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RESEARCH ARTICLE

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Spatial variability of the hydrochemistry of shallow groundwaters and surface waters of the Rensdyrbekken: A case study of a permafrost catchment in Bellsund (SW Spitsbergen, Svalbard)

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Abstract

Progressive climate change may have unpredictable consequences for the Arctic environment. Permafrost catchments off the west coast of Svalbard, described as "thin" and "warm," are particularly sensitive to climate change. The interdisciplinary research on the hydrochemical response of surface and underground water functioning within a small permafrost catchment area focused on the determination of the impact of meteorological conditions (temperature (*T*), precipitation (*P*)) on the mean daily discharge (*Q*), and the lowering of the groundwater table (*H*). We determined physical and chemical properties (*pH* and *SEC*) and concentrations of major elements (*Ca*, *Mg*, *Na*, *K*) and 23 trace elements (i.a. *Cd*, *Cu*, *Hg*, *Pb*, *Zn*) in 280 water samples. The results of the correlation matrix showed that an increase in the average air temperature in the summer of 2021 had a significant impact on the hydrochemistry of both types of waters operating in the catchment. In response to increase in *T*, the lowering of the *H* ($0.52 < r < 0.66$) and a decrease in *Q* ($-0.66 < r < -0.68$) were observed what in consequence also leads to changes in water chemistry. The principal component analysis (CA) indicates that chemical weathering and binding of elements to *DOC* are processes influencing water chemistry. Results of statistical analysis showed that the resultant of the hydrometeorological conditions that

prevailed in that season and the type of geological formations on which they were located had a significant impact on the water chemistry at individual measurement points. Significant differences in the concentrations of elements between points on the same geological formations were also found.

KEYWORDS
climate change, creek, element, metals, permafrost thawing, water pollution

1 | INTRODUCTION

In the 21st century, the Arctic is facing serious environmental transformations such as climate warming, leading to the intensification of glacier melting and thawing of permafrost (Biskaborn et al., 2019; Hanssen-Bauer et al., 2019; Szumińska et al., 2018; Wawrzyniak & Osuch, 2020). These phenomena promote the rapid retreat of glaciers and the expansion of Arctic permafrost areas. The changes are responsible for the acceleration of environmental processes occurring in the Arctic, from natural hydro- and geochemical reactions to the release of pollutants stored in glaciers and permafrost (AMAP, 2012; Dolnicki et al., 2013; Lehmann-Konera et al., 2018; Stachniak et al., 2022).

While permafrost accounts for up to 25% of the terrestrial part of the Earth, permafrost coastlines, mostly located in the Arctic, constitute approximately 34% of the world's coastlines (Christiansen et al., 2018, 2020; Lantuit et al., 2013). Research on mean temperatures of permafrost at a depth of 10–20 m in Svalbard shows that western coastal sites are warmer than the central part (between −2.5°C and approximately −5°C, respectively) (Hanssen-Bauer et al., 2019). Permafrost on the Svalbard west coast is therefore referred to as "warm" and "thin" (Kristensen, 2008) and is vulnerable to climate change (Christiansen et al., 2018). An increase in the thickness of the active layer results in an increase in infiltration of the ground (soil or rock) and changes in hydrological conditions related to the flow and storage of water. This consequently leads to alterations of the surface water level (Lehmann-Konera et al., 2018; Stachniak et al., 2022; White et al., 2007) and catchment geochemistry (Abbott et al., 2015; Carey, 2003; Larouche et al., 2015; Petrone et al., 2006).

The Svalbard Archipelago is a region of the Arctic that has been insufficiently investigated with respect to the chemical composition of groundwaters and surface waters in permafrost catchments. Studies on Svalbard's surface waters such as lakes, rivers, and streams are quite common for organic compound analysis (Kozak et al., 2017; Kwok et al., 2013; Lehmann-Konera et al., 2018, 2019, 2020; Polkowska et al., 2011) as well as ions and elemental composition (Kozak et al., 2015; Lehmann-Konera et al., 2021; Stachnik et al., 2016, 2019; Szumińska et al., 2018). Some studies in glacier-covered catchments of Svalbard also concern chemical composition of groundwaters in terms of major ions (Cooper et al., 2002; Dragon et al., 2015; Dragon & Marciniak, 2010; Olichwer et al., 2013; Wadham et al., 2007). However, there is a knowledge gap regarding the trace elements composition of the shallow groundwaters of permafrost catchments in Svalbard, as well as the impact of hydrometeorological conditions on changes in their levels.

This paper aims at providing a new insight into the hydrochemical variability of surface and subsurface water in a permafrost catchment in the coastal area of Bellsund and to define the effect of changing hydrometeorological conditions on the element composition in particular parts of the catchment. The study covered the Rensdyrbekken (Reindeer Creek) catchment. An interdisciplinary team carried out hydrometeorological monitoring of mean daily water flow rate (*Q*), as well as measurement of shallow groundwater levels (*H*), average air temperature (*T*), and precipitation magnitude (*P*) in summer 2021. Furthermore, for a period of 30 days, 280 water samples were collected for chemical analyses. Chemical analyses included the determination of the following physicochemical properties: *pH*, specific electrolytic conductivity (*SEC*), dissolved organic carbon (*DOC*), as well as major (*Na*, *Ca*, *Mg*, *K*) and trace elements (*Ag*, *Al*, *As*, *B*, *Ba*, *Be*, *Bi*, *Cd*, *Co*, *Cr*, *Cu*, *Fe*, *Hg*, *Li*, *Mn*, *Mo*, *Ni*, *Pb*, *Sb*, *Se*, *Sr*, *V*, and *Zn*) in all types of collected water samples. Moreover, photogrammetry and morphometry surveys were carried out to support the interpretation of the obtained results, permitting the determination of the catchment boundaries, elevation profile, and runoff lines.

2 | MATERIALS AND METHODS

The interdisciplinary research carried out within the framework of the research project included both photogrammetric and morphometric investigation of the Rensdyrbekken catchment, as well as meteorological observations, hydrological monitoring, and chemical analyses of various types of water functioning within the permafrost catchment in the High Arctic. This publication focuses on describing the spatial discrepancies in hydrochemical features of water functioning within a non-glaciated catchment. Therefore, all detailed information on research other than chemical analysis is included in Data S1.

2.1 | Study area and regional settings

The Svalbard Archipelago is in the zone of continuous permafrost (Dolnicki et al., 2013). Its thickness near the coast is less than 100 m and reaches more than 500 m in inland areas with high elevation (Dolnicki et al., 2013; Humlum et al., 2003; Kristensen, 2008). The thickness of the active layer at the west coast and in the central part of Spitsbergen is in a range of 100–200 cm (Hanssen-Bauer et al., 2019). Research on mean temperatures of permafrost at a depth of 10–20 m in Svalbard shows that western coastal sites are warmer than the central part (between −2.5°C and approximately −5°C,

respectively) (Hanssen-Bauer et al., 2019). Permafrost on the Svalbard west coast is therefore referred to as "warm" and "thin" (Kristensen, 2008) and is vulnerable to climate change (Christiansen et al., 2018).

The High Arctic permafrost catchment of the Rensdyrbekken (Figure 1) drains an area of approximately 1.3 km^2 in the NW Part of the Wedel-Jarlsberg Land (Bellsund, Spitsbergen). The catchment is located on the tectonic units of the Calypsostranda Graben. The layer of active permafrost in the study area can reach a thickness of more than 202 cm (Marsz et al., 2013). The surface waters have snow-precipitation-permafrost alimentation regime (Harasimiuk & Gajek, 2013; Lehmann-Konera et al., 2018). The drainage system of the subsurface water is very well-developed due to the domination of brown soils with a light granulometric composition in the catchment area (Klimowicz et al., 2013).

2.2 | Hydrometeorological monitoring and sampling

Research regarding measurements of hydrometeorological conditions in the Rensdyrbekken catchment and the spatial distribution of elements in groundwaters and surface waters was conducted between June 23 and July 23, 2021 (Figure 2). A total of 124 surface water samples were collected during the period directly from the creek, 152 groundwater samples from piezometers.

Meteorological measurements were conducted in the central part of the catchment and covered air temperature (*T*) and precipitation (*P*) occurrence (CR at 38 m a.s.l). Surface water sample collection and hydrological measurements of mean daily water discharge (*Q*) in the Rensdyrbekken were conducted for 4 key cross-sections: a fragment of the estuarine course of the river (RM at 13 m a.s.l.) morphologically constituting a watershed section; the middle course of the river together with its left-hand tributary (RMC; RLT—both at 20 m a.s.l.), where the terrain forms a scoured, flattened depression with a significant proportion of wetlands, and the source zone of the river (RS at 69 m a.s.l.), which is a highly elevated marine terraced area with a slight slope. Measurements of the groundwater table level (*H*) and water sampling were also conducted in 6 piezometric boreholes. The distribution of these measurement points covered: the lower part of the Rensdyrbekken catchment, in the zones of elevated terrain on both sides of the watercourse (PZR_6; PZR_2—both at 27 m a.s.l.); the middle section of the catchment basin with a single point (PZR_5 at 22 m a.s.l.) near the confluence of tributaries, and two points covering the higher parts of the middle part of the catchment (PZR_3 at 29 m a.s.l.; PZR_4 at 32 m a.s.l.) and the upper part of the catchment, which is an elevated marine terrace, with the piezometer on its left wing (PZR_1 at 69 m a.s.l.).

2.3 | Data collection and sampling methods

Photogrammetric and morphometric surveys were used to prepare maps illustrating the morphometry of the catchment during the implementation of the field survey in the summer of 2021. The field materials were collected with use of eBee X fixed-wing drone equipped with a SensiaFly Aeria X camera. Further, the data were subject to photogrammetric processing in the Agisorf Metashape Professional environment and imported to the WGS84/UTM zone33 system (more details in Data S1).

Flow conditions was measured in the RS, RMC, RM, and RLT section of the creek (Figure 2). Water stages were recorded 144 times

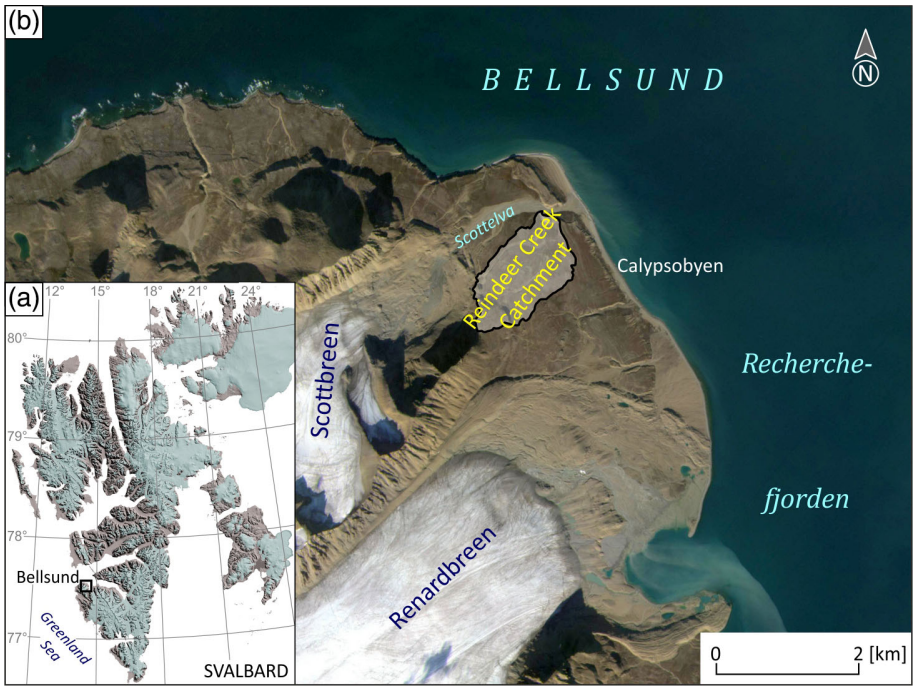

FIGURE 1 Map of Svalbard (a) with location of the Rensdyrbekken catchment in the coastal area of Bellsund (b) (Background: Satellite image, 08/25/2020 – Planet Labs Inc.). [Colour figure can be viewed at wileyonlinelibrary.com]

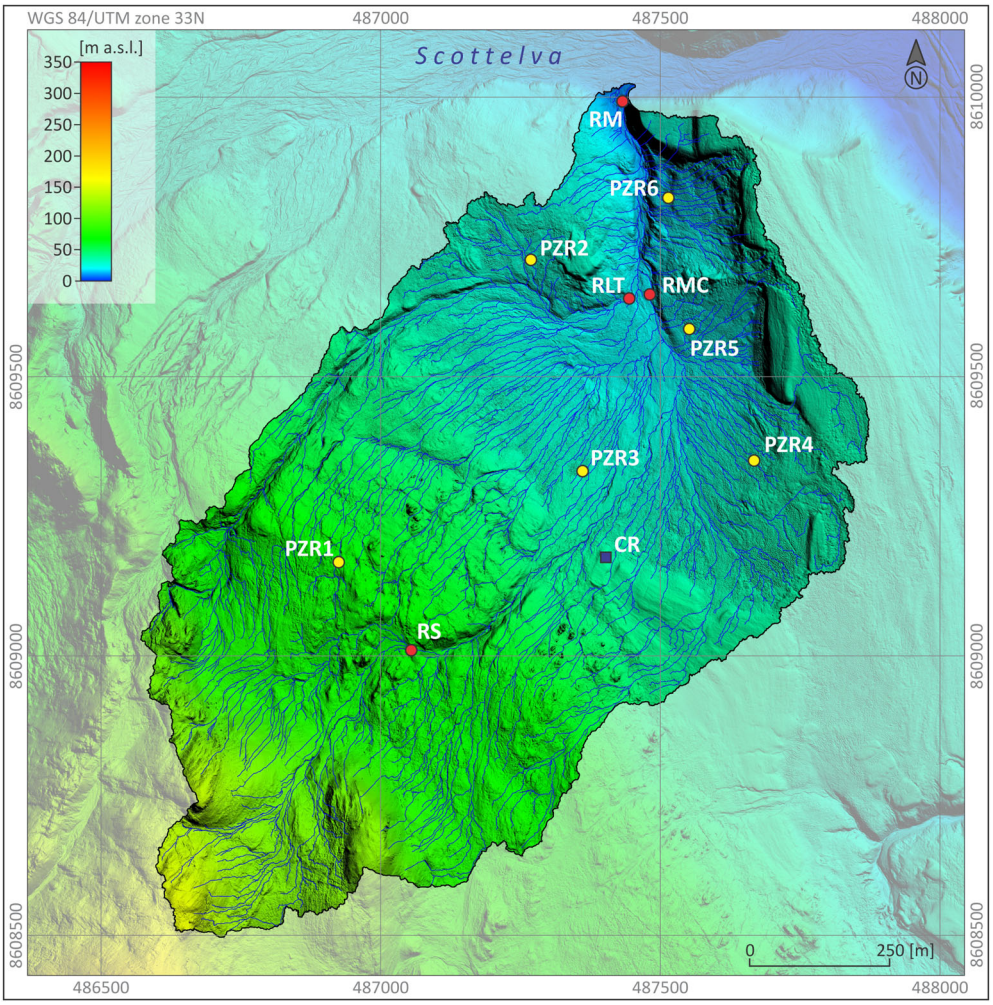

FIGURE 2 Map of Rensdyrbekken catchment with points of hydrological measurements and sampling in surface water (red dots), groundwater (yellow dots), and meteorological measurements point (blue square) (Background: flow network generated based on DEM). [Colour figure can be viewed at wileyonlinelibrary.com]

per day with TD-Diver meter (Eijkelkamp), with a measurement accuracy of ±0.5 cm. The flow velocity was measured by a HEGA I (Biomix, Poland) current meter, with a range of flow velocity measurements of 0.02–3.00 m s^{-1} and 0.2–2.4 m s^{-1} (and an accuracy of ±0.25 cm s^{-1}), respectively. More details and calculations of mean daily discharge are given in Data S1. Measurements of the position of the groundwater table were conducted in the installed piezometers PZR_1–6 (Figure 2). Registration of water levels was carried out manually using a hydrogeological whistle at a frequency of once a day.

Air temperature was measured every 10 min with an automatic temperature datalogger HOBO U12 Stainless Temp Logger. While precipitation was collected with Pronamic Rain-O-Matic Professional rain gauge (CR in Figure 2) with 200 cm^2 inlet surface area, mounted on a stand.

The water samples were collected into 0.25–0.5 L chemically clean plastic bottles made of high-density polyethylene (HDPE). The personnel were equipped with polyethylene gloves to prevent contamination of samples. Surface water samples were collected manually to bottles previously triple rinsed with the sampled water. Groundwater sampling employed a peristaltic pump (Eijkelkamp Soil & Water company). The composition stability and representativeness of water samples for organic analysis were ensured by their filtering through glass microfiber 47 mm GF/C Whatman filters. For inorganic analysis, the samples were filtered through a 0.45 µm PTFE filter to 50 mL plastic vials and subject to acidification by HNO_3 (ultrapure). The samples were stored in dark conditions at a temperature of approximately 4°C for transportation. To mitigate the impact of the procedure and sample containers, a blank sample was used as a control.

2.4 | Chemical analysis

In situ measurements of physicochemical properties of groundwater and surface water employed a multi-parameter YSI Pro1030 pH/conductivity meter. The analysis of dissolved organic carbon (*DOC*) and elements (*Ag*, *Al*, *As*, *B*, *Ba*, *Be*, *Bi*, *Ca*, *Cd*, *Co*, *Cr*, *Cu*, *Fe*, *Hg*, *K*, *Li*, *Mg*, *Mn*, *Mo*, *Na*, *Ni*, *Pb*, *Sb*, *Se*, *Sr*, *V*, and *Zn*) was conducted after the delivery of samples to the laboratory in Poland. Both in the field and in Poland, deionized water of Mili-Q type (Mili-Q® Ultrapure Water Purification Systems, Millipore®) was used during the analytical procedures. *DOC* was determined by catalytic combustion (oxidation) by means of an NDIR detector (Total Organic Carbon Analyzer TOC-VCSH/CSN, SHIMADZU, Japan, Potassium Hydrogen Phthalate

standard). The elements analysis was performed by means of Inductively Coupled Plasma Mass Spectrometry (ICP-MS 2030 Shimadzu, Japan). The inorganic analysis conditions were as follows: Collision Cell Technology, plasma gas flow Ar: 8 L/min, collision cell gas flow He: 6 mL/min. The quality of the analysis was ensured due to use of standards (CRM-IV multi-element standard, Merck, USA); single standards: *As*, *Sb*, *Se*, *Mo*, and *V* (Sigma-Aldrich, USA); internal standard of *Sc*, *Rh*, *Tb*, and *Ge* in 1% HNO_3 solution (Merck, USA), and the application of certified reference materials (CRM ERM-CA713 (sample 125)) of trace elements in wastewater (IRMM—Institute for Reference Materials and Measurements). Details concerning validation parameters such as limit of detection (LOD) and limit of quantification (LOQ) are given in (Table S1).

2.5 | Statistical analysis

The statistical analysis of data employed a Mann–Whitney U test, matrix correlation analysis, and cluster analysis (CA). All statistics were performed for two-tailed $\alpha = 0.05$, using STATISTICA 13.3 (TIBCO®, StatSoft Inc., Tulsa, OK, USA) software and/or Python programming language. Details of the computational methods used to analyze the data can be found in Data S1 as well as the results of Mann–Whitney U test (Tables S3 and S4).

3 | RESULTS

3.1 | Discrepancies in chemical water properties

The results of hydrometeorological measurements and values of chemical analysis results are provided in Table 1, and Figures S2–S4 and Table S2. As shown in Table 1 mean daily air temperature varied significantly between 2.09 and 7.44°C. Only 6 daily total precipitation was noted during that time (Figure S2).

The discharge values varied from 0.750 up to 145 L/s between the spring and mouth of the creek, respectively (Table 1, Figure S3). While the fluctuations of water table varied from 0 to 82 cm below ground level (b.g.l) between PZR_1 and PZR_2, respectively (Table 1, Figure S4). Statistically significant differences of hydrological conditions were observed between the Rensdyrbekken spring (RS), main course (RMC), mouth (RM), and left tributary (RLT) sections (Tables S2 and S3). In the case of groundwater level, the discrepancies were only significant between PZR_2 and PZR_3–6 (Tables S2 and S3, Figure 3).

In the case of physicochemical parameters in the catchment water *pH* oscillated between 7.18 in groundwater and 8.86 in surface water (Table 1). The highest mean values of water *pH* were observed in RLT and the lowest in PZR_6 (Figure 3). Similarities in water *pH* were noted for RS with RMC; RMC with RLT; PZR_2 with PZR_3 and 5; PZR_3 with PZR 4 and 5; and PZR_4 with PZR_5 (Tables S2 and S3). The levels of *SEC* varied in surface water and groundwater from 71.5–250 µS/cm to 167–2,708 µS/cm, respectively (Table 1). The lowest mean value of *SEC* was characteristic of RLT and the highest of

TABLE 1 Data of results of hydrometeorological monitoring (*Q*, *H*, *P*, *T*), and ranges of values of determined physicochemical parameters (*pH*, *SEC*), sum parameter (*DOC*), as well as elements in water samples collected from the studied catchment.

Determined parameters/analytes	Rensdyrbekken	
	Surface water	Groundwater
	RS, RMC, RLT, RM	PZR_1–6
	Min–Max	
Meteorological measurements		
T [°C]	2.09–7.44	
P [mm]	0–6.55	
Hydrological measurements		
Q [L/s]	0.750–145	n.d.
H [cm b.g.l]	n.d.	0–82
Physicochemical measurements		
pH [–]	7.93–8.86	7.18–8.62
SEC [µS/cm]	71.5–250	167–2,708
Sum parameter		
DOC [mg/L]	0.104–1.07	0.597–10.8
Elements [µg/L]		
Ag	0.004–0.423	<LOD – 1.97
Al	1.69–66.9	<LOD – 124
As	0.045–0.351	0.003–2.77
B	0.687–10.7	<LOD – 226
Ba	0.942–26.7	0.719–1,050
Be	0.108–0.316	<LOD – 2.58
Bi	<LOD	<LOD – 0.405
Ca	224–1,120	78.4–17,300
Cd	0.004–0.851	0.010–5.97
Co	0.007–0.303	<LOD – 1.12
Cr	0.057–20.7	<LOD – 6.75
Cu	0.056–9.52	<LOD – 208
Fe	4.35–57.5	<LOD – 363
Hg	<LOD	<LOD – 0.051
K	60.0–565	<LOD – 13,700
Li	0.095–3.69	<LOD – 310
Mg	1,810–9,420	194–318,000
Mn	0.143–3.93	<LOD – 326
Mo	0.054–45.7	0.030–11.1
Na	57.2–431	35.5–7,870
Ni	0.067–1.28	<LOD – 6.09
Pb	0.144–14.6	0.016–191
Sb	0.019–0.424	0.014–7.76
Se	0.051–0.278	0.023–0.860
Sr	12.5–74.7	3.43–1,790
V	0.006–0.382	0.001–0.512
Zn	0.483–14.6	<LOD – 1,100

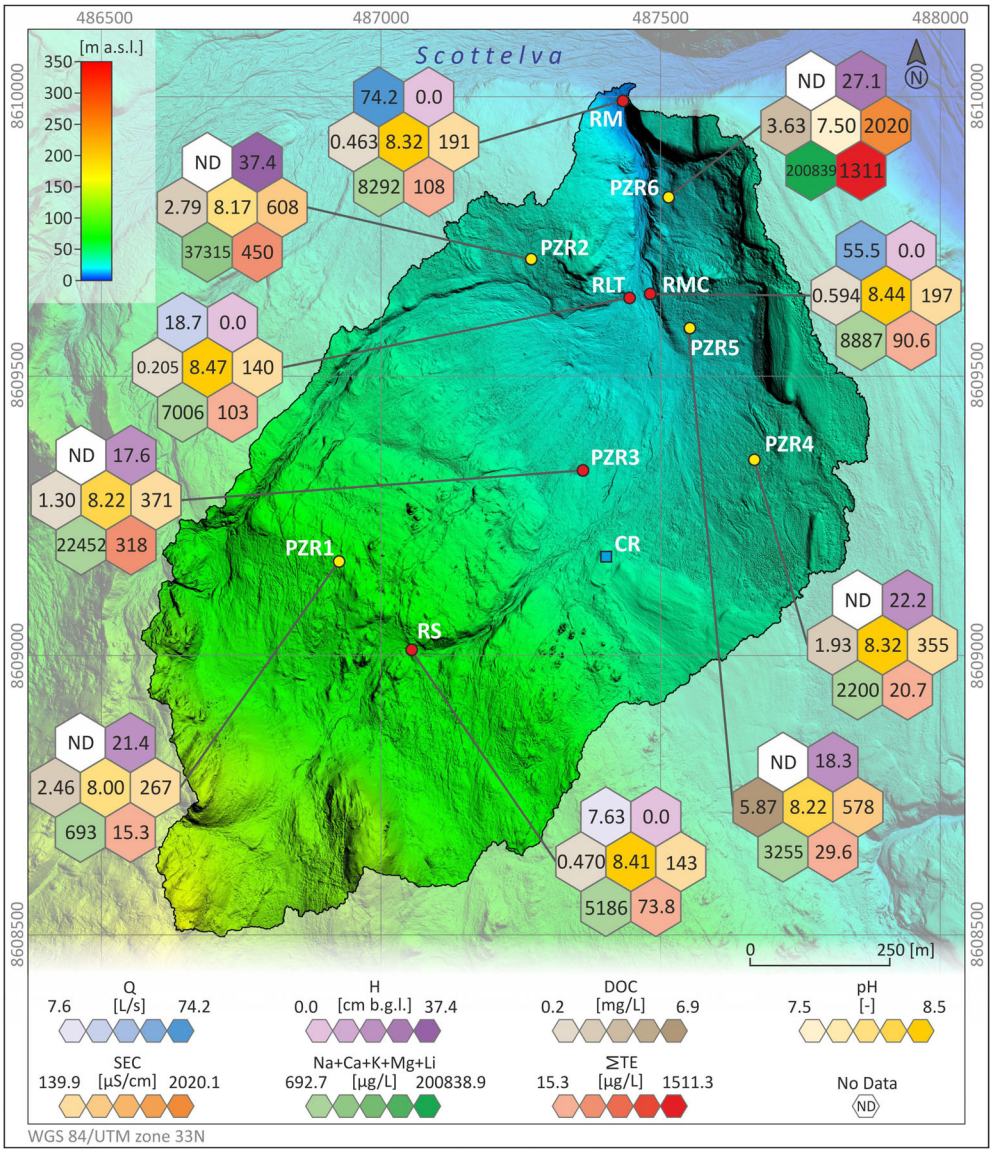

FIGURE 3 Map of the permafrost catchment area with the average values of the results of hydrology and physicochemical parameters at the measurement points of surface water (RSM RMC, RLT, RM; red dots) and shallow groundwater (PZR_1–6; yellow dots). [Colour figure can be viewed at wileyonlinelibrary.com]

PZR_6 (Figure 3). Statistical differences were observed for *SEC* between all groundwater sampling sites (Table S3) and for RS with RMC and RM, as well as RLT with RMC and RM (Table S2). Dissolved organic carbon showed significant differences between sites (Tables S2 and S3). The concentrations of *DOC* in RS, RMC, RLT, and RM did not exceed 1.07 mg/L (Table 1), with similarities in levels between sites RS and RM (Table S2) which mean values of approximately 470 mg/L (Figure 3). For surface water sites, RMC showed the highest mean value of *DOC* (0.594 mg/L) and RLT the lowest one (0.205 mg/L) (Figure 3). *DOC* in groundwater samples varied from 0.597 to 10.8 mg/L, with significant differences between sites. The lowest *DOC* level (0.104 mg/L) was observed at site RLT and the highest one (10.8 mg/L) at both PZR_5 and PZR_6 (Table 1, Table S2).

The elements composition between sites differs significantly in most cases (Tables S2 and S3). It should be emphasized that *Bi* and *Hg* were below limit of detection (<LOD) in all surface water samples. At groundwater study sites, *Bi* was <LOD at PZR_2 and PZR_3, and *Hg* was <LOD at PZR_1–5 but occurred at PZR_6. Moreover, study sites PZR_1, 4, and 5 were mostly characterized by composition of elements lower than that of any other study site (Figure 3). At these study sites, <LOD concerned *Ag*, *Al*, *B*, *Be*, *Co*, *Cr*, *Cu*, *Mn*, *Ni*, *Zn*, and occasionally *Fe*, *K*, *and Li* (Table 1). Surface water composition showed similarities of RS and RMC in concentration of *Ba*, *Fe*, *Mn*, *Mo*, *Ni*, *Se*, and *V*. For RS and RLT, comparable levels occurred in case of *Al*, *Ba*, *Ca*, *Fe*, and *V*. RS and RM show corresponding concentrations of *Al*, *As*, *Fe*, *Pb*, and *Se*. Only some similarities in levels of *Se* and *V* are recorded between the main course of the creek and its left tributary. Although RMC is the main course of the creek, the left tributary of the Rensdyrbekken shows more similarities in elements composition with the mouth section (RM). In the first case (RMC/RM), it concerns only *Ag*, *Mg*, and *Sr*, and in the second case (RLT/RM) *Al*, *B*, *Ba*, *Be*, *Cd*, *Cr*, *Cu*, *Fe*, *Li*, *Mo*, *Pb*, and *Zn* (Table S2). In groundwater samples, similarities in elemental composition were observed between PZR_1, 4, and 5 for elements such as *Al*, *Ba*, *Cd*, *Fe*, *Li*, *Mn*, *Pb*, *Sb*, *Sr*, *V*, and *Zn*. The mean value of major elements at these sites varied between 693 and 3,255 µg/L, and for sum of trace elements (Σ_{TE}) between 15.3

and 29.6 µg/L (Figure 3). PZR_2 and PZR_3 showed similar concentrations of *As*, *Be*, *Cd*, *Fe*, *Pb*, *Se*, and *Zn*. These sites were also characterized by higher mean values of major elements (37,314 µg/L and 22,452 µg/L, respectively) and Σ_{TE} (450 µg/L and 318 µg/L, respectively) than in the case of PZR_1, 4, and 5 (Figure 3). Comparable levels of *Zn* were also observed between PZR_6 with PZR_2 and 3. PZR_6 stood out from all other study sites with the highest mean values of major and Σ_{TE} (200,839 µg/L and 1,311 µg/L, respectively) (Figure 3). Moreover, PZR_3 and 6 showed similarities in concentrations of *Mo* and *Sb*, while PZR_4 and 5 had comparable levels of *Cd*, *Mn*, *Mo*, *Pb*, and *Se* (Table 1).

The results of cluster analysis (CA) (Figure 4. RS, RMC, RM, RLT) permitted the designation of 3 major clusters in the surface water of the Rensdyrbekken catchment at sites RS, RLT, and RMC, despite the differences in elements composition. In the case of RM, elements are grouped in only 2 major clusters. Different cluster analysis groups can be distinguished by their relationship to *pH*, *SEC*, and *DOC*. In the source section of the stream, elements such as *Mo*, *Cu*, *Ag*, *Cr*, *Fe*, *Ni*, *Pb*, *Zn*, *Al*, and *Mn* form the first group RS_C1, showing correlations with *pH*, *SEC*, and *DOC*. No such correlations were observed at the other sites. At site RMC, the first cluster RMC_C1, including *B*, *K*, *Na*, *Li*, *Mg*, *Ca*, and *Sr*, shows links to *pH* and *SEC*. Only the third cluster RMC_C3 represented by *Ag*, *Ba*, *As*, *Se*, *Al*, *V*, *Be*, and *Cr* shows an association with *DOC*. Waters from the left tributary of the stream showed some similarity in grouping of elements in RLT_C1 (*Mo*, *B*, *Li*, *K*, *Sr*, *Ca*, *Mg*, *Be*) with RMC_C1, and their association with *pH* and *SEC*. A similarity was also observed in the grouping of elements in RLT_C2 (*Se*, *Na*, *Ag*, *Ba*, *As*) with RMC_C3 and their association with

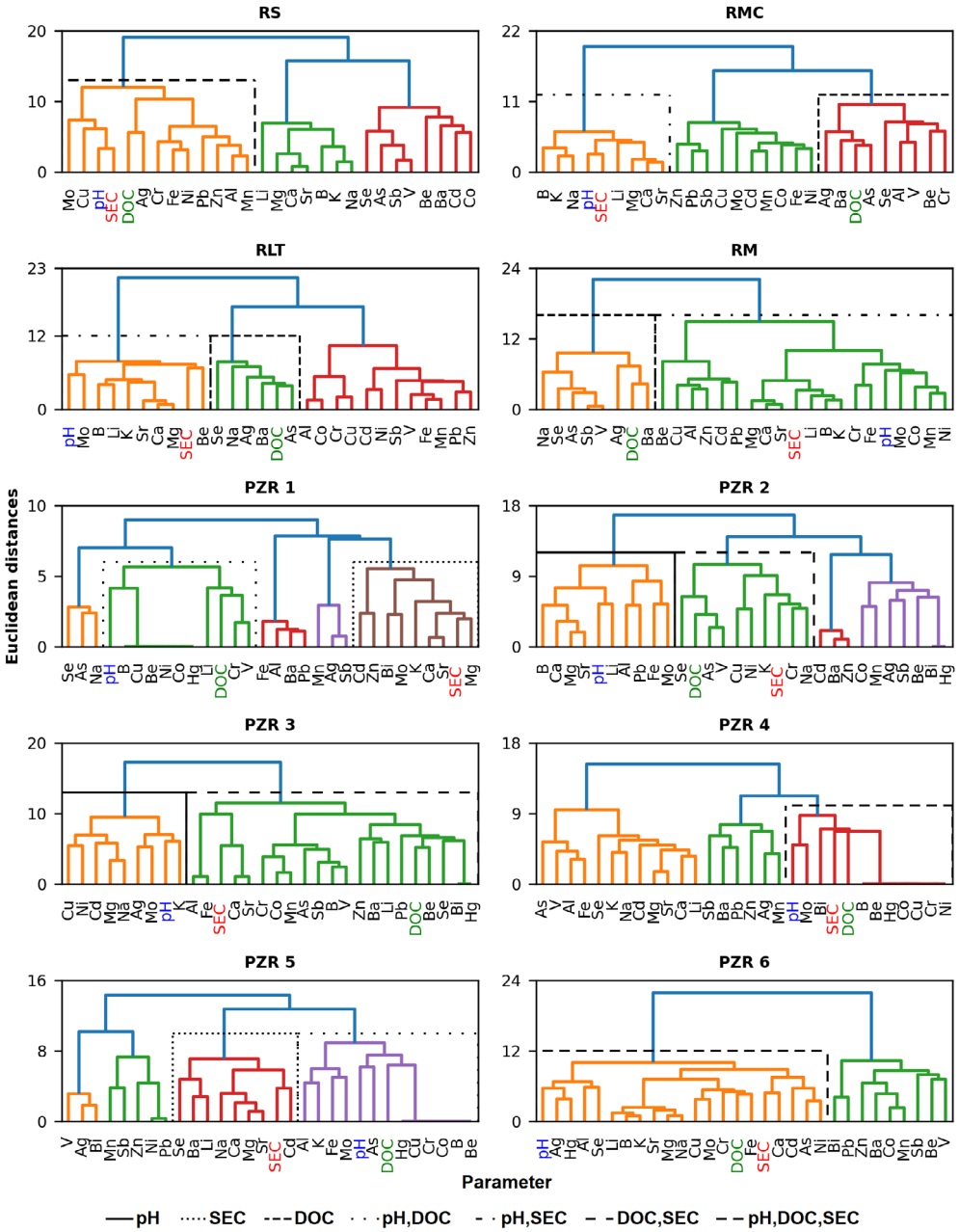

FIGURE 4 Hierarchical dendrograms resulting from cluster analysis of sum parameter and physicochemical indices in the surface water (RS, RMC, RM, RLT) and groundwater (PZR_1–6) of the Rensdyrbekken. Clustering was performed on standardized values, with Ward's method, using squared Euclidean distance. Major clusters characterized by association with pH, SEC, or DOC were marked with a line described in the legend of the figure. [Colour figure can be viewed at wileyonlinelibrary.com]

DOC. Like in RS_C2 and C3, elements grouped in RMC_C2 and RLT_C3 show no association with *pH*, *SEC*, or *DOC*. Against the background of these correlations, the estuary section of the stream is distinguished by the occurrence of only two groups of elements RM_C1 where elements *Na*, *Se*, *As*, *Sb*, *V*, *Ag*, and *Ba* show correlations with *DOC*. Meanwhile, in RM_C2, elements such as *Be*, *Cu*, *Al*, *Zn*, *Cd*, *Pb*, *Mg*, *Ca*, *Sr*, *Li*, *B*, *K*, *Cr*, *Fe*, *Mo*, *Co*, *Mn*, and *Ni* were characterized by an association with *pH* and *SEC*.

Cluster analysis of the groundwater chemistry (Figure 4. PZR_1–6) shows very high variability between the sites. Water samples from PZR_1 had the most numerous clusters (PZR_1-C1 to C5). PZR_2–6 was characterized by a division of elemental composition into 2–4 main clusters. A relation to *pH* was determined for elements belonging to clusters PZR_2-C1 (*B*, *Ca*, *Mg*, *Sr*, *Li*, *Al*, *Pb*, *Fe*, *Mo*) and PZR_3-C1 (*Cu*, *Ni*, *Cd*, *Mg*, *Na*, *Ag*, *Mo*, *K*). Elements whose presence was associated with *SEC* were included in clusters PZR_1-C5 (*Cd*, *Zn*, *Bi*, *Mo*, *K*, *Ca*, *Sr*, *Mg*) and PZR_5-C3 (*Se*, *Ba*, *Li*, *Na*, *Ca*, *Mg*, *Sr*, *Cd*). Elements in clusters PZR_1-C2 (*B*, *Cu*, *Be*, *Ni*, *Co*, *Hg*, *Li*, *Cr*, *V*) and PZR_5-C4 (*Al*, *K*, *Fe*, *Mo*, *As*, *Hg*, *Cu*, *Cr*, *Co*, *B*, *Be*) showed association with *pH* and *DOC*. A relation to both *SEC* and *DOC* were noted for elements belonging to clusters PZR_2-C2 (*Se*, *As*, *V*, *Cu*, *Ni*, *K*, *Cr*, *Na*) and PZR_3-C2 (*Al*, *Fe*, *Ca*, *Sr*, *Cr*, *Co*, *Mn*, *As*, *Sb*, *B*, *V*, *Zn*, *Ba*, *Li*, *Pb*, *Be*, *Se*, *Bi*, *Hg*). Elements whose presence was associated with *pH*, *SEC* and *DOC* were included in clusters PZR_4-C3 (*Mo*, *Bi*, *B*, *Be*, *Hg*, *Co*, *Cu*, *Cr*, *Ni*) and PZR_6-C2 (*Ag*, *Hg*, *Al*, *Se*, *Li*, *B*, *K*, *Sr*, *Mg*, *Na*, *Cu*, *Mo*, *Cr*, *Fe*, *Ca*, *Cd*, *As*, *Ni*). Elements in clusters PZR_1 (C1, C3 and C4), PZR_2 (C3 and C4), PZR_4 (C1 and C2), PZR_5 (C1 and C2), and PZR_6 (C2) showed no association with *pH*, *SEC*, and *DOC*.

3.2 | Relationship between meteorological conditions and catchment hydrochemistry

Table 2 presents results of a matrix correlation analysis between the meteorological conditions and hydrochemistry of the Rensdyrbekken catchment. A statistically significant negative correlation between *Q* and *T* ($-0.66 < r < -0.68$), *pH* ($-0.63 < r < -0.85$), and *SEC* ($-0.79 < r < -0.91$) was recorded in all sections of the analyzed surface water except for RLT. On the contrary, a significant positive correlation was observed between *T* and water *pH* ($0.36 < r < 0.61$) at all measurement sites and *SEC* along the course of the main watercourse from RS ($r = 0.42$) through RMC ($r = 0.53$) and RM ($r = 0.49$). *DOC* showed no correlation with hydrochemistry in the RS section. By contrast, statistically significant positive correlations of *DOC* with *Q* were observed in the RMC ($r = 0.75$) and RM ($r = 0.84$) sections, and negative correlations with *T* in the RMC ($r = -0.62$), RLT ($r = -0.64$), and RM ($r = -0.48$) sections.

Regarding the effect of hydrological factors on the element composition of surface water, a significantly positive correlation was determined in the RS section for *Q* with *As*, *Ba*, *Na*, *Sb*, *Se*, and *V*, in RMC only with *Ag*, *As*, and *Ba*, and in RM with *Ag*, *As*, *Ba*, *Sb*, *Se*, and *V*. A significant negative correlation was recorded for *Q* with *Cu*, *Mg*, and *Mo* in the RS section, with *B*, *Ca*, *Co*, *Fe*, *K*, *Li*, *Mg*, *Mo*, *Na*, *Ni*, and *Sr* in the RMC section, with *B*, *Ca*, *K*, and *Mg* in the left tributary of the stream, and with *B*, *Ca*, *Co*, *Cr*, *Fe*, *K*, *Li*, *Mg*, *Mn*, *Mo*, *Ni*, and *Sr*.

Meteorological conditions prevailing in the catchment area such as mean air temperature (*T*) showed a significantly positive correlation with *Fe*, *Mg*, *Mn*, *Mo*, *Ni*, and *Zn* in RS, with *B*, *Ca*, *Cd*, *Co*, *Cu*, *Fe*, *K*, *Li*, *Mg*, *Mn*, *Mo*, *Ni*, *Sr*, and *Zn* in the main stream, with *B*, *Ca*, and *Mo* in the left tributary, and with *B*, *Ca*, *Co*, *Cr*, *Fe*, *K*, *Li*, *Mg*, *Mn*, *Ni*, *Sr*, and *Zn* in the RM section. A significantly negative correlation of *T* with *As* was recorded in all surface water monitoring points, with *Ba* in RMC and RLT, and with *Sb*, *Se*, and *V* in the RS and RM sections. The occurrence of rainfall (*P*) showed no significant effect on the hydrochemistry of the stream, except for the correlation with *Ba* ($r = 0.41$) in the RM section.

In the case of groundwater (Table 3), on the contrary, the hydrological variable (*H*) showed a statistically significant positive correlation with *T* ($0.52 < r < 0.66$) in all measurement points, with water *pH* at PZR_2, 3, 4, and 6 ($0.52 < r < 0.64$), and with *SEC* at PZR_5 and 6 ($r = 0.80$ and $r = 0.37$, respectively). Moreover, there was also a statistically significant positive correlation between *T* and water *pH* in PZR_2, 3, 4, and 6. Rainfall (*P*) showed a statistically significant correlation with water *pH* ($r = 0.90$) only in PZR_1.

At monitoring site PZR_1, the hydrometeorological factors in the catchment showed a statistically significant negative correlation only with *Mn* ($r = -0.75$). In the remaining monitoring points, the correlations between the variation of hydrometeorological conditions of the catchment and the elements were much more diverse. Moreover, the significant positive correlation between *H* and *T* in groundwater implies their further relationship with the presence of elements in different parts of the catchment. In PZR_2, these factors correlate negatively with *Ag*, *As*, *Se*, and *V*, and positively with *Cd*, *Cr*, *Li*, *Mg*, *Na*, and *Sr*. In PZR_3, positive correlations of *H* and *T* are observed with *Ag*, *Cd*, *Cu*, *Mg*, *Mo*, and *Na*, and negatively with *As*, *B*, *Be*, *Ca*, *Co*, *Cr*, *Mn*, *Sb*, *Sr*, *V*, and *Zn*. A significant positive correlation between *H* and *T* in groundwater projects their further relationship to the presence of the elements in different parts of the catchment. In PZR_2, these factors correlate negatively with *Ag*, *As*, *Se*, and *V*, and positively with *Cd*, *Cr*, *Li*, *Mg*, *Na*, and *Sr*. In PZR_3, positive correlations of *H* and *T* are observed with *Ag*, *Cd*, *Cu*, *Mg*, *Mo*, *Na*, and *Na*, and negative with *As*, *B*, *Be*, *Ca*, *Co*, *Cr*, *Mn*, *Sb*, *Sr*, *V*, and *Zn*. In PZR_4, *H* significantly negatively correlates only with *Ba*, and *T* with *Ag*. For both *H* and *T*, there were significant positive correlations with *Al*, *As*, *Ca*, *Cd*, *Fe*, *K*, *Li*, *Mg*, *Na*, *Se*, *Sr*, and *V*. Like in PZR_4, in PZR_5 *H* and *T* significantly positively correlated with *Al*, *Ca*, *Cd*, *K*, *Li*, *Mg*, *Na*, and *Sr*, while *T* was significantly negatively correlated only with *Ag* and *Bi*. Like in PZR_3, in PZR_6 significant negative correlations were also recorded between *H* and *T* with *Ba*, *Be*, *Co*, *Mn*, and *Zn*. Monitoring point PZR_6 showed the highest number of significant positive correlations between *H* and *T* and elements present at the study site such as *Ag*, *As*, *B*, *Ca*, *Cd*, *Cr*, *Cu*, *Fe*, *Hg*, *K*, *Li*, *Mg*, *Mo*, *Na*, *Ni*, and *Sr*.

4 | DISCUSSION

4.1 | Impact of meteorological conditions

The key factors shaping water chemistry on Svalbard include dry and wet deposition of contaminants and rock-water interactions (Cooper

TABLE 2 Matrix correlation analysis results of meteorological data and results of physicochemical parameters, and elements in surface water samples.

RS	*T*	*P*	*pH*	*SEC*	*DOC*	*Ag*	*Al*	*As*	*B*	*Ba*	*Be*	*Ca*	*Cd*	*Co*	*Cr*	*Cu*	*Fe*	*K*	*Li*	*Mg*	*Mn*	*Mo*	*Na*	*Ni*	*Pb*	*Sb*	*Se*	*Sr*	*V*	*Zn*
Q	**−0.66**	0.19	**−0.85**	**−0.85**	0.29	−0.12	0.15	**0.84**	0.02	**0.73**	0.28	−0.05	0.26	0.22	−0.35	**−0.43**	−0.20	0.29	0.02	**−0.45**	−0.05	**−0.52**	**0.36**	−0.33	0.07	**0.62**	**0.49**	−0.15	**0.47**	−0.13
	T	0.02	**0.48**	**0.42**	0.00	0.30	0.26	**−0.68**	0.09	−0.33	−0.25	0.11	−0.05	0.04	0.35	0.28	**0.37**	−0.20	−0.14	**0.37**	**0.36**	**0.42**	−0.33	**0.41**	0.13	**−0.50**	**−0.45**	0.17	**−0.46**	**0.42**
		P	−0.14	−0.33	0.03	−0.20	0.02	0.12	−0.13	0.07	−0.19	−0.10	−0.08	−0.15	−0.19	−0.14	−0.05	−0.07	0.10	−0.17	−0.08	−0.17	−0.10	−0.11	0.03	0.02	0.00	−0.11	−0.06	−0.06
RMC	*T*	*P*	*pH*	*SEC*	*DOC*	*Ag*	*Al*	*As*	*B*	*Ba*	*Be*	*Ca*	*Cd*	*Co*	*Cr*	*Cu*	*Fe*	*K*	*Li*	*Mg*	*Mn*	*Mo*	*Na*	*Ni*	*Pb*	*Sb*	*Se*	*Sr*	*V*	*Zn*
Q	**−0.68**	0.26	**−0.85**	**−0.79**	**0.75**	**0.63**	0.12	**0.63**	**−0.76**	**0.75**	0.02	**−0.78**	−0.35	**−0.59**	−0.10	−0.25	**−0.50**	**−0.62**	**−0.72**	**−0.90**	−0.28	**−0.79**	**−0.63**	**−0.44**	−0.01	−0.23	−0.11	**−0.75**	−0.13	- 0.24
	T	0.02	**0.56**	**0.53**	**−0.62**	−0.35	−0.01	**−0.42**	**0.55**	**−0.59**	−0.03	**0.48**	**0.47**	**0.56**	0.10	**0.42**	**0.55**	**0.40**	**0.47**	**0.56**	**0.44**	**0.67**	0.26	**0.46**	0.21	0.33	0.11	**0.50**	0.15	**0.36**
		P	−0.16	−0.07	−0.11	0.05	−0.07	−0.06	−0.23	0.03	−0.08	−0.20	−0.07	−0.30	−0.15	−0.13	−0.20	−0.32	−0.17	−0.20	−0.07	−0.14	−0.29	−0.18	0.04	−0.22	0.21	−0.15	−0.31	- 0.09
RM	*T*	*P*	*pH*	*SEC*	*DOC*	*Ag*	*Al*	*As*	*B*	*Ba*	*Be*	*Ca*	*Cd*	*Co*	*Cr*	*Cu*	*Fe*	*K*	*Li*	*Mg*	*Mn*	*Mo*	*Na*	*Ni*	*Pb*	*Sb*	*Se*	*Sr*	*V*	*Zn*
Q	**−0.67**	0.28	**−0.63**	**−0.91**	**0.84**	**0.37**	−0.04	**0.73**	**−0.80**	**0.73**	−0.10	**−0.62**	0.05	**−0.61**	**−0.43**	−0.35	**−0.62**	**−0.76**	**−0.82**	**−0.77**	**−0.84**	**−0.51**	−0.06	**−0.88**	0.13	**0.50**	**0.36**	**−0.68**	**0.47**	**−0.37**
	T	0.02	**0.36**	**0.49**	**−0.48**	−0.32	0.03	**−0.62**	**0.58**	−0.33	−0.01	**0.39**	0.00	**0.43**	**0.46**	0.18	**0.50**	**0.48**	**0.51**	**0.51**	**0.61**	0.18	−0.17	**0.57**	−0.15	**−0.49**	**−0.40**	**0.43**	**−0.46**	**0.44**
		P	−0.10	−0.23	0.21	−0.07	0.24	0.03	−0.18	**0.41**	−0.01	−0.12	0.35	−0.23	−0.01	0.02	−0.03	−0.20	−0.21	−0.13	−0.16	−0.16	−0.13	−0.20	0.26	−0.05	−0.06	−0.15	−0.05	0.15
RLT	*T*	*P*	*pH*	*SEC*	*DOC*	*Ag*	*Al*	*As*	*B*	*Ba*	*Be*	*Ca*	*Cd*	*Co*	*Cr*	*Cu*	*Fe*	*K*	*Li*	*Mg*	*Mn*	*Mo*	*Na*	*Ni*	*Pb*	*Sb*	*Se*	*Sr*	*V*	*Zn*
Q	−0.25	0.30	−0.21	−0.30	0.24	0.35	0.13	0.15	**−0.38**	0.14	−0.25	**−0.55**	−0.01	0.04	−0.04	0.05	0.01	**−0.55**	−0.27	**−0.55**	0.05	0.02	−0.01	−0.03	0.22	−0.06	−0.07	**−0.56**	0.15	0.08
	T	0.02	**0.61**	0.26	**−0.64**	−0.17	−0.10	**−0.49**	**0.45**	**−0.42**	0.18	**0.36**	0.05	0.02	0.04	−0.09	0.23	0.06	0.33	0.33	0.18	**0.36**	**−0.58**	0.21	0.04	0.15	−0.21	0.35	0.04	0.21
		P	−0.15	−0.14	0.15	0.21	−0.11	0.06	−0.31	0.14	0.21	−0.18	−0.07	−0.14	−0.10	−0.08	−0.17	−0.21	−0.28	−0.18	−0.16	−0.11	−0.09	−0.16	−0.12	−0.12	−0.06	−0.13	−0.14	−0.11

Note: Statistical significances ($\alpha < 0.05$) were marked in bold and highlighted in grey.

TABLE 3 Matrix correlation analysis results of meteorological data and results of physicochemical parameters, and elements in groundwater samples.

PZR																															
1	*T*	*P*	*pH*	*SEC*	*DOC*	*Ag*	*Al*	*As*	*B*	*Ba*	*Be*	*Bi*	*Ca*	*Cd*	*Co*	*Cr*	*Cu*	*Fe*	*Hg*	*K*	*Li*	*Mg*	*Mn*	*Mo*	*Na*	*Ni*	*Pb*	*Sb*	*Se*	*Sr*	*V*	*Zn*
H	**0.66**	0.25	0.33	0.05	0.16	−0.39	0.39	0.14	nd	0.21	nd	0.16	0.02	−0.14	nd	0.00	nd	0.08	nd	0.26	0.42	0.32	**−0.75**	0.32	0.26	nd	0.40	−0.33	−0.17	0.13	−0.06	−0.17
	T	0.33	0.30	0.21	−0.23	0.17	0.07	0.14	nd	0.01	nd	−0.32	0.04	−0.39	nd	−0.32	nd	−0.06	nd	0.51	0.02	0.28	−0.37	0.11	0.28	nd	0.16	0.23	−0.02	0.19	−0.51	−0.10
		P	**0.90**	−0.15	−0.08	−0.13	−0.13	−0.02	nd	−0.08	nd	−0.16	−0.13	−0.43	nd	−0.13	nd	−0.23	nd	0.41	−0.27	0.12	−0.29	0.26	−0.03	nd	0.14	−0.16	0.18	−0.02	−0.13	−0.24
2	*T*	*P*	*pH*	*SEC*	*DOC*	*Ag*	*Al*	*As*	*B*	*Ba*	*Be*	*Bi*	*Ca*	*Cd*	*Co*	*Cr*	*Cu*	*Fe*	*Hg*	*K*	*Li*	*Mg*	*Mn*	*Mo*	*Na*	*Ni*	*Pb*	*Sb*	*Se*	*Sr*	*V*	*Zn*
H	**0.52**	−0.05	**0.52**	0.16	−0.31	**−0.57**	0.08	**−0.40**	0.03	0.35	−0.02	nd	0.15	**0.51**	−0.25	**0.47**	0.13	0.31	nd	0.24	**0.64**	**0.60**	−0.05	0.08	**0.36**	0.16	0.23	−0.29	**−0.54**	**0.38**	**−0.43**	0.29
	T	0.10	**0.41**	0.24	−0.31	**−0.39**	0.06	−0.34	0.21	0.04	−0.08	nd	0.33	0.09	−0.21	0.05	0.06	0.08	nd	0.11	**0.49**	**0.60**	0.29	−0.06	0.22	−0.04	−0.01	−0.31	−0.30	**0.53**	−0.31	0.00
		P	0.06	0.19	−0.02	−0.03	0.01	0.10	−0.12	−0.05	−0.02	nd	−0.02	−0.09	−0.10	−0.09	−0.08	−0.21	nd	−0.12	0.18	0.03	−0.09	−0.13	0.12	0.03	−0.06	−0.04	−0.01	0.08	0.11	0.03
3	*T*	*P*	*pH*	*SEC*	*DOC*	*Ag*	*Al*	*As*	*B*	*Ba*	*Be*	*Bi*	*Ca*	*Cd*	*Co*	*Cr*	*Cu*	*Fe*	*Hg*	*K*	*Li*	*Mg*	*Mn*	*Mo*	*Na*	*Ni*	*Pb*	*Sb*	*Se*	*Sr*	*V*	*Zn*
H	**0.53**	−0.19	**0.61**	−0.17	**−0.50**	**0.44**	−0.24	**−0.47**	**−0.50**	−0.29	**−0.41**	nd	**−0.41**	**0.47**	−0.21	**−0.40**	**0.61**	−0.28	nd	0.31	−0.04	**0.58**	−0.14	**0.46**	**0.55**	0.19	−0.29	**−0.60**	−0.13	**−0.38**	**−0.56**	**−0.54**
	T	0.11	**0.48**	−0.31	−0.30	**0.48**	−0.05	**−0.55**	**−0.57**	−0.08	**−0.43**	nd	**−0.44**	0.17	**−0.45**	**−0.51**	0.23	−0.04	nd	0.13	−0.17	0.32	**−0.44**	0.17	0.37	0.17	−0.09	**−0.54**	−0.35	**−0.45**	**−0.59**	−0.25
		P	0.07	−0.14	−0.20	−0.09	−0.06	−0.10	0.01	0.28	0.19	nd	−0.01	0.00	−0.11	−0.04	−0.10	−0.05	nd	−0.37	0.04	−0.01	−0.09	−0.22	0.10	−0.15	−0.02	0.06	0.05	−0.06	−0.02	**0.46**
4	*T*	*P*	*pH*	*SEC*	*DOC*	*Ag*	*Al*	*As*	*B*	*Ba*	*Be*	*Bi*	*Ca*	*Cd*	*Co*	*Cr*	*Cu*	*Fe*	*Hg*	*K*	*Li*	*Mg*	*Mn*	*Mo*	*Na*	*Ni*	*Pb*	*Sb*	*Se*	*Sr*	*V*	*Zn*
H	**0.58**	−0.11	**0.55**	0.19	−0.12	−0.36	**0.42**	**0.43**	nd	**−0.43**	nd	−0.30	**0.58**	**0.66**	nd	nd	nd	**0.65**	nd	**0.55**	**0.70**	**0.87**	−0.15	0.12	**0.61**	nd	−0.26	−0.15	**0.59**	**0.89**	**0.58**	−0.36
	T	0.12	**0.46**	**0.46**	−0.11	**−0.61**	0.28	0.18	nd	−0.28	nd	−0.36	**0.45**	0.15	nd	nd	nd	0.31	nd	**0.46**	**0.50**	**0.58**	−0.37	−0.03	0.30	nd	0.11	−0.02	**0.55**	**0.61**	0.23	−0.17
		P	−0.10	0.00	0.15	−0.06	0.21	0.07	nd	0.19	nd	−0.01	−0.08	−0.05	nd	nd	nd	0.06	nd	0.10	−0.07	−0.09	−0.07	−0.16	0.01	nd	−0.01	−0.05	0.14	−0.14	0.12	**0.74**
5	*T*	*P*	*pH*	*SEC*	*DOC*	*Ag*	*Al*	*As*	*B*	*Ba*	*Be*	*Bi*	*Ca*	*Cd*	*Co*	*Cr*	*Cu*	*Fe*	*Hg*	*K*	*Li*	*Mg*	*Mn*	*Mo*	*Na*	*Ni*	*Pb*	*Sb*	*Se*	*Sr*	*V*	*Zn*
H	**0.63**	0.10	0.14	**0.80**	0.09	−0.33	**0.44**	−0.34	nd	**0.43**	nd	−0.30	**0.64**	**0.79**	nd	nd	nd	0.11	nd	**0.72**	**0.56**	**0.82**	−0.28	0.21	**0.54**	−0.11	−0.11	−0.15	0.21	**0.76**	−0.03	−0.11
	T	0.13	0.34	**0.42**	0.02	**−0.63**	**0.45**	−0.25	nd	0.24	nd	**−0.59**	**0.56**	0.39	nd	nd	nd	0.20	nd	**0.61**	0.29	**0.65**	−0.40	0.37	**0.55**	−0.04	−0.04	−0.24	−0.01	**0.61**	−0.38	−0.10
		P	0.02	0.03	0.21	−0.06	−0.08	−0.26	nd	−0.03	nd	−0.19	−0.11	0.11	nd	nd	nd	−0.26	nd	−0.04	−0.01	−0.03	−0.15	−0.21	−0.05	−0.07	−0.09	−0.06	0.01	−0.09	−0.13	−0.08
6	*T*	*P*	*pH*	*SEC*	*DOC*	*Ag*	*Al*	*As*	*B*	*Ba*	*Be*	*Bi*	*Ca*	*Cd*	*Co*	*Cr*	*Cu*	*Fe*	*Hg*	*K*	*Li*	*Mg*	*Mn*	*Mo*	*Na*	*Ni*	*Pb*	*Sb*	*Se*	*Sr*	*V*	*Zn*
H	**0.58**	−0.14	**0.64**	**0.37**	**0.65**	**0.69**	0.26	**0.50**	**0.91**	**−0.54**	**−0.42**	−0.19	**0.57**	**0.46**	**−0.60**	**0.60**	**0.79**	**0.59**	**0.73**	**0.91**	**0.88**	**0.84**	**−0.74**	**0.69**	**0.84**	**0.50**	−0.22	−0.17	0.30	**0.86**	−0.26	**−0.38**
	T	0.10	**0.48**	0.26	0.23	**0.38**	0.26	0.12	**0.64**	−0.34	−0.33	−0.24	0.20	0.02	**−0.65**	0.28	**0.40**	**0.45**	**0.40**	**0.62**	**0.69**	**0.53**	**−0.60**	**0.57**	**0.60**	0.21	−0.09	−0.25	0.33	**0.56**	−0.02	−0.35
		P	−0.02	0.06	−0.09	0.01	0.20	−0.21	−0.10	−0.05	0.11	−0.05	−0.09	−0.10	−0.08	−0.19	−0.13	−0.05	0.00	−0.12	−0.11	−0.14	0.01	−0.02	−0.14	−0.10	−0.04	−0.06	0.04	−0.10	−0.13	0.03

Note: Statistical significances ($\alpha < 0.05$) were marked in bold and highlighted in grey. nd - lack of results due to not enough set of data necessary to perform the calculation.

et al., 2002; Dragon & Marciniak, 2010). Given the progressive warming of the Arctic climate and the sensitivity of permafrost catchments of Svalbard to changes in air temperature, it is impossible to ignore the impact of climate change on the hydrochemistry of such catchments. The layer of active permafrost in the study area can reach a thickness of more than 202 cm (Marsz et al., 2013). The study period coincided with the beginning of the ablation season (June/July) with some amounts of snow still accumulated in the depressions of the catchment and the mouth of the creek (Figure S1). The mean air temperature for the 2021 measurement period was the same as recorded at Calypsostranda in 2012 (4.88°C) (Table S2) (Lehmann-Konera et al., 2018) and lower than calculated for the multiannual observations 1986–2011 (5.0°C) (Mędrek et al., 2014) and observed in 2016 (5.0°C) (Lehmann-Konera et al., 2023). In terms of daily precipitation total, the study season 2021 was characterized by the lowest amount of precipitation (10.7 mm) (Figure S2) in comparison with the multiannual observations 1986–2011 (32.4 mm) (Mędrek et al., 2014), measurements noted in 2012 (26.4 mm) (Lehmann-Konera et al., 2018) and 2016 (46.7 mm) (Lehmann-Konera et al., 2023). The results of the correlation matrix (Tables 2 and 3) clearly indicate a strong relationship between an increase in average air temperature (*T*) and a decrease in flow rate (*Q*) in the surface water of the stream and the decrease in groundwater table (Figures S3 and S4). With a decrease in the groundwater level, the amount of water that feeds the surface water of the basin also decreases. Moreover, a thicker active layer contributes to an increase in its ability to store water resources (Lehmann-Konera et al., 2018; Stachniak et al., 2022), promoting a decrease in surface water alimentation, and explaining the lack of impact of precipitation on the hydrology of the catchment (Tables 2 and 3). Like in previous studies, discharge intensity in this catchment (Lehmann-Konera et al., 2018) results in lower *pH* and *SEC* in surface waters.

4.2 | Hydrochemical response of the creek

According to the literature, the key factors shaping water chemistry on Svalbard include dry and wet deposition of pollutants and rock-water interactions (Cooper et al., 2002; Dragon & Marciniak, 2010). It is worth noting that coastal areas, such as the Rensdyrbekken catchment, are strongly influenced by marine aerosols, which may be a source of *Na* as well as other trace elements (Kozioł et al., 2021; Lehmann-Konera et al., 2023; Szumińska et al., 2018). Chemical weathering is largely dependent on temperature (Cooper et al., 2002). Because the *pH* of surface water is neutral-light alkaline (Table 1), immobilization of elements and their strong binding to organic matter can occur (Kozak et al., 2016). Hence, in surface waters, the negative effect of an increase in *Q* on elements such as *Ca*, *K*, *Li*, and *Mg* is usually observed (Table 2), while an increase in *pH* and *SEC* is accompanied by an increased presence of these elements. The lowering of the water table in piezometers may occur during the season of thawing of the active layer, which constitutes a barrier to water runoff and migration of chemical compounds (Szumińska et al., 2023). In the case of shallow groundwater in Rensdyrbekken (Figure S4) where lowering the water table results in increased chemical weathering processes, a positive correlation of *H* with both *pH* and *SEC* is observed (Table 3) which, depending on the geology of the measurement point, usually results in a positive correlation with elements due to reduced leaching of compounds from the active layer.

It is not the only process explaining strong correlations between average air temperature (*T*) and an increase or decrease in element levels in both surface water and groundwater of the catchment (Tables 2 and 3). Additional factors include the phenomenon of biogeochemical "breathing" in soils (Chmiel et al., 2013). The catchment area of Rensdyrbekken is rich in brown soils abundant in organic matter and humus (Klimowicz et al., 2013). The presence of *DOC* in stream water leads to changes in the hydrogeochemical cycle of trace elements through red-ox reactions as well as peptization and sorption processes (Kozak et al., 2016). It explains the negative correlations of *DOC* in surface water with individual elements (Table 2).

4.3 | Catchment geology

Regardless of the meteorological conditions and hydrology of the catchment, the rocks within which the catchment functions will have a decisive influence on the final amount of elements in the water. Figure 5 shows the location of the measurement points in separate geological formations, significantly affecting the water *pH*, *SEC*, and concentrations of individual elements in various locations in the catchment. Therefore, the Bellsund Group formation with daimictite covers point PZR_3, and the Bellsund phyllite PZR_1 and RS. The remaining points lie behind the normal fault on tertiary formations (Birkenmajer, 2006). PZR_5 and 6 and RMC lie within the Calypsostranda Group formation rich in sandstone, siltstone, shale, and coal. By contrast, PZR_2 and 4 and RLT lie within marine deposits. The RM section lies on the border of the Calypsostranda Group and marine deposits.

In studied waters, significant levels of *Ca* and *Mg* (Table 1) may be resulted by considerable share of calcite and dolomite in mineral composition of rocks of Bohlinryggen, to which the upper part of catchment belongs (Chmiel et al., 2009). These compounds were indicated as geologically originated in waters of studied area (Chmiel et al., 2013; Szumińska et al., 2018). The other highly represented rocks derived elements, such as *K*, *Al*, *and Fe*, may be the product of aluminosilicates weathering. Furthermore, *Fe* and *Al* is highly represented in study area (Chmiel et al., 2009) and also relatively easily soluble from moraine deposits (Szopińska et al., 2018). These elements are grouped as the one of main clusters in the river mouth (RM_C2) and selected groundwaters (PZR_1-C2, PZR_4-C1, and P_ZR_6-C1) (Figure 4). In the previous study, also *Sr* (associated with mentioned above clusters in this study) were recognized as the rocks derived element (Szumińska et al., 2018). *Na*, which is as well highly represented in studied waters (Table 1), may be associated with both atmospheric and rocks sources. Furthermore, domination of unconsolidated marine deposits in the lower part of the catchment, supported leaching of

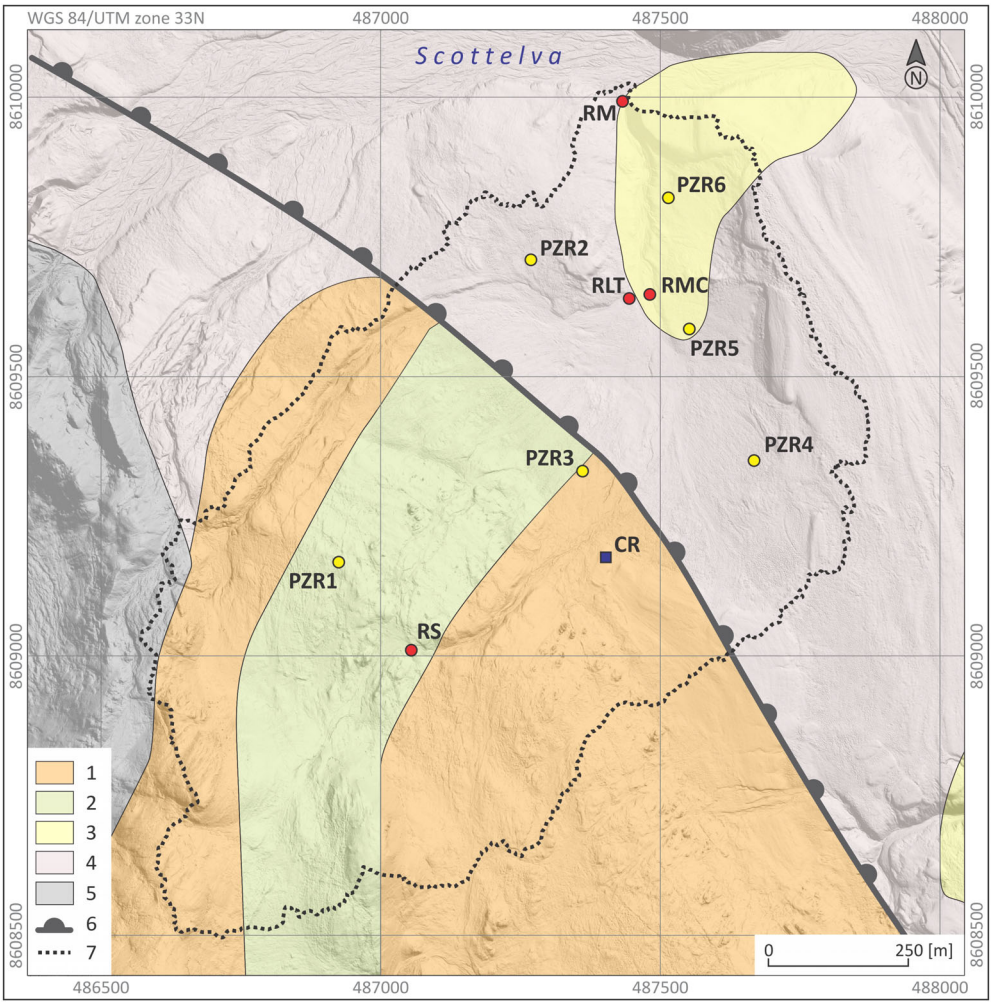

FIGURE 5 Map of geological (*Source*: offline Geological Map of Svalbard, scale 1:75000; NPI 2016): Geological unit: 1. Bellsund Group—undifferentiated (a. lithology: diamictite; b. age period: Cryogenian and/or Ediacaran); 2. Bellsund phyllite unit (a. lithology: phyllitye with clasts; b. age period: Cryogenian and/or Ediacaran); 3. Calypsostranda Group (a. lithology: sandstone, siltstone, shale, coal; b. age period: late Eocene—early Oligocene); 4. marine deposit—unconsolidated (a. lithology: marine deposit; b. age period: Holocene); 5. moraine—unconsolidated (a. lithology: moraine; b. age period: Holocene); 6. normal fault; 7. catchment border. [Colour figure can be viewed at wileyonlinelibrary.com]

elements during active layer thawing and resulted relatively high ∑TE (Figure 3). Extremely high values of ∑TE, *Ca*, *K*, *Li*, *Mg*, and *Na* in PZR_6 coupled with the high *DOC* level may be the result of the occurrence of silt stones, sandstones, shales, and coal in this site (Figures 4 and 5).

In studied catchment geological conditions, soils features (depth, moisture, grain-size matrix) and changing depth of water level influence potential leaching of elements into water. At the beginning of studied period, the water depth in piezometers not exceed 10 cm b.g.l. and increased until the end of July to 60–80 cm b.g.l. in the mot sites excluding PZR_3, where not exceed 30 cm b.g.l. (Figure S4). Therefore, share of atmospheric compounds (dry and wet deposition) vs geological derived compounds could change during progressive seasonal permafrost thawing.

5 | CONCLUSIONS

Interdisciplinary studies of the permafrost catchment of the west coast of Bellsund have shown a strong influence of an increase in mean air temperature on the hydrological and geochemical processes shaping the chemistry of both surface water and groundwater functioning within the study catchment. Compared with previous research seasons, the mean air temperature recorded on Calypsostranda in 2021 did not differ significantly. The situation was different in the case of the total daily precipitation. The 2021 study season was significantly drier in comparison with the previous ones in 2012 and 2016, which resulted in reduced leaching of *DOC* and elements from the well-developed drainage system in the soil formations of the Rensdyrbekken catchment. In the context of the ongoing climate change and an increase in average air temperature, a significant decrease in the level of the groundwater table of the coast of eastern Svalbard can be expected. In the worst-case scenario, it could result in the disappearance of watercourses fed by the thawing of the permafrost in these areas. Large-scale hydrogeochemical studies have shown great variations between the elemental composition of surface water and shallow groundwater on Svalbard even between measurement points within the same geological formations. This study also confirmed the dominant role of rock-water interaction processes as an important aspect in shaping water chemistry in permafrost catchments of the west coast of Svalbard.

AUTHOR CONTRIBUTIONS

S.L.K. involved in conceptualization; S.L.K. and Ż.P. involved in methodology; P.Z., M.F. and Ł.F., M.D. involved in validation; P.Z., K.R., and R.A. involved in formal analysis; S.L.K., P.Z., M.F., Ł.F.,

and K.N. involved in investigation; S.L.K., P.Z., M.F., and Ż.P. involved in resources; S.L.K., P.Z., K.R., and M.F. involved in data curation; S.L.K., P.Z., Ł.F., K.R., M.D., and D.S. involved in writing—original draft preparation; S.L.K., M.R., R.B., P.Z., K.R., D.S., and Ż.P. involved in writing—review and editing; S.L.K, P.Z., Ł.F., K.R., R.B., M.R., and. Ż.P. involved in visualization; S.L.K. and Ż.P. involved in supervision; S.L.K. involved in project administration; S.L.K. involved in funding acquisition; all authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

There is no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

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