Sedimentation patterns and sediment composition in a Norwegian glacial lake during a large magnitude flood

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Abstract In 1979 a large magnitude flood on the southeast side of the Jostedalsbreen ice-cap in western Norway created distinct sediment layers in glacial Lake Nigardsvatn. This paper examines sediment transport and deposition in a glacial meltwater river in 1979, 1993 and 2002, and the downstream variation in thickness of sediment deposits in Lake Nigardsvatn. The thickest deposit was observed next to the delta front and a more rapid downstream decrease occurred during the 1979 event. Particle-size analysis indicated that the 1979 and 2002 sediment layers contained more coarse fractions (>31 μm) than the 1993 layer. During 1979, coarser sediment was deposited closest to the delta compared to the 1993 and 2002 events. The occurrence of rainfall induced floods during the summer of 2011 led to the highest water discharge and suspended sediment load on record. The observed conditions were comparable to that of higher magnitude floods.

Key words sedimentation; glacial lake; suspended sediment loads; varve thickness; large magnitude flood; grain size distribution

INTRODUCTION

Lake sediment deposits are important indicators of flood events that can be used to date sedimentary processes. Such information is relevant to the study of the effects of climate change on sediment transport and deposition processes. Climate models predict an increase in both the frequency and intensity of rainfall induced floods in many parts of the world, including Norway (Roald *et al.*, 2002, 2006). In addition, temperature change is expected to cause some glaciers to melt which will alter stream hydrology and sediment transport. Accordingly, the study of sediment load, particle size distribution and depositional patterns in climate vulnerable landscapes is necessary to predict the implications of future climate change on sedimentary environments.

Sediment transport and sediment composition may vary with time in response to external factors such as temperature and precipitation (Bogen, 1995). Such variations may be reflected in the sedimentation patterns of glacial lakes. Varves are annual sediment layers that shift between thick, light, coarser layers deposited during the summer and the thin, darker layers of mica in the fine clay fraction deposited in winter (Zolitschka *et al.*, 1997). They are used to study variations in sediment transport and sedimentation rates (Kennie *et al.*, 2010). Østrem (2005) demonstrated that the rhythmic sequences in Lake Nigardsvatn are due to annual changes in grain size and mineral composition. These sediment deposits were visible as distinct layers in the sediment cores from the lake. The observed 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 high flow velocity.

This paper examines sediment deposits in glacial Lake Nigardsvatn in order to evaluate the effect of floods on sediment deposition. The results have implications for dating of sedimentary sequences and prediction or interpolation of data in areas or during periods where no hydrological or sedimentological data are available.

METHODS

A series of studies investigating sediment transport and sedimentation patterns were undertaken in a glacial lake in western Norway (Fig. 1). The meltwater river from the Nigardsbreen Glacier delivers sediment to the lake below. The river expands across the delta platform and some of the bedload is deposited at the topset, while the remainder in suspension is carried to the delta front.

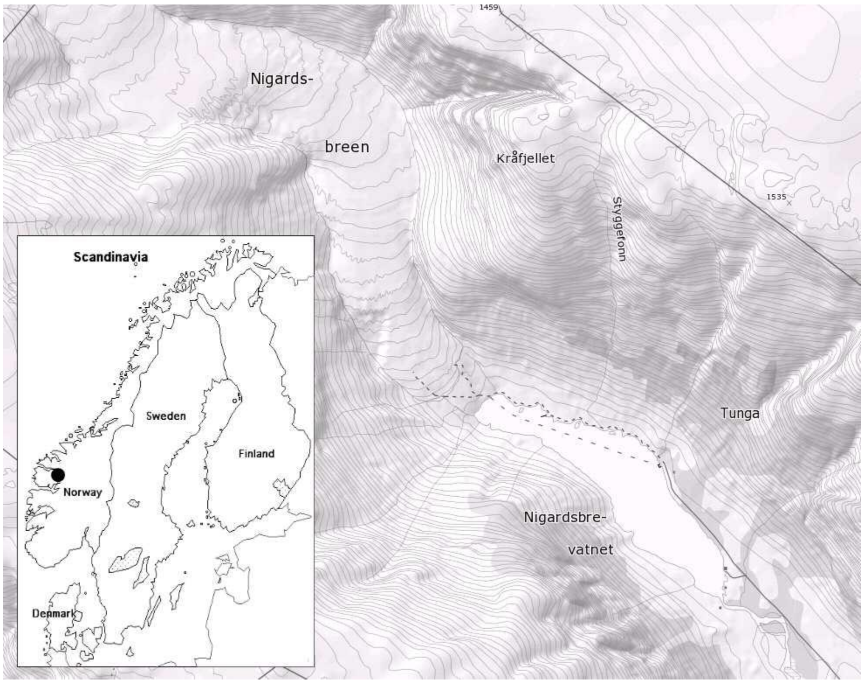


Fig. 1 Location of the Nigardsbreen Glacier and Nigardsvatn Lake. The black circle indicates the position of the study site.

This paper focuses on processes that take place in the lake basin beyond the present delta front. The study of lake sedimentation included systematic laboratory analysis for grain size distribution and total thickness 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 in the glacial melt river sampled at the monitoring station.

Sediment traps described by Håkansson (1976) were deployed on the lake bottom (Fig. 2) to collect sediments during three different periods throughout the summer of 2011. Five traps were set at varying distances from the river outflow for a period of 33 to 35 days. Sediment cores were collected using percussion corers (Reasoner, 1993; Gilbert, 1985).

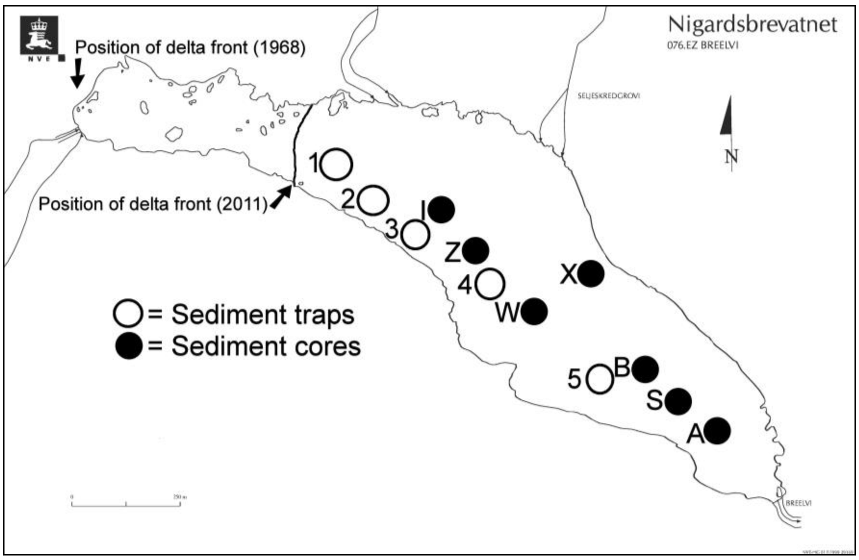


Fig. 2 Locations of the sediment cores and sediment traps.

Sediment transport in the glacial stream was measured several times daily with an ISCO automatic sampler at a monitoring station located by the river flowing from Nigardsbreen Glacier to Lake Nigardsvatn. The sampling methods and subsequent laboratory analyses used by NVE are described in detail by Bogen & Bonsnes (2003). Sediments collected in traps were dried and weighed for each period. Sediment cores were prepared and photographed. The thickness of each varve was calculated with the help of a computer program called JPEG editor which distinguishes between and measures dark and light pixels.

The grain size distribution of sediment in traps was determined with a Beckman Coulter laser diffraction particle size analyser, which analyses in the range of 0.04–2000 µm. Sediment deposits were examined for three years of interest: (1) in 1979 a large magnitude flood occurred with a recurrence interval of 100 years; (2) 1993 had a low melt rate year; and (3) 2002 was a season when large melt rates and high temperatures caused high sediment transport rates to occur. The samples were treated with hydrogen peroxide to remove organic material then sonicated to break up all aggregates.

RESULTS

Suspended sediment load and water discharge

Large seasonal and interannual fluctuations in sediment flux to the lake were observed. The highest sediment concentrations and river discharges were measured in 1979. This season had a large magnitude flood with an estimated recurrence interval of 100 years (Gjessing & Wold, 1980). The August 1979 flood had a very high but short lived water discharge. On 14 and 15 August, the flood peaked at over 80 m^3/s and sediment concentrations were >3000 g/L (Fig. 3(a)). The total water discharge in 1979 was 191×10^6 m^3 and 18 400 tons of sediment was transported.

During 1993, water discharge and sedimentation rates in the lake were low. The total discharge was 95×10^6 m^3 and 4600 tons of sediment were transported. Maximum sediment concentrations never exceeded 80 mg/L and discharge was 24–27 m^3/s. During large parts of the season the water discharge was <10 m^3/s (Fig. 3(b)). During 2002, water discharge was relatively high and it lasted for most of the melting season. Maximum discharge ranged from 30 to 40 m^3/s. During 10 days at the end of August, the sediment concentrations were over 500 mg/L. Conditions in 2002 and 1979 were similar and a short lived pulse with relatively high sediment concentrations occurred in August 2002 with maximum concentrations of 1900 mg/L (Fig. 3(c)). The high water discharge rates observed were due to accelerated glacial melting because of high summer temperatures; it was one of the warmest summers observed in Norway since measurements started in 1876. Total sediment transport in 2002 was slightly larger than the total transport in 1979, and 2002 had the second highest water discharge and sediment transport recorded since the monitoring started, after the year 2011. Total discharge over the season is measured at 255×10^6 m^3 and the total suspended load was 20 000 tons. This estimate is probably lower than the actual value as there is some uncertainty in these measurements because of logistical problems monitoring these parameters, due to the establishment of new meltwater channels from the glacier.

The highest total discharge (259×10^6 m^3/s) on record since the monitoring started in 1968 occurred in 2011. The total suspended sediment transport was 34 000 tons and maximum sediment concentrations were around 1200 mg/L. In 2011, two large magnitude floods occurred. The first culminated on the 19th June at 52 m^3/s, with a recurrence interval of 5 years. The second discharge event (60 m^3/s) on 28 August had a recurrence interval of 10 years. During this event sediment concentrations were over 30 mg/L but later in the season sediment concentrations exceeded 50 mg/L (Fig. 3(d)).

Sedimentation rates

Analyses of the sediment cores showed a decrease in varve thickness h with distance from the delta front (Fig. 4). Sedimentation rates in the lake were higher in 1979, especially in cores that were closer to the delta front. There is evidence too that at some locations further into the lake the

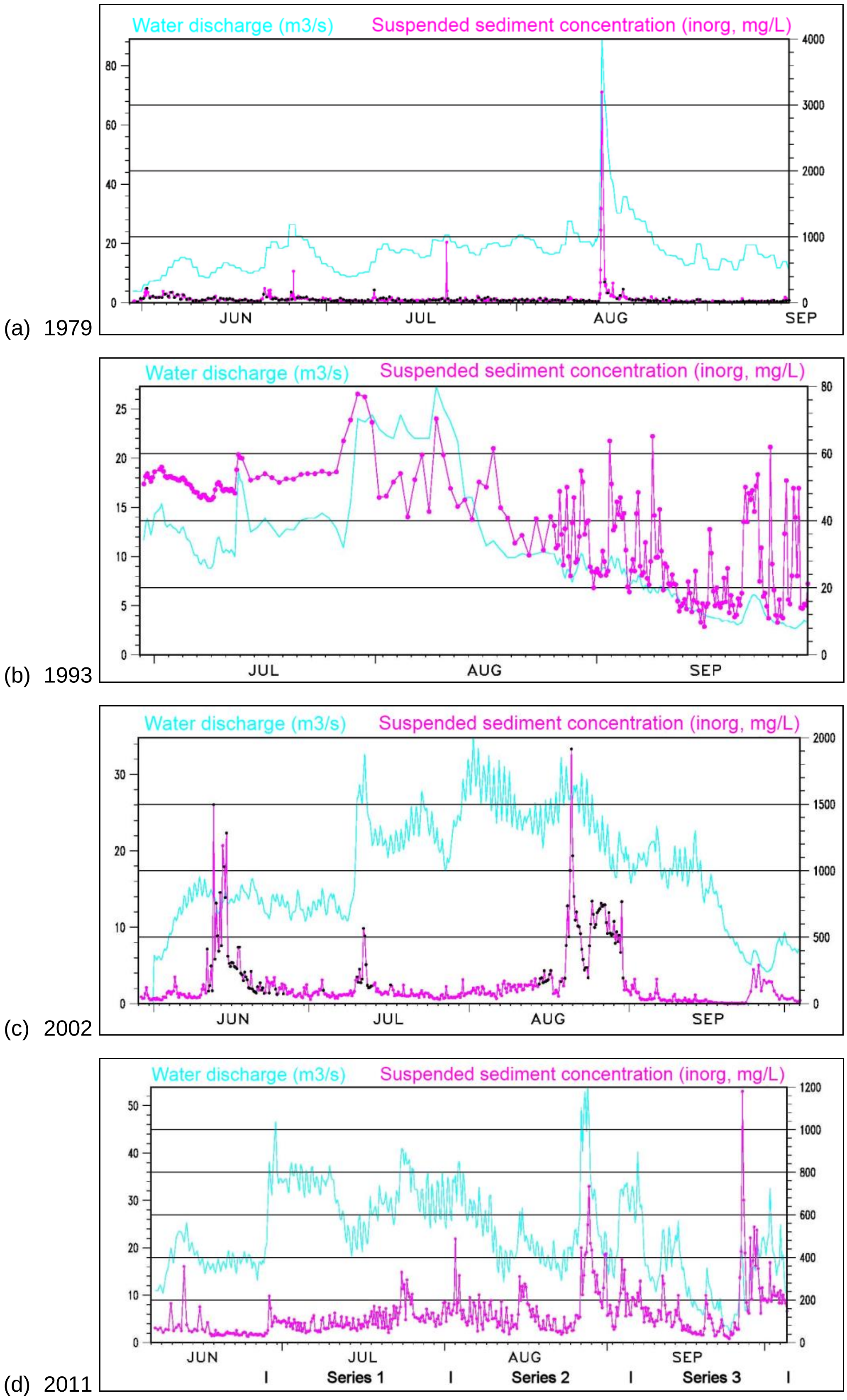


Fig. 3 Discharge and suspended sediment data for the Nigardsbreelv River: (a) 1979, (b) 1993, (c) 2002, and (d) 2011. In 2011, sediment trap deployed for periods: Series 1: 28 June–1 August, Series 2: 1 August–5 September, and Series 3: 5 September–6 October.

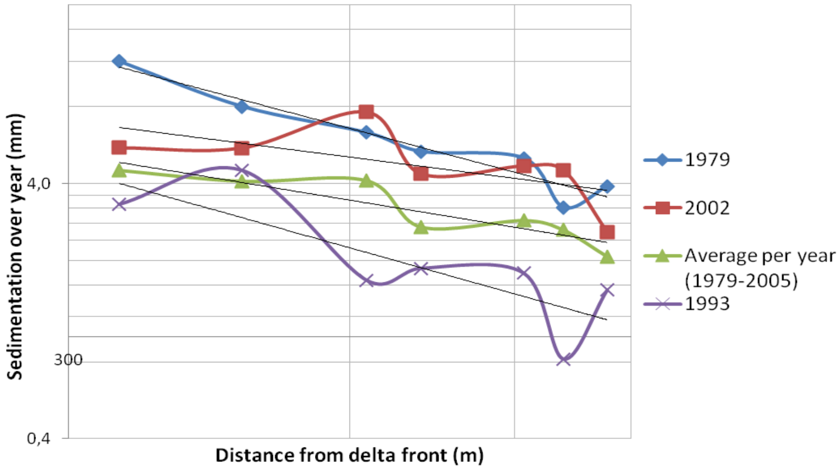


Fig. 4 Annual sediment layer (mm) for sediment cores with decreasing distance from the delta front (m). Included is a trend line and equation for 1979 as well as for the average over all years in the period 1979–2005. The average sediment thickness per year was found by dividing the total sediment thickness from 1979 to 2005 by the number of years.

2002 event caused large deposits to form. Varve thicknesses <2 mm occurred in 1993 but generally decreased exponentially with distance from the delta, along the line of streamflow in the lake. Annual sedimentation curves differed. The downstream decrease in sedimentation rate in lakes close to the river mouth was best fitted to the equation $y = ax^{-b}$ where the exponent b is related to the dynamic and geometric properties of the system, y is sedimentation in either depth or mass per unit of time and x is distance. A large b value implies rapid sediment deposition. When the b value is low, the sediments remain in suspension further downstream (Bogen, 1983). The equation for 1979 is $d = 3.3 \times 10^3 \times x^{-1.0}$ and the equation for yearly average sedimentation 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 metres. The curve for 1979 decreases more sharply with a higher gradient than the other curves, and the curve for 1993 has the lowest gradient.

Sedimentation results were similar for all three series of sediment traps throughout the 2011 summer season, but differences in grain size distribution were observed. The traps at location 1 had low sedimentation rates while the traps at location 2 had much higher sedimentation rates. At locations 3, 4 and 5 sedimentation decreased 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. Figure 5 shows the sedimentation in traps as a function of distance from the delta front for all three series for the summer of 2011, along with an average of daily sedimentation from these traps, as well as the exponential equation for the curve $M = 3.2 \times 10^4 \times x^{-0.9}$ where x is distance from the delta front in metres and M is mass of average daily sedimentation in $g/m^2/d$. 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 m, with the exception of trap number 5 in series 3 which had 751 $g/m^2/d$.

Grain size distribution

The particle size distributions of annual sediment layers with increasing distance from the delta front are shown in Fig. 6. Sediments deposited during the flood of 1979 had a higher percent volume of coarser material in the size range of 31–250 µm than sediments deposited in other years, especially in the cores closest to the river delta. The 1993 sediments had much lower relative percentages of coarser sediments 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.

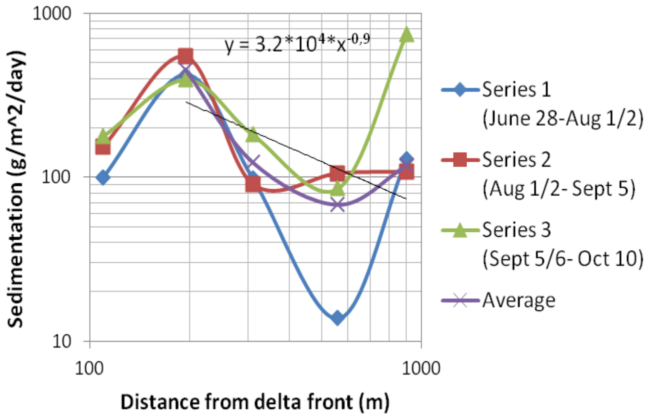
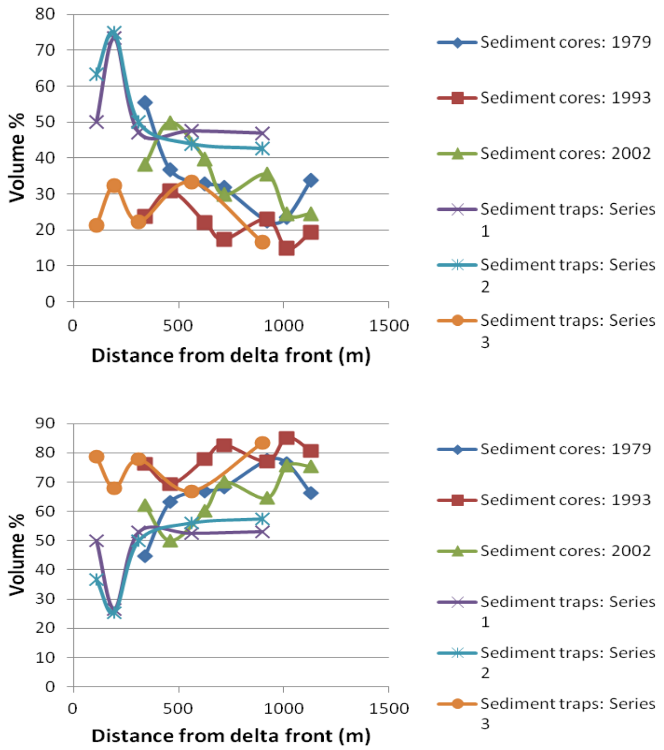


Fig. 5 Total sedimentation in Nigardsvatn Lake (traps 1–5) with distance from the delta front, summer–autumn 2011, including the average daily sedimentation from all series of traps (Series 1–3) in locations 2–5 set out on Nigardsvatn Lake bottom during the melt season of 2011. Location 1 is omitted 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.



(a) >31 µm

(b) <31 µm

Fig. 6 Grain size distribution of sediments accumulated in sediment cores and traps, particles: (a) larger than 31 µm, and (b) smaller than 31 µm.

The grain size distribution curves for material in the size range 31–250 µm deposited in each of the three series of sediment traps as a function of distance from the delta front is also shown in Fig. 6. 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% 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%, much less than the other two series which had from 10 to nearly 40% sand. Series 3 also had a higher percentage finer material

<31 µm. Series 2, with a higher magnitude flood, had a higher percentage of sand than series 1. The size range 125–250 µm was negligible in most traps except at location 2 in series 1, and locations 1 and 2 for series 2. The smaller size ranges, < 31 µm, had the lowest relative amounts in location two, and remained relatively stable or even increased at the other locations further out into the lake.

DISCUSSION AND CONCLUSION

Sedimentation rates

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, cause somewhat different sedimentation patterns in the lake than a relatively large, long-lasting water discharge from glacial melt, and these two situations produce results that differ from low-flow conditions. The 2002 and 1979 data have similar sedimentation patterns, with the exception of the innermost locations, where 1979 has higher sedimentation. A short-lived extremely high water discharge can bring in higher amounts of material than a long lasting relatively high water discharge, and in the extreme flood situation, larger amounts of material with a higher percentage of particles of larger grain size are deposited closer to the delta. There is also a difference in sediment sources. Glacial melting brings in material from the glacier and its sole, whereas rain can wash in sediments from the unglaciated mountain sides.

Each period during which the sediment traps were deployed 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 was during the period of highest melt, July–August, and included 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, as several small streams of water are known to flow into the lake from the sides of the mountain surrounding it and landslides are known to occur, bringing material into the lake from the mountain sides. 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 is probably why the traps at location 2 had so much sedimentation throughout all series.

The results from the sediment traps in 2011 show a situation more similar to the flood year 1979 than 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 1979–2005, measured from the sediment cores, was –0.6 and much smaller than that for the varves from 1979 and the sediment traps in 2011. The sediment transport and water discharge for 2011 is 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 and therefore individual higher water discharges along with higher stream velocities and higher sediment concentrations with a larger grain size correspond to a more negative gradient in the 1979 plot for sedimentation *vs* distance into the lake. This means that during high discharges a higher amount of sediments is transported, but a larger proportion of these settle in the proximal area closest to the delta. This could be attributed to a coarser grain size distribution.

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, values that are much larger than for Lake Nigardsvatn. The depth of these other lakes ranged from 30–50 m in the proximal part of the delta area. The much lower exponents (0.6 to 1.0) found for Nigardsvatn are probably due to the more moderate depth and the relatively high flow velocity throughout this lake.

Grain size distribution

The grain size distribution was generally coarser for the 1979 deposits than the other layers, especially furthest into in the lake, because the higher water discharge during floods led to a higher stream velocity into the lake. The increased forces could carry more particles of a higher diameter in suspension, but these were deposited when the stream velocity decreased as the river flowed into the lake. The particle size distribution of the 2002 deposits was coarse, because discharge and streamflow were high throughout this year. More coarse material (silt and sand fractions) accumulated in the proximal part of the delta, because the stream velocity decreases as the lake deepens and widens. The smaller particles are held in suspension over longer distances and do not settle until a further significant decrease in velocity.

The percentage of coarse sediments, >63 µm, was largest at trap location 2 and decreased with distance 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 (Allen, 1970). Accordingly, the cut-off grain size is from 31–63 µm, where material above this grain size generally accumulates closer to the delta, whereas finer material is deposited with increasing distance into the lake.

The sediment traps from earlier in the season had a larger proportion of coarser sediments (>31 µm) than the sediment cores. At the end of each melting season, the lake freezes over and the sediments in the finest clay fractions then settle. Small velocities from the inflowing river and turbulence from wind are enough to hold a large amount of the finer fractions in suspension throughout the body of the lake during the summer months. Therefore, the clay fractions will mostly accumulate at the end of the season as the water discharge from the glacier declines and the lake is covered with ice.

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