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# Changing sediment supply in Arctic rivers

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**Abstract** Changes in Arctic rivers are integrated signals of changing hydrological conditions in their drainage areas. Water and sediment fluxes are assessed for 50 high-latitude rivers (>55ºN) under conditions of rapid Arctic warming. Controlling parameters have been analysed from regional data sets, i.e. GTOPO30 DEM, UNDel climate grids, combined monthly discharge data, WGI glacier data and a circum-arctic map of permafrost. Based on derived parameters, the BQARTmodel calculates suspended sediment loads. High-latitude river systems contribute 4.86 × $10^{12}$ $m^3/s$ of water to the ocean annually. Calculated suspended sediment fluxes are 347 MT/year for the Arctic Ocean, and 88 and 53 MT/year for the Pacific and Atlantic oceans, respectively. Changes in outflux of water and sediment load are spatially variable between the late 1970s and early 1990s. Large Eurasian and Pacific rivers show pronounced flux increase, whereas the MacKenzie River basin is stable. Validation of these model predictions is typically limited by sparse observations. Strong nonlinear response of sediment flux to environmental changes is recognized. Small rivers are much more sensitive to changes in glacial area and extreme events affecting loads, whereas sinks dampen these signals in continental-scale basins.

**Key words** rivers; modelling; Arctic; sediment; extreme events; scaling

## INTRODUCTION

Climate changes more rapidly in Arctic regions compared to global changes, and scenario modelling of future climate predicts the greatest changes in high-latitude regions (Serreze, 2000). Most likely, hydrological balances are also changing at present, although there is notorious uncertainty in assessing Arctic-wide precipitation (Holmes *et al*., 2002; Peterson *et al*., 2002). Rivers are seen as an integrator of basin-wide changes in hydrological conditions. Moreover, rivers link the terrestrial domain and the Arctic Ocean, propagating climate signals over the land–ocean boundary. Modern Arctic rivers are unique sedimentary systems since they are controlled by a number of processes that are specific to high-latitude and cold-climate regions. Arctic rivers display a strong seasonality of river discharge due to a short melting season. Most river systems are frozen approx. six months of the year and have strong peak runoff limited to two months early in the season. River basins are commonly more extensively glaciated in the high-latitude regions, which may result in exceptionally high sediment yields (as shown for a number of small Nordic catchments by Hallett *et al*., 1996). Another important aspect of these systems is that ice- or moraine-dammed lakes can catastrophically drain favouring extreme events and river flooding. Mermild *et al*. (2006) observed a single event in northern Greenland which transported the equivalent of three years of "normal" annual sediment in a few days.

This paper aims at giving an overview of circum-arctic rivers; we will show how they are unique compared to other regions, and discuss how they are responding to current changes in terms of water and sediment discharge.

## METHODOLOGY

### River basin characteristics

We quantified controlling parameters for 50 Arctic rivers basins (Fig. 1): first-order topographical and climatic characteristics, extent of glaciation and permafrost presence. The selection includes rivers draining to the Arctic Ocean, the Pacific Ocean, as well as the Atlantic Ocean. River mouths are located over 55° north and all basins are over 5000 $km^2$. To delineate river drainage basins and topographical parameters, a digital elevation model (GTOPO30) at 30 arc seconds horizontal resolution and ~30 m vertical accuracy has been analysed (USGS, 1999). Parameters that have

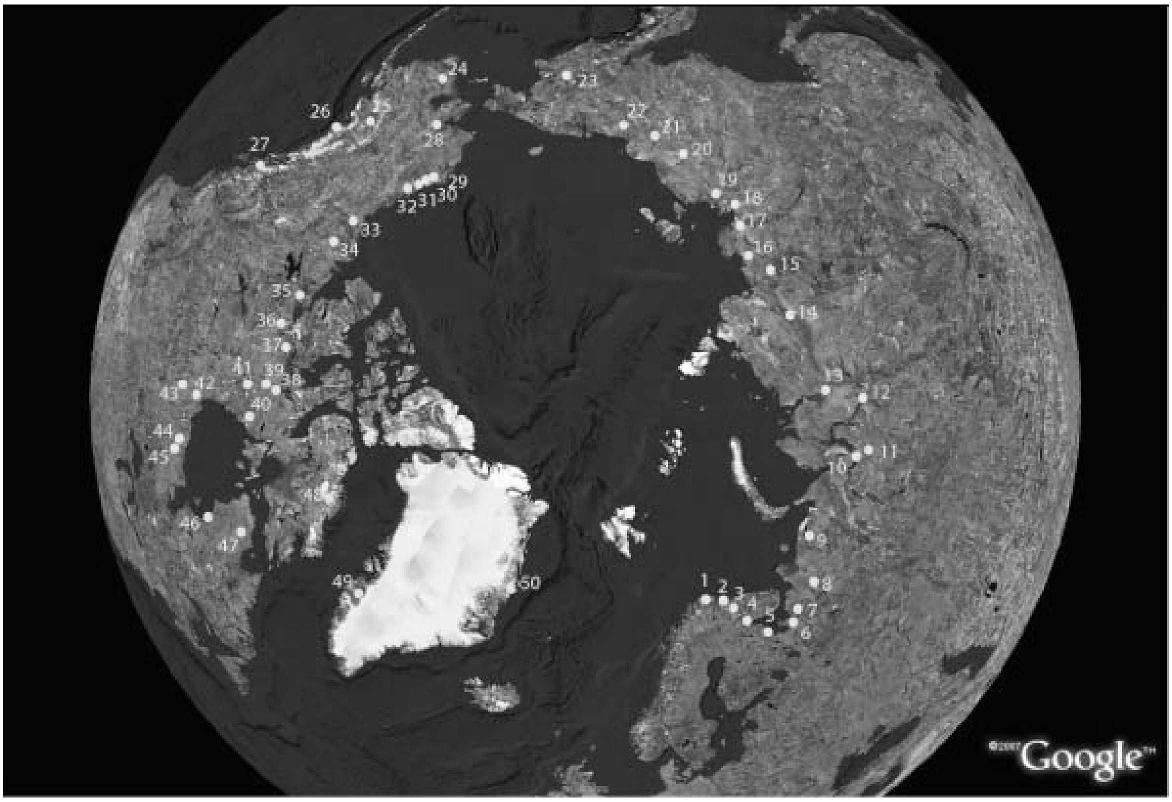

**Fig. 1** Overview of studied river systems. 1. Tana, 2. Patso-Yoki, 3. Tuloma, 4. Kovda, 5. Kem, 6. Onega, 7. Severnaya-Dvina, 8. Mezen, 9.Pechora, 10. Ob, 11. Nadym, 12. Taz-Sidorovk, 13. Yenisei, 14. Khatanga, 15. Anabar, 16. Olenek, 17. Lena, 18. Omoloy, 19. Yana, 20. Yndigirka, 21. Alazeja, 22. Kolyma, 23. Tanurer/Anadyr, 24. Yukon, 25. Susitna, 26. Copper, 27. Stikine, 28. Kobuk, 29. Ikpikpuk, 30. Colville, 31. Kuparuk, 32. Sagavanirktok, 33. MacKenzie, 34. Anderson, 35. Coppermine, 36. Burnside, 37. Ellice, 38. Hayes, 39. Back, 40. Lorrillard, 41. Thelon/Baker, 42. Churchill, 43. Nelson, 44. Severn, 45. Winisk, 46. Nastapoca, 47. Arnaud, 48. Clyde fjord, 49. Kangerlussuaq fjord, 50. Zackenberg fjord.

been derived for each drainage basin are total area, $A$ (in km$^2$), relief, $R$ (in m), and the geographic location of the river mouth (latitude and longitude in degrees). Drainage basin boundaries for each individual basin comprise the main framework for subsequent GIS data analysis.

Monthly mean temperature and precipitation data for 1902–2002 have been assembled by the University of Delaware, USA, on a 0.5 by 0.5 degrees grid, above 45° North, interpolating between at least 6054 meteorological stations (Willmott & Rawlins, 1999; CCR, 2005). The circum-arctic permafrost and ground ice map (Brown, 1998) depicts the distribution and properties of permafrost in the Northern Hemisphere (20–90°N). Permafrost extent is estimated in percent of the basin area (90–100%, 50–90%, 10–50%, <10%, and no permafrost).

The World Glacier Inventory (WGI) contains information for over 67 000 glaciers throughout the world (NSIDC, 2007). Parameters within the glacier inventory include geographic location, area, length, orientation, elevation, and classification of morphological type, and moraines. The inventory entries are based on a single observation in time and should be viewed as a "snapshot" of the glacier at that time. We overlay this data set with the previously described drainage basin boundary data to derive the combined glacier area, $A_g$, in km$^2$ for each drainage basin. Damming impacts river sediment loads worldwide nowadays. Sediment trapped in reservoirs comprises up to 26% of the total load otherwise delivered to the global ocean (Vörösmarty *et al.*, 2003; Syvitski *et al.*, 2005). The World Register of Dams is used to calculate trapping efficiency for each individual basin based on reservoir volume and its position in the drainage basin (Vörösmarty *et al.*, 2003).

### Water discharge

Large areas of the Arctic have not been monitored for river flow (Prowse & Flegg, 2000). A combination of three databases provides a temporal record of monthly river water discharge for this study:

(1) USGS surface water database for the Alaskan Rivers http://waterdata.usgs.gov/usa/nwis/sw.
(2) HYDAT for Canadian Arctic Rivers maintained by the Water Survey of Canada. http://www.wsc.ec.gc.ca/hydat/H2O/index_e.cfm.
(3) R-Arctic for the Eurasian and Asian rivers compiled by Water Systems Analysis Group, University of New Hampshire, USA, http://www.r-arcticnet.sr.unh.edu/v3.0/.

Monthly water discharges and their statistical distributions have been determined for individual rivers over the length of available record. The average record length is 32 years. In rare cases the discharge records span the entire 20th century, for example the Severnaya-Dvina River in the Russian Federation has been gauged for over 111 years. The spatial coverage of the gauging stations Arctic-wide was the largest between 1976 and 1990, when about 71% of the total area contributing to the Arctic Ocean was being monitored. Typical uncertainty in total annual discharge measurements is in the range of 1.5–3.5% (Shiklomanov *et al.*, 2006).

### Suspended sediment load

Suspended sediment load is typically much more sparsely measured than water discharge, so that we rely on modelling of sediment fluxes to make Arctic-wide estimates of sediment flux to the ocean. Suspended sediment load is modelled following the BQART model formulated by Syvitski & Milliman (2007). The model predicts sediment load, $Q_s$, based on water discharge, $Q$, in $m^3/s$, and drainage area, $A$, relief, $R$, and temperature, $T$:

$$Q_s = 2\,w B Q^{0.31} A^{0.5} R \quad \text{for } T < 2°\text{C} \tag{1}$$

where $w = 0.02$ for units of kg/s, or $w = 0.0006$ for units of MT/year, $Q$ is in $km^3$/year, $A$ is in $km^2$, $R$ is in km, and $T$ is in °C. The $B$ term is written as:

$$B = I L (1 - T_E) E_h \tag{2}$$

where $I$ is the glacier erosion factor defined as $I = (1 + 0.09A_g)$, where $A_g$ is the area of the drainage basin as a percentage of the total drainage area; $T_E$ is the trapping efficiency of lakes and manmade reservoirs, such that $(1 - T_E) \leq 1$. In the Arctic region $E_h$ is human impact that is determined to be of no significance in terms of influencing sediment supply. The basin-averaged lithology factor ($L$) is defined to reflect erodibility of the basin; for details on the defined lithology classes we refer to Syvitski & Milliman (2007) and Syvitski & Kettner (this volume). We use sediment load data reported by Holmes *et al.* (2002) and Hasholt *et al.* (2006) for validation of the model predictions.

## UNIQUE CHARACTERISTICS OF HIGH-LATITUDE BASINS

Fifty selected rivers span a large range of drainage basins. A few systems are of continental scale, e.g. the Ob River and Lena River comprise over 2 million $km^2$, whereas we also study small fjordhead river systems, such as the Tana River in Norway with a drainage basin of 14 000 $km^2$. Basin area affected by permafrost is highly variable between basins, averaging 78% overall. Glacier cover also varies a great deal with exceptionally high glacier areas in Arctic Alaskan basins. All basins have low annual mean temperatures, averaging –7ºC. We here show that this group of basins does have unique aspects, both in their respective numbers of water and suspended sediment load, as well as in the effect of the short seasons.

We calculate that Northern Hemisphere high-latitude systems contribute $4.86 \times 10^{12}$ $m^3/s$ of water to the Arctic, Pacific and Atlantic oceans on an annual basis. This is about 13% of the total freshwater pulse to the ocean as calculated by Syvitski & Kettner (2008, this volume). Table 1 shows the distribution of the mean annual discharge to the different receiving ocean basins. Our selected 50 high-latitude rivers comprise about 70% of this total water budget. The 10 largest contributors are all included in our database and are located throughout the Arctic region. They include large Eurasian systems, i.e. Ob River, Yenisei River, Lena River, Kolyma River, Khatanga River and the Dvina River all draining into the Arctic Basin, the Mackenzie River draining from the Canadian Shield into the Arctic Basin, the Nelson River draining into Hudson Bay and eventually in the Atlantic Ocean, and the Yukon River draining into the Pacific Ocean. The fact that these systems are located far apart inherently means the rivers have a vast spectrum of hinterland conditions.

Combined calculated sediment fluxes are 347 MT/year for the Arctic Ocean, and 88 MT/year and 53 MT/year, respectively for the high-latitude systems pulse to the Pacific and Atlantic oceans. The estimate for the Arctic Ocean corresponds to the lower estimates of flux (324 MT/year) to the Arctic Ocean of Hasholt *et al.* (2005), who extrapolate from sparse observations. Their highest estimate is about 884 MT/year, but the high end of this estimate includes supposition of tremendous pulses of sediment coming off the calving Greenland Ice Sheet.

**Table 1** High-latitude water discharge (*Q*) using combined observations and UNH WBM/WTM model simulations (Syvitski *et al.*, 2005); and predictions of suspended sediment load (*Qs*) for modern systems, using Syvitski & Milliman (2007) observations combined with BQART model predictions.

| Receiving ocean | $A$ (km$^2$) | $Q$ (m$^3$/year) | $Q_s$ (Mt/year) |
|---|---|---|---|
| Arctic | $1.55 \times 10^7$ | $3.12 \times 10^{12}$ | 346.6 |
| Pacific | $2.17 \times 10^6$ | $7.24 \times 10^{11}$ | 87.2 |
| Atlantic | $4.23 \times 10^6$ | $1.02 \times 10^{12}$ | 52.93 |

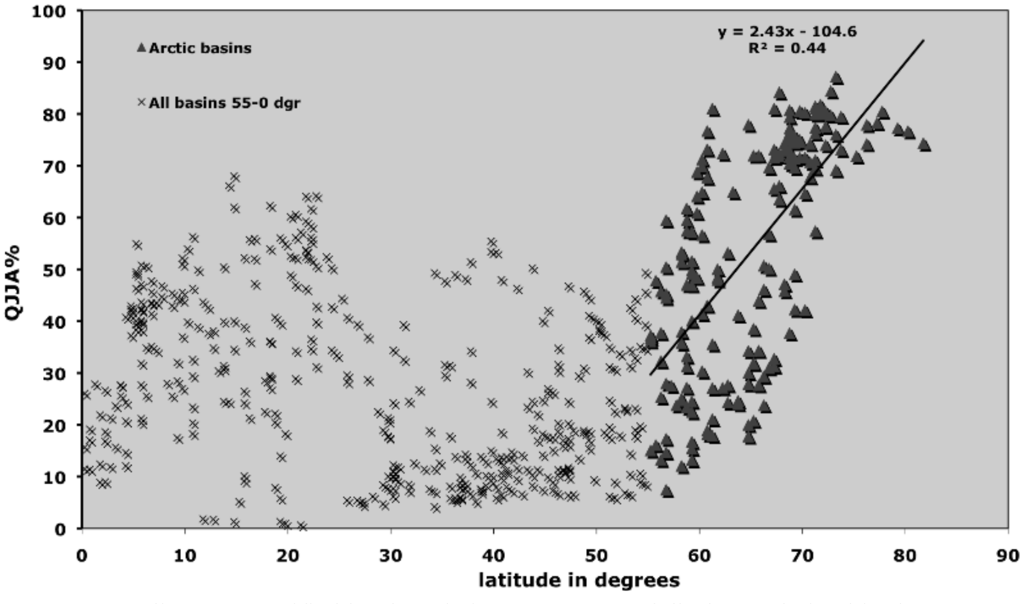

**Fig. 2** Seasonality, as quantified by the relative percentage of discharge drained in the summer months as a function of latitude. High-latitude rivers display a strong trend to increasing seasonality with increasing latitude ($y = 2.43x - 105$ with a regression coefficient of 0.44).

High-latitude rivers (>55°N) stand out if we compare them as a group to rivers of lower latitude (<55°N) (global data presented by Syvitski *et al.*, 2005; Syvitski & Kettner, this volume). Yearly water runoff is relatively lower, about 57% the worldwide average runoff, because the region includes large areas of polar desert. Similarly, annual sediment yield is relatively low for the high-latitude region as a whole, about 37% of the worldwide average yield. Naturally, there is a large range between the predictions of sediment yield for the individual river systems. For example, the Copper River stands out as a basin that has relatively high sediment yield (71 T $\text{year}^{-1}$ $\text{km}^{-2}$), whereas the Nelson River drains presently only 2 T $\text{year}^{-1}$ $\text{km}^{-2}$.

It is not unexpected that Arctic Rivers have a strong seasonality. We quantified "seasonality" as the relative percentage of river discharge that is drained in the months of June, July and August exclusively. Figure 2 shows that seasonality indeed strongly depends on latitude.

The majority of the studied Arctic basins have modest glaciated areas when compared to the total basin area. Outliers are the Copper River and Stikine River in Alaska that both have a significant glacial area. Figure 3 plots sediment yield for all basins as a function of the glacier impact factor. There is no systematic trend, but it has to be noted that the two highest yield basins are the most glaciated basins, which corroborates findings of a range of studies summarized by Hallett (1996).

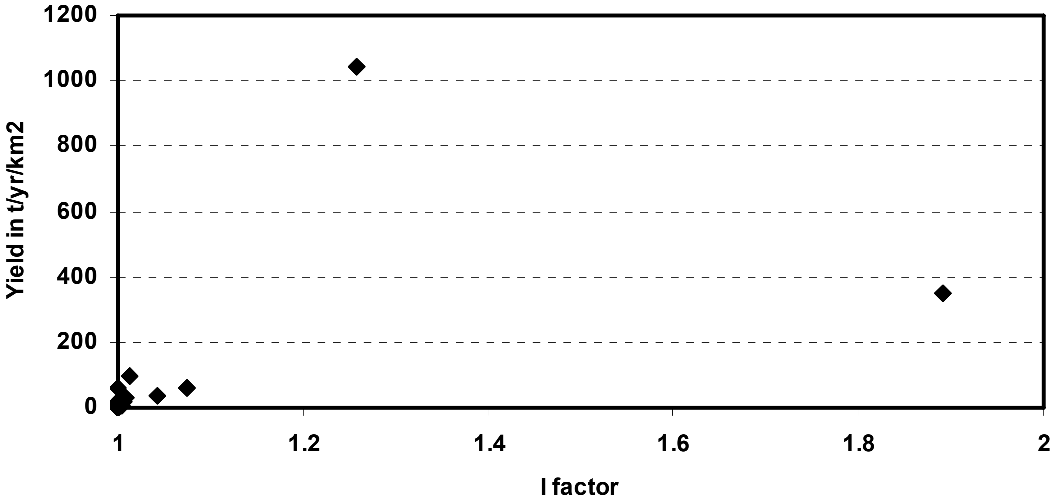

**Fig. 3** Sediment yield for 50 selected Arctic river basins as a function of glacier factor *I* (see equation (2)). The majority of the basins have too low relative glacier coverage to strongly impact the sediment yield; exceptions point to strong impact of glaciers. Two outliers are both located in Alaska; the Copper River (almost 2000 $\text{km}^2$ of its basin is glaciated, *I* factor = 1.25) and Stikine River (over 5000 $\text{km}^2$ of its basin is glaciated, *I* factor = 1.89).

## CHANGES IN ARCTIC RIVERS

Arctic rivers are presently changing under the influence of Arctic-wide warming. We expanded the database Peterson *et al.*, (2002) used to show that discharge of six large Eurasian Arctic rivers increased from 1936 to 1999. The Severnaya Dvina, Pechora, Ob, Yenisei, Lena and Kolyma rivers combined increased 7% in total annual water discharge. Additional data corroborates this pattern for other rivers, but also show that some river systems experienced relatively small changes.

Changes in monthly discharge derived from observational data between the late 1970s and early 1990s (Fig. 4(a) and (b)) show doubling of melt- and summer discharge in the Yukon Basin, whereas relatively minor changes are observed in the MacKenzie River.

The IPCC projects increases of runoff compared to 1900–1970 averages in Arctic regions for the middle of the 21st century under a relatively modest scenario (A1B). The suite of models shows Siberia and Pacific Alaska being impacted strongly, with runoff increasing by 20–40%, whereas changes are more modest in the Canadian Arctic. This reflects trends observed in present-day data.

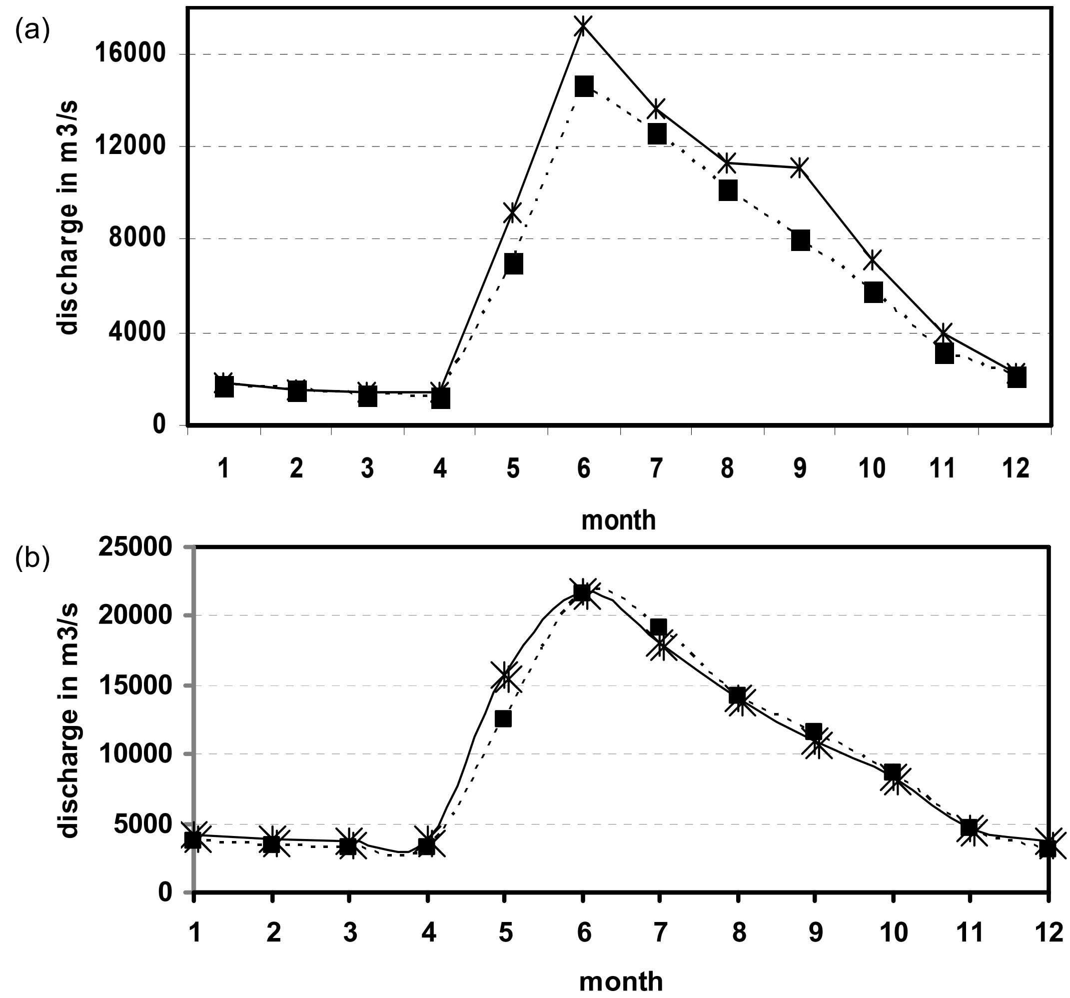

**Fig. 4** (a) Water discharge for the Yukon River, between the late 1970s (squares) and early 1990s (stars). (b) Water discharge for MacKenzie River between late 1970s (squares) and early 1990s (stars). Relatively few changes in water flux are detected.

Suspended sediment load is modelled to depend partly on water discharge, $Q$ (equation (1)). Consequently, rivers with increasing discharge over time will have increased transport capacity to carry additional suspended sediment load. However, $Q_s$ changes solely from $Q$ increases will be suppressed as compared to water discharge changes. For example, the Yukon River load increased (Fig. 4(a)) 5% for the peak runoff month, whereas water discharge increased 17%.

## DISCUSSION

Assessment of Arctic river system changes is hampered by data sparseness as well as high spatial and temporal variability. Using a database which includes all the largest Arctic river systems, as well as a representative selection of medium- and small-scale river basins, allows a more detailed analysis of controlling factors and impacts over a variety of scales. Two major processes appear to be the most scale-dependent: glaciation and outbursts leading to extreme events.

The importance of glaciers supplying sediment strongly scales with river drainage basin area; relatively small basins have proportionally larger glaciated areas. It is interesting that glacial melt within Arctic river basins would affect sediment load in opposite directions over different time scales; in the short-term we may expect to see a slight increase of sediment loads. However, if glacial extents decrease significantly, sediment loads are predicted to be eventually decreasing.

Available data of worldwide glacial retreat as well as of changes of sediment loads do not allow more precise quantitative assessments of this effect.

Another scaling issue is that small basins are most impacted by extreme discharge events, e.g. frequent lake outbursts due to rapid glacier melt, whereas the effect of local events are dampened in the largest Arctic basins. We mapped a 2007 glacier lake outburst in Kangerlussuaq fjordhead, west Greenland, which drains a basin of ~8000 km$^2$. This event discharged approx. 38 tons of water in just 10–12 hours. Estimated concentrations of this flood were exceptionally high at 9 g/L (Hasholt & Mernild, 2008, personal communication). If this event is compared to annual total loads we find that 2% of the total annual load was flushed out in 10–12 hours. It is obvious that such events would not scale linearly with basin size, but be dependent on both sediment availability and the presence of sediment sinks along the river course.

It is of vital importance to better understand such scaling relations to assess individual Arctic river system responses to changes in their boundary conditions.

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