Hydrodynamics and hydrogeochemistry of Werenskiold Glacier forefield, SW Spitsbergen

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Abstract: In the 2008 ablation season, subglacial springs discharge, flow rate and profiling of the proglacial river, physical-chemical parameters (pH, temperature, electrical conductivity) and chemical composition (HCO_3^-, SO_4^{2-}, Cl^-, NO_3^-, NO_2^-, PO_4^{3-}, Ca^{2+}, Mg^{2+}, Na^+, K^+, Fe_{tot}, Mn^{2+}, Al^{3+}, Zn^{2+}, Pb^{2+} and SiO_2) of water in the Werenskiold Glacier forefield were measured. Chemical composition of groundwater as well as water of lakes, the main watercourse, subglacial outflows and water representing direct meltwater recharge were studied to determine their origin, the depth of circulation and recharge systems. The results indicate that the main source of water in the glacial river were the subglacial outflows in the central part of the glacier. They generated 77% of the total amount of water in the glacier forefield. Direct inflow of groundwater from glacier moraine to proglacial river was marginally low and the water circulation system was shallow, fast and variable. There were no evidences for an important role of deeper than suprapermafrost water circulation systems. The water temperature, especially in the lakes, exceeding the mean daily air temperature during the ablation period, is due to the heating of the ground moraine rocks. A clear difference between groundwater chemical composition and surface water as well as subglacial runoff in terms of major ions, together with the homogeneity of chemical composition of the proglacial river from spring to mouth confirmed the marginal role of groundwater runoff in the drainage of the catchment area. It was confirmed that the chemical composition of groundwater and moraine lakes in the glacier forefield was shaped by geological factors, *i.e.*, mainly chemical weathering of sulphides, carbonates and secondary sulphates. The possibility of secondary iron hydroxide precipitation and a high probability of complex aluminosilicate transformations were also demonstrated.

Keywords: Arctic, Svalbard, groundwater, surface water, runoff, temperature, chemical composition.

Introduction

The formation of water runoff of glacier's forefields, both Arctic and mountainous, is an important issue, especially in the time of the climate change and the increasing human impact (Kozak *et al.* 2016; Kaushik *et al.* 2021; Ruman *et al.* 2021; Sjöberg *et al.* 2021). The distribution of chemical components (macro and microelements) and the water dynamics in glacier forefields is a derivative of both the water cycle in cold regions and the chemical cycles of elements in this environment, *e.g.*, carbon, sulfur, heavy metals or nutrients (Anderson *et al.* 2001; Szynkiewicz *et al.* 2013; Singh *et al.* 2015; Kozak *et al.* 2016; Auqué *et al.* 2019; Stachnik *et al.* 2019, 2022). These processes are still little understood, but studies indicate high hydrodynamic and hydrochemical dynamics in the glacier forefield, resulting from local factors, *e.g.*, geological conditions, denivelations and the influence of human activity. Nevertheless, even in such a dynamic environment, researchers noted certain patterns regarding the significant role of surface and subglacial runoff and the sequence of chemical weathering of moraine sediments, *i.e.*, sulphide oxidation, carbonate weathering, formation of secondary phases and weathering of secondary phases, in the distribution of elements from proglacial catchments (Cooper *et al.* 2002; Auqué *et al.* 2019). However, the role of groundwater is only marginally taken into account in the interpretation of these processes (Stotler *et al.* 2009; Kristiansen *et al.* 2013; Auqué *et al.* 2019; Vincent *et al.* 2019; Sjöberg *et al.* 2021).

The main objective of the presented research was to demonstrate the role of groundwater in the formation of outflow from the catchment in the polar environment and its influence on waters hydrogeochemistry on the example of the forefield of the Werenskiold Glacier in SW Spitsbergen. This Arctic glacier has well-recognized natural conditions, so it is an excellent area for groundwater research. It will allow to expand the Arctic database by adding the results of measurements of hydrodynamics and hydrogeochemistry of its forefield water.

Since the very beginning of the Baranowski Polar Station in the Werenskiold Glacier forefield, hydrological research focused on hydrodynamic and hydro-chemical issues has been carried out. The research has so far allowed to examine the evolution of the river network, the hydrological structure, the amount and chemical composition of precipitation, the duration of the ablation period, the water balance of the catchment area and to identify processes forming the chemical composition of water running off the glacier (Baranowski and Głowicki 1975; Pereyma *et al.* 1975; Kosiba 1982; Pulina *et al*. 1984; Krawczyk 1992; Wachniew *et al.* 2008; Staśko *et al.* 2008; Szynkiewicz *et al.* 2013, 2020; Majchrowska *et al.* 2015; Stachnik *et al.* 2016, 2019).

Archival information was used for designing research of the dynamics and chemistry of the Werenskiold Glacier forefield water in the 2008 ablation season. The analysis of subglacial springs' discharge, flow rate in the proglacial river,

physical-chemical parameters and chemical composition of water in the glacier forefield was aimed mainly at determining the origins of water in the glacier forefield, the depth of circulation and recharge systems. It was based on the first-ever studies of groundwater, *i.e.*, shallow or permafrost-related groundwater sampling in piezometers, in the ground moraine sediments and on profiling, including electrical conductivity (EC), temperature and pH of water in the proglacial river from spring to mouth. The results of the analyses of pH, SO_4^{2-}, HCO_3^-, Ca^{2+}, Mg^{2+} from the 2008 ablation season were used for describing the polar sulphur cycle (Szynkiewicz *et al.* 2013).

Study area

The study area of 4.2 km^2 consists of the forefield of Werenskiold Glacier (SW Spitsbergen) from the glacier front, currently situated at the altitude 60–100 m a.s.l., to the terminal moraine and the gorge of the Breelva proglacial river (Fig. 1A). The EEN-WWS oriented glacier itself occupies a 44.1 km^2 basin (Jania 1988) and its firn fields are located *ca.* 650 m a.s.l. (Hagen *et al.* 1993). It is a polythermal glacier, frozen to the bedrock 0.7–1.0 km upstream from its terminus (Misztal and Pulina 1983; Pälli *et al.* 2003), formed by two main ice streams separated by an ice-cored medial moraine (Szponar 1975).

The average air temperature, based on regular climate research conducted in the area since 1979, is at –2.1 °C, with average monthly temperatures varying from –11.5°C in February to +4.4°C in July. The total annual precipitation averages 442 mm, with extreme values of 230 mm in 1987 and 635 mm in 1996. Permanent snow cover usually forms in the second half of September and lasts until the first decade of June (Kwaczyński 2003; Przybylak and Araźny 2006). On average, 246 days with precipitation are recorded per year. Rain, snow or sleet may occur in any month, with rain predominating from May to August. In 2008, the precipitation amounted to 245 mm. This season was characterised by the occurrence of heavy rains, which resulted in rapid increases in spring discharge and surges of water in watercourses (Łepkowska and Stachnik 2018). During the measurement period of July and mid-August, precipitation reached 70 mm with an average daily temperature of 4.1°C (Fig. 2), while the hydrological regime in the Werenskiold Glacier catchment was classified by Majchrowska *et al.* (2015) as a mixed type (ablation-precipitation).

Førland e*t al*. (2011) proved that in 1989–2011, the annual temperature at the different stations in the Svalbard region has increased by 1.0–1.2°C per decade. All the long term precipitation series from the Svalbard region indicate an increase in annual precipitation *ca.* 2–4% per decade. These climatic conditions result in negative water balance and gradual glacier retreat at a rate from 9 m per year, based on a short-period measurements (Jania 1988), to 15 m/year in 1974–1979 and 30 m/year in 1936–1974 (Chmal and Sobik 1988).
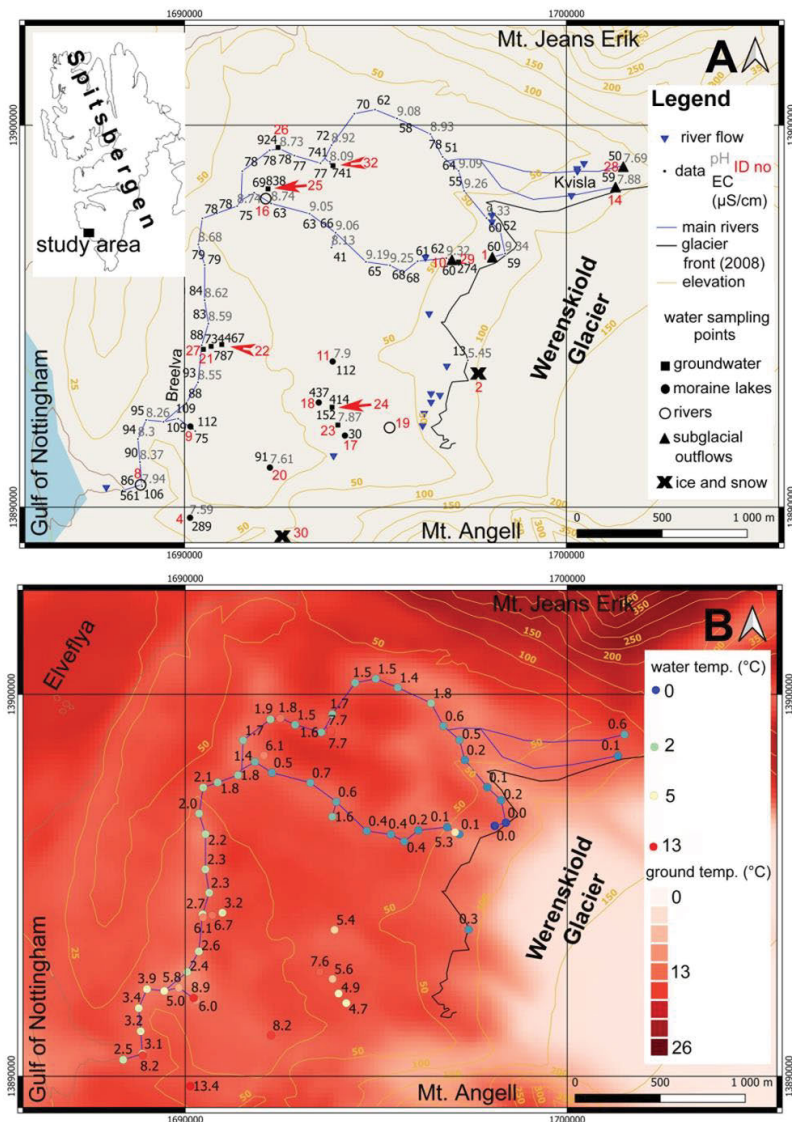
Fig. 1. Study area with the sampling points and results of pH and electrical conductivity measurements (**A**) and results of water temperature measurements on the satellite image of land surface temperature Landsat 8 (band 10), 4th Aug 2020, 11:40 a.m (**B**).

The bedrock of Wernskiold Land is comprised of Precambrian metasediments and metavolcanic rocks, *e.g.*, quartzite, marbles, paragneisses, amphibolites and crystalline schist, belonging to the Hecla Hoek Supergroup, with a thickness reaching 15–17 km (Birkenmajer 1990). The southern part of the glacier is underlain mainly by amphibolites, migmatites and quartzites belonging to the Skalfhellet Group, while the central and eastern parts are dominated by quartzite schists and conglomerates, and secondarily by marbles, limestones and dolomites
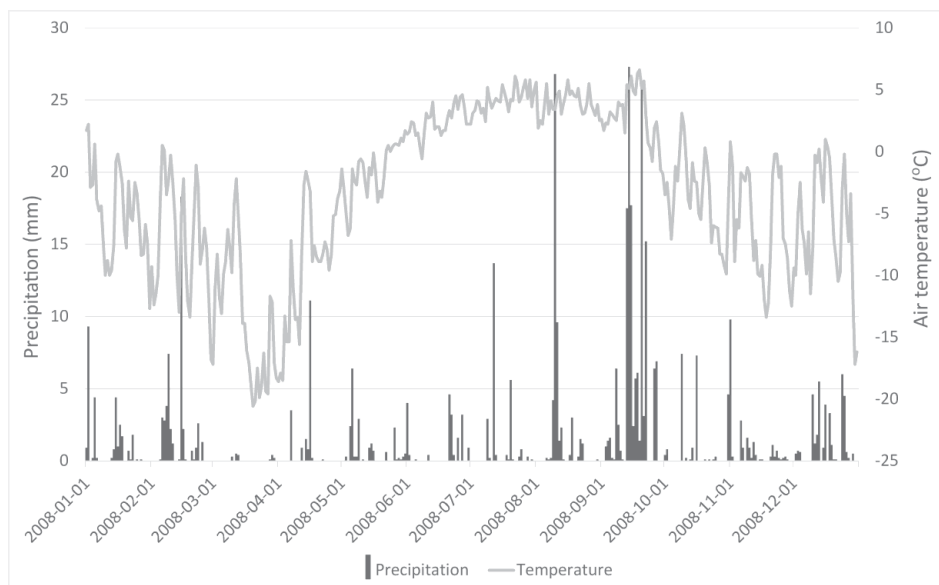
Fig. 2. Precipitation and daily average air temperature in 2008, modified after Wawrzyniak and Osuch (2020).

belonging to the Deilegga Group. In the northern part of the glacier front zone, greenschists have been mapped, and in the central and southern part, quartzite schists and marbles (Czerny *et al.* 1993).

The youngest Quaternary sediments related mostly to the glacial and fluvioglacial water activity are mainly represented by unconsolidated moraine, fluvial, beach and scree deposits. The greatest thickness of these sediments is noted in the marginal zone of the glacier. Tectonic phenomena in the area had been common since the Precambrian times and had led to the formation of a large number of long-range fault lines and discontinuities. The main dislocation zone Vimsodden-Kosibapasset, WNW-ESE oriented, divides the glacier basin into two parts. Tectonic fractures have a major impact on groundwater circulation in the Hornsund area and they are important conduits for groundwater in areas under multiannual permafrost and thermal water locally ascending from deep circulation (Olichwer *et al.* 2013). Sulphide mineralisation is manifested by a presence of pyrite, chalcopyrite, pyrotite, markasite, sphalerite and galena, as massive ores and disseminations in quartz-carbonate veins. These veins, which can reach two meters in width and several hundred meters in length (Kieres and Piętrzyński 1992) are the result of metamorphic processes that acted upon primary pyrite-rich polymetallic sedimentary exhalative mineralization within Precambrian basic and acidic volcanic rocks (Czerny *et al.* 1993).

Archive studies indicate that the water of the Werenskiold Glacier forefield consist mainly of subglacial periodical streams, which frequently outflow before the glacier front and which collect meltwater from englacial and subglacial channels (Pulina *et al.* 1999; Wachniew *et al.* 2008). In turn, the surface water are

a complex network of interconnected ephemeral springs, lakes and flood plains. The water from deeper circulation systems, so-called taliks, come from within the permafrost and are drained by rivers and lakes. The probability of taliks occurrence in the Brelva catchment were indicated by water temperature in lakes of the Werenskiold Glacier forefield, reaching 14.1°C in 2004–2007 (Staśko *et al.* 2008), indicating that permafrost degradation can be expected at low elevations, *e.g.*, close to the coast below *ca.* 100 m a.s.l. in well-drained and dry sites, where taliks likely can develop (Etzelmüller *et al.* 2011). Water temperature in lakes on the Werenskiold Glacier forefield (Staśko *et al.* 2008) significantly exceeded not only the average annual air temperature but also the average temperature of the ablation season.

The main directions of subglacial water inflow, which change over time, are also debatable. They indicated that the main runoff from Werenskiold Glacier is located in the southern part of the glacier as the subglacial outflow called Kvisla. Minor inflows were mapped on the southern side of the medial moraine, *i.e.*, the Duszan, Wiesława and Wrocławski springs (Ignatiuk 2012; Piechota *et al.* 2012). A numerical model (Piechota *et al.* 2012) based on research conducted in 2009–2011 demonstrated that 98% of the sublacial water recharge rivers in the glacier forefield, 65% of which constitute the Kvisla's drainage in the N part of the glacier, with only 35% being drained by rivers recharged from the central and S part of the glacier. The remaining 2% are the water flowing into the sea. Subglacial runoffs in the northern part drain the water from the Skillygg and Slyngfield glaciers, as well as from the NE part of Werenskiold Glacier. The subglacial outflow of the southern part drains the Angellfjellet area, the S part of Werenskiold Glacier and Angellisen Glacier.

According to Piechota *et al.* (2012), the third and least resourceful area is the central part of the glacier, the SW margin of the medial moraine, drained by the Duszan and Wiesława springs. These springs only drain water from the central part of the glacier front, with their flow routes being definitely shorter and more dispersed. However, Pulina and Rehak (1991) indicated long flow routes in this area from the Angellisen basin. In turn, the research on the chemical composition of water in the study area focused on ablation and subglacial water (Krawczyk 1992; Stachnik *et al.* 2016, 2019) as well as on hydrogeochemical processes occurring in moraine deposits (Szynkiewicz *et al.* 2013, 2020; Kwaśniak-Kominek *et al.* 2016; Stachnik *et al.* 2019). It showed complex hydrogeochemical processes forming the chemical composition of the water in the Werenskiold Glacier forefield, including the weathering of sulphides as well as the precipitation and repeated chemical weathering of secondary mineral phases such as sulphates. Nevertheless, only the study by Szynkiewicz *et al.* (2013) has so far presented more comprehensive results of research on groundwater.

In 2004 and 2005, the hydrological cycle on Spitsbergen was active for *ca.* 120 days in June to September (Głowacki 2007). During the summer months,

a number of studies were carried out that have allowed for a relatively good understanding of surface and groundwater drainage in polar conditions, including directly in the Werenskiold Glacier basin. Groundwater in polar areas is associated with three zones (Williams and van Everdingen 1973). The shallowest and most common zone is above the permafrost (suprapermafrost). Below, there is the permafrost (intrapermafrost), while the deepest zone is under the permanent permafrost (subpermafrost). Within the study area of the Werenskiold Glacier forefield, the main source of water is the water associated with the shallowest water circulation zone (suprapermafrost). Groundwater flow starts in the 1–1.5 m-thick active layer thawing in early summer (Głowacki 2007) and derives from the melting glacier, multiannual permafrost and precipitation. Some of the water appearing in the glacier forefield may also originate inside the permafrost and might be drained in the zones of unfrozen ground (taliks), such as rivers or lakes (Van Everdingen 1990; Olichwer and Tarka 2018).

Runoff from the Werenskiold Glacier catchment area shows a marked hydrological contrast between the ablation season and the winter half of the hydrological year (Pulina *et al.* 1984). The conducted research (Førland *et al.* 2011; Nowak and Hodson 2013; Majchrowska *et al.* 2015) clearly demonstrate that the main contribution to the total runoff from the catchment area in this archipelago is the melting of snow and ice, and long-term observations indicate a gradual increase in the contribution of rainwater to the river runoff and increasing importance of shoulder seasons and winter rainfall as a result of climate change.

Methods

Measurements of groundwater and surface water in the Werenskiold Glacier forefield were carried out from July 22 to August 12, 2008. The studies included groundwater and surface water sampling, as well as measurement of the basic physical and chemical parameters of water (temperature, pH, EC). Water sampling points were divided into 5 types: (1) groundwater - water from shallow piezometers drilled with an Ejkelkamp manual drill ⌀70 in ground moraine sediments of the glacier (8 points, sample IDs 21, 22, 23, 24, 25, 26, 27 and 29) and one natural outflow (1 point, sample ID 32); (2) surface water - water of lakes located on ground and terminal moraine of the glacier (6 points, sample IDs 4, 9, 11, 17, 18 and 20); (3) surface water - water of the main watercourse and its inflow (4 points, sample IDs 8, 15, 16 and 19); (4) water of subglacial outflows recharging watercourses and the glacier forefield (4 points, sample IDs 1 - Duszan, 10 - Wiesława, 14 and 28 - outflows to Kvisla); (5) water representing direct meltwater recharge from the glacier's ablation channel and snow (2 points, sample IDs 2 and 30) (Fig. 1A and Tables 1, 2). Physio-chemical parameters (temperature, pH and EC) of water were measured directly in the field with an

Table 1.

Physico-chemical parameters and chemical composition with charge balance errors (CBE) of groundwater, surface water, snow and ice sampled in 2008 in the Werenskiold Glacier forefield.

Group	ID	Date	Temp [°C]	EC [µS/cm]	pH	Ca^{+2} [mg/L]	Mg^{+2} [mg/L]	HCO_3^- [mg/L]	Na^+ [mg/L]	K^+ [mg/L]	SO_4^{-2} [mg/L]	CBE [%]
Groundwater – piezeometers and groundwater outflow	21	31.07.2008	6.70	787	7.71	92.70	74.06	351.0	10.68	5.06	220.70	4.29
	22	31.07.2008	3.20	467	7.56	89.80	71.20	320.0	8.82	4.20	209.90	2.34
	23	02.08.2008	4.90	152	7.87	12.62	8.78	68.0	9.12	3.45	21.90	2.83
	24	02.08.2008	5.60	414	7.92	24.40	22.62	123.0	19.00	5.62	75.40	2.83
	25	04.08.2008	6.10	838	7.37	70.40	50.30	357.0	50.30	5.01	166.70	0.45
	26	04.08.2008	6.70	924	7.50	76.40	62.70	299.0	3.49	4.72	197.10	1.37
	27	04.08.2008	6.10	734	7.53	64.30	34.30	213.0	5.33	5.03	133.40	0.22
	29	11.08.2008	5.31	274	7.49	42.30	19.10	162.0	2.87	2.82	46.90	0.70
	32	12.08.2008	7.70	741	7.7	58.30	38.80	202.0	5.35	3.32	117.20	2.24
Surface water – moraine lakes	4	23.07.2008	13.40	289	7.59	27.20	20.90	78.0	9.24	3.24	91.80	1.20
	9	24.07.2008	8.90	75	7.39	7.93	3.24	36.0	4.18	1.22	16.40	9.04
	11	25.07.2008	5.40	112	7.90	14.30	12.00	55.0	5.32	1.36	46.30	0.60
	17	29.07.2008	4.70	30	6.76	3.45	1.87	8.3	2.40	0.45	11.50	2.62
Surface water – rivers	18	30.07.2008	7.60	437	7.87	34.60	48.80	211.0	20.15	5.80	114.60	3.41
	20	31.07.2008	8.20	91	7.61	8.29	3.32	32.5	4.11	1.32	15.30	4.29
	8	24.07.2008	2.70	93	8.67	11.07	3.92	37.0	5.50	0.91	16.70	1.96
	15	28.07.2008	1.90	77	8.98	14.81	3.29	59.4	3.82	0.71	12.80	5.91
	16	28.07.2008	2.50	73	9.00	14.25	3.33	52.4	3.85	0.74	12.20	1.12
	19	31.07.2008	3.20	102	8.12	11.52	4.53	45.3	4.60	0.79	17.40	2.11
Subglacial outflows	1	22.07.2008	0.00	84	8.95	17.65	3.53	52.0	7.56	1.04	24.20	4.47
	10	22.07.2008	0.00	86	9.06	8.43	3.71	35.0	5.52	0.78	12.60	1.35
	14	28.07.2008	0.10	59	7.88	9.82	1.88	19.0	1.27	0.21	13.80	1.21
	28	06.08.2008	0.60	50	7.69	3.68	1.51	15.5	1.27	0.16	2.20	2.46
Ice and snow	2	22.07.2008	0.30	13	5.45	0.30	0.33	3.00	0.12	1.5	4.20	4.18
	30	11.08.2008	0.00	18	5.49	1.57	0.58	0.99	1.13	7.5	0.50	2.14

Table 2.

Physico-chemical parameters and chemical composition of groundwater, surface water, snow and ice sampled in 2008 in the Werenskiold Glacier forefield.

	ID	Date	Cl^- [mg/L]	NO_3^- [mg/L]	NO_2^- [mg/L]	PO_4^{-3} [mg/L]	SiO_2 [mg/L]	Al^{+3} [mg/L]	Fe_{tot} [mg/L]	Mn^{+2} [mg/L]	Zn^{+2} [mg/L]	Pb^{+2} [mg/L]
Groundwater – piezometers and groundwater outflow	21	31.07.2008	15.0	<0.50	<0.020	0.05	0.85	0.0050	0.022	0.0001	0.0830	0.00060
	22	31.07.2008	12.9	<0.50	<0.020	0.05	0.82	0.0150	0.040	0.0012	0.0710	0.00014
	23	02.08.2008	12.3	<0.50	<0.020	0.08	0.61	0.0380	0.046	0.0023	0.0075	0.00011
	24	02.08.2008	14.1	<0.50	<0.020	0.04	0.6	0.0120	0.024	0.0330	0.0330	0.00059
	25	04.08.2008	12.5	<0.50	<0.020	0.04	0.78	0.0038	0.016	0.0230	0.0670	0.00010
	26	04.08.2008	9.2	<0.50	<0.020	0.04	0.63	0.0047	0.017	0.0005	0.0830	0.00007
	27	04.08.2008	15.7	<0.50	<0.020	0.04	0.65	0.0050	0.017	0.0220	0.0550	0.00007
	29	11.08.2008	9.9	<0.50	<0.020	0.04	0.47	0.0100	0.024	0.0079	0.0150	0.00006
	32	12.08.2008	12.9	<0.50	<0.020	0.03	0.48	0.0030	0.013	0.0250	0.0520	0.00006
Surface water – moraine lakes	4	23.07.2008	15.2	<0.50	<0.020	0.06	0.17	0.0120	0.024	0.0013	0.0290	0.00021
	9	24.07.2008	3.2	<0.50	<0.020	0.06	0.25	0.0410	0.062	0.0088	0.0049	0.00019
	11	25.07.2008	3.3	<0.50	0.030	0.06	0.26	0.0100	0.027	0.0071	0.0140	0.00012
	17	29.07.2008	2.2	<0.50	0.040	0.05	0.17	0.0110	0.023	0.0037	0.0032	0.00007
Surface water – rivers	18	30.07.2008	15.9	<0.50	0.040	0.06	0.22	0.0100	0.056	0.0017	0.0410	0.00009
	20	31.07.2008	3.7	<0.50	<0.020	0.06	0.26	0.0370	0.052	0.0062	0.0073	0.00030
	8	24.07.2008	7.0	<0.50	<0.020	0.05	0.32	0.0620	0.052	0.016	0.0190	0.00071
	15	28.07.2008	2.8	<0.50	<0.020	0.05	0.3	0.0081	0.028	0.0830	0.0036	0.00008
	16	28.07.2008	2.1	<0.50	0.030	0.05	0.28	0.0052	0.025	0.0840	0.0047	0.00010
	19	31.07.2008	3.1	<0.50	0.040	0.05	0.33	0.0270	0.034	0.0166	0.0055	0.00008
Subglacial outflows	1	22.07.2008	10.9	<0.50	<0.020	0.15	0.41	0.1600	0.193	0.105	0.0150	0.00066
	10	22.07.2008	3.5	<0.50	<0.020	0.05	0.33	0.0640	0.061	0.0058	0.0041	0.00023
	14	28.07.2008	2.3	<0.50	0.030	0.05	0.49	0.0350	0.049	0.0220	0.0055	0.00025
	28	06.08.2008	2.1	<0.50	<0.020	0.03	0.14	0.0049	0.013	0.0056	0.0021	0.00004
Ice and snow	2	22.07.2008	1.7	0.50	0.020	0.06	0.11	0.0074	0.028	0.0024	0.0034	0.00018
	30	11.08.2008	1.7	0.50	0.020	0.05	0.24	0.0110	0.037	0.0029	0.0098	0.00049

Elmetron CX-410 multi-parameter meter. The precision of measurements was 0.1°C, 0.01 and 0.01 mS/cm, respectively. Water was collected into polyethylene bottles after filtration through the 0.45 mm pore-sized PTFE filters. The samples for metal analyses were fixed in the field using 10% pure (for ICP-OES) HNO_3. Analyses of HCO_3^- ion as general alkalinity were also carried out in the field. A 100 mL water sample was titrated using 0.05 M HCl in the presence of methyl orange. The alkalinity, in meq units, was calculated as the gram-equivalent of HCO_3^- and the precision was better than ±1 mg/L. Chemical analyses of the other components were performed directly after their transport to Poland. Concentrations of SO_4^{2-}, Cl^-, NO_3^-, NO_2^-, PO_4^{3-} Ca^{2+}, Mg^{2+}, Na^+ and K^+ were measured using an Alliance Waters HPLC with borate/glauconate and HNO_3/EDTA eluents and IC-Pak Anion and IC-Pak Cation M/D columns with detection limits 0.05 mg/L for NO_3^-, 0.02 mg/L for NO_2^- and 0.01 mg/L for the remaining ions. Analyses of Fe_{tot}, Mn^{2+}, Al^{3+} and SiO_2 concentrations were made using HACH DR/2010 Spectrophotometer (analytical precision: 0.006 mg/L for Fe_{tot}, 0.0049 mg/L for Mn^{2+}, 0.016 mg/L for Al^{3+}, 0.0067 mg/L for SiO_2; measurement range: 0.000–1.300 mg/L for Fe_{tot} , 0.000–0.700 mg/L for Mn^{2+}, 0.000–0.800 mg/L for Al^{3+} and 0.000–1.600 mg/L for SiO_2). Analyses of Zn^{2+} and Pb^{2+} concentrations were completed with ICP OES (measurement range: 0.0001–100 mg/L, LOD: 0.0001 mg/L, LOQ 0.0003 mg/L). The quality of analysis was determined by charge balance errors presented in Table 1.

In addition, on August 6 of 2008, a single hydrological investigation was carried out, including velocity-area flow measurement, using a SEBA Hydrometrie Universal Current Meter F1 (20 mm) and volumetric measurements of subglacial outflows in the glacier forefield, inflows from ablation channels and flow rate measurements at the proglacial river mouth. This was done in order to determine whether the proglacial river is of infiltrating or draining nature and to establish the size of direct inflow occurring from spring to river mouth. On August 12 of 2008, watercourse profiling was carried out, aimed at mapping possible zones of direct inflow. The profiling included temperature, pH and EC measurements from spring to mouth (Fig. 1A). Calculations of saturation indices for selected mineral phases were performed using Phreeqc Interactive 3.7.3 programme, with the phreeqc thermodynamic base.

Results

Hydrological mapping. — In the Wereskiold glacier forefield, 15 subglacial outflows (springs) or inflows from glacier ablation channels were mapped (Fig. 1A). Discharge of particular measurement points ranged from 0.004 m^3/s to 2.115 m^3/s. The highest discharge was noted in the Duszan spring (ID 1). The discharge of slightly under half that value (0.981 m^3/s) was measured in the Wiesława spring (ID 10). In turn, the two main outflows, forming the Kvisla

river, provided 0.582 (ID 14) and 0.485 m^3/s (ID 28), respectively. The total inflow of water from the glacier front and subglacial zones was at 5.32 m^3/s, while the runoff from the catchment area of the glacier, measured at the mouth of the proglacial river was at 5.29 m^3/s. Considering three privileged flow zones (northern, southern and central) designated in previous studies (Ignatiuk 2012; Piechota *et al*. 2012), water drained in these zones amounted 1.234 m^3/s (4 points), 0.353 m^3/s (7 points) and 3.734 (4 points), respectively.

88% of water temperatures recorded in the proglacial river were in the range 0–3°C, reaching max. 3.9°C at points of limnic water inflow. The lowest temperatures were recorded in the subglacial outflows of Duszan (0°C) and Wiesława (0.1°C) (IDs 1 and 10). Similar values were recorded in the springs of Kvisla (0.1°C in the spring and 0.6°C in the outflow from a glacier cave; IDs 14 and 28). The temperature in the inflow from the ablation channel was 0.3°C and in the spring flowing out of the ground moraine sediments 7.7°C (ID 32). The values (4.7–8.9°C) were recorded in flow-through lakes (IDs 9, 11, 17, 18 and 20), while in the endorheic lake (ID 4), the water temperature was 13.4°C. At the mouth of the proglacial river, the water temperature was 2.5°C and in piezometers in the glacier forefield the water temperatures ranged from 3.2 to 6.7°C (Fig. 1B).

The lowest values of EC of water, except for the ablation inflow (13 µS/cm), were recorded in the water of subglacial outflows, *i.e.*, 50 µS/cm (Kvisla IDs 14 and 28) and 60 µS/cm (Duszan ID 1, Wiesława ID 10). In the subglacial outflows themselves, depending on the measurement date, the conductivity varied from 50 to 86 µS/cm (Kvisla) and from 60 to 84 µS/cm (Duszan ID 1). Higher conductivity values were found in flow-through lakes (30–289 µS/cm) and endorheic lakes (473 µS/cm). The highest EC value was recorded in water staying in the longest contact with ground moraine sediments, *i.e.*, in a spring from moraine sediments (741 µS/cm) and in piezometers of the glacier forefield (152–787 µS/cm). At the mouth of the proglacial river, a value of 86 µS/cm was recorded (Fig. 1A, Table 1).

Chemical composition of groundwater and surface water. — Chemical analyses of groundwater and surface water of the Werenskiold Glacier forefield demonstrated that the distribution of the main ions are fairly homogeneous (Fig. 3). In the studied period, groundwater represented mainly the Mg-Ca-HCO$_3$-SO$_4$ type. Ca-Mg-HCO$_3$-SO$_4$ type was characteristic of water from 2 piezometers (IDs 27 and 29). The same two types of water, Mg-Ca-HCO$_3$-SO$_4$ and Ca-Mg-HCO$_3$-SO$_4$, were characteristic of water sampled from moraine lakes. Watercourses represented exclusively the Ca-Mg-HCO$_3$-SO$_4$ type. Water of direct recharge, in turn, showed a significantly higher proportion of components characteristic for precipitation water – melted ice from the ablation channel (HCO$_3$-Cl-Ca-Mg-Na type) and snow (Na-SO$_4$-Cl type).

Despite the similarity between the types, chemical composition of the studied water showed a considerable diversity of physio-chemical parameters and
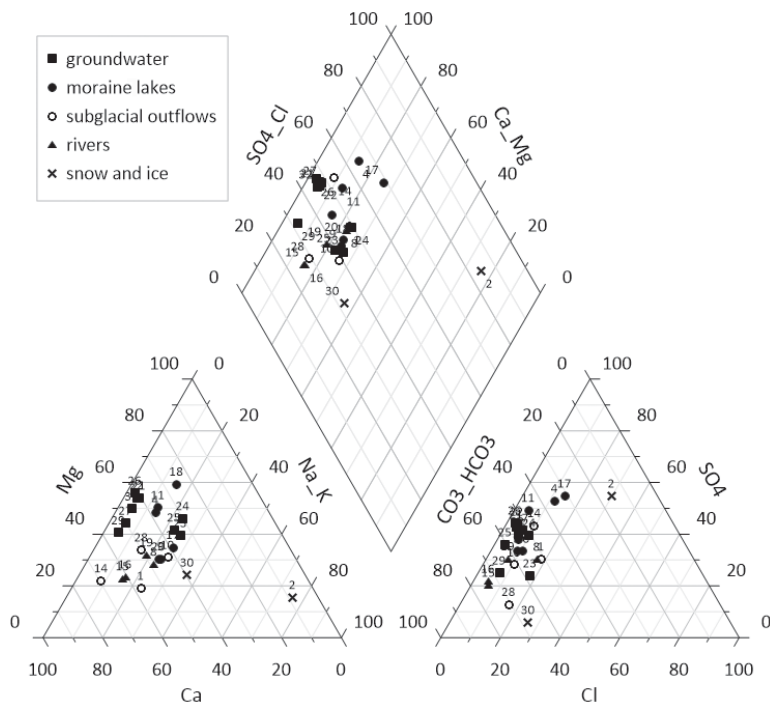
Fig. 3. Hydrochemical types of water sampled in the Werenskiold Glacier forefield in 2008.

concentrations of predominant chemical indicators, depending on a sampling location (Table 2, Fig. 4 and 5). Also within designated water groups, *i.e.*, groundwater, moraine lakes, watercourses or subglacial outflows, a great diversity of the main components was observed (Figs. 4 and 5). Groundwater were of the highest general mineralisation (EC median value 441 µS/cm), with weakly alkaline pH (median value 7.79) and the highest concentrations of the major ions: HCO_3^-, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, Na^+, K^+. During the research period, the groundwater temperature averaged 5.25°C. Water of moraine lakes showed much lower general mineralisation (median EC 441 µS/cm) but similar pH (median 7.49) and the highest temperature (median 7.15°C). Proportionally to EC, lower concentrations of the major ions were observed in these water. Watercourses and subglacial outflows showed similar mineralisation (EC not exceeding 100 µS/cm) and correspondingly lower concentrations of the major ions. These water were characterised by a high, alkaline pH (medians 8.83 and 8.42, respectively) and temperatures *ca.* 0°C for subglacial outflows, usually reaching 3°C in watercourses. Much more limited diversity of the studied water was observed for the subordinate ions. Despite certain differences (Table 2, Figs. 6 and 7), the water generally showed low concentrations of Fe_{tot}, Mn^{2+}, PO_4^{3-}, Pb^{2+} and no mineral forms of nitrogen NO_3^- and NO_2^-. Notably highest concentrations of Zn^{2+} were observed in groundwater. Concentrations of dissolved silica were also very low (<1 mg/L), although they were the highest in groundwater.
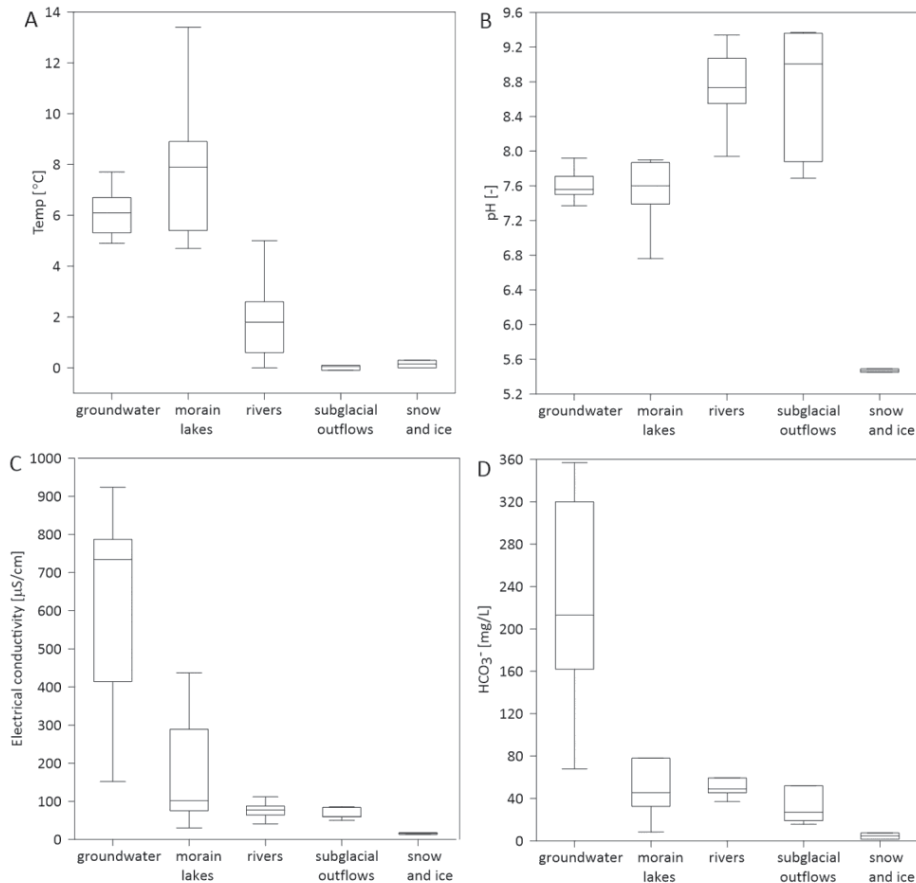
Fig. 4. Statistical differentiation of temperature (**A**), pH (**B**), electrical conductivity (**C**) and concentration of HCO_3^- ions (**D**), showing minimal, maximal, median values as well as 25 and 75 percentiles of selected water types sampled in the Werenskiold Glacier forefield in 2008.

Discussion

Origin of water running from the glacier. — Hydrological measurements carried out on August 6, 2008 showed lack of groundwater inflow to the proglacial river in the area of ground and terminal moraines of Werenskiold Glacier. The amount of runoff water (5.29 m³/s) does not differ from water inflow at the front of the glacier in form of subglacial outflows, ablation channels and periodic springs flowing out of ground moraine sediments (5.32 m³/s). These results are consistent with those obtained by Cooper *et al.* (2011), Marszałek *et al.* (2013) and Stachniak *et al.* (2022), who indicated a very low flux from the moraine complex to proglacial rivers. While researching catchment areas neighbouring the Werenskiold Glacier basin, Marszałek *et al.* (2013), based on research conducted in the 2009–2011 summer seasons, showed that subsurface runoff constitutes up to 10% of the total runoff, while Stachniak *et al.* (2022)
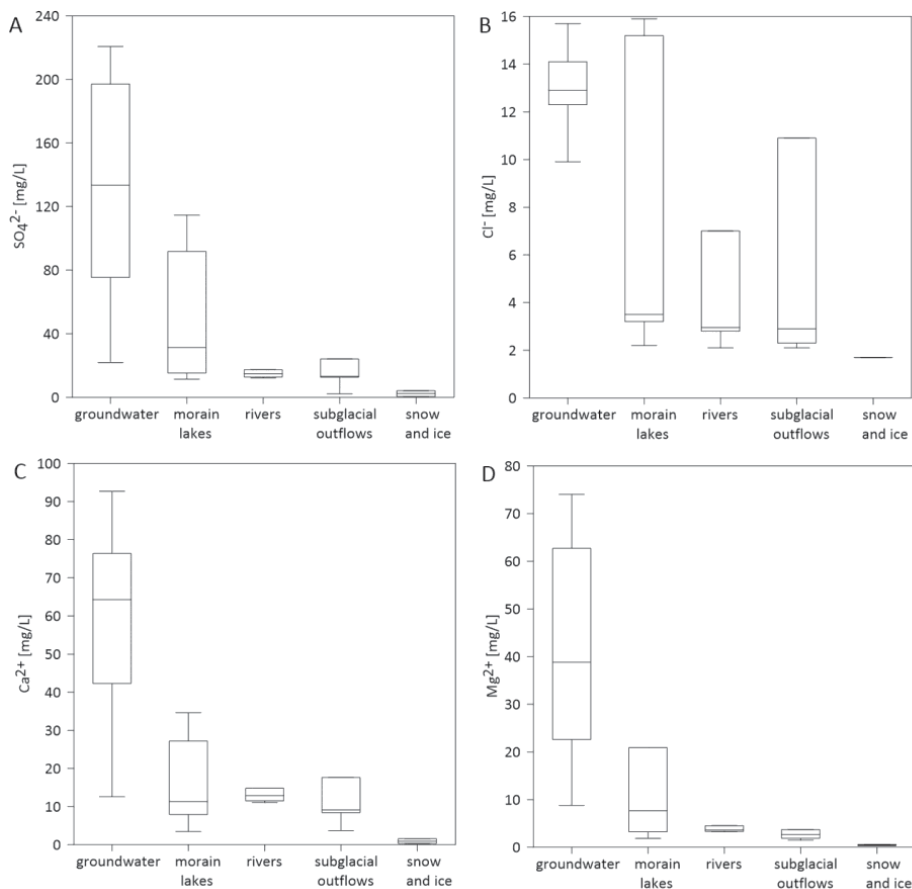
Fig. 5. Statistical differentiation of concentrations of SO_4^{2-} (**A**), Cl^- (**B**), Ca^{2+} (**C**), Mg^{2+} (**D**) ions, showing minimal, maximal, median values as well as 25 and 75 percentiles of groundwater and surface water sampled in the Werenskiold Glacier forefield in 2008.

based on field studies of groundwater in the 2017 ablation season showed, that the groundwater is responsible for *ca.* 2% of the total runoff from the Breelva catchment. Cooper *et al.* (2011), based on field studies over the course of the 1999 melt season, counted that the total annual flux from the moraine complex to the sandur is very small, constituting only *ca.* 1% of the total annual catchment runoff. The obtained results also confirmed the results of Marciniak *et al.* (2014), who indicated variable participation of groundwater to the total outflow. They also estimated the recharge of the proglacial Elba river by groundwater at marginal values of 2.0% in 2007, 3.8% in 2008 and 3.1% in 2009. In their study, during the entire measurement period, the main component of river recharge was meltwater flow from the glaciers. Also the measurements carried out on August 6, 2008 were preceded by a 6-day dry period and in preceding 16 days the rainfall was only 1.6 mm. Low precipitation in such a long period with quick and violent reactions of the proglacial river to the rain indicate that the main recharge
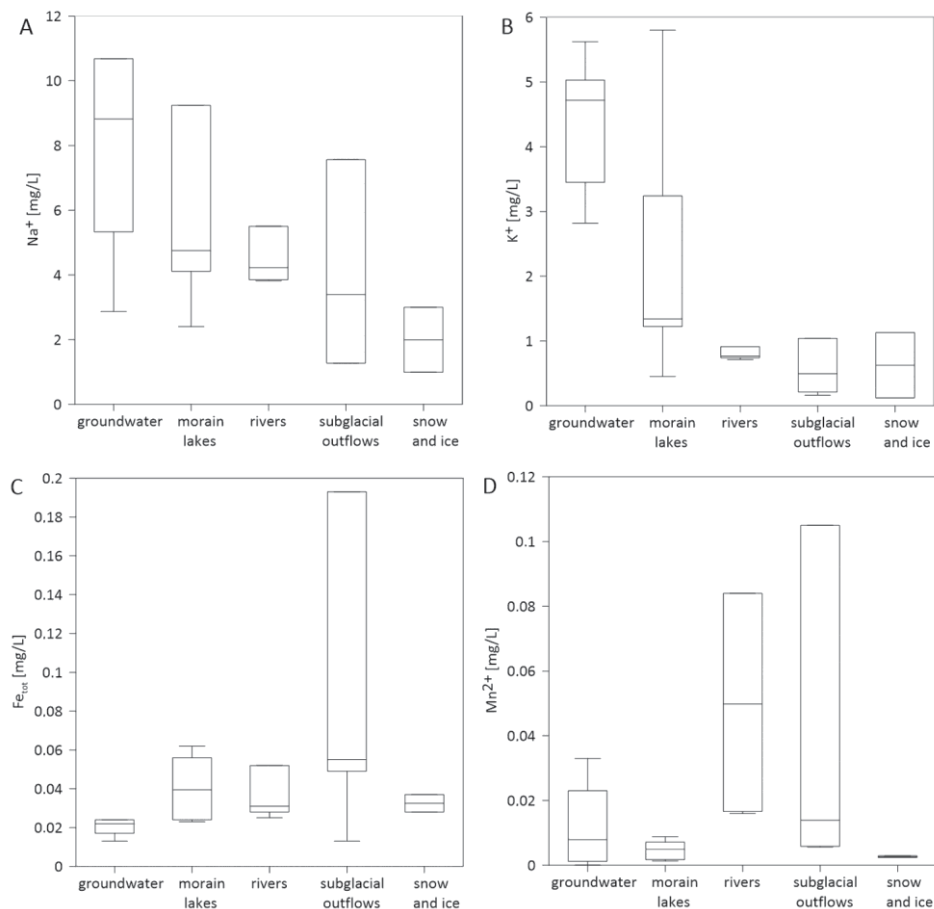
Fig. 6. Statistical differentiation of concentrations of Na^+ (**A**), K^+ (**B**), Fe_{tot} (**C**) and Mn^{2+} (**B**)), showing minimal, maximal, median values as well as 25 and 75 percentiles of groundwater and surface water sampled in the Werenskiold Glacier forefield in 2008.

component of the Breelva river was also meltwater from the glacier. Piechota *et al.* (2012) demonstrated results similar to the measurements presented in our study, showing that the subglacial inflows constitute 98% of the amount of water in the proglacial river and the groundwater resource is low.

Hydrological measurements carried out on August 6, 2008 indicate also a great variability in the inflow of water from the glacier to its forefield. Ignatiuk (2012) and Piechota *et al.* (2012), based on research conducted in 2009–2011, demonstrated that the majority of subglacial water (65–73%) flows to the forefield through the glacier gate recharging the Kvisla river, while the southern and central parts are responsible for *ca.* 35% of the water. Considering the measurements from 2008, this ratio was opposite, amounting to 23% and 77%, respectively. The central part, including the Duszan and Wiesława springs, was the zone supplying the greatest amount of water. It was responsible for 70% of
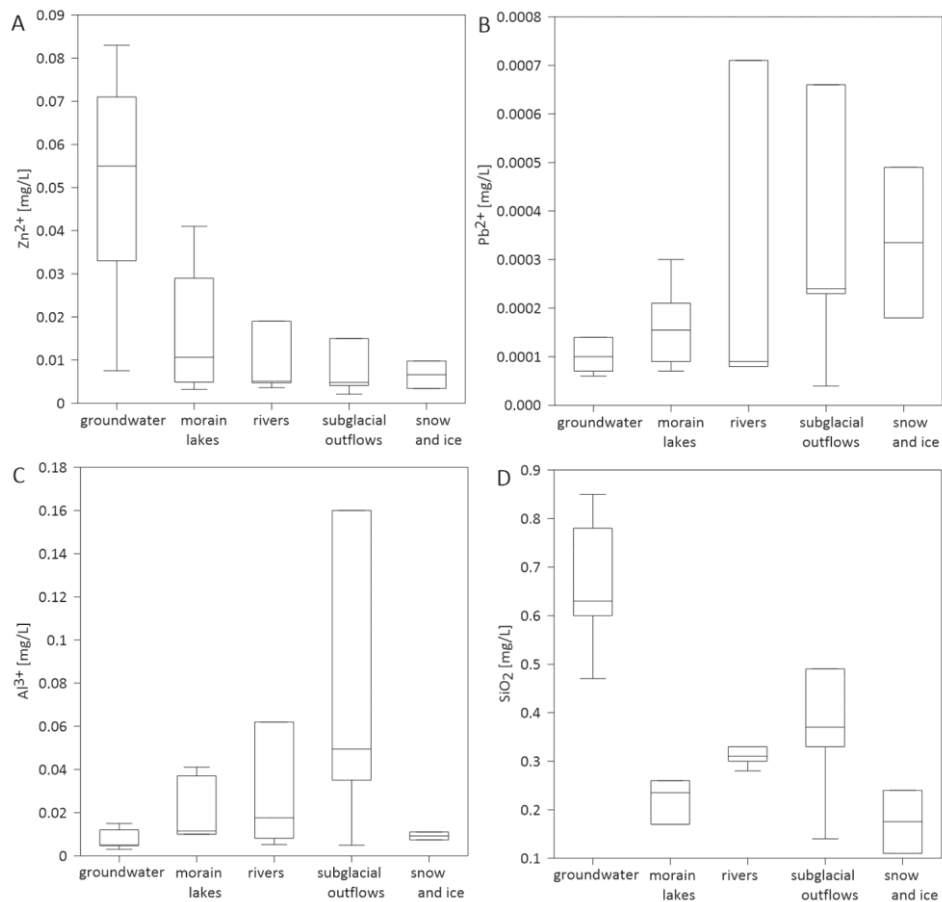
Fig. 7. Statistical differentiation of Zn^{2+} (**A**), Pb^{2+} (**B**), Al^{3+} (**C**) ions and SiO_2 (**D**), showing minimal, maximal, median values as well as 25 and 75 percentiles of groundwater and surface water sampled in the Werenskiold Glacier forefield in 2008.

the proglacial river discharge. Measurements carried out in August 2008 are consistent with the observations demonstrating changes in locations of the main outflows from the glacier since 1986 (Krawczyk and Pulina 1983; Krawczyk and Opołka-Gądek 1994; Stachniak *et al*. 2022).

Previous studies indicate that some of the water in the glacier forefield may originate from the permafrost and be drained in areas with unfrozen ground (taliks) such as rivers or lakes (Van Everdingen 1990; Olichwer and Tarka 2018). The occurrence of this type of water or even thermal inflows through the lake beds could be indicated by elevated water temperatures in the lakes or in piezometers in the Werenskiold Glacier forefield. Water temperatures at these points significantly exceed average daily air temperatures of the ablation period, which might indicate deep water-circulation. Water temperatures in lakes and piezometers in the Werenskiold glacier forefield are, however, derivative of the

land surface temperature, which exceeds 18°C on slightly cloudy days in the glacier forefield. Such temperature was recorded on August 4, 2020 at 11:40 a.m. within Landsat 8 research programme (Fig. 1B), while the average daily air temperature on that day was 7.2°C, with the range between 3.5–9.6°C (Flak *et al*. 2020).

Forming of water chemical composition. — Chemical diversity of water in longer contact with rock environment than those of river and subglacial runoffs (Figs. 4 and 5) confirm that in the studied period, the impact of groundwater on the water outflow from the glacier forefield through watercourses was marginal. The water chemistry of the watercourses was clearly shaped by the main sources of inflow, namely the Duszan (ID 1) and Wiesława (I D2) outflows, as well as the springs feeding the head of the Kvisla river (IDs 14 and 28). Small moraine flow-through lakes could also be of minor significance (IDs 9, 17 and 20). Inflows of water from the glacier surface (ID 2) and direct precipitation (ID 30) were probably also of minor importance during the study period. The observed homogeneity of the chemical composition of the proglacial river from source to mouth also indicates that during the study period, it discharged mainly glacier water (IDs 8, 15, 16 and 19). In turn, the basic chemical composition of the water of moraine lakes of the Werenskiold Glacier forefield indicates that depending on their character (flow-through or endorheic), the groundwater contributions to their chemistry is likely to be varied. Lakes, for which no drain into watercourses was found (IDs 4, 11 and 18), show the dominance of Mg^{2+} and SO_4^{2-} ions, typical of groundwater, while water in flow-through lakes (IDs 9, 17 and 20) are dominated by Ca^{2+} and HCO_3^- ions (Fig. 3).

Importantly, all moraine lakes of the Werenskiold Glacier forefield have a remarkably different chemical composition from lakes and surface water studied by Marszałek and Górniak (2017) in the neighbouring catchment area of Bratteg Valley, recharged mainly by ice and snow meltwater, where a very low mineralisation of water was found (<50 µS/cm) together with the types dominated by HCO_3^-, Cl^-, Ca^{2+} and Na^+ ions. Many authors indicate that the chemical composition of lake water in Arctic and glacial regions is very diverse depending on what factors affect their composition (Anderson *et al*. 2001; Kosek *et al*. 2019; Kaushik *et al*. 2021; Ruman *et al*. 2021). It should be emphasised that all studied moraine lakes of the Werenskiold Glacier forefield show a mixed type of chemistry, shaped by the impact of glacier meltwater and shallow (suprapermafrost) groundwater (Olichwer *et al*. 2013; Ruman *et al*. 2021).

Groundwater during the study period showed higher mineralisation, lower pH and significantly higher concentrations of HCO_3^-, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, Na^+ and K^+ than water running off through watercourses from the glacier forefield (Tables 1 and 2, Figs. 4 and 5). A clear dominance of SO_4^{2-} and HCO_3^- anions as well as Mg^{2+} and Ca^{2+} cations, probable short time and spatially limited area of contact with bedrock, all indicate the main role of easily soluble minerals and rocks in the formation of groundwater chemistry (Dragon and Marciniak 2010;

Kristiansen *et al.* 2013; Auqué *et al.* 2019; Sjöberg *et al.* 2021). The main source of Mg^{2+}, Ca^{2+} and HCO_3^- ions are probably weathered moraines of marbles, limestones and dolomites of the Deilegga Group, as well as secondary carbonates (Szynkiewicz *et al.* 2013). The origin of SO_4^{2-} ions in polar areas, where no primary sulphate rocks occur, is a subject of discussion (Copper *et al.* 2002; Auqué *et al.* 2019). As demonstrated by Szynkiewicz *et al.* (2013, 2020), in the Werenskiold Glacier forefield, precipitation of secondary calcium and magnesium sulphates occurs on the surface of moraine sediments. Due to infiltration of meltwater and precipitation water, concentrations of SO_4^{2-}, Mg^{2+} and Ca^{2+} ions reach high levels in groundwater. The primary source of sulphates, especially in waters of subglacial outflows in the research area, are most likely oxidation processes of sulphides, such as pyrite, chalcopyrite, pyrites, marcasite, sphalerite and galena, present in rocks which form crystalline basement in the area (Krawczyk 1992; Czerny *et al.* 1993; Stachnik *et al.* 2016). These processes are confirmed by the chemical composition and hydrogeochemical model of pore water in moraine sediments of the glacier forefield analysed by Kwaśniak-Kominek *et al.* (2016).

Origin of water ions. — In order to investigate the ability of water to dissolve or precipitate minerals in the glacier forefield, saturation indices were calculated for all analysed water against typical mineral phases. As a positive mineralisation to rock contact-time relationship has been demonstrated, the relations between the saturation indices and EC are presented in Figs. 8 and 9. The results show that all the tested water were significantly undersaturated with respect to calcium sulphate, *e.g.* gypsum, and unlimited with respect to metal sulphides, *e.g.* pirite and sphalerite. This indicates that it is still possible for sulphate water-concentrations to increase through sulphide oxidation processes and dissolution of secondary sulphates. It may confirm the conclusions put forward by Szpikowski *et al.* (2014), who recognised changes in water chemistry type from HCO_3–SO_4–Ca at the beginning of the melting season towards SO_4–HCO_3–Ca at the end of melting season in the Ebbaelva catchment area, where, contrary to the proglacial river, a significant effect of discharging chemical components from the watercourse of the glacier forefield was observed. The change of the dominant anion from HCO_3^- to SO_4^{2-} in pore water of the study area with depth and distance from the glacier front was confirmed by Kwaśniak-Kominek *et al.* (2016).

The possibility of significant chemical variation of water depending on current hydrological and meteorological conditions in Spitsbergen was also demonstrated by Dragon *et al.* (2015). Additionally, it was found that the studied water can dissolve minerals of the albite-anorthite series and potassium feldspar, which is a potential source of Na^+, Ca^{2+} and K^+. However, K-mica cannot be a significant source of K^+, as positive saturation factors in groundwater and surface water have been found. The groundwater and partly the water of the moraine lakes were, in turn, supersaturated with calcium and magnesium carbonates, which indicates the
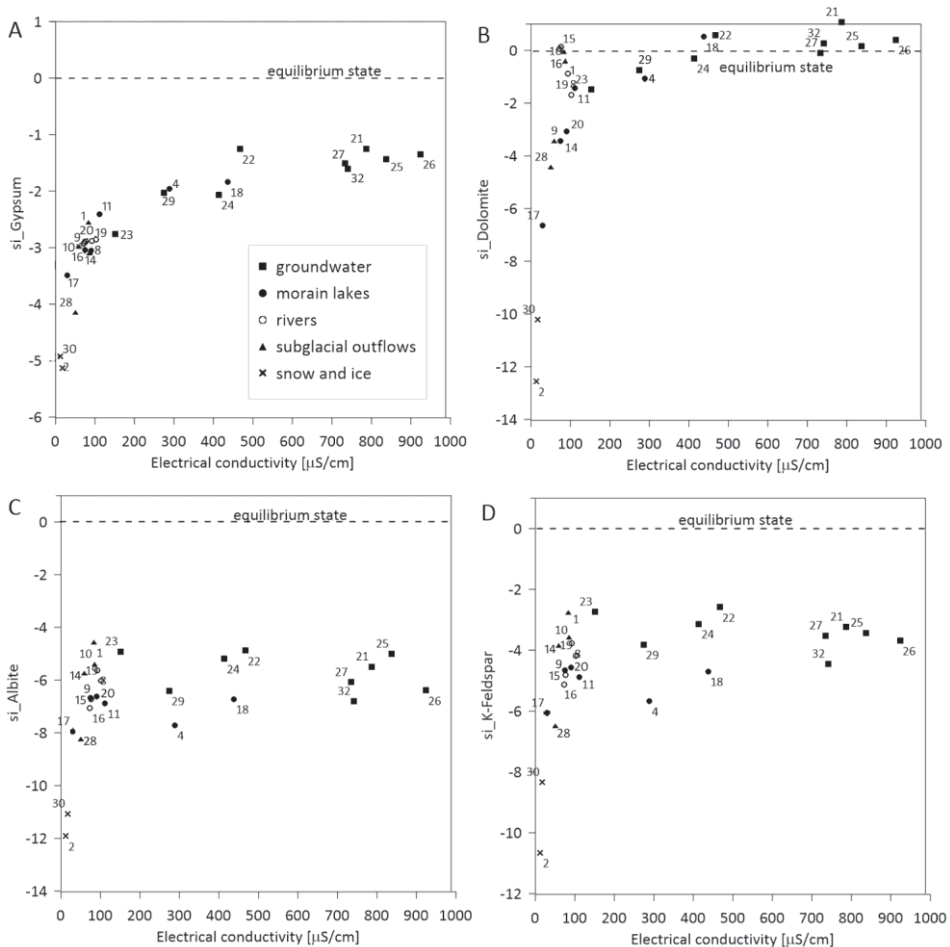
Fig 8. Saturation indices against gypsum (**A**), dolomite (**B**), albite (**C**) and K-feldspar (**D**) versus electrical conductivity values of water sampled in the Werenskiold Glacier forefield in 2008.

possibility of precipitation of these phases, mainly from groundwater. High saturation indices regarding FeOOH and $Fe(OH)_3(a)$ explain low concentrations of iron in the studied water, despite the process of oxidation of sulphides demonstrated by Stachnik *et al.* (2016). These phases are probably precipitated in the oxygenated environment of the moraine weathering, eliminating iron from the water (Kwaśniak-Kominek *et al.* 2016; Auqué *et al.* 2019). The oxidation process of sulphides of the sphalerite group is indicated by rather high concentrations of Zn^{2+} observed in the researched groundwater (median value 55 µg/L) and undersaturation of water in relation to sphalerite. These concentrations were much higher than those found in surface water of Brategg Valley by Marszałek and Górniak (2017). In turn, the analysed concentrations of Pb^{2+} were low (Table 2) and may suggest that weathering of the galena group minerals does not play a significant role in the Werenskiold Glacier forefield.
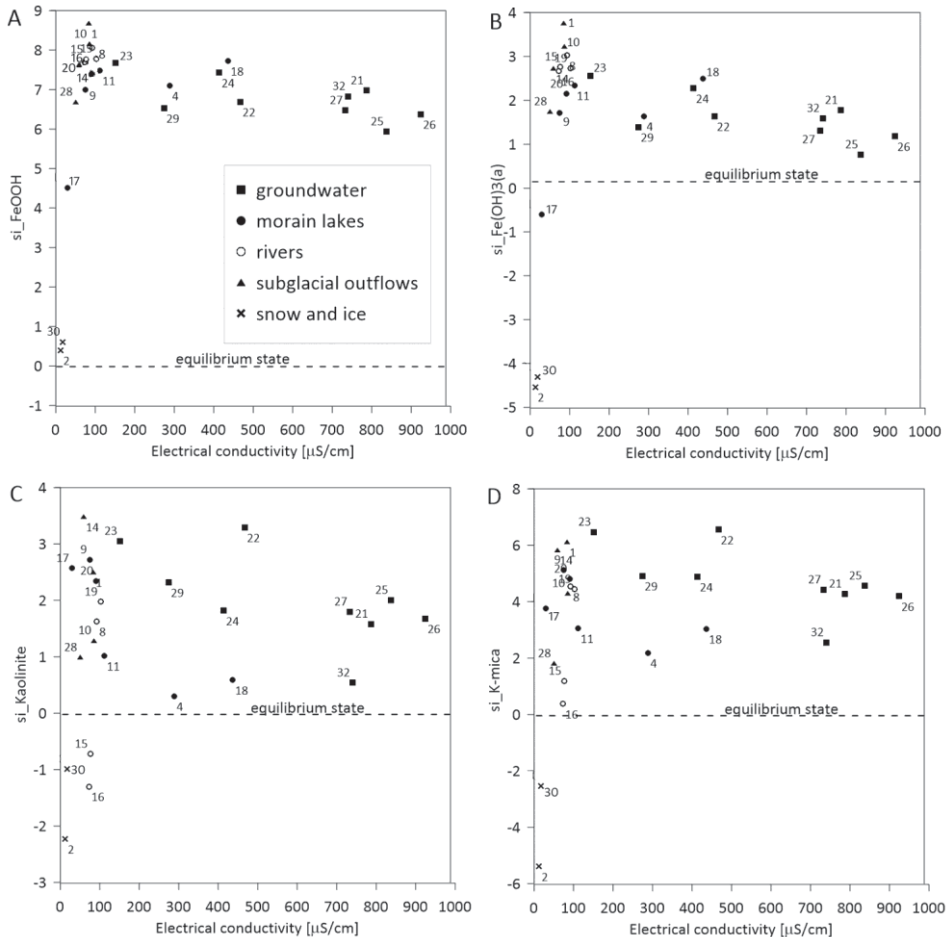
Fig 9. Saturation indices against FeOOH (**A**), Fe(OH)$_3$(a) (**B**), Kaolinite (**C**), K-mica (**D**) versus electrical conductivity values of water sampled in the Werenskiold Glacier forefield in 2008.

Concentrations of Al^{3+} and SiO_2 corresponded to the concentrations found by Stachnik *et al.* (2019) in the runoff from Werenskiold Glacier. In 2008, the highest concentrations of Al^{3+} were found in the water of subglacial outflows, supporting the thesis that weathering of aluminosilicates may have the greatest impact on the chemistry of these water (Stachnik *et al.* 2019). However, generally low concentrations of Al^{3+} and SiO_2 in groundwater may indicate a very dynamic picture of weathering of the primary and even precipitation of the secondary aluminosilicates in the Arctic environment (Hodson *et al.* 2002; Kwaśniak-Kominek *et al.* 2016).

Regarding the mineral compounds of nitrogen and phosphorus, our results indicate that the circulation of these elements is of marginal importance in the study area. Similarly low concentrations of these compounds were found by Stachnik *et al*. (2016). The forefield of Werenskiold Glacier is not an

important habitat for Arctic fauna, which is a potential provider of these compounds and the influence of atmospheric nitrogen, including anthropogenic sources, on the chemistry of the studied water appears to be negligible.

Conclusions

In this study, the marginal role of groundwater runoff in the Arctic catchment was demonstrated. The results from the 2008 ablation season indicate that the main source of water in the glacial river was subglacial outflows. The subglacial outflows with the highest discharge occurred in the central part of the glacier. On August 6 of 2008, it generated 77% of the total amount of water outflowing on the glacier forefield. Direct inflow of groundwater from glacier moraine to proglacial river was marginally low and the entire water circulation system was shallow, fast and variable. It is not impossible that the glacial river may periodically have an infiltration character in particular sections. A clear difference between groundwater chemical composition and surface water as well as subglacial runoffs in terms of major ions, together with the homogeneity of chemical composition of the proglacial river from spring to mouth confirmed the marginal role of groundwater runoff in the drainage of the catchment area in the late 2008 ablation season. There were no evidences for an important role of deeper than suprapermafrost water circulation. The water temperature, especially in the lakes, exceeding the mean daily air temperature during the ablation period is due to the heating of the ground moraine rocks, reaching over 18°C, on slightly cloudy days.

It has also been confirmed that in Arctic catchments, the chemical weathering in shallow moraine sediments takes place in a certain sequence, from weathering of sulphides and carbonates to secondary mineral phases. At the same time, the influence of shallow groundwater on the chemical composition of moraine lakes was demonstrated. The chemical composition of groundwater and moraine lakes, especially endorheic, in the glacier forefield was shaped by geological factors, *i.e.*, mainly chemical weathering of sulphides of iron and zinc, carbonates, both primary and secondary, and secondary sulphates. The possibility of precipitation of secondary iron hydroxide and a high probability of complex aluminosilicate transformations, due to chemical weathering and secondary precipitation, were also demonstrated. Low concentrations of mineral forms of nitrogen and phosphorus suggest a marginal role of anthropogenic factors in shaping chemistry of groundwater and surface water in the studied area.

Groundwater research in Arctic environments are difficult, especially in the absence of springs in the catchment area. However, they should be continued, if only due to the fact that the groundwater environment may be a source or storehouse of substances hazardous to the environment, such as heavy metals or anthropogenic pollutants.

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