# Glacial erosion and sediment transport in the Mittivakkat Glacier catchment, Ammassalik Island, southeast Greenland, 2005

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**Abstract** A station for monitoring suspended sediment concentration with high time resolution was developed and located near the outlet from the Mittivakkat Glacier in order to monitor "true" glacial erosion. Sediment transport at 10 minute intervals for a 64-day period of the 2005 melt season was determined for the Mittivakkat Glacier catchment, southeast Greenland. The total transport for the whole period was 17 800 t based on measurements with an OBS3 (optical backscatter) sensor and 17 300 t with a Partech IR500 (infrared transmissometer), with maximum transport values of 25 and 24 t 10-min$^{-1}$, respectively. The results confirm earlier measurements of specific transport of more than 1000 t km$^{-2}$ year$^{-1}$ from the Mittivakkat Glacier. Comparison with concentrations obtained from manual suspended sediment samples from a station near the outlet to the sea, confirm results based on earlier Caesium-137 inventories indicating that sediment is trapped in the proglacial valley between the glacier and the sea. The material produced from glacial erosion is mainly released in late July–August when the glacier drainage system is fully developed and enough melt water is available for transport.

**Key words** Ammassalik Island; glacial erosion; Greenland; sediment transport

## INTRODUCTION

Glaciations have occurred several times during the geological history of the Earth. The latest (Weichselian) glaciation has formed major parts of the Northern Hemisphere by erosion and deposition of large amounts of sediment as outwash plains, as deltas in lakes and in the ocean. Information about recent glacial erosion and sediment transport is therefore important for the understanding of the development of landforms and the time span needed for them to develop. Today, glacial erosion is found in connection with local glaciers in mountainous areas, in high arctic areas, and along the margin of the Greenland Ice Sheet. These areas are very extensively monitored (Hasholt *et al.*, 2005); results indicate that because of the presence of glacial erosion they can contribute significantly to the present day transport of sediment to the ocean.

Glacial erosion is the erosion form that results in the largest specific sediment loads (e.g. Gurnell & Clark, 1987; Hallet *et al.*, 1996). Specific loads exceeding 1000 t km$^{-2}$ year$^{-1}$ are often observed. Information about sediment transport and erosion from the mostly uninhabited part of the High Arctic areas and Greenland is very sparse (Hasholt, 1996). Most of the investigations of glacial erosion and sediment transport in these areas have been carried out as part of basic research programmes (e.g. Hasholt, 1992; Gilbert *et al.*, 2002; Desloges *et al.*, 2002). The sparse population and the limited economic activity are the most important causes of the insufficient monitoring; other important causes are the logistical costs of operating, the harsh climatic conditions that hinder fieldwork and the operation of standard recording instruments. Most of the investigations are therefore carried out in summer time in connection with field trips of durations shorter than one month. Recent investigations from the field station Zackenberg, northeast Greenland, which is manned throughout the melt season, indicate that single events can deliver as much sediment as several "normal" years (Rasch *et al*., 2000; Mernild *et al*., 2005). This stresses the importance of full season and long-term monitoring in areas with glacial erosion. Although the runoff period (May–September) is short compared to other climatic zones, the presence of personnel at remote locations in this environment is often not possible—a methodology taking this into account has therefore to be developed. A problem for automatic recording is that in areas with glacial erosion, the location of gauging stations is very difficult. One reason is the glacial hydrological regime (Pardé, 1955) which implicates large variations in stage, in particular in cases where glacial outburst is possible. Furthermore, the location of the glacier outlet may change over time and the large amounts of sediment transported results in development of a braided river system downstream of the glacier. Monitoring along braided rivers is extremely difficult, because it is hard to find stable objects (single boulders or rock outcrops) where equipment can be placed safely in this environment. Even if a stable position is found, the movement of the channels in the braided river system can cause the gauging station to be left at dry land after a short period. All together these constraints add to the operating costs and make a thorough knowledge of this special environment mandatory.

Previous investigations (Hasholt, 1976, 1992, 1994) have recorded specific sediment transport rates of ~1000 t $km^{-2}$ $year^{-1}$. The first investigation (Hasholt, 1976) demonstrated that transport at the discharge gauging station consisted of about 20% bed load and 80% suspended- and wash load while at a rapids further downstream all load was in suspension. Investigations of the coastal evolution at the Mittivakkat Glacier catchment outlet indicated that the coast was degrading. A possible explanation was a decreased amount of sediment delivered to the delta area (Nielsen, 1994). This was partly confirmed by Caesium-137 inventories in the system by Hasholt & Walling (1992) and Hasholt *et al*. (2000). Measuring the transport of cobble size material using tracing of cobbles with built in radio transmitters showed that such particles could only pass the low slope part of the braided river system when the discharge is greater than 75 $m^3$ $s^{-1}$ (Busskamp & Hasholt, 1996).

Because previous investigations aimed at monitoring the sediment transport to the sea, the monitoring station was located as close to the outlet as possible. However, results were also used as an estimation of glacial erosion, although investigations showed that the proglacial valley acted as a sink to sediment from the glacier. Therefore it was not possible to give a "true" value of glacial erosion and furthermore it was not possible to link the transport to glacial activity because of storage within the valley and the possibility of later re-suspension of sediment deposited in the valley.

The present investigation is part of a larger research project aiming at monitoring and modelling a complete arctic landscape system (Hasholt, 2005); in this context the "system" includes the southwest lobe of the Mittivakkat Glacier, the adjoining ice-free land and the proglacial valley. The goal of this study is to develop an automatic recording system for measuring sediment concentration and transport with a high time resolution and to locate it as close to the outlet from the glacier as possible in order to determine "true" glacial erosion. Furthermore, the sediment transport should be recorded for a major part of the melt season and the results interpreted in relation to transport processes, climate variables, and at a later stage also to glacial activity.

## STUDY AREA

The Mittivakkat Glacier catchment (65°42′N latitude; 37°48′W longitude) is located on Ammassalik Island, southeast Greenland, approximately 15 km northwest of the town of Tasiilaq (Ammassalik) and 50 km east of the eastern margin of the Greenland Ice Sheet, separated from the mainland by the 10–15 km wide Sermilik Fiord. The Mittivakkat Glacier catchment (18.4 $km^2$) is drained by the glacier outlet from the most southwestern part of the Mittivakkat Glacier through a proglacial valley (Fig. 1). The catchment is characterized by a strong alpine relief and ranges in elevation from 0 to 973 m a.s.l., with the highest altitudes in the eastern part of the catchment. The catchment is covered by parts of the Mittivakkat Glacier complex (temperate glacier) (78%; 14.4 $km^2$). Approximately 22% of the catchment is covered by bedrock (at higher elevations), loose sediments such as talus and debris flow deposits (at lower elevations) and morainic deposits or sediments of fluvial origin in the proglacial valley bottoms, a ~1600 m long valley. The Mittivakkat Glacier area's climate is an ET, tundra climate, according to the Köppen classification system. The mean annual air temperature for the area is –1.6°C (1999–2004), the maximum monthly average is 4.9°C in July and the minimum is –7.6°C in February. The total annual precipitation varies from 1767 mm w.eq. (water equivalent) to 1312 mm w.eq. (1999–2004). About 65–85% of the total annual precipitation falls as snow from approximately mid-September to late May (Mernild *et al.*, 2006).

## METHODS

### Monitoring station

A reconnaissance along the proglacial river was carried out in late 2004. A location immediately at the outlet from the glacier was not possible, because of the risk of rock-fall and presence of snowdrifts on the steep slope. Instead the decision was taken to locate the station just downstream of the cascade and the alluvial cone stretching from the outlet to the beginning of the braided part of the proglacial river, about 500 m from the outlet (Fig. 1). The station is located on top of a rock (Fig. 2). It is built of galvanized iron tubes connected with KeeClamps. An important part of the station is the arm that stretches out over the watercourse. Here an ultra sonic sensor (Campbell SR50) and a temperature sensor are mounted to monitor the water level during melt periods and build up periods of ice and snow. As the sensors are damaged frequently because of strong winds it is important that they can be replaced easily, even when the

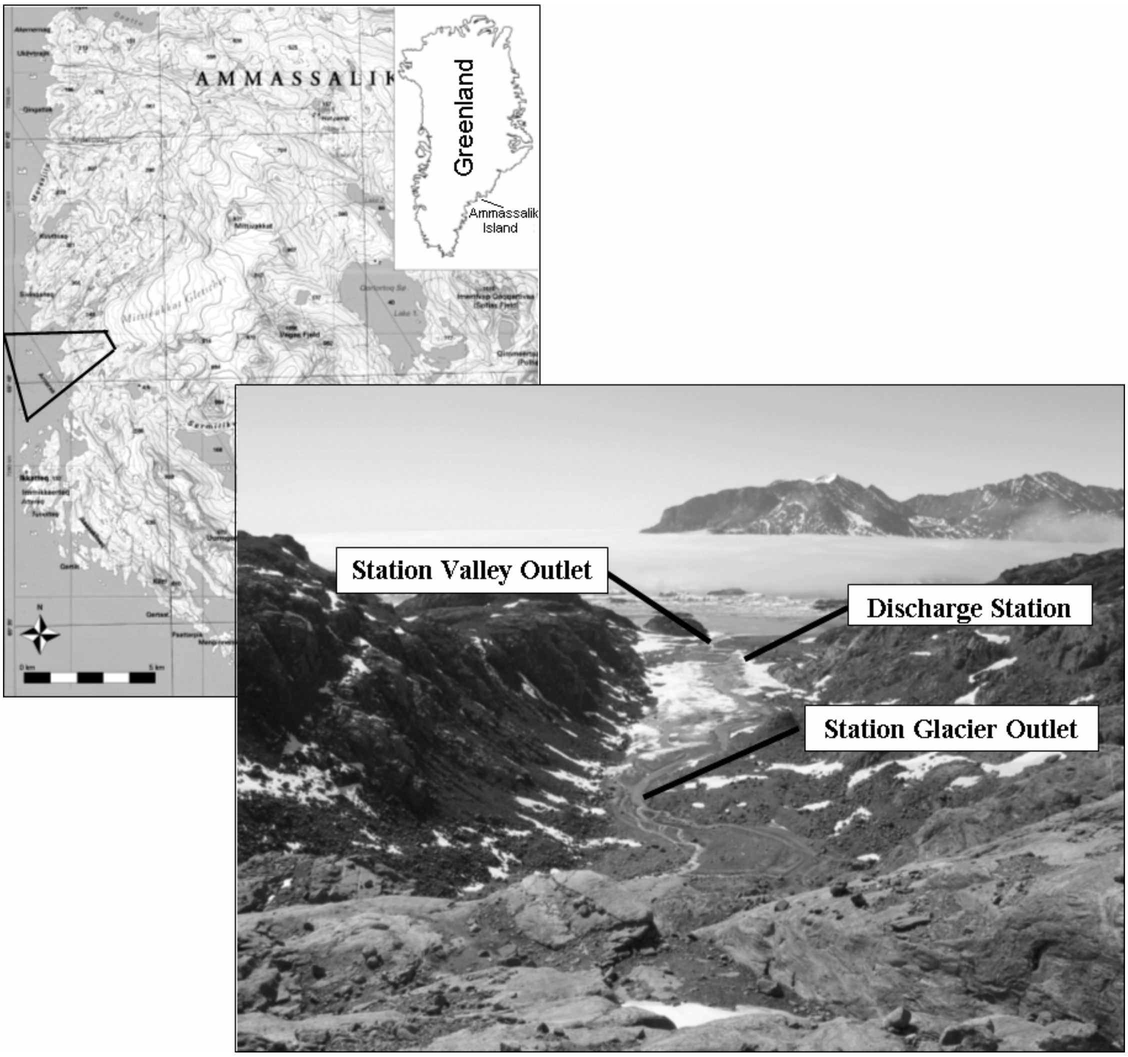


**Fig. 1** Location map showing the Mittivakkat Glacier, Ammassalik Island, including Station Glacier Outlet, Station Valley Outlet (old station), and the Discharge Station in the proglacial valley. The area illustrated in the photograph is within the polygon on the map (modified after Greenland Tourism). The inset figure indicates the general location of the Mittivakkat Glacier catchment within eastern Greenland.

stage is high. Therefore the arm is able to swing to the shore easily, when repair is needed. The Campbell CR10X data logger is placed in a shelter on the vertical mast. The station is powered by 24 Amp-hour batteries charged by a solar panel pointing towards the west, because of the shaded location. Two types of sensors were used for recording sediment concentration: a Partech IR 500 infrared transmissometer and an OBS3 optical backscatter probe. The sensors have to be installed in the watercourse when the drift of ice has ceased, and removed before the freezing begins. The sensors are fixed to tubes that are slid over iron rods which are hammered 0.5–1.0 m into the cobbly river bed at a position where the water is running free. The sensors are placed 20 cm above the bottom. Furthermore an ISCO2700 peristaltic pump automatic water sampler has been installed next to the station and the ¼ inch (0.64 mm) intake tube is fixed together with the Partech transmissometer sensor.

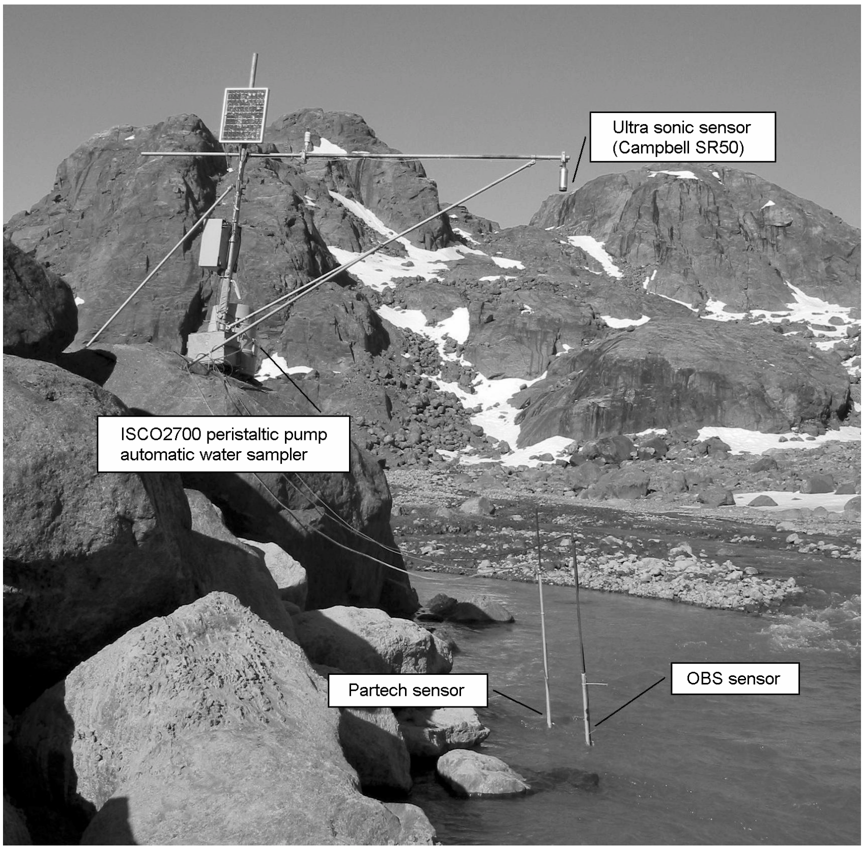


**Fig. 2** Station glacier outlet. The photo is taken in the upstream direction towards the cascade and the alluvial cone.

The station was installed in August 2004 and was assumed to record hourly values of stage until the sediment concentration sensors could be installed in spring 2005. Unfortunately strong storms and wet weather caused the station to break down in January 2005. The station had to wait for repair until the field crew arrived in late May. Because of an unusually warm winter, water was already flowing. However the station was repaired and sensors were placed in the river on 10 June. The station was recording every 10 minutes for 64 days until 13 August when the field crew retrieved the sensors and left. The iron rod carrying the OBS sensor became tilted on 26 June so that records were erratic until it was replaced on 28 July.

## Manual and automatic sampling

Water samples were collected at the glacier outlet station and at the old station at the river outlet to the sea to calibrate the sensors and to compare with previous investigations. Manual samples were collected at least once a day when the field station was manned. The samples were taken with a bottle at a position where the water was fully mixed. The first sample was taken on 29 May and the last on 14 August. The manual samples were mainly collected at around 09:00, but sometimes the sampling time had to be changed because of other field activities. The automatic sampler collected a sample every day at 17:00 h.

## Analysis

After collection the samples were stored in the dark and at a temperature <4°C. The volume of water was determined at the field station using a digital balance (300–900 ml). After weighing, the water was filtered through a pre-weighed Whatman GF/F filter (nominal retention diameter of 0.7 micron). The filters were stored in mint pockets and taken to a laboratory in Denmark. This procedure was needed to avoid expensive transportation and because a balance with the necessary 0.1 mg accuracy was not available at the field station. The filters were dried at 65°C and re-weighed. Thereafter filters were ashed at 550°C to determine weight loss on ignition. After subtraction of the clean filter weight, the concentration was determined by dividing the two weights with the sample volume; results were given in mg $L^{-1}$. Because of the rather large concentration values, the accuracy of the analysed concentration values will most often be better than ±5%; however, the short term natural variation in the concentration may be up to 25%.

## Calculation of sediment transport

The discharge was measured by use of an Ott C31 current meter and the mid-section method at a cross section situated between the two stations (Fig. 1). A stage discharge relationship was determined using the water level recordings from the monitoring station. The accuracy of the discharge measurements are within ±7% as the number of verticals is 20–30 (Hershey, 2001). Comparisons between measured and calculated discharge, based on the stage discharge relationship, indicate that the calculated values are accurate to within ±10–15%.

The concentration for each 10 minute interval was calculated using three different methods:

1. Sediment concentration at a certain discharge was calculated with a rating curve developed from simultaneously measured concentration ($c$) and discharge ($Q$). After removal of three outliers showing very high concentrations at low discharges, a linear relationship, $c = 53.93\ Q - 77.43$; $R^2 = 0.52$ was found.
2. Sediment concentration was found by calibrating the Partech readings against simultaneously measured concentrations. A relationship, $c = 0.95\text{Partech} - 502.3$; $R^2 = 0.69$ was found.
3. Sediment concentration was found by calibrating the OBS readings against simultaneously measured concentrations. A relationship, $c = 6.86\text{OBS} - 111$; $R^2 = 0.77$ was found. Because the OBS sensor was out of use for a period of time (26 June–28 July), it has been calibrated against the Partech sensor for the two periods in which they both functioned. The calibration results from the two periods are used for calculation of the OBS recordings from the missing period. The artificial OBS record was then used in the relationship above.

Sediment transport was calculated by multiplying the concentration values mentioned above with the 10-minute volume of water found from the instantaneous discharge value.

## RESULTS

The concentration measured at station glacier outlet and at station valley outlet (old station) is shown in Fig. 3. Generally the concentration is higher at the glacier outlet station. The difference is largest during extreme events, but around DOY 190 (9 July) and at the end of the period the concentration at the outlet to the sea is slightly higher than at the glacier outlet station on several occasions. The average measured concentration at Station Glacier Outlet is 305 mg $L^{-1}$ and 216 mg $L^{-1}$ at the outlet to the sea. This confirms earlier findings that the proglacial valley acts as a sink. However, because the difference in concentration shows a slight net loss of sediment from the valley around DOY 190 and late in the observation period, it is not possible to indicate the total annual net accumulation precisely. From long-term observations of valley floor changes, the net annual accumulation could be only a few centimetres.

Discharge, suspended sediment transport (per 10-min interval), and accumulated transport calculated using the methods described above are shown in Fig. 4 for the 64-day operation period of the station. Figure 4(a) shows an increasing discharge at the beginning because of melting. Except for a minor peak starting DOY 175 (24 June) the period until DOY 190 is characterized by discharges around 5 $m^3 s^{-1}$ and a daily amplitude of about 2 $m^3 s^{-1}$ increasing to 3 $m^3 s^{-1}$ late in the period. From DOY 190 to DOY 225 (13 August) three major peaks caused by rainfall occur, with discharges up to 22 $m^3 s^{-1}$; the daily amplitude is 5–7 $m^3 s^{-1}$. The maximum peak around DOY 211 (30 July) is caused by a two-day rainfall of 97 mm measured at the ground. At the end of the period the daily average discharge is again 5 $m^3 s^{-1}$. Suspended sediment transport is shown in Fig. 4(b)–(d). The rating curve method (Fig. 4(b)), underestimates peak values and misses the transport peak at the very beginning. The transport values based on the Partech and the OBS recordings correspond very well (Fig. 4(c) and (d)).

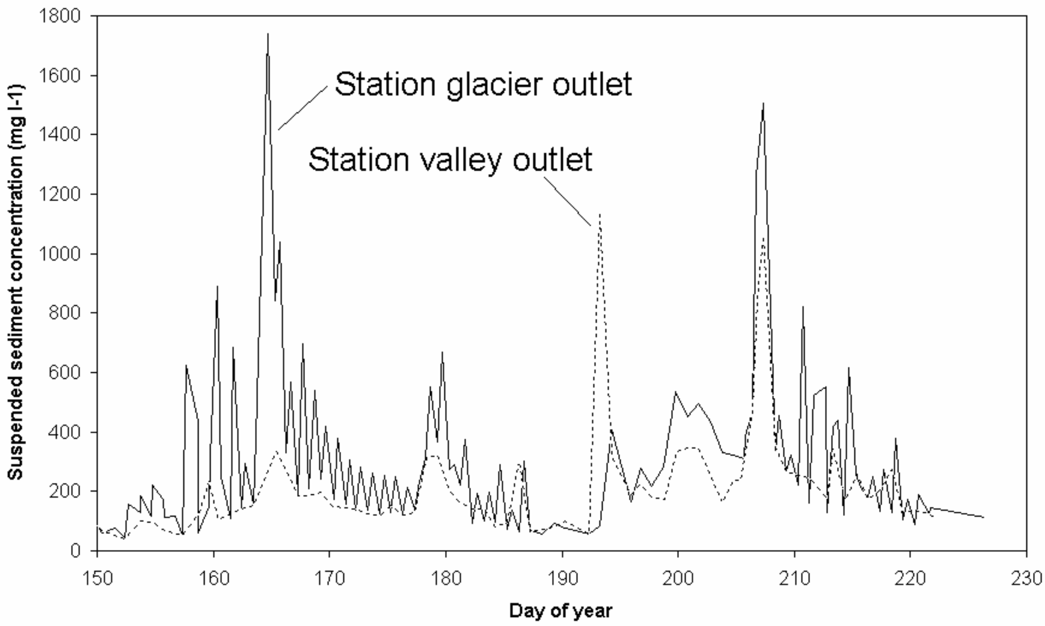


**Fig. 3** Measured suspended sediment concentration at station glacier outlet and at station valley outlet from DOY 150 (29 May 2005) to DOY 226 (14 August 2005).

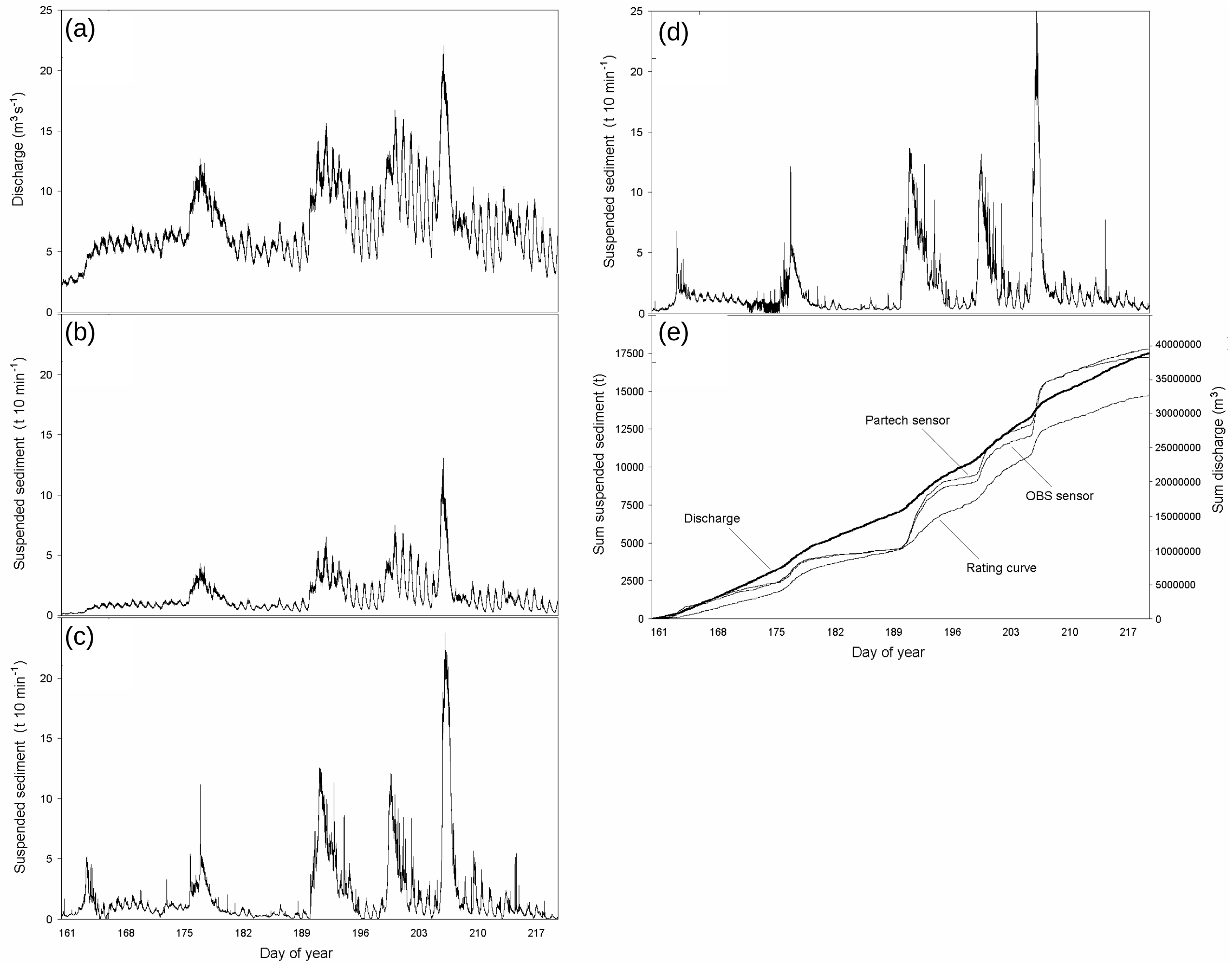


**Fig. 4** Measurements from station glacier outlet (2005): (a) discharge, (b) suspended sediment based on rating curves, (c) suspended sediment from the Partech sensor, (d) suspended sediment from the OBS sensor, and (e) summation curves of discharge and suspended sediment.

Accumulated transport for the different methods is shown in Fig. 4(e), together with accumulated discharge. The total load for the investigation period is 17 300 t based on the Partech recordings and 17 800 t based on the OBS recordings. The total discharge for the same period was $39 \times 10^6$ $m^3$; the resulting average concentration is 437 mg $L^{-1}$. Calculation of load based on the best fit rating curve gives 14 600 t, or 15% lower than the result from the other methods. Maximum 10-min transport is 25 t and 24 t for the OBS and the Partech method, respectively, while the rating curve method gave a maximum of 13 t. The daily transport peak is found to be between 17:00 and 18:00 and the minimum transport is found from 06:00 to 09:00, indicating the runoff delay through the glacial drainage system.

The sediment transport is unevenly distributed through time. Most of the sediment transport occurs along with peak discharges; the five peak periods account for ~70% of the transport in the 64 day period (Fig. 4(e)). The sediment transport is much larger in the second half of the period indicating the significance of the development of the glacier drainage system and the abundance of rain and melt-water.

Examples of the concentration as function of discharge are shown in Fig. 5 for selected peaks. Figures 5(a) and (d) show two diurnal cycles, one (a) in the beginning of the period DOY 170–171 (19–20 June), and the other (d) at the end of the period DOY 213–214 (1–2 August). Figure 5(a) shows that concentration generally increases quite steeply with increasing discharge; however, there is a large spread of observations. Figure 5(d) shows that the concentration increases rather slowly with increasing discharge until 7 $m^3 s^{-1}$, then it rises steeply, indicating that more sediment can be released from the system when the discharge surpasses a certain threshold. Figure 5(b) shows results from the peak period, DOY 178–180 (27–29 June), in which a very well defined relationship between discharge and concentration is found, indicating an abundant sediment supply. Figure 5(c) shows results from the maximum peak period, DOY 208–210 (27–29 July), in which an anticlockwise hysteresis pattern is observed, showing that concentration corresponding to e.g. 15 $m^3 s^{-1}$ is around 600 mg $L^{-1}$ during the rising phase and 1700 mg $L^{-1}$ in the falling phase. Possible explanations are that the large volume of sediment-free rainwater dilutes the river water initially or that a large amount of sediment is released from the system to the river later in the period.

The specific sediment loads determined by Partech recordings are, respectively, 980 and 1240 t $km^{-2}$ for the whole catchment and for the glacier area alone. The load

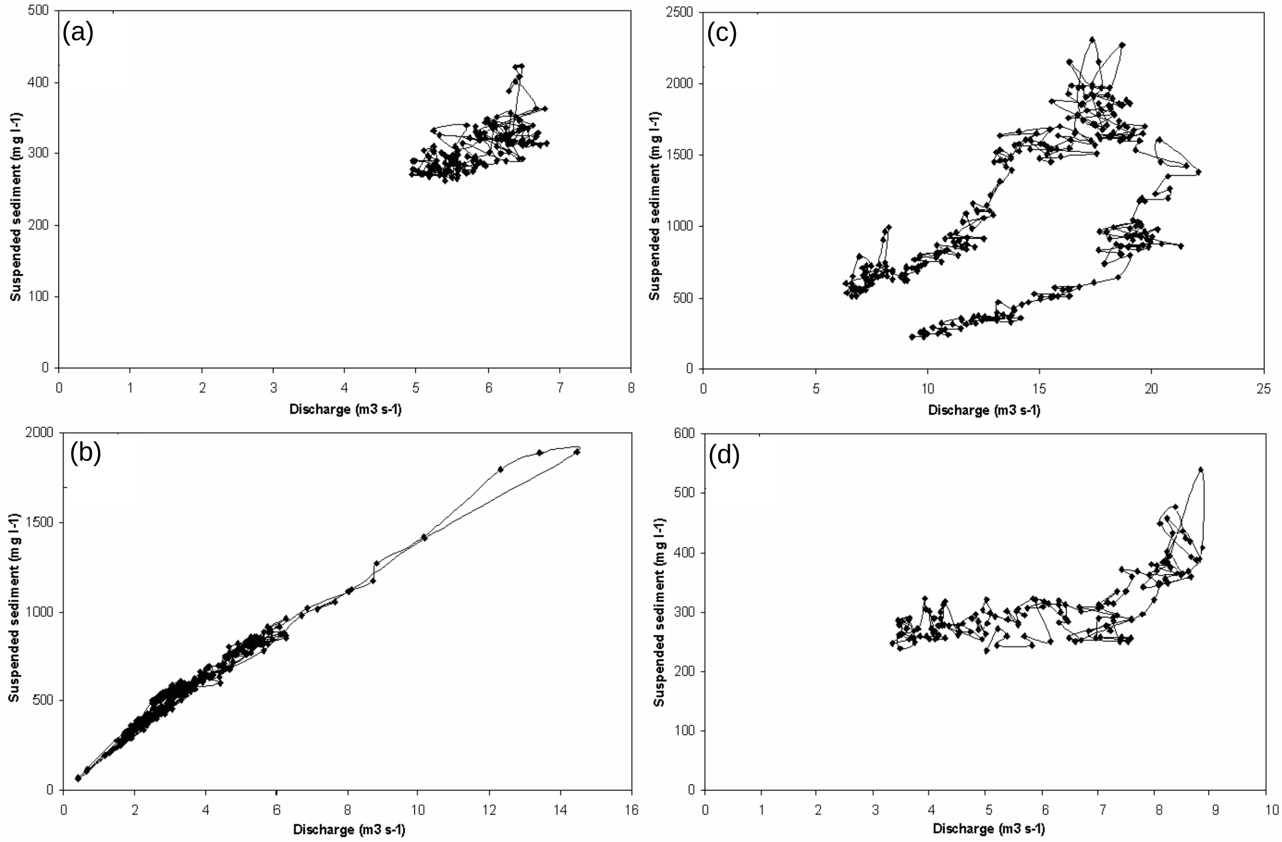


**Fig. 5** Suspended sediment concentrations from station glacier outlet as a function of discharge for selected periods: (a) DOY 170–171 (19–20 June 2005), (b) DOY 178–180 (27–29 June 2005), (c) DOY 208–210 (27–29 July 2005), and (d) DOY 213–214 (1–2 August 2005). Concentration is based on Partech records.

related to the glacier area is a minimum value for the glacial erosion because the observation period does not cover a full year. The full year period load can first be calculated when the recordings from the rest of 2005 are retrieved in spring 2006. Based on earlier investigations (Hasholt, 1992, 1994) it is anticipated that the 2005 annual load for the whole catchment will be well above 1000 t $km^{-2}$ $year^{-1}$.

## SUMMARY AND DISCUSSION

A well functioning sediment transport monitoring station equipped with a Partech and an OBS sensor has been established. Both sensors performed well within the range of sediment concentrations found. Experience shows that, in this unstable environment, the use of more than one sensor is important to secure an unbroken record. The calculated total sediment transport during a 64-day period in summer 2005 was 17 300 and 17 800 t for, respectively, the Partech and the OBS sensor, while the load calculated with the best fit rating curve was 14 600 t. The specific sediment load for the whole catchment area and the glacier area is, respectively, 980 and 1240 t $km^{-2}$ for the period. These high values confirm that erosion must take place underneath the glacier. The expected annual value of specific load higher than 980 t $km^{-2}$ $year^{-1}$ is also in good accordance with earlier findings and with other investigations of glacial transport (Hallet *et al*., 1996). The aim of this investigation was to determine glacial erosion by measuring as close to the glacier as possible, assuming that a dynamic equilibrium exists between erosion and transport from the glacier. It was confirmed that it is important to measure close to the glacier because, as the valley act as a sink, measurements at the outlet to the sea will underestimate the glacial erosion. The glacier will erode the underlying solid rock and loose sediments throughout the year. The annual movement at the equilibrium line is 20–25 m (Knudsen & Hasholt, 2004). However, during winter there is no water available to transport the sediment. The sediment will be released from underneath the glacier when the sub- and englacial drainage systems develop. The maximum transport occurs in late July–August, when the daily discharge amplitude is largest, indicating abundant water and a quick responding drainage system. This investigation covers a major part of the annual sediment transport period (Hasholt, 2003).

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