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THE INFLUENCE OF GROUNDWATER DISCHARGE ON THE RUNOFF OF AN ARCTIC STREAM (EBBA RIVER, CENTRAL SPITSBERGEN)

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Abstract. The article presents investigation of groundwater occurrence in the Ebba River catchment located in central Spitsbergen (Petuniabukta region). It was recognized that groundwater occurs there seasonally in the summer melting season when the melting of active layer take place and enable flow of groundwater. Using data from four groups of piezometers located in different parts of the valley the hydrogeological parameters that characterize this shallow aquifer (thickness of the active layer, hydraulic conductivity, groundwater level fluctuations) were recognized. Using Darcy's low the amount of water that recharge Ebba River was calculated using field data. This calculation enabled more precise estimation of other component of Ebba River recharge (surface and overland water inflow, recharge from glaciers). These calculations were confirmed by interpretation of groundwater and surface water chemistry differentiation.

Key words: active layer, groundwater flow, Svalbard, Arctic regions.

INTRODUCTION

The hydrological investigation at high latitudes in the Arctic has received significant attention over the last years. Particular stress is put on the recognition of water balance calculation within catchments (i.e. the identification of water circulation components within catchment). The complexity of this type of investigation connected with specific Arctic conditions should be taken into consideration (Killingveit *et al.*, 2003). These conditions are related mainly with the irregular polar functioning of meteorological stations (most of them operates only during polar summer) and their irregular spatial locations (most of them are located near the sea-coast). This caused that the investigation of same water balance components is computed approximately or estimated indirectly (Hagen, Lafauconnier, 1995; Cooper *et al.*, 2002; Marciniak *et al.*, 2007).

Groundwater systems in the high Arctic regions (especially deep aquifers) probably belong to the least studied groundwater systems in the world (Haldorsen, Heim, 1999). As Killingveit *et al.* (2003) summarize also shallow groundwater occurring in the seasonally refreezing active layer is the most unique recognized component of water balance.

The aim of the present study is the recognition of groundwater in the active layer of the region of Ebbaelva catchment located in central Spitsbergen. The specific targets are:

- the investigation of the conditions of groundwater occurrence in the shallow seasonally refreezing active layer of glaciated catchment;
- the field estimation of the hydrogeological parameters (thickness of the active layer, hydraulic conductivity, groundwater level fluctuations);
- the calculation of the Ebba River recharge components (special emphasis was put on the calculation of the recharge of the Ebba River caused by groundwater flow).

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THE STUDY AREA

The study area is located in the northern part of Billefjorden (central part of Spitsbergen, at 78°41.98' N and 16°36.69' E) (Fig. 1). The average annual precipitation is approximately 200 mm. The period of time that the air temperature is above 0°C (the period of active groundwater and surface water flow) normally starts in June and lasts until the end of August or mid-September.

Ebbaelva (the Ebba River) is located in the central part of the Ebba Valley. The valley is about four kilometres long and two kilometres wide. The river originates mainly from Ebba-

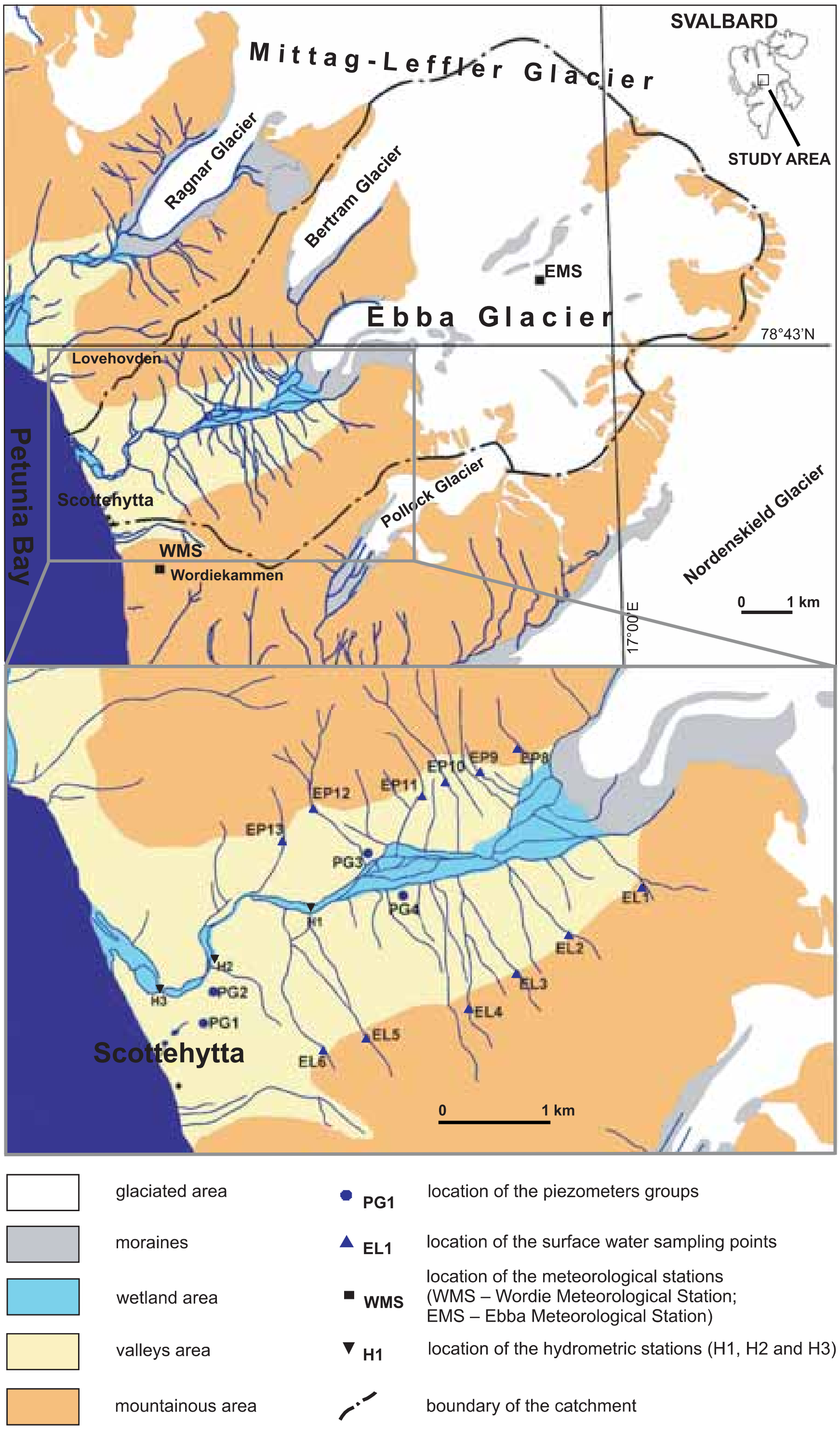

Fig. 1. Location scheme (after Dragon and Marciniak, 2010, modified)

breen (the Ebba Glacier) and Bertrambreen (the Bertram Glacier). The front ice of this glacier is located about four kilometers from the coast. Ebba is a polythermal glacier and has been in recession over the last hundred years. This is manifested by its negative mass balance and the retreat of its ice-front position (Rachlewicz *et al.*, 2007). From the north and south, the valley is surrounded by mountain edges. The streams recharged periodically by snow melt (during the summer season) flow down from mountains edges to the Ebba River.

The boundary of the catchment was assigned using morphological criteria. The boundary on the glaciated area of the catchment is uncertain. The catchment area is about 70 km^2, about 51 km^2 of this area is covered by glaciers.

The part of Ebba Valley closed to the sea is cover by the tundra. The best conditions for tundra existence occur at an elevation between 10 and 50 m a.s.l. In part of the valley closed to the glacier there is lack of vegetation.

The weather conditions in this part of Spitsbergen differ from those of the well studied western coast of the Iceland. It is evidenced mainly by much lower amounts of precipitation (Rachlewicz, Szczuciński, 2008).

GEOLOGY AND HYDROGEOLOGY

Dislocations along the Billefjiorden Fault zone dominate the bedrock geology of the region (Dallmann *et al.*, 2004). The longitudinally orientated faulting caused a wide variety of rock types to outcrop in the study area. The mountain massif in the part of the region close to the glacier (the eastern part) is composed mainly of metamorphic rocks (amphibolites, gneisses and achiest). The central part of the region is dominated by gypsum, dolomite and anhydrite prevail. Sandstone, limestone and dolomite dominate in the area near the seaside.

The Ebba Valley is covered mainly by slope deposits which are composed of rocks originating from the surrounding mountains ridges. In the part of the valley close to the sea, marine shore deposits occur. The central part of the valley near the Ebba River is covered by fluvial and glacifluvial deposits (*op. cit.*).

The slope deposition covering the valley area thaws seasonally and forms a shallow active layer, which enables the flow of groundwater (Shur *et al.*, 2005). Based on field investigation with the support of the hydrochemical data (Dragon, Marciniak, 2010) the conceptual model of water circulation within catchment was formulated (Fig. 2). When the temperature rises above 0°C the flow of water starts and the thickness of the active layer increases. The maximum thickness of the active layer usually occurs at the end of the summer season and varies between 0.3 and 1.6 m (Rachlewicz, Szczuciński, 2008). Streams that flow from the mountain ridges recharge the groundwater occur within the active layer. These streams, in some cases, in the upper portions of the slopes disappear and formulate subsurface flows. In other cases the overland flow is created. At the end of the melting season, when the temperature drops below 0°C (usually in September) the active layer freezes up and water stays locked to the next season (Dragon, Marciniak, 2010).

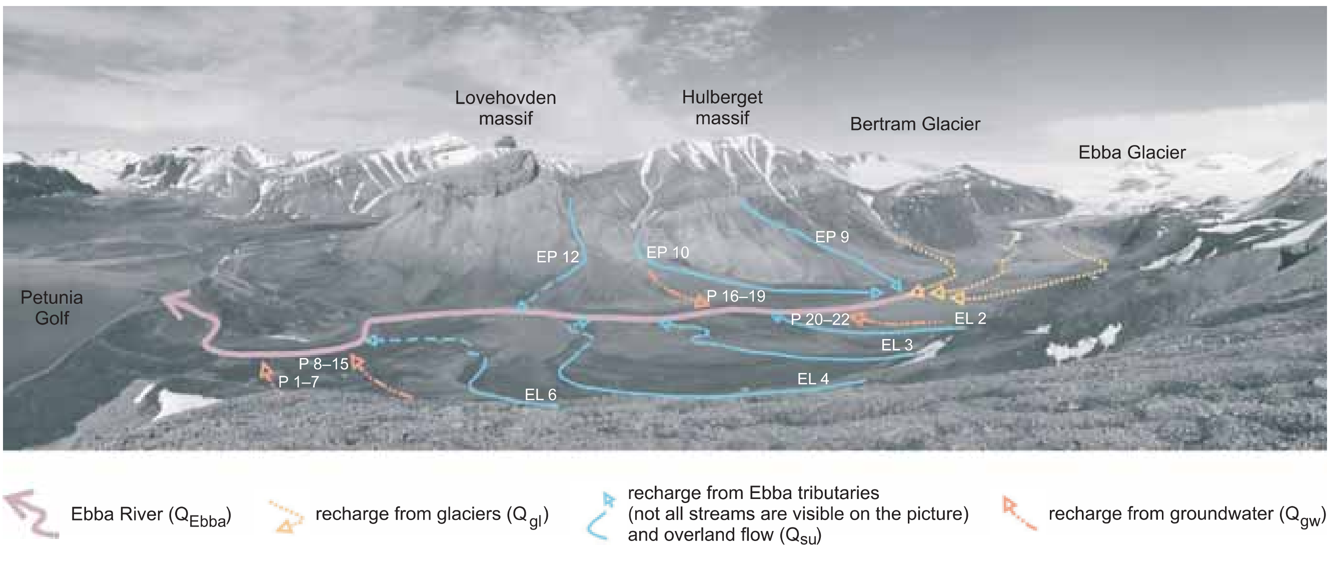

Fig. 2. Conceptual model of water circulation within the Ebba River catchment (after Dragon and Marciniak, 2010, modified)

The arrows mark places of piezometers installations

MATERIALS AND METHODS

The runoff of the Ebba River was measured at three hydrometric stations during the summer of 2008. The first hydrometric station (H1) was located at a place where the river flow is changes from dispersed overland flow to clear channel flow while the third hydrometric station (H3) was located close to the river estuary to the Petunia Bay. The hydrometric station H2 was located at the middle part of the river channel. The measurements were performed with the use of an electromagnetic hydrometric meter (SEBA-Hydrometrie type). Open channel flow measurements were performed every five days (11 measurement series).

Four groups of piezometers were installed within the investigated catchment in the summer of 2007. These piezometers were made of PVC pipes with a diameter of 40 mm. Piezometers were installed using hand drilling equipment during the period when the active layer was at its maximum thickness (the end of July). In the regions of coarse rock occurrence, piezometers were made by digging a pit, but the lower part of each piezometer (the part where the screen is installed) was always drilled to retain the original hydrogeological conditions. The piezometers depth varied between 0.5 and 1.0 m. Each of the piezometers was equipped with a 5 cm long PVC screen and a gravel pack to prevent siltation. The screen was installed at the bottom part of the active layer.

In all piezometers, measurements of water level and temperature were taken at three-day intervals in the period between 20 July and 4 September 2008.

The background data of meteorological conditions were derived from three meteorological stations located in the vicinity of Petunia Bay, called Scotte, Ebba and Wordie. Scotte station is located about twenty meters from the coast (about 5 m a.s.l.). Ebba Meteorological Station (EMS) is located on the Ebba Glacier (about 470 m a.s.l.) and Wordie Meteorological Station (WMS) is located on the Wordiekammen ridge (about 460 m a.s.l.). The following parameters were measured (with automatic recording) at these stations: precipitation, wind speed and direction, air humidity, air pressure and temperature.

RESULTS

The most significant water components that recharge the Ebba River are (Fig. 2):

$$Q_{Ebba} = Q_{gl} + Q_{su} + Q_{gw} \qquad [1]$$

where:

Q_{gl} – recharge from Bertram and Ebba glaciers, [m^3/s],
Q_{su} – recharge from Ebba tributaries (streams originated from mountains ridges) and overland flow, [m^3/s],
Q_{gw} – recharge from groundwater, [m^3/s].

It was assumed that recharge from direct precipitation can be neglected because during all summer period the precipitation intensity was very small. At the Scotte station 27.2 mm of precipitation was measured while at the WMS and EMS 16.2 mm and 33.8 mm was measured (respectively).

The results of the Ebba River runoff is presented on Figure 3. The clear differentiation of the runoff is visible between H1 and H3 hydrometric stations. It is connected with influence of recharge components other than water from glaciers.

The groundwater runoff was calculated using Darcy's law:

$$Q_{gw} = k \cdot b \cdot m \cdot J \qquad [2]$$

where:

Q_{gw} – groundwater runoff, [m^3/s],
k – hydraulic conductivity, [m/h],
b – the width of the recharge (calculated for each groups of piezometers), [m],
m – thickness of the active layer, [m],
J – hydraulic gradient.

The estimation of the hydraulic conductivity (k) of the active layer was assessed in the field using the Paramex method (Marciniak, 1999). In this method tempo of groundwater level movement (recorded direct in the field) caused by compression or is use for estimation of hydraulic conductivity. The hydraulic conductivity is characterise by large differentiation related even to the piezometers located close to each other (Table 1). It is related to the sedimentation environment of the slope deposits (especially talus). Thethickness of the active layer (m) was calculated as the height of the groundwater level above the permafrost. The hydraulic gradient (J) was calculated using measurements of the groundwater level in each groups of piezometers.

First the specific discharge for each groups of piezometers was calculate and then total groundwater runoff for all valley area was assessed. The calculation is presented on Table 2.

It was assumed that difference of total runoff between hydrometric stations H1 and H3 (Fig. 3) was connected with recharge from Ebba tributaries (streams originated from mountains ridges) and overland flow as well as with groundwater recharge:

$$Q_{III} = Q_I + Q_{su} + Q_{gw} \qquad [3]$$

from where:

$$Q_{su} = Q_{III} + Q_I + Q_{gw} \qquad [4]$$

where:

Q_{III} – total runoff at the H3 hydrometric station, [m^3/s],
Q_I – total runoff at the H1 hydrometric station, [m^3/s].

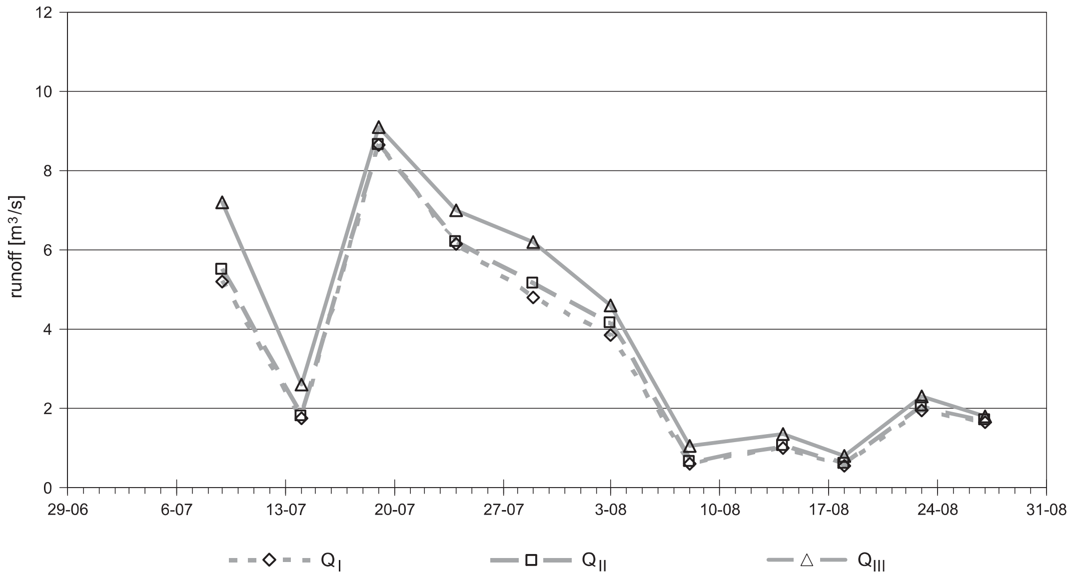

Fig. 3. The runoff of the Ebba River during summer season of 2008

Q_I, Q_{II} and Q_{III} were measured at H1, H2 and H3 hydrometric stations, respectively

Table 1

The hydraulic conductivity estimated for each piezometers using Paramex method

Piezometer No.	Hydraulic conductivity (k) of the active layer [m/h]	Hydraulic conductivity (k); average for each groups of piezometers [m/h]
P01	1.80	2.22
P03	3.96	
P05	0.90	
P08	1.18	1.43
P09	0.89	
P10	0.70	
P11	1.44	
P12	0.32	
P13	1.86	
P14	1.60	
P15	3.44	
P16	3.03	
P17	0.80	1.72
P18	1.22	
P19	1.81	
P20	3.28	4.00
P21	1.23	
P22	7.50	

From field investigation the total runoff of the Ebba River (Q_I and Q_{III}) was known as well as the groundwater runoff (Q_{gw}) was calculated. In this case using equation [4] the calculation of surface runoff – Q_{su} (calculated as a sum of streams tributaries recharged the Ebba River and overland flow) was possible (Table 2).

The recharge of the Ebba River from glaciers (Q_{gl}) was calculated using formula:

$$Q_{gl} = Q_{Ebba} + Q_{su} + Q_{gw} \quad [5]$$

The calculation of the total runoff of the Ebba River is presented in Figure 4 and Table 3. The calculation confirm that the main component of the Ebba River recharge is flow of water from glaciers. The amount of this water was calculated as 80.1% of total runoff. The recharge of the river by surface flow was estimated as 13.0%. The negative value at the end of melting season are connected with the error of estimation. The recharge of the river by groundwater flow was estimated as 6.9% of the total runoff. What is interesting the value of this parameter increase systematically during melting season (Table 3). It is connected with increase of the active layer thickness during summer season. This factor has the biggest importance at the end of the summer when the melting of the glaciers decline but groundwater flow in the active layer is still active.

The most important component of the Ebba River recharge is flow of water from glaciers. At the start of July the snow melt accumulated seasonally on the glacier surface was observed (Fig. 5). In this period of time relative small temperature increase cause increase of the Ebba River runoff. After that in second half of July the melt of glaciers was observed, what is

Table 2

The sample calculation of groundwater flow performed for data measured in the field, 9 July 2008

	J [–]	*m* [m]	*k* [m/h]	*q* [m^3/h·m]	*q* [m^3/s·m]	*q average* [m^3/s·m]	*L Ebba* [m]	Q_{gw} [m^3/s]
Group 1	0.060	0.4	2.22	0.053	0.0000148	0.0000185	4765	0.18
Group 2	0.056	0.5	1.43	0.040	0.0000105			
Group 3	0.051	0.4	1.72	0.035	0.0000094			
Group 4	0.089	0.4	4.00	0.142	0.0000391			

All parameters were estimated using data from measurement performed during one day: *J* – hydraulic gradient, *m* – thickness of the active layer, *k* – hydraulic conductivity (average for each groups of piezometers), *q* – specific discharge, *q average* – specific discharge (average for each groups of piezometers), *L Ebba* – the length of the Ebba River (the width of the recharge from groundwater), Q_{gw} – total groundwater runoff

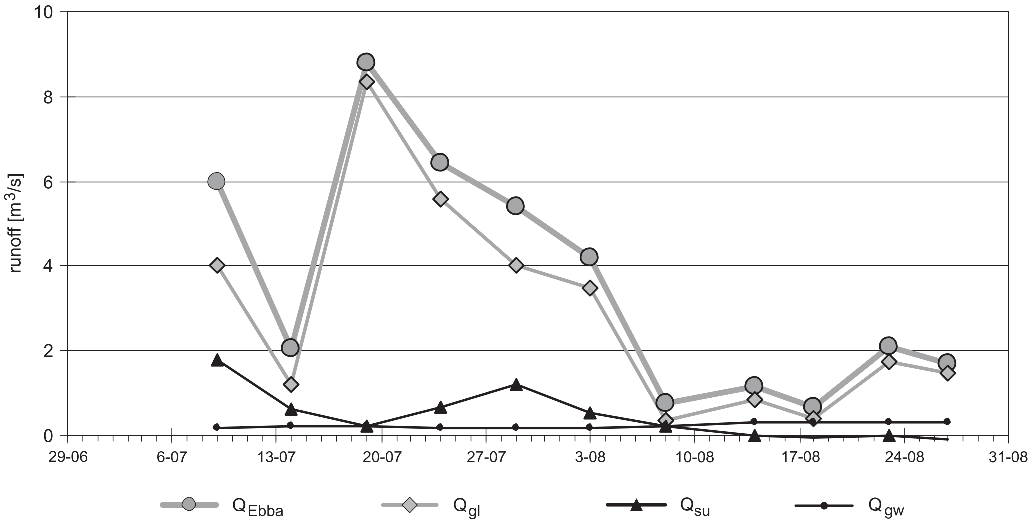

Fig. 4. The total runoff of Ebba River and components of Ebba River recharge during summer season of 2008

For explanations see text

Table 3

The average total runoff of the Ebba River and components of the Ebba River recharge during summer melting season of 2008 (explanations in text)

Date	Q_{Ebba}	Q_{gl}	Q_{su}	Q_{gw}
	m^3/s			
2008-07-09	5.96	4.00	1.78	0.18
2008-07-14	2.06	1.21	0.63	0.22
2008-07-19	8.80	8.35	0.23	0.22
2008-07-24	6.45	5.60	0.66	0.19
2008-07-29	5.39	4.02	1.19	0.18
2008-08-03	4.20	3.47	0.53	0.19
2008-08-08	0.76	0.34	0.21	0.21
2008-08-14	1.14	0.83	–0.01	0.32
2008-08-18	0.65	0.38	–0.05	0.32
2008-08-23	2.09	1.75	0.02	0.33
2008-08-27	1.70	1.45	–0.08	0.33
Maximum	8.80	8.35	1.78	0.33
Minimum	0.65	0.38	–0.08	0.18
Average	3.56	2.85	0.46	0.24
Procent	100.0	80.1	13.0	6.9

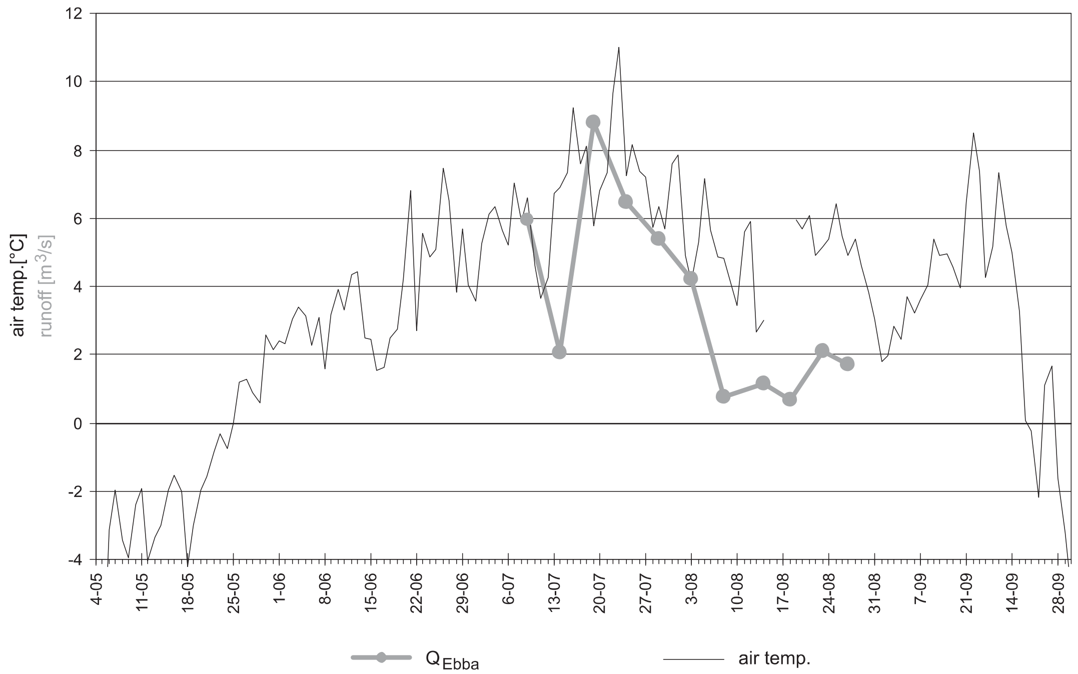

Fig. 5. Ebba River runoff and air temperature measured at meteorological station located in Longyearbyen during summer season of 2008 (www.unis.no)

Table 4

The Ebba River chemistry differentiation along flow line

Parameter		Ebba 1	Ebba 2	Ebba 3
Alkalinity (HCO_3)	mval/l	0.50	0.50	0.60
Cl	mg/l	1.67	1.76	1.83
SO_4		35.1	41.3	40.5
Ca		21.4	22.4	25.4
Mg		2.64	2.17	2.39
Na		1.62	1.53	1.36
K		0.69	0.68	0.59

manifested by strong correlation of the Ebba River runoff and air temperature. Similar temporal differentiation of runoff was observed during summer seasons of 2007 and 2009 (data not presented). This phenomenon is known in the literature as "Stenborg's effect" (Leszkiewicz, 1987).

The calculations of the Ebba River water balance was supported by the interpretation of the hydrochemical data. It was documented that both surface and groundwater that recharge the Ebba River are highly mineralized. The main water components are sulphate, calcium and magnesium as well as biocarbonate. The origin of water chemistry is connected mainly with dissolution of gypsum, anhydrite, dolomite and limestones (Dragon, Marciniak, 2010). The relatively low concentrations of almost all of the hydrochemical parameters was measured in the Ebba River (Table 4). Also water chemistry changes along flow line (variation between sampling points of Ebba 1 and Ebba 3) was not distinct. Only small increase of sulphate and calcium is marked. It is evident that inflow of highly mineralized water (Ebba River tributaries, overland and groundwater flow) is comparatively small compared to the recharge from the glaciers.

CONCLUSIONS

The investigation of groundwater occurrence in the Ebba River catchment located in central Spitsbergen (Petuniabukta region) was documented during ablation season of 2007. It was documented that groundwater occurs there seasonally in the summer melting season when the melting of active layer take place and enable flow of groundwater. These waters at the end of summer season froze up and stay locked to the next melting season.

Using data performed from four groups of piezometers measurements the hydrogeological parameters that characterize this shallow water system (thickness of the active layer, hydraulic conductivity, groundwater level fluctuations) were investigated. Then using Darcy's low the amount of water that recharge the Ebba River was calculated. This calculation enabled more precise estimation of other component of the Ebba River recharge (surface and overland water inflow, recharge from glaciers).

It was calculated that the main component of the Ebba River recharge is flow of water from glaciers (80.1 percent of total runoff). The amount of water originated from the inflow of the Ebba River tributaries and overland flow is 13.0 percent of total river runoff. The amount of groundwater that recharge the Ebba River is 6.9% of the total runoff.

The most unique character have calculation of groundwater flow. This component of recharge in Arctic environment is usually estimated approximately, assessed using conceptual models (Killingveit *et al.*, 2003) or even omitted in water balance calculations (Hagen, Lafauconnier, 1995). The direct field investigation of groundwater flow allow more precise estimation of other recharge components. What is the most important – the field investigation of groundwater occurrence causes lack of the speculation about possibility of groundwater flow within active layer.

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