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# Seasonal hydrological and suspended sediment transport dynamics in proglacial streams, James Ross Island, Antarctica

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## Abstract

Rapid warming of the Antarctic Peninsula is producing accelerated glacier mass loss and can be expected to have significant impacts on meltwater runoff regimes and proglacial fluvial activity. This study presents analysis of the hydrology and suspended sediment dynamics of two proglacial streams on James Ross Island, Antarctic Peninsula. Mean water discharge during 8/1/2015 to 18/2/2015 reached 0.19 $m^3 s^{-1}$ and 0.06 $m^3 s^{-1}$ for Bohemian Stream and Algal Stream, respectively, equivalent to specific runoff of 76 mm $month^{-1}$ and 60 mm $month^{-1}$. The daily discharge regime strongly correlated with air and ground temperatures. The effect of global radiation on proglacial water discharge was found low to negligible. Suspended sediment concentrations of Bohemian Stream were very high (up to 2927 mg $L^{-1}$) due to aeolian supply and due to the high erodibility of local rocks. Total sediment yield (186 t $km^{-2} yr^{-1}$) was high for (nearly) deglaciated catchments, but relatively low in comparison with streams draining more glaciated alpine and arctic catchments. The sediment provenance was mostly local Cretaceous marine and aeolian sediments; volcanic rocks are not an important source for suspended load. High Rb/Sr ratios for some samples suggested chemical weathering. Overall, this monitoring of proglacial hydrological and suspended sediment dynamics contributes to the dearth of such data from Antarctic environments and offers an insight to the nature of the proglacial fluvial activity, which is likely to be in a transient state with ongoing climate change.

## Keywords

James Ross Island; Antarctic Peninsula; hydrology; proglacial; suspended sediment; sediment sources; hydrometeorology; XRF

## Introduction

The Antarctic Peninsula (AP) has experienced rapid warming in the last decades. Mean annual air temperature has increased by 1.5°C since 1950's (e.g.; Vaughan et al., 2003; Turner et al., 2005) and melt seasons have become more prolonged (Barrand et al., 2013), resulting in intensified glacier surface melt (Abram et al., 2013; Barrand et al., 2013). Regional climate models estimate that as much as 66% of the total Antarctic snowmelt is related to AP (Kuipers Munneke et al., 2012). This climate change has coincided with disintegration of ice shelves (e.g.; Vaughan and Doake, 1996; Cook et al., 2005; Hambrey et al., 2015) and retreat (Cook et al., 2005) and thinning (Davies et al., 2012; Engel et al., 2012) of most of land-terminating glaciers in this area.

Glacier dynamics directly influence catchment hydrology via control on meltwater entering proglacial fluvial system. When meltwater from glaciers and/or snowpacks is concentrated into streamflows, fluvial processes often represent one of the most important factors shaping surrounding landscape (e.g.; Ballantyne, 2002; Carrivick et al., 2013). Moreover, they substantially control exchange of material, nutrients (Gooseff et al., 2002; Maurice et al., 2002; Conovitz et al., 2006) and organic matter (Spaulding et al., 1994; Simmons et al., 2013). Equally important is the function of proglacial hydrology as a habitat supporting the existence and evolution of flora and fauna (e.g.; Brown et al., 2007).

Comprehensive understanding of polar ecosystems demands consideration of all contributing parts. However, information on proglacial fluvial systems in Antarctica are exceptionally sparse in space and time, especially when it is considered that in 2005 the total area of deglaciated surfaces in Antarctica reached 44 890 km$^2$ representing 0.32% of the total continent's area (BAS, 2005). Antarctic proglacial stream hydrology has hitherto been studied mainly in the McMurdo Dry Valleys (e.g. Conovitz et al., 1998; Gooseff et al., 2007) but also in South Shetland Islands (Ibar, 1995; Rosa et al., 2014), Vestfold Hills (Bronge, 1999) and the Bunger Hills (Gibson et al., 2002). Unique studies are the long-term analyses of the proglacial discharge of Onyx River (Gooseff et al., 2007; Chinn and Mason, 2016), which is the largest river in Antarctica and where the lengthening of hydrologically active season (since 1968) has been most noticeable (Gooseff et al., 2007). Previous studies of proglacial hydrology in Antarctica have described water discharge variability in the context of solar radiation and air temperature (Bronge, 1999). Conovitz et al. (1998) found a relationship between solar position and diurnal discharge pattern on streams in Fryxell Basin and also suggested that catchment geomorphology represented an important factor determining differences between individual drainage systems.

Previous studies on proglacial fluvial sediment transport in Antarctica have almost exclusively focussed on solute load (Gooseff et al., 2004; Barker et al., 2013; Fortner et al., 2013). Suspended sediment transport was included into the complex study of proglacial zone of the Wanda Glacier on King George Island (Rosa et al., 2014). This study related suspended sediment concentration with increasing water discharge as a consequence of development of subglacial channelled drainage system during intensive glacier ice melting. During the ablation season 1984/85, bedload transport was studied in the Onyx River (Mosley, 1988) and during that time it was predominantly sand fractions transported downstream through the channel. High variability of bedload volume was ascribed to changes in sediment supply (Mosley, 1988).

Positioned near the north-eastern coast of the Antarctic Peninsula, James Ross Island (JRI) presently supports an unglaciated area of 552 km$^2$ and this represents 1.2% of the total ice-free area in Antarctica. Specifically, more than half of the presently ice-free surfaces (312 km$^2$; 12.5% of JRI) are located on the Ulu Peninsula and this situation allows a unique opportunity to monitor the rivers, to understand local and regional specifics of hydrological and suspended sediment dynamics, and thus ultimately of the proglacial landscape evolution in polar regions. With the over-arching motivation to improve the quantitative understanding of the effects of deglaciation on proglacial systems on Antarctic Peninsula, this study aims to (1) report the hydrological behaviour of two streams, which drain meltwater from small glaciers on JRI, and put them in the context with meteorological and climate information; (2) present an analysis of suspended sediment transport seasonal regime including a quantification of suspended sediment concentration (SSC) and calculate suspended sediment load (SSL) and suspended sediment yield (SSY); and (3) assess the nature of material provenance and grain-size for this proglacial fluvial suspended sediment transport.

## Study area

The climate on JRI is cold, polar continental, and strongly influenced by the orographic barrier of Trinity Peninsula, which obstructs moist relatively warm air from the western part of the AP region (Domack et al., 2003; King et al., 2003). The mean annual air temperature near to the Johann Gregor Mendel Station (JGM) at 10 m a.s.l. was -6.9°C in the period 2006–2014 (Hrbáček et al., 2016b). The warmest month is January with maximum temperatures exceeding +8.0°C, otherwise the temperature decreased below -30.0°C in July and August (Láska et al., 2011a). The mean daily global radiation is often higher than 250 W $m^{-2}$ in summer (December-February), with large day-to-day variation affected by the extended cyclonic activity in the circumpolar trough and orographic effects along the AP (Láska et al., 2011b). Precipitation in the northern part of JRI is mainly snow, mainly occurring from March to November (Hrbáček et al., 2016a), and estimated to be between 400 and 500 mm water equivalent per year (van Lipzig et al., 2004). However, most of the snow is blown away and the effective amount of precipitation remaining on land surface is thus much lower (Nývlt et al., 2016).

The catchments studied herein are located on the northern tip of the Ulu Peninsula on JRI and in the vicinity of JGM (**Figure 1A**). Bohemian Stream (**Figure 1B**) is a typical subsequent stream whose course is determined by selective headwater erosion of weak sedimentary strata (Johnson, 1932; Twidale, 2004) and flows NE transverse to the SE general dip of the Whisky Bay Formation bedding surfaces (Mlčoch et al., 2016). Algal Stream (**Figure 1C**) has a subsequent upper part of its catchment, which is parallel to the Bohemian Stream valley axis. Bohemian and Algal Streams catchments (**Figure 2**) lie mostly on Cretaceous marine sediments of James Ross Basin (Del Valle et al., 1992) with upper reaches lying on Neogene volcanic rocks of James Ross Island Volcanic Group (Nelson, 1975; Smellie et al., 2013) and Mendel Formation sediments (Nývlt et al., 2011). Cretaceous strata present in Bohemian Stream catchment are generally made of conglomerates and pebbly to silty sandstones (Ineson et al., 1986; Olivero et al., 1986; Whitham et al., 2006), while fine-grained sandstones and mudstones are more common in Algal Stream catchment (Olivero et al., 1986; Pirrie, 1989; Crame et al., 1991). James Ross Island Volcanic Group rocks cropping out in the studied catchments are represented by hyaloclastite breccia, subaerial basalt caprocks, dolerite dykes (Košler et al., 2009); hyaloclastite tuffs, volcanic ash, lapillistone and volcaniclastic sandstones to conglomerates are associated with Bibby Hill and crop out in the upper part of Bohemian Stream catchment only (Nehyba and Nývlt, 2014; Mlčoch et al., 2016), while the interbedded siliciclastic to volcaniclastic siltstones, diamictites and conglomerates are associated with the Lachman Crags-Berry Hill volcaniclastic delta and they crop out only in the upper part of Algal Stream catchment (Nehyba and Nývlt, 2015; Mlčoch et al., 2016). Mendel Formation sediments cropping out in lower reaches of both catchments are locally made of clast-rich diamictites and tuffaceous laminated siltstones to fine sandstones (Nývlt et al., 2011). Carbonate veins penetrates locally through Cretaceous sediments (Mlčoch et al., 2016).

The area of both catchments has been nearly ice-free for most of the Holocene (Nývlt et al., 2014). The glaciers in the upper part of both catchment might have advanced slightly during the Late Holocene neoglacial phase (Carrivick et al., 2012). Bohemian Stream (outlet coordinates: 63.80009° S, 57.88096° W), together with the most prominent right tributary Dirty Stream, is fed mainly from small hanging glaciers (northern and southern) and snowfields located below the north-east cliff of Johnson Mesa (CGS, 2009). Southern hanging glacier, together with snowfields, represents the source of meltwater also for Algal Stream (outlet coordinates: 63.79903° S, 57.87861° W). The catchments are divided by cuesta formed by more resistant upper Hidden Lake Formation strata. Basic morphometric parameters of each catchment are summarized in **Table 1**.

## Material and methods

All meteorological data were obtained from an automatic weather station (AWS) located in the vicinity of JGM at 10 m a.s.l. and near the Bohemian Stream estuary and Algal Stream delta. Air temperature (AT) were measured at 2 m above ground using EMS 33 sensor (accuracy ±0.15°C; EMS Brno, CZ). Ground temperature at 5 cm depth (GT) was measured using resistance thermometers Pt100/8 (accuracy ±0.15°C; EMS Brno, CZ). Air pressure and global radiation (GR) were measured using a TMAG 518 N4H barometer (accuracy ±0.5 hPa; CRESSTO, CZ) and an EMS11 radiometer (calibration error <7%; EMS Brno, CZ). Snow precipitation and snow cover duration during the study period were determined by two different approaches. Snow thickness data were obtained using ultrasonic depth sensor (accuracy ±1 cm; Judd Communication, USA) every 2 hours. The spatial evolution and changes of snow cover were determined from time-lapse camera (ACORN, USA) capturing the Bohemian Stream valley. All meteorological data were measured and recorded at 30 min intervals unless otherwise stated using V12 datalogger (EMS Brno, CZ) over the period from 8th January 2015 to 18th February, 2015.

Basic field hydrological monitoring was carried out on one profile set for each stream (**Figure 1A**). Profiles were chosen to fulfil essential requirements for the best possible conditions – stable river bed profile, low flow velocity turbulence. Discharge measurements were acquired using standard velocity-area method (e.g.; Herschy, 2009); 11 measurements on Bohemian stream and 7 measurements on Algal stream were performed during January and February, 2015 with Flowtracker Handheld Acoustic Doppler Velocimeter (SonTek, USA). Manual discharge measurements were taken in order to cover the full range of discharge conditions during the melt season. This ranges on Bohemian Stream from 15.5% discharge up to 88.5% discharge of the observed melt season hydrograph. Algal stream measurement covers the range from 10.3% up to 91.8%. Hydrostatic pressure sensors DipperLog F100/M30 (accuracy of ±0.05%; Heron, CA) were used for automatic readings of instantaneous stream stage at 30 min intervals. Automatic readings of water pressure were adjusted using local air pressure to water depth/stage (h) and then transformed via a stage-discharge rating curve to give a continuous discharge (Q) record. Calculated rating equations were $Q = 9.127h^{2.142}$ ($r^2 = 0.906$) for Bohemian Stream and $Q = 0.00005e^{19.56h}$ ($r^2 = 0.983$) for Algal Stream, where e stands for the base of the natural logarithm. The exponential function for rating curve on Algal Stream was used to cover the somewhat nonstandard conditions of channel shape. The channel is rather wide during the high discharges leading to rather small increase in water level. This was intended to be compensated by the exponential function with better fitness during high stages (most important for suspended sediment transport). The average discharge measurement uncertainty according to ISO procedure (ISO, 2003) is 3.3% for Bohemian Stream and 3.9% for Algal Stream. Rating curve uncertainty for Bohemian Stream is 9.1% and 1.2% for Algal

Stream respectively, which gives the total calculated discharge uncertainty 12.4% for Bohemian Stream and 5.5% for Algal Stream.

The hydro-meteorological relationships between GR, AT, GT and water discharge were studied using correlation analysis (e.g.; Wolfe and English, 1995; Hodgkins, 2001). All correlation analysis were tested at the 95% significance level for three different cases a) mean daily values b) daily maximums c) actual values.

Suspended sediment sampling was conducted on the discharge measurement sites. Stream samples of 220 ml were collected during the whole campaign. Samples were then processed directly in the lab at JGM. All samples were filtered with hand-held vacuum pump through pre-weighed Whatman 3 µm filters. Samples were left for drying in the ambient environment for 48 h and then weighed with the precision of 0.0001 g. Continuous SSC time-series were calculated based on ordinary regression analysis of logarithmical transformed data of discharges and in situ sampled SSC. The error in determination of SSC is expected to be less than 1% and is far lower than one related to statistical calculation. On Bohemian Stream, 59 samples were taken including two 24-hour cycles with 1-hour sampling interval of measurements. 14 samples were acquired from Algal Stream. The diurnal pattern of SSC was observed through hourly sampling on 29th/30th January and 6th/7th February, 2015. January cycle represents high discharges in the peak of ablation season. February date captures higher discharge by the end of ablation season when the fine-grain material exhaustion for fluvial transport could be expected.

Analyses of SSC and SSL were carried out only on Bohemian Stream due to a limited number of samples from Algal Stream. Statistical significant correlation ($r = 0.79$) between log-log transformed SSC and discharge for Bohemian Stream permitted interpolation of time series of SSC using exponential equation ($\log SSC = 4.121 * e^{0.822 \log Q}$). Manual sampling was done opportunistically being limited by present local atmospheric conditions and expedition logistics. This resulted in lack of data from the beginning of melt season. Also the sampling was done manually. Therefore, an error arose reaching ±30% for mean values (observed mean SSC/modelled mean SSC is 898/629 mg $L^{-1}$). Positive sum of residuals suggests the underestimation of calculated SSC. SSL was calculated as SSC multiplied by discharge and thus SSL values are biased by the error related to SSC calculation. SSY was calculated as SSL divided by catchment area.

In order to trace the provenance and grain-size of the suspended load sampled in both Bohemian and Algal Streams we measured relative contents of the main lithophile elements by means of X-ray fluorescence method. X-ray fluorescence measurements of dried suspended load were done using portable Innov-X System DELTA analyser. As the amount of suspended material sampled was not sufficient for grain-size analysis we used its geochemical proxy based on the elemental ratio of Zr/Ti. The acquired data of elemental composition, together with the most commonly used ratios of Rb/Sr and Sr/Ca were quantitatively compared with corresponding data from different geological units of the northern ice-free part of JRI to assess the provenance of the material.

## Results

### Climatic context

Mean AT in the period between 8th January and 18th February reached 1.1°C (**Figure 3B**). AT regularly dropped below 0°C during night hours with absolute minimum of -4.8°C (18th January). The warmest period was observed between 26th January and 1st February, when seasonal maximum temperature (10.4°C) was observed on 29th January. Mean GT reached 5.4°C. GT remained positive for nearly whole study period with only three short periods, when temperature dropped below 0°C. The warmest period was observed between 24th January and 1st February, however the maximum GT of 16.5°C occurred in 6th February.

The GR record is dominated by clear-sky days (**Figure 3A**). The mean value of GR in period between 8th January and 18th February was 218.5 $W\ m^{-2}$. The maximum GR reached 1028.3 $W\ m^{-2}$ (29th January). However, daily maximum GR exceeded 700 $W\ m^{-2}$ on 25 other days. The lowest daily maximum of GR was 142.9 $W\ m^{-2}$ (10th February) and this was observed on a very overcast day with snowfall. However, snow cover with only limited thickness remains in the landscape for short time periods during the summer and has thus limited effect on the stream flows.

### Discharge

Continuous discharge measurements (**Figure 3C**) were acquired from 9th January (Bohemian Stream) and 11th January (Algal Stream) until 17th February (both streams). During this period, mean daily discharge reached 0.190 $m^3\ s^{-1}$ for Bohemian Stream (**Table 2**). The maximum daily discharge (**Figure 4**) occurred on 27th January (0.464 $m^3\ s^{-1}$) and the minimum on 11th February (0.027 $m^3\ s^{-1}$). The absolute maximum (0.645 $m^3\ s^{-1}$) was measured at $17^{30}$ on 28th January. The mean daily discharge of Algal Stream was 0.063 $m^3\ s^{-1}$, and the maximum was 0.155 $m^3\ s^{-1}$ (27th and 29th January). The absolute maximum (0.346 $m^3\ s^{-1}$) was measured at $19^{00}$ on 21st January. The daily minimum of Algal stream was 0.011 $m^3\ s^{-1}$ (17 January). Total runoff for 40 days was 655 574 $m^3$ for Bohemian catchment and equivalent to a specific discharge of 76 mm $month^{-1}$ when related to catchment area. Algal Stream catchment measurements covered 38 days. During this period total runoff was 206 924 $m^3$, or 60 mm $month^{-1}$.

Melt season peaked between 24th and 31st January, when the highest discharges were recorded. Periods with substantially lower discharges were documented between 12th and 18th January and 9th and 13th February for Bohemian Stream. Algal Stream experienced a drop in discharges between 11th and 17th January. Later minimum started on 7th February and whereas on Bohemian Stream it was followed by certain increase in discharges after 13th February, on Algal Stream discharges stayed very low until the end of studied period.

Both streams reached peak daily discharge at around $17^{00}$. An intriguing shift of the maximum to earlier times of day ($10^{00}$–$12^{00}$) was observed for both streams in the beginning of studied period until 17th January. The minimum discharge is more variable for both streams (median is $8^{00}$ for Bohemian Stream and $10^{00}$ for Algal Stream).

Overall, Bohemian Stream carries three to four times more meltwater than Algal Stream. The pattern of hydrographs is, nonetheless, very similar. Correlation between discharge at both streams was high and significant ($r = 0.88$). Strong and significant correlations existed between maximum ($r = 0.81$) and minimum ($r = 0.92$) daily discharges. Relationships between hours of maximum ($r = 0.54$) and minimum ($r = 0.42$) discharge were weaker in comparison with other variables, however also statistically significant.

### Hydrometeorological context

Correlation analysis showed a very low effect of GR in general on discharge for both streams (**Table 3**). The strongest and significant relationship was observed in the case of maximum daily GR vs. maximum daily discharge for both Bohemian ($r = 0.55$) and Algal ($r = 0.51$) Streams. No significant relationship was found in the case of mean daily GR vs. mean daily discharge with r = 0.30 (Bohemian Stream) and r = 0.31 (Algal Stream). The relationship between actual values of GR vs. discharge was rather weak (but significant), r = 0.39 (Bohemian Stream) and 0.35 (Algal Stream) (**Table 4**). Strong and significant relationships were observed between mean daily AT vs. mean daily discharge (r = 0.84 for Bohemian Stream and r = 0.73 for Algal Stream) and maximum daily AT vs. maximum daily discharge (r = 0.83 for Bohemian Stream and r = 0.69 for Algal Stream). A weaker, but significant relationship was found between actual AT vs. discharge, r = 0.61 (Bohemian Stream) and r = 0.54 (Algal Stream). Similarly, a strong and significant relationship was observed between mean daily GT vs. mean daily discharge (r = 0.84 for Bohemian Stream and r = 0.77 for Algal Stream), between maximum daily GT vs. maximum daily discharge (r = 0.77 for Bohemian Stream and r = 0.61 for Algal Stream), and between actual GT vs. actual discharge with r = 0.75 (Bohemian Stream) and r = 0.66 (Algal Stream).

### SSC and SSY

SSC were highly variable ranging between 0 and 2927.2 mg $L^{-1}$ (**Table 2**). The highest SSC occurred during high water discharges between 24th January and 2nd February (**Figure 3D**). Water discharges reached up to 0.6 $m^3 s^{-1}$ in this period. Maximum values of SSC during the first diurnal cycle (29th/30th January) were reached between $16^{00}$ and $19^{00}$ and ranged from 2807.5–2971.1 mg $L^{-1}$. The second measured SSC diurnal cycle (6th/7th February) experienced maxima in $16^{00}$ and $17^{00}$ with values of 1024.7 and 890.3 mg $L^{-1}$, respectively. Both SSC diurnal cycles exhibited hysteresis, but whereas the first diurnal cycle had a counter clockwise pattern, the latter was clockwise (**Figure 5**).

The overall range of SSL values from 53 to 59092 kg $day^{-1}$ emphasises the seasonal variability of fluvial sediment transport (**Figure 6**). During the studied period, 388 t of material left Bohemian Stream catchment via the suspended sediment transport, and this represents 301 t $month^{-1}$ and a SSY of 46.5 t $km^{-2}$ $month^{-1}$. Given an ablation season spanning ~ 4 months, the estimated yearly SSY would be 186 t $km^{-2}$ $yr^{-1}$.

### Suspended load grain-size and provenance

A covariant plot of Zr/Ti versus discharge (**Figure 7A**) shows a significant difference of geochemical composition between the studied catchments with respect to water discharge. Regression analysis shows a statistically significant ($p < 0.05$) effect of discharge on the Zr/Ti ratio for Algal Stream suspended load ($r^2 = 0.50$), while no statistically significant relationship was found between discharge and this ratio for Bohemian Stream suspended load (**Figure 7A**). The ratios of Rb/Sr and Sr/Ca have been calculated and plotted in covariant plot (**Figure 7B**), where they are compared with corresponding data from different geological units of the northern ice-free part of JRI, namely the sandstones from Whisky Bay, Hidden Lake and Santa Marta formations of the James Ross Basin, basalts and tuffs of the James Ross Island Volcanic Group, diamictites of the Mendel Formation, marine terrace gravely sand and aeolian sand from lower reaches of the Bohemian Stream catchment. Suspended load from the Bohemian Stream displays rather a large scatter whereas in contrast the geochemical data of the suspended load from Algal Stream shows much smaller variability (**Figure 7B**).

## Interpretation and discussion

### Discharge

Studies on hydrology in Antarctica are very sparse as mentioned above and thus it is difficult to relate streams presented here with the others. Nonetheless, comparison with streams in the

McMurdo Dry Valleys (e.g.; Gooseff et al., 2007; Fortner et al., 2013) suggests a longer melt season and a later timing of peak discharges in our study. Specifically, the flow season in the McMurdo Dry Valleys usually ceases in late January/early February whereas our peak discharges occurred in late January and we recorded continuous flow until beginning of March.

### Hydroclimatological context

The results show close relationship between AT and GT and water discharge in contrast to weak relationship of GR and water discharge. This is consistent with the studies from Svalbard (e.g.; Hodgkins, 2001; Hodgkins et al., 2009), or Canadian Arctic (Wolfe and English, 1995), which described temperature as a more important factor on discharge than the radiation. In general, we found the effect of mean and maximum daily AT and GT on water discharge statistically similar (**Table 3**), which were expected due to a very close relationship of these parameters observed on JRI (Hrbáček et al., 2016c). However, when studying actual values, relationship between GT and discharge was much closer than in the case of AT (**Table 4**). This fact was caused by the variability of discharge in temperatures close and below 0°C. Discharges on Bohemian and Algal Streams did not decrease to 0 $m^3 s^{-1}$ in cases when AT dropped below 0°C, while GT remained positive. The runoff completely stopped (frozen) only in periods when both AT and GT dropped below 0°C. This behaviour of both streams suggest that the active layer represents an important water reservoir for polar streams, which is consistent with findings from the Arctic (e.g.; Woo and Young, 1997; Woo et al., 2008; Cooper et al., 2011).

The overall low effect of GR on water discharge was caused by a high variability of water discharge during clear-sky days (maximum daily GR > 700 W $m^{-2}$) as well as overcast days (maximum daily GR < 400 W $m^{-2}$) (**Figure 3**), which did not respect the variability of GR. We observed very low daily discharges during clear-sky days, while relatively high discharges were observed during overcast days. From this perspective, the positive AT and GT are the triggers of discharge increase, rather than the GR. This finding is in contradiction with studies from other Antarctic sites (e.g.; Conovitz et al., 1998; Bronge, 1999), where GR was the main factor affecting water discharge.

The water discharge during the study period was only marginally affected by precipitation, or melting of fresh snow, which is in contrast to observations from the Arctic (e.g.; Woo and Young, 1997; Young et al., 1997; Hodson et al., 1998, Hodgkins, 2001). The maximum snow thickness did not exceed 4 cm and melted rapidly. In total, six snowmelt periods were observed between 15th and 20th January when the maximum discharge reached 0.26 $m^3 s^{-1}$ and 0.18 $m^3 s^{-1}$ on Bohemian Stream and Algal Stream, respectively. Maximum water discharges during three snowmelt periods between 9th and 11th February reached 0.05 $m^3 s^{-1}$ only on both streams.

### SSC and SSY

The high SSC observed in this study can be explained by the abundant availability of fine-grained material due to aeolian activity and also due to the high erodibility of sediments and rocks within the Bohemian Stream catchment. The presence of less-consolidated hyaloclastite tuffs, volcanic ash, lapillistone and volcaniclastic sandstones to conglomerates (Nehyba and Nývlt, 2014) of the Bibby Hill volcanic cone represent an easily mechanically eroding material, which is blown away by prevailing S-E winds being subsequently deposited as wind-blown silty sands (Davies et al., 2013; Stachoň et al., 2014) on snowpatches, directly in moist places of the Bohemian Stream valley, or filling deep gorges (**Figure 2**) of right obsequent tributaries of Bohemian Stream.

Low discharges clearly decrease the importance of fluvial processes in denudation of deglaciated surfaces in Bohemian Stream catchment. However, SSY is relatively high in comparison with studied rivers draining deglaciated catchments in Scandinavia, Svalbard and Canadian Arctic (Bogen, 1996; Braun et al., 2000; Bogen and Bønsnes, 2003; Cockburn and Lamoureux, 2008). More glaciated catchments are supplied by more melt-water and thus are capable of exerting larger geomorphic effect than documented in Bohemian Stream despite often lower SSC. Higher SSY were reported in arctic (Stott and Grove, 2001; Bogen and Bønsnes, 2003; Hodgkins et al., 2003), as well as alpine (Bhutiyani, 2000; Geilhausen et al., 2013; Leggat et al., 2015) rivers.

A hysteresis effect for suspended sediment transport has been well described for several decades (e.g.; Østrem, 1975; Bogen, 1980). Clockwise hysteresis appears when peak SSC occurs before peak water discharge. It suggests very short distances of transported sediment (Orwin and Smart, 2004). Anticlockwise hysteresis is due to peak water discharge occurring before peak SSC and suggests more distant sources for sediment transport or that sediment transport is supply-limited (Stott and Mount, 2007). A number of studies on proglacial streams has confirmed diurnal clockwise hysteresis (Hodson and Ferguson, 1999; e.g. Geilhausen et al., 2013). In our study, the observed anticlockwise hysteresis for the first day of measurements (29th/30th January) followed by a clockwise hysteresis day one week later (6th/7th February) might suggests the spatio-temporal variability in the in-channel and off-channel material availability (Klein, 1984) within the Bohemian Stream catchment. For detailed interpretation of this process more observations are needed.

### Suspended load grain-size and provenance

The Zr/Ti ratio is often used for granulometric changes of siliciclastic input (e.g.; Kylander et al., 2013). Zirconium is normally enriched in medium to coarse silts, while Ti is associated with finer fraction (Taboada et al., 2006). This means that increasing Zr/Ti ratio indicates coarser (siltier) material, which fits with the discharge increase as shown by regression analysis for Algal Stream suspended load. On the other hand, the Bohemian Stream suspended load samples scatter in the covariant plot without any relationship between the discharge and the Zr/Ti ratio, which might imply multiple material sources (provenance) and this proxy is insensitive to grain.size changes in such a setting.

Comparison with corresponding geochemical data (the Rb/Sr versus Sr/Ca covariant plot) from geological units cropping out in both catchments could be used to track the material sources (provenance) of suspended load in both streams. Bohemian Stream suspended load samples show rather large scatter in both covariant plots implying variable sources of the material. The most likely sources of the Bohemian Stream suspended load are Cretaceous siliciclastic sediments of James Ross Basin, Mendel Formation glacigenic to marine sediments, and gravely sand of the marine terrace in the lowermost reaches of Bohemian Stream. This material could have been washed directly to the stream, or deposited by aeolian action. On the contrary, the Ca-rich volcanic rocks of James Ross Island Volcanic Group (Košler et al., 2009) have not been an important source of the material for suspended load in both streams. Santa Marta Formation sedimentary rocks cropping in the upper and middle reaches of the Algal Stream represent the most important source for the Algal Stream suspended load material. The single-source Algal Stream suspended load coarsens with increasing discharge as shown by the covariant plot of Zr/Ti versus discharge.

High variability of Rb/Sr ratio within the suspended load samples from Bohemian Stream shows on the chemical weathering of some material washed by Bohemian Stream. Strontium is much easier leached by chemical weathering than rubidium, the weathering relic would thus have higher Rb/Sr ratio (Dasch, 1969; Chen et al., 1999). The Rb/Sr ratios have thus been used as an indicator of weathering intensity in catchments (Xu et al., 2010). Higher Sr leaching comparing to Ca, which is also easily weathering element, can be found in approx. 1/4 of the Bohemian Stream suspended load samples, but has not been detected for samples from Algal Stream.

## Summary and conclusions

This study brings together the first information on the hydrological and suspended sediment regimes of streams on the Ulu Peninsula, James Ross Island (JRI), which is a location experiencing the rain shadow of the Antarctic Peninsula (AP). The summary of our findings is that:

- The mean discharge of Bohemian Stream reached 0.19 $m^3 s^{-1}$ (76 mm $month^{-1}$) during the studied period (8th January to 18th February). The water discharge of Algal Stream was one order of magnitude smaller and reached 0.06 $m^3 s^{-1}$ (60 mm $month^{-1}$). The timing of peak discharges in late January/early February and continuous runoff persisting until early March points to a prolonged melt-season (~ 4 months) in comparison with records from the more continental McMurdo Dry Valleys.
- The daily regime of proglacial water discharge on both streams strongly correlated with air temperature (AT) and ground temperature (GT), which is consistent with results from Svalbard and Canadian Arctic. Runoff completely stopped only in short time periods when both AT and GT dropped below 0°C. This suggests that an active layer of permafrost represents an important reservoir of water for streams' runoff. Unlike studies from McMurdo Dry Valleys, we found the effect of global radiation on seasonal variation in discharge as negligible. Effect of snow falls on the water discharge during ablation season was negligible due to its quick melt caused by positive GT and small thickness of snow cover (<4 cm).
- Suspended sediment concentrations (SSC), studied on Bohemian Stream, could be described as function of discharge. SSC reached very high values (up to 2927 mg $L^{-1}$), and these high values could be explained by a high availability of fine-grained material due to aeolian activity and due to the high erodibility of local rocks. Despite limited meltwater runoff volumetrically, suspended sediment yield (~186 t $km^{-2} yr^{-1}$) is relatively high in comparison with other (nearly) deglaciated catchments in arctic and alpine environments.
- Observed anticlockwise hysteresis during diurnal manual sampling on 29th/30th January followed by clockwise hysteresis one week later 6th/7th February suggests varying spatio-temporal material availability within the catchment.
- The sources of suspended load in both streams are mostly local Cretaceous strata, Mendel Formation diamictites and laminites and Holocene marine and aeolian sediments. James Ross Island Volcanic Group rocks are not an important source for suspended load in studied streams.
- The high Rb/Sr ratios for some suspended load samples from Bohemian Stream point to chemical weathering of superficial rocks and regolith but this chemical weathering was not found to be important for Algal Stream catchment.

Overall, proglacial fluvial systems in nearly deglaciated catchments located within the rain shadow zone of the Antarctic Peninsula have activity restricted to few months during short summer. Meltwater runoff is driven by surface snow/ice melt induced by positive air temperatures and by positive ground temperatures, which affects an active layer of permafrost. Meltwater is transferred through low-gradient braided streams into the sea. Due to the high erodibility of local rocks and due to intensive aeolian activity, the volume of sedimentary material that is available for fluvial transport is high, even though material availability varies temporarily. However, the low water discharge substantially decreases transport capacity producing a low sediment yield. This quantification and conceptualisation of polar proglacial fluvial systems offers further implications for comprehensive understanding of long-term evolution of deglaciated landscapes in Antarctica, which have been growing in importance as a consequence of ongoing climate change. Furthermore, proglacial streams represent habitats for living organisms and thus interrelations of processes within fluvial systems are needed to be described in order to fully comprehend current biological and microbial activity in Antarctica.

This novel study on the Ulu Peninsula of James Ross Island linked geological and climatic information with the hydrological behaviour of two proglacial fluvial systems and thus contributed a quantitative understanding of the processes driving landscape evolution during a progressively lengthening melt season. We propose that further work concerning water sources, spatio-temporal variability in water temperature and water chemistry are necessary in order to achieve a quantification of the linkages between these meltwater runoff and suspended sediment processes and their relations to ecology.

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# Tables

**Table 1:** Summary of basic morphometric parameters for catchments and streams. The values for Algal Stream represent sub-catchment delimited by position of discharge measurement site (see **Figure 1**).

| | **area (km$^2$)** | **glacierized area (%)** | **mean altitude (m a.s.l.)** | **mean catchment slope (°)** | **stream length (km)** | **stream gradient (m km$^{-1}$)** |
|---|---|---|---|---|---|---|
| Algal | 2.82 | 2 | 187.48 | 12.94 | 1.65 | 30.3 |
| Bohemian | 6.47 | 6 | 131.90 | 10.37 | 3.26 | 39.9 |

**Table 2:** Descriptive statistics of discharge (Q – in m$^3$ s$^{-1}$), suspended sediment concentrations (SSC – in mg L$^{-1}$), and suspended sediment load (SSL – in kg day$^{-1}$). Values of suspended sediment yield (SSY – in t km$^{-2}$ yr$^{-1}$) and erosion rate (ER – in mm yr$^{-1}$) are included. SD stands for standard deviation.

| | Bohemian Stream | Algal Stream |
|---|---|---|
| $Q_{mean}$ | 0.19 | 0.06 |
| $Q_{max}$ | 0.66 | 0.35 |
| $SSC_{mean}$ | 307 | - |
| $SSC_{max}$ | 2927 | - |
| $SD_{SSC}$ | 414 | - |
| $SSL_{mean}$ | 9512 | - |
| $SD_{SSL}$ | 13699 | - |
| $SSL_{min}$ | 53 | - |
| $SSL_{max}$ | 59092 | - |
| SSY | 186 | - |
| ER | 0.1 | - |

**Table 3:** Correlation matrix between mean and maximum (max) daily values of air temperature (AT), ground temperature at 5 cm (GT) and global radiation (GR) vs. discharge (Q) on Bohemian Stream (BS) and Algal Stream (AS). Bold values indicate significance at $p < 0.05$

| | $AT_{mean}$ | $GT_{mean}$ | $GR_{mean}$ | $AT_{max}$ | $GT_{max}$ | $GR_{max}$ |
|---|---|---|---|---|---|---|
| $Q_{mean\ BS}$ | **0.84** | **0.84** | 0.3 | **0.81** | **0.74** | **0.44** |
| $Q_{mean\ AS}$ | **0.73** | **0.77** | 0.31 | **0.74** | **0.66** | **0.48** |
| $Q_{max\ BS}$ | **0.84** | **0.84** | **0.44** | **0.83** | **0.77** | **0.55** |
| $Q_{max\ AS}$ | **0.65** | **0.68** | **0.33** | **0.69** | **0.61** | **0.51** |

**Table 4:** Correlation matrix between actual measurements of air temperature (AT), ground temperature at 5 cm (GT) and global radiation (GR) vs. discharge (Q) on Bohemian Stream (BS) and Algal Stream (AS). Bold values indicate significance at $p < 0.05$

| | $Q_{BS}$ | $Q_{AS}$ | GT | AT | GR |
|---|---|---|---|---|---|
| $Q_{BS}$ | **-** | **0.83** | **0.75** | **0.61** | **0.39** |
| $Q_{AS}$ | **0.83** | **-** | **0.66** | **0.54** | **0.35** |
| GT | **0.75** | **0.66** | **-** | **0.71** | **0.72** |
| AT | **0.61** | **0.54** | **0.71** | **-** | **0.30** |
| GR | **0.39** | **0.35** | **0.72** | **0.30** | **-** |

## Figure captions

**Figure 1:** A – Regional settings of Bohemian and Algal Streams catchments. B – 3-dimensional model with delimitation of Bohemian and Algal Streams catchments and positions of automatic weather station and hydrometric stations.

**Figure 2:** Geology of Bohemian and Algal Streams catchments as delimited in Figure 1B (modified from Mlčoch et al., 2016).

**Figure 3:** Variability of (a) air temperature, ground temperature at 5 cm and (b) discharges (Q) on Algal Stream and Bohemian Stream in the period 8th January to 18th February 2015.

**Figure 4:** Maximum and minimum discharge for each day and daily amplitude for Bohemian Stream (A) and Algal Stream (B). Time of discharge´s maximum (hQmax) and minimum (hQmin) for Bohemian Stream (C) and Algal Stream (D). Hours are given in local time (UTC-4).

**Figure 5**: Hysteresis effect during two diurnal cycles on Bohemian Stream.

**Figure 6:** Suspended sediment load SSL ($t.day^{-1}$) and daily run off calculated for Bohemian Stream.

**Figure 7:** Covariant plots of Zr/Ti versus discharge (A) indicates grain-size changes of suspended load with discharge changes, and Rb/Sr versus Sr/Ca (B) with corresponding ratios for individual geological units within the studied catchment for suspended load from Bohemian and Algal Stream.