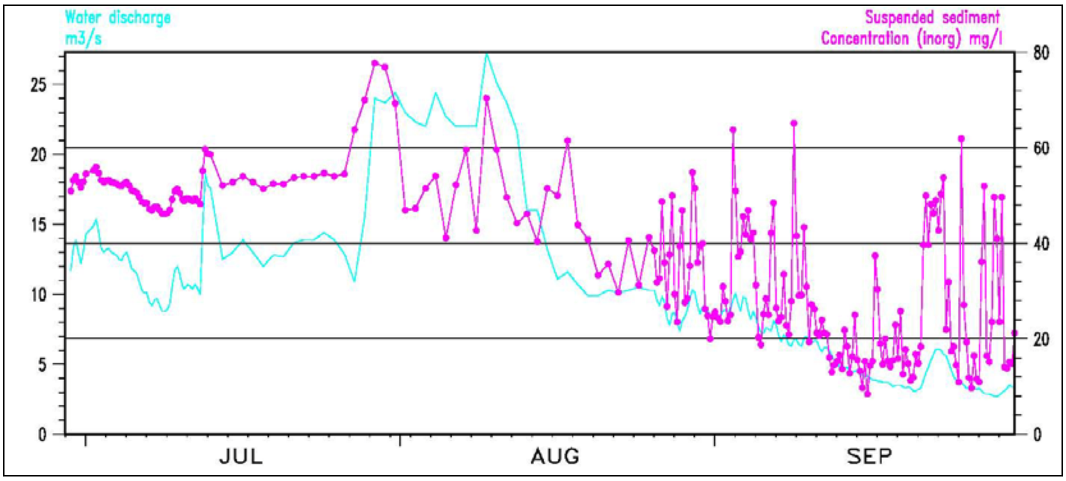


Fig. 12b: Data for water discharge and suspended sediment concentrations for the river Nigardsbreelv, 1993. This year had lower than average water discharge and sediment transport.

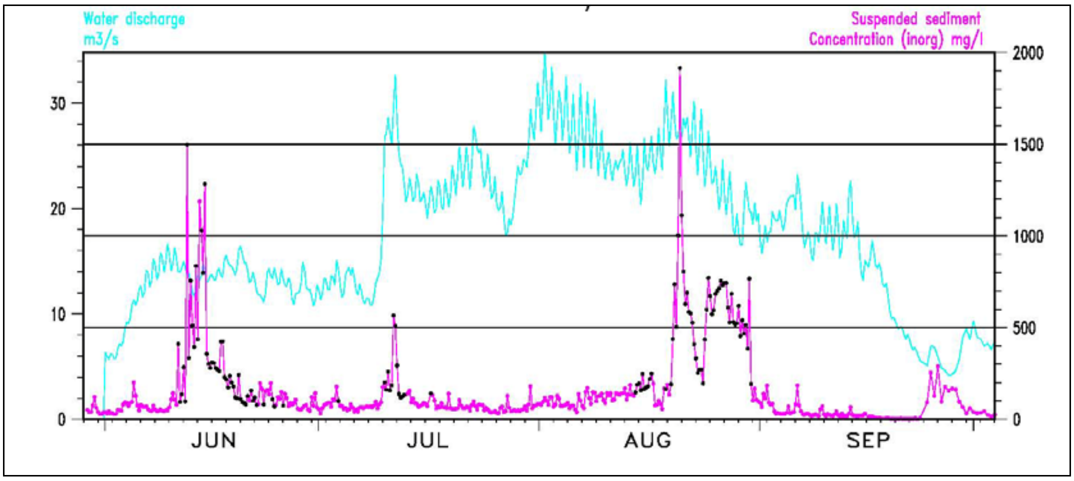


Fig. 12c: Data for water discharge and suspended sediment concentrations for the river Nigardsbreelv, 2002. This year had a warm summer during a period of glacial advance, causing a long lasting higher than average water discharge, subglacial channel changes, and high sediment transport.

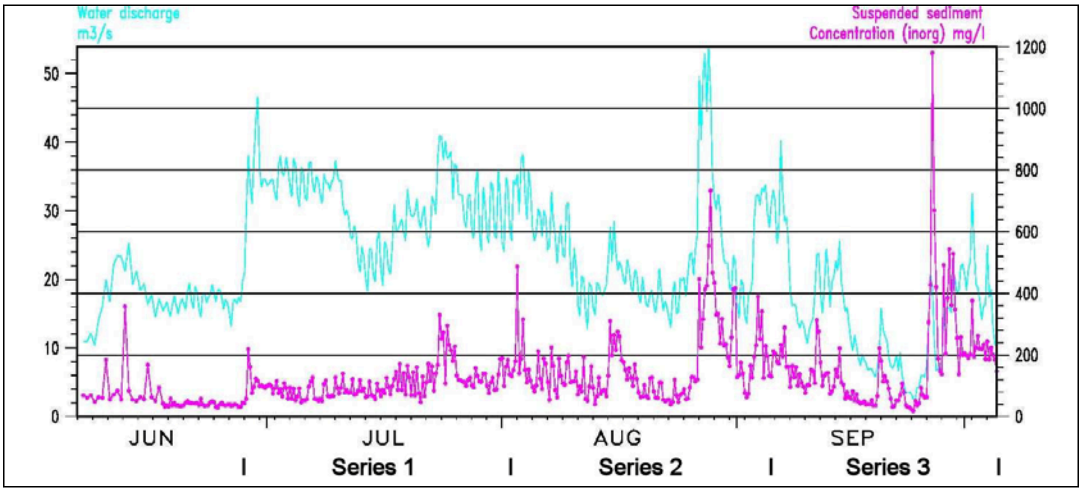


Fig. 12d: Data for water discharge and suspended sediment concentrations for the river Nigardsbreelv, 2011. The periods for each series of sediment traps are indicated; Series 1: June 28-Aug1 and 2, Series 2: Aug 1 and 2-Sept 5, and Series 3: Sept 5 and 6- Oct 10. The two large magnitude floods peaks in June 19th and August 28th can be observed.

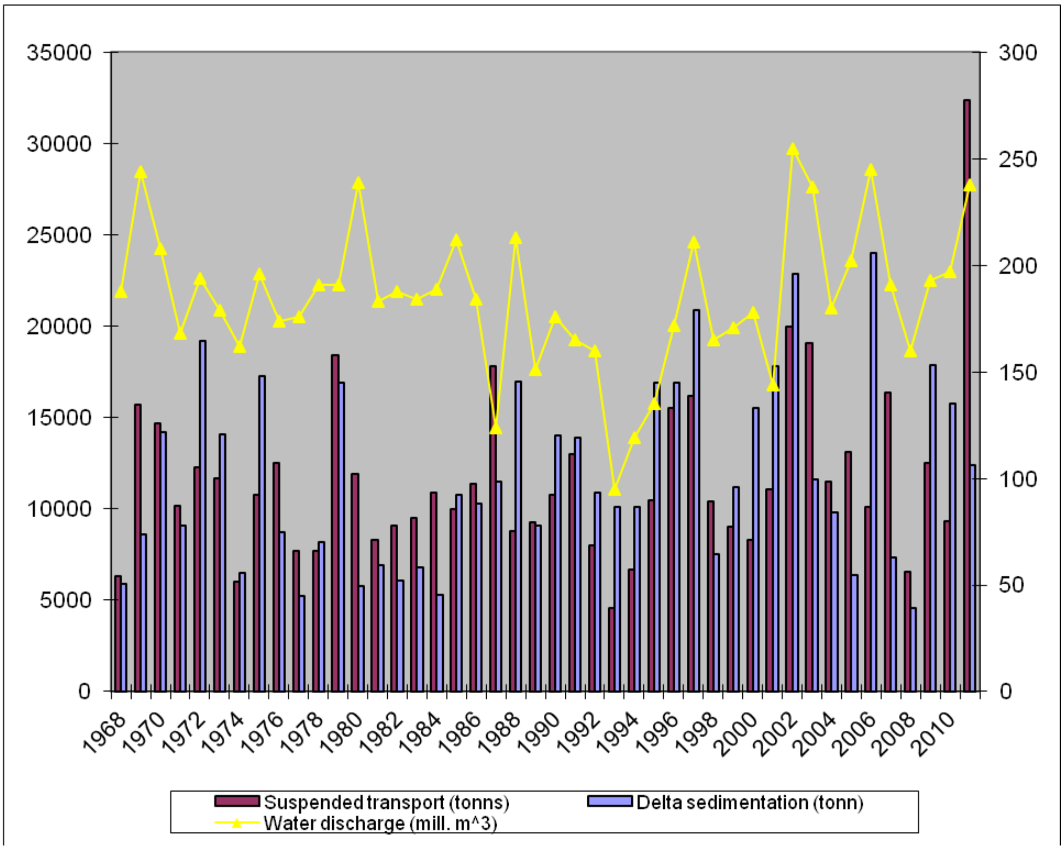


Fig. 13: Suspended sediment transport, delta sedimentation and water discharge per year in Lake Nigardsvatn. The left axis indicated sediment amount in tons and the right axis indicates water discharge in millions of m^3. The focus years of this study are 1979, 1993, 2002 and 2011.

3.1.2 Sediment cores

Kennie *et al.* (2010) estimated total sedimentation in the lake through sediment core analysis. Analyses of the sediment cores showed a decrease in thickness of each varve with distance from the delta front, see Fig. 14 and Appendix 2. The sediment cores showed more sedimentation in the lake during the year 1979 than in most other years, especially in the cores taken closer to the delta front where the sediment thickness deposited during this year was up to 12 mm. The average sedimentation from all cores was 6.3 mm for 1979, 2.2 mm in 1993 and 5.0 mm in 2002. This compares to the average of 3.3 mm for all the years from 1979 to 2005. Although 1979 had significantly higher sedimentation than the other years at the two locations closest to the delta, at some other locations further out into the lake 2002 had larger sedimentation. 1993 had significantly lower sedimentation than all other years with varve thicknesses of less than 2 mm at several locations further away from the delta. The varve thickness of each annual layer generally decreased with distance from the delta, along the line of stream flow in the lake. There is an exponential decrease in varve thickness with distance from the inflowing river. Each year had different sedimentation curves as well as the equation describing sediment thickness as a function of distance from the inlet.

The downstream decrease in sedimentation rate in lakes close to the river mouth is best fitted by potential relationships. The equations are in the form of $y=ax^{-b}$ where the exponent b is related to the dynamic and geometrical properties of the system, y is sedimentation in either depth or mass per unit of time and x is distance. Allen (1968) developed these equations through laboratory experiments with current ripples and small sand deltas. The *b*-value was found to be related to the ratio of Vs/V, where Vs is the settling velocity of sediments and V is the flow velocity in the basin of sedimentation. A large b-value implies rapid fallout of the sediments, and when the *b*-value is low, the sediments are kept in suspension further downstream (Bogen, 1983). The equation for 1979 is $d=3.3*10^3*x^{-1.0}$ and the equation for average sedimentation per year over the period 1979-2005 is $d=161x^{-0.6}$ where d is sedimentation thickness in mm/year and x is distance from the delta front, in m. The equations for 1993 and 2002 are $d=1574x^{1.1}$ and

$d=104x^{-0.5}$ respectively. The curve for 1979 decreases more sharply with a higher gradient than the other curves. The equations are summarized in Table 4.

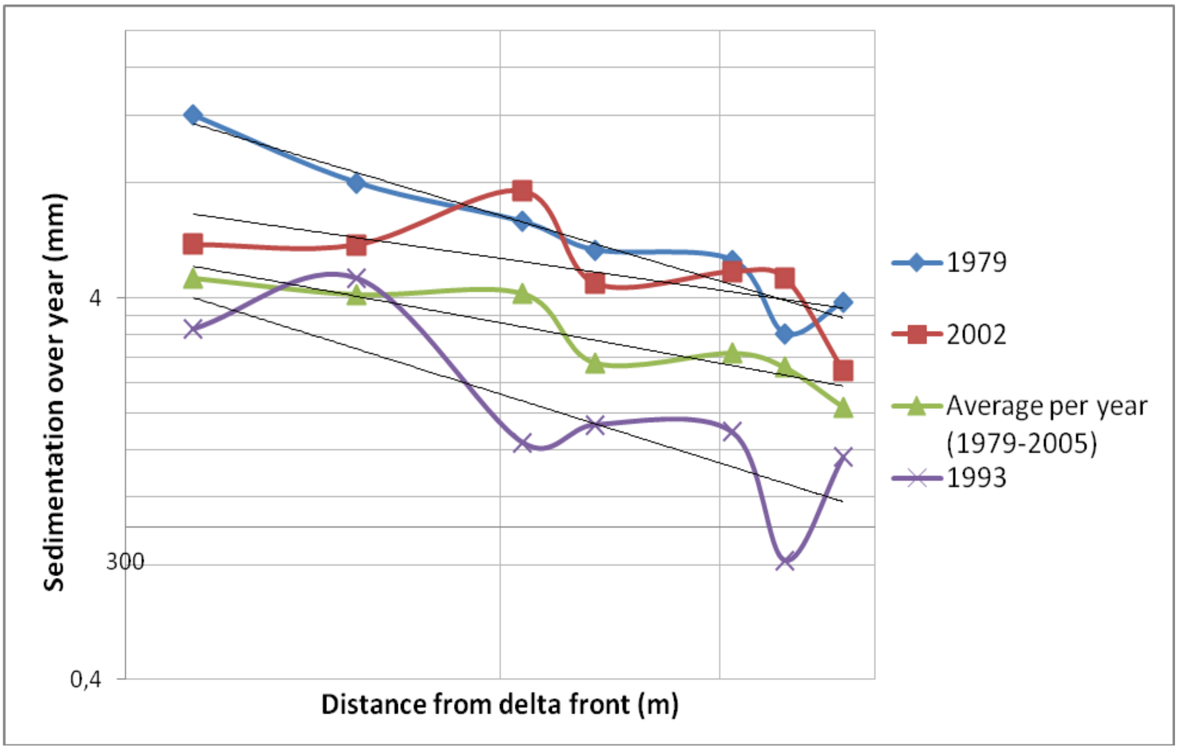


Fig. 14: Thickness of each annual sediment layer (mm) for sediment cores with decreasing distance from the delta front (m). Included is a trend line and equation for 1979 as well as for the average over all years from the period 1979-2005. The average sediment thickness per year was found from dividing the total sediment thickness from 1979 to 2005 by the number of years.

Tabel 4: Sedimentation equations from sediment core varve thickness for respective years 1979, 1993, 2002 and average thickness per year from the entire period 1979-2005.

Year	Equation
1979	$d=3.3*10^3*x^{-1.0}$
1993	$d=1574x^{-1.0}$
2002	$d=104x^{-0.5}$
Average	$d=161x^{-0.6}$

3.1.3 Sediment traps

All three series of sediment traps throughout the 2011 summer season had similar results and trends in sedimentation per day measured by dry sediment weight versus distance from the delta front, but they differed in grain size distribution of the sediments. The traps at location 1 closest to the delta had low sedimentation, the traps at location 2 second furthest from the delta had extremely higher sedimentation than all other traps, and traps at locations 3, 4 and 5 had decreasing sedimentation with increasing distance into the lake. The exception to this is trap number 5 in series 5, which had much higher sedimentation than the other traps. Fig. 15 and Appendix 3 show the sedimentation in traps as a function of distance from the delta front for all 3 series from the summer of 2011, along with an average of daily sedimentation from these traps, as well as the exponential equation for the curve $M=3.2*10^4*x^{-0.9}$ where x is distance from the delta front in meters and M is mass of average daily sedimentation in $g/m^2/day$. The equation is only valid a distance away from the delta front, from trap 2 which is 195 m into the lake. The three series had significantly higher amounts of sediment in trap number two (394-595 $g/m^2/d$), which was second farthest from the delta at approximately 195 meters, with the exception of trap number 5 in series 3 which had 751 $g/m^2/d$.

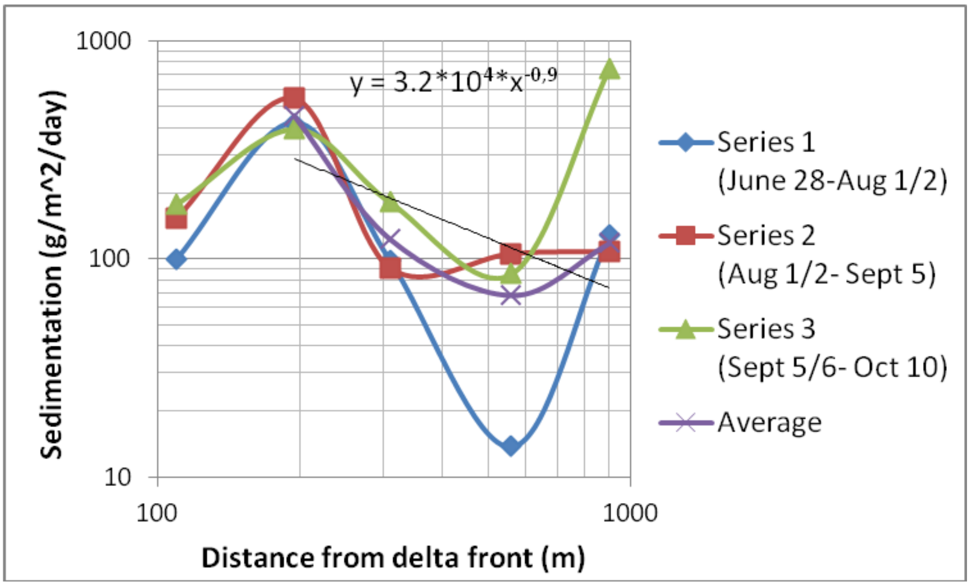


Fig. 15: Total daily sedimentation in traps 1-5 set out on Nigardsvatn lake bottom at varying distances from the delta front, summer-fall 2011, including the average daily sedimentation from all series of traps (Series 1-3) in locations 2-5 set out on Nigardsvatn lake bottom during the melt season of 2011. Location 1 is omitted for the average curve, as it was too close to the delta front and therefore did not have much sedimentation. Series 3, location 5 is also omitted, as it had abnormally high sediment accumulation, most likely from a landslide.

3.2 Grain size distribution

Grain size distribution analysis was conducted from sediments at the monitoring station, sediment cores and sediment traps. Suspended sediments are generally considered to be material under 0.5 mm, or 500 micron. The particle size of suspended sediments is divided into clay (under 2 µm), silt (2-63 µm) and the finer fractions of sand (63-500 µm). Material larger than 0.5 mm such as coarser sand (0.5-2 mm), gravel (2-64 mm), and larger rocks such as cobbles and boulders are only transported as bedload with higher discharges, moving in contact with the river bed. The erodability, transport and sedimentation of each grain size is dependent on the water velocity and turbulence in the river or lake (Hjulström 1935).

3.2.1 Sediment sampled at monitoring station

There were no suspended sediment samples from 1979 to be analyzed for grain size distribution. The average % sand (over 63 micron) from 1993 was 53.7, ranging from 23-79%. In 2002 the amount of sand ranged from 7-88%, with an average of 27.9, and from 2011 it ranged from 10-88% with an average of 39.4% (Figure 16a-c, Appendix 4-6). The grain size distribution shows little correlation with water discharge or suspended sediment concentrations. Some of the largest sand percentages were not during periods with very high water discharge when compared to the hydrograph curves (Fig. 12a-d), and 1993 had much higher sand than the other years.

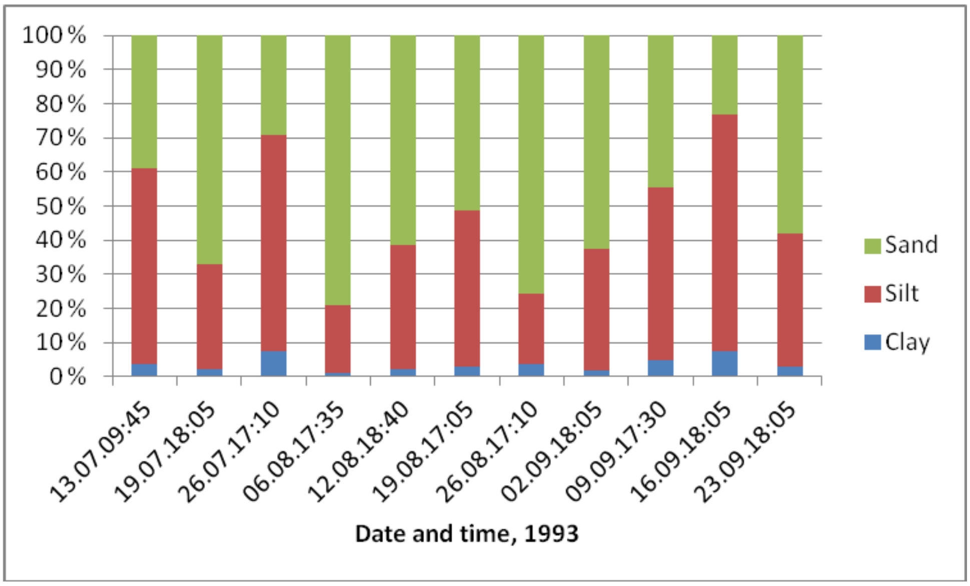


Fig. 16a: Grain size distribution for suspended sediment samples taken at the monitoring station over the melting season 1993

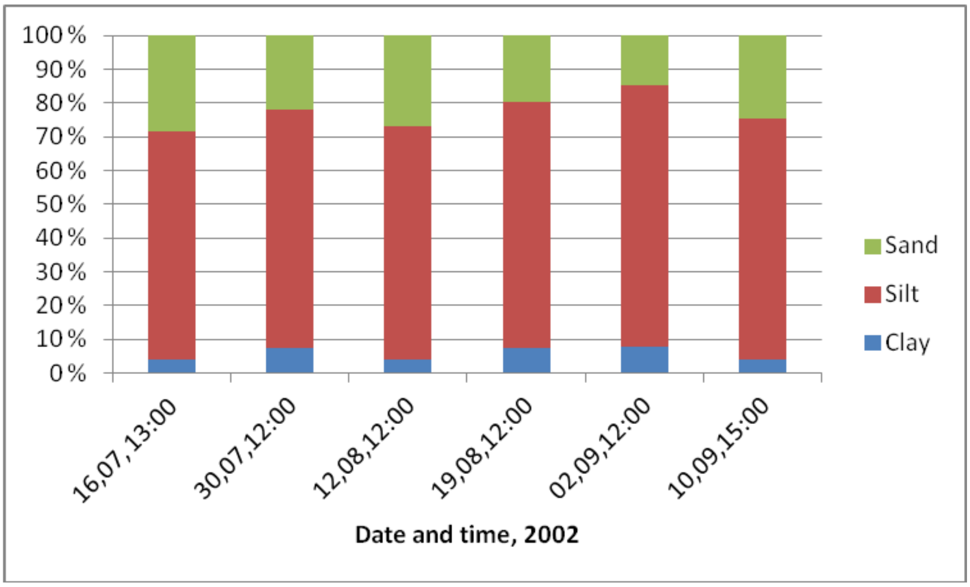


Fig. 16b: Grain size distribution for suspended sediment samples taken at the monitoring station over the melting season 2002

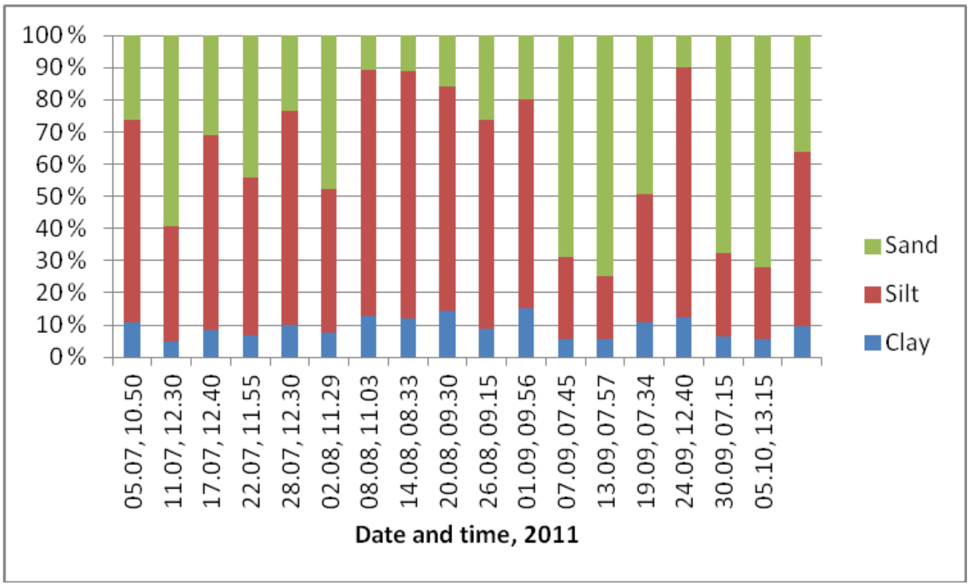


Fig 16c: Grain size distribution for suspended sediment samples taken at the monitoring station over the melting season 2011

3.2.2 Sediment cores

The curves for particle size distribution within each annual layer of the sediment cores as a function of the cores' location in the lake with increasing distance from the delta front is shown in Fig. 17a-c and Appendix 7-9. The sediments deposited during the flood of 1979 had a higher percent volume of coarser material in the size range of 31-250 μm than the sediments deposited in the other years, especially in the cores closest to the river delta. 1993 had much lower relative percentages of coarser sediments than the other years, and larger relative amounts of material under 31 micron. The samples from the year 2002 had a higher percentage of sediments in the larger size ranges than in 1993, and these size ranges dominated in the cores closest to the delta, but 2002 had smaller percentages of these coarser particles than 1979.

Fig. 18 and Appendix 10 show the mean grain size and percent sand for each individual varve from the years 1973 to 2005 in core "S". In this core, the 1979 layer also had a greater percentage in the sand fraction (over 63 micron) and a larger mean grain size (22.82 micron) than the layers from the preceding years and the next several years, but in later years a trend appears towards a higher mean grain size and higher percentage of sediment in the sand fraction. Both the mean grain size and percent sand are larger for the 1979 layer than in all but one of the preceding 6 years as well as the following years until 1997. After 1997 there is a trend towards increased mean grain size and percent sand in the cores. 1979 has larger grain sizes than most of the other years in core S, although not significantly. Cores from other locations closer to the delta had larger volume percentages of material over 63 µm, especially the two cores taken closest to the inflowing river. The volume percentages of sand were 23.35% in core I and 10.32% in core Z in 1979, which are larger than the values for the same cores in the years 1993 and 2002 and the 5.58% in core S which is much further away from the inlet.

Fig. 19 and 20 (Appendix 11-17) show the percent sand and mean grain size respectively in the annual layers of the cores in relation to distance from the delta front. There is a negative trend with a decrease in each of these two parameters with further distance away from the inflowing river. The layer from 1993 with lower water discharge generally had a smaller mean grain size and percentage sand than the other two years. 2002 and 1979 had similar results, but the core closest to the inlet had a much higher mean grain size and percentage sand deposited in 1979.

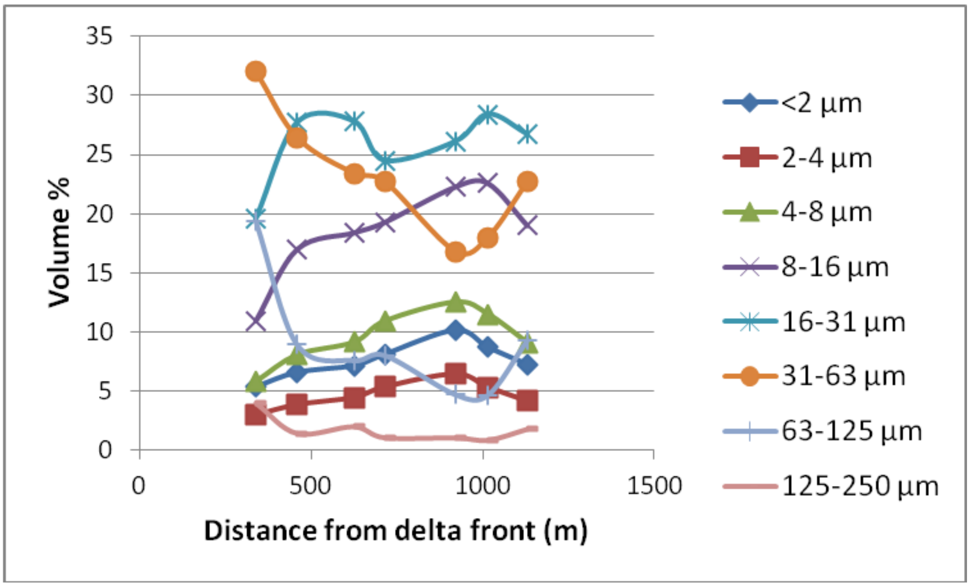


Fig 17a: Grain size distribution for sediment cores, 1979 flood layer

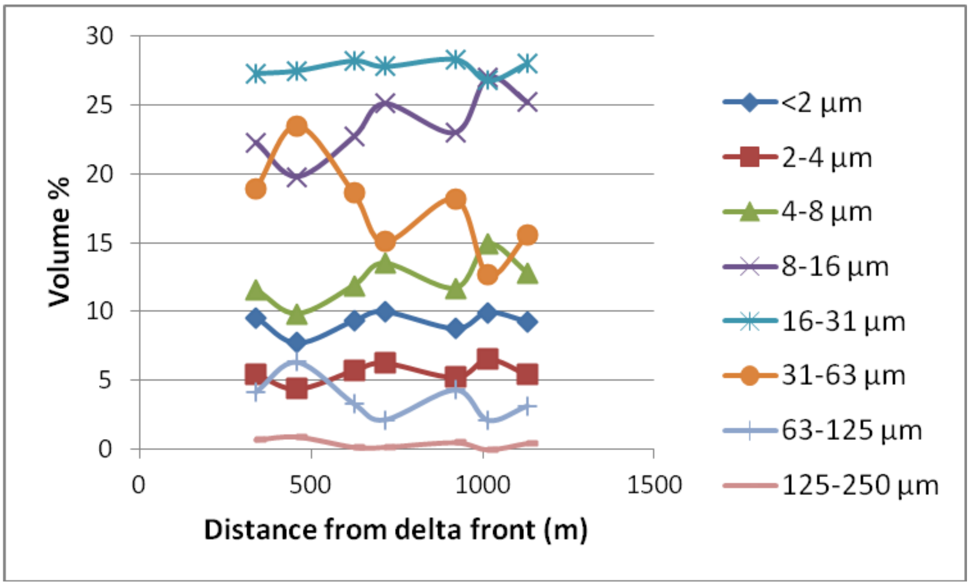
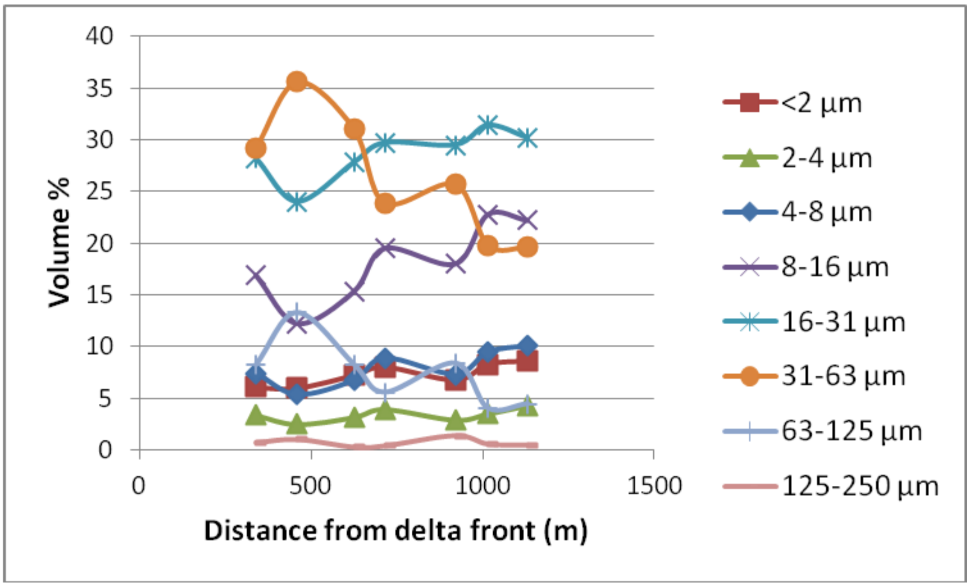


Fig 17a: Grain size distribution for sediment cores, 1993 layer



Fix 17c: Grain size distribution for sediment cores, 2002 layer

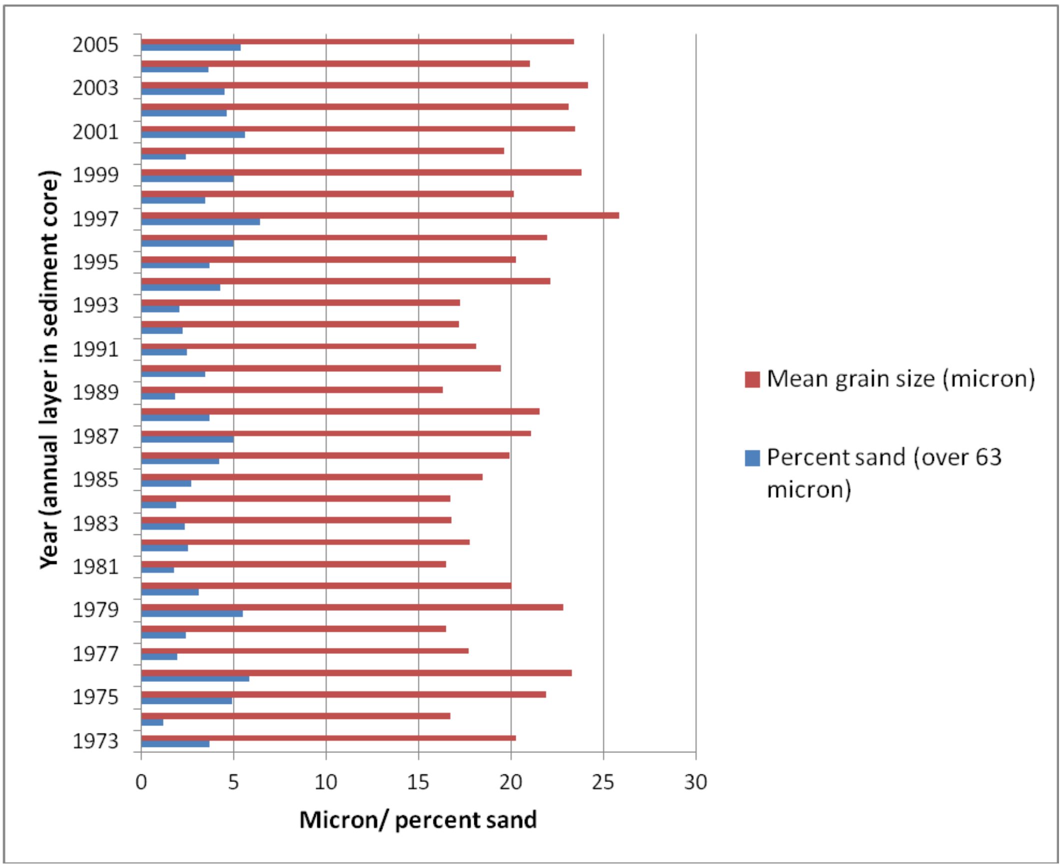


Fig. 18: Mean grain size and percent sand for sediment core ”S”

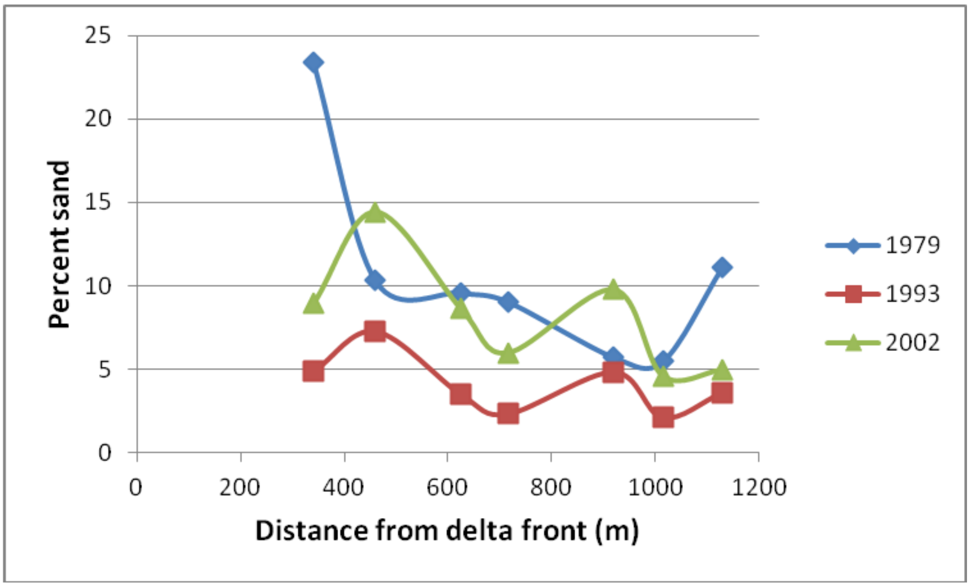


Fig. 19: Percent sand in annual layers of the cores vs. distance from the delta front

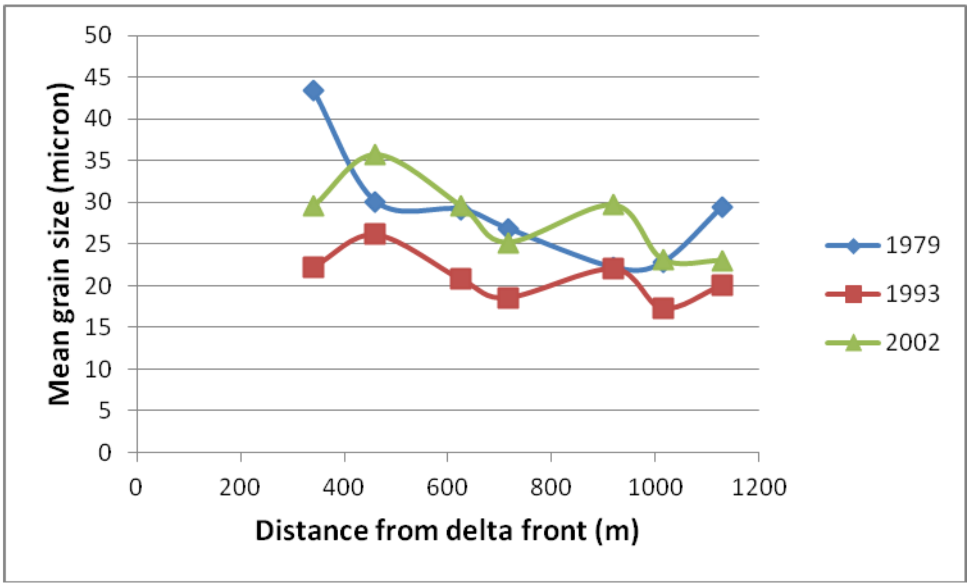


Fig. 20: Mean grain size in annual layers of the cores vs. distance from the delta front

3.2.3 Sediment traps

The grain size distribution curves for material in the size range 31-250 µm deposited in each of the 3 series of sediment traps as a function of distance from the delta front is also shown in Fig. 21a-c and Appendix 18-20. The larger size ranges dominate in the traps at location 2, which is second closest to the delta front at 195 m, with over 40 percent of the material at this location in this size range for the first two series and a sharp reduction as the stream flows further out into the lake. Series 3, the only series without a flood, had only negligible sand, from 1.3 to 6.7 percent, much less than the other two series which had from 10 to nearly 40 percent sand. Series 3 also had a higher percentage finer material smaller 31 micron. Series 2, with a higher magnitude flood, had a higher percentage sand than series 1. The size range from 125 to 250 micron had negligible amounts in most traps except for at location 2 in series 1, and location 1 and 2 for series 2. The smaller size ranges under 31 micron on the other hand, had the lowest relative amounts in location two, and remain relatively stable or increase at the other locations further out into the lake. There was also a higher percentage material in the clay fraction (under 2 micron) in series 3 than in series 1 and 2. Series 1 and 2 which contained floods had significantly more material of a diameter larger than 31 micron that series 3 without a flood.

The material from the traps and cores with a diameter over and under 31 micron is shown in Fig. 22a,b and Appendix 21-24. The traps from series 2 and 3 which experienced floods had much more material over this diameter than the cores, especially close to the delta front, with the exception of the 1979 layer of the core nearest the delta front.

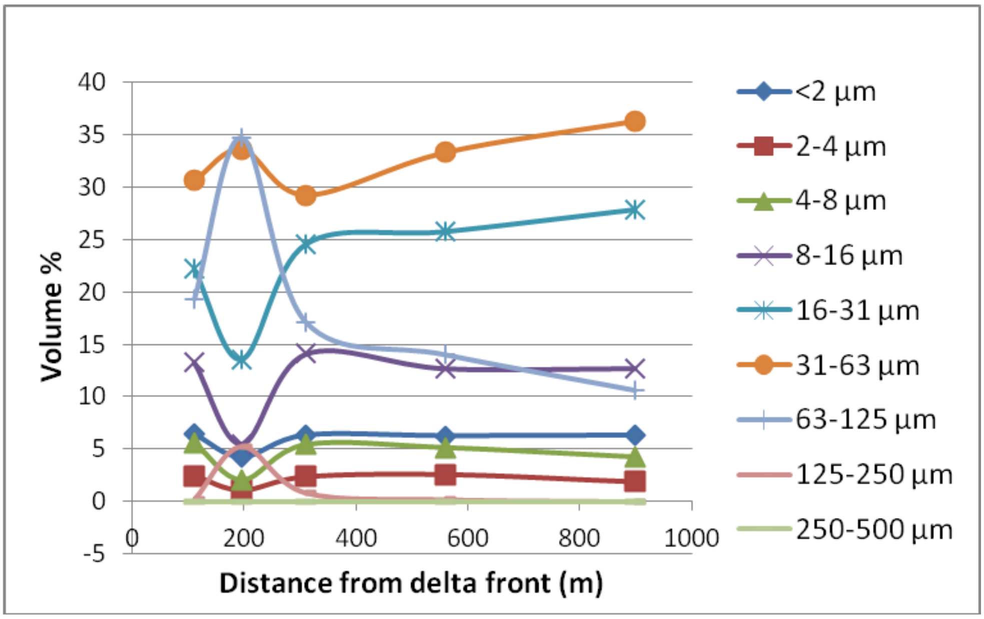


Fig 21a: Grain size distribution curve for sediment traps, Series 1

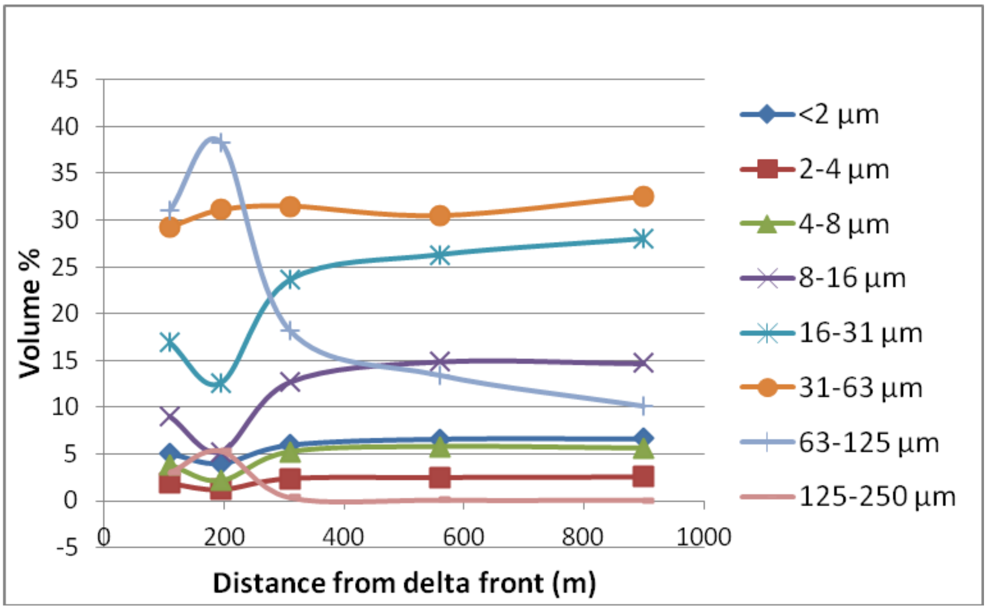


Fig 21b: Grain size distribution curve for sediment traps, Series 2

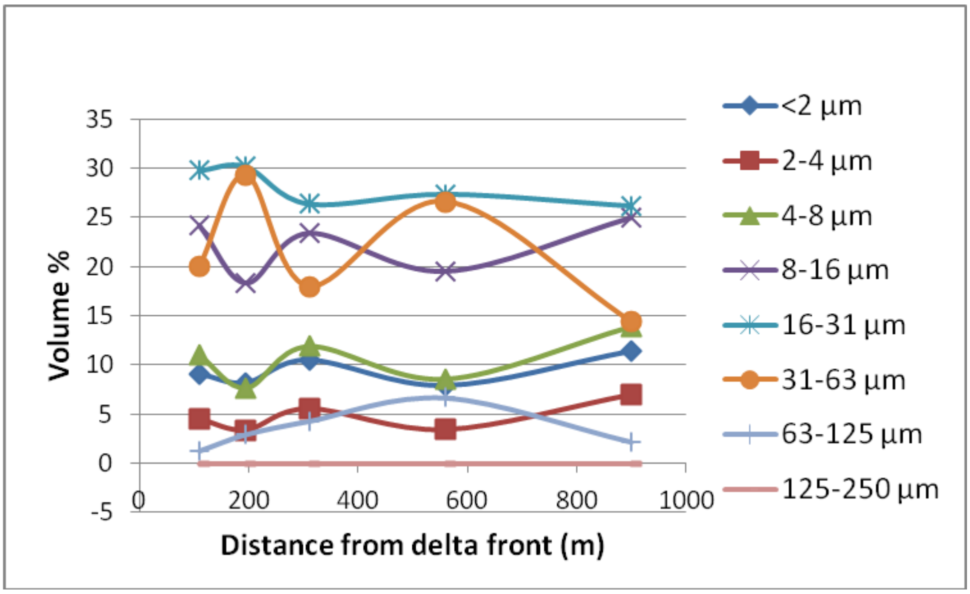


Fig 21c: Grain size distribution curve for sediment traps, Series 3

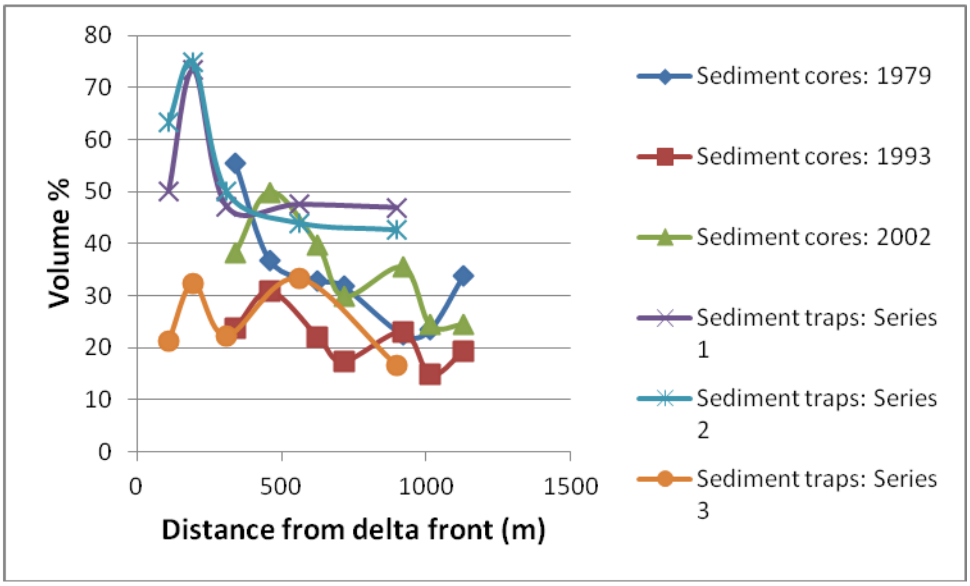


Fig 22a: Grain size distribution for both traps and cores, fractions over 31 micron.

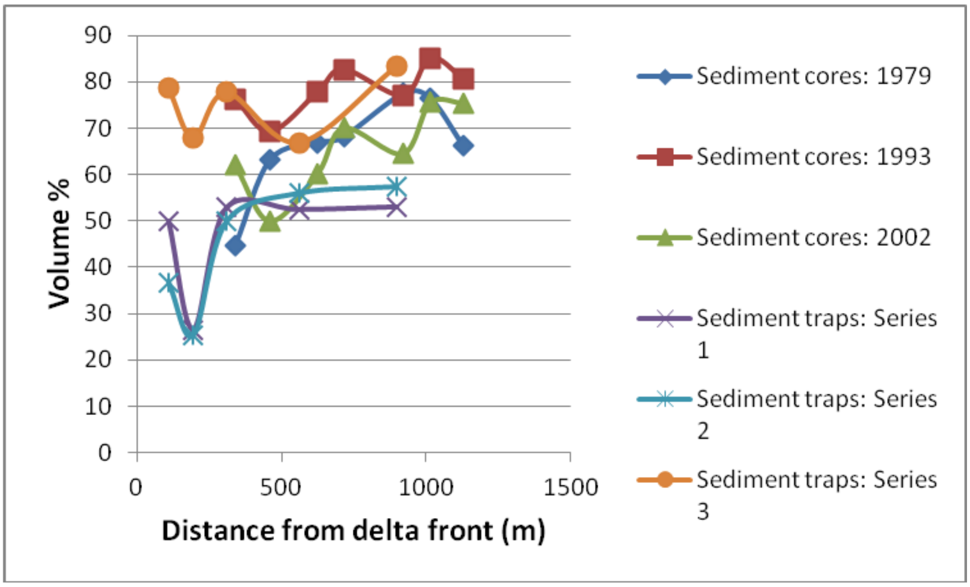


Fig. 22b: Grain size distribution for both traps and cores, fractions under 31 micron.

3.2.4 Delta

Olsen (2008) found that from 6% of the material at the area of the delta closest to the glacial front to 90% of material deposited in the delta closest to the foreset are in the suspended size fraction, with an average of 42.6%.

3.3 Organic material

Analysis for organic carbon was conducted on the suspended sediments collected at the monitoring station as well as sediment cores and traps. Organic sediment, also known as particulate organic matter (POM) consists of particles of organic matter which are the remnants of dead and decomposing organisms or parts of organisms. In water samples, particulate organic carbon (POC) can be distinguished from dissolved organic carbon (DOC) by the grain size of the sediments, where 0.45 µm is the boundary between the two, but this is not used for solid samples. The composition of organic material is mostly carbon (45-55%) along with P, N, O, H and other trace elements, so therefore organic carbon can be a proxy for organic sediments (vanLoon and Duffy 2011). Loss on ignition represents organic matter where organic carbon is approximately half the mass (Rognerud *et al.*, 2000), whereas the carbon analyser analyses for total C.

3.3.1 Sediment sampled at monitoring station

The suspended sediments measured at the monitoring station during the years had varying percents of organic material (Fig. 23, Appendix 25-27). There was no data for the year 1979. The year 1993 had much higher percentages of organic carbon than the years 2002 and 2011, especially in July. The years 2002 and 2011 had similar trends for organic carbon, except 2002 had higher amounts in October of this year.

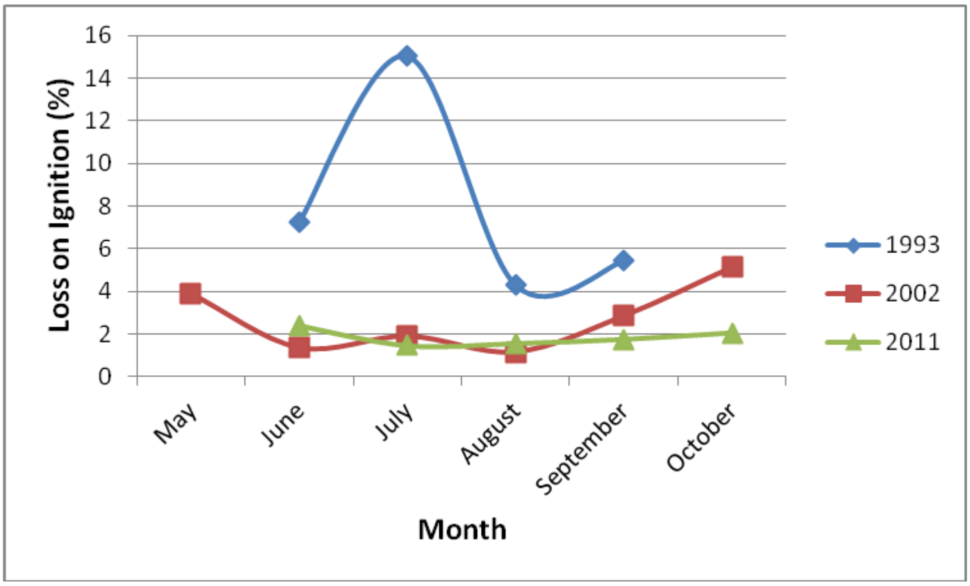


Fig. 23: Loss on ignition each month in the suspended sediment samples collected from the monitoring station at the inflowing river.

3.3.2 Sediment cores

Fig. 24 and 25 (Appendix 28-29) show the results of the analysis for organic carbon from the loss on ignition method, and carbon analyzer respectively. The curves follow the same trend, but the percentages are much lower for the C-analyzer (0.07-0.5 %) than for the LOI method (2.0-7.2 %). The percentage of organic carbon in the cores (2.0-9.7%) was much greater in the traps (0.3-1.3%), from LOI. The 1979 flood layer contained almost double the organic carbon than the other layers (7.2-9.7 % vs. 2.0-4.3 %).

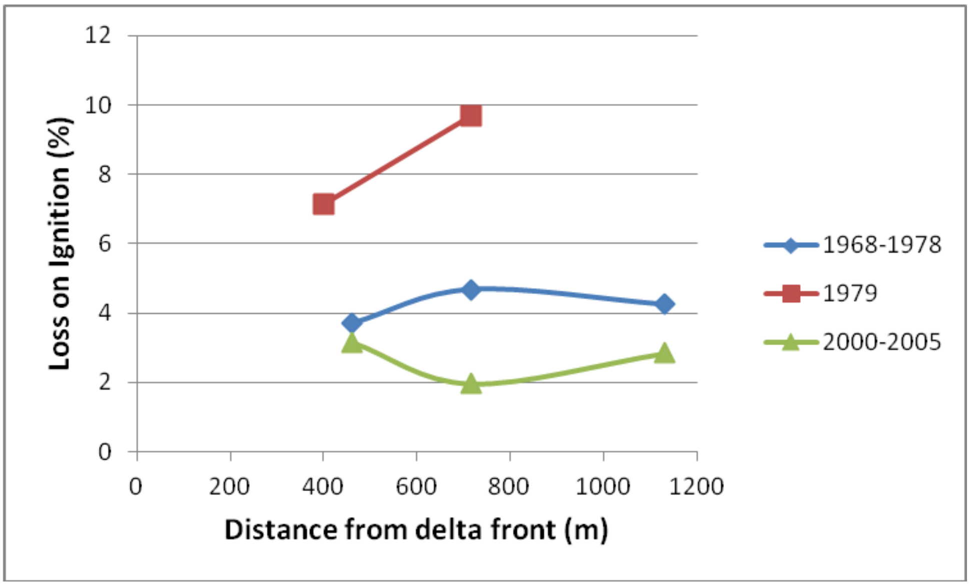


Fig. 24: Loss on ignition as a function of the sediment cores' distance from the delta front for 3 periods; 1968-1978, 1979 (flood year), and 2000-2005 (after glacial advance and subglacial channel changes)

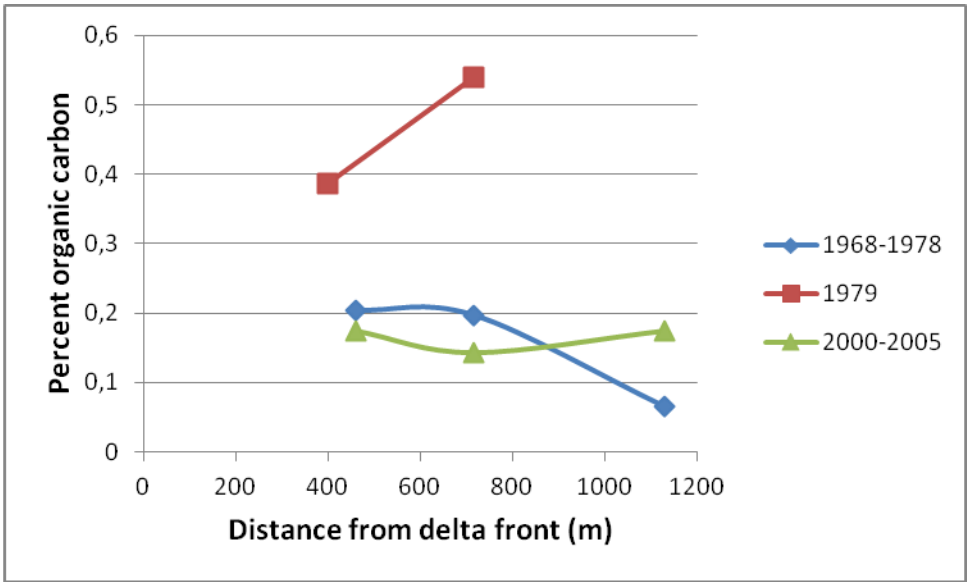


Fig. 25: Percent organic carbon from the carbon analyzer as a function of the sediment cores' distance from the delta front for 3 periods; 1968-1978, 1979 (flood year), and 2000-2005 (after glacial advance and subglacial channel changes)

3.3.3 Sediment traps

Fig 26 and 27 (Appendix 30 and 31) show the amount of organic material in the samples from the loss on ignition method, and the CN-analyzer method. The results are similar and follow the same trend, but the values from the C-analyser

(0.05-0.3 %) are much lower than those from the LOI-method (0.3-1.3 %). The relative amount of organic carbon is lower where there is highest sedimentation, in trap location 2, but the absolute amount is much higher. Series 3 on the other hand, without a flood, has different grain size distribution than series 1 and 2, under which high magnitude floods occurred. For this series, the highest percent organic was at trap 2, whereas the other two series had the lowest percent organic at this location. In addition, series 3 had a higher percent organic carbon at trap location 5 than the other two series. Series 1 trap 4 and series 2 trap 1 have the highest percent organic material.

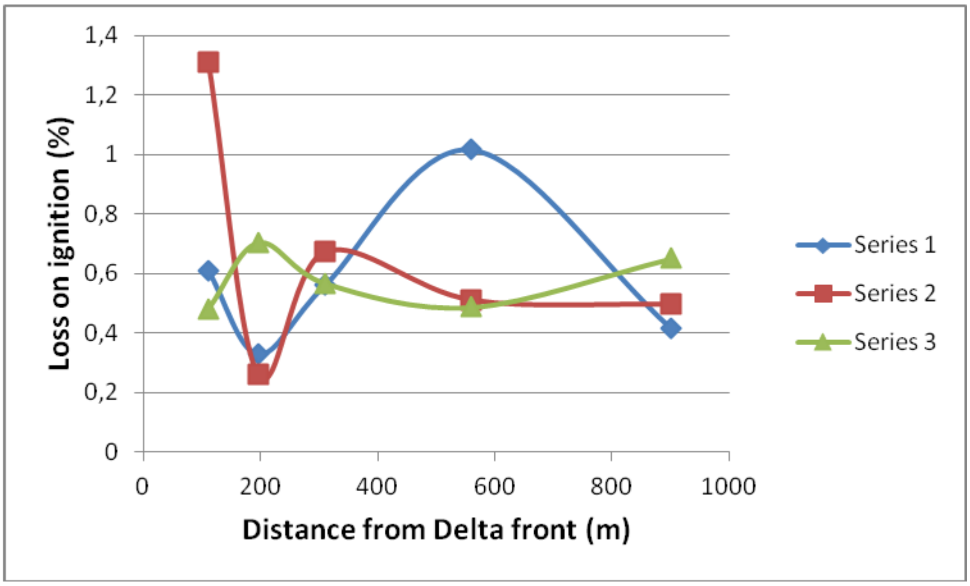


Fig. 26: Loss on ignition as a function of the sediment traps' location in relation to the delta front

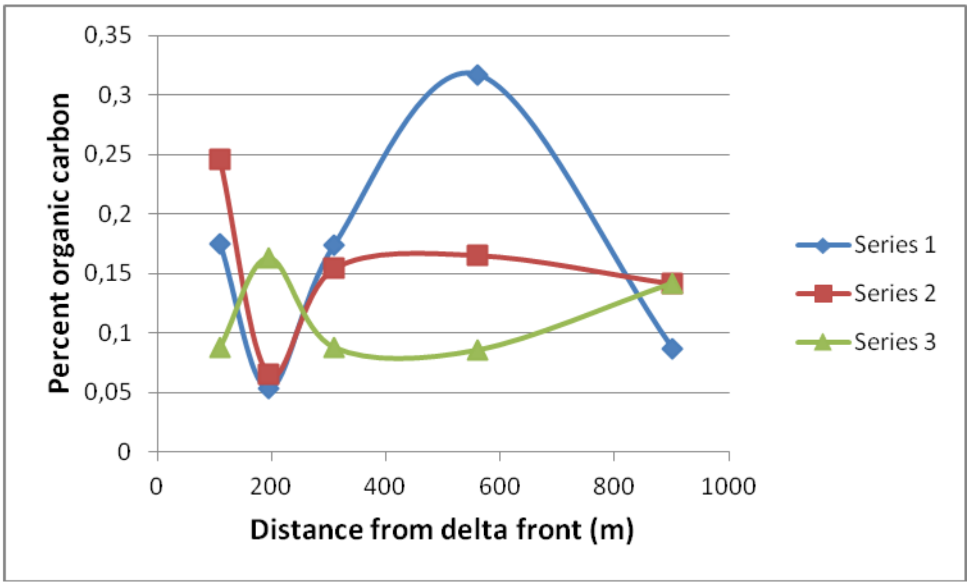


Fig. 27: Percentage organic carbon as a function of the sediment traps' location in relation to the delta front, from the carbon analyser.

3.4 pH

3.4.1 Water samples

The pH in the water sample taken at the lake inlet during the peak of the flood in June, 2011 was 5.5. The pH of the sample taken during the same time period at the outlet was 4.78

3.4.2 Sediment traps

Fig. 28 and Appendix 32 show the pH of the water over the sediments at each trap. The pH varied between 4 and nearly 7. There was no significant difference between the pH during the three different periods, except the two flood periods had a lower pH at the first trap closest to the inlet.

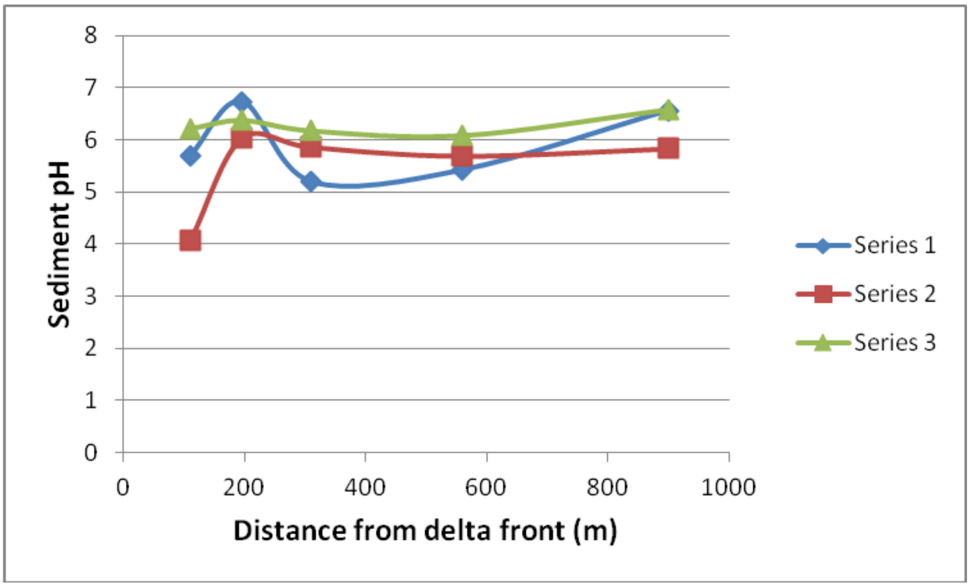


Fig. 28: pH of the sediments from sediment traps

3.5 Conductivity

3.5.1 Water samples

The conductivity in the water sample taken at the lake inlet during the peak of the flood in June, 2011 was 6.33 µS/cm. The conductivity of the sample taken during the same time period at the outlet was 22.6 µS/cm.

3.6 Chemical elements

The analysis for chemical elements in sediment layers deposited in various time periods was conducted for the sediment cores; 1968-1978 before the great flood, the flood year 1979, and 2000-2005 which was the period of the glacial advance and subglacial channel changes. These analyses were also done for the 15 sediment traps.

3.6.1 Sediment cores

All the sediment cores had higher concentrations of Al, Ca, Cu, Fe, K, Mg, Mn, P, S, and Zn in the 1979 flood layer than in the other layers (Fig. 29a-l, Appendix 33). Only the elements Na and Pb did not have higher concentrations in the flood sediments of 1979. The elements Al, Cu, Fe, K, Mg, Mn, Na, Pb and Zn exhibited a trend of higher concentrations in the sediments deposited from 1968-1978 than from 2000-2005 nearest to the delta front, but higher concentrations in the sediments deposited from 2000-2005 further out into the lake. The elements Ca, P and S on the other hand exhibit the exact opposite trend. Iron had larger concentrations in all cores in the 2000-2005 layers than in the sediments deposited in 1968-1978.

3.6.1.1 Aluminium (Al)

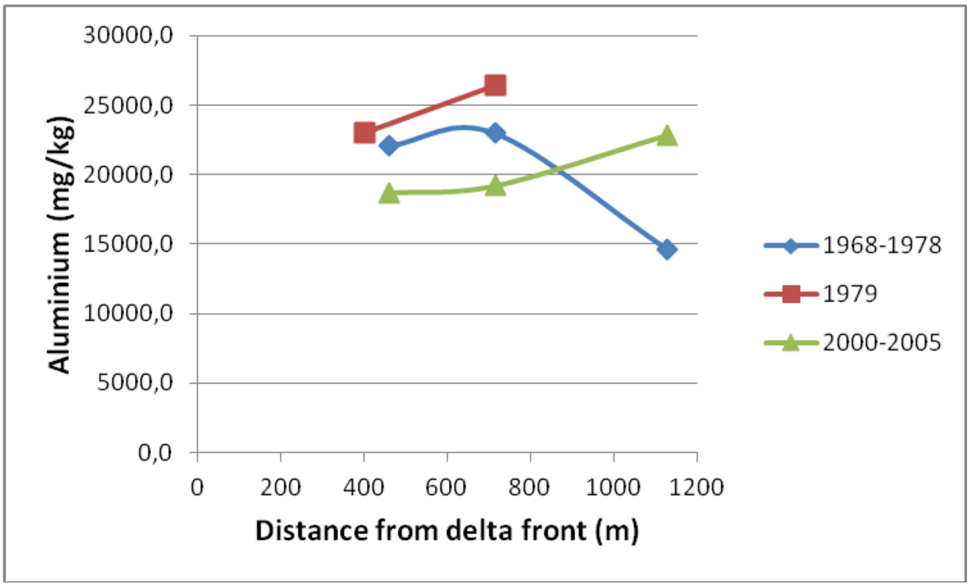


Fig. 29a: Results for the aluminium analysis from the sediment cores

3.6.1.2 Calcium (Ca)

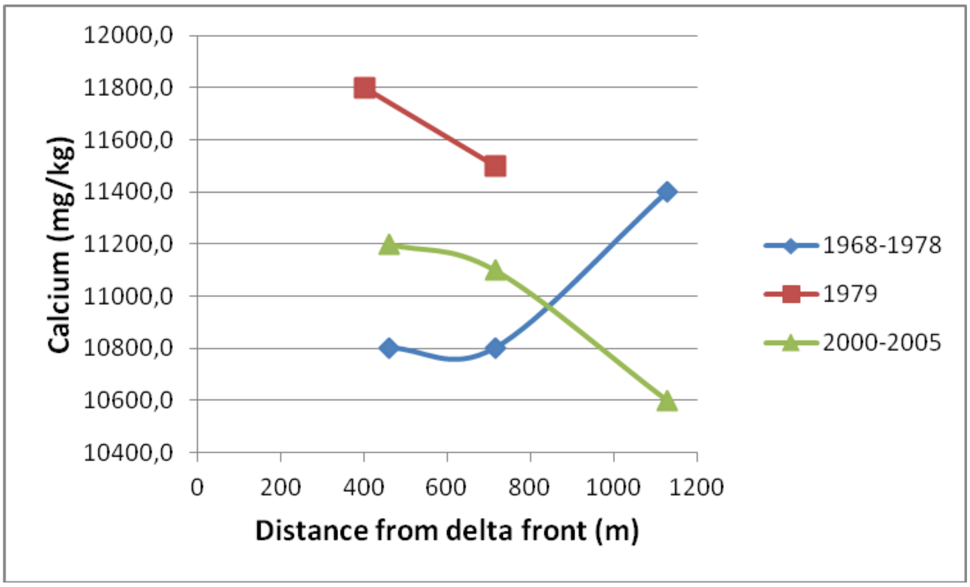


Fig. 29b: Results for the calcium analysis from the sediment cores.

3.6.1.3 Carbon (C)

The results for carbon analysis of the sediment layers in the cores are discussed in section 3.3.2. These results are placed into a separate section due to the connection to organic material.

3.6.1.4 Copper (Cu)

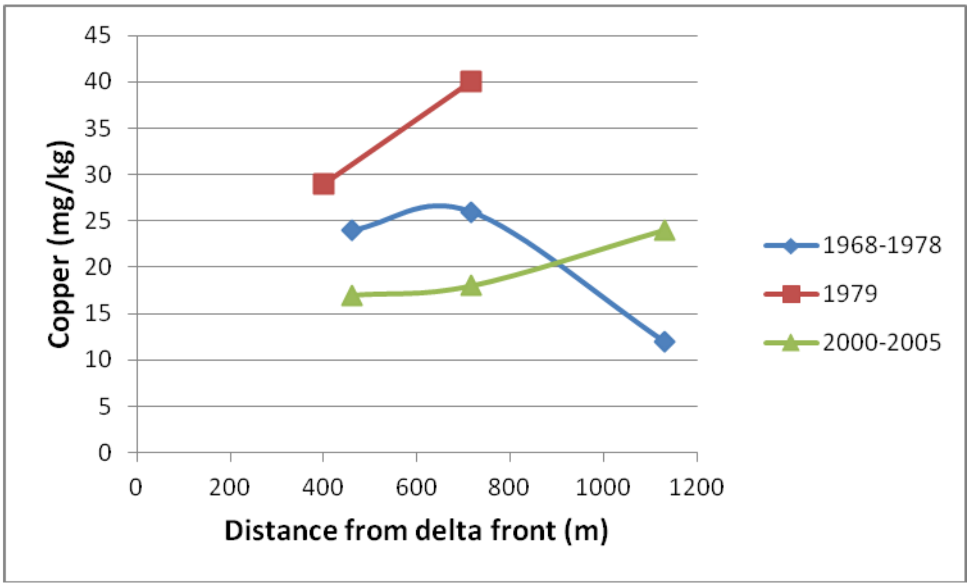


Fig. 29c: Results for the copper analysis from the sediment cores.

3.6.1.5 Iron (Fe)

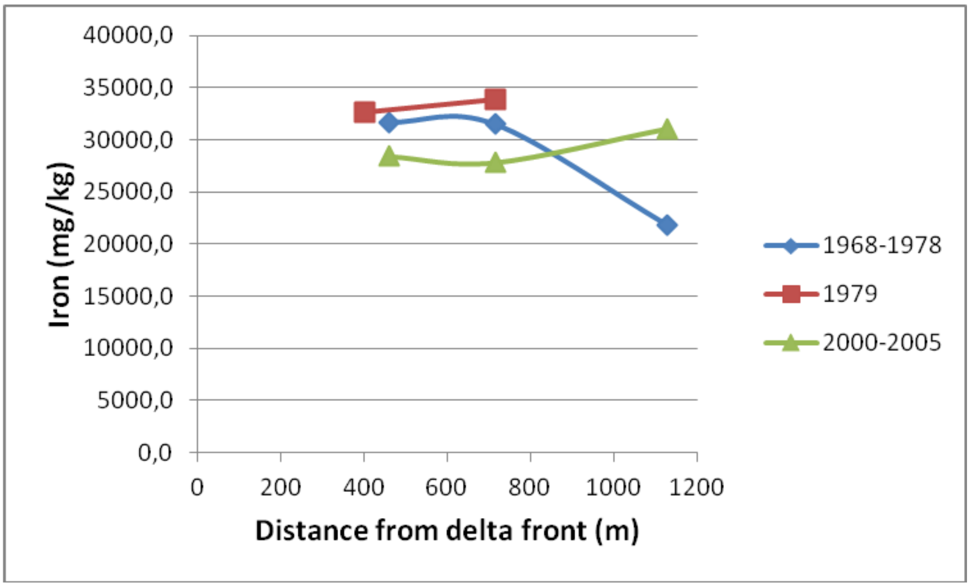


Fig. 29d: Results for the iron analysis from the sediment cores.

3.6.1.6 Potassium (K)

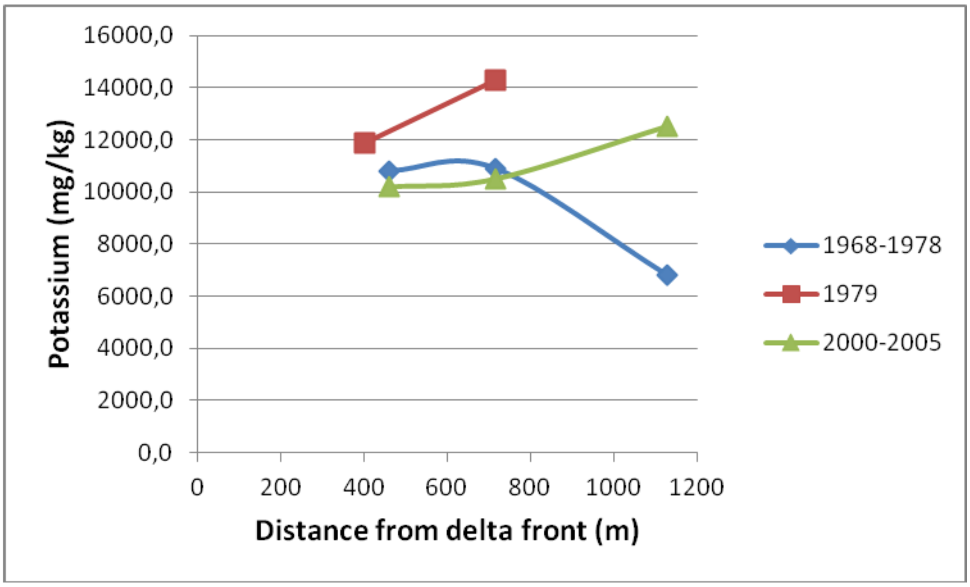


Fig. 29e: Results for the potassium analysis from the sediment cores.

3.6.1.7 Magnesium (Mg)

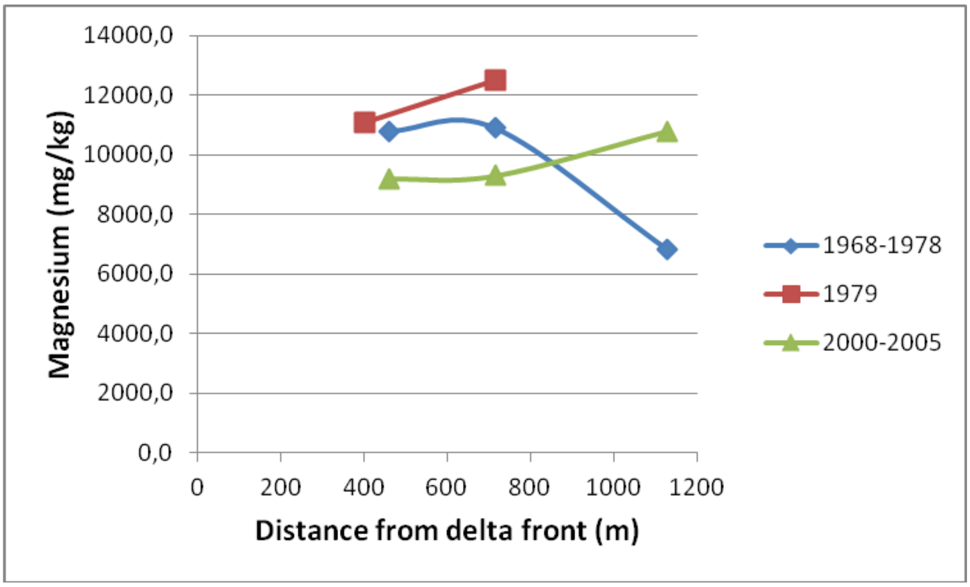


Fig. 29f: Results for the magnesium analysis from the sediment cores.

3.6.1.8 Manganese (Mn)

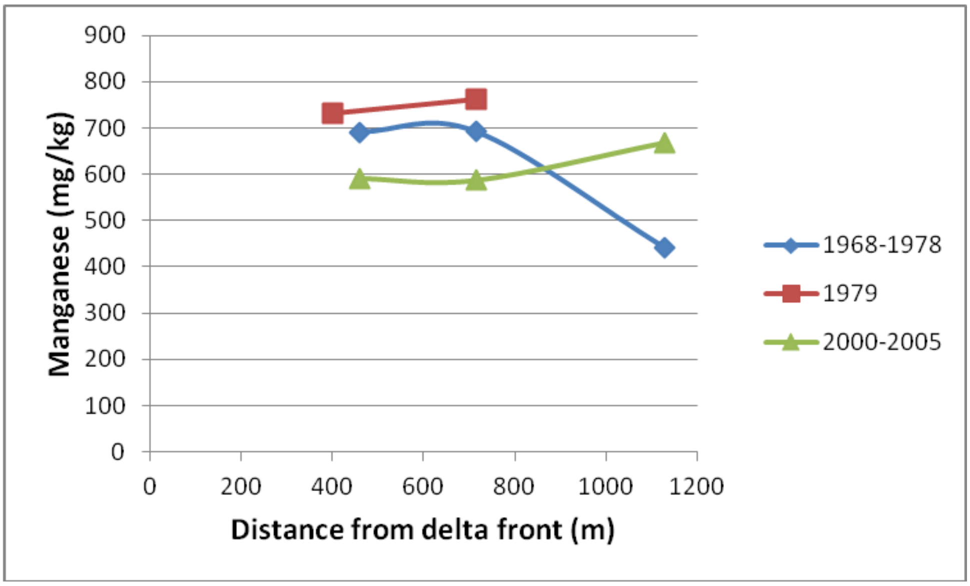


Fig. 29g: Results for the manganese analysis from the sediment cores.

3.6.1.9 Nitrogen

Nitrogen was between 0.00 and 0.03% for all samples from the sediment cores which is below the detection level 0.05%, and therefore these results are negligible.

3.6.1.10 Sodium (Na)

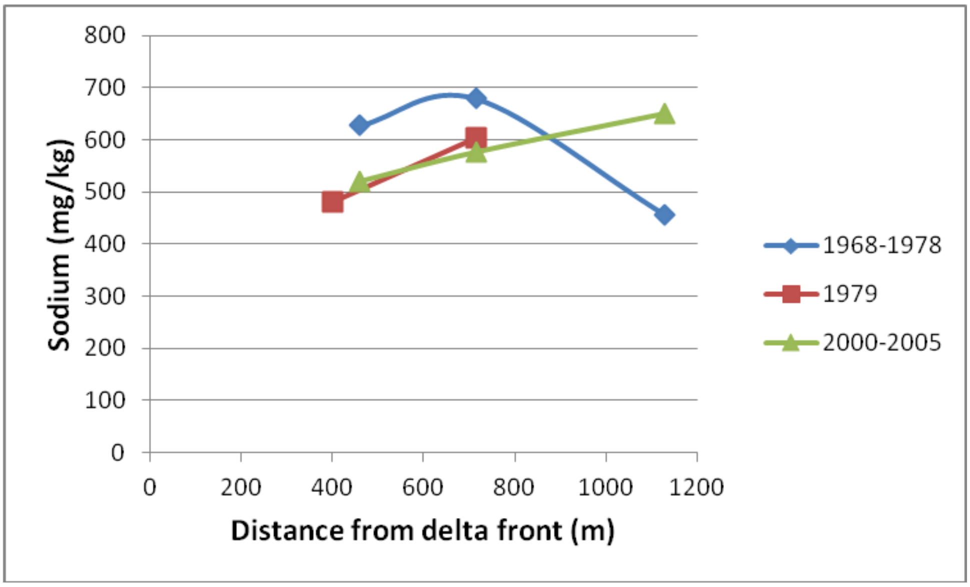


Fig. 29h: Results for the sodium analysis from the sediment cores.

3.6.1.11 Phosphorous (P)

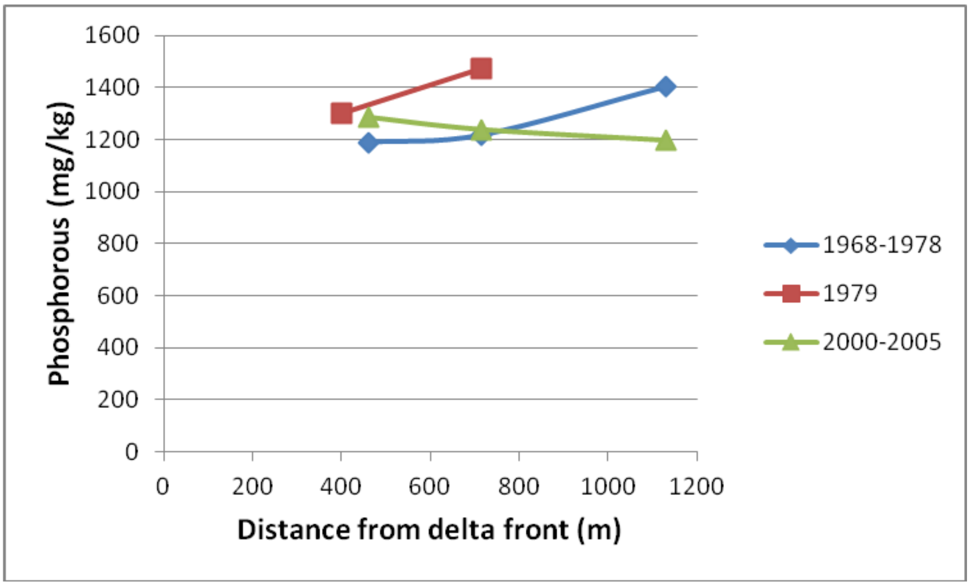


Fig. 29i: Results for the phosphorous analysis from the sediment cores.

3.6.1.12 Lead (Pb)

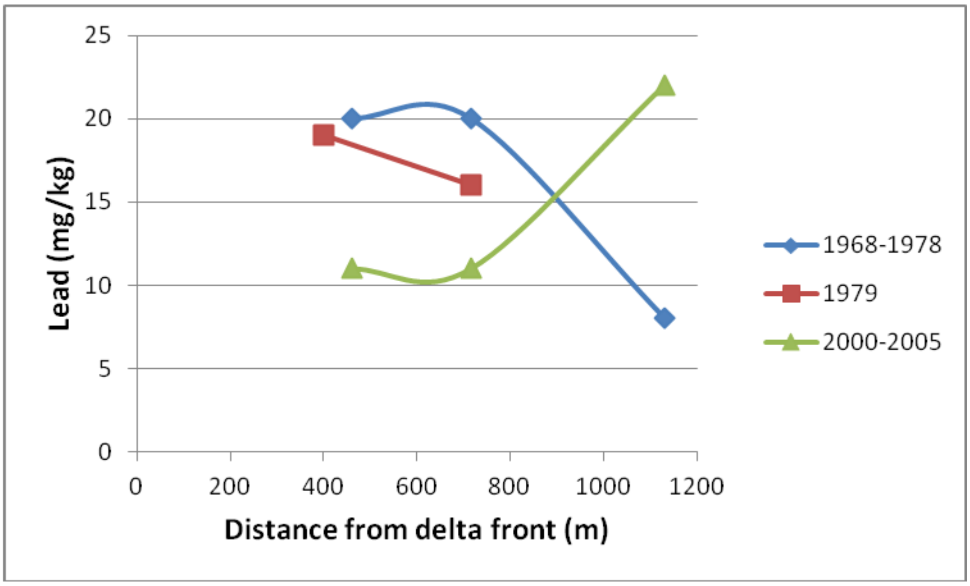


Fig. 29j: Results for the lead analysis from the sediment cores.

3.6.1.13 Sulphur (S)

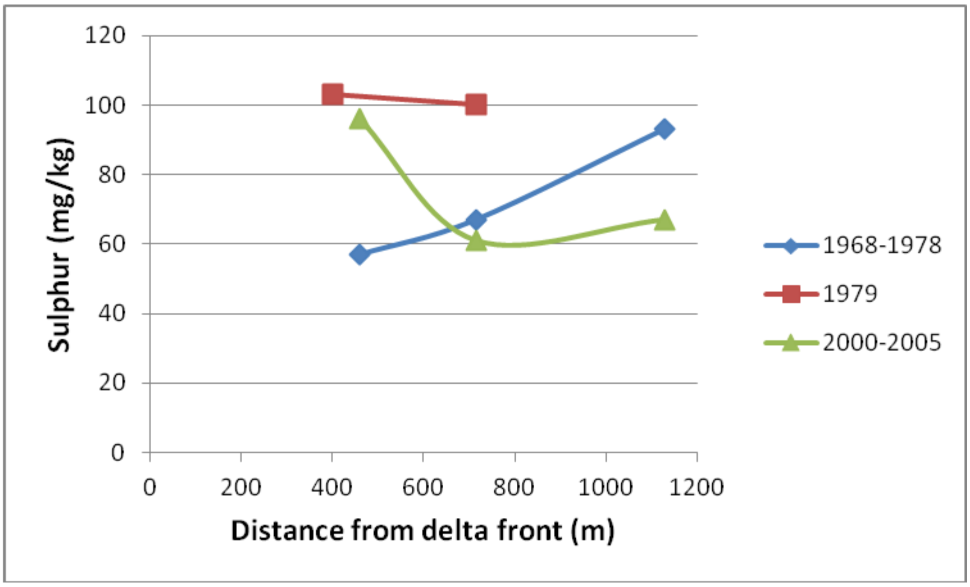


Fig. 29k: Results for the sulphur analysis from the sediment cores.

3.6.1.14 Zinc (Zn)

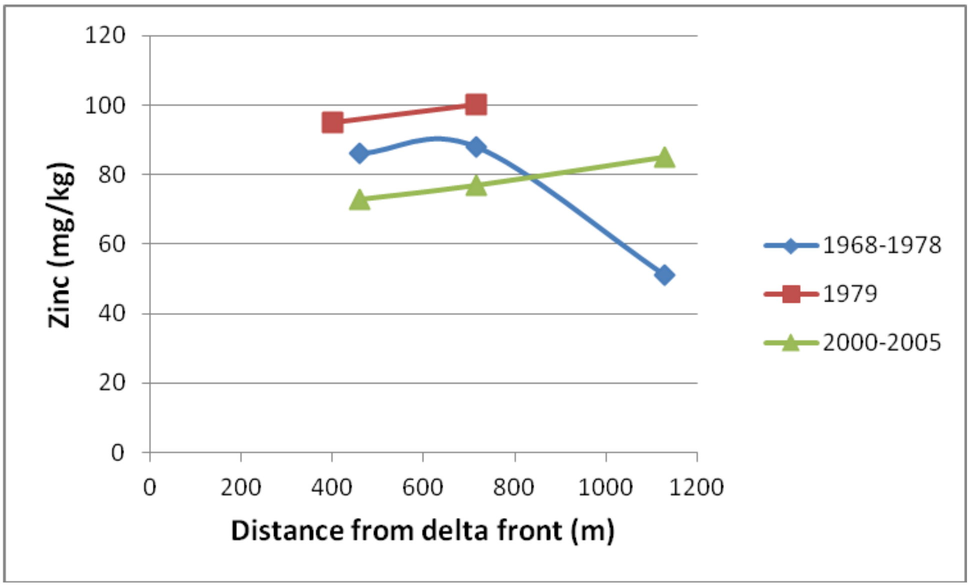


Fig. 29l: Results for the zinc analysis from the sediment cores.

3.6.2 Sediment traps

Concentrations of chemical elements are shown in Fig. 30a-l and Appendix 34. Al, Cu, Fe, K, Mg, Mn and Na in the three series of traps followed a similar trend, with no significant difference in chemical concentrations throughout the melting season. The one distinguishing factor for all these curves is that trap 2 which had the highest sedimentation had lower concentrations of the aforementioned elements in series 1 and 2 which contained high magnitude floods, but higher concentrations in series 3 without a major flood. The two series with floods (1 and 2) had higher concentrations of P.

3.6.2.1 Aluminium (Al)

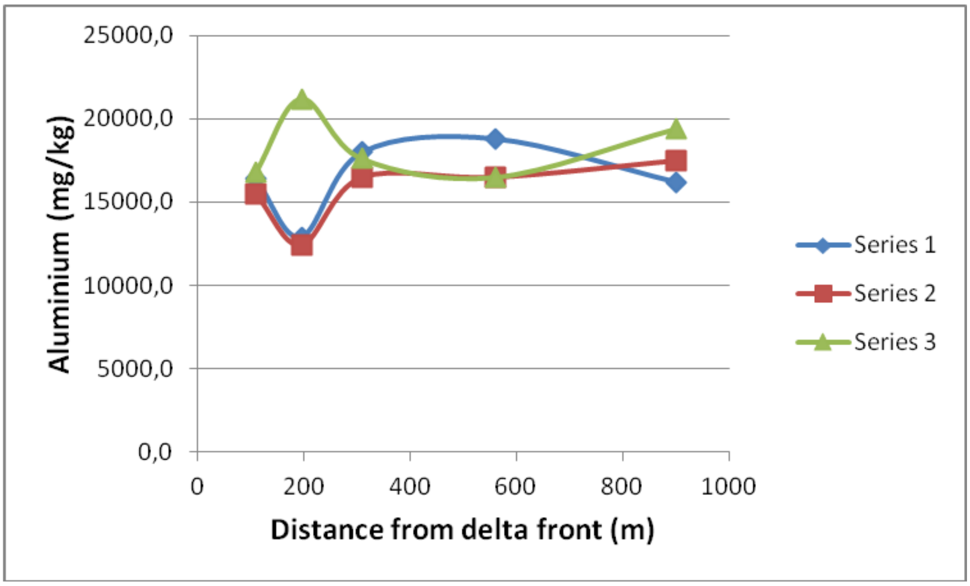


Fig. 30a: Results for the aluminium analysis from the sediment traps

3.6.2.2 Calcium (Ca)

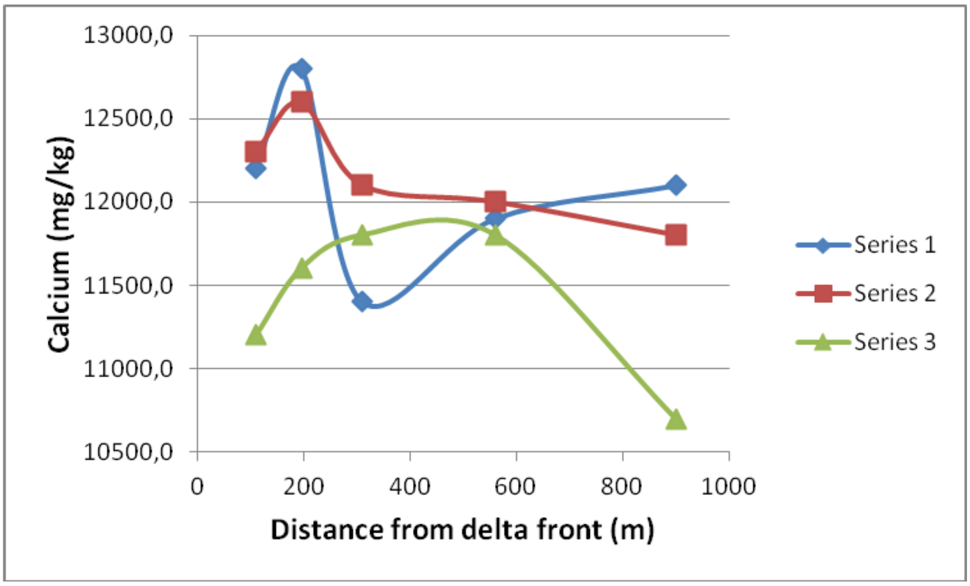


Fig. 30b: Results for the calcium analysis from the sediment traps.

3.6.2.3 Carbon (C)

The results for carbon analysis for the material collected in traps are discussed in section 3.3.3. These results are placed into a separate section due to the connection to organic material.

3.6.2.4 Copper (Cu)

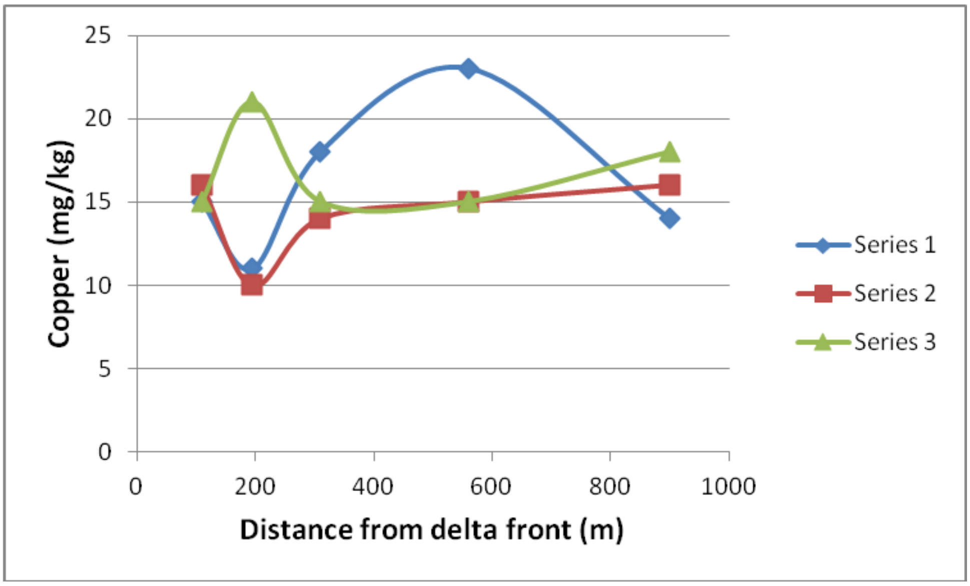


Fig. 30c: Results for the copper analysis from the sediment traps.

3.6.2.5 Iron (Fe)

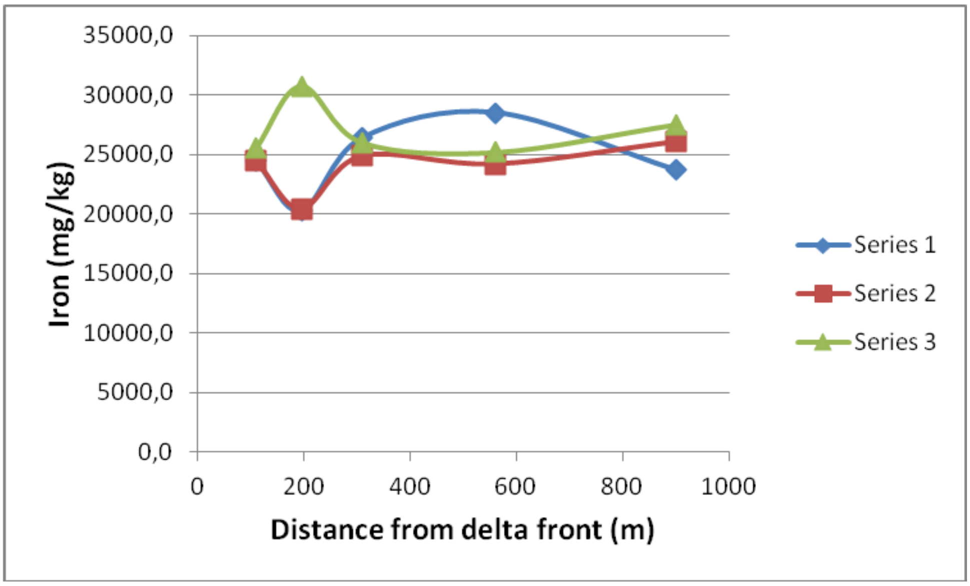


Fig. 30d: Results for the iron analysis from the sediment traps.

3.6.2.6 Potassium (K)

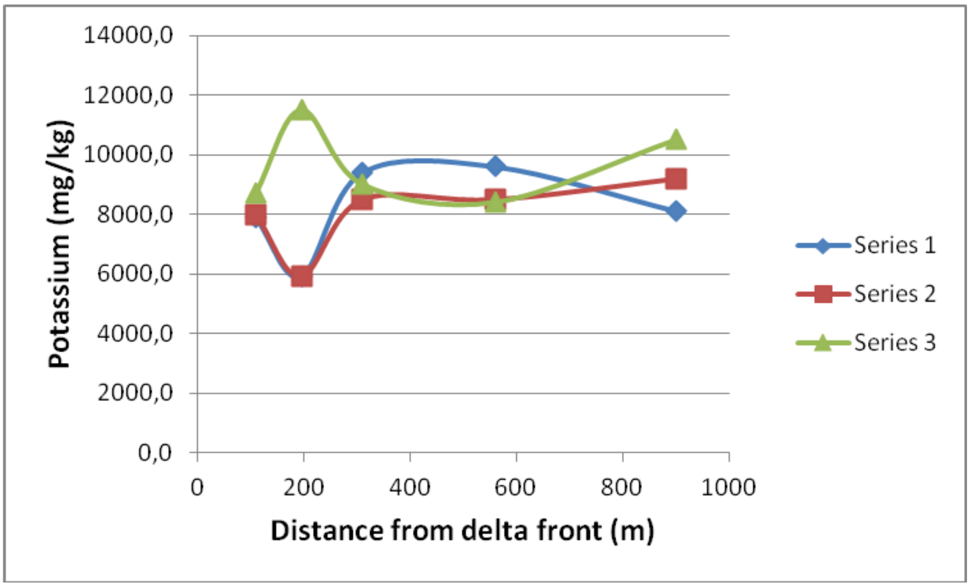


Fig. 30e: Results for the potassium analysis from the sediment traps.

3.6.2.7 Magnesium (Mg)

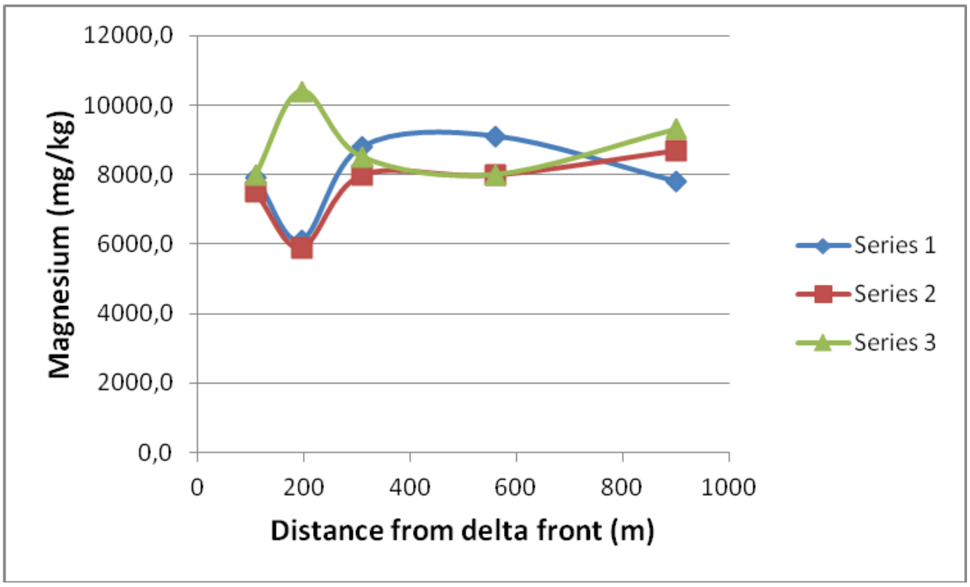


Fig. 30f: Results for the magnesium analysis from the sediment traps.

3.6.2.8 Manganese (Mn)

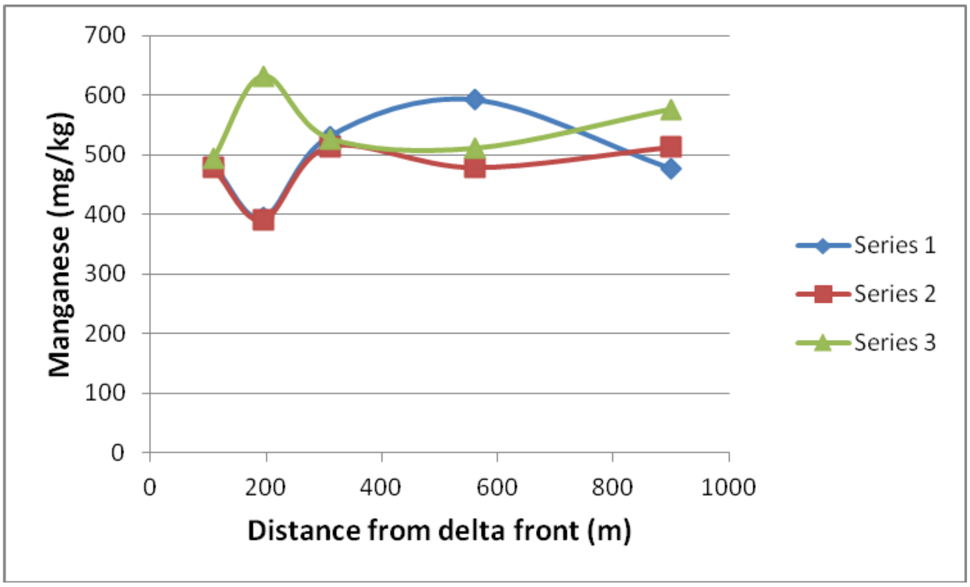


Fig. 30g: Results for the manganese analysis from the sediment traps.

3.6.2.9 Nitrogen

Nitrogen was between 0.00 and 0.03% for all samples from the sediment cores which is below the detection level 0.05%, and therefore these results are negligible.

3.6.2.10 Sodium (Na)

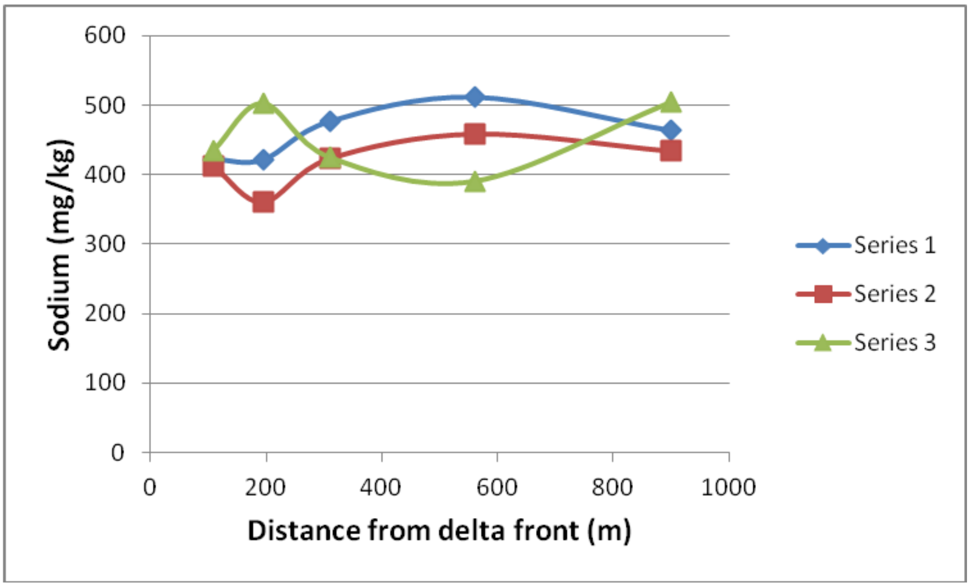


Fig. 30h: Results for the sodium analysis from the sediment traps.

3.6.2.11 Phosphorous (P)

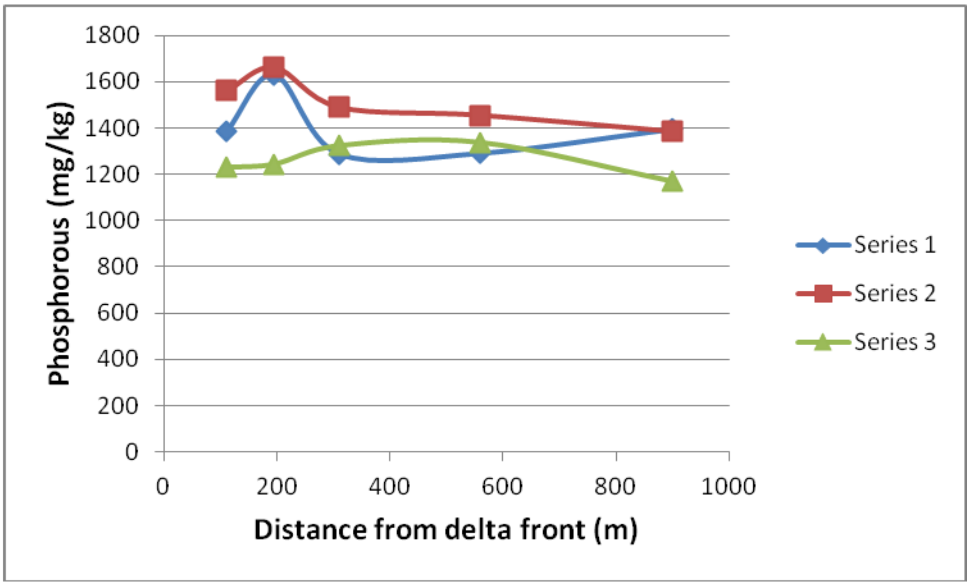


Fig. 30i: Results for the phosphorous analysis from the sediment traps.

3.6.2.12 Lead (Pb)

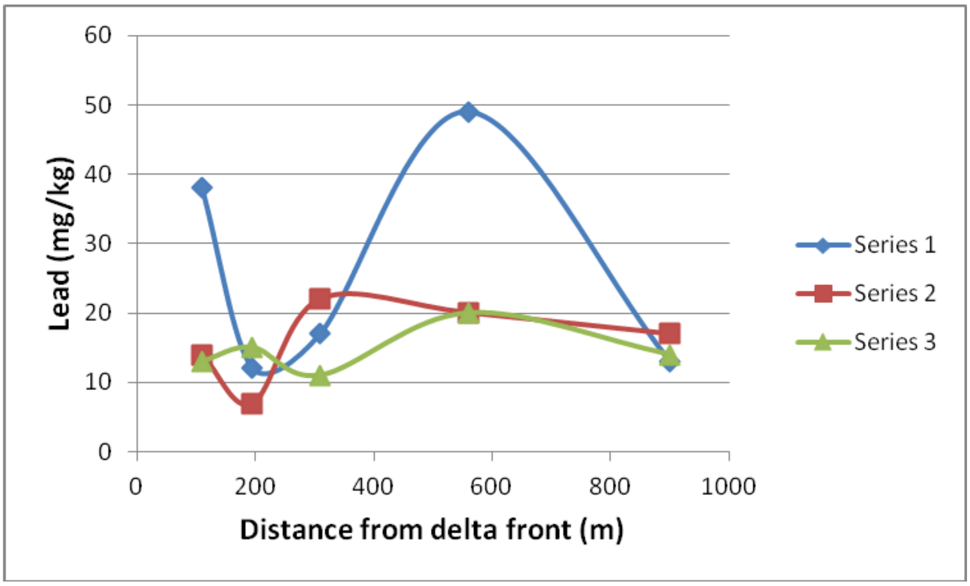


Fig. 30j: Results for the lead analysis from the sediment traps.

3.6.2.13 Sulphur (S)

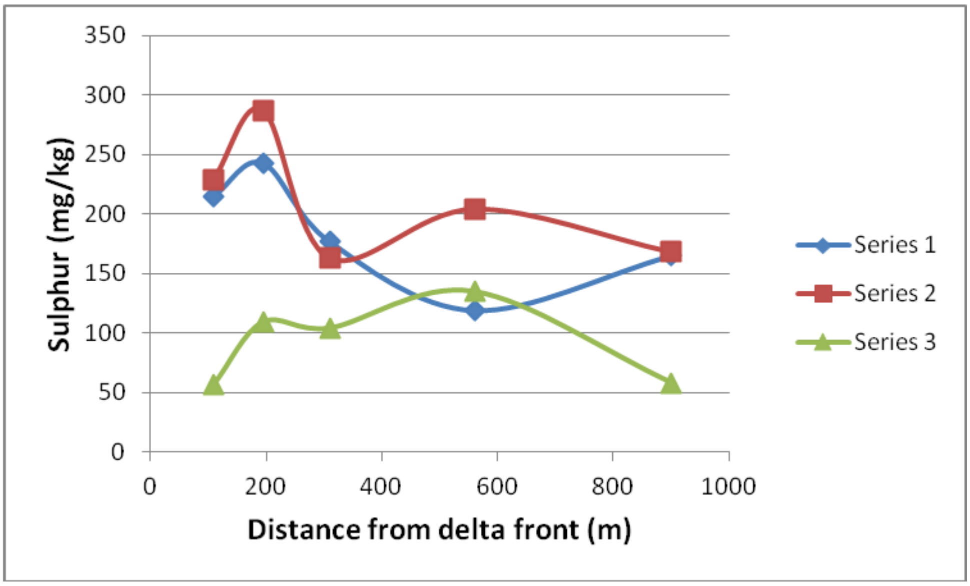


Fig. 30k: Results for the sulphur analysis from the sediment traps.

3.6.2.14 Zinc (Zn)

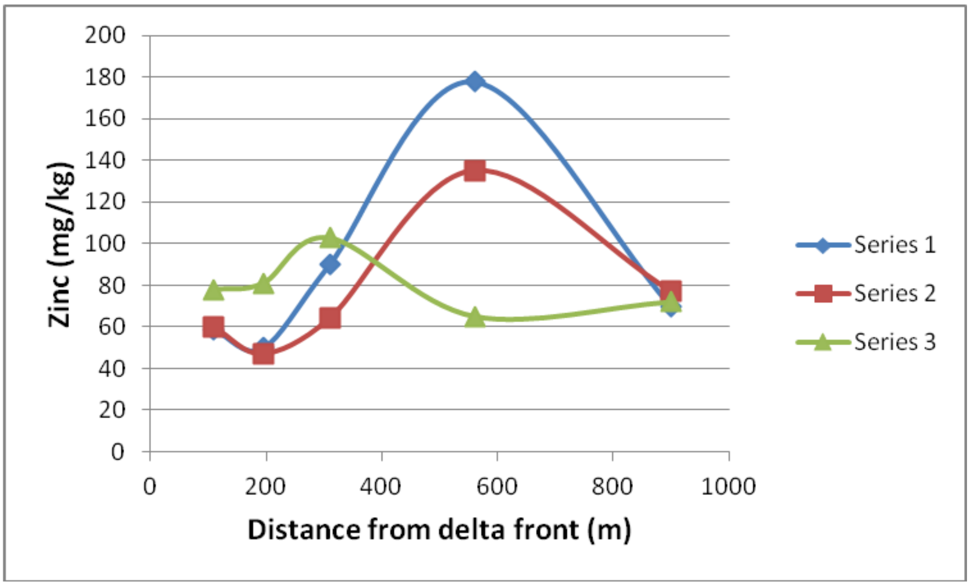


Fig. 30l: Results for the zinc analysis from the sediment traps.

3.7 Density

3.7.1 Suspended sediment

The rock species of the Nigardsvatn area is gneiss and the important minerals are quartz, feldspar, and mica (Olsen & Ziegler, 1987). The density of gneiss is commonly between 2.6-2.9 g/cm^3. The density of water varies with temperature, but the density of water containing sediments increases with the amount of sediments in suspension, since sediments are denser than water.

3.7.2 Sediment cores

Sediment density from cores was found to be between 1.3 and 1.5 g/cm^3 (Olsen, 2008).

3.7.3 Sediment traps

The density of the sediments collected in Trap 1 from Series 1 was found to be 1.43 g/cm^2. The density of the sediments from Trap 5 in Series 3 were 1.25 g/cm^2. Therefore the density can be approximated as somewhere between 1.2-1.5 g/cm^2 which is what other researchers found for glacial lakes (Zolitschka, 1996).

3.7.4 Delta

The bulk density of the delta area is considered to be 2 g/cm^2 (Olsen, 2008).

4 DISCUSSION

4.1 Sediment transport and sedimentation

The results on sediment transport and sedimentation are discussed below.

4.1.1 Suspended sediment and water discharge

The large interannual and interseasonal fluctuations in water discharge and sediment concentrations measured from the monitoring stations at the inflowing river show in some ways correlation between high water discharges and high sediment concentrations. Higher magnitude floods generally show higher sediment concentrations, although like other glacial rivers, Nigardsvatn exhibits poor correlation between discharge and concentrations (Bogen, 1980).

The peak discharge during the flood of August, 1979, estimated at 100 years recurrence interval, was the highest measured during the monitoring series and this period also showed the highest suspended sediment concentrations. The floods of June and August of 2011 had the two second highest sediment concentrations measured during that season, although there was a higher concentration in September of that year. The peak in September does not occur during a period of high discharge, so it could possibly be explained by opening of a new subglacial drainage tunnel (Bogen, 1996; 2010). The opening and expanding of conduits beneath the glacier by the high pressures of excess runoff during intense rainfall is responsible for the high sediment concentrations seen in Nigardsvatn during flash flood events (Bogen, 2010). Bogen (1980) and Bogen *et al*., (2011) found that water discharge often does not correlate to sediment concentrations in Norwegian glacial systems. The complex pattern of sediment concentrations in glacial rivers can be due to complex seasonal changes in the drainage system, and limited availability of sediments (Bogen, 2006). The sediment availability is determined by glaciological parameters on the long term scale such as mass balance, and meterological variables on the seasonal scale, such as precipitation and rate of melting.

The variables of water discharge and sediment concentration often correlate better on the rising than falling limb due to a hysteresis effect (Bogen, 1980). The sediment concentrations are controlled by supply of the sediments and changes in the subglacial drainage patterns can open up a new tunnel system. As the new tunnel opens due to high glacial melt or heavy drainage due to rainfall, a new sediment supply is opened (Bogen, 2006; 2010). High precipitation and runoff during floods can melt and expand existing englacial and subglacial drainage tunnels as well as open new ones, contributing to the transport of new sediment sources and higher sediment concentrations. In addition, higher water discharges and higher flow velocities have the ability to carry more sediments in suspension in a wider range of grain sizes (Hjulström, 1935).

The year 2002 had the highest summer temperatures recorded up to that point since 1876 (Andreasson & Oerlemans, 2009). The high glacial melting with subglacial channel changes and the development of new glacial meltwater rivers caused this season to experience higher than average sediment concentrations. The large peaks in concentration in June and August of this year are not correlated with high precipitation, high water discharge or floods and must be therefore due to changes in the englacial or subglacial melting system.

The summer of 1993 was cold and had lower than average water discharge due to glacier melt, and had extremely low concentrations of suspended sediments. This is likely due to the existing melting system within the glacier being exhausted for sediments, and there was no high runoff due to glacier melt or precipitation to expand or change the existing system and open up new sources of sediment.

There is generally a linear relation between turbidity in NTU and concentration of suspended solids in g/L, although the exact relation is a function dependent on particle size. From the results of the manual water samples taken during the flood of June 2011 the concentration at the outlet of the lake is 75% of that at the inlet of the lake. If the amount of sediments entering the lake from runoff and tributaries on the mountain sides are considered negligible and the only source of sediment into the lake is from the main river Nigardsbreelv melting directly from the glacier, then this means that 25% of the sediments are deposited in the lake and the other 75% are carried in suspension through the lake and exit by the outflowing river Breelvi on the other side. This is true during dry conditions, where the only runoff is from glacier melt water flowing into the lake directly from Nigardsbreelv. During flood situations with high precipitation, sediments are supplied to the lake from other sources when significant amounts of water and suspended sediment enter the lake by runoff from the mountain sides which are not sampled at the monitoring station. Olsen (2008) found that during the monitoring period of 1967-1978, 25% of the sediments transported into the lake pass through the lake while 75% are deposited and Østrem *et al.* (2005) found a similar result, from 70-85% sedimentation and the remaining fraction transported through the lake. This is significantly less than the percentage of sediments in suspension transported out of the lake during the flood conditions in June 2011. During flood situations, the water velocities are higher and therefore sediments are carried in suspension a longer distance downstream. In addition, high precipitation carries more sediments into the lake from the mountain sides through smaller streams, and these are not sampled at the monitoring station at the lake inlet. Therefore a higher proportion of sediments will exit the lake during flood situations than during dry conditions and this accounts for the discrepancy.

4.1.2 Sediment cores

The differences in sedimentation between years and locations in the lake show that different processes such as a short-lasting large magnitude flood due to high precipitation have only partially different sedimentation patterns in the lake than a relatively large, long lasting water discharge from glacial melt, and these two situations show much different results from low-flow conditions. 2002 and 1979 have similar sedimentation patterns, with the exception of the innermost locations, where 1979 has higher sedimentation. The slope on the sedimentation curve for 1979 is steeper on the other hand, meaning a higher proportion of sedimentation occurs closer to the delta front. This can be due to larger grain sizes transported in the high magnitude flood, which fall out of suspension at a shorter distance than smaller grain sizes. A short lived extremely high water discharge can bring in similar amounts of material as a long-lasting relatively high water discharge, but in the extreme flood situation, larger amounts of material with a higher percentage of particles of a larger grain size are deposited closer to the delta. There is also a difference in sediment sources where glacial melting brings in only material from the glacier and its sole, but rain can also wash in sediments from the unglaciated mountain sides.

4.1.3 Sediment traps

Each period in which the sediment traps were set out corresponds to a characteristic hydrological period during the melting season of 2011; the first was during a large magnitude 5-year flood due to high precipitation during late June and July, the second during the period of highest melting of July to August which also contained a 10-year flood, and the last period was from September to October, during a period of colder temperatures and a decrease in glacier melt and water discharge. The high sedimentation in series 3, trap location 5 is probably due to a landslide or high transport from one of the side tributaries, as several small streams of water are known to flow into the lake from the sides of the mountain and landslides are known to occur into the lake.

According to Allen (1968), the pattern of sedimentation with an increase in sedimentation rate close to the river mouth and a decrease thereafter with decreasing flow velocity is related to the diffusion process of grains in the lee of deltas. This agrees with out results, where the traps at location 2 had extremely high sedimentation throughout all series and there was a decrease thereafter in sedimentation rate with distance from the river mouth. The 10-year flood in August of 2011 transported similar amounts of material as the 5-year flood that occured earlier in the season. This could be because, as explained by Bogen (1980, 2006), in glacial systems resources become exhausted and there is a limited availability of sediments for erosion in the subglacial channels. This is why floods in other types of environments produce more sediments than floods in glacial rivers (Bogen, 2006).

4.1.4 Delta sedimentation

The delta sedimentation corresponds only slightly to the water discharge, sediment transport and sedimentation. 1979, 2002 and 2011 had higher than average delta sedimentation while 1993 had lower than average sedimentation, which is in accordance with the water discharge and suspended sediment transport during these years. This is due to the increased water discharge and water velocity being able to carry more material in suspension, and transport more bedload of a larger diameter (Hjulström, 1935). The coarser suspended sediments as well as bedload deposited across the delta platform with a decrease in flow velocity.

The measurements show that 1979 had extremely high transport but this was not one of the highest years for delta sedimentation. This could be partially due to the flood transporting more material beyond the delta area and even eroding some of the previously deposited material in the delta.

1993 on the other hand had much low discharge and transport of suspended sediment and although it had lower than average delta sedimentation it was not one of the lowest years. This could be because the lower discharges cause a higher percentage of the suspended material to be deposited in the delta area, where the low sedimentation in the lake is due to a sorting of material more than limited supply. The water discharge was generally low during the entire season with no high peaks, and therefore the water velocities were not sufficient enough to transport significant amounts of bedload into the delta system. It is likely that the material deposited in the delta this season was of a smaller diameter than that of the other years, because large velocities are necessary in order to move coarser bedload, and the smaller velocities could lead to sedimentation of a higher proportion of the suspended material before it reaches the end of the delta platform. The higher grain size of the material measured at the monitoring station in 1993 can also lead to more sedimentation in the delta area.

2002 had higher delta sedimentation than the other years possibly because it had a constant high discharge throughout the whole season. While peak discharges during high magnitude floods can transport very large amounts of material to the delta area during the period in which it lasts, a sustained higher than average discharge can transport a total higher amount of material during the whole season.

Bedload transport and delta sedimentation depend on sediment supply, sediment size, water discharge and also the height of the water levels over the delta platform, because deeper water leads to a larger reduction in flow velocity and thusfore more sedimentation. Bogen (1980) also found that sediments can be stored in the channel (in this case the river delta) during moderate discharges which are transported further downstream during high discharges. Erodability of the delta is also a factor affecting sediment transport (Bogen, 1995). Therefore, the delta can act as both a source and sink for sedimentary material depending on the discharge and sediment supply.

4.1.5 Comparison of sedimentation from cores and traps

The results from the sediment traps in 2011 show a more similar situation to the sediment samples from flood year 1979 than to years with lower water discharge. The slope of the equation for sedimentation in the traps during 2011 was -0.9 which is similar to the slope of the equation for sedimentation in the varves from 1979 which was -1.0. The slope of sedimentation vs. distance from the delta front for the average of all years from 1979-2005 measured from the sediment cores was -0.6 which is a smaller negative slope than that for the varves from 1979 and the sediment traps from 2011, and means that sedimentation decreases less gradually with distance. The total sediment transport and water discharge for 2011 are the largest over the entire season, but the individual 5- and 10-year floods that occurred during this year contributed much less water and sediments than the 1979 flood. Therefore individual higher water discharges along with higher stream velocities and higher concentrations of sediments as well as larger grain size correspond to a more negative gradient in the plot for sedimentation vs. distance into the lake. This means that during high discharges a higher amount of sediments are transported but a larger proportion of these settle in the proximal area closest to the delta. The coarser grain size distribution during higher magnitude floods causes particles to fall out of suspension faster with a decrease in velocity. In addition, as the opening of the subglacial tunnels is a gradual process, assisted by glacial melt, sometimes floods may drain on the surface of the glacier and therefore less sediment will be transported than expected. Therefore more frequent floods of smaller magnitudes such as the ones in 2011 can deliver a total of more sediment than one high magnitude flood such as the one in 1979 (Bogen, 2008).

Glacial meltwater rivers can also experience a hysteresis effect where the sediment supply is dimished, therefore discharge does not always correlate to sediment load (Bogen, 1980). The relationship between discharge and sediment load is changing continuously during each runoff season and from year to year (Østrem, 1975). Liestøl (1967) found that sediment transport in another Norwegian glacial river was controlled by the size of the area covered by the subglacial drainage system per time, the rate of increase in discharge and the length of time the water had flowed over the area which is exposed to fluvial erosion. This can explain some of the discrepancies in both sediment concentrations in the inflowing river and sedimentation in the lake, since sediment transport can be controlled by sediment supply and availability which are not measured by hydrological variables. Due to the hysteresis effect described by Bogen (1980, 1983) where sediment concentrations during the rising level in the spring is much larger than at the same discharge later in the season, due to the exhaustion of sediment sources, the transport in 2011 could have been much higher for the 10-year flood which occurred in August if it had occurred earlier in the season. Also some material transported during a given season could have actually been melted out of the glacier in previous seasons but deposited in the channel or on the delta platform and resuspended in later seasons (Bogen, 1983; 1995). Another factor affecting sedimentation is, like the river and lake systems discussed in Bogen (1983), the lake level over the delta front increases with increasing water discharge into the lake. The retardation of the river jet is therefore stronger at higher water levels, and the flow velocity at the delta rim is affected. This can reduce the ability of the jets to carry sediments of a larger grain size in suspension at a further distance from the delta.

Bogen (1983) found that the exponent describing the slope of the equations for sedimentation rates in deep fjord lakes varied from 1.5 to 3.4 which is much larger than the values found for Nigardsvatn. The depth of these lakes ranged from 30-50 m in the proximal part of the delta area. The much lower exponentials (0.6 to 1.0) found for Nigardsvatn is probably due to the more moderate depth and the relatively high flow velocity throughout this lake, as Nigardsvatn has an average depth of 10 m.

4.2 Grain size distribution

The results for grain size distribution analyses are discussed below.

4.2.1 Suspended sediment

The large variation in grain size in the inflowing river shows very little correlation with water discharge. Bogen (2010) theorized that large fluctuations in both the amount and grain size distribution of the suspended sediments can vary with the source and supply of the sediment, which can be correlated to subglacial channel changes. The wide range in percentage of material in the sand fraction sampled from the inflowing river shows little correlation with water discharge. This is most likely because the grain size distribution of the sediment source is independent of hydrological variables. The grain size distribution in the sediment cores however varies greatly in the lake, as a sorting takes place. These processes of sedimentation and transport of each grain size through the lake are dependent on water discharge and stream flow velocity.

4.2.2 Sediment cores

The grain size distribution is generally coarser for the layer of sediments deposited in the large magnitude flood of 1979 than in the other layers, especially innermost in the lake. This is because the higher water discharge during the flood led to a higher stream velocity into the lake, which could carry more particles of a higher diameter in suspension, but these were deposited as the stream velocity decreased as the river flowed into the lake and the jet expanded. The cores nearest the delta front clearly show a difference in grain size distribution between the 1979 flood and the other years, whereas at the location of the cores further out in the lake the stream velocity had fallen to such a level where most of the coarser fractions had already fallen out of suspension. The particle sizes of the varves deposited in 2002 are also coarse, because the discharge and streamflow were higher throughout this year, leading to more transport of sediments in the larger size range. From the grain size distribution curves, it can be seen that more coarse material in the silt and sand fractions accumulated in the proximal part of the delta, because the stream velocity decreases as the lake deepens and widens, and the larger particles are the first to fall out of suspension. The smaller particles are held in suspension over longer distances and do not settle until a further significant decrease in velocity.

The mean size and percent sand from core S increase after 2002. This period coincides with a glacial advance, which opened up new subglacial channel systems and made new sources of material available. Another factor leading to the increase in sediment grain size could be that the delta has been building itself out through sedimentation and transport of bedload material throughout the past decades, and therefore the distance from the delta front and the location of the cores is reduced over the years. This leads to a higher stream velocity at the same location out in the lake, and the ability to carry more sediments of a larger grain size to be deposited at this specific location. This core was also taken far away from the delta platform, near the lake outlet. Since the most extreme differences in grain size distribution between years with and without floods are seen in the sediments deposited closest to the inflowing river, the sorting has already taken place and there is less coarse material left in suspension once the water flow has reached the location of core S and this is why the flood layer is less distinguishable by differences in particle size.

4.2.3 Sediment traps

The reason why the percentage of coarse sediments over the particle diameter of 63 micron was largest at trap location two and decreased thereafter with distance from the delta front is because, as discussed above, the water velocity is too high at trap location 1 for significant sedimentation as it is too close to the delta front. The larger particle sizes are the first to fall out of suspension with decreasing stream velocity and therefore locations closer to the delta front have a much higher percentage of sediments in the coarser fractions than the locations further away from the delta front (Bogen, 1988). The opposite trend is true for the finer fractions (<31 µm), as their percentages are much lower in the traps at location 2, and there is an increase in the relative amount of these fractions in the traps further out into the lake because smaller particles are held in suspension much longer with a reduction in stream velocity, are the last to fall out of suspension, and have a longer settling time (Allen, 1970). From the results it can be seen that the grain size from 31-63 µm can be the boundary grain size, where material above this grain size generally accumulates closer to the delta and material of a diameter beneath this particle size has a higher sedimentation rate with increasing distance into the lake. As the river jet flows into the lake, a gradual sorting occurs where the largest particles are the first to fall out of suspension and the smallest stay in suspension with further distances from the inflowing river.

The higher percentage clay in series 3 is due to the fact than the higher stream flow during the large magnitude floods of series 1 and 2 carried more of the clay in suspension all the way through the lake. During series 3, there was lower water discharge, therefore a lower stream current through the lake. The lake started to freeze over during the last part of this period. The reduced turbulence from wind and the inflowing river would have contributed to more settling of clay.

4.2.4 Comparison of grain size in cores and traps

There is a sorting of sediments from the inflowing river with distance into the lake. While there is a high percentage of sand in the inflowing river sampled at the monitoring station, there are only small fractions of sand in the sediment cores and traps. This is because the majority of the sand is deposited across the delta platform and delta foreset, and the hydraulic forces of the streamflow across the lake are not strong enough to hold significant amounts of sand in suspension. During large magnitude floods, the stream velocity is increased and therefore a higher proportion of sand is held in suspension, and carried across the delta and into the lake.

The sediment traps from earlier in the 2011 season had a larger proportion of sediments in the coarser fraction (over 31 micron) than the sediment cores did, because the traps only contain sediments from a portion of the melting season, whereas each layer from the sediment cores contains sediments accumulated over the whole season. At the end of each melting season, the lake freezes over, and the sediments in the finest clay fractions then settle, as they have a lower sedimentation velocity and longer settling time. Small velocities from the inflowing river and turbulence from wind are enough to hold a large amount of the finer fractions in suspension through the body of the lake during the summer months. This means the clay fractions will mostly accumulate at the end of the season after the water discharge from the glacier stops, when the lake is covered by ice and the lake becomes still, so although there is a large amount of clay sediment in glacial rivers and lake, most is carried in suspension out of the lake and there is little sedimentation of this grain size while water discharge is high during the peak melting period. There was less material in the clay fraction in the traps than in the cores for this reason.

Both the sediment cores and traps showed higher sedimentation in the courser size range at the location 200-300 m from the delta front. The results are somewhat similar to those of Bogen (1988) for Tunsbergdalsvatn where the relative percentage of the size fractions under 0.31 µm increased with further distance into the lake. In his study the maximum for grain sizes with a diameter above 0.125 µm was at the location second nearest to the delta (120 m). This is due to the shallower depth in Nigardsvatn than in other glacial lakes, which means flow velocity is less reduced after the delta platform and sediments are held in suspension further distances.

4.3 Organic material

The results for the analyses of organic carbon are discussed below.

4.3.1 Suspended sediment

The relative amount of organic material in the sediments varies throughout the years and seasons due to variation in temperature, precipitation and primary production. These factors vary on a temporal scale, controlling the production and transport of both organic and inorganic sediment. Therefore the ratio of organic to inorganic sediment in glacial lakes can be indicative of a change in climatic and hydrological variables (Kloster & Hongve, 1978). The year 2002 had higher amounts of organic carbon in October than the year 2011. This could be because the higher summer temperatures lead to higher primary production in the catchment and the lake, in the form of vegetation and leaf fall in the catchment area and algae in the lake, as temperature is correlated with higher primary production, decomposition and creation of particulate organic carbon (POC) (Abelho *et al.*, 2005). There are two distinct peaks in the concentrations of organic material, in the spring when snowmelt carries POM into the lake, and in the autumn leaf fall is a significant source. This could explain why the two months with the highest concentrations of POC were May and October in 2002, and June and October in 2011. 1993 had much higher organic material than the other years. 1993 experienced a cold summer so therefore there should have been less production and decomposition of organic material and less organic sediment. The data from 1993 is quite old so there is uncertainty if it is as reliable as new data but if the higher percentages of organic carbon are correct, this could be because there was such a low transport of suspended inorganic sediments, so therefore the relative percentage of organic sediments is higher although the total amount is lower. Inorganic sediments in glacial catchment areas are produced by glacial erosion and their transport is controlled by melting of the glacier. During cold summers glacial melt rate and therefore transport of inorganic sediments is reduced. Organic material on the other hand is produced by primary production and transported into the watercourse through surface runoff so yield of organic sediments is dependent on the climatic variables of temperature and rainfall. In agreement of these results, Bogen (2003) also noticed an inverse relation between concentration of POC in sediments and sediment concentrations, where there was a higher relative percent organic during lower water discharges.

4.3.2 Sediment cores

The sediment layer deposited in the 1979 flood had significantly higher percentages of organic carbon that the sediments deposited in the years before and after, because the heavy rainfall led to large surface runoff, bringing in sediments from different sources than the glacier. Under a normal situation, the water comes from glacial melting, bringing in sediments which are eroded from the glacial bed (Bogen, 1996). During intense rainfall, the high amount of runoff from the vegetated mountain sides bring in large amounts of soil, moss, leaves and remnants of other vegetation from the rest of the catchment area. Østrem & Olsen (1975) also found higher levels of organic material in a sediment core layer deposited during a large magnitude flood, a thick layer containing sand and peat. The sediments deposited from 2000-2005 had a lower percentage organic carbon than those deposited from 1968-1978. This could be because 2000-2005 coincided with a period of glacial advance along with higher sediment transport and sedimentation of the inorganic sediments which melt out of the glacier, therefore the organic fraction can be diluted by the increase in minerogenic sediments produced by glacial erosion.

4.3.3 Sediment traps

The percentage of organic carbon in the sediments collected in traps varied slightly with time period and location in the lake. The difference in the curves between series 1 and 2 which contained large magnitude floods and series 3 without a flood indicates than there are differences in sediment sources during floods and non-flood situations. The presence of a slightly higher percent organic material in series 3 trap 5 can be indicative of a landslide, which brought in more organic material from the sides, since this trap had the largest amount of material than the others. The higher percentages of organic material in series 1 trap 4 and series 2 trap 1 can also mean that there was a higher amount of material coming in from runoff the vegetated mountain sides, as opposed to only glacial melting, as there was high rainfall during these periods and the increase in transport of organic material is common in large magnitude floods (Østrem & Olsen, 1975). At trap location 2, the relative percentage of organic carbon is lower because during periods with large sediment transport, the inorganic sediments dilute the organic sediments, although the total amount of organic material is higher. There can also be a relation between the fine size fraction and organic matter

4.3.4 Comparison between organic material in cores, traps and river

Nigardsvatn has much less organic material than lakes in more productive lowland areas since it is a glacial lake with little sources of allochtonous organic material due to the little vegetation, leaf litter and organic soil in the catchment area. There is also very low production of autochthon sediments from organic biomass produced in the lake because of the low temperatures, limited nutrients and high sediment concentrations. Loss on ignition represents organic matter, where organic carbon is approximately half of the mass of the entire LOI (Rognerud *et al.* 2000). The results for percent organic carbon from the LOI method are much higher than those from the CN-analyser method. This could be due to the many errors associated with the LOI method, including the high amount of clay in glacial lakes which has an affinity to bind water. This sediment pore water is not eliminated through the drying process, but is eliminated during the ignition process, as ignition volatizes hydroxyl groups, evaporates water incorporated into the crystal lattice, and can even cause breakdown of carbonates (Hoskins, 2002). Therefore the LOI method can over-represent the actual amount of organic carbon in the samples.

The cores contain higher percentages organic carbon than the traps and samples taken at the monitoring station because the suspended samples are taken at the Nigardselv river flowing directly from the glacier to the catchment area. Surface runoff transports organic material from the vegetated mountain sides into the lake, and therefore the POC from these sources leads to a higher amount of carbon in the lake than in the inflowing river. The majority of sediments in glacial lakes are produced from glacial erosion and subsequent melting of the sediment-laden ice. This is quite different from other hydrological systems where leaf fall, dead algae and soil erosion supply higher amounts of organic material in other types of river and lake systems such as in forested areas, eutroph lakes, and agricultural areas. The sediments in the cores have a higher amount of organic material than the sediments in the traps because organic material can take longer time to settle out of water. Organic material in the form of DOC can be dissolved in solution but then flocculate, and fall out of solution (Haaland *et al.* 2009). This takes some time, and this process can occur in the winter months after the lake freezes over. In addition, the organic material from the vegetated area on the mountain sides is carried into the lake early in the melting season with snow melt. Since the series of sediment traps only covers the period June-October, and not the very beginning or end of the melting season, this is why the amount of organic material in the traps is underrepresented as an indicator of the actual sedimentation of organic material.

4.4 pH and conductivity

The pH of water and sediment is affected by snowmelt and floods. Low pH is due to little contact with the bedrock and loose material and is controlled by chemistry in the precipitation and course of the melting. There are also seasonal variations in pH where there is higher pH during the period of highest primary production and lower pH in the period of decomposition. This factor is probably less in a glacial oligotroph lake, although the higher than average levels of phosphorous allow for a higher than normal production. The pH was slightly lower in the trap closest to the inflowing river, probably due to the differences in pH in the glacial meltwater river and the runoff flowing in from the rest of the catchment.

The conductivity was around 3 times larger exiting the lake than entering. This could be because the glacier river flowing into the lake has little ionic content, but the water washed in from the rest of the catchment area contains more ions from anthropogenic sources, vegetation in the catchment area and organic material.

4.5 Chemical elements

The concentrations of the elements in both the sediment cores and traps, from highest to lowest was: Fe, Al, Ca, K, Mg, P, Mn, Na, S, Zn, Cu, Pb. The results are discussed below.

4.5.1 Sediment cores

All of the elements with the exception of Na and Pb had higher concentrations in the 1979 flood layer than the other layers. In the flood layer of 1979 there was also higher organic carbon, which can be correlated with these certain elements. Many chemical elements bind readily to organic material (McLean & Bledsoe, 1992; Violante *et al.*, 2010), and the runoff from the vegetated mountain sides carried a higher amount of organic material during the flood. In addition, there are other sources of sediments from the mountain sides, where the sediments area created by weathering processes as opposed to glacial erosion. During periods of high runoff material is also washed in from the area around the lake including a road, parking lot and tourist trail, and the runoff can carry with it traces of anthropogenic pollution from vehicles or other sources. Floods are well documented for transporting high levels of many chemical elements (Langedal, 1996). The concentrations of Al, Cu, Fe, K, Mg, Mn, Na, P, and Zn increased in the sediments deposited in the flood of 1979 with distance from the delta. These elements could have a correlation with the smaller size fractions, which increase with distance from the inflowing river. This could also be because with further distance into the lake there is a higher proportion of sediment washed in from the unglaciated area of the catchment area. The road and parking lot are near the side of the lake furthest from the glacier, and therefore the higher concentrations of certain elements from cores taken in this vicinity could have an anthropogenic source and we washed in from this area. The other elements Ca, Pb and S decrease with distance from the glacier, and this could mean there are higher concentrations of these elements in the glacier area. Ca can also belong to the larger size fraction. Pb, S and Cu can also be related to the distribution of organic matter and Rognerud & Fjeld (2001) found higher concentrations of Pb in sediments deposited since industrialization, from anthropogenic sources.

There was an increase in the concentrations of the elements Ca, P and S with increase in distance from the delta front for the samples from 1968-1978. The opposite trend was true for Al, Cu, Fe, K, Mg, Mn, Na, Pb and Zn, with a decrease in concentration with distance from the delta front during this period. The trend from 1968-1978 was reversed from that of the samples deposited from 2000-2005, where Al, Cu, Fe, K, Mg, Mn, Na and Pb increase with distance from the delta front, whereas Ca, P and S decrease. The difference in trends of chemical concentrations in the sediments with regards to distance from the inlet between the periods 1968-1978 and 2000-2005 as well as the 1979 flood can be due to several factors. From 2000 there was a glacier advance, which caused changes in the subglacial drainage system and opened up new sources of sediment. Surveys of the subglacial morphology showed the existence of several lakes beneath Nigardsbreen glacier (Bogen *et al.,* 2011). Old sediments deposited in the lakes during the historical interglacial period could have been re-suspended with either the 1979 flood or the period of higher glacial melting and changes in the drainage system in the 2000s. Other factors which could have caused this difference in results with time include the morphology of the delta which has changed significantly during the last several decades and increased several hundred meters, which leads to different sedimentation patterns in the lake.

Iron oxides are especially visible due to their rest colour, and since Fe was contained in higher concentrations in the 1979 flood layer, this is a reason why the sediment layer deposited during the flood is more visually distinguishable from the other layers.

4.5.2 Sediment traps

Series 1 and 2 followed similar patterns for sedimentation of chemical elements, as they contained high magnitude floods. Series 1 and 2 had lower levels of Al, Cu, Fe, K, Mg, Mn, Na, Pb and Zn at trap 2, likely because these traps had a higher grain size and less clay. This is because many chemical elements bind to clay, due to the higher surface area to volume ratio, and cohesive forces (Violante *et al.* 2010). Ca, P and S on the other hand were contained in higher concentrations at trap 2. The concentrations of Al, Cu, Fe, K, Mg, Mn and Na at trap 5 were highest in series 3, and this trap collected an extremely large amount of sediments. The hypothesis that this material was carried into the lake from a landslide is supported by this data, as the chemistry of the mountain sides is different from that under the glacier. Concentrations of Ca and S on the other hand were very low in this trap compared to the other traps and series, which could mean they come from other parts of the catchment.

4.5.3 Comparison between chemistry of cores and traps

Many chemical elements are associated with either the clay or organic fraction in sediments. The increase in concentrations of some elements with increasing distance into the lake has a correlation with the increase in the smaller size fractions of sediments, as there is often an increase in the concentration of many elements with increased proportion of clay. Fe and Mn seem to have a strong correlation with the clay fraction. Ca on the other hand has a distinct, unusual distribution which seems to have a correlation with the larger size fractions. Other elements have a correlation with organic material such as Pb, S and Cu. Pb and Cu seem to especially correlate with the amount of organic material in the samples. Cu can also be weakly associated with the Al and Si in the inorganic sediment fraction. Pb is adsorbed to humic material and therefore can be correlated with organic sediment, as well as fine-grained Al-Fe silicates, and can replace K and Ca on sorption sites (Rognerud & Fjeld 2001, Rognerud *et al.* 2000). Zn can be adsorbed to Fe- and Mn-oxides and organic complexes (Rognerud & Fjeld, 2001). *Rognerud et al.* (2000) found the most important covariables for trace metal concentration in lakes were Al, Fe and organic material.

Ca, Mg, Na, and K are the main elements in water (Økland & Økland, 2006). Al, Fe and Mn reflect the composition of the rock species in the catchment area and since there was such large concentrations of Fe and Al, they must have a large composition in the bedrock of the catchment area. Fe and Mn also reflect pH and the redox conditions in the lake, where they fall out of solution into the sediments in oxidic conditions and neutral pH (Økland & Økland, 2006). Cu and S are also bound to the organic fraction and S is affected by pH. Over 90% of phosphorous is transported in the form of sediments, and is bound to clay (Arnell, 2002). From our results there is more P transported during floods.

Zn reflects the composition in the bedrock, as well as atmospheric deposition and pH. Rognerud & Fjeld (2001) found that Pb is strongly associated with organic material and also reflects anthropogenic deposition, Zn is weakly associated with organic matter and Cu on the other hand is associated weakly with inorganic sediments, including Al. There are relatively high levels of P and Ca in the sediments. Although the main bedrock type in the catchment area is gneiss, these concentrations could mean there is also a presence of another bedrock rich in Ca or P such as apatitt. Jostedøla is situated in the area with some of the largest concentrations of P in flood sediments in the entire country of Norway (Ottesen *et al.*, 2000). Rognerud & Fjeld (2001) studied the increase in concentrations of Cu, Pb, and Zn had increased in Norwegian lake sediments since industrialization. The change in concentration was smaller in Jostedal than other areas of Norway for Cu, but Zn and especially Pb experienced very high increases comparable to that in more industrialized areas of Norway. These three elements are transported atmospherically. Pb is mainly from leaded gasoline, and metal industries are responsible for the majority of the release of Cu and Zn as well as some Pb. They also found that the inorganic fraction was associated with Al- and Fe-oxides. Lakes often have higher concentration of chemical elements than overbank sediments and are therefore more efficient traps (Rognerud *et al.* 2000). Karmanchuk *et al*. (2004) found the highest concentrations of Cu and Zn in sediments deposited at a distance from the river mouth equal to about 2 widths of the river mouth whereas for Fe it is equal to three widths because Fe is attached to smaller particles (<0.15 mm and Cu and Zn are attached to larger particles (>0.25 mm).

The chemical and physical processes surrounding particle bound metals is very complex, where the state, species and distribution of the heavy metals depends on many factors including particle size, amount of organic material, solubility, pH, redox conditions, ionic strength and other elements such as Fe or Mn oxides (vanLoon & Duffy, 2011; Jin *et al*., 2010). The factors that control the distribution of chemical elements in the catchment area, water and bed sediments of the lake are anthropogenic sources, natural sources, and transport and sorting of the sediment material based on the clay and organic fractions. There is little anthropogenic pollution in the catchment area as it is a remote location in a national park and near the top of the catchment area. The particle size decreases with distance from the delta front as the heaviest particles settle nearer to the delta, and there are higher amounts of the finer clay particles further out into the lake.

There was less clay in the traps than in the cores since many chemical elements are associated with the finer fractions and more clay settles after the summer melting season due to turbulence and the long settling time. There were significantly higher concentrations of Al, Cu, Fe, K, Mg, Mn and Na in the cores than in the traps. This can be because of the association with finer sediments and organic material, both of which settle later in the season and were therefore contained in larger amounts in the cores than the traps.

4.5.4 Comparison to geochemical map

The results can be compared with those of Norways geochemical atlas, provided by the Geological Survey of Norway (NGU) (Ottesen *et al.*, 2000, Appendix 36-37). This map is based on the overbank sediment method of geochemical mapping and has been used in many countries including Norway and China. During floods, sediments and associated chemical elements are washed into rivers from all parts of the catchment area and deposited on the river banks. Therefore the sampling of sequential sediment sequences can be carried out by digging a vertical profile down into the floodplains alongside a riverbank and taking samples at small intervals vertically of each sedimentary layer (Ottesen *et al*., 1989; Bogen & Ottesen, 2006). Lake sediments can also be used for geochemical maps (Rognerud *et al.*, 2000). The concentrations of elements Al, Ca, Cu, Fe, Mg, Mn, Na, P are within the same range of the concentrations found in the NGU samples. K and Pb on the other hand have much lower concentrations in the samples from Nigardsvatn than further down in the catchment. The higher concentrations of Pb further down in the catchment from Nigardsvatn can come from anthropogenic sources. S and Zn were more prevalent in Nigardsvatn than in the samples taken further down the catchment.

Considering only the NGU data for the total contents of each element which are generally larger than the acid extractable portion, the Al, Ca, Fe, K, Mg, Mn, Na and P concentrations in the samples from Nigardsvatn are lower than those from the overbank sediments sampled further down the watercourse taken by NGU. Since the concentrations of these elements are higher in the flood layers, this could be because during floods a greater number of sediment sources are opened, transporting sediments from a larger area of the catchment and these sediments therefore give a more accurate representation of the actual geochemistry of the area (Ottesen *et al.,* 1989). The differences between Norway's geochemical map and the samples from Nigardsvatn are that the samples from further down the Jostedal river contain sediments from a much larger catchment area, with more anthropogenic sources of contaminants and different types of bedrock containing different chemical elements.

4.6 Discussion of results

Sediment transport and sedimentation is dependent on velocity fields and particle settling velocity. There are both extrinsic and intrinsic variables controlling these forces, where climatic factors are extrinsic, and lake's morphology is intrinsic. Settling velocity is controlled of external factors, independent of the lake morphology, while the velocity fields are dependent on factors specific to the lake in question, such as stream flow in and lake morphology. Bogen (1983) studied the effect of morphology on sedimentation patterns in fjord valley lakes in several other lakes in the area surrounding Nigardsvatn. They had different sedimentation patterns, based on the slope of the gradient regarding increase in depth compared against distance from the inflowing river mouth. Nigardsvatn is a relatively narrow and shallow lake, and therefore the velocity does not decrease as quickly as in wider and deeper lakes with a steeper gradient, with increasing distance from the inflowing river mouth. Therefore the stream current flowing into and through the lake will resemble more a jet flow and have the ability to carry particles in suspension of a larger size further into the lake before they settle.

Most floods transport large amounts of material, but the transport depends on the availability of material. With a higher frequency of floods, some of the material sources will be exhausted, so a second flood of the same magnitude occurring shortly after an earlier flood will therefore not transport as much material (Bogen, 1980). This is especially true in the setting of glacial streams and lakes, where the supply of sediment is steered by the availability of erodible and transportable sediments. Since the results show a difference in the amount and grain size of the sediments as well as composition of chemical elements and organic material we see that the availability and source of sediments are different during years with average runoff and years with large floods. Floods with large precipitation and runoff can transport sediments further distances from larger areas of the catchment (Bogen & Ottesen, 2006). They can also transport larger quantities and grain sizes of sediments, as well as higher amounts of organic material (Østrem & Olsen, 1975).

The differences in sediment transport between different climatic situations is especially true for glaciated areas. During years with little precipitation the sediment and water supply comes from sediments melting out of the glacier. Higher temperatures cause higher melting and higher sediment transport of a larger grain size, whereas a summer season with below average temperatures will experience low discharge and low sediment transport. When there is large precipitation and runoff or high melting of the glacier, new englacial and subglacial drainage tunnels can be opened by the large amounts of water. In large floods, the higher amount of water flowing is able to carry larger amounts of sediment. In addition, higher water velocities have the ability to carry material of a larger particle size. During rainfall the surface runoff water can carry with it sediments from other areas of the catchment, including higher levels of organic material and associated chemical constituents. Therefore sediment transport in glacial lakes is steered by both temperature causing melting of the glacier and precipitation.

4.7 Implications regarding dating

The results from this study can be of use to sediment core dating. In sediment cores, layers deposited during floods or higher than average discharges can often be visually distinguished from those deposited in conditions of low or average discharges. Flood layers in sediment cores can also be very difficult to recognize and interpret, especially in cores taken near the delta front, where the varves are not visible due to too much coarse material. Glaciolacustrine varved sediment and sediment core analysis are used in paleolimnological studies as a proxy for hydroclimate (Hodder *et al.,* 2007; (Leemann & Niessen 1994; Nesje *et al.,* 2008; Shakesby *et al.,* 2007). There are often records of very large floods sometimes dating back hundreds of years so if it is known that a historic flood occurred in the catchment area in a certain year, small layers can be taken out of the core and analyzed for grain size distribution and organic carbon. The layer with the highest fraction of sediments in the coarser size range as well as higher organic carbon can then be assumed to have been deposited during a high magnitude flood. Therefore, sedimentation above this layer can be calculated. Kennie *et al*. (2010) estimated sedimentation in Nigardsvatn after 1979 using the sediment layer deposited in the flood of 1979 as a marker. Years with characteristic meteorological profiles with regards to temperature and rainfall can also be identified through sediment core analysis as demonstrated by 1993 and 2002 in the sediment cores.

Even in rivers and lakes which monitor sediment transport, analysis of sedimentary layers can be used to confirm data on suspended sediment transport when there are uncertainties in the series, for example in the case of quality assurance regarding the sampling equipment or measuring techniques. Therefore uncertain measurements and data from sediment monitoring stations can be corrected or confirmed through analysis of sediment cores and specifically sedimentation layers from large magnitude floods. In addition, the magnitude of historical floods can be somewhat estimated by analysing the various parameters of the flood layers.

4.8 Effect of future climate change

The study of previous events may give an indication to the possible impacts of future climate change on sediment transport in glacier-fed rivers. Climate change models predict changes in both temperature and precipitation, RegClim (2005) predicted an increase of 2.5-4.0 °C in temperatures in Norway by the end of the 21st century with an increase in annual precipitation of 5-20%. This will lead to an increase in both the frequency and intensity of rainfall induced floods in

Norway (Roald *et al,*. 2002; 2006). Most climate models predict higher temperatures which lead to more extreme melting of glaciers, and Nesje *et al*. (2008) predicts that the majority of Norwegian glaciers will melt away by the year 2100. Lappegård et al (2007) found that glaciated catchments will have an increase in summer discharge from 10-70% and for the meltwater river of Nigardsbreen, the magnitude of annual floods as well as 5- and 10-year floods will increase by 20-40%, and the 50-year floods will increase in magnitude by 60%. The increase in melt rate of glaciers and size of floods will also lead to changes in hydrology and sediment transport. During the meltback of the glaciers it is likely that the sediment transport in the glacier melt-water rivers will increase significantly. The study of sedimentation in the past will give a better basis for a prediction of the future development.

An increase in temperature and rainfall can lead to higher production of organic material in the watercourse and catchment area, and more surface runoff during floods transfers terrestrial organic material into the watercourse. Increased discharge from glacial melt or precipitation can transport higher concentrations of sediments, more organic material and transport sediments of a larger grain size further distances.

The increase in sedimentation rate during the first years of the 21st century confirms the tendency for an increase in sediment transport. This points to a future increase in sediment transport due to increased melting. Oerlemans (1997) predicted that Nigardsbreen glacier will melt to 10% of its 1950 volume by the year 2100. With melting of glaciers there will be increased sediment transport in catchment areas containing glaciers, until they entirely melt away. The results from 2002 can give information about future sediment transport due to higher temperatures and glacial melting, and the results from 1979 and 2011 can help predict future scenarios where floods will increase in both frequency and magnitude.

Bogen (2008) predicted a doubling in the sediment yield from Nigardsbreen glacier with temperature rise from the years 2070-2100. Nigardsvatn will fill in faster with sediments, although according to Bogen *et al.* (2012) the glacier will completely melt away before the lake is filled in, since the lifetime of the lake at the current sedimentation rate is calculated at 900 years.

4.9 Implications regarding ecology

An essential question is that the ecology within lakes is affected by the deposition of sediments during floods, as aquatic vegetation, benthic organisms and fish depend on certain bed sediment substrate for their survival and reproduction. It is possible that the increase in sediment transport as a result of climate change involving major floods and increased sedimentation rates may affect living conditions for aquatic organisms. Higher concentrations of suspended sediment, an increase in sedimentation rate, a higher percentage of organic material, coarser grain sizes and higher chemical concentrations of the sediment are all effects of large magnitude floods and have effects on the ecosystem.

The main type of benthic invertebrate in Norwegian glacial rivers and lakes is family Chironomidae, genus Diamese, due to its preference for cold water in the range of 0-2 °C, although mayflies and stoneflies can live in the warmer reaches further downstream from the glacier (Milner et al 2001, Brittain et al 2001), *Diamese spp*. was found to dominate at the upper reaches near Jostedalsbreen, as this species thrives in glacial rivers (Brittain et al 2001). A higher sedimentation rate and sedimentation of a larger grain size can be detrimental for many benthic invertebrates, in addition to bedload transport and channel instability (Brittain et al 2001). On the other hand the transport of organic material and phosphorous associated with floods can lead to more algae and periphyton, which the chironomids consume as their main food source, and particulate organic material can also be utilized as a food source. Therefore the increased transport of organic sediments associated with floods and climate change can have effects on the communities of benthic invertebrates as stated by Allen & Castillo (2009). These effects can be intensified by an increase in water temperature associated with climate change, which also has effects on benthic organisms (Milner *et al.* 2001). Increased runoff from glacier melt and decreased channel stability with increased suspended sediment and bedload transport will reduce the diversity of zoobenthic communities but can cause an increase in the abundance of *Diamesa spp* (Brittain & Milner, 2011).

Macrovegetation is also affected by higher sedimentation, as well as the grain size, chemistry, pH and amount of organic material within the bottom substrate. Higher concentrations of sediment in the water scatter light and reduce the euphotic depth, which has a negative effect on vegetation. Organic material and associated nutrients which are transported during floods can have the opposite effect, positively affecting the growth of vegetation (Allen & Castillo, 2009) and fish species which eat benthos or depend on aquatic vegetation for habitat are ultimately affected. Fish are also negatively affected by increased sediment concentrations, as their gills can be plugged up by high concentrations of suspended sediment, especially the finest fractions. Their eggs can also be smothered from an increase in sedimentation (Berkman & Rabeni, 1987). The sediment transport to the oceans will increase with higher precipitation and glacier melt rate and this can have negative effects on many coastal species such as sugar kelp, which is a keystone species for several types of fish (Bogen, 2009).

The chemical constituents of the sediment transported in floods can also have ecological effects on aquatic organisms. Differences in the amount of organic material, carbon, nitrogen, and phosphorous within or bound to the sediments can have positive or negative effects on primary and secondary production but it can also lead to eutrophication in other vulnerable lakes. The higher concentrations of phosphorous in the sediment associated with higher magnitude floods have large implications for the environment and ecology as P is known as one of the most important nutrients leading to algae blooms and eutrophication (Schindler, 1974). Therefore transport of higher concentrations of this element during floods can have environmental consequences, and the higher concentrations of P combined with higher total amounts of sediment mean that significantly more phosphorous is transported during floods than during normal water discharges. This catchment area has very high values of phosphorous and is situated in the geochemical province with some of the highest concentrations of phosphorous in Norway in overbank flood sediments (Ottesen *et al.*, 2000). The higher levels of P in the area can mean that this lake had a higher productivity of algae in relation to other similar lakes which would support a larger community of benthos as well as fish. Although an increase in productivity of a lake can sometimes be seen as positive, this can eventually lead to eutrophication and algae blooms, which can reduce the quality of the lake (Økland & Økland, 2006). Toxic chemical elements and compounds bound to sediments transported in floods can also have damaging effects to many species in aquatic ecosystems, and even to humans, for example through consumption of fish (vanLoon & Duffy, 2011). All of these ecological consequences due to changes in sediment transport, sediment quality and sedimentation can affect the entire food chain within rivers and lakes.

5 CONCLUSION

In this thesis sedimentation patterns in a Norwegian glacial lake were investigated, with focus on climate-related hydrological processes. Climate change models predict higher temperatures and more precipitation for Norway, resulting in larger and more frequent floods and a higher glacial melt rate (RegClim, 2005). Three different years with extreme climatic situations were chosen for this study as they are representative of conditions characteristic of future climate change; 1979 had a large magnitude flood with a culmination around $90m^3/s$ and a recurrence interval estimated at 100 years, 2002 had the highest summer temperatures since 1876 and extensive glacial melting. The year 2011 had long lasting relatively high rainfall resulting in a long period with water discharge above 30 m^3/s and two large magnitude floods culminating at 46 and 55 m^3/s respectively. These were compared against an extreme low water situation, 1993, which occurred due to a cold summer and low glacial melt rate.

It was found through analysis of sediments collected from cores and traps that sediments transported and deposited during floods can have other characteristics than sediments which are deposited during periods of more moderate water discharge. Studies of the sedimentary sequences in Nigardsvatn confirm that these laminated annual layers are varves due to a seasonal exchange in grain size, mineral composition, and organic material. This thesis focuses especially on the characteristics of floods and high water discharges. It was found that:

- The large floods and years with long-lasting high water discharge can be recognized by thicker sediment deposits where 1979 had an average thickness of 6.3 mm and 2002 had an average sedimentation of 5 mm whereas 1993 had a thickness of only 2.2 mm.
- More organic sediments were found in the 1979 flood layer, around double of that found in the sediments deposited in other years. This was found to be washed out from the non-glacial part of the catchment area during rainfall-induced floods
- The flood layers contain somewhat larger grain sizes. The sand fraction is deposited especially at distances near the delta front. Throughout the entire lake, it was found that the 1979 layer in four of the cores contained 10-30% more material above 31 micron than the 1993 layer.
- Chemical analyses revealed that the flood layers contain more of certain elements that are believed to be washed out from the non-glacial areas. The 1979 layer contained higher concentrations of Al, Ca, Cu, Fe, K, Mg, Mn, P, S and Zn than the other years. Iron oxides are especially visible in flood layers as Fe was contained in higher concentrations, and this is a reason why this layer is distinguishable.
- The sediment trap studies from the period of high transport in 2011, showed much lower concentrations of many chemical elements (Al, Cu, Fe, K, Mg, Mn and Na), as well as less clay and organic material than the cores. This is because many elements are associated with the clay and organic fractions of sediment, and they take a longer time to settle out of suspension, later in the season.

It would be of great interest if it could be possible to reconstruct historical variations in water discharge from sedimentary deposits only. The conclusion from this study is that it is possible to identify only the events of large magnitude sediment transport. However, the other properties found may be helpful for example to distinguish between rain floods and glacier melting events since larger amounts of organic material and chemical elements are washed out from the non-glaciated area subject to rain floods.

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7 APPENDIX

Appendix 1: Data tabell for annual water discharge, suspended sediment transport, and delta sedimentation.

Year	**Water discharge (mill. m^3)**	**Suspended transport (tonns)**	**Delta sedimentation (tonns)**
1968	188	6300	5900
1969	244	15700	8600
1970	208	14700	14200
1971	168	10200	9100
1972	194	12250	19200
1973	179	11700	14100
1974	162	6000	6500
1975	196	10800	17300
1976	174	12500	8700
1977	176	7700	5250
1978	191	7700	8200
1979	191	18400	16900
1980	239	11900	5800
1981	183	8300	6900

1982	188	9100	6100
1983	184	9500	6800
1984	189	10900	5300
1985	212	10000	10800
1986	184	11400	10300
1987	124	17800	11500
1988	213	8800	17000
1989	151	9280	9100
1990	176	10800	14000
1991	165	13000	13900
1992	160	8020	10900
1993	95	4600	10100
1994	119	6700	10100
1995	135	10500	16900
1996	172	15500	16900
1997	211	16200	20900
1998	165	10400	7500
1999	171	9050	11200
2000	178	8280	15500
2001	144	11050	17800
2002	255	20000	22900
2003	237	19100	11600
2004	180	11500	9800
2005	202	13140	6400
2006	245	10110	24000
2007	191	16395	7350
2008	160	6550	4600
2009	193	12546	17870
2010	197	9328	15772

2011	238	32356	12400
Average	183	11040	11850

Appendix 2: Sedimentation in mm from sediment cores

Core	Distance from delta (m)	1979	1993	2002	Total 1979-2005	Average per year (1979-2005)
I	340	12.0	3.3	5.5	121.4	4.5
Z	460	8.0	4.5	5.5	110.0	4.1
W	625	6.3	1.7	7.6	110.7	4.1
X	715	5.3	1.9	4.4	72.9	2.7
B	920	5.0	1.8	4.7	77.4	2.9
S	1015	3.2	0.8	4.5	70.9	2.6
A	1130	3.9	1.5	2.6	55.9	2.1
Average for each year		6.3	2.2	5.0	88.4	3.3

Appendix 3: Total amount of sedimentation in $g/m^2/day$ from sediment traps

Series	Sample	Distance from Delta (m)	Sedimentation (g/m^2/day)
1	1	110	99.55
1	2	195	420.67
1	3	310	98.65
1	4	560	13.82
1	5	900	128.90
2	1	110	153.31
2	2	195	545.55
2	3	310	90.67
2	4	560	105.68
2	5	900	107.85
3	1	110	178.03
3	2	195	394.89
3	3	310	182.50

3	4	560	85.49
3	5	900	751.13

Appendix 4: Percent material in each grain size fraction from 1993, measured from monitoring station

Date	Time	% Clay	% Silt	% Sand	Conc (mg/L)
13.07.1993	09:45	3.85	57.21	38.93	44.79
19.07.1993	18:05	2.31	30.64	67.04	96.26
26.07.1993	17:10	7.31	63.65	29.04	94.86
06.08.1993	17:35	1.24	19.68	79.08	169.86
12.08.1993	18:40	2.24	36.31	61.45	104.56
19.08.1993	17:05	2.82	45.86	51.32	76.13
26.08.1993	17:10	3.81	20.47	75.72	84.53
02.09.1993	18:05	2.02	35.37	62.61	132.17
09.09.1993	17:30	4.99	50.41	44.6	55.96
16.09.1993	18:05	7.44	69.21	23.35	50.1
23.09.1993	18:05	2.99	39.08	57.93	52.82
Average:		3.73	42.54	53.74	87.46

Appendix 5: Percent material in each grain size fraction from 2002. measured from monitoring station

Date	Time	% Clay	% Silt	% Sand
16.07.2002	13:00	3.9	67.8	28.3
30.07.2002	12:00	7.57	70.3	22.1
12.08.2002	12:00	3.93	69.1	27
19.08.2002	12:00	7.55	72.9	19.6
02.09.2002	12:00	8.02	77.1	14.9
10.09.2002	15:00	4.13	71.3	24.6
Average:		5.85	71.4	22.8

Appendix 6: Percent material in each grain size fraction from 2011. measured from monitoring station

Date and time (2011)	% Clay	% Silt	% Sand
05.07. 10.50	10.8	63	26.2
11.07. 12.30	4.7	36.1	59.2
17.07. 12.40	8.3	60.5	31.2
22.07. 11.55	6.8	49.1	44.1
28.07. 12.30	9.9	66.7	23.4
02.08. 11.29	7.8	44.5	47.7
08.08. 11.03	12.7	76.5	10.8
14.08. 08.33	12.2	76.5	11.3
20.08. 09.30	14.4	69.9	15.7
26.08. 09.15	8.7	65.1	26.2
01.09. 09.56	15	65.2	19.8
07.09. 07.45	5.7	25.5	68.8
13.09. 07.57	5.7	19.4	75.2
19.09. 07.34	10.7	39.9	49.4
24.09. 12.40	12.4	77.6	10.1
30.09.	6.3	25.9	67.6

07.15			
05.10. 13.15	5.7	22.4	71.9
Average	9.5	54.1	36.4

Appendix 7: Percentage of material in each size range from the 1979 flood layer from each sediment core

Core (1979):	**I flood**	**Z-flood**	**W-flood**	**X**	**B**	**S**	**A**
Distance (m)	340	460	625	715	920	1015	1130
<2 µm	5.33	6.57	7.15	8.13	10.2	8.72	7.25
2-4 µm	2.97	3.84	4.45	5.35	6.44	5.32	4.14
4-8 µm	5.81	8.07	9.12	10.9	12.5	11.5	9.08
8-16 µm	10.9	17	18.4	19.3	22.3	22.6	19
16-31 µm	19.6	27.7	27.8	24.5	26.1	28.4	26.7
31-63 µm	32	26.4	23.4	22.7	16.8	18	22.7
63-125 µm	19.4	8.92	7.58	8.01	4.69	4.65	9.31
125-250 µm	3.95	1.4	1.97	1.04	1.03	0.83	1.77
250-500 µm	0.00091	0.000069	0.038	0.0002	0.00019	0.0043	0.000053

Appendix 8: Percentage of material in each size range from the 1993 layer from each sediment core

Core (1993):	**I**	**Z**	**W**	**X**	**B**	**S**	**A**
Distance (m)	340	460	625	715	920	1015	1130
<2 µm	9.57	7.75	9.32	9.96	8.77	9.91	9.26

2-4 µm	5.46	4.39	5.73	6.27	5.23	6.54	5.42
4-8 µm	11.6	9.84	11.9	13.5	11.7	14.9	12.8
8-16 µm	22.3	19.8	22.7	25.1	23	27	25.2
16-31 µm	27.3	27.5	28.2	27.8	28.3	26.8	28
31-63 µm	18.9	23.5	18.6	15.1	18.2	12.7	15.6
63-125 µm	4.17	6.37	3.31	2.13	4.33	2.09	3.16
125-250 µm	0.69	0.9	0.17	0.17	0.5	0.0014	0.45
250-500 µm	0.00014	0.0011	0	0	0	0	0.000038

Appendix 9: Percentage of material in each size range from the 2002 layer from each sediment core

Core (2002):	**I**	**Z**	**W**	**X**	**B**	**S**	**A**
Distance(m)	340	460	625	715	920	1015	1130
<2 µm	6.09	6.02	7.24	8.03	6.81	8.31	8.6
2-4 µm	3.38	2.51	3.18	3.95	2.92	3.52	4.31
4-8 µm	7.43	5.34	6.74	8.91	7.32	9.49	10.1
8-16 µm	16.9	12.2	15.3	19.5	18	22.8	22.2
16-31 µm	28.2	24	27.8	29.7	29.5	31.4	30.2
31-63 µm	29.2	35.6	31.1	23.9	25.7	19.8	19.6
63-125 µm	8.21	13.3	8.29	5.57	8.4	4.02	4.47
125-250 µm	0.71	1.01	0.31	0.42	1.36	0.59	0.5
250-500 µm	0.000008	0	0	0	0.00011	0.000031	0.000031

Appendix 10: Mean grain size and percent sand for sediment core "S"

Year (core S)	**Percent sand (over 63 micron)**	**Mean grain size (micron)**	**Median grain size (micron)**	**Mode (micron)**
1973	3.68	20.27	15.45	19.76
1974	1.17	16.75	13.02	16.4
1975	4.91	21.93	16.57	19.76
1976	5.87	23.28	15.65	19.76
1977	1.94	17.69	13.67	18
1978	2.44	16.48	11.65	14.95
1979	5.48	22.82	16.73	21.69
1980	3.09	20.04	15.83	19.76
1981	1.76	16.49	12.62	16.4
1982	2.52	17.75	13.21	16.4
1983	2.34	16.81	11.96	14.94
1984	1.92	16.75	12.47	16.4
1985	2.7	18.48	14.09	18
1986	4.2	19.93	13.98	18
1987	4.96	21.12	13.64	16.4
1988	3.7	21.57	17.01	21.69
1989	1.86	16.32	12.13	14.94
1990	3.48	19.46	14.51	19.76
1991	2.49	18.14	13.78	18
1992	2.26	17.19	12.78	16.4
1993	2.09	17.25	13.24	16.4
1994	4.26	22.14	17.23	21.69
1995	3.69	20.25	14.76	18
1996	4.95	21.97	15.86	19.76
1997	6.42	25.89	20.8	26.14

1998	3.49	20.16	15.09	19.76
1999	5	23.83	18.21	23.81
2000	2.43	19.64	15.81	19.76
2001	5.6	23.47	17.66	21.69
2002	4.61	23.12	18.17	21.69
2003	4.51	24.15	20.26	26.14
2004	3.64	21.03	16.54	21.69
2005	5.41	23.41	18.06	21.69

Appendix 11: Percent sand. mean. median and mode from core A

Year (core A)	**Percent sand (over 63 micron)**	**Mean grain size (micron)**	**Median grain size (micron)**	**Mode (micron)**
1979	11.1	29.46	20.94	23.81
1993	3.6	20.08	15.02	19.76
2002	4.97	23.00	17.87	21.69

Appendix 12: Percent sand. mean. median and mode from core B

Year (core B)	**Percent sand (over 63 micron)**	**Mean grain size (micron)**	**Median grain size (micron)**	**Mode (micron)**
1979	5.73	22.2	15.43	21.69
1993	4.83	22.04	16.49	21.69
2002	9.76	29.69	22.83	26.14

Appendix 13: Percent sand. mean. median and mode from core I

Year (core I)	**Percent sand (over 63 micron)**	**Mean grain size (micron)**	**Median grain size (micron)**	**Mode (micron)**

1979	23.4	43.35	35.31	50.22
1993	4.86	22.25	16.41	21.69
2002	8.92	29.54	24.04	31.54

Appendix 14: Percent sand. mean. median and mode from core W

Year (core W)	Percent sand (over 63 micron)	Mean grain size (micron)	Median grain size (micron)	Mode (micron)
1979	9.59	29.17	21.09	26.14
1993	3.48	20.76	16.12	21.69
2002	8.61	29.55	25.10	34.58

Appendix 15: Percent sand. mean. median and mode from core X

Year (Core X)	Percent sand (over 63 micron)	Mean grain size (micron)	Median grain size (micron)	Mode (micron)
1979	9.06	26.88	19.16	26.14
1993	2.31	18.54	14.29	19.76
2002	5.98	25.19	20.15	26.14

Appendix 16: Percent sand. mean. median and mode from core Z

Year	Percent sand (over 63 micron)	Mean grain size (micron)	Median grain size (micron)	Mode (micron)
1979	10.3	30.08	23.14	28.70
1993	7.27	26.16	19.78	26.14
2002	14.4	35.74	30.96	41.68

Appendix 17: Summary of percent sand and mean grain size for annual layers in the sediment cores

Core	**Year**	**Distance from delta**	**Percent sand**	**Mean grain size (micron)**
I	1979	340	23.4	43.35
I	1993	340	4.86	22.25
I	2002	340	8.92	29.54
Z	1979	460	10.3	30.08
Z	1993	460	7.27	26.16
Z	2002	460	14.4	35.74
W	1979	625	9.59	29.17
W	1993	625	3.48	20.76
W	2002	625	8.61	29.55
X	1979	715	9.06	26.88
X	1993	715	2.31	18.54
X	2002	715	5.98	25.19
B	1979	920	5.73	22.2
B	1993	920	4.83	22.04
B	2002	920	9.76	29.69
S	1979	1015	5.48	22.82
S	1993	1015	2.09	17.25
S	2002	1015	4.61	23.12
A	1979	1130	11.1	29.46
A	1993	1130	3.6	20.08
A	2002	1130	4.97	23

Appendix 18: Grain size distribution for the sediment traps. Series 1

Series 1:	**Trap 1**	**Trap 2**	**Trap 3**	**Trap 4**	**Trap 5**
Distance	110	195	310	560	900

(m)					
<2 µm	6.4	4.27	6.32	6.26	6.31
2-4 µm	2.46	1.12	2.37	2.58	1.9
4-8 µm	5.62	2.08	5.46	5.17	4.28
8-16 µm	13.3	5.45	14.1	12.7	12.7
16-31 µm	22.2	13.6	24.6	25.8	27.9
31-63 µm	30.6	33.6	29.2	33.3	36.3
63-125 µm	19.3	34.7	17.1	14	10.6
125-250 µm	0.19	5.21	0.84	0.2	0.0047
250-500 µm	0	0.0013	0	0	0

Appendix 19: Grain size distribution for the sediment traps. Series 2.

Series 2:	**Trap 1**	**Trap 2**	**Trap 3**	**Trap 4**	**Trap 5**
Distance (m)	110	195	310	560	900
<2 µm	5.04	3.98	5.96	6.6	6.64
2-4 µm	1.86	1.22	2.38	2.49	2.54
4-8 µm	3.83	2.18	5.21	5.76	5.59
8-16 µm	9.03	5.23	12.7	14.9	14.7
16-31 µm	16.9	12.6	23.6	26.3	28
31-63 µm	29.3	31.1	31.5	30.5	32.5
63-125 µm	31	38.3	18.2	13.4	10.1
125-250 µm	3.02	5.36	0.35	0.077	0.066
250-500 µm	0	0	0	0	0

Appendix 20: Grain size distribution for the sediment traps. Series 3.

Series 3:	Trap 1	Trap 2	Trap 3	Trap 4	Trap 5
Distance (m)	110	195	310	560	900
<2 µm	9.1	8.19	10.5	7.91	11.4
2-4 µm	4.49	3.4	5.54	3.42	6.95
4-8 µm	11	7.69	11.9	8.58	13.9
8-16 µm	24.2	18.3	23.4	19.5	25
16-31 µm	29.8	30.2	26.4	27.4	26.2
31-63 µm	20	29.3	18	26.6	14.4
63-125 µm	1.32	2.97	4.32	6.68	2.22
125-250 µm	0	0	0.008	0	0.00027
250-500 µm	0	0	0	0	0

Appendix 21: Percentage of material over 31 µm from the 3 annual layers from the sediment cores.

Core (coarse)	I	Z	W	X	B	S	A
Distance (m)	340	460	625	715	920	1015	1130
1979 over 31	55.35	36.72	32.95	31.75	22.52	23.48	33.78
1993 over 31	23.76	30.77	22.08	17.4	23.03	14.79	19.21
2002 over 31	38.12	49.91	39.7	29.89	35.46	24.41	24.57

Appendix 22: Percentage of material over 31 micron for the 3 series of sediment traps

Traps (coarse)	Trap 1	Trap 2	Trap 3	Trap 4	Trap 5

Distance:	110	195	310	560	900
Series 1	50.09	73.51	47.14	47.5	46.90
Series 2	63.32	74.76	50.05	43.98	42.67
Series 3	21.32	32.27	22.33	33.28	16.62

Appendix 23: Percentage of material under 31 μm from the 3 annual layers from the sediment cores.

Core (Fine)	I	Z	W	X	B	S	A
Distance (m)	340	460	625	715	920	1015	1130
1979 under 31	44.61	63.18	66.92	68.18	77.54	76.54	66.17
1993 under 31	76.23	69.28	77.85	82.63	77	85.15	80.68
2002 under 31	62	50.07	60.26	70.09	64.55	75.52	75.41

Appendix 24: Percentage of material under 31 micron for the 3 series of sediment traps

Traps (Fine)	Trap 1	Trap 2	Trap 3	Trap 4	Trap 5
Distance:	110	195	310	560	900
Series 1	49.98	26.52	52.85	52.51	53.09
Series 2	36.66	25.21	49.85	56.05	57.47
Series 3	78.59	67.78	77.74	66.81	83.45

Appendix 25: Organic material/carbon from suspended samples in 1993 from loss on ignition (LOI)

1993	Inorganic (mg/l)	Organic (mg/l)	Percent Organic

June	52.43	4.11	7.27
July	57.18	10.13	15.05
August	47.28	2.12	4.29
September	28.57	1.64	5.43
Average	46.365	4.5	8.01

Appendix 26: Organic material/carbon from suspended samples in 2002 from loss on ignition (LOI)

2002	Inorganic (mg/l)	Organic (mg/l)	Percent Organic
May	50.95	2.07	3.9
June	195.39	2.69	1.36
July	97.44	1.88	1.89
August	289.8	3.37	1.15
September	45.19	1.33	2.86
October	29.63	1.61	5.15
Average	118.07	2.16	2.72

Appendix 27: Organic material/carbon from suspended samples in 2011 from loss on ignition (LOI)

2011	Inorganic (mg/l)	Organic (mg/l)	Percent Organic carbon
June	75.8	1.85	2.38
July	110.3	1.64	1.47
August	173.4	2.76	1.57
September	167.3	3	1.76
October	177.6	3.73	2.06
Average	134.2	2.31	1.69

Appendix 28: Organic material/carbon from sediment cores from loss on ignition (LOI)

Year	Core	Distance	Percent loss (org carbon)
1979	Z/I	400	7.15
1968-1978	Z	460	3.72
2000-2005	Z	460	3.17
1979	X	715	9.67
1968-1978	X	715	4.68
2000-2005	X	715	1.96
1968-1978	A	1130	4.25
2000-2005	A	1130	2.84

Appendix 29: Organic material/carbon from sediment cores from C-analyzer

Year	Core	Distance	Percent organic carbon
1979	Z/I	400	0.387
1968-1978	Z	460	0.204
2000-2005	Z	460	0.174
1979	X	715	0.54
1968-1978	X	715	0.197
2000-2005	X	715	0.143
1968-	A	1130	0.065

1978			
2000-2005	A	1130	0.174

Appendix 30: Organic material/carbon from sediment traps from LOI

Series	Trap	Distance (m)	Percent loss (organic carbon)
1	1	110	0.61
1	2	195	0.33
1	3	310	0.56
1	4	560	1.02
1	5	900	0.42
2	1	110	1.31
2	2	195	0.26
2	3	310	0.67
2	4	560	0.51
2	5	900	0.50
3	1	110	0.48
3	2	195	0.70
3	3	310	0.57
3	4	560	0.49
3	5	900	0.65

Appendix 31: Organic material/carbon from sediment traps from C-analyzer

Appendix:Series	Trap	Distance (m)	Percent organic carbon
1	1	110	0.175
1	2	195	0.053

1	3	310	0.174
1	4	560	0.317
1	5	900	0.087
2	1	110	0.246
2	2	195	0.065
2	3	310	0.154
2	4	560	0.165
2	5	900	0.141
3	1	110	0.088
3	2	195	0.163
3	3	310	0.088
3	4	560	0.086
3	5	900	0.142

Appendix 32: pH of the sediments from the sediment traps

Series	Sample	pH
1	1	5.7
1	2	6.73
1	3	5.19
1	4	5.42
1	5	6.56
2	1	4.08
2	2	6.03
2	3	5.86
2	4	5.69
2	5	5.83
3	1	6.22
3	2	6.38
3	3	6.18

3	4	6.09
3	5	6.58

Appendix 33: Chemistry of the sediment cores (mg/kg or ppm)

Core	**Year**	**Distance (m)**	**Al**	**Ca**	**Cu**	**Fe**	**K**	**Mg**	**Mn**	**Na**	**P**	**Pb**	**S**	**Zn**
Z+I	1979	400	23000	11800	29	32600	11900	11100	733	480	1299	19	103	95
Z+I	1968-1978	460	22100	10800	24	31700	12000	10800	691	627	1188	20	57	86
Z+I	2000-2005	460	18700	11200	17	28400	10200	9200	591	519	1284	11	96	73
x	1979	715	26400	11500	40	33900	14300	12500	763	603	1471	16	100	100
x	1968-1978	715	23000	10800	26	31500	12900	10900	692	679	1216	20	67	88
x	2000-2005	715	19200	11100	18	27800	10500	9300	587	576	1239	11	61	77
A	1968-1979	1130	14600	11400	12	21800	7300	6800	442	456	1402	8	93	51
A	2000-2005	1130	23000	11800	29	32600	11900	11100	733	480	1299	19	103	95

Appendix 34: Chemistry of the sediment traps (mg/kg or ppm)

Series	Sample	Distance (m)	Al	Ca	Cu	Fe	K	Mg	Mn	Na	P	Pb	S	Zn
1	1	110	16400	12200	15	24500	7900	7900	483	422	1385	38	215	59
1	2	195	12900	12800	11	20300	5900	6100	395	421	1631	12	243	50
1	3	310	18000	11400	18	26400	9400	8800	531	476	1289	17	177	90
1	4	560	18800	11900	23	28500	9600	9100	592	511	1292	49	119	178
1	5	900	16200	12100	14	23700	8100	7800	477	463	1396	13	165	70
2	1	110	15500	12300	16	24500	8000	7500	478	412	1561	14	229	60
2	2	195	12400	12600	10	20400	5900	5900	391	360	1664	7	287	47
2	3	310	16500	12100	14	24900	8500	8000	514	423	1490	22	163	64
2	4	560	16500	12000	15	24200	8500	8000	479	459	1455	20	204	135
2	5	900	17500	11800	16	26100	9200	8700	513	434	1385	17	168	77
3	1	110	16800	11200	15	25500	8700	8000	493	435	1229	13	56	78
3	2	195	21200	11600	21	30700	11500	10400	632	503	1243	15	109	81
3	3	310	17600	11800	15	26000	9000	8500	527	425	1324	11	104	103
3	4	560	16500	11800	15	25200	8400	8000	510	390	1338	20	135	65

3	5	900	194 00	107 00	1 8	275 00	105 00	930 0	5 7 6	5 0 5	11 68	1 4	5 8	7 2

Appendix 35: Average. median. maximum. minimum and standard deviation of concentrations of chemical elements in all samples (in mg/kg or ppm)

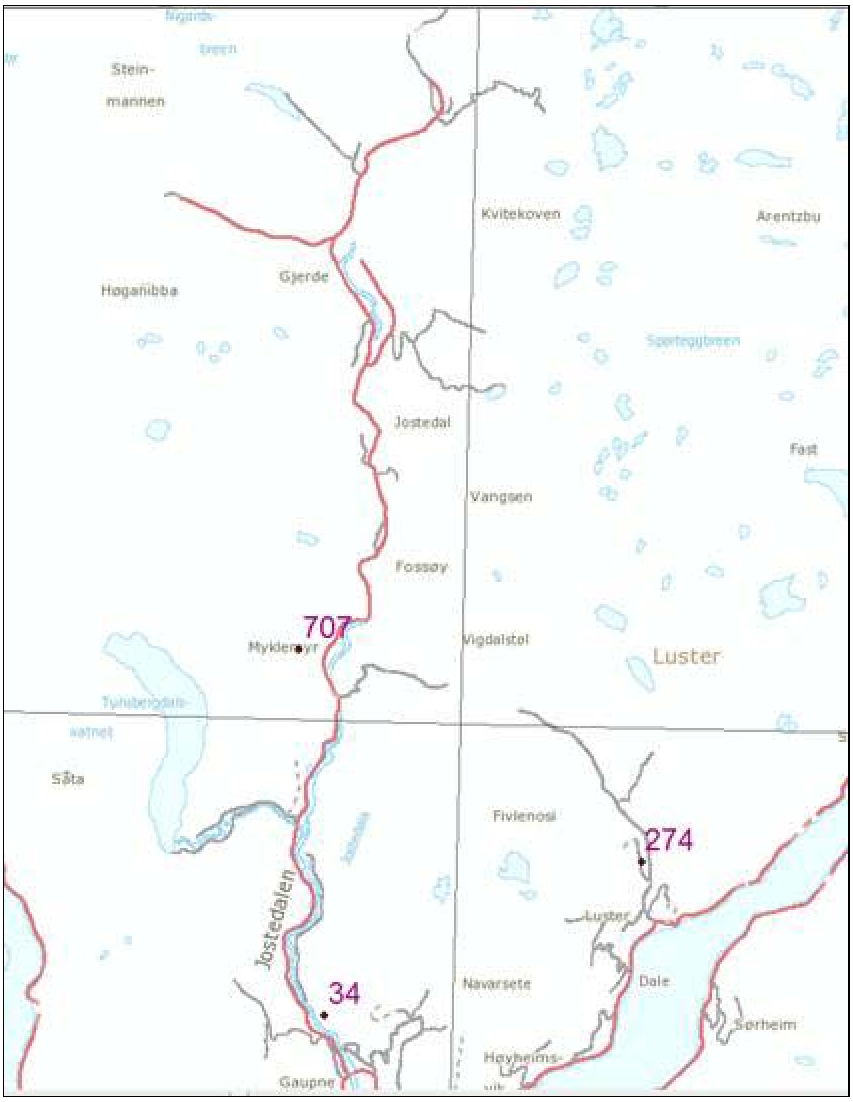
	Avg	**Median**	**Maximum**	**Minimum**	**Standard deviation**
Al	18348	17600	26400	12400	3425
Ca	11630	11800	12800	10600	587
Cu	19	16	40	10	7
Fe	26835	26100	33900	20300	3750
K	9596	9200	14300	5900	2139
Mg	8843	8700	12500	5900	1646
Mn	555	527	763	391	102
Na	488	463	679	360	85
P	1354	1324	1664	1168	139
Pb	18	16	49	7	8
S	134	109	287	56	65
Zn	82	77	178	47	28

Appendix 36: Geochemical data from NGU (Norwegian geochemical atlas). concentrations in ppm of mg/kg. The samples from location 707 were taken in Myklemyr not far downstream of Nigardsvatn in the Jostedal catchment. and location 34 is the samples taken further down the river. north of Gaupne. The results for acid extractable elements are from analyses done at NGU and the results for the total contents of each chemical element were done again at an external lab (SGAB).

	Al	**Ca**	**Cu**	**Fe**	**K**	**Mg**	**M n**	**Na**	**P**	**Pb**	**S**	**Zn**
Gaupne-34 (NGU)	70 00	97 00		12 60 0	29 00. 0	36 00	21 2.9	17 9.4	29 00. 0			24. 7
Myklemyr -707	15 80	48 00		17 40	58 00.	65 00	30 1.9	15 4.0	99 6.9			51. 5

(NGU)	0			0	0							
Gaupne-34 (SGAB)	72338	32354	21.0	45120	27710	8026	558	25728	3190	54.0	70	30.0
Myklemyr-707(SGAB)	79409	18439	11.0	34461	34293	10855	534	21002	1785	75.0	100	70.0
Average	43637	16323	16	27395	17676	7245	402	11766	2218	65	85	44

Appendix 37: Map of the locations (707 and 34) used for the NGU geochemical analysis of overbank sediment for Norways geochemical map. Nigardsvatn is in the top left.



Appendix 38: List of figures and tables

Table 3: Climatic, geographic and hydrological data for the catchment area of Nigardsvatn outlet (Breelvi)

Tabel 4: Sedimentation equations from sediment core varve thickness for respective years 1979, 1993, 2002 and average thickness per year from the entire period 1979-2005.