POLISH POLAR RESEARCH
vol. 38, no. 1, pp. 21–39, 2017 doi: 10.1515/popore-2017-0003

Bedload transport in two creeks at the ice-free area of the Baranowski Glacier, King George Island, West Antarctica

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Abstract: This paper presents a unique case study and methodology for measurements of the bedload transport in the two, newly created troughs at the forefield of the Baranowski Glacier: Fosa and Siodło creeks. The weather conditions and the granulometric analysis are presented and discussed briefly. Rating curves for the Fosa and Siodło creeks are presented for the first time for this region. Changes of the bedload transport as well as water discharge and water velocity at both creeks are investigated. The hysteresis for the relationships between rate of bedload transport and water discharges were identified showing that for both creeks for the higher water levels a figure of eight loop may be easily recognized. Moreover, a new method for the calculation of bedload transport rate, based on the weighted arithmetic mean instead of the arithmetic mean, is proposed.

Key words: Antarctica, South Shetlands, ecohydraulics, proglacial hydrology, sediment transport.

Introduction

Based on the classical definition given by Graf (1971) the sediment in an open channel flow may be transported in the form of wash load, suspended load and bedload. The wash load is the sediment that is transported near the top of the flow in a river or creek. The suspended load is the sediment that almost never has connection with the bed, whereas the bedload particles move in still connection with the channel bed. Moreover, the bedload particles may be transported in the form of sliding, rolling and saltation (Fernandez-Luque and van Beek 1976; Bridge and Dominic 1984; Drake *et al*. 1988; Parker 1990;

Bialik and Czernuszenko 2013). During their movement these particles can form different morphological forms, such as sand or gravel waves. Their shape and especially the sediment transport rate mostly depend on the hydrological conditions, namely the discharge and flow velocities (Nikora *et al*. 1997; Carling *et al*. 2000; Bialik *et al*. 2014; Sziło and Bialik 2016). Thus, the understanding of these relationships is the key to quantifying how sediment moves as bedload.

Studies on the relationship between catchment hydrologic conditions and glacial sediment transport in polar regions have been concentrated mainly on glaciers located in the Arctic (Nicholas and Sambrook Smith 1998; Orwin and Smart 2004; Strzelecki 2007; Beylich and Kneisel 2009; Rachlewicz 2009; Orwin *et al*. 2010) and focused on the calculation of sediment suspended concentration and dissolved matter in a stream of water. In contrast, measurements of bedload transport in glaciated catchments are limited to only several publications (Østrem 1975; Ashworth and Ferguson 1986; Pearce *et al*. 2003; Bogen and Møen 2003; Kociuba *et al*. 2010, 2012; Kociuba and Janicki 2014, 2015; Kociuba 2016a, b, in press). This situation is similar with regards to the study of general polar hydrology. Most researchers turned their attention on Arctic rather than Antarctic glaciers (*e.g*., Hodgkins 1997; Hodgkins *et al*. 2009; Nowak and Hodson 2013; Sobota 2014; Majchrowska *et al*. 2015; Franczak *et al*. 2016). According to the relationship between sediment transport and water flows from glaciers, for instance, Kociuba and Janicki (2014) developed new techniques in measurements of bedload transport in gravel streams. They used river bedload traps for study in the Scott catchment on Svalbard and showed that flow values are strongly associated with the ablation period. Moreover, they indicate correlation between intensity of bedload transport and occurrences of high water flow. However, as claimed by Pearce *et al*. (2003), this finding has not been confirmed in glaciated catchments. This study is the first that has focused on measurements of bedload transport from the glaciers in the Antarctica by evaluating material streams from the glaciers, located on the forefield of the Baranowski Glacier in western shore of Admiralty Bay. Moreover, we seek to address the following scientific question: what is the relationship between water discharge in the glacial catchment and the bedload transport, which in the case of rivers located in temperate climates is also poorly understood.

Study area

The Baranowski Glacier is located on the western shore of the Admiralty Bay at the King George Island in West Antarctica (Fig. 1). The island is under the influence of the sub-polar and maritime climatic conditions, which as suggested by Oerlemans and Fortuin (1992), are more sensitive to climate change than continental ones. Blindow *et al*. (2010) confirmed this statement and noted that

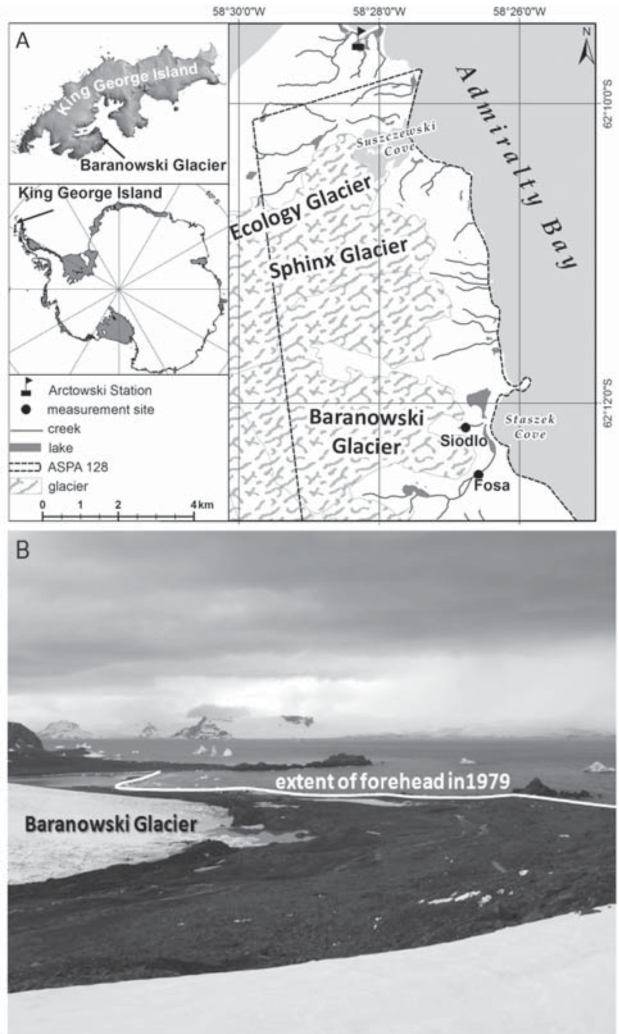

Fig. 1. The study area with location of the measurement sites (**A**) and extent of the Baranowski Glacier (**B**) (photo by J. Sziło, January 2016).

ice caps covering the King George Island (KGI) are very sensitive to climate fluctuations. In particular, one of the most important factors of decrease in glaciers' area is mean annual air temperature. For the period of 1948–2011, the mean air temperature calculated from Admiralty Bay (1948–1960), Deception Island (1948–1967), Bellingshausen (1968–2011) and Ferraz Station (1986–2010) was -2.5°C (Kejna *et al*. 2013a). Similarly a mean air temperature of -2.8°C was given for Fildes Peninsula by Simões *et al*. (1999) for the period of 1947–1995. It is important that during this period the temperature was highly variable and for the coldest years 1948–1950, the mean annual temperature was equal to -3.6°C. In addition, a significant warming trend is observed, reaching 0.19°C per decade (Kejna *et al*. 2013a). Due to the increase in air temperature, the response of the glaciers is clearly visible. Since 1956, observations of glacial front positions have been carried out in this region (Wunderle 1996; Kejna *et al*. 1998; Park *et al*. 1998; Birkenmajer 2002; Braun and Grossman 2002; Rückamp *et al*. 2011; Da Rosa *et al*. 2014; Sobota *et al*. 2015; Simões *et al*. 2015) and a general tendency to recession of the glaciers located on the KGI has been observed. Since 1956, KGI has lost about 7% of its original ice cover (Simões *et al*. 1999). A similar situation is associated with the mass balance of the glaciers. From January 2008 to January 2011, mass loss was -0.64 ± 0.38 m w.e.a^{-1}, for the entire ice cap (Osmanoğlu *et al*. 2013). Recently, negative mass balance was also confirmed by Rückamp *et al*. (2010) and Simões *et al*. (2015). The short-term observation of mean annual net mass balance of Ecology and Sphinx glaciers system is +17.8 cm w.e. in 2012–2013. However, long-term observations confirm that their area loss reached 41%, between 1979 and 2012 (Sobota *et al*. 2015). This situation could be treated as the response of the glaciers to the regional warming.

The Baranowski Glacier is the fastest retreating land-based glacier located at the Admiralty Bay. The specific surface area of deglaciation between 1979 and 2015 is equal to 0.73 km^2 and was calculated based on the stereo images from the aerial photo taken in 1979 and the snow-free satellite Landsat images from 2015. Figure 1B shows the extent of the forehead in 1979 and the ice-free area, which deglaciated during the last 45 years. This area is characterized by several proglacial lakes and by several riverbeds. Most run only during intense rainfall or snow melt after winter, while two creeks are more stable with water flow throughout the summer season. Fosa Creek, is located in the southern part of the Baranowski Glacier and starts from the Ginger Lake, collecting water from dead ice and melting ice of the glacier (Fig. 2A). Then, it runs through the moraine and flows to the Staszek Cove south of the Cape Block, being fed there by seepages from the moraine. The second creek, located north from Fosa Creek, has no name so for the purpose of this study we call it the Siodło Creek, as it starts as a subglacial outflow from the Baranowski Glacier close to the Siodło (Fig. 2B).

Methods

The field campaign was carried out from 8 January to 11 February 2016. During 35 days of measurements, data of the bedload sediment transport, water discharge and flow velocity were collected within 24 h intervals at two measurement sites. The first site at Fosa Creek was established in the lower

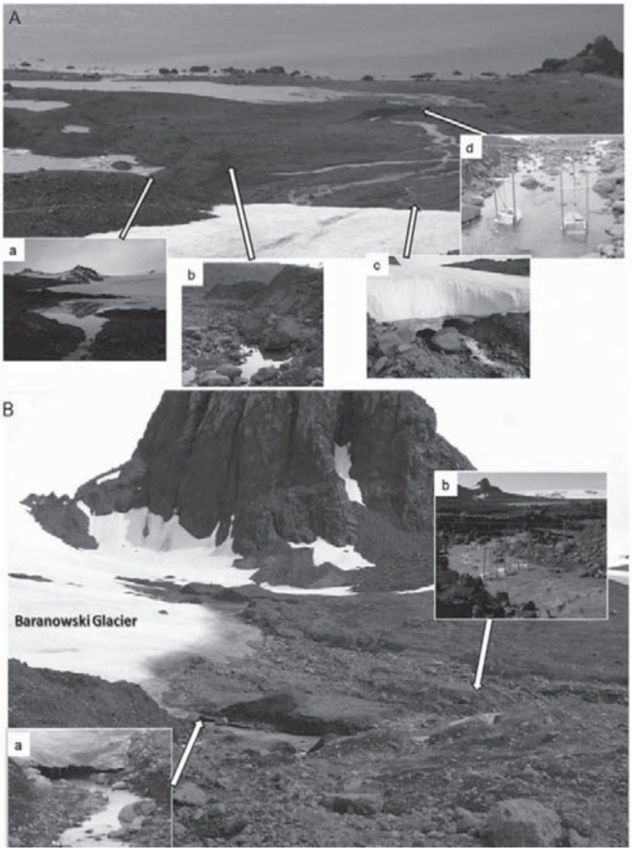

Fig. 2. Study areas; (**A**) Fosa Creek: a – outflow from the lake close to Baranowski Glacier, b – seepage from the end moraine ridge, c – outflow from dead ice and Ginger Lake, d – measurement site and (**B**) Siodło Creek: a – subglacial outflow, b – measurement site. (photos by J. Sziło, January 2016).

part of the channel, around 300 m from the forehead of the Baranowski Glacier (Fig. 2A) while the second site was set up at Siodło Creek in the upper part of this channel around 15 m from the glacier (Fig. 2B).

Bedload sediment transport was obtained with the use of the River Bedload Trap (RBT) sets following the (Kociuba 2016a) design and the measurement strategy, first time implemented in the melt season 2009 (Kociuba *et al*. 2010), and verified in the field in years 2010–2013 (Kociuba 2016a, b, in press). Rachlewicz *et al*. (in press) conducted comparative studies between three bedload samplers (*e.g*. portable Helley-Smith, portable sample of Polish Hydrological Services and RBT). They suggested that RBT obtained the best results in relation to the results of continuous measurements, with the possibility of anchoring which fixes this device in one position and allowing a more practical approach to conduct research in polar regions. However, they simultaneously noticed that the main disadvantage was its oversize, which was confirmed during the presented field works. Nevertheless we were able to successfully carry out the planned experiments and the set of two and three RBT modules were installed in Fosa Creek and Siodło Creek, respectively. During the first day of measurement, it was recognized that in Fosa Creek the bedload transport was expected to be very similar in the whole cross-section of the stream due to the very flat and regular shape of the channel, whereas in Siodło Creek, we expected significant changes in sediment transport rate across the cross-section, as the channel was in the process of forming and was located very close to the glacier forehead. Thus, in this channel, it was decided to install a set of three traps. The differences in the sediment transport were confirmed during the measurements and will be discussed in the next section.

Following Kociuba and Janicki (2014) and Rachlewicz *et al*. (in press), the individual transport rate index q_b was calculated based on the following formula:

$$q_b = \frac{G_s}{S_w t}, \tag{1}$$

where G_s is the mass of caught in the sampler bedload material [kg], S_w stands for the width of the sampler's inlet [m] and t describes time of measurement [s].

Moreover, the bedload flux Q_b was calculated from the formula:

$$Q_b = W_c \overline{q_b}, \tag{2}$$

where $\bar{q}_b$ is the average bedload transport rate [kg] and W_c stands for the width of wetted river bed in measuring cross section [m].

In addition, all the material was collected every day and transported to the laboratory at the *Arctowski* Polish Antarctic Station, in order to obtain the granulometric distribution curves of non-moving material on the bed and transported material of Fosa Creek and Siodło Creek. The sediment samples of bed were taken from three randomly chosen positions located around 5 m to each other. For each of these cases around 5 kg of sediment was collected. In contrast to the previous studies (*e.g*. Kociuba and Janicki 2015), the samples were subjected to drying, and only then weighed. The grading curve was obtained later for this dry sample.

Finally, the water discharge and flow velocities were measured with the use of an Electromagnetic Open Channel Flow Meter (manufactured by Valeport, model 801). Measurements were performed in the cross-sections located around 40–50 cm in front of the location of the RBT. Moreover, at Fosa Creek the CTD diver manufactured by the Eijkelkamp was used for the monitoring of continuous water levels.

Results and interpretation

Figure 3 shows the difference in granulometry of the material of the individual channels. The left panel represents a sample of the material being transported in Fosa Creek, the middle panel is the sample of sediment transported in Siodło Creek and the right panel illustrates the bed material from Siodło Creek. Figure 4 shows the largest stones that were caught in traps located in Siodło Creek, and so were transported during the period of measurement's campaign.

Figure 5 shows granulometric distribution curves of the bed and transported sediment and Table 1 presents basic statistical characteristics displaying all considered cases. Based on the Wentworth (1922) grain size classification, it can be stated that the material forming the trough of the two creeks was very coarse gravel, whereas the transported sediment was very fine gravel. Moreover, the bed material in Fosa Creek was poorly sorted and in Siodło Creek was moderately sorted. On the other hand, the transported sediment in both channels was moderately well sorted.

During the measurement campaign, the mean daily air temperature was 1.8°C, with a maximum of 5.9°C on 29 January and a minimum of -1.6°C on 11 January (Fig. 6). Data were measured by Campbell Weather Station at the *Arctowski* Station on the King George Island. The values of the temperature were in agreement with the observation conducted by Kejna *et al*. (2013b) who noticed that in 2012 the mean daily temperature of January was 2.4°C and of February was 2.0°C at the *Arctowski* Station. Large variability in water levels

Fig. 3. Examples of sediment samples, representing transported sediment in Fosa Creek (left), transported sediment in Siodło Creek (middle), and bed sediment of Siodło Creek (right).

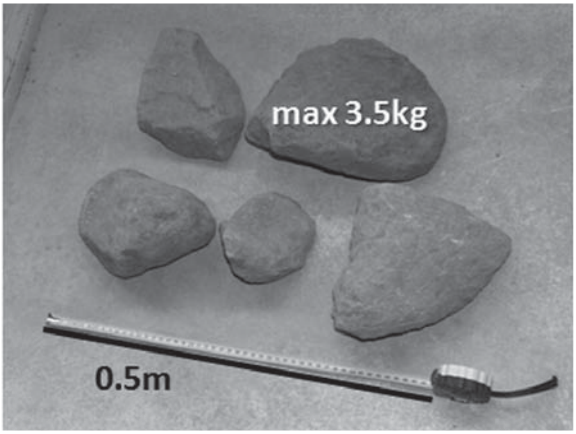

Fig. 4. The largest boulders that were caught in traps in Siodło Creek on 1 February, 2016.

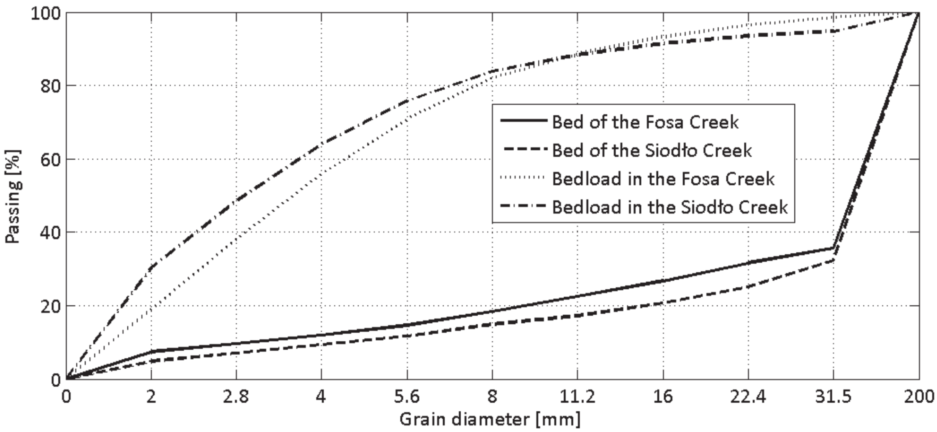

Fig. 5. Granulometric distribution curves of bed and transported sediment from Fosa and Siodło creeks.

and discharges were observed in the period of the field works. Figure 7 shows the calculated rating curves for Fosa Creek and Siodło Creek, as well. It should be noticed that these are the first data calculated for the creeks flowing at the western shore of the Admiralty Bay. Maximum water discharge and maximum mean water velocity measured on 31 January were 0.719 m^3s^{-1} and 0.714 ms^{-1}, respectively. The second channel, Siodło Creek, which flows directly from the glacier, received the maximum water discharge equal to 0.259 m^3s^{-1} and maximum mean water velocity 1.000 ms^{-1}, measured on the same day as in Fosa Creek. In addition, Fig. 6 shows the precipitation and mean daily temperature during the measurement days. It can be noticed that the maximum value of

Table 1

Basic statistical characteristic of sediment, where M stands for the graphic mean and D describes inclusive graphic standard deviation.

	Basic statistical characteristic of sediment				
	D_{16} [mm]	D_{50} [mm]	D_{84} [mm]	M	D
Bed of Fosa Creek	1.53	2.96	8.85	1.77	0.63
Bed of Siodło Creek	1.85	3.55	9.24	1.98	0.58
Bedload in Fosa Creek	6.57	108.99	114.51	5.44	1.03
Bedload in Siodło Creek	9.52	109.43	114.77	5.62	0.90

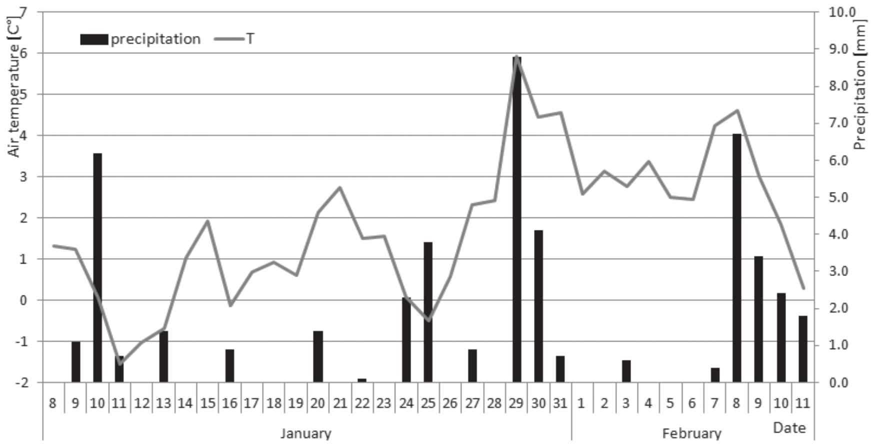

Fig. 6. Mean daily air temperature and precipitation at the *Arctowski* Station during the 2015/2016 summer season.

about 9 mm was observed on 29 January and was continuing until 31 January when the maximum mean daily temperature and the maximum discharges were observed in both creeks.

Figure 8 shows a comparison of the spatial distribution of the water velocity on 31 January during the most intense water discharge. Vertical velocity distributions in the profiles, where the RBT samplers were installed have a classic logarithmic distribution. However, the situation looks more interesting considering the distribution of the cross-section. In the case of Fosa Creek, large differences are not visible, whereas at Siodło Creek differences can be clearly identified, especially at the central part of the channel, where the speed of water is considerably greater than at the other two locations. It seems that it should influence the sediment transport in this part of the trough causing it to be greater in the central part of the channel. This problem will be considered further in the paper.

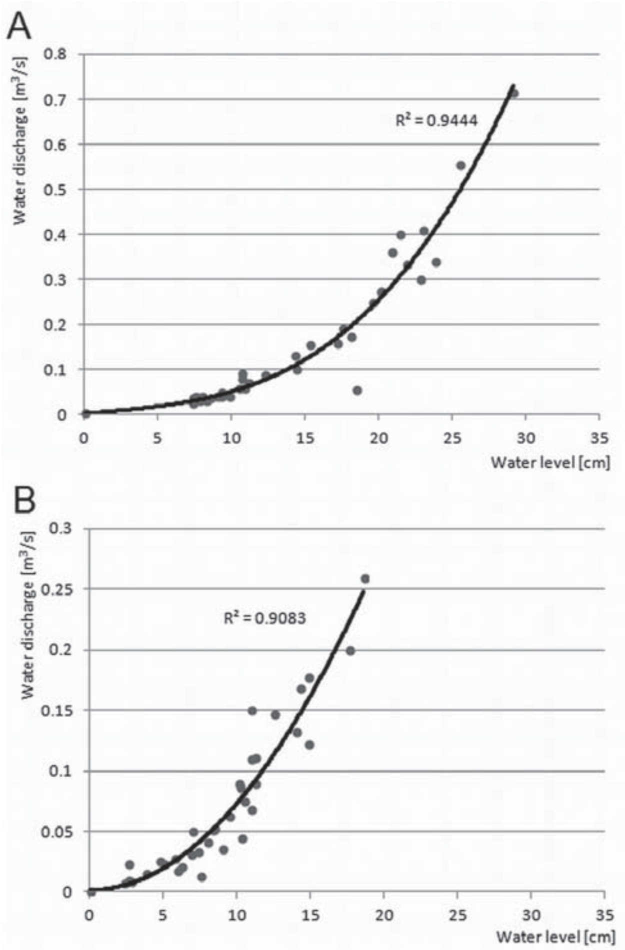

Fig. 7. Rating curves for Fosa Creek (**A**) and Siodło Creek (**B**).

In spite of the fact that both troughs are cut down into the same moraine cover, the differences in the intensity of the bedload transport as well as in the distribution of grain size were observed. In contrast to Siodło Creek, where the bedload transport exists continuously, in Fosa Creek only one extreme event of intense transport was indicated. Moreover, in Siodło Creek the largest boulders caught in the bedload traps weighed above 3 kg while in Fosa Creek only 0.3 kg. Figure 9 shows the changes in time of the bedload transport and water discharge. Main basic characteristics of bedload transport parameters are presented in Table 2.

According to Williams (1989), the relationship between water discharge and sediment transport is influenced by various factors. In particular, the most important

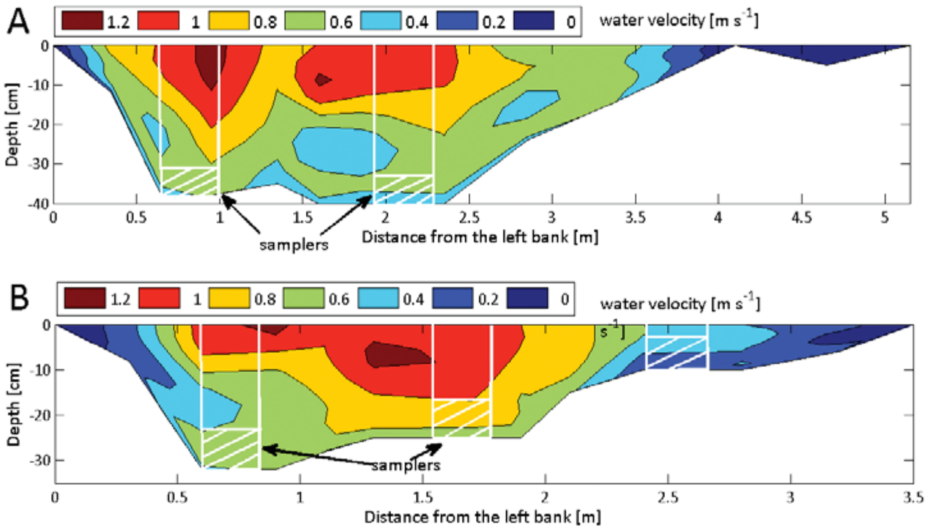

Fig. 8. Water velocity spatial distribution measured on 31 January at Fosa Creek (**A**) and Siodło Creek (**B**).

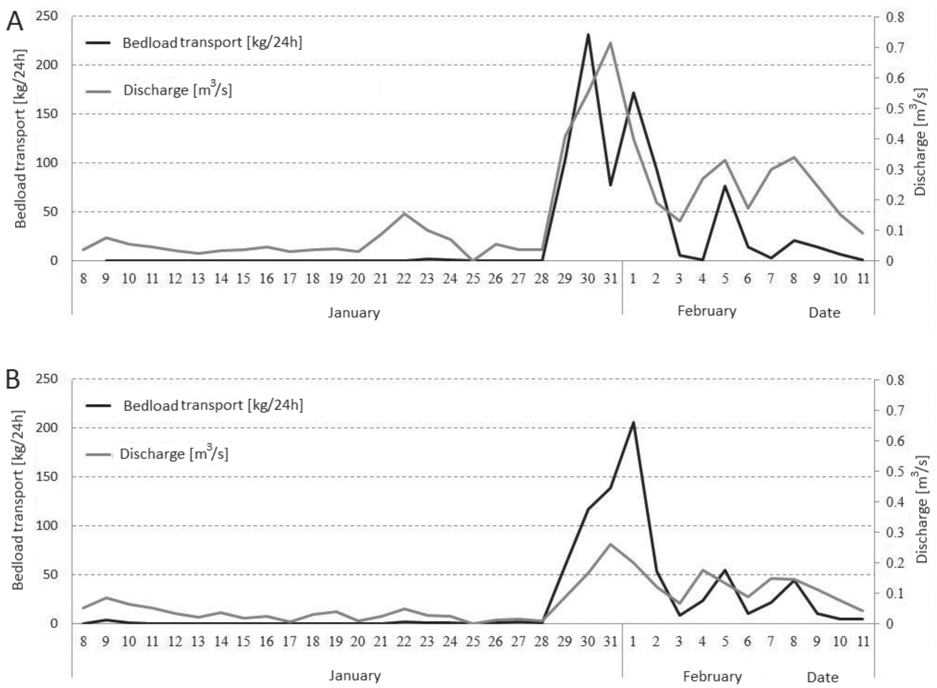

Fig. 9. Changes of the bedload transport and water discharge at Fosa Creek (**A**) and Siodło Creek (**B**).

Table 2

Characteristics of bedload transport parameters.

Site	Number of samples	Bedload transport rate [kg/m 24h]		
		Min.	Mean	Max.
Fosa left	19	0	10.5	75.2
Fosa right	16	0	6.0	47.2
Siodło left	26	0	5.6	83.1
Siodło middle	33	0	16.7	106.2
Siodło right	16	0	5.8	25.7

are those upon which the same water flow is dependent, *e.g*. the weather conditions and the geomorphology of the channel. As previously mentioned, the maximum precipitation and mean daily air temperature occurred two days before the maximum water levels (Fig. 8). Williams (1989) suggested that based on the "*comparison between sediment concentration and water discharge ratio at a given discharge on the rising and falling limbs of the discharge hydrograph may be a consistent, reliable method for categorizing C-Q relationships*". He proposed 5 possible C-Q relationships: (1) single-valued line; (2) clockwise loop; (3) counterclockwise loop; (4) single-valued line plus loop; and (5) figure eight. However, dependence on the processes related to the sediment transport such as duration of the availability of the sediment or its travel rate or distance is less known.

Figure 10 shows the bedload sediment transport and water discharge relationships for Fosa Creek and Siodło Creek. Both of the considered cases have a single loop for the lower water levels, when the bedload transport varies directly with the water discharge, while for the higher water levels figure of eight loops are easily visible. However, for Fosa Creek this is a clockwise loop, while for Siodło Creek a counter-clockwise loop is observed. This observation is in agreement with those given by Arnborg *et al*. (1967) and further confirmed by Williams (1989) who concluded that for the long existing and continuous sediment concentration associated with long flood, the C-Q relations is a figure of eight with a clockwise loop at high flows and a counter-clockwise loop for a low flows. Considering both creeks, discharge was higher for Fosa Creek, although the bedload sediment transport was lower in this channel. However, it seems that also the sorting of the material plays a significant role in this relations. The bed material of Fosa Creek was poorly sorted, whereas in Siodło Creek, it was moderately sorted as presented in Fig. 5. This suggests that the bed material in Siodło Creek is less armored and thus should be more easily transported, as the trough is at a lower stage of forming and easily reaches the erosion process. However, the relationship with the water discharge is the most influential for this phenomenon.

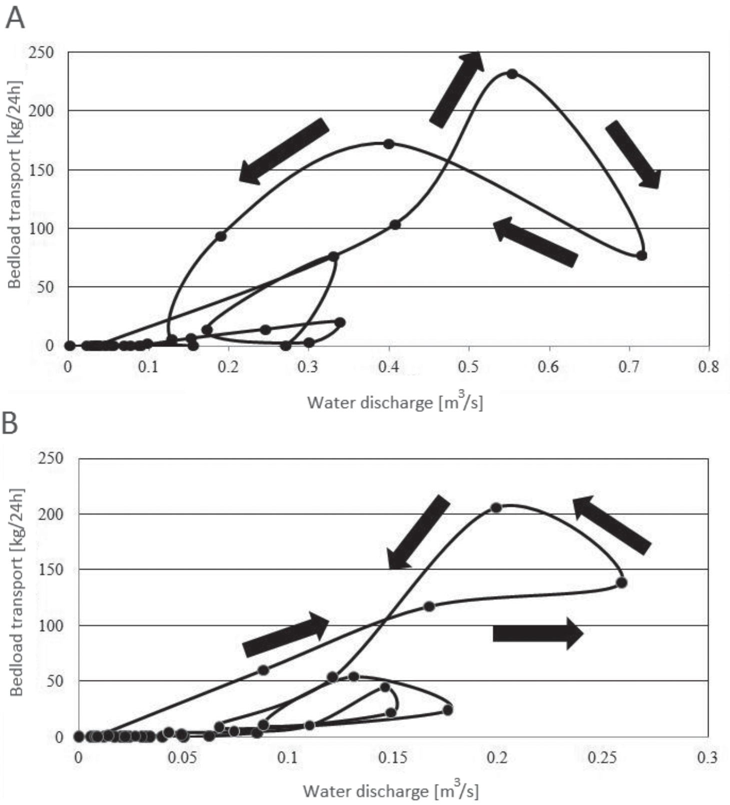

Fig. 10. The bedload sediment transport and water discharge relationships for Fosa Creek (**A**) and Siodło Creek (**B**).

Figure 11 shows the measured total bedload while in the Fig. 12 the measured bedload with specifying values obtained for individual samplers are presented. It is clear that the ratio between the materials caught in the samplers changed every day. For example, in Siodło Creek, the weight of the material caught in the left sample from 29 January to 1 February was almost equal to the weight of the material caught in the middle sampler. However, since 2 February the amount of material caught in the left sampler was significantly lower than for the remaining samplers. The same situation was noticed for Fosa Creek, where from 30 January to 2 February the amount of the bed material caught in the right sampler was comparable to the left sampler that in the coming days has a predominant share in the amount of debris caught. In such a situation, it seems that the average bedload transport rate used in eq. (2) is incorrect as the participation in the calculation of bedload transport rate depends on the bed stress conditions and it would be preferable to use the weighted average instead of arithmetic mean. Kociuba (in press) the first suggested that the method of

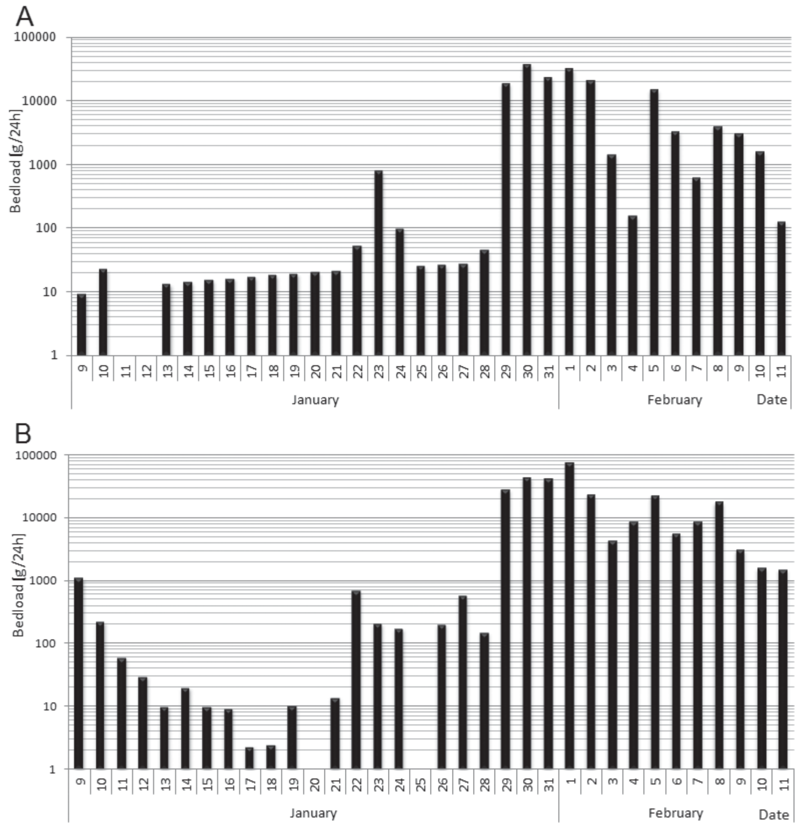

Fig. 11. The measured weight of bedload at Fosa Creek (**A**) and Siodło Creek (**B**).

calculating the bedload transport rate should be based upon the location of the samplers in the stream. In such a situation, one solution is to employ the weight that complies with an average velocity of water occurring on the surface of the sampler, presented for example in Fig. 7. Figure 13 shows a comparison between bedload transport normalized by use of an arithmetic mean and a weighted arithmetic mean. We suggest the weighted mean is a more accurate method to represent bedload transport since the use of arithmetic mean underestimates the major contribution of the central sampler.

Conclusions

In this paper, we suggest that the differences in the intensity of the bedload transport between two creeks flowing at the forefield of the Baranowski Glacier may be explained by less armored of Siodło Creek than Fosa Creek. Moreover, our research provides additional information on the connection between hydrological

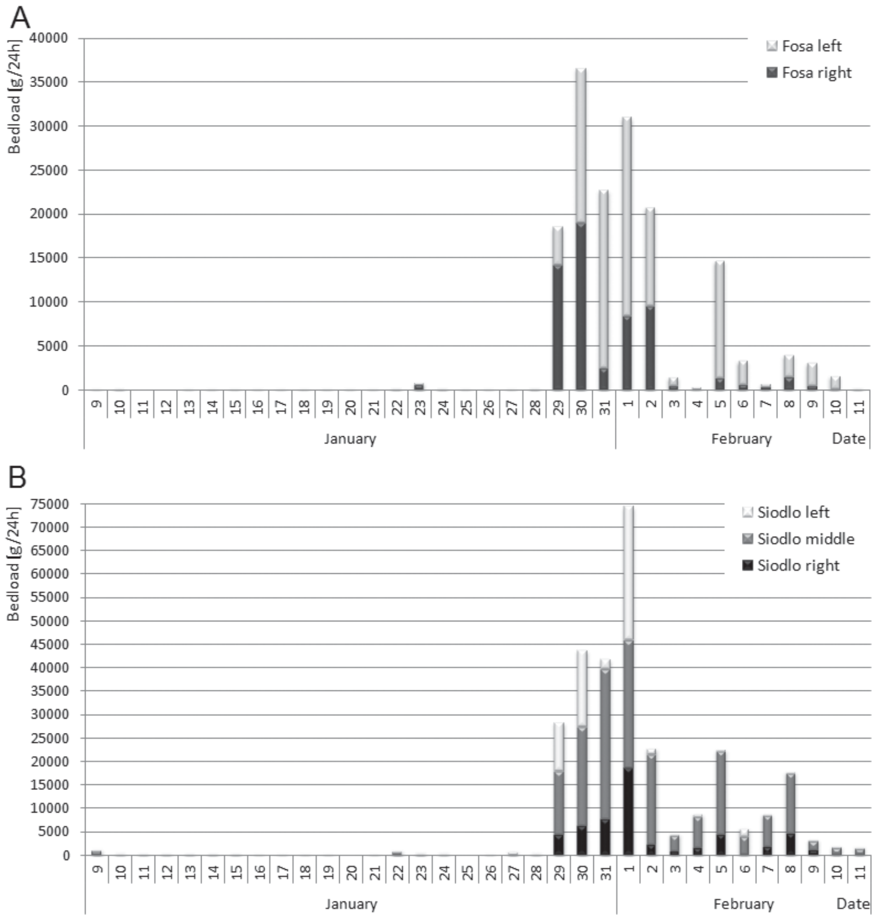

Fig. 12. The measured weight of bedload with specifying values for individual samplers at Fosa Creek (**A**) and Siodło Creek (**B**).

and geomorphological conditions in polar regions extending the previous results. In particular, we clarify the relationship between bedload transport, the rapid outflow and high water discharge and identify hysteresis in both creeks. For Fosa Creek, it has a single loop for the lower water levels, when the bedload transport varies directly with water discharges, while for the higher water levels a figure of eight clockwise loop was easily recognized, which suggests that the bedload was not synchronized with water discharge. On the other hand, for Siodło Creek the hysteresis also has a single loop for the lower water levels. However, in contrast to Fosa Creek, for the higher water levels a figure of eight counter-clockwise loop was observed. We suggest that this is due to the fact that the rate of increase of bedload was greater than of water and the bedload peaked first. This phenomenon appears probably because the bed material of

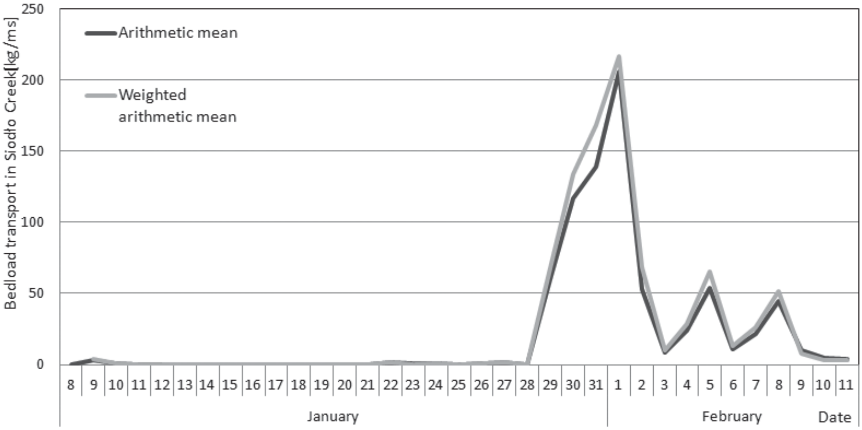

Fig. 13. The bedload transport normalized by use of an arithmetic mean (black line) and a weighted arithmetic mean (gray line) for Siodło Creek.

Fosa Creek was poorly sorted, whereas in Siodło Creek, it was moderately sorted and this suggests that the bed material in Siodło Creek should be more easily transported, as the trough is at a lower stage of forming and easily reaches the erosion process. However, we highlight that the relationship with the water discharge is the most influential factor in this process. Moreover, we suggest that the weighted arithmetic mean should be applied instead of the arithmetic mean in calculation of bedload transport rate with use of eq. (2).

Acknowledgements. — The publication has been partially financed from the funds of the Leading National Research Centre (KNOW) received by the Centre for Polar Studies for the period 2014–2018. We are grateful to Waldemar Kociuba for the loan of the equipment that we used in our field works. The data used in the paper were collected based at the *Arctowski* Polish Antarctic Station. We thank the two anonymous reviewers for their constructive remarks.

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Received 19 September 2016
Accepted 3 January 2017