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Method for estimation of the delivery of sediments and solutes from Greenland to the ocean

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Abstract Greenland is the largest island in the world, with an area 2 415 100 km^2 and a smoothed coastline length of 7500 km, bordering the Atlantic Ocean, the Arctic Ocean and the sea between west Greenland and Canada. Very few gauging stations at which discharge is measured are located in this huge area, and the dissolved and sediment load are monitored at even fewer stations. Estimating the supply of sediment and solutes to the surrounding seas is therefore in reality a case of estimating loads from an ungauged area. This presentation discusses methods for estimation, and presents preliminary estimates of loads.
Key words dissolved load; Greenland; sediment load; ungauged basins

BACKGROUND AND SCOPE

Greenland stretches from 60 to 84°N, with an area of 2 415 100 km^2, of which 75% is covered by the Greenland Ice Sheet. Around the Greenland Ice Sheet, a narrow band of land is found with a width that reaches up to approximately 200 km. In several places, ice lobes from the Greenland Ice Sheet reach the open sea directly, whereas in other places the ice lobes emerge in the inner parts of fiords with longer distances to the open sea. Several local glaciers are located in this band of land, which in some places discharge directly into the sea and in others discharge into fiords or shallow coastal waters. The part of the land not covered by glaciers drains into the sea through rivers.

Due to its northern location and the presence of the Greenland Ice Sheet, Greenland suffers from an arctic to high arctic climate. The annual average temperature is 2°C at Narsarsuaq (in the south) and –17°C at Station Nord (in the north). The annual temperature amplitude varies between 15 and 33°C. The annual precipitation varies from 1000 to 3000 mm along the south and southeast coast, down to 100–200 mm in the northern part. Most of the precipitation falls as snow. As a consequence of the climate, strong mechanical weathering takes place, together with periglacial processes and glacial erosion. The river regime is glacio-nival, with a flood period during the spring.

Previous investigations and results

Information about precipitation, evaporation and runoff can be found in Ohmura & Reeh (1991) and in the Atlas of World Water Balance (1977). The earliest measure ments of discharge are from 1958 (Valeur*,* 1958), followed by investigations during the IHD (1965–1974). During the period 1975–1990 a discharge monitoring programme aiming at the development of hydropower was established. A summary of runoff investigations in Greenland is found in Hasholt (1997). The recent monitoring programme is carried out by ASIAQ. Direct measurements of sediment transport and dissolved load were first carried out in 1972 (Hasholt, 1976). Sediment transport investigations were carried out related to hydropower projects, pollution studies and scientific purposes. A summary is presented by Hasholt (1996). Recently, a long-term study was initiated in the Greenland National Park at Zackenberg (Rasch *et al.*, 2000; Hasholt & Hagedorn*,* 2000). Knowledge of the transport of sediment is important for linking the studies of cores of the Greenland Ice Sheet with the investigations of sediment cores from the ocean bottom. Because of Greenland's size and location, bordering the Atlantic and Arctic Oceans, the load contributed by Greenland may be important for global mass balances, but its magnitude is presently unknown.

Discharge is measured using current meters and stage-discharge relationships. Gauging stations are often located at outlets of lakes, because of difficulties with the installation of stage recorders in rivers with ice and sediment transport. Measured annual runoff has varied between 9 and 92 l s^{-1} km^{-2} (Hasholt, 1997), and it has been shown that simple hydrological models could provide fair estimates of annual runoff.

The sediment load consists of bed load, suspended load and wash load. Bed load has been measured using different types of samplers or by determination of the volume of bed forms and their travel velocity. Suspended and wash load have been measured by collecting water samples, either at locations with full mixing or by using a depth-integrating sampler. The water samples were filtered and concentration in mg l^{-1} is multiplied with discharge to calculate sediment load. Annual loads are calculated using rating curves based on simultaneous measurements of discharge and concentration. Dissolved load is calculated using concentrations found by drying of water samples or by summation of elements found by chemical analysis of the water samples. A summary of results is found in Hasholt (1996).

In 1999, a surging glacier was observed on Disko Island, West Greenland, and measurements of sediment transport were carried out, showing very high concentrations of up to several g l^{-1} (Gilbert *et al.*, 2002). It is obviously not possible to calculate the load from major parts of Greenland based on direct monitoring. To do this, a number of monitoring stations have to be established at representative locations, and the measurements must cover a representative length of time. This will probably not happen within a short time, and therefore to evaluate the load from Greenland to the neighbouring seas, a method to estimate loads from ungauged areas must be developed.

The aims of this work are:

(a) To identify gaps in the information and problems in calculation of loads due to different erosion and transport processes.

(b) To find and discuss methods for estimation of load from Greenland.

(c) To produce preliminary estimates of load, and discuss possible future improvements.

METHODOLOGY

Actual processes influencing load

Greenland has been shaped by glaciations for at least 250 000 years. As a result, the country has a steep relief with altitudes of up to 3200 m. The area not covered by the Greenland Ice Sheet and local glaciers is 384 850 km^2. It is mountainous and most often the rocks are bare or covered with a few metres of glacial deposits from earlier glaciations. The steep terrain is prone to water erosion, and the erosion rate depends on the type of rocks at the land surface. This is clearly demonstrated at the research station Zackenberg, where areas with crystalline rocks produce much less sediment than nearby areas with sedimentary rocks (Rasch *et al.*, 2000; Hasholt & Hagedorn, 2000). Nivation also plays an important role in the detachment of sediment at both Zackenberg and Sermilik, as demonstrated by Christiansen (1998). Glacial erosion is without any doubt the most important sediment-producing process in Greenland as shown by Hasholt (1976). This is in accordance with findings cited by Bogen (1996) and Gurnell & Clark (1987). Local glaciers, e.g. the Mittivakkat Glacier in southeast Greenland, produce approximately 1000 t km^{-2} $year^{-1}$ (Hasholt, 1976). Studies of sediment deposition have shown that substantial amounts of sediments are trapped in the proglacial braided river valley and in lakes (Hasholt & Walling, 1992; Hasholt *et al.*, 2000). Jökulhaups produce very large floods (Valeur, 1959) that can carry enormous loads of sediment (Tomasson, 1991). Recent investigations have shown that sediment production by surging glaciers can be extremely high (Møller *et al.*, 2001; Thorsøe, 2002). Such glaciers are present on Disko Island (Weidick, 1988) but could possibly be found elsewhere in Greenland. Ice streams or permanently surging glaciers, e.g. the Jakobshavn ice stream, are probably the largest producers of sediment in the world. In several places, lobes of the Greenland Ice Sheet go directly into the sea; here also a large production of sediment must be expected, but is not measured. Investigations of transport by surging and calving glaciers are needed to remedy this lack of knowledge.

Rational methods

The best way to determine transport and delivery would be an application of rational methods for the calculation. The term “rational methods” in this context refers to methods based on a description of the ongoing physical processes using models to apply the basic laws of physics.

Several models describing detachment, transport and delivery of sediments and solutes exists. Examples are WEPP (Nearing *et al.*, 1989) and EUROSEM (Morgan *et al.*, 1994), both needing detailed information about rainfall and operating on an event base. Furthermore, detailed and distributed information about soil parameters is needed. In Greenland, such information is very rare if it exists at all. These models are developed primarily for agricultural areas in temperate climates, and the description of erosional processes in cold climates is poor. This is a serious problem, because investigations in Nordic countries (Øygarden, 2000) clearly indicate increased erosion related to frozen soils and snowmelt events.

Semi-empirical models such as the USLE (Wischmeier & Smith, 1978) have often been applied in ungauged areas because of their simplicity and because they include important parameters. Such models, however, suffer from the same drawbacks as the more sophisticated ones. It is therefore concluded that rational methods cannot be applied to larger areas in Greenland at the moment. For this reason, it is attempted to develop an empirical method for calculating sediment and solute export from Greenland.

Empirical method

The method comprises two steps. The first step is intended to identify homogeneous areas with respect to production of solutes and sediment. The second step is intended to describe the amount of sediment and solutes that can be expected to reach the ocean.

Production of solutes and sediments

Source areas The production of sediments and solutes depends heavily on the geology and the geological history of the area. Hard crystalline rocks areas will be much more resistant to mechanical erosion and solution than sedimentary rocks and unconsolidated loose sediments. Source areas might then be subdivided into classes of erodibility based on geology.

Erosional processes The amount of solutes and sediments actually detached from a source area depends on the geomorphic agents and the processes in operation. Weathering depends on temperature. The rate of chemical weathering increases with higher temperatures, and hence warmer climates will produce a larger amount of solutes. On the other hand, mechanical erosion is often dominant in cold climates where freezing occurs. In particular, the presence of freeze-thaw cycles is important for the detachment of sediments. Thus, cold environments favour mechanical erosion compared to solution, and this trend will increase when moving north to the high arctic conditions.

The presence of water is imperative for solution and for shattering the rocks by freezing of water in fissures and cracks. Large amounts of rainfall means lots of available water for detachment processes and for transport to the ocean. Precipitation as snow partly protects the surface against extreme temperatures during the winter, but the available melt water and the freeze-thaw cycles increase the effectiveness of nivation processes. When snow accumulates, firn and later glaciers are formed. Glacial erosion is one of the most potent forms of erosion, but the actual status (advancing, retreating) of the glacier is very important for the amount of sediment produced. High drainage densities and the presence of large streams indicate the importance of water erosion.

Sediment delivery The amount of sediment reaching the ocean depends on the distance from the source area to the ocean: the longer the distance, the less sediment is transported to the ocean. The slope of the transport route also influences transport as a steeper slope leads to higher transport capacity and bed shear. In addition, the time of concentration is diminished compared to areas with low slope. The occurrence of sinks e.g. large valleys and lakes, along the transport route can modify the amount of sediment very significantly. The amount of retained sediment depends on the volume of the lake relative to the inflow. Relations for calculating trapping efficiency have been presented by Brune (1953) and others. A shallow-water coast with little wave activity and a small tidal range will trap sediments more efficiently than a deep-water, dynamic coast. The plan form of the coast will also influence the amount of sediment reaching the ocean. Watercourses and rivers debouching in fiords and archipelagos will deposit part of their load in these waters.

Sediment production matrix The factors determining sediment and solute production rates can be treated separately. Higher temperatures will lead to higher rates of solute production for a given rock type. This is not necessarily the case for sediment production. Temperature domains having higher and lower than average production can be distinguished. If production rate is plotted against the difference between annual maximum and minimum temperatures, domains of higher and lower rates than average can be separated. Similar diagrams of sediment and solute production rates against runoff, steepness (relative relief), percentage snow cover and percentage glacier area can be plotted. A common feature of nearly all diagrams is that the production of solutes and sediment increases with increasing values of the parameter. Values above average result in a high ranking and values below average in a low one. Due to the lack of determination of actual diagrams a subjective ranking must be made.

In the production matrix (Table 1), the combination with the six lowest rankings will have the lowest production for a given rock type while the combination with the six highest rankings will have the highest. The actual values of production are taken from the literature or from research results from Greenland. The production matrix values are the values that will reach the ocean in case of a delivery ratio of 100%.

Delivery function matrix To estimate the delivery ratio, a similar matrix can be constructed based on factors that influence delivery ratios. The delivery ratio will decrease when the distance from the source area to the coast increases. Distances shorter than average will therefore have a high ranking whereas distances longer will be given a low ranking. Steeper areas will have higher delivery ratios, so that slopes higher than average rank high while lower slopes rank low. High runoff values are given a high rank while low runoff values are given a low rank. The presence of sinks can be treated in different ways. In drainage basins, the percentage of lakes will determine the ranking. Depending on the type of coast, a significant amount of sediment might be trapped in the near-shore zone. Ranking in this case must be determined as a function of the shortest distance from river mouth to the ocean. Finally, a relationship between coastal dynamics and delivery ratio might be constructed. By chance this function also had the lowest delivery ratio for a combination of six low scores and the highest for a combination of six high scores.

Values in this function are derived from the literature, but due to the rather limited availability of data from this environment, the values provide an estimate of the relative delivery ratios of the areas rather than absolute values. The function is shown

Table 1 Sediment production matrix (t km^{-2} year^{-1}). Sediment production factors: (1) Temperature regime; (2) Temperature variability; (3) Runoff; (4) Slope steepness; (5) Snow cover; (6) Glacier %. Estimates are based on interpretation of Bogen (1996), Gurnell & Clark (1987), Hasholt (1996), Hasholt & Hagedorn (2000), Meltofte & Thing (1998), Meltofte & Rasch (1998), Rasch (1999), Rasch *et al.* (2000), Tomasson (1991) and Thorsøe (2002).

Crystalline rocks	5	10	50	100	200	500	1000
Sedimentary rocks	10	20	80	200	500	1000	2000
Loose sediments	20	50	100	500	1000	5000	10000
Score/ranking	0H 6L	1H 5L	2H 4L	3H 3L	4H 2L	5H 1L	6H 0L

Table 2 Delivery function. Delivery ratio factors: (1) Distance from source to coast; (2) Slope steepness; (3) Runoff; (4) Presence of sinks; (5) Coastal sinks; (6) Dynamics of coast. See Table 1 for references.

Delivery %	5	10	20	30	40	70	100
Score/ranking	0H 6L	1H 5L	2H 4L	3H 3L	4H 2L	5H 1L	6H 0L

in Table 2. To estimate the amount of sediment or solutes reaching the ocean from a certain area, first the production is determined from Table 1 and the production in t km^{-2} year^{-1} is multiplied by the basin area. The mass of sediment is then multiplied by the delivery ratio determined using Table 2.

Application of the methodology in Greenland

It must be stated that the methodology so far has not been applied throughout Greenland. This section therefore describes how the methodology could be implemented based on the available information.

First of all, a map scale should be chosen. Most of Greenland is covered by maps with a scale of 1:250 000 and a 50 m contour interval. In northeast Greenland, maps with a scale of 1:100 000 with a 100 m contour interval have been produced recently. It is therefore recommended to use 1:250 000 maps for topographic variables and maps with a similar or smaller scale for geology and the Greenland Ice Sheet.

The following procedure is used: first a "base" coastline is defined. It follows the open coast, the front of deltas and glaciers that enter directly into the sea. In the case of fiords, the coastline is drawn at the mouth of the fiord, and in the case of islands (skaergaard) the delimitation is a line connecting the coast of the outermost islands. On the topographic maps the drainage basins are identified for all rivers running to the open sea or to fiords. Areas without watercourses bordering the sea are also delimited. The borders of the Greenland Ice Sheet and glaciers with direct contact with the sea are then identified. For all larger basins, the area of the different categories of bedrock, lakes and local glaciers is determined. This information is then used to determine the ranking in Table 1, and transport distances are measured and included in the determination of the delivery function in Table 2. For each basin, the output is calculated as the production from Table 1 multiplied by the delivery ratio from Table 2.

Preliminary estimate of delivery from Greenland

Although the detailed calculations described above have not been carried out, the concept can be used to present a very rough, preliminary estimate of the annual delivery of solutes and sediments from Greenland to the surrounding seas. The part of Greenland draining to the Polar Basin will have a low score in both Tables 1 and 2, and it is estimated therefore that a sediment yield of about 10 t km^{-2} $year^{-1}$ is delivered to the sea. East Greenland draining to the North Atlantic Ocean is more complicated. Several glaciers and parts of the Greenland Ice Sheet calve into the sea, resulting in a very high delivery of more than 200 t km^{-2} $year^{-1}$. About a third of the length of the coast consists of large fiords and islands along the coast. A large production might be derived using Table 1, but the delivery function will give low values, resulting in an estimate of 50 t km^{-2} $year^{-1}$. Half of the length of the coast in the south will have a high production and a rather high delivery because of drainage directly to the sea or into rather short fiords, resulting in an estimate of 100 t km^{-2} $year^{-1}$.

The southern part of the West Greenland coast has conditions similar to the east coast; therefore the estimate is 100 t km^{-2} $year^{-1}$. The next section of the coast has a low production of sediment and the water from the Greenland Ice Sheet travels to the sea via long fiords, resulting in an estimated sediment yield of 10 t km^{-2} $year^{-1}$. The section of coast around the Jakobshavn ice stream and Disko Island probably has the largest variation in production and delivery. Because of the ice stream and the presence of surging glaciers, the overall delivery is estimated to be high and greater than 200 t km^{-2} $year^{-1}$. Along the remaining part of the coast, the Greenland Ice Sheet is very close to the shore and production very much depends on how active the glacial erosion is. No data are available, and estimated delivery is 50 to 100 t km^{-2} $year^{-1}$.

Delivery of solutes differs from the delivery of sediments because of the absence of sinks. An estimate can be found by multiplying the average concentration with the runoff rate found from the water balance. The delivery of solutes from areas with high runoff rates in southern and eastern Greenland is estimated as 50 to 100 t km^{-2} $year^{-1}$. For the drier parts of western and northern Greenland, solute delivery is estimated as 1 to 5 t km^{-2} $year^{-1}$.

DISCUSSION AND CONCLUSIONS

It has been demonstrated earlier (Hasholt, 1996) that information on sediment transport in Greenland is very sparse. On global maps of sediment delivery, Greenland is shown as *terra incognita*. Greenland as a whole therefore qualifies as an ungauged area and in the light of the demand for data for global modelling it is a relevant task to try to estimate the delivery from Greenland to the surrounding seas. Our knowledge about processes is increasing, but there is still a lack of knowledge of glacial erosion and transport capacity in cold environments that makes the use of models developed mainly for temperate climates obsolete. Furthermore, these models have a very high demand for data. At the moment it is therefore necessary to use empirical methods to estimate sediment delivery from this extensive, ungauged area. The methodology presented here is based on evaluations of the production and detachment of solutes and sediments, and of sediment transport. Knowledge of the geology (erosivity) and of six other parameters describing the erosional potential is incorporated. Factors determining delivery are found using topographic maps.

The weakness of the system is that ranking of the parameters has to be done subjectively by experience, as actual values are not known. Another point of criticism could be that the effect of each parameter on the ranking is equal, not taking into account, for example, that slope could be more important than temperature. At the moment, however, there is not enough information to give different weights to parameters. Furthermore, the rates of sediment production found in the literature might not cover all areas equally well, but so far it is the only information available. Secondly, the method uses six parameters to establish a delivery function. This function mainly accounts for the transport and deposition of sediments, because solutes will be transported directly to the sea. Again, a possible point of criticism is that there are equal weights for all parameters. The main criticism is that the actual values of the different parameters in Greenland are not known. This could be solved by using programs such as River Tools (1999) in digital terrain models and by using GIS to delimit homogeneous areas.

In conclusion, a methodology for estimating the delivery of sediments and solutes from Greenland to the ocean has been developed based on knowledge of erosion and transport. The method has been used to produce preliminary, rough estimates of the actual delivery. Finally, possibilities for improving the methodology are mentioned.

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