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The coupling between hydrology, the development of the active layer and the chemical signature of surface water in a periglacial catchment in West Greenland

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Abstract. The chemical signature of surface waters is influenced by the interactions with soil particles and old groundwater. In permafrost landscapes ground ice restricts the flow of water in soils, and this implies a limited influence of, e.g., weathering on the chemical signature of the runoff. The aim of this study was to test to what extent freeze-thaw processes, hydrology and water-age play for shaping the chemical and isotopic signature of surface water and shallow groundwater in a catchment in West Greenland. Measuring runoff in remote catchments is challenging, and we therefore use a validated hydrological model to estimate the daily runoff over multiple years. We have also used a particle tracking simulation to determine the age of groundwater, and isotopic and chemical data from various water types (surface water, groundwater, lake water and precipitation) collected during different hydrological situations. Together this shows that even though the age of the groundwater rarely exceeds 4 years, runoff is dominated by subsurface flow, and overland flow is restricted to the early snowmelt period and heavy rain events. Our monitoring of the active layer indicates a rapid thaw, especially in connection with running water, and melting of ground ice quickly becomes an important fraction of the runoff. Taken together our data indicate that, similar to in other climatic settings and despite the lack of truly old groundwater and a shallow active layer, there is a profound influence from soil processes on the chemical and isotopic signature of the runoff.

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1 Introduction

The water that falls as precipitation carries a signature that reflects the chemical conditions in the atmosphere. This chemical signature – or water quality – is subsequently altered as the water flows through the catchment, where it interacts with water stored in the landscape, vegetation, soil particles and the bedrock (Sprenger et al., 2019). The resulting water quality not only determines the ecological and chemical status of local and downstream aquatic systems (EU, 2002), it can also shed light on hydrological pathways and biogeochemical cycling within catchments (Lyon et al., 2010a; Fischer et al., 2015; Lidman et al., 2014; Jutebring Sterte et al., 2022). A thorough understanding of the interplay between soil processes and water that moves through the landscape also allows for prediction of future changes in hydrological pathways and biogeochemical cycling of elements (Frey and Mcclelland, 2009; Vonk et al., 2015; Winnick et al., 2017).

The atmospheric state, and depth of the soil and groundwater stores determine the transit time of water (Condon et al., 2020), with water transit times ranging from several days in the shallow soil layers (0–10 cm) to durations exceeding several years as depth increases. In addition to storage characteristics, the long and cold winters in high latitude regions result in a reduced flow of water during a considerable part of the year, where the single most important event of the hydrological year is the snowmelt period (Bring et al., 2016; Johansson et al., 2015a). Not only is the runoff high, but the meltwater also flows through a system where ground ice limits the interaction between the meltwater and the soil (Johansson et al., 2015a; Bosson et al., 2013). That is, at least during the initial phase of the snowmelt period the water that reaches a stream can be expected to mostly reflect the chemical signature of the melting snow (Chiasson-Poirier et al., 2020).

As the upper soil layers thaw, the meltwater can infiltrate the ground surface. This not only leads to increased interactions between the meltwater and the soil particles, but it also means that recent snowmelt water can interact and mix with pre-existing older water that was stored prior to the onset of the snowmelt event (i.e., pre-event water; Tetzlaff et al., 2018). It is therefore reasonable to expect that the chemical signature changes and also starts to reflect processes in the soil, i.e., weathering and decomposition of organic material (Quinton and Porneroy, 2006). A prerequisite for the interaction between snowmelt water and soil is that the soil thaws while the snowmelt period is still ongoing. This is the case in forested catchments in the boreal region, where stream-water DOC concentrations increase during the snowmelt period (Laudon et al., 2004; Jutebring Sterte et al., 2018). However, in adjacent wetland catchments where the high heat capacity of the ice-rich peat results in slower thaw rates, the limited infiltration of snowmelt water results in a decrease in DOC during the snowmelt period and shorter transit time of the water (Laudon et al., 2004; Jutebring Sterte et al., 2018; Lyon et al., 2010b).

In permafrost regions the upper part of the soil that thaws each summer, i.e., the active layer, constitutes a much thinner aquifer than what is common in boreal systems without permafrost, suggesting a low water storage capacity in the active layer (Petrone et al., 2016). This would be consistent with a study of a polygon tundra site in Alaska (Throckmorton et al., 2016), where no traces of snowmelt water were found in soil water collected during summer. Similar, in a catchment scale study conducted in the Northwest Territories in Canada, Tetzlaff et al. (2018) reported that during the snowmelt period, streamflow was primarily governed by snowmelt inputs and short transit times. These transit times progressively increased to longer than 1.5 years, with significant contributions from subsurface and the riparian zones to streamflow in late summer. These findings suggest that, during the snowmelt period, the impermeable ground ice and slow permafrost thaw rate result in most of the meltwater leaving the system as evaporation or overland flow. In time, however, pre-existing older water that was stored prior to the onset of the snowmelt event becomes more important for the chemical signature of the runoff.

Thaw rates in the active layer are not only a consequence of air temperatures. On the one hand, the latent heat of ground ice also plays an important role, which implies that wetter soils should thaw slower (Clayton et al., 2021). On the other hand, wet soils have a higher thermal conductivity and could thereby thaw quicker (Clayton et al., 2021). In addition, running water contains considerable amounts of heat that could influence the thaw process (Sjöberg et al., 2016). This advective heat transfer would suggest that wetter areas and areas in close connection to surface-water flow-paths could thaw faster than drier areas further away from running water. In addition, microtopography influences the distribution of snow, and because snow insulates the ground during winter, it can be expected that low lying areas will have higher ground temperatures in spring (O'connor et al., 2019). Taken together this means that it can be difficult to predict how thaw rates and the active layer thickness vary spatially across the landscape.

After the intense snowmelt period follows a period with less water moving through the catchment and a progressively thicker active layer. In boreal systems, deeper flow paths and increased age of the water generally leads to a chemical signature more influenced by soil processes (e.g., weathering and OM decomposition of organic matter (OM); Jutebring Sterte et al., 2021a). Higher temperatures also lead to an increased evaporation, which concentrates both elements supplied with atmospheric deposition and those elements supplied through weathering and decomposition (Alvarez et al., 2015). Taken together we could expect that water collected during the summer, when transit times are longer, should have a very different chemical signature compared to the snowmelt period. However, even in late summer the active layer is relatively thin, which means that even the deepest flow paths are very shallow compared to boreal systems (Petrone et al., 2016; Jutebring Sterte et al., 2021b). This implies that the average age of the runoff water in a stable periglacial landscape is younger, that the flow paths are shorter and that most of this water leaving the system has had a more limited time to interact with the soil particles compared to boreal systems (Tetzlaff et al., 2018). Hence, the question remains to what extent the water chemistry in permafrost landscapes, characterized by the absence of confined stream-channel networks and the presence of temporary runoff recharging lakes, is affected by – and reflects – processes in the catchment, or if the water leaves the system too rapidly to pick up any discernible signature from the catchment.

This knowledge is essential to make reliable predictions regarding how future changes in the climate will affect biogeochemical cycling. Despite located in a global climate hotspot (Rantanen et al., 2022), the declining research infrastructure in the Artic (Laudon et al., 2017), few spatiotemporal data associated with the region's remote location and extreme climatic conditions (Throckmorton et al., 2016; Tetzlaff et al., 2018) makes that the processes influencing the water quantity and quality remain poorly understood.

In order to better understand how flow paths, water age and chemical signatures covaries over different time scales in a periglacial landscape we have used a well-studied catchment of a lake in West Greenland, i.e., Two-Boat Lake (Johansson et

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al., 2015b; Lindborg et al., 2016; Petrone et al., 2016; Lindborg et al., 2020; Rydberg et al., 2023; Rydberg et al., 2016). One key feature of our study is the well constrained, distributed, hydrological model that has been developed for this catchment (Johansson et al., 2015a). From this hydrological model we could derive information on the temporal variability in both total discharge and the importance of different flow paths through the landscape. We also used a particle tracking simulation to determine the age of the groundwater. This data was then compared to chemical signatures of the water over both shorter (within season) and longer (between seasons and years) time scales. We also used field observations on thaw depth in the active layer to answer the following specific research questions: i) is the thaw of the active layer fast enough to allow the meltwater from snow to interact with soil particles during the snowmelt period, ii) considering the dry conditions and the shallow active layer, can we see any substantial influence of groundwater in the runoff to the lake (i.e., are the terrestrial soils hydrologically connected to the aquatic system).

2 Methods

2.1 Study area

Two-Boat Lake (TBL: also referred to as SS903, 0.37 km^2) and its terrestrial catchment (1.7 km^2) is situated in West Greenland (Lat 67.126° Long -50.180°), about 25 km east of the settlement of Kangerlussuaq (Fig. 1). Even though the Greenland ice-sheet (GrIS) is only about 500 m from the lake, it receives no direct input of glacial meltwater from the GrIS (Johansson et al., 2015a). Permafrost in the Two-Boat Lake catchment is continuous and reaches down to about 400 m, except under the lake itself where a through talik has formed (Claesson Liljedahl et al., 2016). Bedrock consists mostly of tonalitic and granodioritic gneisses (Van Gool et al., 1996) and is covered by till or glaciofluvial deposits that are, in turn, overlain by a layer of eolian material (Petrone et al., 2016). The climate of this region is cold and dry, with mean annual air temperature for the Two-Boat Lake catchment of -4.4 °C (Johansson et al., 2015b). The annual precipitation for the period 2011-2013 was 270 mm yr^{-1} of which about 40% of the annual precipitation fells as snow, and about half of the runoff (70 mm yr^{-1}) occurred during the snowmelt period (Johansson et al., 2015a). Between 2010 and 2019 the catchment has been the study site of the Greenland Analogue Surface Project (GRASP), which was funded by the Swedish Nuclear Fuel and Waste Management Company (SKB). During GRASP data regarding meteorology, hydrology, Quaternary deposits, vegetation cover, active layer thickness was collected together with samples from soils, groundwater, surface and lake water for chemical analysis. For this study we have focused on a sub-catchment (0.6 km^2) in the northern part of the Two-Boat Lake catchment (Fig. 1).

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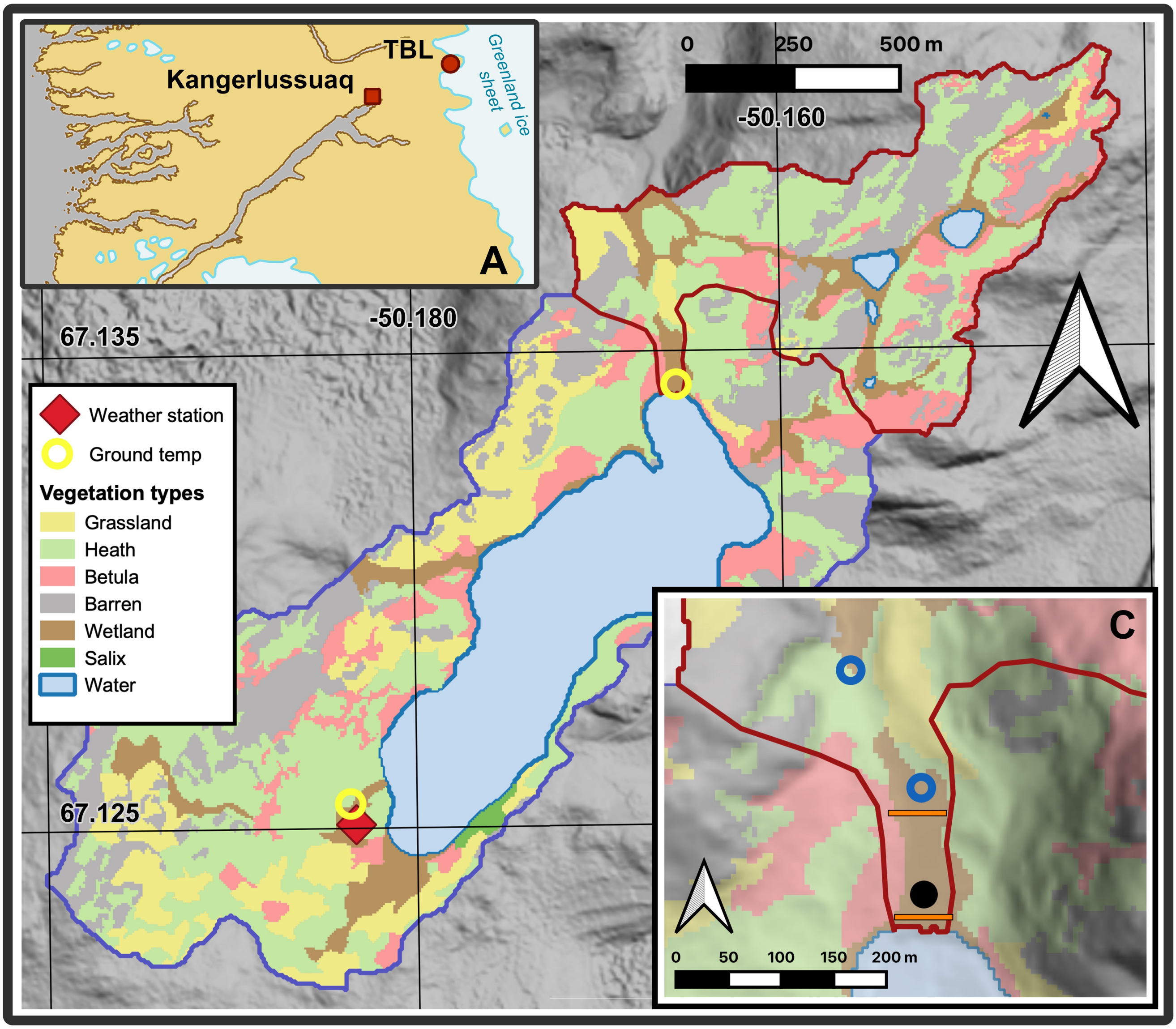

125 **Figure 1: A vegetation map over the Two-Boat Lake catchment with the locations of the automated weather station (AWS) and ground temperature loggers marked (a). The read outline corresponds to the sub-catchment used for this study while the blue outline marks the entire catchment area. The insert to the let (b) shows the Two-Boat Lake catchment in West Greenland. While the insert to the left (c) shows a close-up of the lower part of the studied sub-catchment with the two transects where active layer depth was measured during the intense monitoring period (orange lines), as well as the location of lysimeters and groundwater wells that were used as registration points for the particle tracking simulations. The digital elevation model and vegetation map has been developed within the GRASP-project and are described in Petrone et al. (2016) and Clarhäll (2011), respectively.**

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2.2 Monitoring of active layer thaw

Between May 18th and May 31st 2017 the progress of thaw in the active layer was monitored using a steel rod along two 50-m long transects (AL-transects; Fig. 1). Every second day (7 measurements in total) we measured the active layer thickness at every 0.5 m along the transects. Each measurement spot was also classified as wet (water table at or above the ground surface) or dry (water table more than 5 cm below the ground surface), and we measured the depth of any surface water. Thaw rates were then calculated by dividing the change in thaw depth between two consecutive measurements by the time between the same measurements. Thaw rates for the whole observation period and for each point along the transects, were calculated as the mean thaw rate for all dates observed. An estimate of error in the thaw rates was calculated using negative changes in thaw depth between dates, based on the assumption that the active layer thickness never decreased during this period (air temperature was only below zero for a few hours on May 22nd), and that all negative changes are therefore solely due to measurement error.

2.3 Meteorology and ground temperatures

Air temperature and precipitation (as both rain and snow) were recorded using an automated weather station (AWS) placed in the Two-Boat Lake catchment (Johansson et al., 2015b). Ground temperatures were measured at different depths in the active layer (Fig. 1; Johansson et al., 2015b). Time Domain Reflectometry (TDR) sensors are located in a cluster consisting of four points, each with sensors at four depths in the active layer, in the studied sub-catchment (Johansson et al., 2015b).

2.4 Estimate of the amount of ground ice

To estimate how much water that was released from melting ground ice during the observation period, soil moisture content at the time of freeze-up in the fall, as recorded by the TDR sensors, was used to estimate ground ice content at thaw at different depths. This estimate should be considered as a minimum, because moisture migration towards the thaw front could give a higher ice content. The depth of water released from melting ground ice was calculated based on the water content linearly interpolated for each depth between observation depths and the thaw depth for each point along the transects at the end of the observation period.

2.5 Hydrological modelling

There are no permanent streams or confined stream channels in the catchment. Instead, surface runoff occurs in small (typically < 1m wide) and temporary surface streams that are activate only during high runoff situations, particularly the snowmelt period (Johansson et al. 2015). Because high resolution discharge measurements were not possible, runoff during the period 2010-2019 were estimated using a distributed, three-dimensional integrated surface and groundwater model developed by Johansson et al. (2015b) using the modelling system MIKE SHE. The model domain has a horizontal resolution of 10x10 m, and covers the entire catchment, as well as the area directly downstream of the lake outlet (to avoid boundary effects). Vertically, the model is composed of four layers in the seasonally thawed active layer (top 100 cm) and four layers in the underlying

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permafrost (1-200 m depth). Observed daily precipitation and potential evapotranspiration (calculated from observed meteorological data) are applied as the upper boundary condition.

The model simulates the catchment water balance where incoming precipitation is partitioned into evapotranspiration, surface runoff, or infiltration for each cell in the model. The subsurface is composed of an unsaturated zone, from which water can evaporate via the soil matrix or through plant roots, percolate to the saturated zone, or remain in storage. The unsaturated zone varies in thickness depending on the location of the simulated groundwater table. Below the groundwater table water can move vertically and horizontally as simulated by Darcy's law. Because MIKE SHE does not support freeze-thaw thermal modelling (i.e., permafrost), the active layer and permafrost were modelled by adjusting the hydraulic properties (hydraulic conductivities, surface roughness and infiltration capacity) following a temporal pattern based on the ground temperatures at different depths. By using this method frozen and thawed conditions, based on ground temperature measurements, are captured in the model. Water in the subsurface zones is thereby only mobile when the ground is thawed. For more details regarding the model, please refer to Johansson et al. (2015a).

Code developments in MIKE SHE between the original model and the extended model run for the present study resulted in two model versions and associated evaluation periods. For the original 2010-2013 period, we use the original modelling run made by Johansson et al. (2015a). For the extended 2013-2019 period the same model was used, but with an extended model area was included as part of the catchment. This part is a transient area and the runoff contribution from this area depends on the intensity and magnitude of the snowmelt and summer rain events. Therefore, it is not connected to the rest of the catchment via a predefined stream network. If ponded water forms in the model it can be routed downhill or infiltrate to reach the downstream areas of the catchment as shallow groundwater flow.

2.6 Particle tracking simulation to estimate groundwater age

The numerical model was also used to estimate the age of the groundwater using particle tracking. The MIKE SHE particle tracking module releases particles (in arbitrary units of water) along the established 3D flow field in the saturated zone only. Particles are tracked along the flow path and move via advective flow until they leave the saturated zone to a temporary surface stream, areas with standing water, the unsaturated zone or a model boundary. Thus, the age (i.e., time since entering the saturated zone) and location are recorded for each particle, for each time-step of the model run. Once it leaves the saturated zone, the particle is lost and removed from the simulation.

The number of particles released into the sub-catchment was flow weighted, i.e., the more water that recharged to the saturated zone the more particles were released. One particle was created for each millimetre of recharging water. To ensure enough time for most particles to leave the saturated zone, the particles were released during the first year of the simulation. For this particle tracking simulation, the flow field from the MIKE SHE hydrologic model (described above) was cycled repeatedly for the years 2016-2019 to create a 100-year simulation cycle.

Groundwater age was estimated by noting the date the particle entered the saturated zone and the date when the particle reached a registration point. The three registration points used were the groundwater wells and lysimeter locations where water samples

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had been collected (Fig. 1). Each location was further subdivided into three registration depths in accordance with the established vertical layers of the model (0–25 cm, 25–50 cm, 50–75 cm).

2.7 Sampling and chemical analysis

Precipitation (rain and snow), surface-water, groundwater and lake-water samples have been collected from temporary surface streams, groundwater wells and zero tension lysimeters at an irregular, low, frequency between 2010 and 2019 (Lindborg et al., 2016). These water samples have been analysed for their elemental composition using Inductively-Coupled Plasma Sector-Field Mass Spectroscopy (ICP-SFMS) at ALS in Luleå, and organic carbon (DOC) using the NPOC-method at either Stockholm University (Dept. of Ecology, Environment and Plant Science), ALS in Luleå or Umeå University (Dept. of Ecology and Environmental Science; (Lindborg et al., 2016).

In addition to this low frequency sampling, a number of samples were collected simultaneously as the monitoring of the active layer thaw (i.e., between May 18th and May 31st, 2017). One set of samples were used for ICP-SFMS and DOC measurements. This sample set consists of samples from where one of the temporary surface streams enter Two-Boat Lake, the uppermost groundwater well (GW-12), one lysimeter (15-cm depth) and a snowpack above GW-12 (Fig. 1). A second set of samples were used for analysing stable isotopic signatures (δD and $\delta^{18}O$). Surface water was sampled every second day from two small temporary surface streams that crossed the transects used to monitor active layer depth. Snow was sampled on at three locations in the sub-catchment, and water from ground ice in the active layer was sampled on at three locations along one of the temporary surface streams (pieces of frozen ground was thawed in plastic bags, and the meltwater was sampled). All samples were taken as duplicate samples (field replicates), and the isotopic composition in each sample was analysed in triplicate (laboratory replicates). All calculations and statistical treatments were made using the average isotopic composition of the laboratory replicates.

2.8 Statistical methods and data treatment

2.8.1 Water samples

To evaluate similarities and differences between different types of water samples the chemical data from rain, snow, temporary surface streams, groundwater wells, lysimeters and the lake itself were subjected to a principal component analysis (PCA). For temporary surface streams, groundwater wells and lysimeters only samples from Emma valley were included. Prior to the PCA, elements where the majority of observations were below the reporting limit in all compartments were removed. For the remaining elements all values below the reporting limit were replaced with half the reporting limit, and the data was then converted to z-scores (average=0; variance=1) to remove any effects of scaling. After an initial PCA, we also removed elements with communalities <0.7, as well as two snow samples that had elemental concentrations similar to lake water indicated they are not contaminated by lake water (collected 2014-04-11), and a single sample from groundwater well 11 (2011-09-13) that had an very strong influence on the outcome of the PCA (scores were assigned passively). This resulted in a total of 35 elements

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and 52 observations (rain=8, snow=6, surface water=7, groundwater=23, lake water=8). All principal components (PCs) with Eigenvalues above one were extracted, and a Varimax rotated solution was used.

2.8.2 Correlation analysis

All statistical calculations for the comparisons between hydrological variables and the chemical signature were done using SPSS v.29 (www.IBM.com). Correlation coefficients were calculated as Pearson correlations (denoted r) if both variables were normally distributed (according to a Shapiro-Wilk test) or Spearman rank correlations (denoted r_s) if at least one variable was non-normally distributed. For all tests a significance level of 0.05 was used. The majority of the runoff in the Two-Boat Lake catchment occurs as groundwater, and several of the hydrological parameters reported from the model are highly correlated. We have therefore only used the total runoff to the lake and the proportion of deep groundwater for the correlation analysis (these two parameters show no correlation to each other).

3 Results

3.1 Meteorology and hydrological modelling – 2011-2019

The observed mean annual precipitation for the extended modelling period (i.e., 2013-2019) was 308 mm yr^{-1}, and varied from a minimum of 247 mm yr^{-1} in 2014 and a maximum of 407 mm yr^{-1} in 2017. Based on the local meteorological observations, the hydrological model estimates that most of the precipitation leaves the system as evapotranspiration (65%), and the period from late April through October was characterized by a precipitation deficit (i.e., precipitation minus evapotranspiration was less than zero), whereas the winter period had a precipitation surplus. On an annual basis the mean, modelled, net input of water to the catchment (i.e., precipitation minus evapotranspiration) was 109 mm yr^{-1}, with a variation from 64 mm yr^{-1} (2018) to 170 mm yr^{-1} (2017). The snowmelt period was the dominant runoff event in all modelled years and most commonly the runoff peaked in early June. During the early snowmelt period a substantial part of the runoff occurred as overland flow directly to the lake (i.e., water that has not been in contact with the subsurface), but for the latter part of the snowmelt period and the summer season the runoff was dominated by groundwater discharging directly to the lake or via temporary surface streams. The exception to this pattern was 2018, when overland flow also occurred late during the snowmelt period and during summer. On an annual basis overland flow made up 7-52 % of the annual runoff (mean 28 %). Here, 2016 and 2018 stand out from the remainder of the years with about half the water leaving the catchment as overland flow.

Ground temperatures down to 2 meters depth show a clear seasonal pattern that becomes muted with depth (Fig. 2). On average for the 2011-2018 period the maximum thaw depth, which occurs in August, reaches the temperature sensor at 0.75 m. The thawed period at 25 cm starts in late May (May 29th) and reaches 50 cm by mid-June (June 20th). The ground then stays unfrozen for about four months, and freezes at 25 cm in late September and in mid-October at 50 cm. That the deeper parts of the active layer (at 50 cm) stay unfrozen for almost a month after air temperature goes below zero and the surface layers freeze means that groundwater flow can occur also after the surface has frozen.

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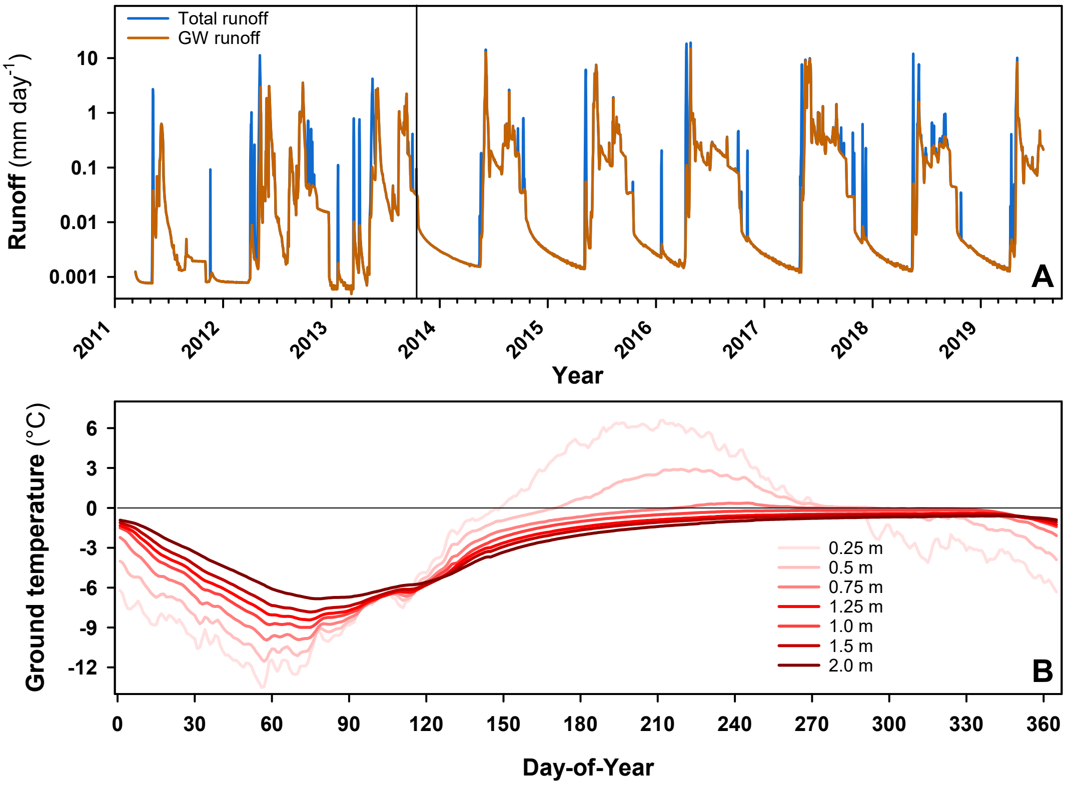

260 **Figure 2. The upper panel (a) shows the modelled median daily runoff (total and as groundwater) to Two-Boat Lake for the entire modelling period (March 2011 to July 2019). The horizontal line denotes the division between the original modelling run presented in Johansson et al. (Johansson et al., 2015a), and the extended period presented here. The lower panel (b) shows the observed ground temperature (daily mean for 2011-2018) down to 2 m depth (cf. Fig. 1 for location)**

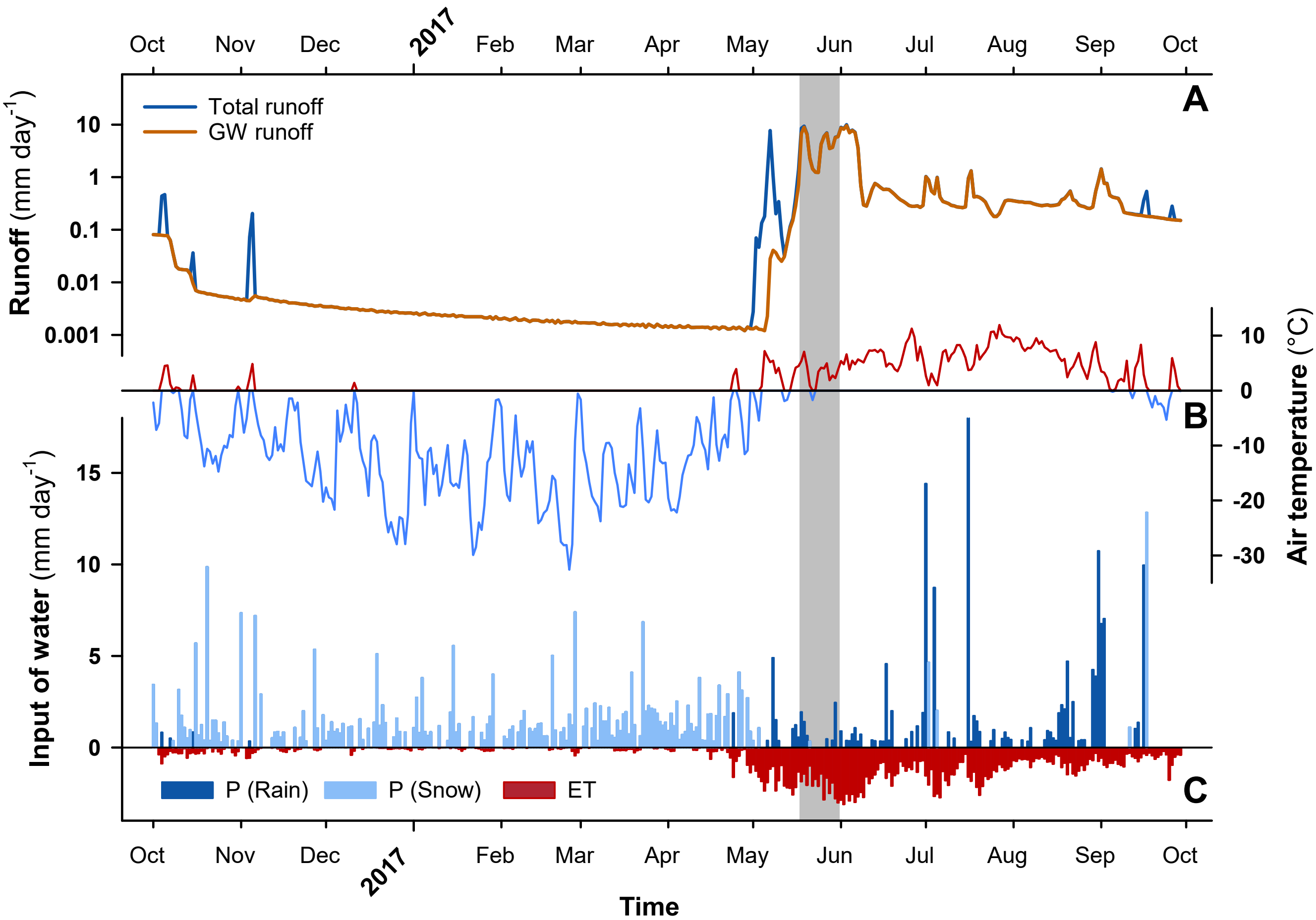

Figure 3. Modelled mean daily runoff from the hydrological model for the period 2016-10-01 to 2017-9-30 (a), observed daily air temperature (mean) for the Two-Boat Lake catchment for the same period (b), and precipitation as snow or rain for the same period (c). The intense monitoring period (May 18th to May 31st) is indicated by the grey box

3.2 Groundwater age

The particle tracking simulation was done for the period 2016-2019, and during this period most of the groundwater moved through the upper layer of the active layer saturated zone (0-25 cm; Fig. 4). From the start of the snowmelt period until the end of June the upper layer of the saturated zone was dominated by very young water i.e. generally infiltrated within the last 3 months, and most particles are registered during April and May. As the unfrozen season progressed the young water leaves the system, and the mean water age increased. In deeper layers the peak in registered particles occurred later in the season (May-June and September for 25-50 cm and 50-75 cm, respectively), and deeper soil layers also tended to have higher water ages. Similarly, as for the upper most layer of the saturated zone the age of the water in deeper layers also increased later in the

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season (Fig. 4). Almost all the water that moved through the deepest part of the active layer had spent more than a year in the saturated zone, and about two thirds was older than two years. It should be noted that water ages only relate to particles released as they infiltrate the saturated zone.

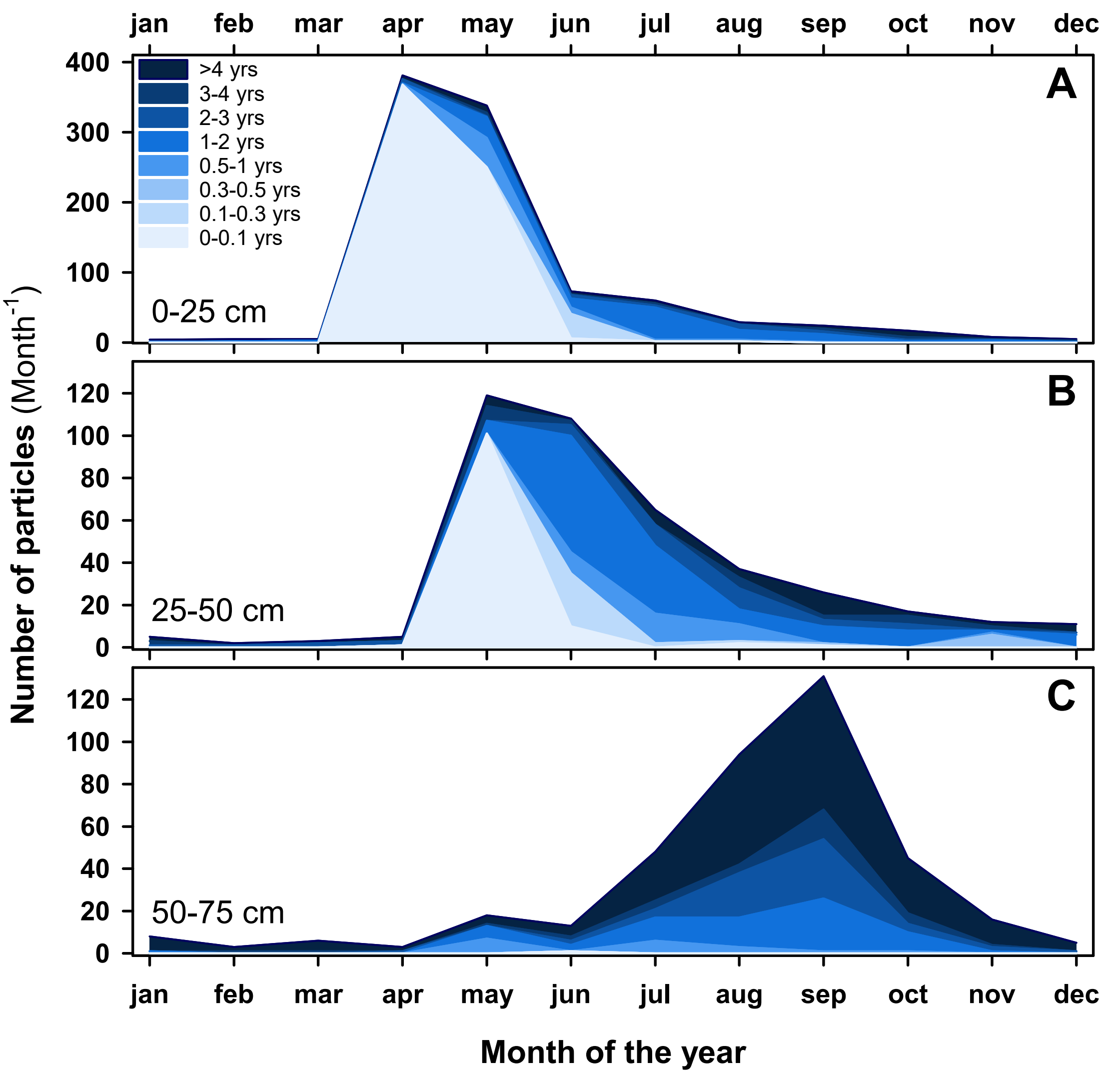

Figure 4, Age distribution for water particles reaching the three registration points used in the particle tracking simulation for three depth layers (a: 0-25 cm, b: 25-50 cm and c: 50-75 cm). Note that the scale differs between the 0-25 cm layer and the two deeper layers.

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3.3 Intense monitoring period of spring 2017

During the winter 2016/2017, which preceded the intense monitoring period in late May 2017, the precipitation measurements in the Two-Boat Lake catchment indicate that 260 mm of snow-water equivalents accumulated in the catchment, of which 26.5 mm were lost to evaporation or sublimation (Fig. 3). According to the hydrological modelling the snowmelt started on April 30th, with about 8 % of the snowmelt associated runoff occurring before May 13th, mainly as overland flow directly to the lake (Fig. 3). This means that at the beginning of the intense monitoring period (May 18th to May 31st), a substantial part of the accumulated snowpack had already melted (or sublimated) and snow patches were mainly confined to higher elevations in the catchment. Even so, multiple small temporary surface streams were still observed across the catchment, and according to the hydrological model the runoff remained high until June 10th, but then most of the water had spent some time as groundwater before entering a temporary surface stream or reaching the lake.

Time Domain Reflectometry (TDR) sensors installed at different depths in the ground at four locations on the hillslope in the sub-catchment, showed a soil moisture content of approximately 30 % during soil freeze-up in the fall of 2016. Furthermore, the ground temperature sensors in the sub-catchment showed that thawing of the ground at 5 cm depth started on May 10th, and reached 15 cm depth on May 20th. The active layer thaw of ground ice corresponds to a total water release of at least 18 mm of water during the sampling period, assuming that the recorded soil temperatures and water content at the TDR sensors are representative for the entire sub-catchment. During the intense monitoring period (May 18th to May 31st) there was also an input of total of 7 mm of rain, with the largest rainfall event of 0.8 mm occurring on May 30th.

3.4 Active layer thaw rates

The average thaw depth along the two transects closely resembled the thaw depth observed using the ground temperature sensors in the sub-catchment, but there was considerable variability in ground thaw along the two transects (Fig. 1). At the start of the monitoring period (May 18th to May 31st) the average thaw depth along the studied transects was 10.4 (±0.2) cm, and by the end of the period it had increased to 15.3 (±0.2) cm. On the first day of sampling, May 18th, 30 % of the measurement points had a water level at or above the ground surface, and 7 % were covered by surface water. The surface water formed several puddles, and two temporary surface streams crossed the upper transect of which one stream also crossed the lower transect (Fig. 1). During the monitored period, wet locations (with water table at or above the ground surface) exhibited a higher thaw rate (0.8 cm day^{-1}) than dry locations (0.6 cm day^{-1}, p-value <0.0001). The maximum observed thaw occurred under one of the temporary surface streams, where the active layer reached down to 48 cm on the last day of the monitoring period (May 31st).

3.5 Isotope signature

The isotopic composition of water from temporary surface streams sampled in May 2017, as well as precipitation samples taken in 2011, 2014, 2017, and 2019, is shown in Fig. 5. For the precipitation samples there was a clear seasonality in the composition with more negative values in the snow samples (average δD = -159.7 ‰, standard deviation 12.5 ‰) compared to rain samples (average δD = -115.8 ‰, standard deviation 9.3 ‰). The compositions in samples from surface water (average δD = -140.6 ‰, standard deviation 2.0 ‰) and ground ice (average = -137.5 ‰, standard deviation 0.8 ‰) showed a much smaller spread, and the isotopic values fall between the winter (snow) and summer (rain) values (Fig. 5).

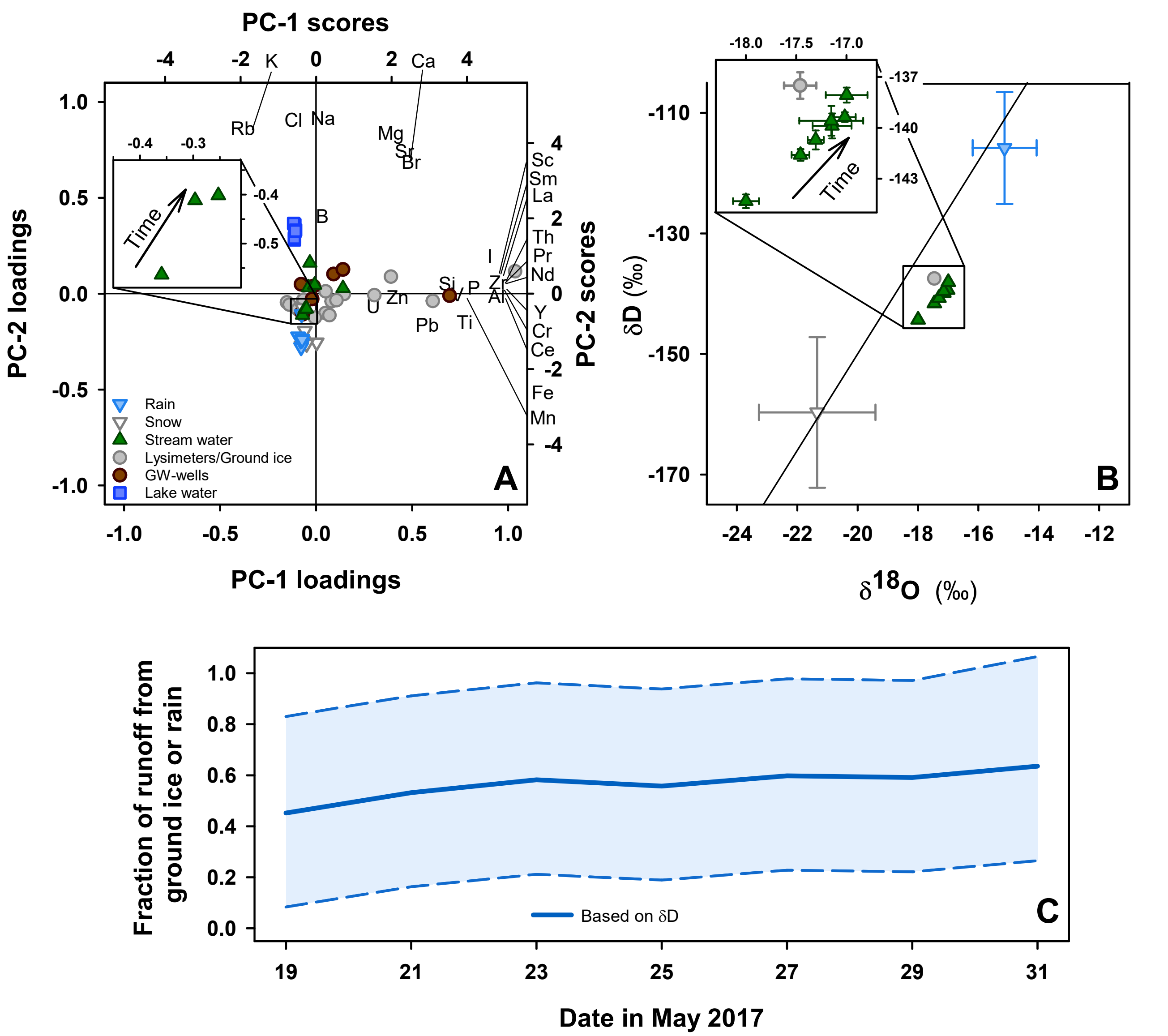

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Figure 5, The upper left panel (a) consists of a combined loadings and score plot for the first two PCs (PC-1 and PC-2). Precipitation samples are found in the lower left-hand corner, while lake water samples are found in the upper left-hand corner. Surface water and soil water samples (lysimeter and groundwater wells) generally have similar or higher PC-1 scores compared to precipitation and lake water, with the highest scores found in soil water samples. For PC-2 surface and soil water are intermediate to precipitation and lake water samples. The insert shows the three water chemistry samples from the intense monitoring period, with the arrow indicating the trend with time. In the upper right panel (b) shows the Isotopic composition (δD and $\delta^{18}O$) in snow, rain, ground ice samples and surface water samples. The symbols indicate the sample means, while the error bars indicate the standard deviation of all replicate samples. The insert shows the isotopic composition in the six samples from the intense monitoring period, with the arrow indicating the trend with time. The lower panel (c) shows how the fraction of melting ground ice and rain increases in the surface water over the intense monitoring period. The mixing model is based on the change in δD in the temporary surface stream and using the mean of rain (including ground ice) and snow as endmembers.

During the two-week intense monitoring period the isotopic composition in samples from the temporary surface streams changed considerably (Fig. 5). At the end of the monitoring period the δD signature of the surface water was heavier and more closely resembled rain than snow. The mixing model – which was based on the Deuterium signatures in temporary surface streams, rain, and snow samples – showed that on the first day of sampling 39 % of the surface water originated from rain, while 49 % can from rain on the last day of sampling (Fig. 5). The uncertainty range is high due to the high spread of values in snow and rain samples. Only 7 mm of rain fell during the sampling period (and 3 mm the week before), while the estimated water released from melting of ground ice in the active layer was 18 mm. Most of the rainwater therefore likely originated from rain that fell during the previous year and that had been stored in the active layer as ground ice during winter.

3.6 Surface water chemistry

The PCA identified five principal components (PCs) with Eigenvalues above one, and together they explain 90% of the variance in the data (Fig. 5). The first PC (PC-1) is driven by differences in elements related to silicate minerals that can be assumed to be released through weathering (e.g., Al, Ce, Nd, La, Pr, Sc, Th, Y, Zr. P; Deer et al. 1992). Samples with high PC-1 scores coming from lysimeters and groundwater wells, i.e., water that has had more contact with soil particles, and samples of precipitation and lake water have negative scores. DOC, which couldn't be included in the PCA because it was not analysed in all of the samples used for geochemical analyses, showed a high positive correlation with PC-1 scores (r_s=0.95, p-value <0.001). The second PC (PC-2) is driven by elements that originate from the ocean (e.g., Cl, Br, Na), and that are delivered to the catchment with precipitation. Here we can see a split between samples from the lake on the positive side and precipitation on the negative side (with soil water samples in the middle). That the lake water has considerably higher concentrations of these elements (Cl, Na, Sr, Mg, K, Ca) as compared to the precipitation, indicates that the enrichment is caused by evaporation (cf. Rydberg et al., 2023). The remaining three PCs are driven primarily by a small number of samples without any obvious trends, and they are therefore difficult to interpret in terms of general processes. For the remainder of this

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paper, we will focus on PC-1 and PC-2, which both reflect differences that are reasonable to assume should vary over the course of the year, e.g., depending on the source of the water and the intensity in the runoff.

3.7 Correlations between hydrology and chemical signature of surface and soil water

During the intense monitoring period samples for geochemistry were collected on three occasions (May 19th, 25th and 31st). During this period the hydrological modelling suggests that the total runoff as both groundwater and overland flow decreased between May 19th and May 25th, from 9.4 mm to 4.2 mm, and that it then increased slightly to 6.0 mm on the May 31st. During the same period the proportion of deep groundwater increased from 2.5, to 4.1 and finally 4.4 % of the total runoff. Looking at the PC-scores, both PC-1 and PC-2 scores increase over the intense monitoring period. The PC-1 scores went from -0.36 on May 19th, to -0.30 and then -0.25 on May 31st. For PC-2 the main shift occurred between the 19th and 25th when the score increased from -0.56 to -0.41. On May 31st the PC-2 score was essentially the same as on May 25th (-0.40). During this period DOC changed from 20.8 mg L^{-1} to 13.5 mg L^{-1} and finally 14.7 mg L^{-1}.

If we look at surface-water samples collected during the entire 2011-2019 period (n=7) the chemical signature in the surface water varies considerably. When the proportion of deep groundwater is high, there is an increase in the concentrations of weathering products (PC-1 scores). This results in a positive correlation between PC-1 and proportion of deep groundwater (r_s=0.79, p=0.036). For elements where the source mainly is precipitation (PC-2) and that is enriched through evaporation, there is an increase in the concentrations as the total runoff decreases over the course of the unfrozen season. For example, PC-2 scores are positively correlated with day-of-year (DOY; r_s=0.89, p=0.007), and there is a negative correlation between PC-2 scores and total runoff (r=-0.81, p=0.029). For the surface-water samples neither PC-1 nor PC-2 scores are correlated with DOC, but similar to PC-2 scores, DOC is negatively correlated to the total runoff (r=-0.59, p=0.017).

When looking at the lysimeters and groundwater wells – i.e., the soil water – a different pattern emerges. First, the chemical signature in the soil water is even more variable compared to the surface water. Second, PC-1 and PC-2 are correlated (r_s=0.47; p=0.021), and both are correlated with DOC (r=0.92, p=0.001 and r=0.86, p=0.001, respectively). This indicates that even if the processes driving PC-1 (weathering), PC-2 (evapotranspiration) and DOC (organic matter decomposition) are not related, there is a tendency that soil water is enriched in all three in a similar way. In the soil water, DOC shows a negative correlation with total runoff (r_s=-0.92, p<0.001), while neither PC-1 nor PC-2 scores are correlated to any of the hydrological variables, and neither PC-1, PC-2 nor DOC are correlated to sampling depth.

4 Discussion

4.1 Fast and shallow flow paths controls water chemistry

The output from the extended hydrological modelling period (2013-2019) largely corroborates the findings from the original modelling period (2011-2013; Johansson et al., 2015a). This is in line with findings that the study area has not experienced any significant change in climate over this period (2001-2019), even though a long-term (1981-2019) warming trend has been detected for the region (Hanna et al., 2021). All years except 2017, which was slightly wetter (405 mm yr^{-1}) compared to the previously wettest year, i.e., 2012 (366 mm yr^{-1}), falls within the range of 2011-2013 for both precipitation, evapotranspiration and total runoff from the catchment to the lake (Fig. 2). The annual pattern in the runoff is also very similar. It is highest during the snowmelt period, which accounts for about half of the annual runoff to the lake (Johansson et al., 2015a). During summer the total runoff decreases as a response to increased evapotranspiration, while in the fall (August-September), evaporation decreases and the total runoff to the lake increases again (Fig. 2).

According to our particle tracking simulation most of the water that moves through the sub-catchment is young, especially during the snowmelt period when almost all groundwater is less than 1-year old. Old groundwater is typically associated with deep and long flow paths, which are generally lacking in supra-permafrost groundwater systems in areas with continuous permafrost (Walvoord and Kurylyk, 2016). Because our simulation does not include any warming trend that could induce permafrost thaw, there is no considerable release of older groundwater from melting of permafrost ground ice. The results of our particle tracking simulation aligns with studies of water transit times in permafrost areas using tracer methods, indicating that most of the water moves through the landscape is young (e.g. Tetzlaff et al., 2018; Throckmorton et al., 2016; Cochand et al., 2020). A high proportion of young water is common in streams in all climate zones (Jasechko et al., 2016), but in continuous permafrost landscapes it appears that water ages are even lower than in areas without permafrost (Wang et al., 2022; Hiyama et al., 2013). For example, a similar particle tracking simulation made for a boreal catchment indicated that most of the water was between 0.8- and 3.7-years old (Jutebring Sterte et al., 2021b). However, unlike for the TBL catchment, where the maximum age of water was a few years, a considerable fraction (~25 %) of the water in the boreal system had an age of between 10 and 1000 years. In continuous permafrost areas in northern Alaska, water emanating from springs exhibited similar traces of mixture with older water that could have moved through deeper taliks (Koch et al., 2024). It should be noted that our model only calculates the age of groundwater and that during the snowmelt period runoff occurs to a varying degree also as overland flow in the temporary stream network. Therefore, our simulated water ages cannot be directly compared to results from tracer-based methods.

Even if the groundwater in TBL generally is young, there is a clear seasonal trend with increasing water age as the unfrozen season progresses. This pattern can be seen in the 0-25 cm, but it is especially pronounced in the 25-50 cm layer. At the deepest layer, i.e., 50-75 cm, there is no clear seasonal trend, but most of the water that moves in this layer is older than two years. These patterns imply several things. First, the movement of water in the uppermost layer (i.e., 0-25 cm) is mostly restricted to the snowmelt period, and as the thaw depth increases, the groundwater takes deeper flow paths. Similar patterns have been documented from other permafrost regions (Zastruzny et al., 2024; Lebedeva, 2019; Juhls et al., 2020). Second, the turnover time in the uppermost layers is relatively short, but the time that the water has spent in contact with the soil particles increases as the unfrozen season progresses. Third, for the deepest analysed layer (i.e., 50-75 cm) the turnover time is longer, and most of the water has spent several seasons in the active layer, i.e., this water has undergone at least one freeze-thaw cycle.

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Most of the variability in water chemistry can be explained by either the amount of weathering products in the water (PC-1), or the degree of evaporative loss the water has experienced (PC-2). Based on the correlations between the PC-1 and PC-2 scores for the surface-water samples and the hydrological variables it seems as if these two components are controlled by separate hydrological factors. For surface-water samples, elements supplied with precipitation – which are concentrated through evapotranspiration (PC-2) – show a negative correlation with total runoff. In spring, when snowmelt water moves through the system, the chemical signature is close to that of precipitation, but when runoff progressively decreases over the unfrozen season, the signature shifts towards one that is more characteristic for the lake water (Fig. 5). That is, as the water from precipitation resides in the catchment, it becomes more concentrated in elements that were present in the precipitation when it fell. This interpretation is also consistent with the PC-2 scores being positively correlated with DOY, and with water ages increasing as the unfrozen season progresses (Fig. 4). For elements supplied through weathering it is not primarily the amount of runoff that is of importance. Instead, it is the proportion of runoff classified as deep groundwater (i.e. 50-75 cm depth in our model) that has an effect. In July and August, the majority of this deep groundwater had spent more than two years in the saturated zone, while about one third to one fourth of the water at 25-50 cm had been there less than one year (Fig. 4). That older and deeper groundwater is richer in weathering products is consistent with studies in other systems and other regions (Jutebring Sterte et al., 2021b; Williams et al., 2015).

Even if DOC was not measured on all sampling occasions, and hence, could not be included in the PCA, the correlation between PC-1, PC-2 and DOC helped us to assess if organic carbon behaves like weathering products or elements supplied with precipitation. For the surface-water samples there is no correlation between PC-1, PC-2 and DOC, but similarly to PC-2, DOC is negatively correlated to the total runoff. The different behaviours of weathering products (PC-1) and DOC could be related to where in the soil profile these products originate. DOC production is highest in surficial soil layers, where the decomposition of relatively fresh OM is highest (Clark et al., 2008). These surficial layers thaw relatively rapidly, and hence, the DOC source is activated already during the snowmelt period. This means that, like PC-2, DOC is diluted when the runoff is high, but unlike PC-2, DOC in the upper soil layers can become depleted with time and PC-2 and DOC are therefore not correlated (Stewart et al., 2022). Weathering products on the other hand are primarily produced deeper in the soil profile (Fouché et al., 2021), and it is not until later in the season when these deeper layers thaw – and the proportion of deep groundwater increases – that this source becomes activated. The same transition in water chemistry as the active layer thaws below the upper, most organic rich soil layer, has been observed in other areas with continuous permafrost (Chiasson-Poirier et al., 2020).

Looking at the soil water sampled using lysimeters and in groundwater wells, PC-1, PC-2 and DOC are all correlated, which could indicate that older groundwater, and deeper, groundwater is enriched in both weathering products, elements supplied with precipitation and DOC. This would be consistent with many previous studies that have shown that deeper and older groundwater has elevated concentrations of a large selection of elements (Clark et al., 2008; Fouché et al., 2021; Stewart et al., 2022). However, neither PC-1, PC-2 or DOC showed any correlation to lysimeter depth, which likely have several reasons. First, the depths where the lysimeters are installed (15, 30 and 35 cm), are all in the two upper layers used in the particle

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tracking simulation (i.e., 0-25 and 25-50 cm). In these two layers the age of the water is relatively similar, and it is possible that a clearer pattern would have emerged if the deepest lysimeter had been placed in the deepest layer used in the particle tracking simulation (i.e., 50-75 cm) where the water is considerably older. Second, the deeper lysimeters could only be sampled late in the season when the total runoff is low because they are frozen during the snowmelt period. The lack of trend with depth could therefore be a result of this bias in the data. Third, there is a considerable vertical movement of water in the shallow active layer that results in mixing. This is supported by the generally similar age for the two upper layers in the particle tracking simulation.

Similar to the original modelling period for TBL by Johansson et al. (2015a), the runoff in the catchment is dominated by groundwater, either directly to the lake or via the temporary surface streams, but the extended modelling period reveals more between-year variability also for years with relatively similar amounts of precipitation. Even though the annual precipitation is relatively similar between 2014, 2015, 2016 and 2018 (247, 284, 286 and 261 mm yr^{-1}, respectively) the amount of overland flow varies considerably. 2014 and 2015 have a very low contribution of overland flow (less than 15 % of total runoff), whereas in 2016 and 2018 almost 50 % of the annual runoff occurred as overland flow either directly to the lake or via temporary surface streams. Our results from combined hydrological modelling and water sampling over several years, show that his interannual variability in runoff processes is an important determinant for water chemistry in the catchment.

4.2 Thaw rate variability during snowmelt

The differences in partitioning of simulated groundwater and overland flow between years is linked to both the amount of accumulated snow in the catchment and the thaw rate of the active layer, especially early in the thaw season. The amount of winter precipitation (October to March, which dominantly fell as snow) was relatively close to the average during the winters preceding the snowmelt periods of 2014 and 2015 (105 and 155 mm, respectively) and the snowmelt started relatively late (mid to late May), which resulted in a low proportion of the runoff as overland flow. In 2016, considerably more snow fell during the preceding winter (220 mm) and the snowmelt started in early April, resulting in a higher proportion of the runoff leaving the catchment as overland flow. For 2018, the amount of accumulated snow was relatively low (91 mm) and the snowmelt period started in mid-May, i.e., similarly as 2014 and 2015. However, the preceding year, 2017, was considerably wetter compared to other years (407 mm yr^{-1} of annual precipitation). This likely resulted in a high soil moisture and high groundwater levels at the time when the active layer froze in the autumn of 2017. A high content of ground ice in the active layer implies that the capacity for infiltration during the snowmelt period was limited, and the high associated latent heat content could have contributed to a slower thaw rate in the active layer this year (Clayton et al. 2021). As the active layer thawed, the high soil moisture content may have contributed to saturation excess overland flow occurring also during the late snowmelt and summer periods. For all other years, overland flow did not occur during summer, presumably because the generally dry conditions (evapotranspiration exceeds precipitation) normally result in a high infiltration capacity. For example, observations in the field confirm that temporary surface streams only appear during limited periods during the snowmelt period and during fall.

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While our hydrological modelling indicated that interannual variability in active layer thaw exerts a strong control on hillslope runoff processes, our field observations revealed fine scale spatial connections between hydrology and thaw rates. The thaw depth monitoring in the active layer during May 2017 showed that wet locations thawed significantly faster than drier locations. This would support earlier findings from areas with continuous permafrost, where variability in the active layer thickness has been attributed to the development of a hillslope groundwater drainage system (Chiasson-Poirier et al., 2020). The fastest thaw rates and largest thaw depths were measured in the wet locations of the slope and directly under the temporary surface streams. This would suggest that advective heat transport with surface and near-surface water plays an important role in determining the thaw rate, as has been observed elsewhere in the Arctic near concentrated groundwater flow paths (Dagenais et al., 2020; De Grandpré et al., 2012; Sjöberg et al., 2016). When compared to earlier investigations in the TBL catchment, it is noticeable that the maximum measured thaw depth during the intense monitoring period (48 cm ±9 cm), was almost the same as the average active layer thickness observed under similar vegetation cover (wetland) in August 2011 by Petrone et al. (2016). This indicates that the active layer in connection to temporary surface streams develops rapidly, but that rate of thaw is much slower during the remainder of the summer season. At the drier location (on the border between heath and wetland vegetation) where the ground temperatures are monitored down to 200-cm depth the thaw depth developed slower. In 2017 the 50-cm sensor reported above zero temperatures on June 9th and the 75-cm sensor on July 27th. Taken together with the drier vegetation types having a deeper maximum thaw depths compared to wetlands (70-80 cm; Petrone et al., 2016), this indicate that even if wetter locations thaw more rapidly in spring the effect of the latent heat in wet soils might become more important in determining the maximum thaw depth later in the season (Clayton et al., 2021).

This fine-scale variability in active layer thaw rates was not included in our hydrological modelling and subsequent particle tracking simulation. The finding that the active layer thaw is faster under the temporary stream network suggests that water that reaches the lake during the snowmelt may interact more with soils than what our modelling indicates. Our simulated groundwater ages may also underestimate the content of older water earlier in the season, as considerably deeper soil layers are thawed earlier in the season and possibly in a connected drainage pattern, similar to that observed by Chiasson-Poirier (2020) in northern Canada.

That there are additional factors controlling the chemical signature of the water is also supported by the isotopic and chemical signature in surface-water samples collected during the intense monitoring period (May 18th to May 31st 2017). During this period the isotopic composition shifts from a signature similar to that of snow (lower δD and δ^{18}O) to a progressively heavier isotopic signature of rain and ground ice (Fig. 5). At the end of the intense monitoring period the isotopic signature of the surface water flowing into Two-Boat Lake more or less completely resembles that of ground ice (Fig. 5). Ice in the active layer most likely formed from the water present in the active layer during the fall as the active layer froze, although some infiltration and migration of water during winter melt events cannot be completely excluded. According to the particle tracking simulation, most water present in the active layer at this point in time is at least one year old and a substantial fraction of the water is older than four years. In light of this, the isotopic composition of the ground ice falling somewhere in the middle between those of snow and rain is to be expected and has also been found using similar methods in the continuous permafrost zone in northern

Canada (Tetzlaff et al., 2018). In comparison to findings in lowland polygonal tundra in the continuous permafrost zone in Alaska, where winter precipitation did not contribute to the isotopic signature of active layer pore waters, water in the active layer in TBL appear to be more well mixed at least in the fall (Throckmorton et al., 2016).

Similar to the isotopic signature, there is a shift in the chemical signature during this period. PC-1 increased, PC-2 first increased and then remained stable, and DOC first decreased and then increased slightly. The increase in PC-1 is consistent patterns observed over the entire unfrozen period, and it increases as the proportion of deep groundwater increases. For PC-2 and DOC, the trends during the intense monitoring period do not show the same negative correlation with total runoff as during the entire unfrozen season. For PC-2 the initial increase from May 19th and May 25th, when the total runoff decreases, is consistent with the expected trend (Fig. 3). However, when the total runoff then increases again to May 31st, the PC-2 scores remain virtually the same as on May 25th. The DOC decreases when the total runoff decreases from May 19th to May 25th, and it then increases slightly until May 31st.

Even if the PC-2 scores for the last two sampling occasions are similar, the long-term data would suggest a stronger response to changes in the total runoff. However, the chemical and isotopic signature is not merely a question of more or less water, we also need to consider where the water comes from. From the isotopic signature of the ground ice, we can see that the isotopic signature of the surface water becomes progressively more similar to that signature over the monitoring period. This suggests that thawing ground ice acts as a source of water to the temporary surface streams during the rapid evolution of the active layer that occurs over this period. The thawing water from the ground ice will not only be enriched in heavy D and ^{18}O, from the soil water data we also know that it likely also has higher PC-2 scores and higher DOC concentrations.

That ground ice and the thaw of permafrost have a profound effect on the chemical signature of soil water in permafrost regions have also been reported from sites in Alaska (Fouché et al., 2021), and that pre-event water and elements that can be flushed from surficial soil layer have been shown to be important also under a wide variety of environmental settings (Brown et al., 1999; Fischer et al., 2017; Ross et al., 2017). Furthermore, presumably most of the melted ground ice comes from the near stream zone, where the thaw rate is highest. This suggests that these temporary "riparian" zones are important for the evolution of the isotopic and chemical signature of the surface water, which is analogous to the importance of the riparian zone in other systems (Lidman et al., 2017; Jutebring Sterte et al., 2022).

Conclusions

With the exception of the initial phase of the snowmelt period, the hydrological model suggests that the runoff to Two-Boat Lake is dominated by groundwater. For most of the season this groundwater is younger than one year, but later in the season and at larger soil depths the age of the water can be considerably older than >2-4 years. Together with total runoff – which dilutes elements supplied with precipitation and DOC – this "deep" groundwater plays an important role in forming the chemical signature of the runoff to Two-Boat Lake during the entire unfrozen season. Looking at the snowmelt period – when temporary surface streams appear in wetland areas – the isotopic and chemical signature of the surface water initially resembles the snow, but as the active layer thaws it rapidly shifts towards a signature similar to that of the melting ground ice. That is, even with a relatively thin active layer water from the previous fall contributes with a specific chemical signature to the lake. Together this shows that even in dry periglacial landscapes there is a strong coupling between the terrestrial and aquatic systems, and groundwater and pre-event water needs to be considered when assessing the transport of elements. It should be recognized though, that the sub-catchment used in this study is wetter than average for the Two-Boat Lake catchment, and that considerable parts of the catchment do not contribute with any runoff to the lake during drier periods. Together this paints a picture of a system that is highly variable, both in terms of hydrological conditions and the chemical signature of the water.

Data availability

The data used in this study is available mainly through three publications, Petrone et al. (Petrone et al., 2016), Lindborg et al. (Lindborg et al., 2016) and Johansson et al. (Johansson et al., 2015b), each with an adjoined Pangaea database (doi:10.1594/PANGAEA.845258, doi:10.1594/PANGAEA.860961 and doi.pangaea.de/10.1594/PANGAEA.836178, respectively). For Johansson et al. (2015) and Lindborg et al. (2016) additional data has been made public through additional Pangaea databases. Meteorological data from the automated weather station (labeled KAN_B) is available via www.promice.org.

Author contribution

JR: Conceptualization, Formal analysis, Investigation, Writing – Original draft, **EL**: Conceptualization, Methodology, Formal analysis, Writing – Review & Editing, **CB**: Formal analysis, Writing – Review & Editing, **BMCF**: Writing – Review & Editing, **TL**: Conceptualization, Investigation, Writing – Review & Editing, **YS**: Conceptualization, Formal analysis, Investigation, Writing – Original draft.

Competing interests

Ylva Sjöberg is a member of the editorial board of The Cryosphere

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