Sediment transport in Greenland

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Abstract A review of sediment transport investigations in Greenland has been carried out. The concentration of sediment in water courses with a significant contribution from glacierized areas ranges from 50 to more than 20 000 mg l^{-1}. From non-glacierized areas the sediment concentration is mostly less than 100 mg l^{-1}, and commonly less than 20 mg l^{-1}. The measured annual sediment transport from glacierized areas ranges from 84 to 1500 t km^2 $year^{-1}$. From non-glacierized areas the measured transport ranges from 1 to 56 t km^2 $year^{-1}$. These figures are minimum values because it has not been possible to monitor the transport during the early spring, late autumn and winter. It is shown that a large proportion of the sediment transport is often deposited before it reaches the sea. Greenland is probably the main contributor of sediment to the North Atlantic Ocean and to the waters west of Greenland. Calving ice fronts and ice-streams are probably the main contributors to long distance transport.

INTRODUCTION AND AIMS

Greenland is the largest island in the world, with an area of 2 175 600 km^2. About 84% of the area is covered by the Greenland Ice Sheet, an ice sheet with altitudes extending to more than 3000 m above sea level. The Greenland Ice Sheet is nearly everywhere surrounded by a strip of land with a maximum width of about 200 km. During the Ice Ages, the Greenland Ice Sheet covered different parts of the fringe of land or the whole fringe.

As glacial erosion is one of the most sediment productive types of erosion, the extension of the Greenland Ice Sheet and of the ice free border zone will have a major impact on the amount of sediment delivered to the surrounding oceans. With the increasing interest in studies of climate change by use of ice and ocean bottom cores, knowledge of the sediment transport from Greenland is of major importance for linking and interpretation of the cores. Also the exploitation of water power in Greenland has created a need for information about sediment transport.

The aim of this paper is to present a review of investigations dealing with sediment transport in Greenland, to extract quantitative information and to discuss the implications of the information assembled.

METHODOLOGY

The review has been carried out using the library search programs GEOBASE and REX, through personal enquiries at institutions carrying out research in Greenland, e.g.

Greenland Geological Survey, former Greenland Technical Organization, Greenland Environmental Research Organization, Danish Polar Center and universities in Copenhagen and Aarhus, and through enquiries to scientists visiting Greenland from other countries. Results from personal investigations published previously are also summarized. The review only includes investigations where direct measurements of sediment transport were carried out; indirect measurements, such as sediment cores, are not included.

The individual researchers and institutions have applied different methods and it is therefore difficult to make detailed comparisons between the results. Sampling is often carried out manually, at best where total mixing is present. In some investigations, however, a depth integrating sampler of Swedish origin (Nilsson, 1969) has been used. The earliest investigations use paper filters as described by Østrem (1969). Recent investigations use Whatman GF/F or /C or Millipore 0.45 and 0.22 μm filters. Indirect *in situ* measurements of concentration have been carried out using Partech transmissometers.

Automatic sampling has been undertaken by use of Manning samplers, although in this case particle separation was observed. Other investigations have mainly used ISCO samplers. Few observations of bed load transport exist. A Danish pressure difference sampler has been utilized and modified Helley-Smith samplers and dune tracking have also been used. The corresponding discharge has been measured by use of ordinary current meters and established stage/discharge relationships.

It is obvious that the investigations of sediment transport in Greenland have been *ad hoc*, and that a systematic approach has been taken in only a few areas. Therefore the results are most often from a single site and the duration of the measuring programme is short. The implication of this is that information on seasonal variations is limited and that only one long time series of sediment transport data exists. In the following, a summary of the results of the review is provided. The individual projects are described briefly.

RESULTS

The map in Fig. 1 shows the locations in Greenland where measurements of sediment transport have been carried out. The findings of the different investigations have been summarized in Table 1. The individual investigations are briefly summarized chronologically below. For further information the reader is directed to the original publications.

The first measurements of sediment transport in Greenland were initiated in 1972 on Ammassalik Island (Hasholt, 1976). Runoff and material transport from the Mittivakat Glacier (No. 10 on Fig. 1) were monitored for a 44 day period. Suspended, bed and dissolved load were measured. The total sediment load was 9380 t corresponding to more than 938 t km^2 year^{-1}. Dissolved load was 380 t. The relative contribution from suspended, bed and dissolved load was 72%, 22% and 6% respectively. The sediment transport in this area has been investigated further in following years (Hansen & Tastum, 1979; Hasholt, 1992, 1993, 1994; Hasholt & Walling, 1992 and Busskamp & Hasholt, 1996). Sediment transport starts in May-June, when the melting season starts. Initially the transport is very random, because the meltwater cuts through an icing. The transport peaks simultaneously with the runoff maximum from the glacier, generally in July. A regular daily variation is often seen in August. In late August and September a

Fig. 1 A map of Greenland showing the location of the study areas cited in the text.

secondary maximum caused by ice formation is observed. From October, only minor runoff, forming an icing, takes place. The regular pattern may be obscured when larger rainfall or foehn winds influence the area. The glacier has been retreating since the first observations in 1933. It has been observed that the emerging pro-glacial valley acts as

Table 1 Results from sediment transport studies in Greenland.

Locality number	1	2	3	4	5	6	7	8	9	10	11
Latitude (N)	71°07′	69°44′	69°17′	69°20′	67°00′	67°	66°06′	64°03′	61°25′	65°40′	74°28′
Longitude (W)	51°17′	54°40′	53°35′	52°40′	50°00′	50°-53°30′	50°07′	50°06′	45°30′	37°55′	20°37′
Year(s)	1978-1989 1) 1983-1989 2)	1993	1976	1991	1988, 1994	1977	1982	1981	1979	1972, 1979, 1989 1990, 1991, 1992	1991
Month(s)	6-10	8	8	7	7,8	8	7, 8	8	7, 8	(6), 7, 8, (9)	7, 8
Basin (km^2)	177 1) 31 2)	55	66	117	?	?	25	563	146	10 1)	470
Glacier %	59 1) 65 2)	<10	21	28	? 1)	?	95	2	24	80 1)	19
Lake %	*c*.5 1) 0 2)	<1	0	0	?	?	0	16	7	0	*c*. 5
Concentration average ($mg\ l^{-1}$)	12-41 1) 259-1085 2)	4 1) 37 2)	15	200	?	?	189	0-1	43	29-737 2)	?
Concentration range ($mg\ l^{-1}$)	5-47 1) 5-22519 2)	4-80 1) 35-38 2)	7-469 1)	95-650	100-200 1) 650-900 2) 400-2000 3)	2-7 1) 34-1800 2)	30-1950	0-19	36-48	67-1797	72-1032 30 1) 1559 2)
Suspended transport ($g\ s^{-1}\ km^{-2}$)	0.04-0.7 1) 2.6-24 2)	0.04-0.08 1.7 3)	1-122	9-30	?	?	1-183	near 0	4-6	10-1229	1-49 231 3)
Suspended load ($t\ km^{-2}\ year^{-1}$)	1.4-22.8 1) 84-750 2)	?	?	?	?	?	>86 214 1)	<5	>218 1) >56 2)	1000-1500 3) >938 4)	?
Bed load %	0 1) ? 2)	?	?	?	?	0-?	?	0	0	<25	?

Notes: 1 = Marmorilik: 1) to A-Fjord, 2) to Q-Fjord; 2 = Mellemfjord: 1) non glaciated, 2) partly glaciated 3) after rainstorm; 3 = Røde Elv: 1) after rainstorm; 5 = Russel Glacier, 1) coarse grained fan, 2) fine grained fan, 3) Watson River; maximum was 4000 mg/l indicating higher loads in other outlets from the Greenland Ice Sheet; 6 = Sisimiut: 1) non glaciated, 2) from local glaciers and Greenland Ice Sheet; 7 = Amitsuloq: 1) authors' estimate including bed-load and another outlet; 9 = Nordbo Lake: 1) from area covered by glacier, 2) outlet from lake; 10 = Sermilik: 1) Approximate area (8-12 km^2) final value will be obtained by survey of bottom topography in 1996, 2) depending on period, 3) estimate including bed load, 4) longest period of record; 11 = Zackenberg: 1) outlet from lake with input from glaciers, 2) from tributary draining weathered sedimentary rocks, 3) from sedimentary rocks basin only.
? means no information. In the case of bed load it means that it is probably present but not measured.

a sink for a part of the glacially eroded material (Hasholt & Walling, 1992; Busskamp & Hasholt, 1996).

The transport of sediment in Røde Elv, near Godhavn on Disko Island, (No. 3 on Fig. 1, has been monitored in connection with a field course arranged by the Institute of Geography, University of Copenhagen (Humlum, 1976). The river mainly drains an ice free area, but part of the water comes from a local glacier, the Chamberlain Glacier. Suspended sediment concentrations varied from 7 to 469 mg l^{-1}. During the measurement period, the concentration was mostly very low, indicating that the contribution from glacial erosion was low. The high concentration was observed after a rainstorm.

In 1976 the ice-free area from Søndre Strømfjord to Sisimiut (No. 6 on Fig. 1) was surveyed (Hasholt & Søgaard, 1978). A "snapshot" record of discharge and sediment concentration was obtained. The results are comparable because the observations took place after a long period with no rainfall. Clear distinctions could be made between water from the Greenland Ice Sheet and local glaciers (up to 1800 mg l^{-1}) and water from ice-free areas, the latter having very low concentrations (<20 mg l^{-1}). Furthermore, a belt with saline lakes due to excess evaporation was observed in an arid zone near the Greenland Ice Sheet. Turbid water could be seen clearly in lakes with a contribution from glaciers. A major part of the sediment from Watson River was deposited in the inner part of the fjord.

At Marmorilik (No. 1 on Fig. 1), a lead and zinc mine was in operation from 1972 to 1989. Due to the resulting pollution, an environmental monitoring programme, including sediment transport measurements, was initiated in 1978. Results are reported in Pedersen (1988; 1989). First, the runoff and sediment concentration flowing to the A-Fjord, a minor fjord situated east and south of the ore treatment plant, was measured. The area of the drainage basin feeding the A-Fjord is *c.* 180 km^2. Of this, 105 km^2 is ice draining to a 3.3 km^2 lake that drains to the fjord through a minor lake. The measurements were started when the outlet could be reached in early June and continued until late September, when runoff had practically ceased. The computed sediment load therefore closely approximates the annual transport rate, which is unique in Greenland. The "annual" transport varies from 250 t to 4046 t, and the corresponding values in t km^2 $year^{-1}$ were 1.4 and 22.8 respectively. The mean annual transport for the 12 year period is 2040 t or 11.5 t km^2 $year^{-1}$.

In 1983 a measurement programme was initiated in collaboration with the Institute of Geography, University of Copenhagen (Hasholt, 1983), in the valley leading from the Wegener Glacier to the Q-Fjord, north of the A-Fjord. The reason for this was that mine tailings were being deposited in large dumps in the valley and on a tributary glacier. This, together with water from the mine, was leading to pollution of the Q-Fjord. Difficulties in placing the recording station occurred because of shifting of the flow paths in the valley. Finally two ISCO samplers were installed covering the lateral variation. Measurements here were also started in June and terminated in September, so that a "annual" value was obtained. Very high values of sediment concentration were observed. Maximum values of 20 000 mg l^{-1} were not unusual. The absolute maximum was 166 000 mg l^{-1}, and was caused by a slide of mine tailings into the river. The "annual" transport varied from 84 to 750 t km^2 $year^{-1}$ with an average of 472 t km^2 $year^{-1}$ for the 7 year period (Pedersen, 1988, 1989). The Wegener Glacier is a tributary glacier to the Greenland Ice Sheet and these results are representative of an area with a strong glacial influence.

In 1979 investigations of sediment transport from Nordbo Lake (No. 9 on Fig. 1) near Narsarssuag were initiated (Hasholt & Thomsen, 1980). The lake could be used for production of water power. The Nordbo Glacier, a tributary from the Greenland Ice Sheet, calves into the lake. The transport at the outlet was monitored continuously and samples were taken of the inflows to the lake. The sediment content of the ice was also analysed and the sediment concentration in the lake water and the sedimentation on the bottom were measured on two occasions, so that a balance could be established. By use of this balance, the input to the lake could be computed. The daily variation of sediment concentration at the outlet, with low values around noon, was interpreted as reflecting sedimentation caused by the sinking of sediment-laden water at 0°C being warmed to 4°C, where a density maximum occurs. This process explains the homogenous mixing of sediment in the lake. The concentration in ice samples varied from 15 mg l^{-1} to 40 000 mg l^{-1}. The concentration in inflows to the lake varied from 5 to 163 mg l^{-1}, while at the outlet it varied from 14 to 45 mg l^{-1}. The output from the lake was 1653 t, and the computed input was at least 7624 t, corresponding to a trap efficiency for the lake of 78%. Sand grains in the outlet water could only be explained by transport of ice blocks from the glacier across the lake. The glacial abrasion was estimated to be at least 218 t km^{-2} $year^{-1}$, based on the input and an approximate glacier area of 35 km^2. The transport to the nearest fjord is only 56 t km^{-2} $year^{-1}$.

Sediment transport in the Buksefjord area (No. 8 on Fig. 1) was investigated in 1981 (Hasholt, 1982). The area is dominated by a large lake with an outlet at the eastern end. Low values of sediment concentration were found, even in water courses with some glacial input. Most of the sediment is trapped in the lake, so that the concentration in the outlet was sometimes zero. If the accuracy of the analysis is taken into account, this indicates that the concentration was lower than 1-2 mg l^{-1}. It is clear that the production of sediment is low in this rather dry area, and that the output is further diminished by the presence of the lake.

The Amitsuloq area (No. 7 on Fig. 1), was investigated in 1982 (Hyldegaard, 1983). Measurements from this area represent sediment transport from a local glacier between the Greenland Ice Sheet and the Sukkertoppen Icecap. The concentration shows a wide range (30-1950 mg l^{-1}), which is characteristic of glacial rivers. Most of the sediment will be trapped in the lake below.

Several investigations have been carried out near the Russel Glacier (No. 5 on Fig. 1), and along the margin of the Greenland Ice Sheet east of Søndre Strømfjord. Information concerning sediment concentration is found in De Jong (1992) and Russel *et al.* (1994, 1995). Concentrations ranged from 100 to more than 4000 mg l^{-1}. Very complex conditions are found because of the presence of frequent jøkulhlaups. It is not possible to estimate the area that contributes to the sediment load. Preliminary results indicate very high sediment concentrations in outlets from the Greenland Ice Sheet south of the Russel Glacier.

The Tuapat area (No. 4 on Fig. 1) is situated on the southeast coast of Disko Island. Measurements were carried out during a field course arranged by the Institute of Geography, University of Copenhagen, (Int. report, 1991). The sediment concentration in the area varied from 95 to 650 mg l^{-1}. The northwest part of the basin has a larger areal proportion of glaciers. This area and a minor area with sandy sediment near the coast have the highest concentrations of suspended sediment.

The Zackenberg area (No. 11 on Fig. 1) is situated in the North-East Greenland

National Park. A scientific field station is being established in the park at Zackenberg. A preliminary investigation of sediment transport was carried out in connection with a reconnaissance visit in 1991 (Jakobsen *et al.*, 1991; Jakobsen, 1992). The western part of the area consists of gneiss, partly covered by glaciers. Most of the sediment from this area is trapped in a lake. The eastern part of the drainage basin leading to the Zackenberg River consists of highly weathered sedimentary rocks. Water from this area has very high values of sediment concentration (1559 mg l^{-1}), comparable to highly glaciated areas. The outlet from the lake is clearly influenced by glacial meltwater. However, the concentration is only 30 mg l^{-1}, indicating a high trap efficiency for the lake. Dissolved load varied between 20 and 40 t day^{-1} or from 2 to 40% of the suspended load. Bed load is judged to be of minor importance, because the stream bed is covered by stones.

Another area on Disko Island was investigated in 1993 (Humlum *et al.*, 1995). A drainage basin in Mellemfjord (No. 2 on Fig. 1) was selected. The basin is ice free except for small local glaciers. The sediment concentration values varied between 4 and 80 mg l^{-1}. The 80 mg l^{-1} was recorded after heavy rainfall. The highest values were recorded in the outlets from the glaciers, where the concentration varied from 35 to 38 mg l^{-1}, when it was 4 mg l^{-1} in the outlet from the basin. The concentration of dissolved solids was low at 4 to 9 mg l^{-1}.

DISCUSSION AND IMPLICATIONS

From Table 1 it is seen that the concentrations of suspended sediment cover a very wide range, from 0 to 22 519 mg l^{-1}. The value of 166 000 mg l^{-1} for Marmorilik is excluded because it is influenced by human activity. It is also seen that the transport of sediment ranges from 1.4 to 1500 t km^{-2} per "year". These values are minimum values because none of the investigations cover a whole year.

A clear distinction can be made between sediment transport from areas without glaciers, or with only minor local glaciers, and from areas with a large proportion of glaciers. The first areas have very low transport values, close to those found in temperate areas (e.g. Hasholt, 1985; Brandt, 1982; Bogen & Nordseth, 1986). The latter areas have very high values, comparable to other glaciated areas of the world (e.g. Bogen & Nordseth, 1986; Thomasson *et al.*, 1973; Gurnell & Clark, 1987). From the transport values it is seen that local glaciers can erode as much as tributaries from the main Greenland Ice Sheet. The main problem is, however, to relate the recorded transport to the area eroded. Even for quite well-surveyed areas such as the Sermilik, Mittivakat Glacier, the area has changed when new knowledge became available. The exact area will probably be known when mapping of the bottom topography of the glacier is finished in 1996. For the tributaries from the Inland Ice and for the major ice streams, such as the Jakobshavns Icestream, it is very difficult, if not impossible, to give exact figures for the eroded area. The areas listed are estimated from knowledge of surface topography and may be misleading and result in erroneous values for the denudation in t km^2 $year^{-1}$. As mentioned above, none of the investigations cover whole years. Many of them are carried out during the latter part of the melting season, when sediment transport is rather low. It must therefore be recognized that the figures given as "annual" values will tend to underestimate the true transport values, with the degree depending of the length of the measurement period.

Both for the ice free areas and for glaciated areas, the transport to the sea will be diminished when the water enters a lake on its way to the sea. Trap efficiencies of 80%, or probably more, have been recorded. Most of the coarse sediment is trapped, so that only fine material can reach the sea. It has, however, also been demonstrated that sandurs and braided river systems in front of glaciers can act as sinks (Hasholt & Walling, 1992). The proportion of sediment that reaches the sea may change in situations where the braided system is growing due to a retreating ice front. Coarse sediment can pass through a lake carried on drifting ice (Hasholt & Thomsen, 1980). The formation of anchor ice, slush ice and ice breaking away from banks may also transport coarse sediment to the sea, together with the ice, when the hydraulic conditions as such are able to transport only fine sediment (Hasholt, 1994). In the case of ice free areas and river systems running through lakes, only fine sediment is able to reach the sea. From glacierized areas large amounts of sediment are able to reach the sea, particularly where the outlets are near to the coast. The largest amounts of sediment may reach the sea in cases where glaciers flow directly into the sea or have calving ice fronts.

The high erosion rates from glacierized areas and the enormous area of Greenland covered by ice, together with its insular form, probably make Greenland the major contributor of sediment to the North Atlantic Ocean and to Baffin Bay and the Davis Strait. The delivery of sediment to the oceans is, however, highly dependent on the form of the coastal zone (Nielsen, 1994), the energy level of the coast, currents and the formation of sea ice. This fact is clearly demonstrated in the Marmorilik and the Søndre Strømfjord case and to a lesser degree also in the Sermilik area. In the cases mentioned above the rivers originating from glaciers all flow into the sea through fjord systems. In the Marmorilik case most of the sediment is deposited a short distance from one of the outlets and it is trapped behind a threshold in the fjord bottom in the other. Thresholds are found in many fjords. In Søndre Strømfjord the distance from the outlet to the sea is nearly 200 km, meaning that most of the sediment will be trapped in the inner part of the fjord. In the Sermilik case the outlet is in a fjord approximately 10 km from the sea, and even in this case only a minor part of the sediment will reach the ocean, as seen from the plume of fine sediment. Much sediment released from the eastern coast of Greenland will be carried southwards by the Polar Current together with the drifting ice along the east coast of Greenland. An approximate indication of what are probably the most important sediment producing areas can be obtained by looking at maps and identifying ice fronts, calving glaciers (Reeh, 1994), and areas where glaciers are near to open high energy coasts. Such areas are marked on Fig. 1. It is, however, clear from this investigation that much further research is needed before a reliable estimate of the sediment contribution from Greenland can be given. Research is needed regarding sediment delivery from fjord systems and in particular from ice streams and calving glaciers. Some of the highest concentrations are found here and the ice may act as a transport vehicle for long distance transport.

The present investigation provides, however, a state of the art review of existing knowledge of sediment transport in Greenland, which has to date been shown as unknown on maps of global erosion.

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