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Occurrence and temporal variations of groundwater outflows in the Petuniabukta region, Spitsbergen

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Abstract: The occurrence and temporal variations of polar shallow groundwater systems and associated seasonal springs and seeps are studied using the example of springs and seeps in the vicinity of the eastern coast of Petuniabukta in central Spitsbergen, Svalbard. Altogether, 37 groundwater outflows were documented. The outflows were mostly located at the foot of talus slopes and were characterised by small discharges (<1 dm^3s^{-1}). The water emerging from the outflows varied widely in terms of temperature and specific electrical conductivity (SpC). These outflows were supplied mainly by water from permafrost, melting snowfields and rainfall. Daily changes were studied in four of the outflows during July 2006. The observed water discharges ranged from 0.04 to 0.7 dm^3s^{-1}, and the temporal variations for the particular outflows were on the order of 50% of the average value. The water temperature amplitude for particular outflows was up to 1.5°C. The SpC was approximately 200 μScm^{-1} and increased with time by almost 40 μScm^{-1} in the case of two outflows draining talus slopes. The water emerging from two springs in carbonate and sulphate rocks had an SpC up to 1295 μScm^{-1}, and in one case, its increase with time was observed to be 300 μScm^{-1}. The increase in the SpC with time probably reflects a decrease in the contribution of snow meltwater in the groundwater recharge. Among the major local factors affecting the groundwater outflows' water quality and discharge rate were the following: geomorphology, rock type, meteorological conditions, state of permafrost and local water storage.

Key words: Arctic, Svalbard, groundwater, springs, seeps, water temperature, specific conductivity.

Introduction

Springs are known to be good indicators of the hydrological cycle (*e.g.* Alley *et al.* 2002). The properties of spring water can provide information about groundwater environment conditions and processes and the initial state of river waters and may also reflect climate changes (Rademacher *et al.* 2002; Haldorsen *et al.* 2010). In polar regions, however, springs are not as common as in other climate zones due to the widespread existence of permafrost, and they have not been extensively studied. Most previous works have focused on thermal springs, for example, in the Canadian Arctic (Pollard 2005; Omelon *et al.* 2006) and in Svalbard (Krawczyk 1989; Pociask-Karteczka 1989; Lauritzen and Bottrell 1994; Banks *et al.* 1998; Salvigsen and Hogvard 1998) and springs related to subpermafrost waters, often in karst regions (*e.g.* Pulina and Postnov 1989; Haldorsen *et al.* 2010). Although the immediate importance of polar springs seems to be minor, some issues on springs in cold regions may be crucial for the consideration of such problems as potential water sources on Mars (Andersen *et al.* 2002).

Banks *et al.* (1998) classified the springs on Spitsbergen into three types: springs deriving from sub-permafrost groundwater systems, thermal springs and springs generated during the short polar summer. The groundwater outflows described in the present paper belong to the last type. The existence of these outflows is limited to the summer season, *i.e.* to the period when air temperatures are above 0°C. In Svalbard, this period lasts three to four months (Hanssen-Bauer *et al.* 1990). In summer, the topmost 1 to 1.5 m of permafrost is warmed to above 0°C (Grześ 1990; Humlum *et al.* 2003; Rachlewicz and Szczuciński 2008), causing melting of the ground ice in the active layer along with water recharge from snow melting and rainfall, giving rise to a very shallow groundwater system and springs. This type of spring has been described, for instance, in the Calypsostranda region in Bellsund, SW Spitsbergen (Bartoszewski 1998; Chmiel *et al.* 2007). These springs usually appear at the end of June and the beginning of July, and they disappear in August/September. The Calypsobyen spring studied by Bartoszewski (1998) during summers in 1986–1989, and also in 1993, ceased to be active in the last decade of August. However, in some years, it has been briefly reactivated during autumn rainfalls.

These summer springs, which are widespread in the ice-free parts of Spitsbergen, have not been subjected to systematic investigations. The objectives of the present paper are twofold. The first is to document the occurrence of groundwater outflows and their basic properties in terms of various local climatic and geologic conditions in a region east of Petuniabukta. The second is to determine the short-term temporal changeability of the springs' discharge and water properties in relation to meteorological conditions. The presented data can also serve as a future reference for studies of the reactions of these systems to hydrological changes caused by climate change.

Study area

The investigated area is located around the northern and eastern coast of Petuniabukta, the northernmost extension of Billefjorden in central Spitsbergen (Fig. 1). The area is mostly built of Carboniferous sedimentary rocks (Dallmann *et al.* 1994). The most common rock types are sandstone, mudstone, limestone, dolomite, anhydrite and gypsum. The valley floors and lower parts of the slopes are

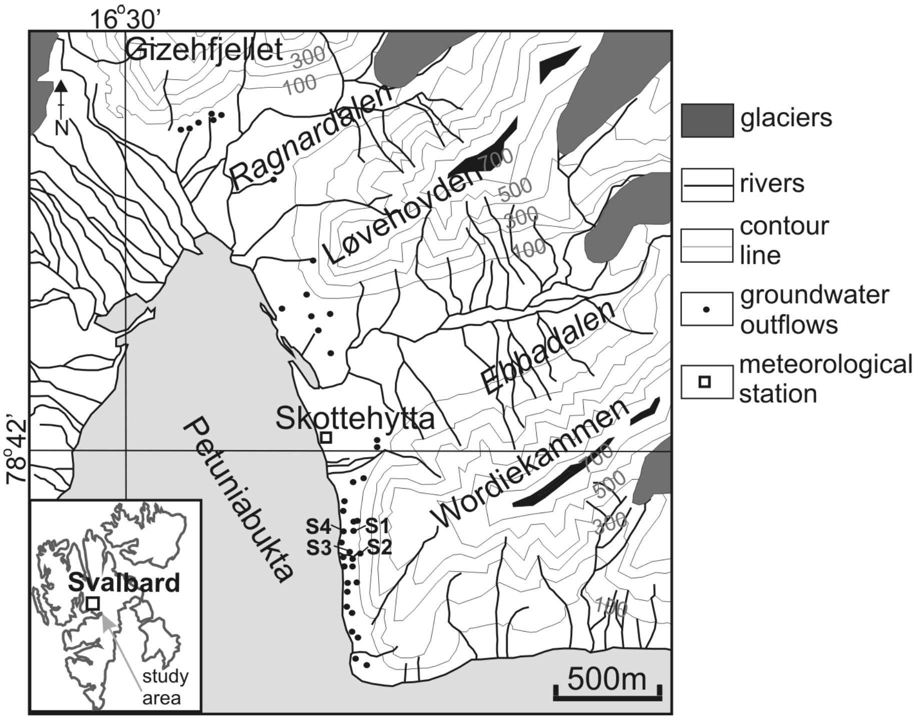

Fig. 1. Study area and the locations of the mapped and investigated springs. Springs S1 to S4 were studied daily in July 2006.

mainly covered with Holocene deposits of variable origin (Karczewski *et al.* 1990). Along the coast of Petuniabukta are well-preserved raised marine terraces composed mostly of sand and gravel, but locally also of finer deposits (Stankowski *et al.* 1989).

The region belongs to the warmest and most continental type of climate along the western coast of Spitsbergen (Przybylak *et al.* 2007). The average annual temperature is -6.5°C (Hanssen-Bauer *et al.* 1990). The period of above-zero temperatures starts in mid-June and lasts until the mid-September (Rachlewicz 2009). The warmest months are July and August (5 to 6°C on average, but recently even above 7°C – Rachlewicz 2003). Precipitation total is very low – approximately 200 mm annually (Hagen *et al.* 1993). During summer (July–August), the total precipitation has been as low as 32.3 mm in 2005 and 13.8 mm in 2006 (Przybylak *et al.* 2007).

Water circulation in the region is limited mostly to the summer season and is determined by three major storage systems: glaciers, snow cover and permafrost. However, only the latter two are important for the recharge of the studied groundwater outflows. Snow cover at the beginning of July is absent at altitudes below 200–300 m except for some chutes on mountain slopes. The thickness of the permafrost active layer increases gradually during the summer, reaching a depth of 1 m to 1.5 m at its end (Kostrzewski *et al.* 1989; Gibas *et al.* 2005; Rachlewicz, Szczuciński 2008), and it determines the range of water infiltration.

Methods

Hydrographic mapping was performed to document the groundwater outflows in the summers of 2002 (August, by Małgorzata Mazurek), 2005 (July) and 2006 (July). The documentation included the estimation of the discharge and the type of groundwater outflow, a description of the geomorphological setting, measurements of the water temperature and specific electrical conductivity (SpC) in the outflows. The groundwater outflow locations were obtained with the help of a hand-held Vista-C GPS receiver (*Garmin*). Four springs located at the foot of the western slope of Wordiekammen were selected for daily monitoring (Fig. 1). The observations included discharge, water temperature and SpC and were performed in July 2006. The water discharge was measured by the volumetric method, with an accuracy of ±1%. The water temperature was measured with a calibrated electronic thermometer with an accuracy of 0.1°C. The SpC, which is an indirect measure of the concentration of ionic (dissolved) constituents, was obtained with a CC-401 conductivity meter (produced by *Elmetron*, Poland) with automatic compensation to a reference temperature of 25°C, with an accuracy of 0.1%. Daily precipitation and air temperature data were recorded simultaneously at a meteorological station located approximately 600 m north of the monitored springs, next to the Skottehytta hut (Fig. 1), which is situated at 8 m a.s.l. on a raised marine terrace (Zwoliński *et al*. 2006).

Results

Locality, types and water properties of groundwater outflows. — A total of 37 groundwater outflows were documented during the hydrographic mapping conducted along the eastern coast of Petuniabukta. The results of the mapping are presented in Fig. 1 and Table 1. The outflows were represented by springs (a concentrated outflow of groundwater) and seeps (a non-concentrated outflow). The mapped outflows consisted of small springs and seeps found on the southern slopes of Gizehfjellet in Ragnardalen, in Ebbadalen, and along the western slopes of Wordiekammen. All springs were of the gravity flow type; no springs of the artesian type were observed. Taking into account the hydrogeological environment (aquifer rocks) drained by the outflows, the outflows may be classified as fissure or layer. The fissure outflows reach the surface via fractured bedrocks (mainly dolomites and anhydrites), and the layer outflows appear at the foot of talus slopes in debris covers or below raised marine terraces. The outflows in rocks take the form of springs, whereas those in loose sediments or weathering covers are mostly seeps.

Most of the outflows (23), in the form of both springs and seeps, were found at the foot of Wordiekammen (Fig. 1). These outflows occurred at the feet of talus slopes and at coastal cliffs. The average water temperature was 1.6°C in August

Table 1

Summary of the basic properties of the mapped groundwater outflows in 2002

Location	Aquifer	Number of outflows	Water temperature [˚C]			SpC [μScm^{-1}]			Mean discharge [dm^{3}s^{-1}]
			min	mean	max	min	mean	max	
western slopes of Wordiekammen	debris cover	9	0.4	1.6	2.9	206	257	380	0.1
	fissured rock	14	0.6	1.9	3.9	934	1588	2070	0.3
western slopes of Løvehovden	debris cover, deposit of terraces	8	1.3	3.6	8.7	511	970	1955	0.1
southern slopes of Gizehfjellet	debris cover	6	1.2	3.3	6.4	202	393	785	0.1

2002 and 1.4°C in July 2005, but temperatures above 2°C were recorded in some springs. The discharges were 0.2 dm^{3}s^{-1} on average.

At the foot of Løvehovden mountain, two springs were found that had an average temperature of 2.4°C (in August 2002) and 1.8°C (in July 2005) and an average discharge of 0.2 dm^{3}s^{-1}. Below them, on the slopes of raised marine terraces, there were four seeps with an average water temperature of 4.9°C, (in August 2002) and 2.2°C (in July 2005) and an average discharge of 0.01 dm^{3}s^{-1}. The maximum recorded water temperature in one of the seeps was 8.7°C (August 2002).

The next six outflows (three springs and three seeps) were recorded at the foot of the southern slopes of Gizehfjellet (Fig. 1). Their average water temperatures were approximately 3.3°C (in August 2002) and 1.6°C (in July 2005), and the average discharge was 0.1 dm^{3}s^{-1}.

The SpC of all the groundwater outflows ranged from 202 to 2070 μScm^{-1} in August 2002 (Table 1). The water of the outflows emerging from the sulphate and carbonate cliffs had SpC from 1588 to 2070 μScm^{-1}. In the seeps on talus cones, the SpC ranged from 202 to 785 μScm^{-1}. Outflows emerging from marine terraces had SpC between 511 and 1955 μScm^{-1} (Table 1).

Temporal variations of spring parameters. — Four springs located on the western slopes of Wordiekammen (Fig. 1) were investigated daily from July 4 to July 30, 2006. The water of two of the springs (S1 and S2) emerged from the lower end of a talus slope covering a raised marine terrace at an altitude of approximately 40 m a.s.l. The spring water fed small streams, which infiltrated into fractured bedrock. Springs 3 and 4 flowed from fissures in the sulphate and carbonate rocks forming the coastal cliff. The daily variations of the discharge, water temperature and SpC of the springs are presented in Fig. 2.

Spring S1 had stable, small discharges of approximately 0.1 dm^{3}s^{-1}. The water temperatures ranged between 1.1 and 2.1°C with an average of 1.4°C. The SpC varied between 169 and 211 μScm^{-1} with an average of 195 μScm^{-1}. The second spring (S2) had a generally similar discharge. The water temperature of S2 was slightly lower, ranging between 0.4 and 2°C with an average of 0.9°C. The SpC of

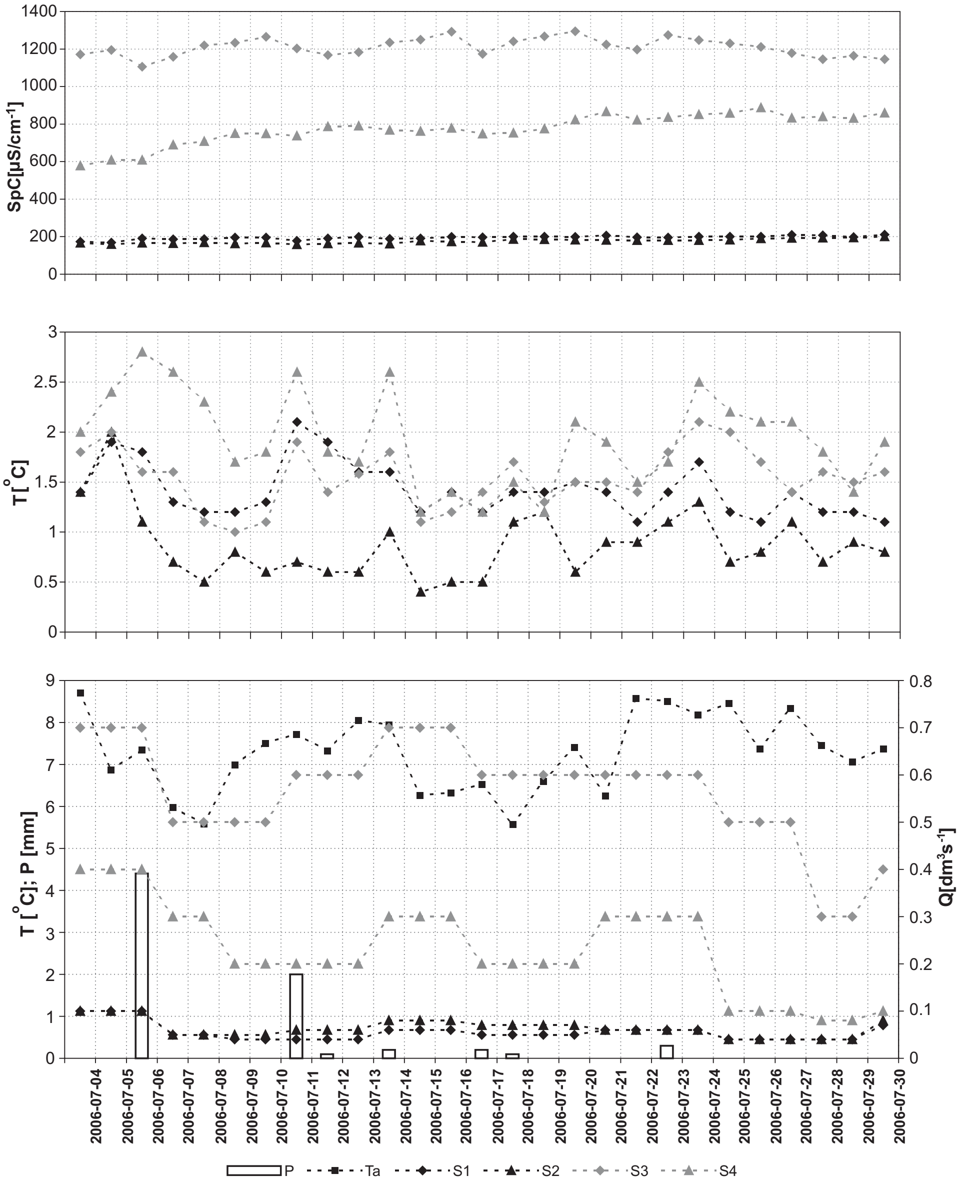

Fig. 2. Daily changes in spring waters in July 2006. **A**. Specific electrical conductivity (SpC). **B**. Temperature (T). **C**. Discharge (Q) and meteorological conditions at Skottehytta in July 2006. Ta – air temperature 2 m above ground, P – precipitation total. Data from Zwoliński *et al.* (2006).

S2 was also very similar, within the range of 158 to 201 µScm^{-1} (176 µScm^{-1} on average). In both springs, the SpC showed an increase with time to approximately 40 µScm^{-1}. Spring S3 had the highest discharges observed, reaching 0.7 dm^{3}s^{-1} at the beginning of the monitoring period and decreasing to approximately 0.3 dm^{3}s^{-1} towards the end of the period. The water temperature of S3 was similar to that of the previous springs, and it ranged between 1 and 2.1°C with an average of 1.5°C. The SpC of S3 was significantly higher and ranged from 1106 to 1295 μScm^{-1} (1210 μScm^{-1} on average). In contrast to the other springs, the SpC of S3 first increased (by almost 190 μScm^{-1}) but then decreased in the last days of the investigation, reaching values similar to those at the beginning. The fourth spring (S4) was also in the coastal cliff and had a variable discharge from 0.1 to 0.4 dm^3s^{-1} at the end and beginning of the monitoring period, respectively. The average water temperature was the highest among all of the springs at 1.93°C (range from 1.2 to 2.8°C). The SpC of S4 was also high, although not as high as S3, ranging from 578 to 888 $\mu S\ cm^{-1}$ with an average of 744 $\mu S\ cm^{-1}$. This value increased by more than 300 μScm^{-1} during the observation period.

The meteorological conditions during the same period are presented in Fig. 2, which shows that they were relatively stable. The air temperature varied between 5°C and 9°C. The precipitation total was very low, approximately 7 mm per month, and most of it fell during two small rainfall events on 5 July (4.5 mm) and 10 July (2 mm).

Discussion

Characteristics of seasonal summer polar springs in Svalbard. — The basic characteristics of the groundwater outflows around Petuniabukta are similar to the groundwater outflows reported from other parts of Spitsbergen (Bartoszewski 1998; Chmiel *et al.* 2007). However, the latter have not been subjected to systematic hydrometric and hydrochemical measurements, and the possibility of an overall comparison is limited. All the outflows are seasonal phenomena and are limited to the ablation season because the main sources of water are melting snow and ice.

In the studied area, the documented seasonal spring water temperatures were in the range of 0.4 to 8.7°C. The highest temperature (8.7°C) was registered in a spring emerging at the foot of the slope of Løvehovden. The relatively high water temperatures may have resulted from the participation of waters from deep-water circulation. Active water circulation along the fault line next to this spring has already been suggested by Gulińska *et al.* (2003) as an explanation for the higher uranium and PAHs found in the soils nearby.

The water temperature of the studied groundwater outflows was higher on average by 0.8°C in August 2002 than July 2005. It is likely caused mainly by difference in air temperature in the two periods. The average monthly air temperature was 7.8°C in August 2002 (Rachlewicz and Styszyńska 2007) and 2.3°C in July 2005 (Przybylak *et al.* 2006).

The spring waters of the studied area were characterised by SpC values from approximately 200 to 2000 μScm^{-1}. These characteristics are related to the origin of the water emerging in the outflows and to the rock types present on the flow path of the groundwater. The groundwater outflows, which drain waters from melting of snow-cover or waters flowing through carbonate rocks typically have SpC values in the range of 200 to 400 μScm^{-1}. These values are close to the SpC range (70 to approximately 300 μScm^{-1}) observed in the glacial meltwater rivers of this region (Rachlewicz 2009). However, in the groundwater outflow draining waters, which were in contact with gypsum and anhydrite on the way from the recharge area to the outflow, the water SpC was much higher – from 400 to approximately 2000 μScm^{-1}. The measured high values of SpC in the groundwater outflows was similar to the range of approximately 1000 to nearly 4000 μScm^{-1}, as reported by Dragon and Marciniak (2010), in surface waters and groundwaters flowing down from the Ebbadalen slopes (see Fig. 1), where there are several outcrops of easily soluble sulphate rocks and where bird colonies may cause enrichment in nitrogen compounds in the waters. The springs with the highest SpC values are similar in terms of mineralization and water discharge to gypsum karst springs described from surrounding of Kongressvatne, west Spitsbergen (Pulina and Postnov 1989).

Dissolved load discharge from gypsum karst springs. — The two of the monitored springs (S3 and S4) emerging in the coastal cliff are similar in characteristics to karst springs. The obtained data on spring water discharges and chemistry may allow a rough estimation of chemical denudation by groundwater and of dissolved load discharge through the spring system to the adjacent Petuniabukta. Water chemistry was not analysed in detail in the present paper, however, Krawczyk and Ford (2006, 2007) showed that in case of particular types of karst waters the SpC is well correlated with dominating ions and allows for the estimation of their concentration.

Using the measured daily water discharges and SpC for two springs with the highest SpC, emerging in coastal cliff next to Petuniabukta (springs S3 and S4) an assessment of dissolved loads was made. The spring water analyses (Mazurek, unpublished) revealed that the sum of bicarbonate, nitrate, chloride anions to total anions is <33%, and chloride anions are <5%. It allowed to apply the following relationship obtained by Krawczyk and Ford (2007) for gypsum karst waters:

$$\text{GYP [mg L}^{-1}\ \text{CaSO}_4{\cdot}2\text{H}_2\text{O]} = 1.12\ \text{SpC} + 62,$$

where SpC value was taken from daily measurements.

The calculations revealed that on average the waters of springs S3 and S4 contain about 1420 and 930 mg of gypsum per 1 liter, respectively. Those values are similar to dissolved salt concentrations of gypsum karst springs in Linné valley, western Spitsbergen (Pulina and Postnov 1989). During the study period the dissolved load delivered through the springs is on average about 69 kg (spring S3) and 18 kg (spring S4) of gypsum per day. If the springs are active for 3 months per year, almost 8 tons of gypsum may be delivered to Petuniabukta annually through the two springs. Because the catchment area of the springs is not well constrained, the calculations of the denudation rates are not possible.

Factors controlling temporal spring water variability. — The temporal variations of the studied springs shown in Fig. 2 were relatively small and depend on several factors. One of the factors influencing the properties of the studied spring waters was air temperature, which obviously affected the spring water temperature. For instance, the mean daily air temperature on 4 July, which reached 8.7°C, caused the temperature of the waters to rise on 5 July by an average of 0.4°C. An even higher increase in the water temperature, by an average of 0.7°C, was recorded on 24 July (however, in one spring only), two days after the mean daily air temperature was 8.6°C. The highest rise in temperature on that day was measured in springs S3 and S4 at 0.7°C (from 1.4 to 2.1°C) and 1°C (from 1.5 to 2.5°C), respectively. With the lowering of the mean daily air temperature to 5.8°C on 7 and 8 July, the temperature of the spring waters dropped on 9 July by an average of 0.6°C. The largest decline was observed in S4: 0.9°C (from 2.6 to 1.7°C). The above mentioned relations indicate a short (1–2 days) reaction time of some of the spring systems to air temperature changes.

The spring water temperatures and their temporal changes are generally similar, but they reflect a good correlation with air temperature only in some periods. As an example, the relationship between the spring water temperature and the air temperature of the previous day are discussed below.

The spring water temperatures in S1 and S2 revealed the highest correlation coefficient to the previous day's air temperatures in the first part of July, when the coefficients were 0.58 ($n = 13$, $\alpha = 0.05$) and 0.51 ($n = 13$, $\alpha = 0.05$), respectively. In the second part of July, the correlation coefficient decreased. This change may be the result of the impact of permafrost, which is the next major factor influencing the properties of spring water. At the beginning of the summer season, water emerging from S1 and S2 came mainly from melting snow patches on the slopes of Wordiekammen. Because the active layer of permafrost was then only a few to a few tens of cm thick (Rachlewicz and Szczuciński 2008), the melting water flowed close to the ground surface and was more easily affected by air temperature changes. During the mid-summer as the active layer of permafrost became thicker, the influence of air temperature on the groundwater decreased.

However, changes in the relationship of air temperature, permafrost thawing and spring water temperature reflected in S1 and S2 were more complex than in S3 and S4, emerging from the cliff at the foot of the Wordiekammen slopes. The water temperature in S4 was better correlated with the previous day's air temperature in the second half of July. The correlation coefficient then was 0.62 ($n = 13$, $\alpha = 0{,}05$). In S3, the relationship between air temperature and water temperature was strong throughout the observation period, with correlation coefficients of 0.68 ($n = 13$, $\alpha = 0{,}05$) and 0.72 ($n = 13$, $\alpha = 0{,}05$) in the first and second halves of July, respectively. The good correlation in S3 may have been caused by the circulation route of the spring water. These waters were likely the same as those emerging from the springs at the foot of talus cones (*e.g.* S1; see further discussion below).

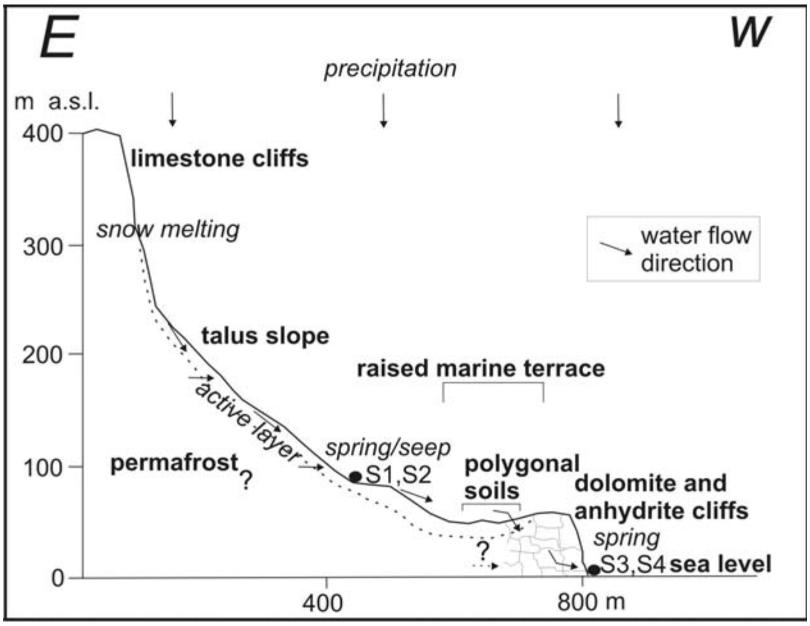

Fig. 3. The concept of a shallow groundwater system exemplified by the western slope of Wordiekammen, where the investigated springs, S1 to S4, are located. The active layer is not to scale.

These waters flowed as surface waters for 30–40 m and were affected by atmospheric factors (radiation, warming–cooling) before being infiltrated again in the ground to emerge as spring water (*e.g.* S3) at the foot of the coastal cliff (Fig. 3). The spring S4 may be supplied by waters of similar origin as S3; however, its water temperature was not well correlated with the air temperature in the first part of July, which may be related to the smaller discharge (in S4 – 0.3 dm^3s^{-1} and in S3 – 0.6 dm^3s^{-1}) and the relatively larger contribution of melting permafrost waters at the beginning of the summer season.

The spring water SpC changes were partly due to changing groundwater origin and were also, to some extent, controlled by summer permafrost thawing. At the beginning of the summer season, when the permafrost active layer was only a few cm thick, the majority of the groundwater came from snowmelt. Later, the active layer was thicker, and the primary source of water changed from snowmelt to the melting of ground ice. The explanation is likely to be changes in the SpC of the spring waters, which increased slightly with time from approximately 50 to above 200 μScm^{-1} during the summer season. A similar trend has been documented for instance in case of rivers and streams draining ice-free catchments (*e.g.* Pulina *et al*. 1984; Krawczyk and Pettersson 2007; Rachlewicz 2007), tundra lakes (Zwoliński *et al.* 2008) and in spring waters (Chmiel *et al.* 2007). There is probably no single explanation for that tendency, but one of the factors responsible may be a steady decrease in the contribution of low-conductivity water from snowmelt. The much higher SpC in S3 and S4 than in S1 and S2 may point to a different source (possibly deep circulation), which is, however, less likely than fast enrichment in a dissolved load due to flowing through sulphate rocks (anhydrite and gypsum) (*e.g.* Pulina 1999). A rapid increase in SpC due to contact with sulphate rocks has already been documented in the surficial and groundwaters of the Petuniabukta region by Dragon and Marciniak (2010) who found an increase of SpC up to 1000 μScm^{-1} over a water flow distance of 500 m.

Another potential controlling factor of spring water properties was precipitation. In the monitored springs, the water SpC was lower after rainfall and persisted for the next two or three days. For instance, after a rainfall on 5 July, the SpC of S3 dropped by 89 μS cm^{-1} (from 1195 to 1106 μS cm^{-1}). A similar situation was recorded on 8 and 16 July, when the values decreased by 97 and 118 μS cm^{-1}, respectively. This relation was also observed in the other springs, but it was only this clear in S3.

The spring water discharges generally decreased with time in the studied springs, which could be partly due to the lower precipitation in the second part of the monitoring period but was mainly due to the lower supply from the shrinking snow patches.

Analyses of the discharges, temperatures and SpC of groundwater flowing out on the western slopes of Wordiekammen, along with the spatial distribution of the springs, suggests a potential linkage between the upper springs (S1 and S2) emerging from talus slopes and the lower springs (S3 and S4) flowing from the fissures in the sulphate and carbonate rocks of the coastal cliff. The obtained data were used to construct a conceptual model (Fig. 3) of a shallow polar groundwater system. However, to confirm such a linkage in water circulation, a study that applies tracers would be necessary in future. The conceptual model (Fig. 3) may be useful because such shallow groundwater systems with similar talus slopes ending on raised marine terraces and faced with cliff coasts are common on Svalbard (Szczepanik 1993; Bartoszewski 1998). The upper springs (*e.g.* S1 and S2) and/or seeps located in the lowermost part of a talus slope are supplied mainly with water from the melting of snow patches flowing within the permafrost active layer through the debris cover on the slope. Lower springs (*e.g.* S3 and S4) are probably supplied with water from the upper springs, and their water temperatures are slightly higher, which is likely due to warming during their brief flow on the surface. Then after infiltrating and moving through the fractured sulphate and carbonate rocks of the coastal cliff, the water changes its SpC, which may also be indicative of a supply of water from a deep circulation.

As exemplified by the model and by the monitoring of the studied springs, the main controls of the system are probably as follows:

– morphology (slope gradient of approximately 40°), partly controlling the water flow rate and water residence time in the aquifer;
– geology (existence of surface debris cover or fissured rocks), controlling permeability and the SpC of groundwater;

– meteorological conditions (precipitation and temperature), controlling the water supply (through precipitation and snow/ice melting) and the thickness of the permafrost active layer (thickness of aquifer);
– state of permafrost (thickness of the active layer, rate of thawing); and
– water storage (supply from snow patches, ice in permafrost).

Conclusions

Shallow groundwater systems and the associated seasonal springs and seeps are fairly widespread phenomena around Petuniabukta (central Spitsbergen) and are likely to be common in the whole of the Svalbard archipelago. The presented results document the occurrence and temporal variability of these outflows on Svalbard and may serve as a reference for future studies on their spatial and temporal changes. The study of the documented 37 groundwater outflows revealed the following:

- most of them are developed as seeps or springs at the foot of talus slopes or in rock cliffs, with relatively small discharges – under 1 $dm^3 s^{-1}$;
- they are supplied mainly by waters from melting snow patches and the active layer of permafrost;
- they have a short (1–2 days or less) time of reaction to meteorological phenomena, such as a rainfall event;
- their properties evolve with time, and the spring waters' SpC generally increase with time, probably reflecting a change in the proportions of water sources (a decrease in snow meltwater);
- the major factors controlling the seasonal groundwater outflows belong to the geomorphology of the drainage area, type and structure (loose, fractured) of the aquifer rocks, meteorological conditions, the thickness of the permafrost active layer and local water storage.

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