Permeability of active layer sediments and groundwater runoff in Brattegg River catchment, SW Spitsbergen

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Abstract: This paper presents the permeability of the permafrost active layer determined in the Brattegg River catchment (SW Spitsbergen) for the 6-years interval of 2005–2010. The field permeability measurements technique of weathered rocks on various geomorphological forms allows to assess the value of their hydraulic conductivity ($k$). High variability of $k$ values, ranging from $6.37 \times 10^{-9}$ to $4.0 \times 10^{-3}$ m s$^{-1}$, indicates the permeability of rocks from very low in clay to very high in gravel-rock rubble. Among the geomorphological forms, the best permeability was observed in boulder covers and rock debris, and the lowest one in patterned ground. The obtained results were used to determine the groundwater runoff ($q_{tot}$), assuming the unit thickness of the active layer aquifer. The $q_{tot}$ value from the Brattegg River catchment was calculated at 130 L s$^{-1}$, which is from 15% to 47% of the average surface runoff.

Keywords: Arctic, Svalbard, active layer aquifer, geomorphological forms.
Introduction

Multidisciplinary studies, identifying the processes responsible for progressive climate change, have been carried out for many years in the Brattegg River catchment (Migala et al. 2008; Owczarek 2010; Migoń and Kasprzak 2013; Marszałek and Górniak 2017). Increase in air temperature caused the glacier recession, development of young geomorphological forms and vegetation succession (Owczarek et al. 2014). Water from precipitation, melting glaciers, perennial permafrost and snow cover flows directly or indirectly into the sea in the form of surface and groundwater runoff in the Brattegg River catchment (Marszałek et al. 2013a). There is no evidence of a deep regional groundwater circulation beneath permafrost in this catchment, therefore groundwater runoff seems to form only during the Arctic summer within the subsurface active layer of permafrost. The volume of runoff strictly depends on its thickness and the permeability of the rocks that build it.

Studies of permeability of the active layer sediments and groundwater runoff have not been carried out to a greater extent in the polar regions. The hydrological studies conducted in the Arctic mostly focused on assessing of total or surface runoff (Pulina et al. 1984; Sobota 2000; Sobota et al. 2010; Bartoszewski and Michalczuk 2013; Marszałek et al. 2013a; Majchrowska et al. 2015). Groundwater presence in cold areas (Haldorsen and Heim 1999; Lemieux et al. 2016), the residence time of groundwater in the rock environment (Hiyama et al. 2013), the exchange of ground- and surface water (Ge et al. 2011) and changes in the groundwater runoff depending on the thawing of permafrost (St. Jacques and Sauchyn 2009; Walvoord et al. 2012; Duan et al. 2017; Evans et al. 2018; Lamontagne-Hallé et al. 2018) were also discussed. The influence of frequent freezing and thawing of sediments on their permeability and structure is relatively well recognized (Burt and Williams 1976; Chamberlain and Gow 1979; McKenzie et al. 2007; Watanabe and Flury 2008), as well as the relationships between hydraulic conductivity of the sediments and their saturation with water (Scheidegger 2013). In these works, the values of the hydraulic conductivity were not determined, but were taken from the literature, and the relationships were determined on the basis of calculations or modeling.

The attempts to separate the underground component of water flow from the active layer of permafrost are made rarely, mainly due to the lack of recognition of filtration parameters in unconsolidated rocks (Marciniak et al. 2011; Marszałek et al. 2013b; Lamontagne-Hallé et al. 2018). Difficulties in assessing groundwater runoff, which is often ignored (Hagen and Laflauconner 1995; Killinqveit et al. 2003), affect the credibility of water balance calculations. Field studies of rock permeability, necessary for the accurate determination of groundwater runoff, are carried out rarely (Quinton et al. 2008; Kim et al. 2020; Chen et al. 2021). In Spitsbergen, this type of studies were completed only in the
Ebba River catchment located in the Petunia Bay area, but mainly well-permeable sediments were investigated (Marciniak et al. 2011).

The measurements of permeability of subsurface unconsolidated rocks, which have been conducted for the first time in the Brattegg River catchment, provided the information for the correct assessment of dynamic water flow in the top layers of permafrost. Permeability of active layer, expressed by hydraulic conductivity, influences groundwater flow and the velocity of pollutants migration. The Brattegg River catchment is a good test site because of its small area, recharged by the glacier located in its upper part, and the variety of sediments and geomorphological forms.

The main aim of this research was to assess the permeability of different sediments that build the active layer of permafrost in the Brattegg River catchment and in different surface geomorphological forms. Spatial differentiation of the hydraulic conductivity, that was evaluated from field investigations, enable to calculate the groundwater runoff for the aquifer. The volume of the groundwater runoff was compared with the total runoff determined from the measurements of the Brattegg River flow rate. The results, covering all major lithological types and geomorphological forms, can be used for more detailed analyses of the groundwater circulation within the active layer in other polar regions.

Study area

The Brattegg River catchment is located in Wedel Jarlsberg Land in the Sør-Spitsbergen National Park (SW Svalbard). With a surface area of 8.2 km², it belongs to a partly glaciated river-lake system composed of three lakes linked by the Brattegg River (Figs. 1 and 2). The Myrktjørn Lake, with the depth of 6.9 m, has the largest area of 1.4 km² (Marszałek and Górniak 2017). The Brattegg River drains coastal parts of the western Spitsbergen during summer Arctic seasons, starting from small glacier and flowing towards the Greenland Sea. The hill-slope of the river valley in the upper part (6% on average) decreases below the Myrktjørn Lake outflow, where it reaches a flat sea terrace level. Two main types of relief were distinguished in the catchment: (i) mountainous terrain with widespread debris and valleys partially covered with glaciers, rock glaciers and (ii) coastal platform with a system of raised marine terraces, occurring in the studied catchment up to an altitude of 80 m a.s.l. (Migoń and Kasprzak 2013) (Fig. 1). The coastal zone is dominated by a strandflat, i.e., a wide platform at an elevation of 4–25 m a.s.l. with well-rounded marine pebbles. On the ground surface, various periglacial forms such as patterned ground, solifluction stripes and lobes, orthogonal frost crack networks and spotted tundra surfaces with “islands” of clayey material, surrounded by larger clasts and debris, are observed. Mountain slopes are mainly covered by rock, talus or debris-mantled slope with boulders and finer debris (Migoń and Kasprzak 2013).
The climatic conditions are characterized by low average annual temperatures (–2.1°C) and limited precipitations of 422 mm on average, with variations from 230 mm in the dry year (1987) to 635 mm in the wet one (1996). Permanent snow cover usually occurs in the second half of September and lasts generally until the first decade of June (Kwaczyński 2003; Przybylak and Araźny 2006). Snow is the dominant form of precipitation during the year (Marsz et al. 2013).

The daily Brattegg river discharge usually changes during the summer season, from late June to mid-July exceeding 1 m³ s⁻¹ (sometimes >1.5 m³ s⁻¹),
and from late July to August it decreases markedly to <0.5 m$^3$s$^{-1}$. Some peak flows $>2$ m$^3$s$^{-1}$ were observed (Stachnik et al. unpublished).

Geologically, the Brattegg River catchment is composed of Middle Proterozoic metamorphic rocks of several crystalline formations including mainly amphibolites, mica-schists, quartzites of the Brattegg Valley Formation and white or green quartzites of the Gullichsenfjellet Formation (Czerny et al. 1993; Birkenmajer 2013) (Fig. 2). Crystalline rocks are covered by sands and sea gravels, forming terraces and boulder fields in the coastal zone. Inside the catchment area, excluding the highest mountain parts, the weathered cover with the admixture of various clay fractions, can be found. The river valleys are filled with coarse clastic material. In the upper part of the catchment, moraines are common. They formed as a result of local glacier advances or stillstands.

Groundwater outflows, occurring in the studied catchment during the summer season, represent the shallowest circulation system associated with the subsurface zone of the bedrock lying above the permafrost. Their presence is related to the drainage of the active layer of permafrost, formed in the well-permeable upper parts of weathered crystalline rocks. There is no evidence of deeper groundwater circulation, i.e., subpermafrost aquifer, in the catchment (Modelska and Buczyński 2023).

Materials and methods

The permeability of the subsurface profile of the active layer was directly determined by field measurements during the summer seasons (July–August) of 2005–2010. The tested sediments were completely defrosted during the investigations. These measurements were preceded by detailed geological mapping aimed to assess the variability of lithology across the selected transects running through the Brattegg River catchment (Fig. 2).

In order to determine the permeability of the unconsolidated rocks, field study was carried out to assess the hydraulic conductivity ($k$), using two methods: the Porschet method (23 measurements) and the double-ring infiltrometer (Giryński's method, after Pazdro and Kozerski 1990) (41 measurements). Their locations are shown on Fig. 2. The measurements using the Porschet method were conducted in those locations where it was not possible to press the double-ring infiltrometer, into the ground. Both methods are complementary, providing similar results (Wasik 2003).

Using the Porschet method, the velocity of infiltrating water was measured three times in a drilled hole with a depth of ~50 cm and a diameter of ~12 cm. The drilled hole was filled with water and the height of the water table above the bottom was measured at specified intervals (Fig. 3a). The following formulas were used for the calculations of $k$ (Pleczyński 1981):
\[ k = \frac{[\varphi(x_1) - \varphi(x_2)]}{\Delta t} \]  

where:

\[
\varphi(x_1) = \frac{r}{2}(\log x_1 + \frac{r}{2}),
\]

\[
\varphi(x_2) = \frac{r}{2}(\log x_2 + \frac{r}{2}),
\]

\[ \Delta t = t_2 - t_1, \]

\( k \) - hydraulic conductivity (m s\(^{-1}\)),

\( x_1, x_2 \) – the height of the water table above the bottom of the hole (m),

\( t_1, t_2 \) – time of lowering the water table from \( x_1 \) to \( x_2 \) (s),

\( r \) – the drilled hole diameter (m).

In order to measure the permeability using the Eijkelkamp double-ring field infiltrometer, two rings (Fig. 3b) were hammered concentrically to a depth of

Fig. 2. Geological map of the Brattegg catchment after Czerny et al. (1993) with location of permeability measurements points and sampling.
several centimeters of the sediment. Then, water was poured into both rings and decrease of the water level was measured. Water infiltrated from the outer ring saturates the sediment below the infiltrometer and formed a buffer zone. This caused holding the water inside of the inner ring where the infiltration measurement was conducted. Measurements have been repeated three times to mirror the prevailing conditions in the saturated and the unsaturated zone at the measurement site. It was assumed that the rate of infiltration is approximately equal to the permeability of the unsaturated zone (Eijkelkamp 1983). The infiltration rate was determined by measuring the drop in the height of the water column in the infiltrometer per unit time.

The hydraulic conductivity \( k \) is related to the grain-size distribution of granular porous media (Freeze and Cherry 1979), therefore, a grain-size analysis was conducted for 17 sediment samples. They were collected only in the lower part of the catchment area in 2009, mainly due to better development of investigated geomorphological forms and easier access. The grain size analyses enabled to identify the sand, gravel and pebbles, while pipette analysis discriminated between silt and clay fractions. Fractions coarser than pebbles were not taken into account. Both analyses were conducted following published guidelines (Myślińska 2001) in the Laboratory of Soil Mechanics Institute of Geography and Regional Development, Wrocław University.

The main grain indexes were calculated using the formulas after Racinowski et al. (2001) in order to characterize the investigated sediments based on diameters expressed in phi units:

\[
M_z = \frac{\Phi 16 + \Phi 50 + \Phi 84}{3}
\]

\( \delta_I \) – standard deviation (graphical standard deviation), or sorting

Fig. 3. Field measurement of sediment permeability using Porschet method (A) and the Eijkelkamp double-ring infiltrometer (B).
Skewness (graphic skewness)

\[ S_{kl} = \frac{\Phi 84 - \Phi 16}{4} + \frac{\Phi 95 - \Phi 5}{6.6} \]  

\( S_{kl} \) – skewness

\[ K_G = \frac{\Phi 95 + \Phi 5}{2.44(\Phi 75 - \Phi 25)} \]  

\( K_G \) – flattening of the grain size distribution

\[ d_{60}, d_{10} \] – grain diameters (in mm), which together with smaller grains account for 60% and 10%, respectively.

Using the sediment permeability data, the amount of the groundwater runoff \( (q) \) within the individual lithological types and geomorphological forms was calculated, for the accepted unit values of the aquifer thickness \( (m) \) and the groundwater stream width \( (B) \). The total groundwater runoff \( (q_{tot}) \) from the Brattegg River catchment was also calculated, for the assumed \( m \) of 1 m. The calculations were based on the measurements carried out in the period of 2007–2009. For the calculations purposes the formula below was used (Freeze and Cherry 1979; Pazdro and Kozerski 1990):

\[ q_{tot} = k \frac{\Delta H}{\Delta l} m B \]  

\( q_{tot} \) – the amount of groundwater flow \( (L \text{ s}^{-1}) \),

\( k \) – hydraulic conductivity \( (m \text{ s}^{-1}) \),

\( \frac{\Delta H}{\Delta l} \) – hydraulic drop, pressure difference to the distance over which it occurs,

\( m \) – thickness of the water layer \( (m) \),

\( B \) – width of the groundwater stream \( (m) \).

The amount of the groundwater runoff in the summer season is primarily determined by the active layer thickness and the permeability of rocks expressed by the \( k \) values, which are variable. Rock permeability depends, among others, on the defrosting degree of the aquifer or water temperature. In the calculations of the groundwater runoff, the unit thickness of the aquifer and the constant \( k \) value
determined for completely thawed rocks were assumed. In order to calculate the groundwater runoff to the Brattegg River, the average values of the hydraulic conductivity of rocks and geomorphological forms lying on both sides of the river were determined. Due to lack of data on changes in the thickness of the melted active layer in the summer season, the authors did not have the opportunity to compare different states of groundwater runoff and river flows. The results were compared with the average river discharge, i.e., surface runoff, measured in the hydrometric gauge cross-section installed in the lower part of the Brattegg River catchment at 24 m a.s.l. (Stachnik et al. unpublished). This enables to roughly assess which part of the total runoff constitutes the groundwater runoff. The propeller-type current meter OTT C31, with measurement range from 0.025 to 10 m s\(^{-1}\) and accuracy ±2%, was used to measure the Brattegg River flow rate.

Results and interpretation

**Characteristics of the active layer sediments.** — Based on the field macroscopic observation and the results of grain size analyses of loose sedimentary rocks found in the Brattegg River catchment (Fig. 4), seven main lithological types were distinguished: loams, sandy loams, sand with debris, multi-grained sand, pebbly debris, sand-gravel debris and loamy debris. These materials were deposited in sedimentary environments characterized by different dynamics, indicated by significant variations in the calculated values of the average grain size (Tables 1 and 2). Moreover, very weak or extremely weak sorting of \(\delta_I\) of all tested sediments indicates a variable dynamics of the environment during their deposition (Czyżewska 1997; Racinowski et al. 2001). Such sorting (\(\delta_I\) values 2.49–4.64) is typical for sediments formed as a result of slope processes or direct accumulation of the glacial material, e.g., boulders of bottom moraine. An uneven grain size distribution is also indicated by high values of the graining uniformity coefficient, usually ca. 10–500.

The skewness (\(S_{kl}\)) of the graining distributions of the studied sediments varies from very negatively oblique to very positive oblique, \(S_{kl}\) values ranging from –0.47 to 0.73. It also indicates a wide range of the sedimentation environment dynamics. Negative values indicate the enrichment of the material with coarser fractions, and positive values indicate the opposite process, i.e. bringing fine fractions to the sediment. Such a distribution of \(S_{kl}\) values indicates that the sedimentation was related not only to non-current environments (deluvial sediments, loam), which are usually characterized by positive skewness (Łanczont 1994), but also other environments, e.g., aquatic and aeolian.

The characteristics of the \(K_G\) flattening of the grain size distribution indicate different environments of loose material deposition. Non-current sludge is characterized by low \(K_G\) values. 75% of the studied sediments have a platykurtic or very platykurtic particle size distribution (\(K_G < 0.9\)), which indicates variable
conditions during their sedimentation, high saturation of the sedimentation environment with mineral material and an initial stage of sediment differentiation (Racinowski et al. 2001). In several sediment samples, the particle size distribution was mesokurtic ($K_G = 1.06$ in a sample of gravel and debris), leptokurtic ($K_G = 1.13$ and $1.29$ in two clay samples with pebbly debris) and very leptokurtic ($K_G = 2.09$ in a sample of sandy-gravel debris and loamy debris). The leukocurtic nature of the particle size distribution indicates a selective deposition.

**Characteristics of sediments permeability.** — The permeability of the active layer sediments is primarily determined by the content of the fine fraction and the size of the pores, uniformity of the graining and the representative diameter of the grains. The obtained $k$ values of sediments vary from $6.37 \times 10^{-9}$ to $4.0 \times 10^{-3}$ m s$^{-1}$ (Table 3). Such a range of values proves their different permeability. The lowest permeability, very low and low according to Dowgiało et al. (2002), is mostly typical for clays ($k$ ranging from $6.37 \times 10^{-9}$ to $8.99 \times 10^{-7}$ m s$^{-1}$). Sandy loams and loamy debris ($k$ from $2.60 \times 10^{-7}$ to $7.57 \times 10^{-5}$ m s$^{-1}$) have slightly higher permeability, i.e., from low to medium. Various types of debris and differently-grained sands, with $k$ values ranging from $6.09 \times 10^{-6}$ to $1.69 \times 10^{-3}$ m s$^{-1}$, are more permeable, i.e., fall into medium to very high permeability class. The highest permeability, i.e., high and very high and with $k$ values from $1.75 \times 10^{-4}$ to $1.69 \times 10^{-3}$ m s$^{-1}$, is typical for gravel and pebbly debris.

Most of the studied formations can be described as non-insulating, only sandy loams and loamy debris have very poor insulation properties, and the loams are poorly and very poorly insulating (Table 3). The degree of insulation indicates the presence of relatively favorable conditions for groundwater supply in the Brattegg River catchment as a result of rainwater or surface water infiltration.

**Permeability characteristics of geomorphological forms.** — The characteristics of the geomorphological forms occurring in the Brattegg River catchment take into account the results of permeability tests of the sediments that formed them (Table 4). Pebble sediments and boulder covers are characterized by
### Table 1.

Graining parameters of the clastic rocks in the Brattegg River catchment.

<table>
<thead>
<tr>
<th>Measurement location</th>
<th>$s_1$</th>
<th>$s_2$</th>
<th>$s_3$</th>
<th>$s_4$</th>
<th>$s_5$</th>
<th>$s_6$</th>
<th>$s_7$</th>
<th>$s_8$</th>
<th>$s_9$</th>
<th>$s_{10}$</th>
<th>$s_{11}$</th>
<th>$s_{12}$</th>
<th>$s_{13}$</th>
<th>$s_{14}$</th>
<th>$s_{15}$</th>
<th>$s_{16}$</th>
<th>$s_{17}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average grain size $M_Z$</td>
<td>4.26</td>
<td>–1.67</td>
<td>0.88</td>
<td>5.29</td>
<td>4.48</td>
<td>3.18</td>
<td>3.04</td>
<td>6.13</td>
<td>5.68</td>
<td>5.26</td>
<td>3.18</td>
<td>1.42</td>
<td>0.01</td>
<td>4.04</td>
<td>2.27</td>
<td>1.42</td>
<td></td>
</tr>
<tr>
<td>Average diameter $S_S$</td>
<td>3.70</td>
<td>–0.46</td>
<td>1.00</td>
<td>3.68</td>
<td>–2.93</td>
<td>3.32</td>
<td>2.76</td>
<td>3.68</td>
<td>–2.93</td>
<td>3.32</td>
<td>2.76</td>
<td>3.68</td>
<td>–2.93</td>
<td>3.32</td>
<td>2.76</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard deviation (sort) $\delta_I$</td>
<td>3.30</td>
<td>3.62</td>
<td>4.64</td>
<td>3.30</td>
<td>3.62</td>
<td>4.64</td>
<td>3.30</td>
<td>3.62</td>
<td>4.64</td>
<td>3.30</td>
<td>3.62</td>
<td>4.64</td>
<td>3.30</td>
<td>3.62</td>
<td>4.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skewness $Sk_I$</td>
<td>–0.19</td>
<td>0.53</td>
<td>0.08</td>
<td>0.58</td>
<td>0.08</td>
<td>0.53</td>
<td>0.08</td>
<td>0.58</td>
<td>0.08</td>
<td>0.53</td>
<td>0.08</td>
<td>0.58</td>
<td>0.08</td>
<td>0.53</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flattening $KG$</td>
<td>0.80</td>
<td>1.06</td>
<td>0.57</td>
<td>0.61</td>
<td>2.09</td>
<td>0.68</td>
<td>0.68</td>
<td>0.68</td>
<td>0.68</td>
<td>0.68</td>
<td>0.68</td>
<td>0.68</td>
<td>0.68</td>
<td>0.68</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graining uniformity coefficient $U$</td>
<td>24</td>
<td>344</td>
<td>320</td>
<td>121</td>
<td>65</td>
<td>57</td>
<td>75</td>
<td>1294</td>
<td>7</td>
<td>11</td>
<td>303</td>
<td>364</td>
<td>436</td>
<td>171</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Characteristics of sediments graining in the Brattegg River catchment.

<table>
<thead>
<tr>
<th>Sediment category</th>
<th>Sample number</th>
<th>Share of granulometric fractions</th>
<th>Average grain size $M_Z$</th>
<th>Average diameter $S_S$</th>
<th>Standard deviation (sort) $\delta_I$</th>
<th>Skewness $S_M$</th>
<th>Flatten $K_G$</th>
<th>Graining uniformity coefficient $U$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loam</td>
<td>s4, s13, s14, s15</td>
<td>1.40–1.69</td>
<td>32.68–44.29</td>
<td>22.07–36.51</td>
<td>17.51–42.13</td>
<td>0</td>
<td>1.42–5.68</td>
<td>2.17–4.44</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>s7, s8</td>
<td>0.95–1.28</td>
<td>25.33–33.92</td>
<td>35.68–42.31</td>
<td>19.12–31.42</td>
<td>0</td>
<td>3.18–4.48</td>
<td>2.76–3.48</td>
</tr>
<tr>
<td>Loam with debris</td>
<td>s10, s11, s16, s17</td>
<td>1.02–1.55</td>
<td>22.43–51.09</td>
<td>26.58–45.16</td>
<td>11.55–36.72</td>
<td>0–13.24</td>
<td>0.01–6.12</td>
<td>1.05–4.94</td>
</tr>
<tr>
<td>Multi-grained sand</td>
<td>s1</td>
<td>1.17</td>
<td>26.88</td>
<td>54.86</td>
<td>17.09</td>
<td>0</td>
<td>4.26</td>
<td>3.70</td>
</tr>
<tr>
<td>Debris</td>
<td>s2, s9, s12</td>
<td>0.42–1.60</td>
<td>9.70–36.89</td>
<td>21.32–45.02</td>
<td>16.49–61.85</td>
<td>0–24.54</td>
<td>−3.04–5.26</td>
<td>−0.46–4.24</td>
</tr>
<tr>
<td>Loamy debris</td>
<td>s3, s5, s6</td>
<td>0.17–0.85</td>
<td>3.70–31.12</td>
<td>9.03–40.05</td>
<td>22.61–54.79</td>
<td>0–32.30</td>
<td>−3.45–4.10</td>
<td>−2.93–3.32</td>
</tr>
</tbody>
</table>
Table 3. Characteristics of sediments permeability in the Brattegg River catchment.

<table>
<thead>
<tr>
<th>Sediment category</th>
<th>Number of measurements</th>
<th>Hydraulic conductivity $k$ (m s$^{-1}$)</th>
<th>Permeability class (Dowgiałło et al. 2002)</th>
<th>Class of insulating rocks (Dowgiałło et al. 2002)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>min.</td>
<td>max.</td>
<td>weighted average</td>
</tr>
<tr>
<td>Loam</td>
<td>8</td>
<td>$6.37 \times 10^{-9}$</td>
<td>$8.99 \times 10^{-7}$</td>
<td>$3.22 \times 10^{-7}$</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>3</td>
<td>$2.60 \times 10^{-7}$</td>
<td>$5.24 \times 10^{-6}$</td>
<td>$2.91 \times 10^{-6}$</td>
</tr>
<tr>
<td>Sand with debris</td>
<td>8</td>
<td>$7.04 \times 10^{-7}$</td>
<td>$7.57 \times 10^{-5}$</td>
<td>$1.76 \times 10^{-5}$</td>
</tr>
<tr>
<td>Multi-grained sand</td>
<td>2</td>
<td>$1.45 \times 10^{-5}$</td>
<td>$2.22 \times 10^{-4}$</td>
<td>$1.18 \times 10^{-4}$</td>
</tr>
<tr>
<td>Pebbly debris</td>
<td>12</td>
<td>$1.75 \times 10^{-4}$</td>
<td>$4.00 \times 10^{-3}$</td>
<td>$1.69 \times 10^{-3}$</td>
</tr>
<tr>
<td>Sandy-gravel debris</td>
<td>14</td>
<td>$3.14 \times 10^{-5}$</td>
<td>$1.00 \times 10^{-3}$</td>
<td>$3.64 \times 10^{-4}$</td>
</tr>
<tr>
<td>Loamy debris</td>
<td>17</td>
<td>$6.09 \times 10^{-6}$</td>
<td>$3.12 \times 10^{-4}$</td>
<td>$8.20 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
Table 4. Characteristics of the geomorphological forms permeability in the Brattegg River catchment.

<table>
<thead>
<tr>
<th>Geomorphological forms</th>
<th>Number of measurements</th>
<th>Hydraulic conductivity $k$ (m s$^{-1}$)</th>
<th>Permeability class (Dowgiałło et al. 2002)</th>
<th>Class of insulating rocks (Dowgiałło et al. 2002)</th>
<th>Lithological types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rocky initial soils</td>
<td>3</td>
<td>2.15 $10^{-5}$</td>
<td>medium–high</td>
<td>non-insulating</td>
<td>debris, loamy debris</td>
</tr>
<tr>
<td>Sorted patterned ground (middle part)</td>
<td>12</td>
<td>6.37 $10^{-9}$</td>
<td>very low–weak</td>
<td>poorly insulating–non-insulating</td>
<td>loam, sandy loam, loam with debris</td>
</tr>
<tr>
<td>Sorted patterned ground (outer part)</td>
<td>6</td>
<td>5.24 $10^{-6}$</td>
<td>weak–high</td>
<td>non-insulating</td>
<td>debris, loamy debris, loam with debris, sandy loam</td>
</tr>
<tr>
<td>Pebbly alluvial sediments</td>
<td>13</td>
<td>6.09 $10^{-6}$</td>
<td>weak–high</td>
<td>non-insulating</td>
<td>debris, loamy debris, multi-grained sand</td>
</tr>
<tr>
<td>Boulder blankets</td>
<td>4</td>
<td>4.76 $10^{-4}$</td>
<td>high–very high</td>
<td>non-insulating</td>
<td>debris</td>
</tr>
<tr>
<td>Solifluction stripes</td>
<td>9</td>
<td>6.68 $10^{-6}$</td>
<td>weak–high</td>
<td>non-insulating</td>
<td>debris, loamy debris, loam with debris</td>
</tr>
<tr>
<td>Talus</td>
<td>9</td>
<td>1.43 $10^{-4}$</td>
<td>high–very high</td>
<td>non-insulating</td>
<td>debris</td>
</tr>
<tr>
<td>Nonsorted patterned ground</td>
<td>8</td>
<td>3.24 $10^{-6}$</td>
<td>weak–high</td>
<td>non-insulating</td>
<td>loamy debris, loam with debris, sandy loam</td>
</tr>
</tbody>
</table>

Note: The hydraulic conductivity $k$ is given in m s$^{-1}$; weighted average and standard deviation are also provided.
the highest $k$, estimated at $7.35 \times 10^{-4}$ m s$^{-1}$ and $5.74 \times 10^{-4}$ m s$^{-1}$, respectively. These values determine the permeability of sediments filling the space between larger boulders, with an average diameter of several dozen centimeters, but also larger. The lowest permeability with the order of $10^{-9}$ to $10^{-6}$ m s$^{-1}$ was determined for the central part of the sorted patterned ground built up of clayey material. Much more permeable ($k$ values $5.24 \times 10^{-6}$ to $7.69 \times 10^{-4}$ m s$^{-1}$) are the outer parts of the grounds due to the greater share of coarser particles. Similar permeability (mean $k$ of the order of $10^{-5}$ to $10^{-4}$ m s$^{-1}$) is observed in the remaining geomorphological forms (Table 4).

In the Brattegg River catchment, a large variation in the permeability of sediments within a given geomorphological form is observed, due to the presence of several lithological types in each form. Moreover, at a relatively short distance, a high variability of geomorphological forms may be observed (Fig. 5).

In the studied catchment, the more permeable sediments can be found usually in the marginal and channel parts of the river valley. The edge parts of the valley, adjacent to mountain slopes or a lateral moraine, are often covered with rock sediments and boulder covers. The Brattegg River bed is filled with coarse-grained river sediments, e.g., pebbly alluvial sediments, whereas the bottom of the valley is filled with sediments of different, generally weaker permeability. This creates a system where supply and drainage zones contain sediments with higher permeability, and in the transit zone of groundwater flow sediments show lower permeability. Such conditions in the marginal part of the Brattegg valley facilitate the recharge of groundwater during the summer season in the melted layer of permafrost, as a result of rainwater infiltration and lateral inflow of waters flowing from the mountain slopes surrounding the valley. On the contrary, the lower permeability of the sediments at the bottom of the valley impedes the outflow of groundwater to the drainage zone, which is the Brattegg river bed. In regions with lower sediments permeability, groundwater flowing from the edge of the valley and from melted permafrost are dammed up, as a result of which the water table is closer to the ground surface. Therefore, in these regions, the waterlogged grounds can be often observed.

**Groundwater runoff in active layer.** — The value of the groundwater runoff is determined by the three parameters: rock permeability determined by the values of the hydraulic conductivity, the thickness of the aquifer and the hydraulic gradient. The most important in that case is the permeability due to its possible high variability, even within the same lithological type. Our calculations seem reliable owing to the use of field results.

In order to explore ways of forming the groundwater runoff within individual lithologies and geomorphological forms, the values of the unit groundwater runoff $q$ were calculated. Unit values were adopted for the thickness of the aquifer ($m = 1$ m) and the width of the groundwater stream ($B = 1$ m). Due to the shallow water table from a few cm to $>1$ m below the ground level and the lack of precise knowledge on its depth, the value of the hydraulic gradient of 0.05 was
Fig. 5. Geological cross-sections through the Brattegg River catchment. The cross-section lines comply with Fig. 2.
assumed for the calculations, corresponding to the slope of the bottom part of the Brattegg River valley.

The obtained results indicate extremely different conditions of groundwater flow formation inside of the studied sediments (Table 5). The flow with the highest intensity in the range from $8.75 \times 10^{-3}$ to $0.20 \text{ L s}^{-1}$ ($8.45 \times 10^{-2} \text{ L s}^{-1}$ on average) may occur in the area of gravel and rock debris, and the lowest one in loams, ranging from of $3.18 \times 10^{-7}$ to $4.49 \times 10^{-5} \text{ L s}^{-1}$ ($1.61 \times 10^{-5} \text{ L s}^{-1}$ on average).

For geomorphological forms, the most favorable conditions for the flow of groundwater occur when land is covered by rock debris, pebbly and boulder sediments. The average values of $q$ calculated for these geomorphological forms are $3.67 \times 10^{-2}$ and $2.87 \times 10^{-2} \text{ L s}^{-1}$, respectively (Table 5). On the other hand, the worst conditions for shaping the groundwater flow occur in the areas where sorted patterned ground has been developed. Within their central, more clayey part, the flow of groundwater is practically impossible, with the mean value of the unit flow $q$ reaching only $2.94 \times 10^{-6} \text{ L s}^{-1}$. Slightly better conditions for groundwater flow were found in the outer part, with the $q$ value up to $6.40 \times 10^{-4} \text{ L s}^{-1}$, but still lower than the values calculated for the other geomorphological forms (Table 5).

Table 5.

<table>
<thead>
<tr>
<th>Geomorphological forms</th>
<th>Specific groundwater runoff $q$ (L s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>min.</td>
</tr>
<tr>
<td>Sediment type</td>
<td></td>
</tr>
<tr>
<td>Loam</td>
<td>$3.18 \times 10^{-7}$</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>$1.30 \times 10^{-5}$</td>
</tr>
<tr>
<td>Sand with debris</td>
<td>$3.52 \times 10^{-5}$</td>
</tr>
<tr>
<td>Multi-grained sand</td>
<td>$7.25 \times 10^{-4}$</td>
</tr>
<tr>
<td>Pebbly debris</td>
<td>$8.75 \times 10^{-3}$</td>
</tr>
<tr>
<td>Sandy-gravel debris</td>
<td>$1.75 \times 10^{-3}$</td>
</tr>
<tr>
<td>Loamy debris</td>
<td>$3.04 \times 10^{-4}$</td>
</tr>
<tr>
<td>Rocky initial soils</td>
<td>$1.07 \times 10^{-3}$</td>
</tr>
<tr>
<td>Sorted patterned ground (middle part)</td>
<td>$3.18 \times 10^{-7}$</td>
</tr>
<tr>
<td>Sorted patterned ground (outer part)</td>
<td>$2.62 \times 10^{-4}$</td>
</tr>
<tr>
<td>Pebbly alluvial sediments</td>
<td>$3.04 \times 10^{-4}$</td>
</tr>
<tr>
<td>Boulder blankets</td>
<td>$2.38 \times 10^{-2}$</td>
</tr>
<tr>
<td>Solifluction stripes</td>
<td>$3.34 \times 10^{-4}$</td>
</tr>
<tr>
<td>Talus</td>
<td>$7.15 \times 10^{-3}$</td>
</tr>
<tr>
<td>Nonsorted patterned ground</td>
<td>$1.62 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
The total amount of the specific groundwater runoff ($q_{\text{tot}}$) from the Brattegg River catchment has been also calculated. The layout of the river network in the catchment is limited only to the Brattegg River, to which contribute only a few watercourses of a short length and low flow rate. Consequently, the Brattegg River is the main base for groundwater drainage. In the given scope, the efficiency of the groundwater stream flowing into the Brattegg River was estimated. The calculations were based on the average values of the hydraulic conductivity calculated for the geomorphological forms, a hydraulic gradient of 0.05 and the unit thickness of the aquifer. Data related to the variability of geomorphological forms along the Brattegg river bed were also needed as well as the results of direct observations (Fig. 5) and archived data (Fig. 1) (Jania et al. 1984; Migoń and Kasprzak 2013; Zwoliński et al. 2013; Owczarek et al. 2014).

The specific groundwater runoff $q_{\text{tot}}$ from the Brattegg River catchment was calculated at 130.13 L s$^{-1}$. These calculations were completed for the three catchment areas: its upper part – above Myrktjørn Lake, the middle part, and the lower part – below Myrktjørn Lake (Fig. 6), showing a clear disproportion of $q_{\text{tot}}$ in different areas. The specific groundwater runoff in the lower part is the lowest and amounts to 19.75 L s$^{-1}$, which is 15.2% of its total value; in the middle part it is slightly higher, i.e., 25.18 L s$^{-1}$ (19.3%) and in the upper part it is definitely the highest, i.e., 85.2 L s$^{-1}$ (65.5%). These differences are determined by the large variability in the permeability of the sediments filling the bottom of the Brattegg valley. Groundwater runoff from the parts of the catchment covered mostly by pebbly debris formations, i.e., in the upper part of the catchment and the outflow from the right-hand part of catchment, accounts for 84.5% of the total groundwater runoff.

The calculated value of $q_{\text{tot}}$ from the Brattegg River catchment in the amount of 130.13 L s$^{-1}$ is from 15% to 47% of the average surface runoff amounting for the years 2005–2010 from 276 to 842 L s$^{-1}$. On the other hand, the value of $q_{\text{tot}}$ is only 2% of the maximum flow rate of the Brattegg River measured in 2008 at 6 595 L s$^{-1}$ (Stachnik et al. unpublished).

Conclusions

The sedimentary rocks of the permafrost active layer are characterized by high variability in permeability. The hydraulic conductivity, determined for 64 sediment samples, ranging from $6.37 \times 10^{-9}$ to $4.0 \times 10^{-3}$ m s$^{-1}$, indicate the permeability of the sediments from very low in the case of loams to very high for pebbly-gravel debris. The loose rocks in the studied catchment were formed in sedimentary environments, characterized by variable dynamics, as a result of slope processes and direct accumulation of glacial material. They were also formed in aquatic and aeolian environments. The tested sediments are relatively young and their permeability should be expected to change as a result of further
The permeability of geomorphological forms is determined by their lithology. The highest one is estimated for boulder-pebbly covers and rock debris, and the lowest for patterned ground.

Sediment permeability is the main factor influencing the amount of the groundwater runoff, which in the major part of the studied catchment takes place most often within rock debris and boulder covers, and only to a small extent in areas with structured-polygon soils. The calculated values of the specific groundwater runoff represent the potential flow, which may be reached only

Fig. 6. Spatial distribution of the potential specific groundwater runoff in the Brattegg River catchment.
during the summer season, when the active layer is watered. In fact, for most of the year, the flow of water below the ground surface stops. In winter, the active layer of permafrost freezes. At the end of the Arctic summer, it is drained, especially in areas covered with sediments with high permeability.

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**References**


