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Suspended sediment in a high-Arctic river: An appraisal of flux estimation methods

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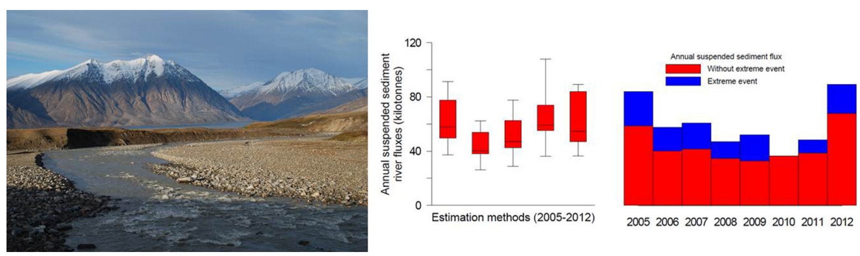
HIGHLIGHTS

- Increased melt water and potentially higher transport of suspended sediment in the Arctic rivers is expected due to climate warming.
- The high diurnal and seasonal variations of Arctic rivers call for a reassessment of sampling and estimation procedures.
- Choice of estimation method, sampling strategy and sampling frequency significantly influences estimated fluxes.
- In the high-Arctic Zackenberg River, sampling can be reduced to every fourth day.
- Daily variations must be taken into account and events sampled high-frequently.

GRAPHICAL ABSTRACT



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ABSTRACT

Quantifying fluxes of water, sediment and dissolved compounds through Arctic rivers is important for linking the glacial, terrestrial and marine ecosystems and to quantify the impact of a warming climate. The quantification of fluxes is not trivial. This study uses a 8-years data set (2005–2012) of daily measurements from the high-Artic Zackenberg River in Northeast Greenland to estimate annual suspended sediment fluxes based on four commonly used methods: M1) is the discharge weighted mean and uses direct measurements, while M2-M4) are one uncorrected and two bias corrected rating curves extrapolating a continuous concentration trace from measured values. All methods are tested on complete and reduced datasets. The average annual runoff in the period 2005–2012 was 190 ± 25 mio · $m^3\ y^{-1}$. The different estimation methods gave a range of average annual suspended sediment fluxes between 43,000 ± 10,000 t y^{-1} and 61,000 ± 16,000 t y^{-1}. Extreme events with high discharges had a mean duration of 1 day. The average suspended sediment flux during extreme events was 17,000 ± 5000 t y^{-1}, which constitutes a year-to-year variation of 20–37% of the total annual flux. The most accurate sampling strategy was bi-daily sampling together with a sampling frequency of 2 h during extreme events. The most consistent estimation method was an uncorrected rating curve of bi-daily measurements (M2), combined with a linear interpolation of extreme event fluxes. Sampling can be reduced to every fourth day, with both method-agreements and accuracies <±10%, using 7 year averages. The specific annual method-agreements were <±10% for all years and the specific annual accuracies <±20% for 6 years out of 7. The rating curves were

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less sensitive to day-to-day variations in the measured suspended sediment concentrations. The discharge weighted mean was not recommended in the high-Arctic Zackenberg River, unless sampling was done bi-daily, every day and events sampled high-frequently.

1. Introduction

Climate changes in the Arctic are more pronounced than elsewhere (IPCC, 2013). Arctic rivers transport both solid and dissolved material from glaciers and terrestrial ecosystems to coastal and marine ecosystems (McClelland et al., 2014; Syvitski, 2002), and the fluvial runoff and sediment fluxes of Arctic rivers are expected to increase in the near future due to climate warming (Overeem and Syvitski, 2010; Shiklomanov et al., 2007; Syvitski, 2002). It has been shown through stochastic modelling that sediment fluxes in Arctic rivers increase with increasing temperature and discharge. The magnitude of the increase was 22% with a warming of 2 °C, and 10% with an increase in runoff of 20% (Syvitski, 2002). From a Greenland perspective, the fresh water input from melting ice caps and the Greenland Ice sheet is considered to have global impact in relation to future sea level changes (Straneo and Heimbach, 2013). Also, climate warming in the Arctic is expected to change landscape stability through permafrost degradation, thus altering sediment availability (Favaro and Lamoureux, 2015; Hilton et al., 2015). The melting glaciers and the warming-induced thawing of permafrost and changing snow coverage patterns in the proglacial and fluvial drainage basins alter the water balance and associated runoff. This will potentially intensify erosion and the transport of sediments and nutrients (Favaro and Lamoureux, 2015; Syvitski, 2002; Søndergaard et al., 2015) and introduce changes in the seasonal variation due to variation in peak snowmelt and availability of erosive sediments. The challenge to monitor and quantify these potential changes in the transport of suspended sediment in the Arctic rivers makes consistent estimation methods and sampling strategies paramount. Monitoring glacier-fed Arctic rivers, especially in mountainous areas, poses a particular challenge due to characteristic variability in flow and concentrations during the ablation period (Bogen and Bønsnes, 2003; Singh et al., 2005). The discharge of glacier-fed rivers strongly fluctuates, both on a diurnal and a seasonal basis, with most rivers in the Arctic being only active in a number of months between river break-up in spring and freezing in fall. The daily variations in solar radiation and air temperature during the ablation period cause variations in the snow and glacier melt in the drainage basin, which directly impact the discharge and long periods of cloud cover dampens the temporal variation of the hydrologic regime (Syvitski, 2002). The regular cycles are often interrupted by days of intense snow melt, rain- or snowfall, or the collapse of ice-dammed lakes, so-called Glacial Lakes Outburst Floods (GLOFs) (Beylich and Gintz, 2004; Knudsen et al., 2007; Overeem and Syvitski, 2008; Overeem and Syvitski, 2010). Sediment fluxes are influenced by the discharges related to cycles and extreme events, but not always directly related to discharge (Meybeck and Moatar, 2012). In permafrost regions, increased sediment input due to permafrost collapses or landslides in the drainage area can cause sudden very high suspended sediment concentrations (SSC) in the river, which are not necessarily correlated to the discharge. The amount of sediment available to erosion is variable (Collins, 1979) and dependent on e.g. the progressive soil thaw during summer, snow and ice cover in the river bed and banks, the sedimentology of the exposed river banks, the varying surface area of the stream flow system, and on the varying path and energy of the water stream flow during events (Beylich and Gintz, 2004; Favaro and Lamoureux, 2014).

Current sampling strategies and estimation methods are largely discussed from a non-Arctic point of view (Coynel et al., 2004; Skarbøvik et al., 2012), despite the unique nature of arctic rivers in small, mountainous catchments being strongly influenced by daily and seasonal patterns and sudden extreme events. Existing studies show that: 1) smaller, flashier watersheds with high temporal variation in suspended sediment concentrations require more frequent samplings in order to provide accurate estimates of seasonal annual suspended sediment fluxes, regardless of estimation method (Horowitz et al., 2008; Moatar et al., 2006; Raymond et al., 2014); 2) reliable river flux estimations require long time series covering a range of hydrological situations (Coynel et al., 2004; Horowitz, 2003; Horowitz, 2008); 3) the estimation methods show contrasting results between watersheds in temperate rivers, in general showing decreasing accuracy with decreasing basin scale and decreasing sampling frequency, with the smallest basins having the highest sensitivity (Cohn, 1995; Coynel et al., 2004; Horowitz 2008; Moatar et al., 2006; Phillips et al., 1999); 4) there is a lack of Arctic studies on the potential divergence between estimation methods. Therefore, there is an urgent need for providing recommendations for future sampling strategies and estimation methods relevant for Arctic rivers with characteristic temporal variations. To our knowledge, there are only a limited number of Arctic rivers with intensively measured discharge and sediment concentrations, where daily and seasonal cycles and extreme events are monitored over years. The present study uses a unique 8-years data set (2005–2012) of daily discharges and suspended sediment concentrations of the high-Arctic Zackenberg River in Northeast Greenland. The measurements are performed in a cross-section of the river close to its delta in order to catch almost all the runoff from the catchment. The sampling point is ca. 1 km from the tidally influenced delta plain. The estimation of annual suspended sediment fluxes is based on commonly used methods. The aims of the study are to 1) quantify the annual suspended sediment fluxes; 2) evaluate the influence of the estimation method and sampling strategy and frequency on the annual rates; and 3) explore the importance of cycles and extreme events on estimations of annual fluxes.

2. Methods

2.1. Study site

The drainage basin of the Zackenberg River located in Northeast Greenland (74°28′N, 20°34′W) is 514 km^2, of which 106 km^2 is covered by glaciers and 51 km^2 by lakes (Jensen et al., 2013; Rasch et al., 2000). The largest contribution of water to the Zackenberg River is the A.P. Olsen Glacier, which is not connected to the Greenland Ice Sheet. The altitude varies between 0 m a.s.l. and 1469 m a.s.l. (Fig. 1). The geology of the area is dominated by Caledonian gneissic and granitic bedrock (422 km^2) in the west and by Cretaceous and Tertiary sedimentary rocks and basalt (90 km^2) in the east (Koch and Haller, 1971). The two settings are separated by a fault running through the two valleys: the Lindeman valley and the Zackenberg valley (Fig. 1). Vegetated areas are mostly found below 300 m a.s.l. and in the lower areas near Store Sødal (Søndergaard et al., 2015). The higher grounds of the basin are dominated by barren rock and loose sediments up to boulder size (Palmtag et al., 2015; Fig. 1). The Zackenberg valley is a wide lowland valley with Quaternary non-calcareous sediments occurring as tills in various moraines and as marine/deltaic deposits in raised marine deltas in areas lower than 70 m a.s.l. (Mernild et al., 2007) with significant periglacial activity and continuous permafrost (Christiansen et al., 2008). The mean tidal range is 1 m, and the influence of the tides is restricted to the delta plain.