Late Autumn Runoff and Sediment Transport in a Proglacial Drainage System, Sermilik, East Greenland

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Field investigations of runoff and sediment transport were carried out in the proglacial area of the Mitdluagkat Glacier drainage basin in September 1992. Runoff in the proglacial stream was 32 l/s/km^2. Runoff from the northern flank of the glacier at the outlet of Lake Kugssuag was 14 l/s/km^2. Mean daily sediment transport was 17 t/d in the proglacial valley and 0.2 t/d at the outlet of the lake. It was clearly demonstrated that the formation of frazil ice and anchor ice caused increased sediment transport, dominating the total load of the proglacial stream during the measuring period 2/9-19/9.

Key words: *hydrology, sediment transport, ice*

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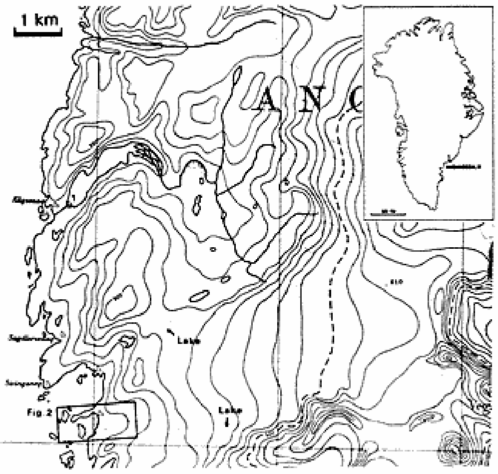

Fig. 1. General view of the investigation area.
1. Measuring station at Kugssuag. Frame shows location of fig. 2.
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The first glaciological investigations in the area were organized in 1933 by Milthers (Fristrup, 1961). Hydrological investigations were carried out in 1958 (Valeur, 1959). Sediment transport was first measured in 1972 (Hasholt, 1976). A summary is presented in Hasholt (1986).

Sediment transport in morphological environments with glaciers is quite well described for alpine systems (e.g. Gurnell and Clark, 1987). Probably due to the harsh environment and logistic problems, decidedly fewer investigations are carried out in the Arctic.

The greenhouse effect has drawn attention to the arctic environment because relatively large temperature changes are expected here. The present programme, carried out by the Institute of Geography, has a system dynamic approach. The object of study is drainage basin analysis so that processes and the resulting sediment production may be tracked from their point of origin to their point of deposition in the sea. The project, which started in 1990, has three phases: 1) Identification of active processes in the system. 2) Quantification of processes 3) Modelling of processes and their interaction in order to predict the system response to climatic changes. The project is now in phases 1 and 2, and the results of the sediment transport investigation are reported in Hasholt (1992) and Hasholt and Walling (1992).

The aim of this part of the investigation is to describe and quantify processes of sediment transport in late autumn and early winter. The relative importance of subglacial contribution is evaluated as well as the trap efficiency of a lake which receives water from the northern flanks of the glacier.

The study area is shown on Fig. 1 and Fig. 2. The proglacial valley has a very large percentage of its basin covered by the glacier, approx. 90-95%, whereas the outlet of Lake Kugssuag is only about 20% covered.

METHODS

Stage is measured at the stations shown on Fig. 1 and Fig. 2, either by a mechanical stage recorder, Ott XX or by DRUCK pressure transducers connected to Campell 21X or CR10 dataloggers. Stage discharge relationships are established by measuring the discharge with Ott Labor or C31 current meters. Water samples are collected simply by using bottles where the mixing is complete or with a depth integrating sampler of Swedish origin (Nilsson, 1969) in other cross sections. At the main station, an ISCO automatic water sampler is installed. Indirect measurements of sediment concentration are carried out every 2 minutes using Partech IR light transmission sensors. Water samples are filtered through Whatman GF/F filters and the concentration is used either for the computation of sediment transport directly or for calibrating the IR-sensor readings. Water temperature is recorded frequently during the investigation period. Moreover, conductivity is measured at selected sites. Water chemistry is analyzed using selected samples. The location of measur-

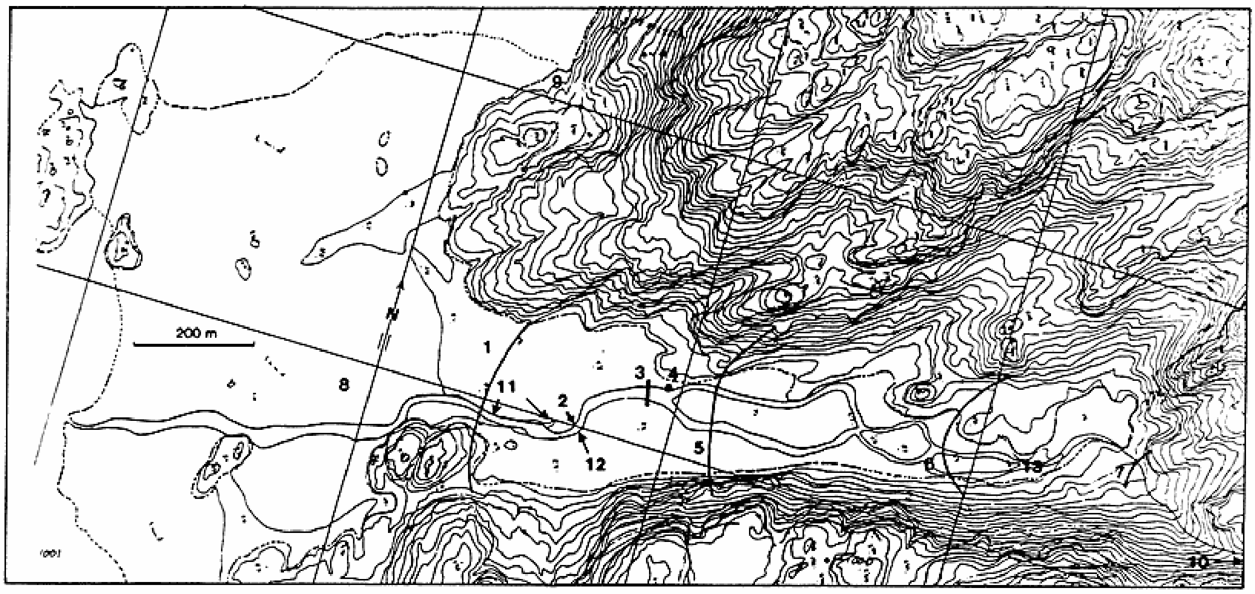

Fig. 2. Detailed map of the proglacial valley. 1. Terminal moraine. 2. Total load. 3. Discharge, wash load. 4. Stage recorder. 5. Ice margin 1933. 6. Ice margin 1958. 7. Ice margin 1970. 8. Delta, tidal flat. 9. Field station. 10. Subglacial outlet. 11. Bank erosion. 12. Gullies. 13. Sink holes.

ing stations is shown on Fig. 1 and Fig. 2. The two main stations are shown on Fig. 3 and Fig. 4.

RESULTS

Morphological observations

On arrival, September 3rd 1992, a reconnaissance was carried out in the proglacial valley. For the first time in 20 years, severe bank erosion was observed on the right bank of the narrow outlet channel at the sea. The removed volume of sediment was 50-200 m^3 which had been delivered to the tidal flat. Near Station 2 (Fig. 2) bank erosion was seen on the right bank of the western branch of the river which was then dry. Along the left bank of the river branch at Station 2, three small gullies had been eroded by water coming from the flat area there. The erosion had taken place during periods with much larger discharge

Fig. 3. Total load station, 2 on fig. 2.
1. Partech IR-sensors. 2. ISCO sampler. 3. Temperature. 4. Dataloggers and battery.

Fig. 4. Measuring station at Kugssuag, 1 on fig. 1.
1. Stage recording and IR-sensors. 2. Stage benchmark. 3. Discharge cross section.

values. Erosion to the right bank seemed to be caused by the stream, while the gullies were caused by meltwater from the valley.

At the stream gauging cross sections no changes were observed. In the braided section higher up, some of the water was now running near to the side of the valley. Newly developed sink holes (Fig. 5) were observed approximately 50 m east of Station 6 (Fig. 2). Between Station 6 and Station 7 (Fig. 2), the surface in some places was covered by 10-20 cm of a mixture of silt and sand with larger stones intermingled. This deposit was interpreted as material carried to the area by debris flows from the neighbouring steep valley sides. The uneven surface of the deposit indicated that part of the debris flows had been deposited on snow and ice which later melted. Near the snout of the glacier, the valley sides were covered with loose material identified as ablation till. The reconnaissance showed that a lot of loose material was present and available for transport in the upper part of the system.

The meltwater from the northern flank of the Mitdluagkat Glacier drains to Lake Kugssuag through a system of small lakes. Lake Kugssuag drains to the sea through a narrow, approx. 300 m long cleft. As the lake surface is about 15 m above sealevel, there is no backwater effect from the sea at high tide. The water from the lake is weakly milky, indicating the contribution of glacial meltwater. It was observed that silt deposits on rock surfaces were approx. 0.5 above the observed water level, indicating that higher sediment concentrations had occurred, probably during the maximum runoff period caused by snowmelt. The surface area of the lake is 0.6 km^2, the length 1.5 km, and the width at the narrowest point 0.2 km. A braided river system enters at the eastern end of the lake where a large delta has formed. The material on the topset is sand. The level of the topset at the delta front is approx. 1 m below present water level.

It was also observed that at the delta front there was a steep foreset reaching down to a depth of about 30 m. The lake basin is separated in two sub-basins by a threshold at the narrow point. The western basin has depths up to 70 m, the eastern basin from 30-60 m. Cores taken from the bottom showed that the sediment here ranges is fine silt and clay. The depth above the threshold is 30-50 m. The lake and its deposits will be treated in detail in a later paper.

The observations would indicate that all the bedload and coarser part of the suspended load is deposited in the delta zone, and that only very fine material is carried through the lake.

Fig. 5. Sink holes and formation of bank ice.

Sermilik proglacial stream valley

Data from IR-sensor readings showed a sharp rise in the "concentration" measured by the IR-sensor located at 10-11 p.m., while a sharp drop occurred at 10-11 a.m. (Fig. 6). In between both readings there are high values. The 0-300 ppm sensor was most often in Hi-range. This was first believed to be caused by ordinary daily variations in discharge, but stage recordings showed no regular diurnal variation, and the "ordinary" concentration and discharge maximum usually occurred around 5 p.m. During the following days, the sample site was revisited at different hours and the explanation was found. Due to low temperatures at night, ice formed long the banks and on the bottom there was anchor ice. Ice drifting in the stream, which carried a lot of sediment as well as frazil ice, was obscuring the measuring gap of the sensors.

Water samples collected manually at the beginning and end of the ice formation period showed a variation from 68 mg/l to 1797 mg/l with a mean of 735 mg/l. At night,

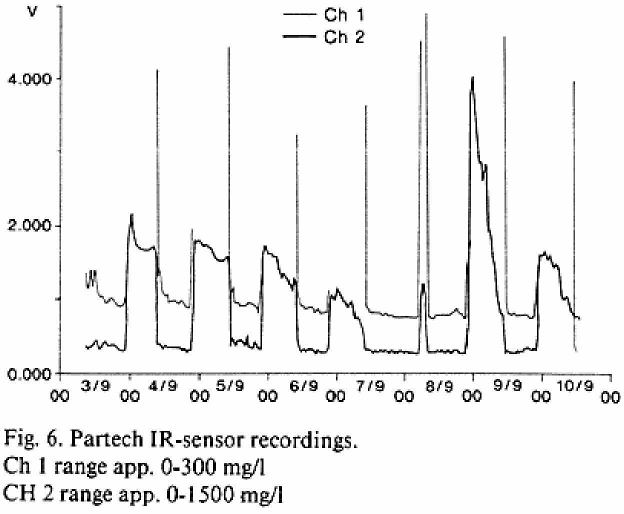

Fig. 6. Partech IR-sensor recordings.
Ch 1 range app. 0-300 mg/l
CH 2 range app. 0-1500 mg/l

bottles in the automatic ISCO sampler remained empty as a result of ice blocking the intake tube. In order to evaluate the simultaneous input from the glacier into the valley, water samples were collected at the subglacial outlet from the glacier. Concentrations varied from 15.5 mg/l to 46.7 mg/l, with a mean of 28.8 mg/l.

The water samples were filtered in the field, the final weighing of filters and analysis were carried out in Denmark. The measured discharge and stage recordings were used to compute discharge and runoff. Discharge was multiplied by concentration values in order to find daily values of sediment transport.

The discharge was 1050 l/s at the beginning of the period, decreasing to 400 l/s at the end. Due to rainfall, there was an intermittent short rise to 500 l/s on the 16th September. The mean daily discharge through the period 2/9 to 19/9 was 660 l/s. The matching runoff values, based on the same area as used in earlier publications for comparison, were; 51, 19, 24 and 32 l/s/km^2 respectively.

A daily value for sediment transport was computed by use of daily discharge and available concentration values based on water samples. This procedure underestimated the transport during the ice drift periods and must therefore be considered as a minimum value. The daily transport varied between 5.3 t/day and 0.3 t/day with a mean of 2.1 t/day. The total sum of the daily transport values during the investigation period was 38 t. Due to drifting ice, it was not possible to establish calibration curves for the IR-sensors. An estimation of the sediment transport during periods with ice drift was found by multiplying the discharge in these periods with the mean concentration of sediment found in water samples. The daily transport during periods with ice formation varied from 0-32 t/d. The total amount of sediment transported in connection with ice during the whole period was 283 t. The combined transport from periods with and without ice was 305 t. During the whole period, the subglacial input to the proglacial valley was found to be approx. 30 t, indicating a loss of sediment from the valley.

The conductivity of the water varied between 45.2 and 52.0 μ s/cm. The sum of ions analyzed was approx. 30 mg/l. Water temperature recordings were below zero at night, apart from a milder period due to rainfall on September 15th.

The Kugssuag system

The measurements were carried out in connection with a coring programme in Lake Kugssuag. The water level in the lake fell by 7.5 cm from September 7th to 13th, or 1.25 cm/day. The storage reduction accounted for approx. 87 l/sec. At the outlet, the discharge was 480 l/s on Sept. 7th and 246 l/s on Sept. 13th. The corresponding runoff values were 18 l/s/km^2 and 9 l/s/km^2. Measured sediment concentration in the outlet from the lake was 3.9-7.5 mg/l, and in the inlet it was 45.3 mg/l. The output from the lake was 236 kg/d on Sept. 7th and 121 kg on Sept. 13th. The corresponding input was 1528 kg/d and 618 kg/d respectively, giving a trap efficiency of 85-80%. The conductivity at the outlet was 28.4-28.9 μ s/cm and the water temperature was 5.5°-5.2°C.

Discussion and implications

The formation of ice takes place and can obscure the measuring gap of the Partech IR-sensors. This will cause failure of any calibration function between reading and sediment concentration. On the other hand, if sufficient supplementary information on the physical conditions of the system is present, the IR-sensor can be used to detect the occurrence and formation of frazil ice and release of anchor ice.

The formation of ice also causes trouble for automatic water samplers by blocking the intake tube and exhausting the batteries.

Problems with stage recordings have also been registered due to the formation of temporary ice dams.

All together these problems mean that results from this period are less accurate than those made in summer and early autumn.

Visual observations confirmed that ice formed, and this was supported by the registration of negative temperatures for the air and water . Fortunately, water samples were collected so that actual sediment concentrations could be determined.

Although the results are less accurate there is no doubt that the formation of ice by stream banks and on the stream bed caused the plucking of sediment and thereby increased the sediment transport during the investigation period. The computed transport values are in the right order of magnitude and indicate that the formation of ice can cause the transport of sediment to be approx. 10 times larger than during periods without ice formation.

As the simultaneous contribution of sediment to the valley by the subglacial outlet from the glacier is much less than the amount measured at the outlet to the tidal area, it can be concluded that the valley has a negative sediment balance during this period.

No ice formation took place at the outlet from Lake Kugssuag because the temperature of the lake water was much higher. The sediment concentration was slightly lower than measured in August 1972 (Hasholt, 1976), but this seems reasonable, and is due to the recession in the system. The concentration at the inlet to the lake is higher, which could be a result of ice formation in the braided river upstream from the delta. The trap efficiency of the lake was higher than in 1972. The weather was dry during both measuring periods, but it was warmer in 1972. Judging by the morphological characteristics of the lake, high trap efficiency values should be expected. However, in periods with no suspended bedload, and in periods without ice formation, low trap efficiencies might occur because the concentration in the inlet is low. A trap efficiency of 78% was measured in Nordbo Sø, 1979 (Hasholt and Thomsen, 1980), but this lake was not directly comparable to Lake Kugssuag.

Runoff values are low, both in the proglacial valley and in the Kugssuag basin, indicating that the melting of the glacier is of minor importance, although it is still significantly above the contribution from basal melting alone.

It was the first time that field investigations of sediment transport were carried out in late autumn in this area. It is now possible to combine the results with those from earlier investigations to produce a picture of the annual sediment cycle. During the winter (Oct.-May), erosion takes place at the glacier sole and on snowfree rock surfaces. Sediment can be moved in the system by movements of the glacier, rockfalls and avalanches. The transport capacity is less than the sediment production most of the time. During Föhns, water may run on surfaces with thin snow cover and debris flows may be formed. The basal flow will stabilize and increase the icing that covers the valley floor.

In the spring (May-July), snow will melt, firstly in the lower part of the basins. Flows and surface runoff will occur and bring sediment down from the valley sides that had been covered earlier by the glacier. Results of Cs 137 inventories, (Hasholt and Walling, 1992), indicate that fine material may have this origin. The icing will break down, and the resulting channels can have a severe erosional effect in the valley, (see section above on morphological observations). The meltwater will first be stored in the glacier and its internal drainage system. Probably, glacial erosion will increase, and the sediment pool in the glacier will be at a maximum.

During the summer (July-August), the meltwater will be released from the glacier, causing a flush out of sediment from the glacier sediment storage. In the valley, the flood will cause a transport maximum in the early summer. The valley, which is covered with loose sediment, will react to changing hydraulic conditions as an alluvial system, therefore daily variations will normally show a good correlation between the discharge and sediment concentrations. Erosion to banks, and the final collapse of icing causing sinkholes, are also observed.

During autumn (August- October), melting gradually decreases, and the sediment storage is exhausted. This causes low transport values, sometimes interrupted by rain which washes loose sediment down from the ice free steeper slopes. Larger runoff periods might be caused by Föhns. During late autumn, as demonstrated here, a secondary sediment transport maximum may occur because of the freeze-thaw effect, before the whole area is frozen and covered with snow as the icing gradually builds up.

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