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Sediment transport to the Arctic Ocean and adjoining cold oceans*

Bent Hasholt[1], Nelly Bobrovitskaya[2], Jim Bogen[3], James McNamara[4], Sebastian H. Mernild[1], David Milburn[5] and Desmond E. Walling[6]

[1]Institute of Geography, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.
E-mail: *bh@geogr.ku.dk*
[2]State Hydrologic Institute, St. Petersburg, Russia
[3]Norwegian Water Resources and Energy Directorate, Oslo, Norway
[4]Department of Geosciences, Boise State University, Boise, ID 83725, USA
[5]Water Resources Division, Department of Indian Affairs and Northern Development, Yellowknife, Northwest Territories, X1A 2R3, Canada
[6]Department of Geography, University of Exeter, Exeter, Essex, EX4 4RJ, UK

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Abstract This paper reviews and synthesises available information on sediment transport to the Arctic Ocean and adjoining seas with open contact to the Atlantic and Pacific Oceans. Special emphasis is placed on calculation and estimation of the sediment flux from the mostly ungauged high Arctic areas on the American continent, in Greenland, and on islands in the Arctic Ocean, and from Russia. In the absence of reliable information on bedload fluxes for most rivers, attention is directed primarily to suspended sediment loads. By combining available monitoring data and estimates for ungauged areas, the total sediment transport to the Arctic Ocean is estimated to be 324–884 $\times$ $10^6\,\mathrm{t\,yr^{-1}}$. Of this total, a maximum of about 56% can be considered as monitored, while the rest is based on different types of estimate. It is clearly demonstrated that the monitoring network in the high Arctic is inadequate and that there is a lack of knowledge concerning the proportion of the load that actually reaches the sea, as well as bedload.

Keywords Arctic; Arctic Ocean; glacierized basins; non-glacierized basins; sediment fluxes; sediment transport; specific sediment yields

Introduction and scope

The Arctic Ocean and the adjoining cold oceans play an important role in the global energy balance, by strongly influencing the global ocean current circulation. These oceans are predominantly ice covered. The influx of freshwater and sediment influences the formation of ice. In recent years, it has been widely accepted that the globe is warming, and in several areas this has caused increased melting of icecaps and local glaciers, resulting in an increased influx of fresh water (ACIA 2005). However, the influence of global warming on the influx of sediment cannot be treated as a simple function of the increased fresh water input, because the magnitude of the sediment flux will also depend on both sediment availability and the presence of sinks. Syvitski and Morehead (1999) noted that the magnitude of the sediment load transported by a river is positively correlated with the mean annual temperature in its drainage basin. Further Syvitski (2002) analysed the available sediment yield data for 48 circumpolar

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Arctic basins and estimated that, if mean annual temperature was to increase by 2 °C, the sediment load carried by rivers in the Arctic would increase by about 30%. Several global-scale assessments of sediment transport and sediment yield to the oceans have been carried out (e.g. Milliman and Meade 1983; Jansson 1988; Walling and Webb 1996; Syvitski and Morehead 1999). Common to all these assessments is the conclusion that the sediment input to the Arctic Ocean is low; furthermore, there is a recognition that the available information on sediment inputs is currently rather limited.

Icecaps and glaciers cover many parts of the land area surrounding the Arctic Ocean and several authors (e.g. Bogen 1996; Gurnell *et al.* 1996; Hallet *et al.* 1996; Hasholt 1996) have observed that glacial erosion is responsible for some of the largest specific sediment yields in the world. In contrast, other parts of the Arctic Ocean are bordered by areas dominated by pristine boreal forests and tundra with low relief that are known to have some of the lowest specific sediment yields in the world (e.g. Bobrovitskaya *et al.* 1996, 2003). The magnitude of the specific sediment yields of rivers discharging to the Artic Ocean is therefore extremely variable in space and time.

Information on sediment transport to the Arctic Ocean and adjoining cold oceans is spread through a wide range of literature; some is available from literature dealing with fluvial transport and erosion, some from the work of coastal geomorphologists and geologists using sea-bottom cores to investigate sedimentation rates and some from the work of geochemists investigating the global carbon cycle. However, results from sea-bottom cores are not included here.

The aims of this contribution are: (1) to review existing knowledge regarding sediment transport to the cold oceans with particular emphasis on high arctic areas; (2) to provide a state-of-the-art update of current knowledge relating to the geomorphological processes responsible for erosion and sediment mobilisation processes in the region; (3) to evaluate contemporary measuring programmes and their limitations; and (4) to identify future research needs.

Study area

The Arctic Ocean is clearly the primary area of interest, but its margins bordering the continents incorporate a number of local seas, which are the primary recipients of the sediment transported from the adjoining land areas. Chukchi, Beaufort, Lincoln, Wandel, Greenland, Norwegian, Barents, Kara, Laptev, and the East Siberian seas, are all treated as part of the Arctic Ocean.

The main exchange between the Arctic Ocean and the other oceans takes place through the Denmark Strait and between Iceland and Norway. Therefore, information from East Greenland, Iceland and Norway is included in this study. Other areas where exchange is of less importance are considered, when the information is of relevance to the main study area. The Arctic Ocean and the main catchments that drain into it are shown in Figure 1.

The Alaskan catchments are rather small, delimited to the south by the Brooks Range, and are characterized by tundra with low relief. The western part of Canada is dominated by the Mackenzie River basin outflow. Other basins along the coast and the archipelago up to Ellesmere Island are small and of moderate relief. Ellesmere Island has several ice caps and steep relief. The parts of Greenland bordering the Arctic Ocean include both local glaciers and outlets from the Greenland Ice Sheet. Iceland is characterized by loose sediments (volcanic ash) and both glaciers and areas with high relief. Norway is mountainous, having some local glaciers. The major landmass contributing to the Arctic Ocean is situated in Russia. Here the topographic divide is situated up to 2000 km from the coast of the Arctic Ocean, the relief is relatively low and the terrain is covered by tundra or boreal forest. Close to the Bering Strait the relief is greater, but, as in Alaska, the contributing area is less. Within

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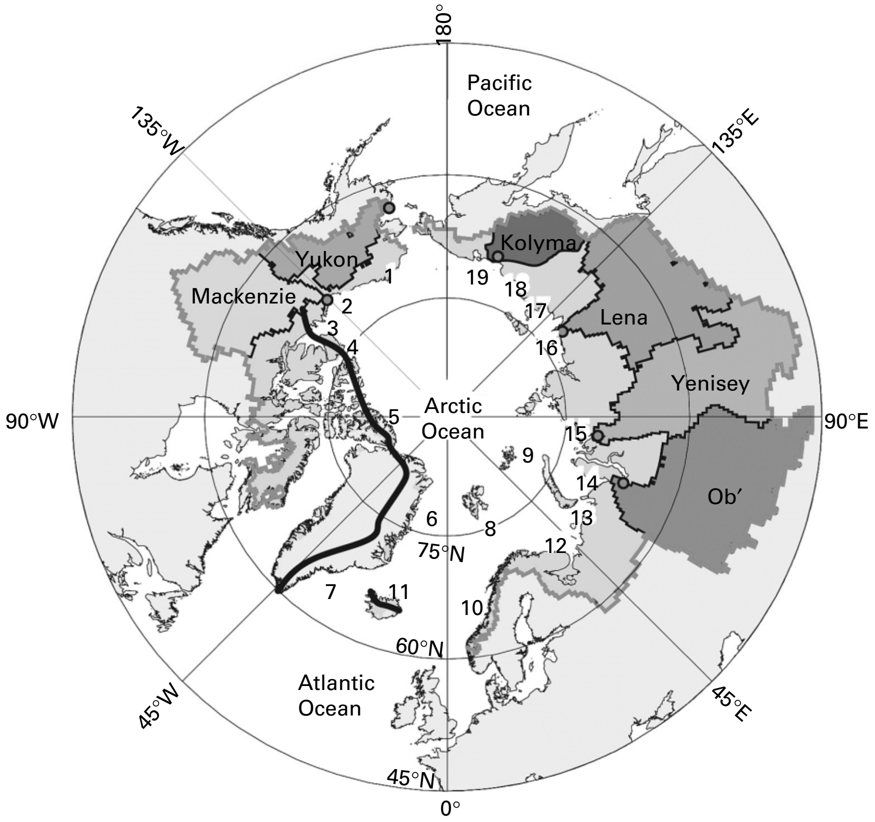

Figure 1 The Arctic Ocean and the main contributing catchments. The heavy black line delimits the catchment area in Arctic Canada, Greenland and Iceland. Numbers refer to particular river basins and catchment areas: (1) Colville River and others, (2) west of Mackenzie River, (3) east of Mackenzie River, (4) low Arctic islands, (5) high Arctic islands, (6) north-east Greenland (Zackenberg), (7) south-east Greenland (Sermilik), (8) Svalbard, (9) Russian Arctic islands, (10) Norway, (11) northern Iceland, (12) Severnay Dvina, (13) Pechora, (14) Ob, (15) Yenisey, (16) Lena, (17) Yana, (18) Indigirka, (19) Kolyma

the Arctic Ocean there are several islands characterized by steep relief and the presence of glaciers, namely, Svalbard, Franz Joseph Land, Novaja Zemlya, and North Land.

Geomorphological processes in the high Arctic

Surface processes

A number of cold-region surface processes dictate the rate of sediment production. Mechanical weathering due to the frequent freeze–thaw cycles is important (e.g. Harbor and Warburton 1993). Land clearance for agriculture or for timber harvesting may cause a substantial increase in the mobilisation of sediment from Arctic catchments. Another human activity that can significantly increase sediment mobilisation is mining, especially the hydraulic operations used in gold recovery (Bobrovitskaya *et al.* 2003).

Periglacial processes including cryoturbation, gelifluction, active layer detachment and thermokarst are all effective in producing and transporting sediment to the fluvial system (French 1996). The accumulation of snow on the lee sides of hills produces altiplanation terraces and tors by nivation, with associated erosion and transport of sediment from the hillsides (e.g. Christiansen 1998). Intrusive or segregated ground ice may occupy up to 90% of the volume in frost-susceptible soils (Mackay and Dallimore 1992). Active layer detachment is becoming more common in the Artic, due to global warming (Harris and

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Lewkowicz 1993), producing abundant sediment as it occurs, and exposing ice-rich permafrost to subsequent thermokarst development.

Channel erosion

In combination with periglacial processes, bank erosion can mobilise large amounts of loose sediment that are transported downstream. Sidorchuk (1994), studied floodplain processes on the Jamal peninsula in western Siberia and found high erosion rates of 0.5–0.7 m yr^{-1} along banks of a meandering river over a 200 yr period.

Rates of bank erosion in areas subject to adjustments after meander cutoffs were even higher, up to 1.5–2.0 m yr^{-1}. However, Scott (1978) reported that permafrost restricted bank erosion during the break-up period in streams draining the North Slope of Alaska, due to the increased soil strength. Slumping and bank failure tended to occur later in the season as the soil thaws. The slumping process can be intensified by freezing of water in vertical cracks developed in the banks, in particular along the concave parts of meander bends. Ice frozen to the banks can be lifted and broken loose by the river and incorporated material originating from the banks may be transported long distances as ice-rafted material. Evidence of such long distance transport is provided by the presence of Siberian driftwood, with roots still present, on the shores bordering the Arctic Ocean.

In-stream ice has been shown to both enhance and restrict erosion in ice-affected rivers. Smith (1979) reported that channels in northern Alberta, Canada tend to be enlarged due to the scouring action of ice during break-up. Although these rivers are not in the Arctic, the same principle may apply wherever floating ice exists. However, Kellerhals *et al.* (1972) suggested that scouring by ice is not a significant geomorphic process and Kellerhals and Church (1980) indicated that the channel enlargement reported by Smith (1979) is not caused by ice scour, but is probably caused by the increased water levels associated with ice jams downstream. In either case, however, it appears that in large, ice-affected rivers, ice may be responsible for enlarged channels and enhanced sediment transport.

Sediment transport

Sediment transport in arctic rivers is frequently dominated by extreme events. Recent investigations at Zackenberg, north-east Greenland have shown that an event in 1998 which lasted only a few days transported as much sediment as would be transported during several normal years (Mernild *et al.* 2006). Extreme events may be caused by the collapse of snow dams, glacial outburst floods, and major debris flows or landslides entering a river, perhaps in connection with slush flows. When anchor ice formed on the riverbed is released, the resulting ice rafting can transport even coarse material over long distances and explain the existence of clasts within the finer deposits found in lakes and coastal areas. In terms of more ‘normal’ years, Walker and Hudson (2003) report that about 62% of the annual sediment load of the Colville River, Alaska is transported in about 13 days, or 4% of the year.

McNamara (2000) has proposed that in headwater streams, where ice typically freezes to the streambed, the presence of ice might reduce, rather than enhance, sediment transport. In such streams, flow during the breakup period tends to occur over ice that protects the bed sediment from entrainment. Oatley *et al.* (2005) demonstrated that peak flows during the snowmelt period in the Upper Kuparuk River were competent to move sediment in the cobble-bed stream during 3 out of 10 years, although minimal movement actually occurred because of anchor ice. During the study period, a large summer rainstorm occurred that caused dramatic channel changes. A detailed analysis, involving tracer cobbles, cross-section surveys, and scour gauges, indicated that this single event transported approximately the same amount of material as the three competent snowmelt floods would have moved during 10 years, if anchor ice were not present. This implies that, although rainstorms

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produce the largest sediment loads in headwater streams, the suppression of bed load transport by river ice may be a significant factor in producing the low sediment yields characteristic of the Arctic. Prowse (1993) has described large concentrations of suspended sediment related to ice break-up and Milburn and Prowse (2002) have described the formation of a plume of cohesive sediment before the ice break-up.

The building of dams and reservoirs will significantly reduce downstream sediment transport by trapping fluvial sediment. To date few dams have been built in sparsely populated northern drainage basins, although a number of the major Russian rivers draining to the Arctic Ocean are now influenced by dams. Major projects previously proposed in Canada and Siberia are not now being actively considered.

Glacial erosion and transport

Glacial erosion produces its own type of sediment termed till that is deposited in a systematic pattern in relation to the glacier as moraine deposits. Material released by glacial erosion is frequently transported over large distances by the meltwater emanating from the glacier. Large areas of the northern hemisphere, which were covered by ice during the Pleistocene Ice Ages, are now covered by glacial deposits, which are currently being eroded by other types of erosion or by advancing glaciers.

Several authors (e.g. Gurnell *et al.* 1996; Hallet *et al.* 1996) have suggested that contemporary glacial erosion produces the highest specific sediment yields in the world.

Large ice-streams, such as the Jakobshavn Ice Stream, emanate from the Greenland Ice Sheet and calving produces icebergs that carry eroded material over long distances within the ocean (Gilbert 1990). Rates of calving have been estimated by Reeh (1994) and Weidick (2000): they are needed to evaluate the potential transport.

Surging glaciers advance dramatically during short periods between longer periods of quiescence. Because of the remote locations of such glaciers and the short duration of the surge, few observations on surging glaciers are available (e.g. Hattersley-Smith 1969; Higgins and Weidick 1988; Humphrey and Raymond 1994). In recent years, a surge event has been well documented on Disko Island in Greenland (Møller *et al.* 2001; Gilbert *et al.* 2002). The investigations show that surging and fluvial transport can result in very high rates of sediment transport to the sea, but the amount of material transported depends on the amount of loose sediment present beneath the surging glacier and in the valley system in front of the advancing glacier.

Measurements of sediment fluxes in Arctic rivers

Although international and national standards are available for many methods of measuring sediment transport, e.g. ISO 772, CEN, and EN 872, the methodology employed in this field is often based on methods developed for specific projects or standard methods modified to suit particular local conditions. New developments are also taking place, including, for example, the use of continuously recording sensors, including OBS (optical backscatter) probes and other types of transmissometer. Bed load is not included in most monitoring programmes and where attempts are made to measure this component of the total sediment load they are usually based on specialised methods, including, for example, the use of tracers, monitoring of bed form movement or inserting radio transmitters in pebbles.

Sampling techniques

Information on sediment transport in Arctic rivers is commonly restricted to the suspended load and monitoring programmes usually involve the measurement of discharge in a river cross-section and the collection of water samples from the section which are subsequently used to determine the suspended sediment concentration. The product of the water discharge

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and the mean suspended sediment concentration in the cross-section provides an estimate of the suspended sediment load. Where the suspended sediment is fine-grained and uniformly mixed throughout the cross-section, a representative sample of the concentration can be obtained relatively easily using a simple bottle sampler. However, this is generally not the case, and specially designed time- and/or depth-integrating samplers are usually employed to obtain isokinetic samples that provide a representative estimate of the mean concentration in the cross-section. The most widely used samplers are the USDH-48 and USDH-49 depth integrating samplers and the US P-61 point integrating sampler (Hershy 1999).

In Scandinavia and Greenland, a sampler of Swedish origin (Nielsson 1969) is widely used, whilst in Russia a standard national sampler is employed. Automatic water samplers are often used in different countries when it is necessary to obtain frequent samples. The use of such samplers is generally restricted to smaller rivers and streams, due to their use of a single fixed sampling intake. In Norway most of the sediment monitoring programmes are based on the collection of samples from turbulent river reaches using ISCO automatic samplers, which employ a peristaltic pump to withdraw the sample from the river (Bogen 1988, 1992).

OBS (optical backscatter) probes and transmissometers have been used in several investigations (e.g. by Hasholt 1992) to investigate short-term fluctuations in concentration, since they are capable of providing continuous records of turbidity. However, the records provided by such instruments need to be calibrated against measurements of suspended sediment concentration undertaken on conventional water samples.

Analysis of suspended sediment samples

To establish the suspended sediment concentration associated with a water sample, the sediment is separated from the water by filtering. In recent years many different types of filter have been used. Millipore HA 0.45 μm membrane filters are often used but they require a very long time for the filtrate to pass through the membrane when the sediment concentration is high. Glass fibre filters are often used as they are more rapid and therefore more practical. The nominal retention diameter is 0.7 μm for Whatman GF/F filters and 1.2 μm for GF/C filters. These filters correspond to Millipore APFC filters and have been adapted as the EC standard (CEN 1996). As different filters are used in different countries, the resulting concentration data are not always strictly comparable, although the differences involved are likely to be minor.

Sampling networks

The number of monitoring stations in Arctic areas is generally low. Furthermore, the monitoring stations have frequently been established to monitor the environmental impact of particular human activities, such as mining, or as part of the investigations of landscape evolution, rather than to assess land–ocean fluxes. Sediment monitoring networks are currently being operated in Alaska, parts of Canada, Norway, and Russia. However, in Canada and Russia there has been a marked reduction in the number of stations in recent years. In Greenland only two stations on the east coast are currently operating for small basins; at least one additional station is being planned at the outlet of a major basin draining the Greenland Ice Sheet.

Sampling frequency

Manual samples are generally collected at infrequent intervals, sometimes on a regular basis and sometimes on a more irregular basis related to the occurrence of significant flood events, etc. Where samples are collected once per day, the existence of significant diurnal variation may bias the resulting data (Mernild *et al.* 2006). More often, however, samples are collected

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weekly or even monthly. Automatic samplers can provide more frequent samples. However, even with automatic samplers, often only one sample, representing a composite of several samples collected during the day, is analysed. Automatic samplers often suffer from problems with battery voltage in cold environments. During winter, sampling is not carried out when ice covers the river or during the ice break-up, because of the hazards involved. Temporally sparse sampling may result in misleading results, particularly in areas with glacial outbursts, where load can be underestimated by more than 100%.

Position of the sample

In focused studies, several samples are commonly taken in the cross-section, in order to take account of the variation of sediment concentration both laterally and vertically. In most cases, however, only a single sample is collected to represent the concentration in the cross-section. In this case the sample is most often taken in the deepest third of the cross-section; in Russia, it is generally collected at 0.6 of the depth from the surface, where the average velocity is found. Depth-integrated samples are used increasingly, but in some studies, such as that of the Colville River in Alaska reported by Arnborg *et al.* (1967), samples were collected near the surface.

Load calculation procedures

The instantaneous suspended sediment load at the time of sampling (e.g. kg s^{-1}) can be established by multiplying the discharge and the corresponding sediment concentration determined by laboratory analysis. In most cases, however, estimates of the longer-term (e.g. annual) load will be required and it is necessary to combine the flow record with the values of suspended sediment concentration provided by infrequent samples. When daily, or at least weekly, samples are available, the load is commonly calculated using linear interpolation to estimate the values of hourly or daily concentration which are multiplied by the corresponding discharge values. This procedure has been applied in Norway. When the sampling frequency is too low to permit the use of linear interpolation, rating curves expressing concentration as a function of discharge are often applied. Very often the spread of observations around the fitted line is large and the relationship is frequently not well defined, resulting in R-square values less than 0.1. This situation can lead to significant errors in the resulting load estimates or biasing of the results by one order of magnitude.

Synthesis of the available data on sediment loads

Sediment load data are rarely fully standardised or readily available. Furthermore, significant variations in both the density of the measuring network and record duration, as well as in the likely accuracy and reliability of the data, can make combination of data from different sources and different countries difficult. Recent reviews for parts of the area covered by this study are, however, provided by Walling and Webb (1996), Hallet *et al.* (1996), Syvitsky and Morehead (1999), and Holmes *et al.* (2002). Other information is available for individual studies, published in scientific journals, technical reports and theses. The information available for individual countries is summarised below. Although the objective is to quantify sediment inputs to the Arctic Ocean, it must be recognised that the data presented relate almost exclusively to the suspended sediment load, rather than the total sediment load, since bed load is rarely measured. Furthermore, the measuring stations for which data are available are rarely located where the river meets the sea, since measurements of sediment transport are difficult to undertake at such sites. As a result, the available values or estimates of sediment flux may overestimate the land–ocean flux, since appreciable deposition may occur within the lower reaches of a river system, particularly where major floodplains exist, and within estuary and delta systems.

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Alaska (United States of America)

In this paper we refer to Alaska, rather than the United States. The US Geological Survey has been operating stream-gauging stations in the Alaskan Arctic since 1962. The maximum number of stations was 25, but the network has now been reduced to 4 stations, including the Colville River (53 000 km^2), the Kuparuk River (8140 km^2), the Sagavanirktok River (4815 km^2), and a tributary of the Sagavanirktok called the Atigun River (126 km^2). Sediment monitoring has not been undertaken routinely at any of the stations and has been restricted to short periods of time. Short-term investigations have measured sediment transport by other rivers in conjunction with specific projects (e.g. Trefry *et al.* 2003), but no comprehensive evaluation of sediment discharge has taken place for the Alaskan Arctic.

In 1962, sediment transport by the Colville River, which drains to the Beaufort Sea (Figure 1), was investigated by Arnborg *et al.* (1967). Water samples were collected close to the surface and the sampling frequency ranged between daily and weekly. Calculations of the transport were based on rating curves. The annual sediment flux from the 53 000 km^2 drainage basin was estimated to be 4.1–5.8 × 10^6 t yr^{-1}, corresponding to a specific sediment yield of 77–109 t km^{-2} yr^{-1}. Because the samples were collected from the surface of the water column, these values probably underestimate the true flux. Using similar methods in 2001, Trefry *et al.* (2003) reported an annual load for the Colville River of 5.0 × 10^6 t yr^{-1}, which corresponds to a specific sediment yield of 94 t km^{-2} yr^{-1}. In addition to the Colville River, Trefry *et al.* (2003) reported that the annual load of the Sagavanirktok River was 0.3 × 10^6 t yr^{-1} (69 t km^{-2} yr^{-1}) and that of the Kuparuk River was 0.02 × 10^6 t yr^{-1} (2 t km^{-2} yr^{-1}). Although the specific sediment yields of the Sagavanirktok and Colville Rivers are different, they are both of a similar magnitude and very much larger than that of the Kuparuk River. The relatively low specific sediment yield of the Kuparuk River is likely to reflect the lack of glaciers in the catchment. Approximately 55% of the area of the North Slope of Alaska is drained by basins containing mostly small glaciers (based on the 100 m DEM of the North Slope and the World Glacier Inventory archived at the National Snow and Ice Data Center, Boulder, CO, USA). Using a weighted average of the specific sediment yields of the Colville and Sagavanirktok Rivers (82 t km^{-2} yr^{-1}) to represent glacierised catchments and the specific sediment yield from the Kuparuk River to represent non-glacierised catchments, the mean specific sediment yield of the area draining to the Arctic Ocean is estimated to be 46 t km^{-2} yr^{-1}. The associated estimate of the total sediment output from Alaska to the Arctic Ocean is 19 × 10^6 t yr^{-1}.

The Copper River (63 000 km^2) drains into the Gulf of Alaska. It is included here because it is representative of the contribution from basins with a substantial coverage of glaciers. The contribution from the Copper River (MacNamara personal communication, April 2005) has been reported to be 84 × 10^6 t yr^{-1}, providing a corresponding specific sediment yield of 1334 t km^{-2} yr^{-1}. The Yukon River, the largest in Alaska, drains into the partially closed Bering Sea (Figure 1), which is not part of the Arctic Ocean. The annual sediment transport from the Yukon River was 38 × 10^6 t yr^{-1} and the corresponding specific sediment yield is 46 t km^{-2} yr^{-1}. Because of the relatively small area of the Bering Sea, the sedimentation rate expressed as a ratio of the sediment influx from the surrounding land area to the area of the sea is high. The southern part of the Chukchi Sea (Figure 1) receives sediment from the Noatak River, which drains into the enclosed Kotzebue Sound. No information is available for this river, and its contribution must be estimated on the basis of its catchment area and the likely specific sediment yield. The rest of the Chukchi Sea from Point Hope to Point Barrow receives drainage from the northern slopes of the Brooks Range, where the rivers are rather short and without glaciers in their catchments and pass through tundra areas near to the coast. The lack of major deltas indicates a modest sediment contribution.

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Canada

Sediment transport has been monitored in Canada as part of its national hydrometric programme since the 1960s, although sediment sampling on a project-specific basis started in 1948. The national programme reached its peak in 1975, when 273 full-time stations and 200 targeted or event-driven stations were sampled. The national programme has been decreasing in size ever since, and there are now only 11 full-time stations and 165 targeted stations. None are in northern Canada.

Various studies aimed at designing a sediment monitoring network for northern Canada have demonstrated that a comprehensive network covering remote reaches of northern rivers would be costly, and consequently sediment surveys have been limited to specific research needs or project appraisals. Because of rising costs of the network, the number of measuring stations was reduced, based on an evaluation of the information obtained after 30 years of observation (Day 1988). By 1999, the sediment survey component of the hydrometric programme was eliminated. At present, suspended sediment is monitored only through surface water quality programmes and thus the resulting suspended sediment data do not truly reflect the actual sediment loads that would be derived using information obtained from sampling the full water column. An exception to the water quality surveys is the ongoing Pan Arctic River Transport of Nutrients, Organic Matter and Suspended Sediment (PARTNERS) to the Arctic Ocean initiative, sponsored by the US National Science Foundation. Regular, whole-river, depth-integrated sampling of water quality and suspended sediment concentrations is conducted on the Mackenzie River at Arctic Red River.

The major north-flowing rivers to the Arctic Ocean include the Anderson, Back, Burnside, Coppermine, Ellice, Hood, Hornaday, Mackenzie, and Tree rivers. The Back, Hood and Horton rivers and the headwaters of the Coppermine River flow across Precambrian Shield bedrock and are characterised by low suspended sediment fluxes. The lower reaches of the Coppermine River produce higher suspended sediment concentrations and had a suspended sediment monitoring programme in the past, but the overall loading to the Arctic Ocean is dominated by the inputs from Mackenzie River and its tributaries. The annual spring break-up is the driving mechanism for sediment mobilisation and transport and it has been observed that, just before break-up, in-channel hydraulic conditions cause the formation of a fine-grained sediment plume followed by a dramatic rise in sediment concentrations at break-up, as moving ice erodes the channel bed and banks (Milburn and Prowse 1998, 2000). Sediment concentrations remain relatively high in these river systems throughout the open-water period and decrease to low concentrations before freeze-up. As discussed below, there are other minor contributions from rivers on the Arctic islands of Canada.

The Mackenzie River is one of the great river systems in the world and ranks twelfth by drainage area and eleventh in terms of mean annual discharge. The basin area is 1.68×10^6 km^2 and comprises five major rivers (the Peace, Athabasca, Slave, Liard, and Peel rivers), three major lakes (Athabasca, Great Slave, and Great Bear), two significant freshwater deltas (Peace-Athabasca and Slave) and the tenth largest marine delta (Mackenzie) (Lewis *et al.* 1992). All major rivers in the basin transport significant amounts of sediment and the contribution of suspended sediment from both the boreal forest and tundra regions transported to the Mackenzie Delta is $124 \times 10^6\,t\,yr^{-1}$, which corresponds to a specific suspended sediment yield of $74\,t\,km^{-2}\,yr^{-1}$. In addition, an annual bed load flux of $4 \times 10^6\,t\,yr^{-1}$ has been reported by Carson *et al.* (1998).

Close to the border of Alaska, the area is drained to the sea by short (less than 200 km), high gradient rivers, while on the eastern side of the Mackenzie River Basin, longer (less than 500 km) rivers with moderate gradients are found. Neither of the areas has significant glacier coverage. East of Cape Bathurst, the rivers drain into the essentially closed Amundsen Gulf and therefore probably only a minor proportion of the load will reach the

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Beaufort Sea. North of Cape Bathurst, Banks Island, Prince Patrick Island, and some minor islands, which are part of the Queen Elizabeth Islands archipelago, border the Beaufort Sea. Rivers on these islands are quite short and the contributing land areas draining to the sea are quite small and the glacier coverage is also quite low. Overall, the load from this area can be expected to be of minor importance, but this cannot be confirmed by actual measurements. Further north from these islands, Axel Heiberg Island and the northern coast of Ellesmere Island are steep and are characterized by substantial glacier coverage. This is likely to result in a significant contribution to the Arctic Ocean from their catchments.

Suspended sediment sampling, during the period of the Sediment Survey (1960–75) was conducted opportunistically, whenever hydrometric measurements were taken. National standard methods, equipment (USDH 49, USDH 59, and USDH 96) and analyses were employed. Focused research programs, such as those reported by Milburn and Prowse (1998, 2002) and Milburn and Krishnappan (2003), also used these standard methods.

The total sediment output from Canada to the Arctic Ocean can be estimated as the sum of the measured output from the Mackenzie River and an estimate of the contribution from the remaining area, based on the area not covered by glaciers multiplied by a specific sediment yield equal to similar areas in Alaska and Siberia (approx. 5–10 t km^{-2} yr^{-1}), and the product of the area of Axel Heiberg Island and Ellesmere Island draining towards the Arctic Ocean and a specific sediment yield representative of similar glacierised areas. The total estimated annual output from Canada is in the range of 160–180 × 10^{6} t yr^{-1}.

Greenland

A summary of the results of sediment transport measurements undertaken in Greenland has been presented by Hasholt (1996). A glacierised basin of 18 km^2 had a specific sediment yield of about 1000 t km^{-2} yr^{-1}, whereas non-glacierised basins had specific sediment yields as low as 5 t km^{-2} yr^{-1}. Measurements undertaken since 1996 at Zackenberg have been documented by Hasholt and Hagedorn (2000), Rasch *et al.* (2000), and Mernild *et al.* (2006). They report an annual sediment load of 15 000–130 000 t yr^{-1}, which corresponds to a specific sediment yield of 29–253 t km^{-2} yr^{-1}. Findings by Hasholt and Hagedorn (2000) indicate that the contributing area is less than 514 km^2, because of sediment trapping in lakes, resulting in a higher specific sediment yield from areas underlain by sedimentary rocks. Recent measurements at Sermilik by Hasholt and Mernild (2006) confirm the earlier reported sediment yields of about 1000 t km^{-2} yr^{-1} from the glacierised area.

On Disko Island, West Greenland, observations of a surging glacier and associated sedimentation in the adjoining fiord system have been reported by Møller *et al.* (2001), Gilbert *et al.* (2002), Desloges *et al.* (2002), Thorsøe (2002), and Rasch *et al.* (2003). These studies found an annual transport of 2.3 × 10^{6} t yr^{-1}, which corresponds to a specific sediment yield of 4243 t km^{-2} yr^{-1}. The results clearly demonstrate the very large amounts of sediment emanating from the glacier during the surge; the concentration of suspended sediment in several water samples exceeded 10 g l^{-1}.

There is, however, no regular network of stations for monitoring sediment transport in operation in Greenland. Along the whole coast of East Greenland, only two stations have been operating and are still operating. Only the Zackenberg Station covers the whole melt season. Monitoring at the Sermilik Station has covered a few full seasons, but for the most part only the later part of the melt season has been monitored. In this report, the main focus is on the north and east coast of Greenland, because sediment transported from West Greenland ends up in Davis Strait, which is not connected to the Arctic Ocean.

Attempts have been made to extrapolate the few measured values for Greenland to larger areas. Møller *et al.* (2001) have used measurements of concentration and discharge from several water courses to investigate the correlation between specific transport in kg s^{-1} km^{-2}

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and catchment characteristics, such as per cent coverage by glaciers, catchment slope and the percentage of the catchment occupied by lakes. The importance of the area covered by glaciers was confirmed as well as the effect of slope. However, the results are representative of areas underlain by basaltic rocks and are not readily transferable to other areas of Greenland, partly because detailed information on catchment characteristics is not available for all of Greenland.

Hasholt (2003) has suggested a different approach to data extrapolation where the erosion rate (t $km^{-2} yr^{-1}$) from areas underlain by a specific lithology is estimated, based on six erosion parameters, namely, temperature regime, temperature variability, runoff, slope steepness, snow cover, and glacier percentage. The amount of sediment actually reaching the open sea (delivery ratio) depends on distance from source to coast, slope steepness, runoff, the presence of sinks (lakes), the presence of coastal sinks and the dynamics of the coast. This procedure can be used for basins not influenced significantly by the Greenland Ice Sheet, but not where glaciers calve into the sea. To apply the method the contributing area must be known, but the available statistics on land types in Greenland are frequently inconsistent. The total ice-free area is reported to be 410 449 km^2 by the *Greenland Statistical Yearbook* (2003) and as 384 850 km^2 by the *Kalaallit Nunat Atlas (1989)*. The ice-free area for the individual regions can be obtained from the atlas, but the ice-free area of North Greenland and East Greenland must be estimated as the difference between the total area and the sum of the ice-free areas of the other regions. The resulting estimates of the ice-free area, extending from Thule to Scoresby Sund, range from 178 000–204 000 km^2. The north coast of Greenland from Robeson Channel to Nordostrundingen is characterised by a cold dry climate producing little runoff, resulting in a low to moderate specific sediment yield of approx. 10 t $km^{-2} yr^{-1}$, according to Hasholt (2003). However, local glaciers are present on Peary Land, and the contribution of sediment from this area is estimated to be of the order of 200 t $km^{-2} yr^{-1}$ based on similarity with Zackenberg. The overall sediment contribution from the northern part of Greenland (approx. 70 000 km^2) is therefore estimated to be 6.7×10^6 t yr^{-1}excluding the contribution from calved ice. From Nordostrundingen to Ile de France, several local glaciers are present and also some major outlets from the Greenland Ice Sheet. The supply of sediment from this reach is assumed to be greater and of the order of 200 t $km^{-2} yr^{-1}$. The outlets from the Greenland Ice Sheet are believed mainly to deliver sediment when calving. From Ile de France south to Scoresby Sund, the local glaciers are located some distance from the coast and sediment is transported to the sea via fiord systems. The Zackenberg Station is located in this area. Taking the possibility of sedimentation in the fiords into account, a specific sediment yield of 50 t $km^{-2} yr^{-1}$ is seen as reasonable for this part of the coastline. The sediment load reaching the open sea from this area is estimated to be approximately 9.5 t $km^{-2} yr^{-1}$ based on the procedure from Hasholt (2003). From Scoresby Sund to Ammassalik Island, the terrain is very steep, precipitation is 1000–2000 mm and the glaciers are close to the coast. This area is probably one of the major contributors of sediment to the Denmark Strait, estimated at 6.5×10^6 t yr^{-1} based on data from Ammassalik Island. The coast further south to Kap Farvel is also assumed to contribute significant amounts of sediment, with a sediment flux estimated at 3.3×10^6 t yr^{-1}. The total input of sediment of fluvial and glacio-fluvial origin to the ocean from North and East Greenland is then estimated to be approximately 26×10^6 t yr^{-1}. Sediment from the west coast is not included, because the ocean current travels north around Kap Farvel into the essentially enclosed Davis Strait.

Weidick (2000) noted that about 200 potential surging glaciers are located within the high land on the east coast of Greenland, but the frequency of surging and its influence on sediment fluxes has not yet been assessed.

Estimates of runoff from the Greenland ice sheet are published by Hanna *et al.* (2005), they were 264 (±26) $km^3 yr^{-1}$ in 1961–1990 and 372 (±37) $km^3 yr^{-1}$ in 1998–2003. It is not possible to separate the contribution from the north and east part of the ice sheet but an

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order of magnitude of 130–190 $km^3 yr^{-1}$ seems realistic. The concentration of suspended sediment is not known either, but samples from an outlet at Kangerlussuaq showed variations from 100 $mg\,l^{-1}$ to 9 $g\,l^{-1}$ during the runoff period (Hasholt and Mernild 2005). If an average concentration of 300 $mg\,l^{-1}$ is assumed, the resulting sediment transport contribution from this source is $40–60 \times 10^6\,t\,yr^{-1}$, from the range in concentration the actual transport could be 10 times higher.

The amount of sediment transported by icebergs is extremely difficult to estimate with any degree of accuracy. The estimated annual total volume of calved ice produced from Greenland is 350 km^3 (Reeh 1994; Weidick 2000). Approximately 69 km^3 calves from the high land between Ammassalik and Dronning Louise Land on the east coast; the remaining parts of the northern and eastern coast are estimated to produce 130 km^3, giving a total of 200 km^3. The sediment content of the icebergs is not known (Gilbert 1990), but can be substantial. In a warm based glacier, the sediment will be concentrated near the bottom, whilst in cold based glaciers the sediment can be located higher up in the ice. Based on density considerations the maximum concentration of sediment in a floating iceberg can be as great as 160 $g\,l^{-1}$, although this is greater than found in most icebergs. However, Gilbert *et al.* (2004) reports the occurrence of iceberg fragments that were submerged because of their high sediment content. From personal observations of icebergs it is estimated that a sediment content of 0.1–0.01% by volume is more realistic, providing an estimate of the amount of sediment transported to the sea by calving in the range $50–500 \times 10^6\,t\,yr^{-1}$.

Reeh *et al.* (1999) found that the dominant mechanism of iceberg formation is bottom melting north of 77°N, while it is calving south of this latitude. There is a potential for increased ice-rafted detritus (IRD) transport in relative warm periods and it should be recognised that north-east Greenland is an area that is affected by global warming.

Svalbard and other islands in the Arctic Ocean

A useful summary of information on sediment transport from Svalbard is provided by Bogen (2004), together with a synthesis of information on sediment transport from other high Arctic areas. Three basins in Svalbard have been monitored for periods ranging from 4 to 13 years and these are some of the most accurate observations from this environment. Specific sediment yields were reported to be 359 $t\,km^{-2}\,yr^{-1}$ for the glacier-fed Bayelva river and 586 $t\,km^{-2}\,yr^{-1}$ from the Brøggerbreen glacier and the moraine covered part of the same catchment. A non-glacierised basin had a sediment yield of 82.5 $t\,km^{-2}\,yr^{-1}$.

More short-term measurements in other parts of Svalbard have provided estimates of specific sediment yields ranging from 28 to 38 $t\,km^{-2}\,yr^{-1}$ in non-glacierised catchments. In glacierised catchments, much higher specific sediment yields, in the range of 303 $t\,km^{-2}\,yr^{-1}$ to 2900 $t\,km^{-2}\,yr^{-1}$, have been reported (Elverhøy *et al.* 1983; Kostrewski *et al.* 1989; Svendsen *et al.* 1989; Barsch *et al.* 1994; Hodson and Ferguson 1999).

In Svalbard, the glaciers are polythermal and glacial erosion rates are influenced not only by lithological and glaciological controls, but also their temperature regime. The largest sediment yields are associated with large, warm-based glaciers. The total area of Svalbard is 36 598 km^2, of which about 2229 km^2 represents glaciers. The temperature regime of all the glaciers is not known, but one third of the area is occupied by small glaciers that are believed to be cold and frozen to the bed. If the specific sediment yield of 586 $t\,km^{-2}\,yr^{-1}$, documented for the Brøggerbreen glacier, is assumed to be representative of the remaining glaciers and a specific sediment yield of 82.5 $t\,km^{-2}\,yr^{-1}$ is assigned to the non-glacial area, the annual sediment contribution from Svalbard can be estimated to be of the order of $16 \times 10^6\,t\,yr^{-1}$ (Bogen and Bønsnes 2003a, b).

Other high Arctic islands, with a large proportion of their area covered by glaciers, include Zemlya Frantsa Josifa, the northern part of Novaya Zemlya and Severnaya Zemlya.

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If the observations from Svalbard are treated as representative of these areas, the total amount of sediment derived from these islands, which have a total area of about 140 000 km^2, is 12–50 × 10^6 t yr^{-1}.

Norway

The variability of specific sediment yield between the different glaciers in mainland Norway is large, ranging from 20 to 1600 t km^{-2} yr^{-1}. However, this range may be further subdivided by the recognition of distinct groups of glaciers. Disregarding glaciers on schistose bedrock that occupy only minor areas, the calculated mean sediment yield of smaller cirque or plateau glaciers is 116 t km^{-2} yr^{-1}. The yields of larger valley glaciers and outlet glaciers from ice caps are somewhat larger, and a mean value of 528 t km^{-2} yr^{-1} has been ascribed to this group (Bogen 1996, 2004). The total glacier-covered area in Norway is 2806 km^2. Out of this area, 1042 km^2 is covered by glaciers smaller than or equal to 3 km^2, while 1763 km^2 is covered by larger glaciers. The total amount of sediment derived from glacial erosion and from glacierized areas is estimated to be 1100 × 10^6 t yr^{-1}.

The mean value for the measured sediment yields from areas classified as ‘forests’ has been given as 1.9 t km^{-2} yr^{-1} (Bogen 1996). A very large part of the country falls into this category and areas of marshland and areas with sparse vegetation are also included in the 148 140 km^2 ascribed to this category. The sediment yields from this area vary regionally according to the thickness and occurrence of Pleistocene sediments and temporally with their availability for erosion. The inclusion of long term data (Bogen 2004) produced a somewhat larger mean specific sediment yield of 2.9 t km^{-2}, giving an estimated yield from this area of 0.4 × 10^6 t yr^{-1}.

The sediment yield of unglacerised mountain areas varies in the same manner, according to the availability of sediments for erosion. In estimating the sediment yield of a large region, it is also necessary to take into account the variable thickness of the sediment cover and the large number of lakes. Thus, a new estimate for these areas was made where the sediment yields reported by Bogen (1996, 2004) were related to the whole of their catchments and not to the ‘contributing areas’. In this way a mean sediment yield of 5.0 t km^{-2} yr^{-1} was proposed for the mountain areas in mainland Norway. Their total area is 152 819 km^2, giving a total sediment supply of 0.8 × 10^6 t yr^{-1}. A recent estimate of the soil loss from agricultural areas throughout the entire country is 1.9 × 10^6 t yr^{-1} (Eggestad 2005), which corresponds to a mean specific sediment yield of 37 t km^{-2} yr^{-1}.

The sediment yield from gullies incised in clay areas outside the agricultural land is subject to large variations caused by differences in stability (Bogen 1996). To obtain an estimate for the whole country, the mean value for the erosion activity in the 340 km^2 clay area within the catchment of the river Leira was applied. The mean sediment yield from this area has been estimated as 155 t km^{-2} yr^{-1}, from data given by Bogen *et al.* (1993). The most extensive marine clay areas are situated in the southeastern and central parts of the country, but significant deposits are also found in northern Norway. Assuming that the area affected by river and gully is approximately 1000 km^2, the overall sediment supply from this type of erosion activity may be estimated at 0.2 × 10^6 t yr^{-1}. The total sediment supply from all the different areas in Norway amounts is estimated to be 2.6 × 10^6 t yr^{-1}. Since most rivers deposit much of their sediment load in the fjords or the coastal zone, this value provides only an indication of the sediment flux from Norway into the ocean. However, even in southern Norway parts of the fine material enter the Norwegian costal current and are carried northwards into the Norwegian Sea.

It is interesting to note that the estimate given above is of the same order of magnitude as the grand total of 4.2 × 10^6 t yr^{-1} estimated by Holtan *et al.* (1991). That estimate was calculated in a completely different way, and also took industrial and sewage effluents into account.

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Iceland

Sediment transport investigations from Iceland have been reported by Tomasson (1991). Icelandic glacial rivers are characterised by very high sediment yields, ranging from 1000–20 000 t km^{-2} yr^{-1}. The reason for the high values is that glacial erosion is acting on loose sediments, predominantly volcanic ashes. However, most of the glacial-fed rivers drain towards the south coast, which is outside the area of interest of this study. Measured sediment transport to the northern coastal areas is 18.1 × 10^{6} t yr^{-1}. At least two of the rivers draining towards the north provide evidence of the occurrence of catastrophic floods.

Russia

Results of sediment transport investigations from Russia have been reported by Bobrovitskaya *et al.* (1996, 2003) and Holmes *et al.* (2002). Some of the longest records of sediment transport to the Arctic Ocean are from Russia (the former Soviet Union) where measurements started in 1935. Unfortunately several stations were closed in the late 1980s.

Although values as high as 7000 t km^{-2} yr^{-1} have been reported from the piedmont regions in the upper part of the basins, sediment yields at the mouths of the very long rivers are relatively low, and only around 5 t km^{-2} yr^{-1} (Bobrovitskaya 1996). The record is long enough to demonstrate the effect of increased human activities, in particular the effects of dam building in reducing sediment loads, which has lowered the specific yield from 5.4 to 1.8 t km^{-2} yr^{-1}. Recently reported values for the mean outputs to the Arctic Ocean from the Ob River and Yenisey River are 15.2 × 10^{6} t yr^{-1}, and 5.6 × 10^{6} t yr^{-1}, respectively. The latter was reduced from 12.4 × 10^{6} t yr^{-1} because of the building of dams upstream. Bobrovitskaya *et al.* (2003) reported that sediment transport in the Kolyma River has increased nearly 100% because of gold mining in the catchment. Results from stations situated close to the mouths of the rivers are given in Table 1.

In Holmes *et al.* (2002) the sampling and calculation procedures applied on Russian arctic rivers are described. He reports ‘best estimates’ of the six largest rivers and characterises the confidence of flux estimates from good to fair except for Pechora: Yenisej 4.6 × 10^{6} t yr^{-1}, Lena 20.7 × 10^{6} t yr^{-1}, Ob 15.5 × 10^{6} t yr^{-1}, Kolyma 10.1 × 10^{6} t yr^{-1}, Pechora 9.4 × 10^{6} t yr^{-1}, and Severnay Dvina 4.1 × 10^{6} t yr^{-1}. Holmes *et al.* (2002) also report results from 10 minor rivers, Indigirka 11.1 × 10^{6} t yr^{-1} and Yana 4.0 × 10^{6} t yr^{-1}. Sediment yield from the 10 rivers varies from 3.4–36.4 t km^{-2} yr^{-1}. Based on an estimation of the areas without monitoring stations and an assumed sediment yield for the respective areas the resulting unmeasured load is calculated and given in Table 1. The total transport from Russia is then 72.8 × 10^{6} t yr^{-1}.

Summary

The total transport of sediment to the Arctic Ocean and the northern part of the Atlantic Ocean is estimated to be between 324–884 × 10^{6} t yr^{-1} (Table 1). The lower number is in accordance with an estimate of the suspended sediment yield to the Arctic Ocean produced by the USSR National Committee for the International Hydrological Decade (IHD) 1965–1974, Bobrovitskaya pers. com. The part of this load that is actually monitored is approximately 56% of the lower estimate of the total but only around app. 22% of the higher estimate. A substantial part of the uncertainty is related to the contribution from the Greenland ice sheet. The specific sediment yields reported for individual catchments are characterised by considerable variation, ranging from about 5 t km^{-2} yr^{-1} to 7000 t km^{-2} yr^{-1} and for Iceland up to 20 000 t km^{-2} yr^{-1}. The highest specific sediment yields are found in mountains and in glacierised areas. A major part of the range in estimates can be attributed to the difficulty of estimating the contribution from calving glaciers.

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Table 1 Sediment transport to the Arctic Ocean and adjoining cold oceans from Alaska, Canada, Greenland, Svalbard and other Arctic islands, Norway (mainland), Iceland, and Russia

River/station	Area (km^2)	Period	Years	Gaps	P_s (kg s^{-1})	Sediment load (10^6 t yr^{-1})	Specific sediment delivery (t km^{-2} yr^{-1})	Contribution to Arctic Ocean (%)*	Measured (%)
Alaska									
Copper River	63 000	1957–65				84	1334		
Susitna River						23			
Yukon River		1963–66				38	46		
Colville River	53 000	1962	1			4.1–5.8	77–109		100
Sagavanirtok River	4815					0.3	69		100
To Chuckhi Sea						8.16		2.0	0
To Beaufort Sea						10.9		2.6	32
Sum Arctic Ocean						**19**	**46**	**4.6**	**16.8**$^{+}$
Sum Alaska						168.1–169.8			
Canada									
West of Mackenzie River						5.9–9.3	74–116	1.4	0
Mackenzie River	1680 000					124 + 4 bedload	74	29.9	100
East of Mackenzie River						13.0–20.3	74–116	3.1	0
Low arctic islands						4.4–6.8	74–116	1.1	0
High arctic islands						10.6–19.0	200–359	2.6	0
Sum Canada						**157.9–179.4**		**38.1**	**78.5**$^{+}$
Greenland									
North coast						6.7	10–200	1.6	0
Zackenberg	514	1994–2005	10	0		0.015–0.13	29–253		100
East coast						19.3	50–200	4.7	0
Sermilik	10	1972–2005	4 + part of season			0.01	1000		90
Greenland Ice Sheet runoff						40–60	?	9.7	
Calving						50–500		12.1	0
Sum to Arctic Ocean and Greenland Sea						**116–586**		**28.0**	**< 1**$^{+}$
Svalbard	36 598					**16**	**83–2900**	**3.9**	**20?**$^{+}$
Other Arctic islands	~140 000					**12–50**	**83–359**	**2.9**	**0**$^{+}$

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Table 1 – *continued*

River/station	Area (km^2)	Period	Years	Gaps	P_s (kg s^{-1})	Sediment load (10^6 t yr^{-1})	Specific sediment delivery (t km^{-2} yr^{-1})	Contribution to Arctic Ocean (%)*	Measured (%)
Norway Mainland									
Glacial areas	2806					1.05	22–1577		
Forest etc.	148 140					0.43	1.9–2.9		
Mountain	152 819					0.76	5		
Agricultural	187 433					0.16–0.19	37–155		
Sum						**2.58**		**0.6**	**50?**$^{+}$
Iceland									
North coast						**18.1**	**10–20 000**	**4.4**	**90**$^{+}$
Russia									
Severnaya Dvina at Ust-Pinega	348 000	1950–1988	39	24	96.2	3.0	8.7	0.7	100
Pechora at Ust-Tsilma	248 000	1951–1988	38	28	232	7.3	29.5	1.8	100
Ob at Salekhard	2430 000	1938–1996	59	8	482	15.2	6.3	3.7	100
Yenisei at Igarka	2440 000	1941–2000	60	22	177	5.6	2.3	1.4	100
Lena at Tabaga	897 000	1942–1992	51	1	245	7.7	8.6	1.9	100
Yana at Verkhoyansk	45 300	1936–1992	45	8	49.9	1.6	34.7	0.4	100
Indigirka at Vorontsovo	305 000	1937–1986	31	2	381	12.0	39.4	2.9	100
Kolyma at Ust-Srednakan	99 400	1936–1988	48	0	87.1	2.7	27.6	0.7	100
Other areas	2833 000					17.7	6.2	4.3	0
Sum						**72.8**		**17.6**	**75.7**$^{+}$
Total min. to Arctic Ocean +Greeland Sea						**324.4**		**87.9**	**56.3**$^{++}$
Total min. incl min. calving						**374.5**		**100**	**49.5**$^{++}$
Total max. to Arctic Ocean +Greenland Sea						**383.9**		**107**	**46.2**$^{++}$
Total max. incl max. calving						**883.9**		**228**	**21.7**$^{++}$

*Contribution in per cent of total minimum including minimum calving. $^{+}$Per cent of area contribution. $^{++}$Per cent measured of actual total sediment load

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As emphasised above, any attempt to assess the total transport of sediment to the Arctic Ocean depends heavily on the availability of measurements and the considerable uncertainties in extrapolating those measurements to ungauged areas. The results presented above can therefore only be viewed as a tentative and provisional estimate. Further work is required to assess the accuracy and precision of the available data and the problems of integrating data collected over different periods and which are likely to show trends as a result of the impact of human activities, such as dam building and catchment disturbance. In addition, it should be recognised that the data and results presented relate almost exclusively to the suspended load component of the total sediment load. It is traditionally assumed that the suspended load dominates the total load, but this requires explicit confirmation. Furthermore, it must also be recognised that any attempt to assess land–ocean fluxes needs to take account of the point along the river-estuary/delta–coast–ocean continuum for which the measured data are available. Much of the sediment load recorded as passing a measuring station in the lower reaches of a river system may be deposited further down the river, in the estuary or delta, or in the coastal sea, before reaching the ocean. The sediment load ultimately reaching the ocean is, therefore, likely to be significantly less than the estimates proposed above, which relate primarily to sediment fluxes in the lower reaches of the rivers draining to the ocean.

Future research needs

Both the number of monitoring stations in Arctic areas and the sampling frequency employed at those stations are relatively low. As a result the estimates of the sediment flux to the Arctic Ocean from several areas involve considerable uncertainty. Compared to its area and length of coastline bordering the Arctic Ocean and the Greenland Sea, the monitoring network in Greenland is very sparse. In particular, there is a lack of information from major basins draining the Greenland Ice Sheet. The presence of glaciers, in particular surging glaciers or ice-streams, can result in very high sediment transport rates for relatively short periods, which could lead to overestimation if the length of the surge cycle is not known. Even in areas where glaciers are less important, extreme events of short duration can produce sediment loads larger than those associated with several years of ‘normal’ transport.

The need for accurate information must be carefully assessed. It is not necessarily the same in all areas. When decided, the appropriate number of monitoring stations and the appropriate sampling frequency must be established. In order to avoid the high cost of an extensive network, a strategy based on the monitoring of representative areas could be adopted. Selection of representative areas could be based on landscape analysis using GIS. Results from research catchments can also be upscaled to larger areas using DEMs and distributed hydrological modelling. More monitoring of sediment transport from surging glaciers and ice streams and detailed investigation of the associated erosion processes is needed. However, the mechanisms resulting in very large sediment transport rates from other Arctic areas should also be given more attention. The potential importance of iceberg rafting and the sediment content of icebergs again require further investigation.

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