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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 functioning of polar 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; 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 Ebba River caused by groundwater flow).

THE STUDY AREA

The study area is located in the northern part of Billefjorden (central part of Spitsbergen, Figure 1). 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.

The Ebba Riber originates mainly from the Ebba Glacier and the Bertram Glacier. The Ebba is a polythermal glacier and has been in recession over the last hundred years (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 (Figure 1). 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.

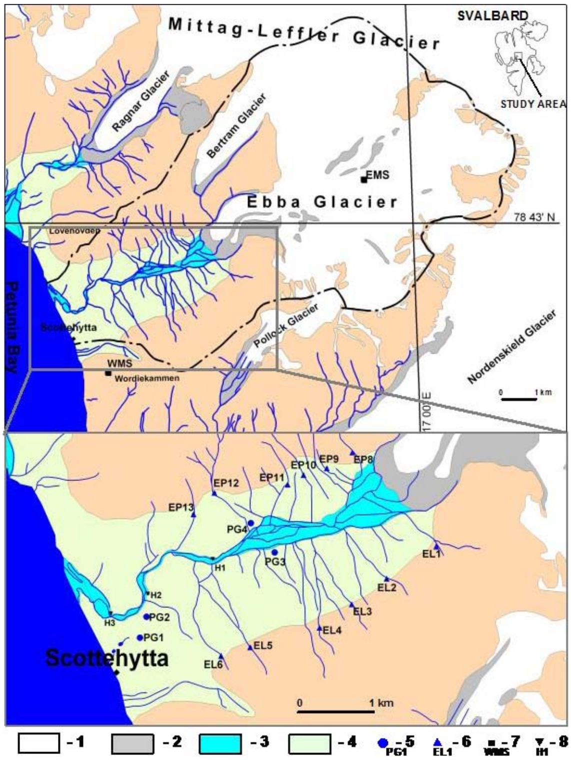

Figure 1. The location scheme (after: Dragon, Marciniak, 2010, modified). 1 — glaciated area; 2 — moraines; 3 — wetland area; 4 — valleys area; 5 — location of the piezometers groups; 6 — location of the surface water sampling points; 7 — location of the meteorological stations (WMS — Wordie Meteorological Station; EMS — Ebba Meteorological Station); 8 — location of the Hydrometric Stations (H1, H2 and H3).

Dislocations along the Billefjiorden Fault zone dominate the bedrock geology of the region (Dallmann et al., 2004). 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. 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 (Dallmann et al., 2004).

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 (Figure 2). When the temperature rises above 0°C the flow of water starts and the thickness of the active layer increases. 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 the active layer freezes up and water stays locked to the next season (Dragon, Marciniak, 2010).

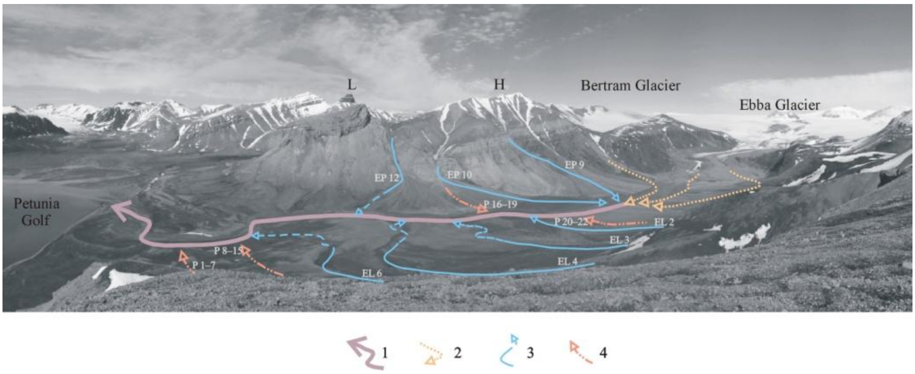

Figure 2. Conceptual model of water circulation within Ebba River catchment (after Dragon, Marciniak, 2010, modified). Explanations: 1 — Ebba River (Q_{Ebba}); 2 — recharge from glaciers (Q_{gl}); 3 — recharge from Ebba tributaries (not all streams are visible on the picture) and overland flow (Q_{su}); 4 — recharge from groundwater (Q_{gw}). The arrows are marked at 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 (Figure 1) while the third hydrometric station (H3) was located close to the river estuary. 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. 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 (installed at the bottom part of the active layer) and a gravel pack to prevent siltation. 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 (EMS) and Werdie (WMS) (Figure 1). 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 (Figure 2):

$$Q_{Ebba} = Q_{gl} + Q_{su} + Q_{gw} \quad (1)$$

where:

- Q_{gl} — recharge from the Bertram and Ebba glaciers,
- Q_{su} — recharge from the Ebba tributaries (streams originated from mountains ridges) and overland flow,
- Q_{gw} — recharge from groundwater.

It was assumed that the recharge from direct precipitation can be dissembled because during the whole summer period the precipitation intensity was very small (Dragon, Marciniak, 2010).

The clear differentiation of the runoff is visible between H1 and H3 hydrometric stations (Fig. 3A). It is connected with the influence of recharge components other than water from glaciers.

The groundwater runoff was calculated using Darcy's law:

$$Q_{gw} = kbmJ \quad (2)$$

where:

- Q_{gw} — groundwater runoff,
- k — hydraulic conductivity,
- b — the width of the recharge (calculated for each groups of piezometers),
- m — thickness of the active layer,
- 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). The thickness of the active layer (m) was calculated as the height of the groundwater level above the permafrost. The hydraulic gradient (J) was calculated using measurement of the groundwater level in each groups of piezometers.

First, the specific discharge for each group of piezometers was calculated and then the total groundwater runoff for the whole valley area was assessed (Table 1).

Table 1. The sample calculation of groundwater flow performed for data measured in the field 09 July 2008.

2008-07-09	*J*	*m*	*k*	*q*	*q*	*q average*	*L Ebba*	Q_{gw}
	[—]	m	m/h	m³/h/m	m³/s/m	m³/s/m	m	m³/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			

Explanations (all parameters was 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 Ebba River (the width of the recharge from groundwater),
- Q_{gw} — total groundwater runoff.

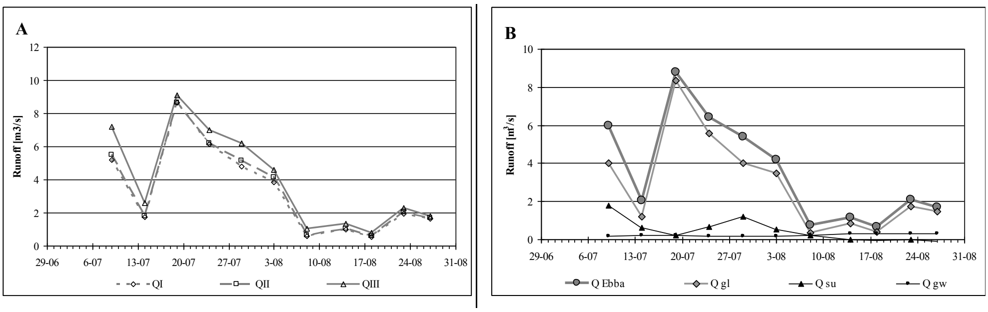

Figure 3. The runoff of the Ebba River during summer season of 2008 (A) and the total runoff of Ebba River and components of Ebba River recharge (B). QI, QII and QIII were measured at H1, H2 and H3 hydrometric stations (respectively), the rest of explanation in text.

It was assumed that the difference in total runoff between hydrometric stations H1 and H3 (Figure 3A) was connected with recharge from the Ebba tributaries (streams originating from mountains ridges) and overland flow as well as with groundwater recharge:

$$Q_{III} - Q_{I} = Q_{su} + Q_{gw} \quad (3)$$

from where:

$$Q_{su} = Q_{III} - Q_{I} - Q_{gw} \quad (4)$$

where:

- Q_{III} — total runoff at the H3 hydrometric station,
- Q_{I} — total runoff at the H1 hydrometric station.

The total runoff of Ebba River (Q_I and Q_{III}) was known from field investigation and 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 recharging 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 on Table 2 and Figure 3B. The calculation confirms that the main component of the Ebba River recharge is the flow of water from glaciers. The amount of this water was calculated as 80.11 percent of total runoff. The recharge of the river by surface flow was estimated as 13.02 percent. The negative value at the end of melting season is connected with the error of estimation. The recharge of the river by groundwater flow was estimated as 6.87% of the total runoff. What is interesting the value of this parameter increase systematically during the melting season (Table 2). It is related with the 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 present.

Table 2. The average total runoff of Ebba River and components of Ebba River recharge during summer melting season of 2008 (explanations in text).

Date	Q_{Ebba}	Q_{gl}	Q_{su}	Q_{gw}
	m³/s	m³/s	m³/s	m³/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
Percent	100.00%	80.11%	13.02%	6.87%

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 water at the end of summer season froze up and stay locked to the next melting season.

Using data performed from four groups of piezometers measurement 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 Ebba River was calculated. This calculation enabled more precise estimation of other component of Ebba River recharge (surface and overland water inflow, recharge from glaciers).

It was calculated that the main component of Ebba River recharge is flow of water from glaciers (80.11 percent of total runoff). The amount of water originated from the inflow of Ebba River tributaries and overland flow is 13.02 percent of total river runoff. The amount of groundwater that recharge Ebba River is 6.87% of the total runoff.

The calculation of groundwater flow has the most unique character. 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 allows the other recharge components to be estimated more precisely. What is the most important — the field investigation of groundwater occurrence eliminates the speculations about the possibility of groundwater flow within active layer.

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