



Forming of water chemistry in active layer, Steinvik River catchment, SW Spitsbergen

Michał RYSIUKIEWICZ* , Henryk MARSZAŁEK 
and Mirosław WĄSIK 

*Department of Applied Hydrogeology, Institute of Geological Sciences,
Wrocław University, Pl. Maksa Born'a 9, 50-204 Wrocław, Poland*

** corresponding author <michal.rysiukiewicz@uwr.edu.pl>*

Abstract: The objective of this work is to demonstrate the results of hydrogeochemical studies carried out in the Steinvik River catchment for the first time, in order to provide detailed information regarding the chemical composition of groundwater in the Hornsund region, SW Spitsbergen. The water chemistry in the non-glaciated Steinvik River catchment is largely controlled by hydrological processes related to thaw of the near surface permafrost. Groundwater runoff is generated from the fast flow through well-permeable active layer. Recharge from melting snow, permafrost and rain, together with short residence time of groundwater, favors the forming of low-mineralized water, reaching 41 and 50 $\mu\text{S}/\text{cm}$ for surface and groundwater, respectively, with the dominance of HCO_3^- , Cl^- , Mg^{2+} , Ca^{2+} and Na^+ ions. In some water samples, increased concentrations of aluminum (up to 268 $\mu\text{g}/\text{L}$) were found. The highest concentrations of phosphate, nitrite and ammonium in water seem to be related to the presence of bird colonies. Groundwater of active layer in the studied catchment belongs to young meteoric water with the age limited to one summer season.

Keywords: Arctic, Svalbard, river catchment, shallow groundwater, chemical composition.



Introduction

Arctic ecosystems are particularly sensitive to global warming processes related to the anthropogenic climate change (Roberts *et al.* 2017; Kendrick *et al.* 2018). Especially vulnerable are freshwater ecosystems affected by anthropogenic pressures such as permafrost thaw, direct pollution, atmospheric deposition as well as an increasing terrestrial vegetation growth (Culp *et al.* 2012). These freshwater ecosystems are generally young, low-mineralized and nutrient-poor (Wrona *et al.* 2013; Marszałek and Górniak 2017), therefore are susceptible to changes in water chemistry. The transboundary transfer of contaminants from Asia, Europe and North America and also from the local pollution sources can significantly affect of the Arctic regions (Moiseenko *et al.* 2020). Permafrost thawing can result in the increased sediment and nutrient loading to aquatic environments that leads to the disturbance of natural habitats (Kendrick *et al.* 2018).

Increased recharge of active layer from the permafrost thaw is reflecting in the groundwater chemistry. Freezing and thawing of the shallow groundwater is also important for its subsurface circulation (van Everdingen 1990). Freshwater ecosystems of the catchment can be recharged by glacier melting. The Steinvik River catchment belongs to non-glaciated area, where the most important part in forming of some hydrological processes plays the snow cover and permafrost thaw. However, it can be also an example of a small model catchment built of crystalline rocks, in which the hydrochemical processes take place in a similar way to the other Arctic areas, where rapid climate changes are observed. Similar phenomenon takes place in the neighboring catchment of the Brattegg River (Marszałek and Górniak 2017).

The problems of climate impact on changes in the forming of groundwater chemistry in polar regions are widely described in the literature (Cochand *et al.* 2019). Such studies have been carried out in various hydrogeological systems in southern Spitsbergen since the 1970s. The most important studies characterizing both surface and groundwater include works of Bieroński (1977), Pulina (1977), Leszkiewicz (1982), Krzyszowska (1985), Krawczyk (1990, 1992), Haldorsen and Lauritzen (1995), Haldorsen *et al.* (1996), Pulina *et al.* (1999), Cooper *et al.* (2002), Krawczyk *et al.* (2008), Marszałek and Wąsik (2013) and Olichwer *et al.* (2013). These studies concerned both fresh and thermal waters of various depth of flow, including karst water. The majority of studies were focused on the chemical composition of different types of waters, including those which occur in the vicinity of the Hornsund region. However, there are no results of detailed hydrogeochemical research conducted in the Steinvik River catchment so far. Thus, this work fills the gap and provides information on the chemical and isotopic composition of waters in this part of southern Spitsbergen.

Study area

The Steinvik river catchment with the area of 2.3 km² is located in the southwestern part of Spitsbergen (Svalbard), in the coastal zone of the Greenland Sea between the Hans and Werenskiöld glaciers (Fig. 1). It belongs to the small, non-glaciated catchment with clearly diversified morphology of the terrain. Its eastern mountain part reaches a height of up to 643 m a.s.l., while the western one has the character of a flat coastal platform (Strandflat) located at an altitude of 4 to 25 m a.s.l. The platform includes a well-developed, stepped system of raised marine terraces, which were created as a result of the rapid, post-glacial, isostatic lifting of southern Spitsbergen (Jahn 1968; Karczewski *et al.* 1981). At the mouth of the Steinvik valley, there are sea pebbles at quite high altitudes from 100 m (Jahn 1968; Chmal 1987) up to 205 m a.s.l. (Kasprzak 2012; Migoń and Kasprzak 2013). The coastal zone is built of a gravel and rocky beach with storm embankments. The average height of the Steinvik catchment is 321.5 m, while its average slope is 42.67%. In the lower part of the catchment area, there is a clear, positive form in the shape of a torrential cone, built of debris with an area of >0.5 km², covering older accumulation forms (Kasprzak 2012). The sharp relief of the mountain part of the catchment intensifies the surface runoff. Only its lower part, which has the character of a flat marine terrace, and small fragments in its central part, are more predestined to supply groundwater.

The climatic conditions of the catchment area, typical of SW Spitsbergen, are characterized by low temperatures and not very high rainfall, despite the influx of humid air masses from the south. The average temperature in the Hornsund Station for the study period of 2009–2011 was −2.8°C and the average annual rainfall was 502 mm. Average temperature for the Wrocław University Station located in the Bratægge River catchment for the period of 2005–2011 was −1.7°C (Pereyma *et al.* 2013). Maxima of rainfall occur in September and October, while the lowest rainfall values are recorded in June. The monthly amount of precipitation in the SW Spitsbergen ranges from 20 mm to 120 mm. The observed episodes with the daily sum of rainfall exceeding 30–40 mm caused, among others, increased ablation and outflow (Migala and Wawrzyniak 2013). Most of the precipitation in Spitsbergen is solid. Apart from the summer period (July–August), when the overall level of rainfall intensity is relatively small (<5%), snow is the dominant form of precipitation (Marsz *et al.* 2013).

The river network of the Steinvik River catchment is poorly developed. Permanent streams are 3.9 km long and the length of the Steinvik River is 2.9 km. The springs of Steinvik River flow out at an altitude of about 390 m a.s.l. In the northern part of the catchment, in the area of the Jahn Pass, the largest tributary of the Steinvik originates. The Steinvik River flows into the Greenland Sea in two places that are approximately 350 meters apart. In the area of coastal flattening, during the low water levels, the stream flow takes place in loose sediments of sea terraces.

Geological setting

The Steinvik River catchment is located within the Eimfjellet group of Caledonian crystalline rock formations (Skjerstranda, Eimfjellbreane, Skålfjellet, Bratteggdalen and Guliksenfjellet) ranging in age from the Proterozoic to the early Silurian (Hoel 1918; Orvin 1940; from Czerny *et al.* 1993). Most of the study area is built of the Skålfjellet Formation composed of amphibolites with enclaves of acid plutonic rocks (Fig. 1). Amphibolites occur mainly in the aphanite and fine-blast form, while in metabazalts there are enclaves of anorthosite metagabros and metagranitoids (Czerny *et al.* 1993; Majka 2006). Metagranitoids are represented by two separate horizons, *i.e.*, the lower leukocratic white coarse-grained quartz-albite and pink or red varieties, rich in potassium feldspar, and quartz monzonite (Czerny *et al.* 1993). The remaining formations are mainly represented by the quartzite rocks (Guliksenfjellet, Skjerstranda) or amphibolites with metaryolite inserts, chlorite and biotite shales, black coarse amphibolites and mica shales (Bratteggdalen) as well as chlorite and biotite shales (Eimfjellbreane).

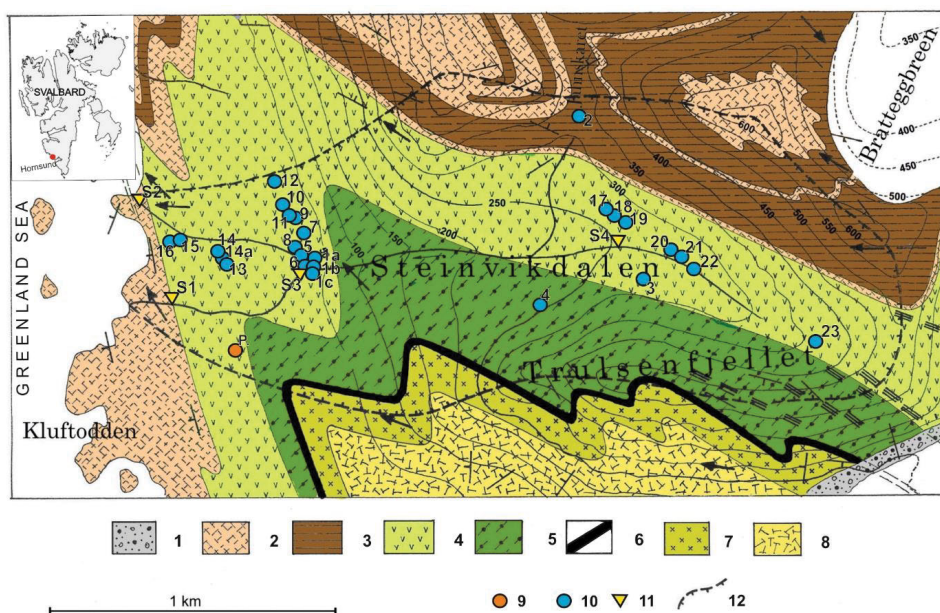


Fig. 1. Location of sampling points in the Steinvik River catchment on the geology background, adopted after Czerny *et al.* (1993); 1 - moraine deposits (Q), metamorphic rocks (Pt): 2 - white or green quartzites, 3 - mica schists with amphibolite and meta rhyolites inserts, 4 - amphibolites with metagabbro enclaves, 5 - amphibolites, 6 - amphibolites with metagranitoid enclaves, 7 - white and green quartzites, chlorite or biotite schists, 8 - feldspar quartzites with intercalations of amphibolites, 9 - piezometer, 10 - springs (1 through 23), 11 - hydrometric gauge cross-sections (S1 through S4), 12 - catchment border.

The metamorphic hard rocks are covered by clastic materials in form of weathering residuals and Holocene sandy-gravel sediments of glacial, river and sea origin. Weathered rock debris, mainly produced by intense physical weathering, commonly covers the slopes of the rock massifs. Thickness of debris material is difficult to determine, but probably does not exceed a few meters. In the top parts of the area, due to significant slope and the Alpine relief of the mountain ridges, their thickness is reduced to zero. The mountain part of the Steinvik valley is covered by the dense or scattered boulder formations with solifluction material displaced on the slopes. It has the nature of a mixed debris material embedded in a clay slope. Larger amounts of debris material in the form of scree cones accumulate at the foot of the ravines and chutes, while the suspended nature of the Steinvik valley causes the accumulation of an alluvial cone at its outlet, made of relatively well-permeable deposits. The flat area of the lower parts of the catchments is mostly covered by sediments of marine terraces formed in a shape of coarse gravel and pebbles, with poorly developed sediments of modern river accumulation overlaid on them. The penetration depth of the infiltrating water into the bedrock is limited by the shallow permafrost roof.

Methods

Water sampling was carried out in the Arctic summer during the period of 2009–2011. Eighteen points were selected for the measurements. In total, 38 water samples were analyzed in the Steinvik River catchment over three summer seasons. During the hydrogeological mapping in August 2009 such parameters as water temperature, electrolytic conductivity (EC), and pH were measured at the same time in all 27 points. Chemical analysis includes the basic ionic composition and selected physicochemical properties of water, such as EC, pH, HCO_3^- , Ca^{2+} , Mg^{2+} , Na^+ , K^+ , SO_4^{2-} , NO_3^- , NO_2^- , NH_4^+ . Additionally, the following ions as: PO_4^{3-} , Cl^- , Mn^{2+} , Fe_{tot} and microelements: Al_{tot} , Cd, Cu, Pb, Zn, As were determined. Temperature, EC and pH of water were measured directly in the field using an Elmetron CPC-401 portable multifunction meter. The analyzes of the chemical composition of water were carried out in the certified Chemical Laboratory of the Institute of Geography and Regional Development of the University of Wrocław. For determination of cations, the atomic absorption spectrometry (AAS) method with flame and graphite furnace was used. Anions were determined by colorimetric method. Alkalinity was measured in the laboratory by colorimetric titration with HCl. In both used methods, the precision and accuracy measures were <1.5% and <0.5%, respectively.

In addition to chemical analyzes, measurements of the isotopic composition in 15 water samples were also completed. Stable isotope ratios of oxygen (^{18}O) and hydrogen (^2H) in water were used as environmental tracers for evaluation of

the relationships between surface and groundwater. All samples were analyzed in the laboratory of the Faculty of Physics and Nuclear Technology of AGH University of Science and Technology in Krakow. Measurements were carried out using a Finnigan Delta S mass spectrometer. The uncertainties of measurements of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ representing single standard deviation (1σ) and including sample preparation are equal $\pm 0.1\text{‰}$ and $\pm 1\text{‰}$, respectively. They were determined based on a long-term record of measurements of an internal laboratory standard.

Results

Chemical composition of active layer water. — All groundwater outflows that occurred in the catchment area during the summer season, represent the shallowest circulation system associated with the subsurface zone of the bedrock lying above the permafrost. Therefore, it can be concluded that their presence is related to the drainage of the active layer of permafrost, formed from the well-permeable upper parts of weathered crystalline rocks of the Quaternary age. The rapid flow of water from the recharge areas to the drainage zones and the short residence time of water in the rocks built of the permafrost active layer results in low water mineralization. The electrolytic conductivity EC of groundwater measured during the mapping of the catchment in August 2009 was in the range of $17\text{--}174\text{ }\mu\text{S cm}^{-1}$. The highest values were found in the mountain part of the catchment, mainly in the areas where bird colonies are present. The mean EC value was then $54\text{ }\mu\text{S cm}^{-1}$. The measurements of water EC in later periods exceeding even the EC value of $240\text{ }\mu\text{S cm}^{-1}$ occurred in one of the springs (no. 1a) and $245\text{ }\mu\text{S cm}^{-1}$ in the piezometer located on the coastal flattening (Table 1). Such high EC values were temporary and most likely related to the presence of birds in the mountain part, in the area of spring recharge zones. The delivery of the load of organic pollutants is evidenced by the fact that there was a significant drop in EC at the end of the summer season, when the birds left this part of Spitsbergen. The distribution of EC values shows an increasing tendency with a decrease in elevation (Fig. 2).

The active layer water of the Steinvik River catchment is characterized by a variable pH, from acidic to alkaline with value from 4.88 to 8.32 (5.79 on average, Table 1). In the case of surface waters, the mean value of pH was slightly higher and amounted to 6.01. In general, the distribution of this parameter in the catchment area tends to increase with highest altitude (Fig. 3), contrary to the EC (Fig. 2).

In the chemical composition of water, HCO_3^- , Cl^- , Na^+ , Mg^{2+} and Ca^{2+} ions dominate. The ion concentrations values are low. In surface waters, the dominant of bicarbonate and chloride anions reach a maximum of 16.74 mg L^{-1} and 11.85 mg L^{-1} , respectively, while in the group of cations, sodium concentrations

Table 1.

The basic ionic composition of surface and groundwater in the Steinvik River catchment in the period of 2009–2011. Values in in brackets indicate limit of quantification.

Water		EC [$\mu\text{S cm}^{-1}$]	pH	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	HCO ₃ ⁻	SO ₄ ²⁻	Cl ⁻	NO ₃ ⁻
				[mg L ⁻¹]							
Surface	mean	41.1	6.01	1.66	2.50	3.09	0.25	10.84	1.22	7.33	1.82
	min	25.3	5.26	0.78	1.52	1.82	0.15	5.58	0.13 (<1.0)	4.16	0.15 (<0.2)
	max	71.7	6.30	2.37	3.36	4.35	0.34	16.74	2.94	11.85	3.19
Ground water in active layer	mean	49.9	5.79	3.26	2.81	3.84	1.08	15.55	2.04	9.71	2.51
	min	25.3	4.88	1.17	1.24	2.06	0.09	4.59	0.27 (<1.0)	4.96	0.18 (<0.2)
	max	245.3	8.32	9.95	5.68	8.20	17.46	49.10	6.70	25.49	8.67

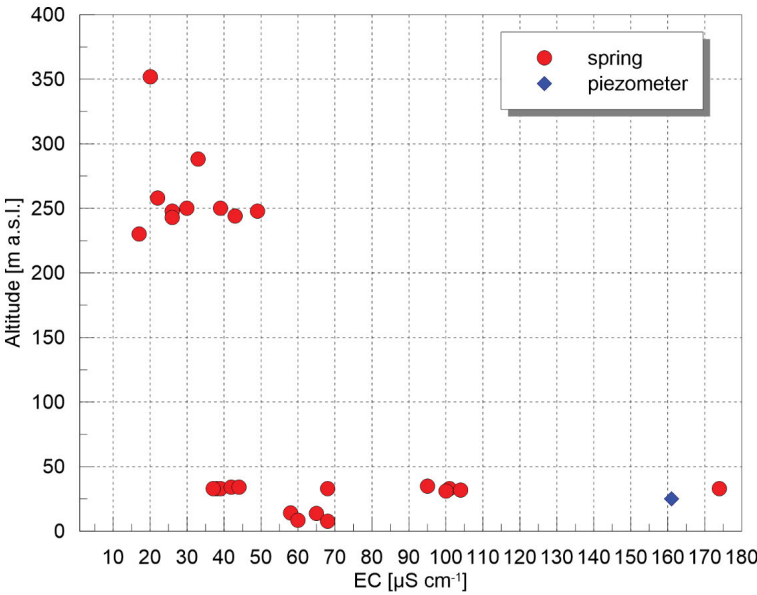


Fig. 2. Electrolytic conductivity (EC) vs. altitude of water sample (August 2009).

reach 4.35 mg L⁻¹ and magnesium 3.36 mgL⁻¹ (Table 1). In the case of groundwater in the active layer, the highest concentrations are reached by the anions HCO₃⁻ (up to almost 50 mg L⁻¹) and Cl⁻ (up to 25.5 mg L⁻¹), while the dominant cations in the concentration of calcium and sodium reach a maximum of 9.95 mg L⁻¹ and 8.2 mg L⁻¹, respectively (Table 1). Occasionally, relatively high, even up to 17.45 mg L⁻¹ of cation K⁺ are found. The values of NO₃⁻ anion concentrations (maximum 8.67 mg L⁻¹) are relatively low, considering the

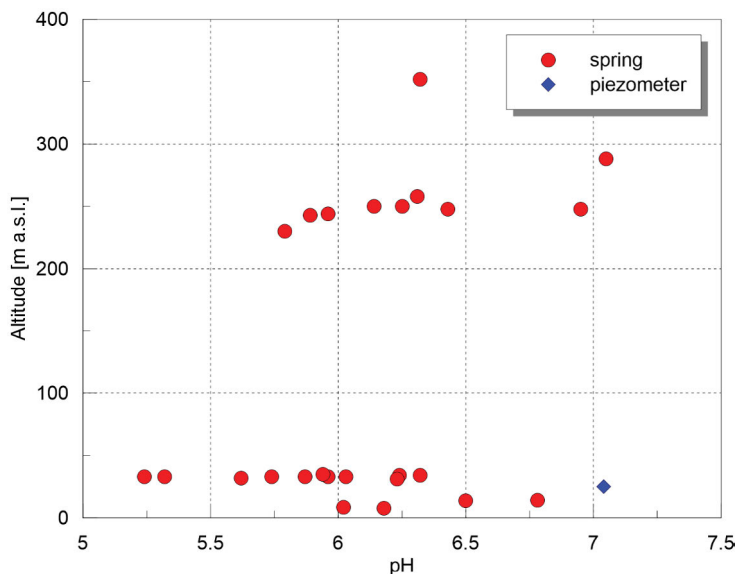


Fig. 3. Water pH vs. altitude of water sample (August 2009).

presence of significant bird populations. The contents of the remaining macrocomponents, especially sulphates, are low. In surface waters they are much lower than in groundwater of the active layer (Fig. 4 and Table 1).

There is no elevated concentrations of microcomponents in the analyzed water samples. The contents of metals in all eight analyzed samples are usually very low. Slight exceedances of the drinking water standard were measured only once in the case of Mn (0.9 mg L^{-1}) concentration in the piezometer in 2010 and Al ($268 \text{ } \mu\text{g L}^{-1}$) in the spring no. 4 during the summer of 2011. Apart from aluminum, which is definitely dominant in the composition of microcomponents, slightly higher concentrations of Zn (up to $12.18 \text{ } \mu\text{g L}^{-1}$), Pb (up to $6.69 \text{ } \mu\text{g L}^{-1}$) and Cu (up to $3.58 \text{ } \mu\text{g L}^{-1}$) were observed (Table 2). Important water components related to biotic factors are phosphate, nitrite and ammonium ions. From this group, the highest concentrations, up to a maximum of 18.78 mg L^{-1} , were recorded for the NH_4^+ ion in the waters of the active layer, tested in the piezometer. The average value of this ion in the tested water samples was 0.02 mg L^{-1} .

Temporal changes of selected physicochemical parameters. — The short seasonal field investigations in the Steinvik River catchment did not allow to observe all changes in the chemical composition of the waters during the entire period of groundwater runoff forming. To evaluate the temporal physicochemical changes in active layer waters, only periodic measurements of EC, pH and water temperature were carried out in the springs no. 1 (a, b, c), 13, 14 and 14a in the summer of 2010 and 2011 (Fig. 5). These changes are presented on the background of their total discharge. Both spring groups represent the drainage of the lower, flat part of the catchment area, located between the raised mountain range and the shore of the Greenland Sea.

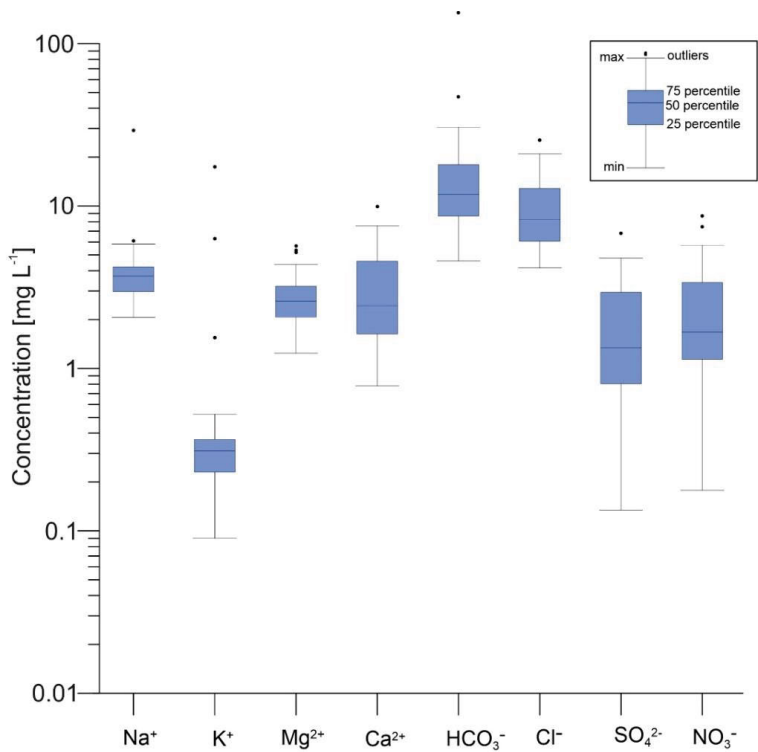


Fig. 4. The concentration of basic ions in groundwater of active layer in the period of 2009–2011.

Table 2

Microcomponents of surface and groundwater in the Steinvik River catchment in the period of 2009–2011.

		PO ₄ ³⁻	NO ₂ ⁻	NH ₄ ⁺	Fe _{tot}	Mn ²⁺	Cu ²⁺	Pb ²⁺	Zn ²⁺	Cd ²⁺	Al ³⁺	As ³⁺
		[mg L ⁻¹]					[μg L ⁻¹]					
Surface water	mean	<0.05	0.01	0.22	0.02	<0.02	0.62	<0.2	4.12	0.01	36.10	<1.0
	min	<0.05	<0.01	0.09	<0.02	<0.02	<0.2	<0.02	0.83	<0.01	13.93	<1.0
	max	0.11	0.02	0.46	0.07	0.02	2.35	0.30	8.22	0.03	69.00	<1.0
Ground-water in active layer	mean	0.11	0.01	0.87	0.02	0.04	0.65	0.90	4.11	0.02	58.83	<1.0
	min	<0.05	<0.01	<0.06	<0.02	<0.02	<0.02	<0.02	0.81	<0.01	14.19	<1.0
	max	1.22	0.03	18.78	0.28	0.90	3.58	6.69	12.18	0.27	267.52	<1.0

All periodically observed spring groups, although located close to each other, differed slightly in water temperature. The differences reached 1.5°C. The water temperature of springs 1a to 1c ranged from 0.9 to 5.3°C (Fig. 5). In the group of springs located in the central part of the coastal plain, the water temperature of individual outflows did not differ so much. The temperature range was 0.9–2.7°C

(Fig. 5). Quite stable and low water temperatures in these springs can confirm their direct recharge from permafrost.

The variability of the electrolytic conductivity in water springs located near the mountain slope and those located further away from it, is different. In springs 1a, 1b and 1c, the EC values of water, most often in the range of $25\text{--}50\ \mu\text{S cm}^{-1}$,

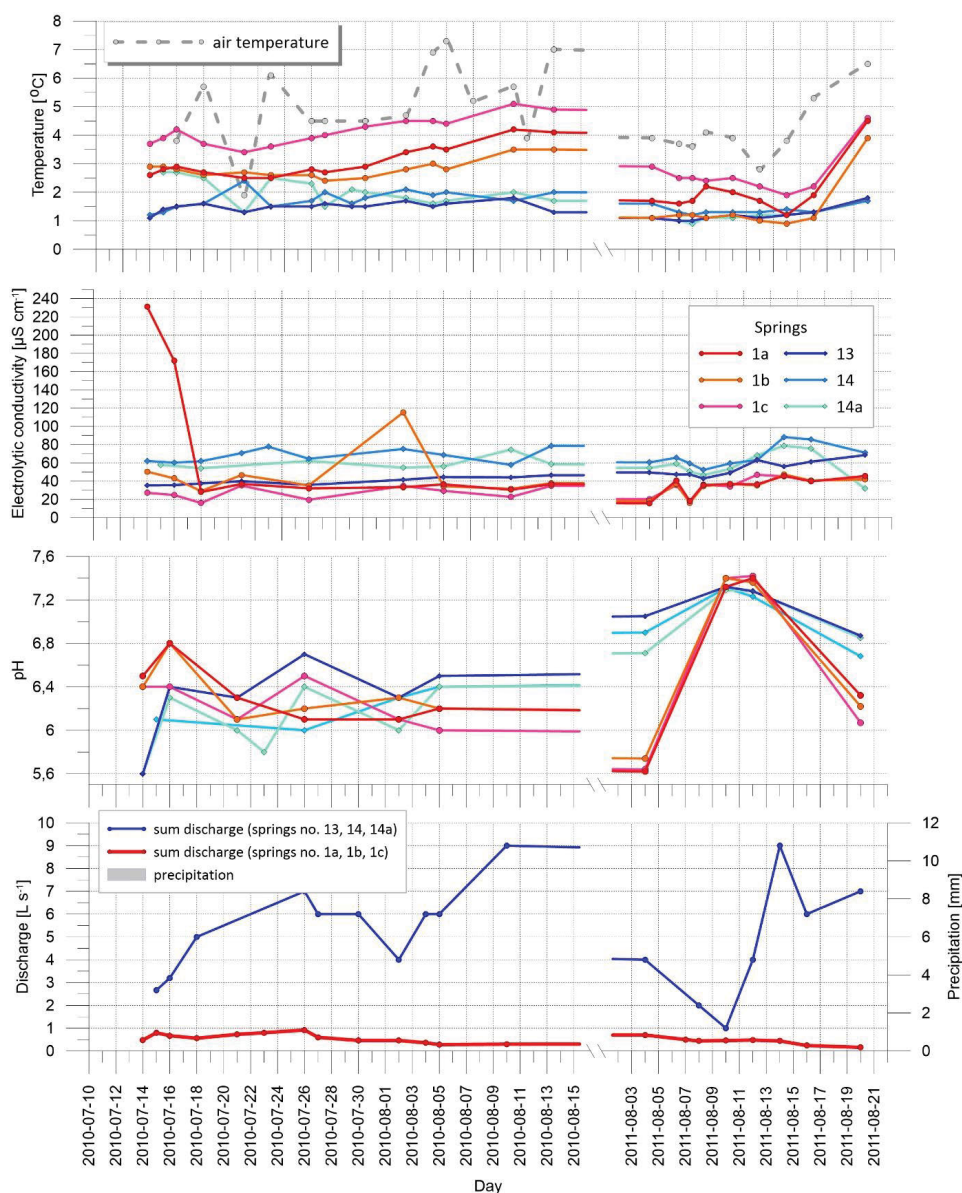


Fig. 5. Temporal changes of selected physicochemical parameters of selected water springs on the background of their discharge. Precipitation and air temperature as recorded at the Hornsund Station.

were largely consistent (Fig. 5). A sudden increase in the EC value was observed only twice in the outflow of 1a (up to $231 \mu\text{S cm}^{-1}$) and 1b (up to $\sim 110 \mu\text{S cm}^{-1}$). Interpretation of this phenomenon is difficult. The most likely reason for the increase in EC could be the periodical supply of some mineral components derived from the bird colony habitats.

In the group of closely located springs no. 13, 14 and 14a, the discrepancies in EC values were much larger (Fig. 5). The lowest values were observed in the spring 14a and the highest in the outflow 14. The EC amplitudes for these three outflows were respectively $33.1 \mu\text{S cm}^{-1}$ for the outflow 13, $36.1 \mu\text{S cm}^{-1}$ for 14, and $47 \mu\text{S cm}^{-1}$ for 14a. Apart from the outflow 1b, no increase in water mineralization was observed along with a decrease in the discharge of the springs. In the springs located near the mountain slope, the mineralization is practically constant regardless of changes in air temperature and discharge, while in outflows distant from the mountain part, such tendencies of increasing EC with discharge drop of spring are already visible (Fig. 5).

Considerable compliance of the changes was observed in case of the water pH of two spring groups. In some cases, the amplitudes of pH changes reached 2. In the group of springs located at the mountain slope, the pH values ranged from 5.62 at point 1a to 7.42 at point 1c (Fig. 5). The differences in the water pH of the second group of springs were similar, from the value of 5.60 in springs 13 and 14 to 7.32 in point 13, but the trend of changes was similar for all three springs (Fig. 5).

Isotopic composition of water. — The determination of the stable isotopes $\delta^{18}\text{O}$ and $\delta^2\text{H}$ was helpful in assessing the age of groundwater of the catchment. The results were visualized on the background of the World Precipitation Line (WMWL) and the local line developed for Spitsbergen (Yde *et al.* 2012). The values of stable isotopes concentrations range from -10.24 to -9.36‰ for $\delta^{18}\text{O}$ and from -71.0 to -61.0‰ for $\delta^2\text{H}$. For the comparison purpose a single sample Gn was also collected from the outflow of karst groundwater near the Gnålodden massif, located outside the analyzed catchment in the southern part of Spitsbergen. This sample differs markedly from the others collected in the Steinvik catchment. For $\delta^{18}\text{O}$, its value was -10.91‰ and for $\delta^2\text{H}$ -75.1‰ (Table 3; Fig. 6). The rain sample (Br) collected in the neighboring catchment of the Brattegg River catchment in the summer season of 2009 shows isotopic composition (-8.23‰ for $\delta^{18}\text{O}$ and -66.9‰ for $\delta^2\text{H}$) significantly different from the global precipitation line (Fig. 6).

Discussion

The study area belongs to young postglacial river system formed after the recession of permanent ice cover of the last glaciation. The forming of the physicochemical properties of surface and groundwater in the mountainous regions of the polar areas depends on a number of factors, mainly abiotic ones.

Table 3.

Isotopic composition of different types of water.

Point number	Type of point (location)	Altitude [m a.s.l.]	Date of sampling	$\delta^{18}\text{O}$ [‰]	$\delta^2\text{H}$ [‰]
P	piezometer	22	24.08.09	-9.73	-68.7
S1	stream	20	24.08.09	-9.54	-66.3
S2	stream	1	24.08.09	-9.36	-65.4
S3	stream	40	24.08.09	-9.51	-65.5
S4	stream	260	24.08.09	-10.03	-68.8
1a	spring	33	24.08.09	-9.64	-66.8
1b	spring	33	24.08.09	-9.65	-66.9
1c	spring	33	24.08.09	-9.62	-66.7
2	spring	288	24.08.09	-8.79	-61.0
3	spring	258	24.08.09	-9.45	-66.3
4	spring	230	24.08.09	-10.24	-71.0
13	spring	14	24.08.09	-9.66	-66.9
23	spring	352	24.08.09	-9.82	-67.8
Br	rain water (Brattegg River catchment)	-	26.08.09	-8.23	-66.9
Gn	karst spring (Gnålodden)	1	21.08.09	-10.91	-75.1

Waters in the subsurface weathered rocks are supplied by dissolved material. Intensive river drainage in the morphologically elevated upper part of the catchment area causes erosion of weathered metamorphic rocks and transport of suspended material downstream and its deposition on the flat coastal platform. However, in the Steinvik River catchment, the presence of bird colonies also strongly influences the water chemistry. The river runoff takes place during the polar summer, usually between June and September, when air temperatures are the highest (Marszałek and Wąsik 2013). The melting of snow and upper part of permafrost recharges streams and groundwater of active layer. The catchment is also recharged by precipitation, sometimes exceeding in summer 120 mm per month (Pereyma *et al.* 2013).

Cold and very low-mineralized melted water reduces mineralization of both, surface- and active layer groundwater, drained by numerous springs. The thickness of permafrost active layer is rather limited, rarely exceeding 2 m (Migala 1994). In the coastal zone of Greenland Sea the seawater intrusion occurs inland, which caused the “permafrost wedge” (Kasprzak 2020). This structure, reaching 60 m in length and 20 m in thickness, recognized geophysically, decreases toward the shoreline.

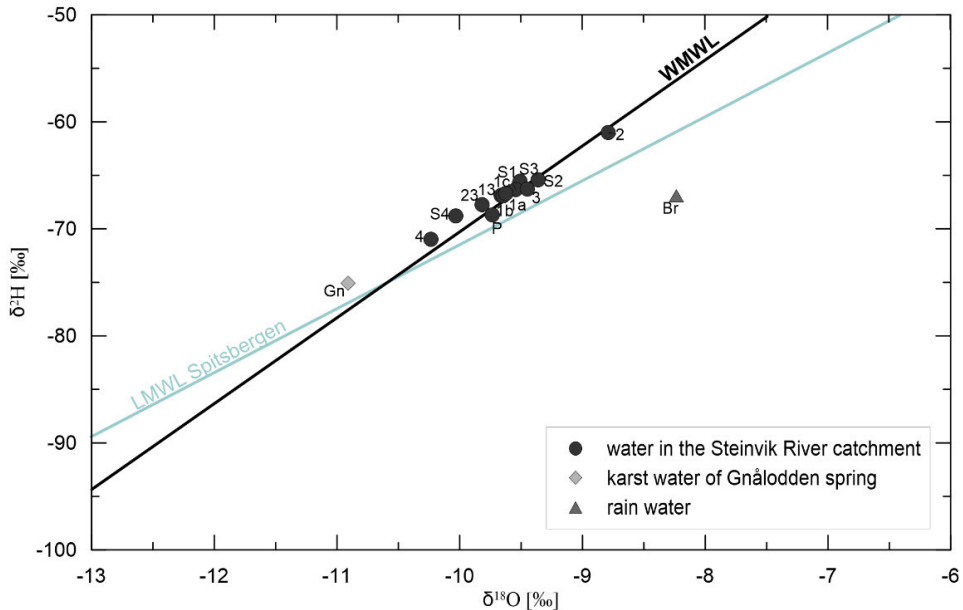


Fig. 6. Isotopic composition of active layer groundwater in the Steinvik River catchment compared with karst water from the Gnålodden spring and rain water sampled in the Brattegg River catchment; LMWL – Local Meteoric Water Lines, WMWL - World Meteoric Water Line.

High permeability of loose rocks material favors the fast flow of water through the active layer. Short residence time of groundwater determines their low mineralization. The electrolytic conductivity EC of surface water in the Steinvik catchment is most of the time low ($41.1 \mu\text{S cm}^{-1}$ on average) and is slightly lower than for groundwater ($50 \mu\text{S cm}^{-1}$; Table 1). The values are close to the lower limit of the hydrogeochemical EC background ($36\text{--}188 \mu\text{S cm}^{-1}$) determined for this part of Spitsbergen by Marszałek and Wąsik (2013).

The predomination of bicarbonates in the chemical composition of river water tends to be typical considering their recharge by groundwater related to the active layer of permafrost. Bicarbonates seems to source from weathering of the primary silicates and aluminosilicates in metamorphic rocks, because there are no carbonate rocks in the catchment area. Chloride ion content is significant in most of the tested samples. This is presumably related to the influence of marine aerosols from the Greenland Sea. As a result of evaporation, sea water releases its Cl^- loads to the atmosphere, which then, together with atmospheric precipitation, are transferred to surface and groundwater in the catchment area. Major cations as sodium, magnesium, and calcium also originate also from the weathering of crystalline rock minerals as well, but the presence of Na^+ may be also linked to the seawater transport in the form of aerosol. Other ways of chlorides delivery to shallow groundwater systems, including active layer, are rather questionable. Sea water intrusions can only cause a change in the salinity of the groundwater occurring at greater depths (Kasprzak 2020). In the case of the active layer water,

salinity may increase only in a narrow coastal zone as a result of onshore impact of waves.

The content of ions, depending on the influence of natural factors, affects the hydrochemical type of water. Low mineralization of water favors the forming of various, most often multi-ionic, hydrochemical types. According to the chemical composition of waters shown on the Piper diagram (Fig. 7), the predominant hydrochemical types are $\text{HCO}_3\text{-Cl-Mg-Ca}$, $\text{Cl-HCO}_3\text{-Mg-Na}$, $\text{Cl-HCO}_3\text{-Mg-Ca}$, and other various combinations of the above ions.

Thermokarst processes related to permafrost thawing and erosion play an important role in forming of water chemistry, soil and climate regimes (e.g., Jones *et al.* 2011; Vincent *et al.* 2013). The leached and dissolved material from the soils and weathered rocks enrich surface and groundwater in chemical compounds. Arctic soils can deliver a load of chemical elements to water. Cryosols contain 3–10% of carbonates, whereas soils located close to birds colonies have an elevated organic matter content and high concentration of nitrogen and phosphorus of animal origin (Kabała and Korabiewski 2013;

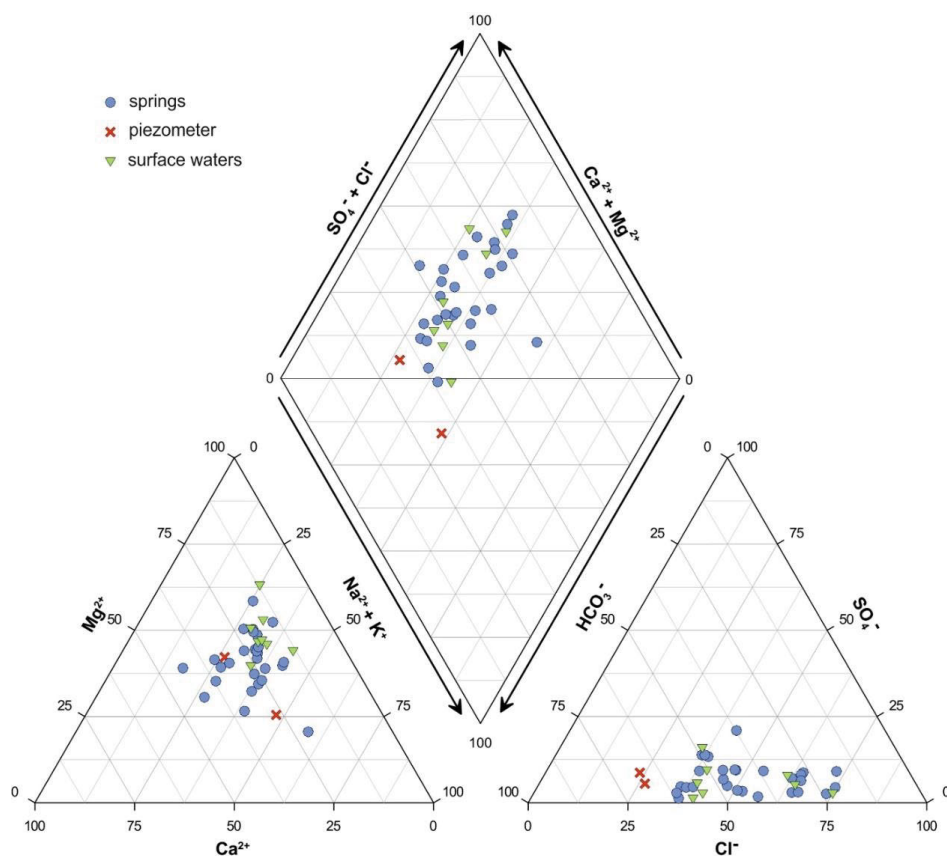


Fig. 7. Ionic composition of groundwater and surface waters in the Steinvik River catchment in the period of 2009–2011

Marszałek and Górniak 2017). The supply of nutrients can increase the EC value. The natural concentrations of trace metals in surface waters are rather low and depend on both geological and anthropogenic factors.

The physicochemical properties and the analysis of groundwater circulation in the Steinvik River catchment indicate their young age. Low mineralization of waters confirms their short residence time in the rock environment and fast circulation in the catchment area. The reaction of the springs water temperature to the air temperature indicates a shallow, often near-surface groundwater flow. The lack of tritium measurements does not allow for a more accurate determination of the age of the waters in the studied catchment.

Besides the chemical variability also the isotopic composition of waters changes slightly alongside the river system. The stable isotopes values depend mainly on the phase transformation of the atmospheric water portion in the water cycle (Zuber 2007). In Steinvik surface waters, the value range is limited, from -10.3 to -9.36% for $\delta^{18}\text{O}$ and from -68.8 to -65.4% for $\delta^2\text{H}$. Mean values of groundwater stable isotopes for the Steinvik River catchment, -9.62% for $\delta^{18}\text{O}$ and -66.78% for $\delta^2\text{H}$, show that these waters belong to young meteoric waters with different infiltration times. All the tested samples from the Steinvik River catchment show a high compliance with the WMWL line, but they do not follow the local line. To determine the cause of such distribution would require additional determinations of the isotopic composition of waters.

Taking into account the location in the depth profile and the formation of the aquifer in the permafrost active layer, the water age is limited to one summer season. So, it amounts to a maximum of about 4 months. The path of water flow from the recharge area, both at the morphological elevations and from the permafrost top, to the seaward drainage area is relatively short. This is due to the small size of the catchment area, small thickness of the active layer and relatively high filtration parameters of loose deposits in zones of privileged flow. Another problem, not analyzed in this study, is the age of the waters trapped in the permafrost ice, recharging the groundwater of the active layer.

Quite different isotopic composition of karst waters sampled in the Gnålodden massif (sample Gn on Fig. 6 and Table 3) confirms deeper (subpermafrost) groundwater circulation in carbonate rock systems developed under permafrost. The deep groundwater flow is confirmed by the high water temperature (13°C), which is much higher than the temperature of most of the springs draining the active layer in the Steinvik River catchment.

Conclusions

The study area belongs to the small, non-glaciated catchment where the forming of hydrogeological conditions, including the dynamics and chemistry of groundwater, is controlled by many processes. The location of catchment in the

Arctic determines the presence of permafrost limiting water infiltration into the deeper part of the bedrock. The groundwater runoff is related only to subsurface flow in active layer of permafrost, because there is no evidence of any deep groundwater circulation, *i.e.*, subpermafrost aquifer, in the Steinvik River catchment. Apart from abiotic also biotic factors are responsible for the physicochemical properties of surface and groundwater in the study area. High permeability of active layer weathered rocks material favors the fast flow and short residence time of groundwater. Therefore, water is characterized by low mineralization and temperature, the dominance of HCO_3^- or Cl^- , Mg^{2+} , Ca^{2+} , and Na^+ ions, and sometimes increased concentrations of such microcomponents as aluminum and other metals. The presence of bird colonies is responsible for providing nutrient compounds to the water and soil, such as phosphate, nitrite and ammonium. Groundwater of active layer in the Steinvik River catchment water belongs to young meteoric water with the age limited to one summer season.

Acknowledgements. — This work was partially financed from the statutory funds of the Wrocław University (Project No 2213/w/ING/09). Authors would like to thank two anonymous reviewers for their comments.

References

- Bieroński J. 1977. Chemical properties of waters around Hornsund. *Materiały z Sympozjum Spitsbergeńskiego*, Wrocław: 39–43 (in Polish).
- Chmal H. 1987. Pleistocene sea level changes and glacial history of the Hornsund area, Svalbard. *Polar Research* 5: 269–270.
- Cochand M., Molson J. and Lemieux J.M. 2019. Groundwater hydrogeochemistry in permafrost regions. *Permafrost and Periglacial Processes* 30: 90–103. doi: 10.1002/ppp.1998
- Cooper R.J., Wadham J.L., Tranter M. and Peters N. 2002. Groundwater hydrochemistry in the active layer of the proglacial zone, Finsterwalderbreen, Svalbard. *Journal of Hydrology* 269: 208–223. doi: 10.1016/S0022-1694(02)00279-2
- Culp J.M., Lento J., Goedkoop W., Power M., Rautio M., Christoffersen K.S., Guðbergsson G., Lau D., Liljaniemi P., Sandøy S. and Svoboda M. 2012. Developing a circumpolar monitoring framework for Arctic freshwater biodiversity. *Biodiversity* 13: 215–227. doi: 10.1080/14888386.2012.717526
- Czerny J., Kieres A., Manecki M. and Rajchel J. 1993. *Geological map of the SW part of Wedel Jarlsberg Land Spitsbergen, 1:25 000*. Institute of Geology and Mineral Deposits, University of Mining and Metallurgy, Kraków.
- Haldorsen S. and Lauritzen S.E. 1995. Subpermafrost groundwater in Spitsbergen. In: Banks S. and Banks D. (eds) *Hydrogeology of Hard Rocks*. Memoir of the 24th Congress of the IAH, NGU, Trondheim, Norway: 940–949.
- Haldorsen S., Heim M. and Lauritzen S.E. 1996. Subpermafrost groundwater, Western Svalbard. *Nordic Hydrology* 27: 57–68.
- Hoel A. 1918. Rapport preliminaire de l'expédition norvegienne de 1918 au Spitsberg. *Geographie* 32: 231–235.

- Jahn A. 1968. The raised shorelines and beaches in Hornsund and the problem of postglacial vertical movements of Spitsbergen. In: *Results of investigations of the Polish Scientific Spitsbergen Expeditions 1957–1960*. Wydawnictwa Geologiczne, Wrocław: 173–176.
- Jones B.M., Grosse G., Arp C.D., Jones M.C., Walter A.M., Romanovsky V.E. 2011. Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. *Journal of Geophysical Research: Biogeosciences* 116. doi: 10.1029/2011jg001666
- Kabała C. and Korabiewski B. 2013. Soils. Geographical environment in the vicinity of the Stanisław Baranowski Polar Station-Werenskioldbreen. In: Zwoliński Z., Kostrzewski A. and Pulina M. (eds.) *Ancient and modern geoecosystems of Spitsbergen: Polish geomorphological research*. Bogucki Wydawnictwo Naukowe, Poznań: 114–118.
- Karczewski A., Kostrzewski A. and Marks L. 1981. Raised marine terraces in the Hornsund area (northern part), Spitsbergen. *Polish Polar Research* 2: 39–50.
- Kasprzak M. 2012. Morphometry, forms and sediments of the Steinvik Valley (SW Spitsbergen). In: Krawczyk E. and Styszyńska A. (eds.) *Streszczenia referatów i posterów, XXXIV Sympozjum Polarne*, Sosnowiec: 84 (in Polish).
- Kasprzak M. 2020. Seawater intrusion on the Arctic Coast (Svalbard): The concept of onshore-permafrost wedge. *Geosciences* 10: 349. doi:10.3390/geosciences10090349
- Kendrick M.R., Hurn A.D., Bowden W.B., Deegan L.A., Findlay R.H., Hershey A.E. and Schuett E.B. 2018. Linking permafrost thaw to shifting biogeochemistry and food web resources in an arctic river. *Global Change Biology* 24: 5738–5750. doi: doi.org/10.1111/gcb.14448
- Krawczyk W.E. 1990. Thermal springs below Raudfjellet, South West Spitsbergen. Results of Investigations of the Polish Scientific Spitsbergen Expeditions. *Acta Universitatis Wratislaviensis VII*, 1069, Wrocław: 67–74.
- Krawczyk W.E. 1992. Chemical characteristics of water circulating in the Werenskiold Glacier (SW Spitsbergen). In: *Proceedings of the 2nd International Symposium of Glacier Caves and Karst in Polar Regions*, Międzygórze-Velká Morava, Poland, 10–16 February 1992, Silesian University, Sosnowiec: 65–80.
- Krawczyk W.E., Bartoszewski S. and Siwek K. 2008. Rain water chemistry at Calypsobyen, Svalbard. *Polish Polar Research* 29: 149–162.
- Krzyszowska A.J. 1985. Tundra degradation in the vicinity of the Polish Polar Station, Hornsund, Svalbard. *Polar Research* 3: 247–252.
- Leszkiewicz J. 1982. Rasstupet karst springs in the South Spitsbergen based on researches in the 1978. *Polar expeditions of the University of Silesia 1977–1980*, Katowice: 77–86 (in Polish).
- Majka J. 2006. Monazite dating results from the S part of Wedel Jarlsberg Land, Svalbard. *Mineralogia Polonica* 28: 139–141.
- Marsz A.A., Niedźwiedz T. and Styszyńska A. 2013. Contemporary changes in the climate of Spitsbergen as the basis for determining landscape changes. In: Zwoliński Z., Kostrzewski A. and Pulina M. (eds.) *Ancient and modern geoecosystems of Spitsbergen: Polish geomorphological research*. Bogucki Wydawnictwo Naukowe, Poznań: 391–413 (in Polish).
- Marszałek H. and Górniak D. 2017. Changes in water chemistry along the newly formed High Arctic fluvial-lacustrine system of the Bratteg Valley (Wedel Jarlsberg Land, SW Spitsbergen). *Environmental Earth Sciences* 76: 449–462. doi: 10.1007/s12665-017-6772-9
- Marszałek H. and Wąsik M. 2013. Some physico-chemical features of water in suprapermafrost zone in the Hornsund region (SW Spitsbergen). *Biuletyn Państwowego Instytutu Geologicznego* 456: 397–403.
- Migala K. 1994. Features of the permafrost active layer in the climatic conditions of Spitsbergen. *Acta Universitatis Wratislaviensis* 1590, *Prace Instytutu Geografii, C, Meteorologia i Klimatologia* 1: 79–111 (in Polish).

- Migala K. and Wawrzyniak T. 2013. Climate. Geographical environment in the vicinity of the Stanisław Siedlecki Polish Polar Station in Hornsund. *In: Zwoliński Z., Kostrzewski A. and Pulina M. (eds.) Ancient and modern geoeosystems of Spitsbergen: Polish geomorphological research*. Bogucki Wydawnictwo Naukowe, Poznań: 71–76.
- Migoń K. and Kasprzak M. 2013. Geographical environment in the vicinity of the Stanisław Baranowski Polar Station - Werenskioldbreen. *In: Zwoliński Z., Kostrzewski A. and Pulina M. (eds.) Ancient and modern geoeosystems of Spitsbergen: Polish geomorphological research*. Bogucki Wydawnictwo Naukowe, Poznań: 104–114. (in Polish)
- Moiseenko T.I., Gashkina N.A., Dinu M.I., Kremleva T.A. and Khoroshavin V.Y. 2020. Water chemistry of Arctic lakes under airborne contamination of watersheds. *Water* 6: 1659. doi: 10.3390/w12061659.
- Orvin A. K. 1940. Outline of the geological history of Spitsbergen. *Skrifter Svalbard Ishauet* 78: 57 pp.
- Olichwer T., Tarka T. and Modelska M. 2013. Chemical composition of groundwaters in the Hornsund region, southern Spitsbergen. *Hydrology Research* 44: 117–130. doi: 10.2166/nh.2012.075
- Pereyma J., Migala K. and Sikora S. 2013. Geographical environment in the vicinity of the Stanisław Baranowski Polar Station - Werenskioldbreen: Climate. *In: Zwoliński Z., Kostrzewski A. and Pulina M. (eds.) Ancient and modern geoeosystems of Spitsbergen: Polish geomorphological research*. Bogucki Wydawnictwo Naukowe, Poznań: 118–121 (in Polish).
- Pulina M. 1977. Remarks about karst phenomena in the south part of Spitsbergen. *Karst and Speleology* 1: 104–125 (in Polish).
- Pulina M., Krawczyk W. and Galas W. 1999. Chemical characteristics of waters in the Hornsund region in the summer of 1998. *Polish Polar Studies* 26: 243–250.
- Roberts K.E., Lamoureux S.F., Kyser T.K., Muir D.C.G., Lafrenière M.J., Iqaluk D. and Normandeau A. 2017. Climate and permafrost effects on the chemistry and ecosystems of high Arctic Lakes. *Scientific Reports* 7: 13292. doi: 10.1038/s41598-017-13658-9
- van Everdingen R.O. 1990 Ground water hydrology. *In: Prowse T. D. and Ommanney C. S. L. (eds.) Northern Hydrology: Canadian Perspectives NHRI Science Report No. 1*. National Hydrology Research Institute, Environment Canada, Saskatoon, Saskatchewan: 77–101.
- Vincent W.F., Pienitz R., Laurion I. and Walter A.K. 2013. Climate impacts on Arctic lakes. *In: Goldman C.R., Kumagai M. and Robarts R.D. (eds.) Climatic change and global warming of inland waters: impacts and mitigation for ecosystems and societies*. Wiley, Chichester: 27–42. doi: 10.1002/9781118470596.ch2
- Wrona F.J., Reist J.D., Amundsen P.A., Chambers P.A., Christoffersen K.S., Culp J.M. and Zavalko S. 2013. Chapter 13: Freshwater ecosystems. *In: H. Meltøfte (Ed.) Arctic biodiversity assessment. Status and trends in Arctic biodiversity*: 335–377.
- Yde J.C., Hodson A.J., Solovjanova I., Steffensen J.P., Nørnberg P., Heinemeier J. and Olsen J. 2012. Chemical and isotopic characteristics of a glacier-derived naled in front of Austre Grønfjordbreen, Svalbard. *Polish Polar Research* 31: 3–18. doi: 10.3402/polar.v31i0.17628
- Zuber A. (ed.) 2007. *Tracer methods in hydrogeological studies*. Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław (in Polish).

Received 31 August 2022

Accepted 5 October 2022