Particle Size Characteristics of Fluvial Suspended Sediment in Proglacial Streams, King George Island, South Shetland Island

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Abstract. In this study, the characterization of particle size distribution of suspended sediment that is transported by streams (Ornithologist Creek, Ecology Glacier Creeks, Petrified Forest Creek, Czech Creek, Vanishing Creek, Italian Creek) in the area of the Arctowski Polish Antarctic Station is presented. During the first period of the summer season, the aforementioned streams are supplied by the melting snow fields, while later on, by thawing permafrost. The water samples were collected from the streams at monthly intervals during the Antarctic summer season (January - March) of 2016. The particle size distribution was measured in the laboratory with a LISST-25X laser diffraction particle size analyser. According to Sequoia Scientific Inc., LISST-25X can measure particle sizes (Sauter Mean Diameter) between 2.50 and 500 μm. The results of particle size measurements were analysed in relation to flow velocity (0.18–0.89 m/s), the cross-sectional parameters of the streams, suspended sediment concentration (0.06–167.22 mg/dm³) and the content of particulate organic matter (9.8–84.85%). Overall, the mean particle size ranged from 28.8 to 136 μm. The grain size of well-sorted sediments ranged from 0.076 to 0.57, with the skewness and kurtosis values varying from -0.1 to 0.4, and from 0.67 to 1.3, respectively. Based on the particle size characteristics of suspended sediment, the streams were divided into two groups. For most of the streams, the sediment was very well sorted, while fine sand and very fine sand were dominant fractions displaying symmetric and platykurtic distributions, respectively. Only in two streams, the suspended sediment consisted of silt-size grains, well or moderately well sorted, with coarse-skewness and mostly mesokurtic distribution. The C-M chart suggested that the transportation processes of suspended sediment included the suspended mode only. The grain-size distribution of suspended sediment was mainly influenced by the stream runoff, surface sediment type and biological processes.

1. Introduction
At present, Western Antarctica is one of the most rapidly warming areas on Earth. In the last 50 years, the air temperature during the Antarctic winter increased on average by up to 6°C [1]. The significant changes in the environmental components of this region [2] have been observed as indirect effects of warming, including strong ablation, glacial retreat, and decreased nival areas. As a consequence, the water circulation has also changed, i.e. both the surface runoff and the transport of sediment in streams increased. The altered characteristics of sedimentary material transported via streams into Admiralty...
Bay further affect the processes that take place in the marine environment, e.g. the variation in suspension concentration affecting the water transparency [3], the effect on benthic communities [4], or sedimentation processes. In the case of sedimentation processes, it is particularly significant to determine the grain-size of fractions which undergo transportation in the form of suspended matter.

The watercourses on King George Island have been described with regard to many aspects, mainly dealing with the occurrence of cyanophyta and other algae, and nutrients. The hydrological issues, i.e. flow characteristics, and the discharge of ions and suspended matter have been presented in detail by Zwoliński [5].

2. Study area
King George Island, the largest and most northern and eastern island of the South Shetland Archipelago (Figure 1), has a surface area of ca. 1 250 km² [6]. The length of the island is 64.8 km, while its width is ca. 40 km [7]. The island is mostly formed from volcanic rocks, i.e. basalt and andesite, pyroclastic rocks, loose volcanic sediments as well as gabbro and granodioric rocks [8]. Over 90% of the island’s surface is ice-covered, however, in the past decade, a noticeable increase in the ice-free surface areas has been observed [9]. In the years 1979-1999, the ice coverage in the study area decreased by half [10]. One of the underlying causes of the observed changes is the aforementioned increase in the annual average air temperature in this area.

Field observations were mainly conducted in the vicinity of Henryk Arctowski Polish Antarctic Station, which is located on the western coast of Admiralty Bay. Close to the station, there is a well-developed system of streams that drains the ice-free areas during the summer season (figure 1). The streams belonging to the Admiralty Bay catchment area are periodically supplied in water due to glacial ice and snow ablation and permafrost melting. The following watercourses are located in this area: Petrified Forest Creek, Czech Creek, Vanishing Creek, Italian Creek, Ecology Creeks (streams originating from Ecology Glacier) and Ornithologist Creek. The streams are relatively short (length < 1.5 km), with rocky, gravel and sandy beds. They flow on surfaces devoid of plants [12]. Ornithologist Creek is an exception because it runs through the area rich in plants such as mosses, while the lower part of the stream even undergoes eutrophication. Ornithologist Creek flows close to the largest

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Figure 1. Study area, location of sampling stations (adapted from [11])

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penguin colony on the island and then discharges into a small lake nearby the coast of Admiralty Bay. Over short distances, some streams disappear in narrow thermokarst dips [13]. With an exception of Ecology Glacier Creeks, the catchment area of the analysed streams is not covered with ice (Figure 2).

Figure 2. Investigated streams (photo by Joanna Plenzler)
(A-Petrified Forest Creek, B-Ornithologist’s Creek, C-Italian Creek, D-Czech Creek, E-Vanishing Creek, F-Ecology Glacier Creek II, G-Ecology Glacier Creek I)

The investigated creeks are seasonal. The water flow is usually observed in the summer months, i.e. from December until March, although, it can also start in October and extend into April. January is the warmest month in spring (average temperature of 2.4°C), characterized by increased rainfall [14, 15]. The water flow in the streams has also been observed during mid-winter thaws [5].

3. Methods
Field observations were carried out within the framework of hydrological monitoring on Jan 9, Feb 11 and Mar 21, 2016. In January, the measurements were performed at Petrified Forest Creek, Ornithologist Creek and Ecology Creeks, while in February and March, all watercourses were assessed.

The geometry of stream bed and the flow velocities were measured along the specified profiles in order to calculate the water discharge. Water samples were collected each time to determine the concentration and grain-size of fractions transported in suspension. The measurements of water temperature were also performed.

In the laboratory at Arctowski Polish Antarctic Station, all the collected samples, with a volume ranging between 250 and 900 ml, were individually filtered through Whatman grade GF/F glass microfiber filters. The filters were frozen prior to further analysis at the Oceanography Institute, University of Gdansk. The share of organic matter in suspension via loss on ignition (LOI) method and the concentration of suspended matter (mg/dm³) were determined based on the filtered material.

The water samples preserved with Lugol’s solution were stored and transported at low temperatures until analysis. The particle size analysis was performed under laboratory conditions by means of LISST-25X Suspended Sediment Sensor (Sequoia Scientific, Inc.). The sensor has been designed for conducting both in situ and laboratory measurements of particle size distribution [16]. The Sauter Mean Diameter (SMD) was the main parameter measured in the range 2.5–500 µm and in the subrange 63–500 µm; the volume concentration, optical transmission and depth at which the measurement is made were also determined. During the laboratory tests, each sample was analyzed in the test chamber with a volume of 1.35 l. In order to avoid flocculation, each sample was treated with dispersant, while the test chamber was placed on a magnetic stirrer to maintain the homogeneity of the analysed solution [17].
4. Results and discussion

4.1. Water velocities and discharges of analysed streams
During the sampling period, Ecology Glacier Creeks were characterized by the highest water velocities and very low variation of flow (0.64–0.89 m/s). In the case of Ornithologist Creek and Czech Creek, the observed differences in velocity values were also small (0.22–0.28 m/s). The remaining streams displayed the highest variation of water flow (0.15–0.67 m/s). The season-dependent changes in the amount of water discharged into the streams resulted in the altered bed parameters of streams flowing into Admiralty Bay. The largest values of bed width and depth were observed in January and February, which coincided with the highest water discharge. The volume flow rate in the analysed streams varied from 4.86 to over 127 dm$^3$/s (Figure 3).

The investigations conducted in the years 1990–1993 led to the conclusion that during the summer season, the flow rates of watercourses within the ice-free catchment areas vary from a couple to a couple hundreds of dm$^3$/s, while in the case of watercourses in ice-covered catchment areas or streams running around the frontal margin of the glacier, the flow rates reach even a couple of m$^3$/s [5].

![Figure 3. Flow velocities and discharges of analysed streams](image)

In June 1991, the flow rates measured in Petrified Forest Creek during mid-winter thaw varied in dependency on the location of measuring station from 5 to 23 dm$^3$/s, while those measured in Ornithologist Creek and Ecology Glacier Creeks, from 12 to 25 dm$^3$/s, and from 33 to almost 100 dm$^3$/s, respectively [5]. Due to different sampling date, the aforementioned values are lower than those measured during the summer season of 2016. In the years 1990-1993, the measurements were conducted systematically from October until April. In this period, the flow values in Ecology Glacier Creek varied from several to almost 900 dm$^3$/s, while those in Petrified Forest Creek and Ornithologist Creek, from a couple to 250 dm$^3$/s, and from a couple to circa 80 dm$^3$/s, respectively [5].

4.2. Suspended sediment concentration
During the investigated period, the concentration of suspended matter varied broadly from 0.06 to 167.22 mg/dm$^3$ (Figure 4). Regardless of the month in which research was conducted, Ecology Glacier Creeks were characterized by the highest suspension concentration, while Czech Creek, by the lowest.
The results reported by Zwoliński [5] span a wider range of values because the time of observation was longer and continuous. The author also noted the highest concentrations of suspension in Ecology Glacier Creek, i.e. from 1 to 2000 mg/dm³, and sporadically up to 9000 mg/dm³. In the case of Ornithologist Creek and Petrified Forest Creek, these values were lower and varied from 0.9 to 100-700 mg/dm³, and from 0.1 to 100-550 mg/dm³, respectively.

It is difficult to find a temporal correlation between the streams with the maximum or minimum concentrations of suspended matter; each stream has its individual level of suspension concentration. The least variation of suspension concentration was observed in February (0.92-18.8 mg/dm³), while in March, the variation was definitely higher (0.06-167.22 mg/dm³).

The differences in the composition of suspended matter during a three-month period are visible. In January, inorganic materials dominated in suspension. In February and March, the share of organic matter increased up to 55% (Ornithologist Creek, Czech Creek, and Italian Creek). The lowest quantitative differentiation of transported material was found in the waters of Ecology Glacier Creeks where the share of organic matter was the smallest.

4.3. Characteristics of suspended sediment particle size

Based on the conducted analysis, it was established that the particles transported in suspension ranged in size from 12.6 to 128 µm (Figure 5). For most of the analyzed streams, the dominant fractions were fine sand and very fine sand whose contents ranged from 94 to 100%. The silt fraction was pronounced in the suspension from Ecology Glacier Creeks, with its content varying between 57 and 100%.

The sand fractions transported in suspension were very well sorted, while the silt fraction was well or moderately well sorted. In the case of Ecology Glacier Creeks, despite the stable energy conditions, the characteristics of water feeding the streams determined the rather poor sorting.

The obtained grain-size distributions were positively skewed or symmetrical, although in one case only (Petrified Forest Creek; January), the values showed a negative skewness. The dominance of
positive skewness values indicates that the small-size fraction had reached the suspended sediment load.

![Graph showing grain size distribution](image)

**Figure 5.** Distribution of suspended sediment grain size, (A-Petrified Forest Creek, B-Ornithologist’s Creek, C-Italian Creek, D-Czech Creek, E-Vanishing Creek, F-Ecology Glacier Creek I, G-Ecology Glacier Creek II)

The kurtosis values of grain-size distributions were mostly low (platykurtic distributions), which is a predominant characteristic of streams transporting the sand fractions. The obtained distributions indicate the high saturation of current with inorganic material originating from the stream beds. The Hjulström curve indicates that the suspended fractions within the analyzed velocity range may have originated from the erosion of stream bed through which snow water drained. The low values of kurtosis also point to the intermittent changes of energy conditions in the environment. The flattened grain-size distribution of suspended matter from Ecology Glacier Creeks was mostly mesokurtic, which is typical for the conditions characterized by the normal level of saturation with inorganic material. In one case, the distribution assumed high values (leptokurtic curve), which points to a deficit of inorganic material. This phenomenon was observed for the highest flow rates measured in Ecology Glacier Creek (II).

Based on the analysis of Passega C-M diagram [18], it can be concluded that the suspended matter undergoing sorting in Italian Creek, Vanishing Creek and Czech Creek was transported under moderate turbulence conditions. In the remaining streams, the sorting of suspension took place under weak turbulence conditions, while the presence of homogeneous suspension characterized by differentiated grain-size distribution was also detected.

5. Conclusions
The presented results describing the stream flow conditions and the characteristics of suspended sediment load allow for dividing the analysed streams into two distinct groups in dependency on the type of inflow feeding the streams. The first group is represented by Ecology Glacier Creeks, which
are characterized by a dominant inflow of subglacial and supraglacial waters. These streams have the highest values of discharge, and the suspension concentrations that are higher than those measured in other streams. The dominant share of suspension is the moderately sorted silt which is transported via subglacial water flow.

Differing characteristics of the remaining streams result from the fact that the streams are fed by inflow from the melting snow cover and thawing permafrost. The catchments of the streams are not ice-covered, and are located within the rock and rubble areas with a limited content of weathered material. Some catchments are locally inhabited by lichens and mosses, which also limits the access to weathered material. The amount of weathered material and the water flow parameters determine the river erosion and the selectivity of suspended sediment load transported by a river. Therefore, the sediment found in the analysed suspension almost exclusively belonged to the very well sorted fraction of fine sand.

The presented issues require systematic observations in order to identify the scale of changes that take place in relation to both the quantity and quality of sedimentary material transported via streams to Admiralty Bay.

**Acknowledgment(s)**

Data used in this article were collected in cooperation with Henryk Arctowski Polish Antarctic Station during the XL Antarctic Expedition. I would like to express my special thanks to Joanna Plenzler who conducted the monitoring.

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