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The sediment budgets of arctic drainage basins

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Abstract The characteristics of arctic drainage basins are discussed in relation to sediment transport processes. Methods used for quantification of the processes are described, together with the technical problems encountered in their application in this environment. A preliminary budget for the glacierized Mittivakkat drainage basin, situated in Greenland, is presented. The dominant processes are glacial erosion and the fluvial transport of the eroded material.

Key words arctic; Greenland; sediment budget

INTRODUCTION AND SCOPE

Many studies have focused on the erosion processes operating within a drainage basin or the sediment yield at its outlet. However, there is a need to establish sediment budgets which attempt to quantify the relationships between the various components of the basin erosion-transport-deposition system. Establishing a sediment budget for a single drainage basin, a landscape, or a region is similar to the application of the water balance concept. The budget is a logical framework for the description of sediment mobilisation, transfer, storage, and output, based on the law of mass conservation. By quantifying all the elements, the budget can serve as a control to confirm that the description of the system is adequate and that the various elements have been correctly quantified. Budgets can also be used to identify gaps in knowledge, or to estimate missing values by applying the continuity equation when all other terms are known.

Arctic drainage basins have recently attracted increased attention because of the climatic changes that are expected to exert a significant impact on these areas. Warming will cause icecaps and local glaciers to melt, which can lead to increased transport of sediment and solutes to the ocean. Equally, the retreat of glaciers and icecaps will lead to exposure of areas earlier covered by ice; these areas can act as sediment sinks and can therefore lead to reduced transport to the ocean. Sediment budgets can be used to elucidate the relative importance of such opposing trends.

The aim of this contribution is to present and discuss the methodologies commonly applied in establishing sediment budgets in arctic environments and to present preliminary results from a specific drainage basin in Greenland.

THE STUDY AREA

According to the Köppen climate classification, artic areas can be characterized as ET (tundra) climate, with the mean temperature in the warmest month being <10°C. A further subdivision into high arctic (temperature of warmest month <5°C) and low

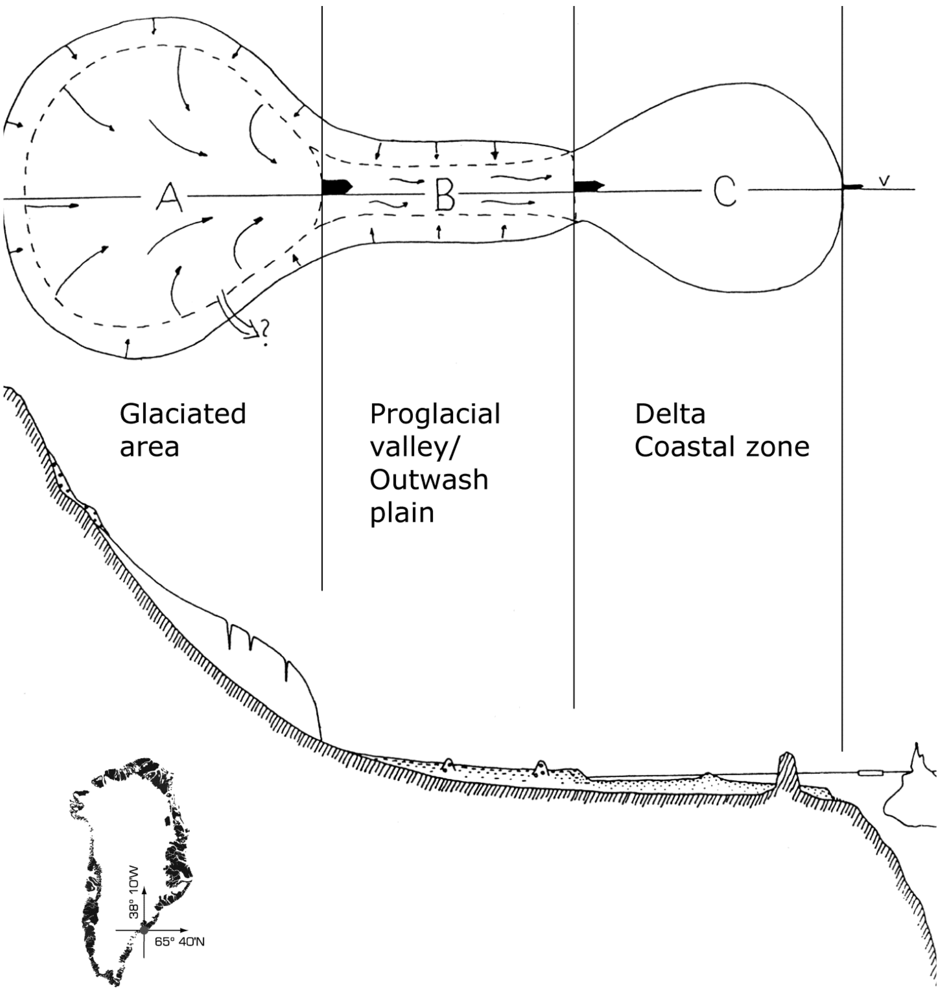

Fig. 1 A schematic representation of the sediment transport system in an arctic drainage basin with a glacier (based on an original figure produced by N. Nielsen).

arctic (>5°C) can be applied (see Born & Böcher, 2000). In the context of this contribution, the focus is on artic areas (cold climates) where glaciers are present. The presence of glaciers in a drainage basin is controlled by the cold climate, but also by the altitudinal distribution. Thus, in other climatic zones with mountainous areas (e.g. the Alps or the Himalayas), drainage basins including glaciers are also found. The river regime according to Pardé (1955) is glacial or glacio-nival. An attempt to provide a generalized description of the sediment transport system in a basin containing a glacier is presented in Fig. 1.

The drainage basin that provides the focus for this paper is located in Greenland. Greenland is dominated by the Greenland Ice Sheet, which covers most of the area except for a narrow, 0–200 km wide, marginal zone. In this marginal zone, there is an abundance of local glaciers disconnected from the main Ice Sheet. The study drainage basin is located in southeast Greenland and includes parts of the Mittivakkat Glacier (see Figs 2 and 3).

The average temperature is 1.7°C and the mean annual precipitation is 984 mm (uncorrected). The processes operating in the drainage basin are assumed to be representative of those found in glaciated drainage basins along the margin of the Greenland

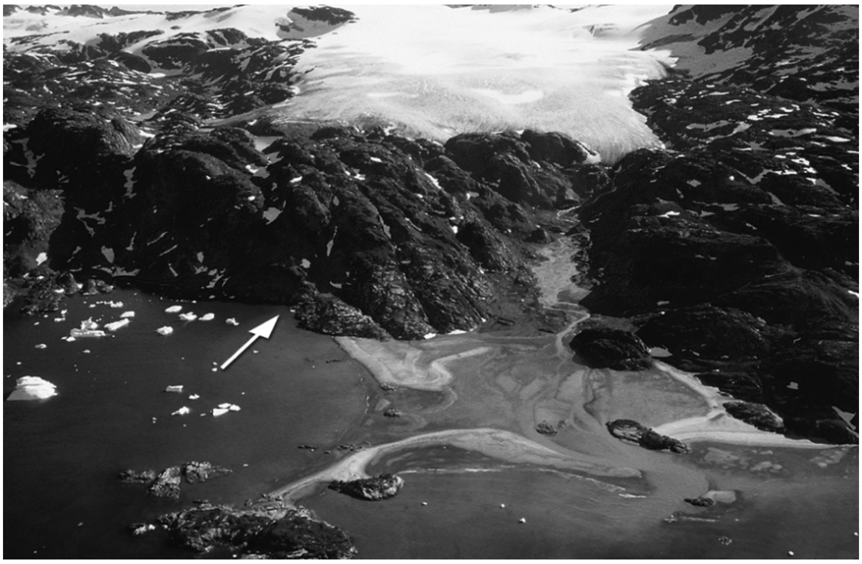

Fig. 2 Aerial photo of the actual basin, seen from the west.

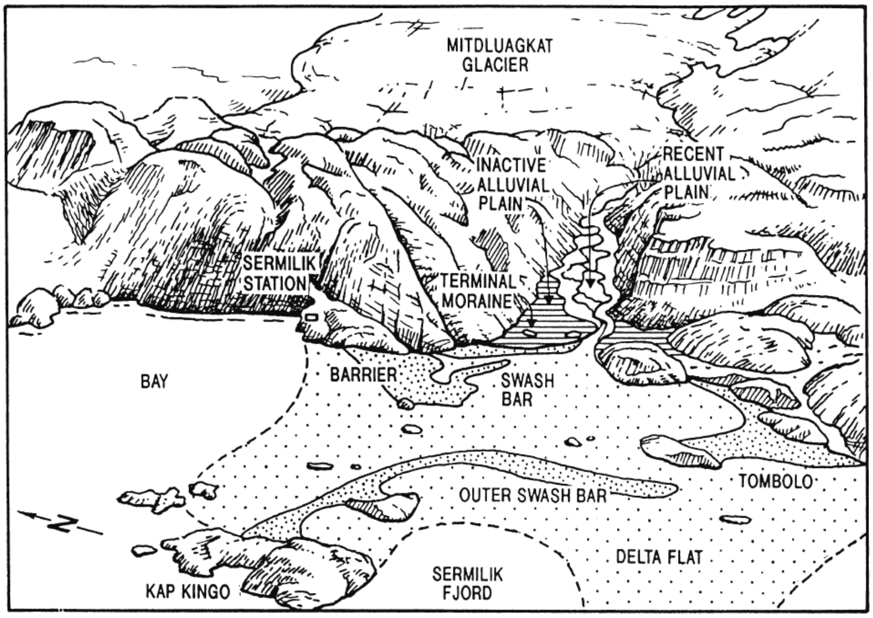

Fig. 3 Drawing showing the same area as in Fig. 2, and indicating the major landscape elements (based on Nielsen, 1994).

Ice Sheet, but the findings also should be applicable to drainage basins in other glaciated areas.

PROCESSES RELATED TO THE SEDIMENT BUDGET

Sediment mobilization processes

Mechanical weathering caused by rapid temperature changes, and freezing of water in cracks and fissures breaks down the solid rock into smaller particles. This weathering acts on all exposed rock surfaces in the drainage basin and the result is easily seen in the form of concentric flakes loosened from the underlying rock. In addition, many pieces that, like a puzzle, can be put together to form the original piece of rock prior to weathering can be found in the area. In the contact zone between the moving ice and the underlying surface, the enormous pressure can crush the rock surface or minor rocks lying on the surface. The moving ice can abrade or excavate the underlying surface, or it can directly pluck out whole pieces of rock delimited by fissures or internal zones of weakness. Glacial erosion is the strongest geomorphic agent acting in the drainage basin. Abrasion caused by sediment-laden water and cavitation in supercritical flow may also contribute to the mobilization of sediment for transport. Such flow conditions mainly are located around the steeper parts of the glacier margin, inside the glacier, and on an alluvial cone in front of the main glacier outlet. Coastal erosion has recently reworked material from old moraines, but direct erosion of solid rocks caused by tidal lift of the ice foot has, so far, not been observed. Wind-polished rocks have been observed, but the wind mainly redistributes particles of sand and silt that already have been mobilized.

Sediment transport

On the steep mountain slopes, sediment loosened by mechanical weathering can be transported downwards under the influence of gravity as rock falls or rockslides. Such transport particularly takes place on the southern and eastern margins of the glacier. Sediment transport can be associated with the movement of snow, as in the case of avalanches; but this transport must be of minor importance because only a few slopes on the south side of the glacier produce major avalanches. Heavy rainfall on rock surfaces covered with finer sediment left from the glacier could wash the sediment from such surfaces; this type of transport could explain the rapid increases in sediment concentration/transport during rainfall. On less steep surfaces, covered by thicker layers of loose sediment, transport can occur as mass movements (e.g. landslides and debris flows). Sediment delivered to the surface of the glacier by the processes mentioned above will be transported downward with the moving ice. Some of the material might be embedded in the glacier and transported as englacial sediment. However, most of the sediment transport takes place at the bottom of the glacier. Part of this material will follow the velocity of the moving ice, but a major part of the eroded sediment will be transported by water in the cavities developed at the glacier bottom.

The sediment from beneath the ice leaves the glacier along its lower margin. Several outlets exist, but the major part of the water and sediment is released through a glacier portal situated in the southwestern part of the terminus. From here, the water and sediment mixture cascades down an alluvial cone. At the bottom of the cone, the water flows into a braided river system, which discharges into a tidal delta from where it can be transported into the fjord, and then to the open sea. Within the tidal delta, sediment can be transported by wave energy, but during dry spells with strong winds, sand and silt can be redistributed by wind action and minor aeolian dunes can develop. Both in the stream channels and in the coastal zone, ice rafting can transport sediment. Thin layers of sand with entrapped air that have been lifted and carried along the coast by the tidal current, have been observed.

Sediment deposition

The sediment transported by the ice may be deposited as till in moraine deposits, either in front of advancing ice, or left behind when the ice front retreats. Such deposits are found in the proglacial valley, where they can be a few tens of metres thick. The glacier has been retreating at least since 1933, and recent deposits are found all along the margin below the equilibrium line, but the deposits are shallow, and generally less than a metre thick. When meltwater discharges from the glacier carrying its sediment load, size selective transport occurs in the part of the valley where the slope is moderate, so that coarser particles are deposited closer to the alluvial cone whereas the finer material is deposited in the lower part of the valley and in the tidal delta area. Part of the material transported as suspended load will be deposited in the delta zone, or further out in the fjord. The northern part of the glacier drains toward the sea through a string of lakes. All coarser particles are successively trapped in the lakes, so that only the finest part of the wash load escapes to the sea.

METHODOLOGY

A prerequisite for establishing sediment budgets is an accurate map. The oldest map (1933) covering this area is based on oblique aerial photos; it was drawn with 50 m contour intervals. This map is not well suited for this application because it has proved difficult to determine the topographic divide at several locations. Maps based on aerial photos from 1972 and 1981, with contour intervals from 5 m to 25 m, now are used. Recently, digital elevation models (DEM) have been developed based on these maps, but information from satellites also has been utilized (e.g. ASTER data have been used for developing a DEM).

The glacier surface is dynamic; it has to be surveyed quite frequently to establish its mass balance. The terminus has been surveyed nearly every year since 1969, and the winter- and summer-balance has been determined since 1994 using a stake net (Knudsen & Hasholt, 2003). The balance measurements show that the glacier is retreating and losing mass, and indicate a negative balance for all years except one. The topography underneath the glacier must also be known to determine flow directions and to establish the spatial extent of the sediment producing area to estimate the specific sediment yield (t km^{-2}). In this case, the topography below the glacier has been established using radio echo sounding (Knudsen & Hasholt, 1999). The map of the subglacial surface shows that the glacier actually flows in two separate valleys separated by a low ridge; the southernmost drains toward the main outlet, whereas the northern drains into a string of lakes.

An understanding of the processes can be obtained by personal observation. It is very important to carry out such observations throughout the year, in particular during the snowmelt period. Due to logistical problems and costs, year round personal observation is impossible, but this problem has been partly solved by use of automatic cameras installed at strategic positions. The cameras record images every day at noon. The cameras have shown the development of icing, and the occurrence of minor floods during winter warm spells. The cameras also have been able to document the spring thaw break, and the development of alternating flow patterns during this period (e.g. flow over the icing and the cutting of channels through it).

Geomorphological mapping is used to distinguish the glacial and fluvial deposits in the valley. To establish the volume of loose sediments deposited in the valley and the coastal zone it is necessary to determine the solid rock boundary below the sediments. In this case, geoelectrical surveys have been employed using a Schlumberger set-up that indicated that the solid rock boundary was from 6 to 23 m below the surface. However, it was difficult to place rods and wires because of restrictions caused by surface water; hence, other methods (e.g. seismic or ground-penetrating radar) might be better suited to the local conditions and might provide more complete coverage that could delimit different sediment types, but they were not available. Changes in surface elevation caused by erosion or deposition have also been monitored for selected cross sections. These surveys have shown that the level of the valley floor has been quite stable, except for minor erosion in the lower part of the stream channel, in recent years.

Water discharge has been measured with Ott current meters in a fixed cross section near the sea, at a site free from tidal influence. A stage/discharge relationship has been established to provide a continuous record of discharge. Originally, an ordinary float-operated stage recorder was used, but there were frequent problems with the installation due to ice and shifting of the stream channels in this braided river environment. These problems have been overcome by the use of Campbell SR50 ultrasonic sensors connected to a CR10X data logger. Water samples are taken manually with a depth-integrating water sampler (Nilsson, 1969). Sampling frequency has been daily when the station is manned. Water samples were filtered through Whatman GF/F filters for the determination of suspended sediment concentration and loss on ignition. In some periods when the station has been unmanned, water samples were collected using an ISCO automatic peristaltic pump water sampler. Partech transmissometers and OBS turbidity sensors also have been used to provide additional information on the temporal variability of suspended sediment concentrations (see Hasholt, 1976, 1992, 1993). Wash load concentrations are determined using samples collected by the depth-integrated water sampler positioned 8 cm below the surface, to have the air outlet under water. Sediment concentration and discharge data have been used to establish rating curves to estimate sediment transport during unsampled periods. Information on bedload transport has been obtained by measuring the travel velocity of bed forms and by using a Helley-Smith type sampler. The competence of the stream has been investigated using tracer pebbles with built-in radio transmitters (Busskamp & Hasholt, 1996). These studies show that under the present summer conditions, larger pebbles were unable to pass through the lower part of the valley to the coastal zone.

Deposition in selected parts of the system has been documented by lake coring, and from flood plains. Cores were analysed for varves using X-ray photographs and by ^{210}Pb and ^{137}Cs dating (see Hasholt, 1995; Hasholt *et al*., 2000). These studies have demonstrated that the string of lakes that drain the northern flank of the glacier are a very effective sink, but the investigation has also shown that sediment is retained in the proglacial valley draining the main glaciar outlet. This is consistent with observations of the dynamics of the coastal zone (Nielsen, 1994) where repeated measurements of the surface indicate degradation of the delta caused by a reduction of the recent load from the glacier compared to earlier periods, when the glacier was closer to the coast.

THE SEDIMENT BUDGET

An attempt to quantify the components of the sediment budget for the system is presented in Table 1. The three areas A, B and C refer to the theoretical divisions shown in Fig. 1, but the actual location of these areas can be found in Figs 2 and 3. Three columns are shown in the table, volume, weight, and weight per year. In the last column two values are given when possible, the first refers to the main outlet from the glacier (see Fig. 2), and the second refers to the part of the glacier that drains north through a string of lakes into the sea. When it has not been possible to estimate the timespan associated with a certain volume of erosion or deposition, the associated fields in the table have been left void. The values in the table have been derived as follows. The "maximum" erosion volume in area A represents the present volume of the glacier and the equivalent mass is found by multiplying the volume by a density of 2.65 t m^{-3}. The time required to erode this valley is unknown; therefore the t $year^{-1}$ column is left void. Rock fall is estimated based on the length and height of the exposed mountain slopes and an average rate of erosion derived from the volume of rock accumulating on the glacier surface below the slopes. The input from glacial erosion processes is unknown, because the storage of loose material beneath the ice cannot presently be measured. Recent storage is derived from the average width of the annual retreat of the glacier along its margin, the length of the margin zone, and a visual estimate of the thickness of the deposits. Recent output is based on the measured transport in area B. Maximum erosion in area B represents the volume of the valley plus the volume of loose sediment below the present surface, the mass of which has been estimated by multiplying its volume by a density of 1.6 t m^{-3}. Recent input from the glacier is based on the measurements of sediment transport in the area. The volume of talus is based on the length of the steep valley sides, and a visual estimate of the dimensions of existing talus deposits. The annual talus production is estimated as for area A. Aeolian inputs have been determined from an estimate of the area of wind deposits and their average thickness. The estimate of annual input is based on the fact that deposition has only been observed in the last five years. Storage of glacial deposits is based on proportion of valley surface covered by these and measurements of the depth to solid rock. Fluvial deposition has been quantified based on the area of braided flood plain and an estimated depth of about 2 m, based on the dimensions of covered minor terminal moraines. Aeolian storage is equivalent to the input noted above. Output also is based on measured transport, and this has been tentatively reduced using an estimate of the amount of trapped stones and pebbles, which has been unable to pass through the valley under present conditions. The net deposition in area C is found from the surface area of the delta and information on depths to solid rock. Input from the river is the output from area B. Input from ice rafting has been estimated from the volume of deposits left by stranded icebergs and an increased contribution from the river during ice formation in autumn, and drifting ice floes during the break-up period. Re-deposition by aeolian activity is based on the area of aeolian deposits and their height. The aeolian input to area B originates from this location. Redeposition by marine activity has been estimated based on the surface area and dimensions of swash bars, barriers, and tombolo deposits. Wash load is based on the concentration of suspended sediment in surface water. The coastal erosion listed here refers to the inner coast, and probably will be redeposited in area C; net erosion on the outer coast has not been measured.

DISCUSSION AND PERSPECTIVES

The present attempt to quantify the components of the sediment budget involves different levels of accuracy for each component. Some estimates, for example those for talus formation, represent little more than guesswork. However, most estimates are based on knowledge of the study area obtained through 30 years of fieldwork, while others, such as those for sediment transport, represent direct measurements whose primary limitation is their temporal representativeness. Therefore, it is believed that all

Table 1 Components of the sediment budget; areas A, B and C refer to Fig. 1.

	m^3	*T*	t $year^{-1}$
Area A:			
Gross erosion	2024×10^6	5400×10^6	
Recent input, rock fall			100–200; 0–10
Recent input, glacial erosion			
Recent storage, deposition at margin			500–1000; 600–1200
Recent output, sediment transport			>8200; ? >9400 [a]
Area B:			
Gross erosion	60×10^6	160×10^6	
Recent input from glacier			8200; 9400
Recent input from talus formation	14000	23000	50–100; ?
Recent aeolian input	20	32	6; 0
Storage, glacial deposits	$\sim 2.0 \times 10^6$	$\sim 3.2 \times 10^6$	?; ?
Storage, fluvial deposits	$\sim 0.2 \times 10^6$	$\sim 0.32 \times 10^6$	> 0; ~9000
Storage, aeolian deposits	20	32	6; 0
Output, fluvial transport			~8000, ~400
Area C:			
Net deposition	7.7×10^6	12.3×10^6	; 0
Recent input from river			~8000; 0
Recent input from icerafting	< 1	< 1.6	?; 0
Redeposition aeolian activity	100	160	?; 0
Redeposition marine activity	7000	11000	?; 0
Output, washload			3500–7200; ~400 [b]
Output, coastal erosion	150	240	?; 0

[a] Assumed same erosion per km^2 of glacier area. [b] Measured washload %, 43–90% of total load.

the component estimates are of the right order of magnitude, and represent the best state-of-the-art as regards their relative importance in the study area.

Glacial erosion clearly dominates the sediment budget; this is consistent with findings from other areas. The term maximum erosion, used in the budget, could be questioned because it is not possible to date the onset of erosion. The valley system might have been carved out during previous glaciations, or even by earlier fluvial erosion. Based on the present sediment transport rate, it would have taken 6–700 000 years to erode a volume equal to the present glacier. The net deposition of eroded material beneath the glacier is unknown. In the proglacial valley, the net deposition accounts for about 4% of the total eroded volume in the valley. The measured total deposition (excluding the unknown amount of material under the glacier) is only 0.5% of the total maximum eroded volume. In fact, the sediment transport measured in the proglacial river represents only part of the total volume eroded underneath the glacier that is transported to the outlet from the glacier. Depending on glacial activity, under some conditions all eroded material might be transported to the outlet, whereas under other conditions, the transported material could consist only of material derived from earlier periods with strong glacial erosion, which is now being removed by the meltwater. When glacial erosion rates are given, based on measurements outside the glacier, it is assumed that a dynamic equilibrium exists, with all eroded material being transported to the outlet. Depending on glacier dynamics, this might not be the case. An improved understanding of glacier dynamics, englacial and subglacial storage, and related transport in proglacial streams is required. Methods to determine the amount of loose sediment within the glacier sole also are an important need. Recently, a project aimed at providing simultaneous measurements of glacier dynamics and sediment transport has been initiated in the area.

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