Received: 30 September 2020 | Revised: 9 July 2021 | Accepted: 22 July 2021

DOI: 10.1002/hyp.14350

RESEARCH AND OBSERVATORY CATCHMENTS: THE LEGACY AND THE FUTURE

WILEY

Subarctic catchment water storage and carbon cycling – Leading the way for future studies using integrated datasets at Pallas, Finland

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Funding information
Academy of Finland, Grant/Award Numbers: projects 316349, 316014, 308511, 312559, 337523; K. H. Renlund foundation; Koneen Säätiö; Kvantum institute; Maa- ja vesitekniikan tuki ry; Strategic Research Council; UArctic Research Chairship

Abstract

Subarctic ecohydrological processes are changing rapidly, but detailed and integrated ecohydrological investigations are not as widespread as necessary. We introduce an integrated research catchment site (Pallas) for atmosphere, ecosystems, and ecohydrology studies in subarctic conditions in Finland that can be used for a new set of comparative catchment investigations. The Pallas site provides unique observational data and high-intensity field measurement datasets over long periods. The infrastructure for atmosphere- to landscape-scale research in ecosystem processes in a subarctic landscape has recently been complemented with detailed ecohydrological measurements. We identify three dominant processes in subarctic ecohydrology: (a) strong seasonality drives ecohydrological regimes, (b) limited dynamic storage causes rapid stream response to water inputs (snowmelt and intensive storms), and (c) hydrological state of the system regulates catchment-scale dissolved carbon dynamics and greenhouse (GHG) fluxes. Surface water and groundwater interactions play an important role in regulating catchment-scale carbon balances and ecosystem respiration within subarctic peatlands, particularly their spatial variability in the landscape. Based on our observations from Pallas, we highlight key research gaps in subarctic ecohydrology and propose several ways forward. We also demonstrate that the Pallas catchment meets the need for sustaining and pushing the boundaries of critical long-term integrated ecohydrological research in high-latitude environments.

KEYWORDS
biogeochemistry, catchment, hydrology, isotopes, measurements, subarctic

1 | INTRODUCTION

High-latitude areas are facing an unprecedented transition in the near future as warming air, precipitation changes, and sea ice cover reductions continue to drive broad-scale and long-term change across the northern areas (Bailey et al., 2021; Bekryaev et al., 2010; Bintanja & Selten, 2014; Buchwall et al., 2020; Cohen et al., 2014; Ernakovich et al., 2014; Lee et al., 2011; Liston & Hiemstra, 2011; Neumann et al., 2019). Such transitional changes result in loss of freshwater ice (MacGreggor et al., 2020; Prowse et al., 2006; Sharma et al., 2019), with associated climate and ecological repercussions (Brown & Duguay, 2010). Long-term scientific monitoring programs are critical for detecting changes, understanding the baseline conditions, and quantifying the magnitude and frequency of change at high latitudes (Buchwall et al., 2020; Laudon et al., 2017; Luo et al., 2011). It is particularly important to have integrated research programs with cross-disciplinary approaches, uniting multiple scientific fields and enabling comprehensive analyses across boundaries in the Arctic landscape.

The Arctic water cycle is currently undergoing marked changes in three key components: the cryosphere, atmosphere, and hydrosphere (Cohen et al., 2020; Vihma et al., 2016). Changes in the Arctic water cycle reflect complex interactions in Arctic landscapes, processes, and ecosystems. Examples include retreating seasonal snow cover, increasing temperatures and precipitation, and shifts in precipitation from snow to rainfall (Bring et al., 2016; Hansen et al., 2019; Krasting et al., 2013; Pulliainen et al., 2020). Seasonal soil frost and permafrost conditions are predicted to change substantially (Aalto et al., 2018; Ala-Aho et al., 2021a, 2021b; Biskaborn et al., 2019; Wang et al., 2019), modifying hydrological pathways and biogeochemical processes (Czimczik & Welker, 2010; Lupascu et al., 2018; Nowinski et al., 2010; Serikova et al., 2018) and causing infrastructure failure (Hjort et al., 2018). The consequences of warming are likely to be severe in subarctic systems in the near future as slight changes in temperature can alter the magnitude and timing of snow accumulation and melt (Carey et al., 2010; Mioduszewski et al., 2014; Richter-Menge & Druckenmiller, 2020). Increased temperatures and the shift in growing seasons will cause rapid changes in the hydrosphere and ecohydrological connections within subarctic catchments, for example by amplifying lake bed drying and forest and shrub encroachment, and modifying CO_2 and CH_4 feedbacks (Blanc-Betes et al., 2016; Ives et al., 2012; Shen et al., 2014; Tape et al., 2012).

Understanding the complex linkages and interactions between water inputs, storages, water turnover times and outputs, and how hydrology controls biogeochemical cycles and vegetation water usage represents a major challenge in ecohydrology (Guswa et al., 2020). However, substantial progress has been made using water isotope forensics (Ala-Aho et al., 2021a, 2021b; Bailey et al., 2019; Jespersen et al., 2018; Penna et al., 2018). A better understanding of hydrological processes is especially important in subarctic mosaic landscapes with high variability in connectivity between diverse landscape elements (Laudon & Sponseller, 2018; Lyon et al., 2010). It is important to gain a better understanding of how large-scale changes affect ecohydrological processes and to predict and mitigate these effects, particularly in subarctic and Arctic regions where ongoing changes are rapid (Bring et al., 2016). Long-term research stations offer valuable potential for monitoring ecohydrological processes and supporting modelling efforts, yet there are few stations with a full catchment-scale platform for ecohydrological studies in the subarctic region (Laudon et al., 2017). Due to the shortage of synchronous measured data on the climate-cryosphere-hydrology-ecology system in subarctic regions, and the highly variable spatial seasonal connectivity and disconnectivity within subarctic catchments, a clear understanding of their ecohydrological functioning is currently lacking (Jencso et al., 2009; Tetzlaff et al., 2007; Wainwright et al., 2011).

Hydrological processes are key factors that control carbon (C), nitrogen (N), and greenhouse gas (GHG) exchange and balances (Blanc-Betes et al., 2016). Lateral carbon fluxes, which occur in the form of dissolved organic (DOC), dissolved inorganic carbon (DIC) and particulate C, act as a key link between terrestrial and aquatic ecosystems (Csank et al., 2019; Giesler et al., 2014; Zimmer & McGlynn, 2018). To date, the few studies combining high-frequency atmospheric and aquatic flux measurements at the individual forest or peatland sites indicate that the proportion of aqueous flux in the net C balance may be considerable (Nilsson et al., 2008; Öquist et al., 2014; Worrall et al., 2009), but in other systems, it comprises only a small fraction of catchment C fluxes (Tomco et al., 2019). Furthermore, recent studies highlight the role of headwaters as hotspots of CO_2 losses from streams and show that groundwater contributes disproportionately to CO_2 in headwater streams (Duvert et al., 2018; Rocher-Ros et al., 2019).

Here, we synthesize new and existing data to produce a conceptual ecohydrological model for the Pallaslompolo catchment in Arctic Finland (hereafter Pallas). Pallas is an established research site for atmospheric, ecosystem, and environmental research (Lohila et al., 2015). We propose ways forward and provide research suggestions for ecohydrology studies in the subarctic. A better understanding of subarctic ecohydrological processes at temporal and spatial scales can be a means of predicting and managing ecohydrological change. We also introduce the subarctic Pallas research catchment as a platform for atmospheric, terrestrial, and ecohydrological research, and a successful example of the benefits obtained from scientific cooperation and integration across disciplines.

2 | SITE DESCRIPTION

The Pallas area has a long monitoring history. The first weather station in the Pallas region was established in 1935, atmospheric research started in 1991 with air pollution monitoring, and in 1994 a Global Atmosphere Watch (GAW) station was established (Lohila et al., 2015). The first eddy covariance flux station for monitoring ecosystem-atmosphere exchange of GHG was established at Kenttärova forest in 2002, followed by flux stations at Lompolojänkkä wetland (2005), Sammaltunturi fell mountain top (2011), and Pallaslompoloniemi lakeshore (2013, Lohila et al., 2015; Aurela et al., 2015). The Pallas station is situated -in the sub-arctic region, in an area comprising forests, wetlands, lakes, and treeless fells (Aurela et al., 2015). Pallas is part of the long-term Integrated Carbon Observation System (ICOS) network in Finland, which produces high-resolution gradient measurements of carbon dioxide (CO_2), water vapour, and energy exchange fluxes, together with several other ecosystem variables. Additionally, GHG fluxes are measured at various upland locations using, and in the stream and lake using floating chambers. The subcatchment Pallaslompolo, which is part of Lake Pallasjärvi catchment (total area 105.2 km^2), is part of the national research infrastructure in Finland (INAR RI Ecosystems) and in the wider circumpolar region. It contributes to over 15 European and global research and monitoring programs (Lohila et al., 2015).

The Pallas catchment (total area 4.42 km^2) of the Lompolonjängänoja stream is located next to Pallas-Ylläs National Park in northern Finland (Figure 1). The catchment drains to Lake Pallasjärvi and ranges in altitude from 268 m to 364 m a.s.l. Forest soils at Pallas are Podzols that consist of gravelly sandy and sandy tills, with an average organic layer depth of 3–4 cm, distinct eluvial Ae and enriched Bf/Bs horizons of varying thicknesses, and soil organic matter content that gradually decreases from ~10% in topsoil to less than 1% at 90 cm depth. Hydraulic conductivity for forest soils ranges from $1.25{\cdot}10^{-5}$ m/s to $1{\cdot}40^{-6}$ m/s at 5 cm depth and decreases ($7.66{\cdot}10^{-6}$ to $9.78{\cdot}10^{-7}$) at 30 cm depth. Although we do not have undisturbed soil samples for hydraulic conductivity analysis from deeper soil, a decrease in mean porosity from 0.53 at 5 cm depth to 0.26 at 60 cm depth and dry bulk density increase from 0.90 g/cm^3 to 1.89 g/cm^3 indicates that hydraulic conductivity may decline rapidly due

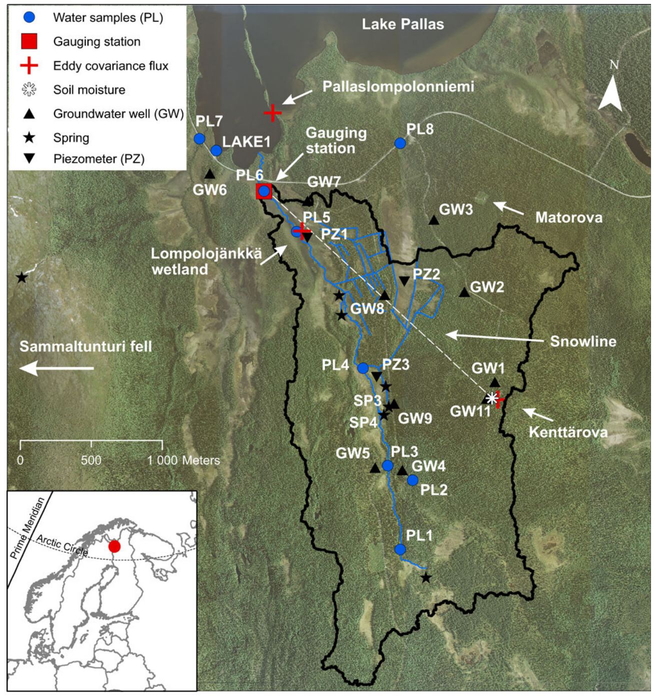

FIGURE 1 Overview of the Lompolonjängänoja catchment at Pallas, northern Finland. The study catchment drains into the freshwater Lake Pallas. In addition to the gauging station at the outlet of the catchment, hydrological fluxes are monitored across the catchment. A network of stations providing meteorological, soil, and snow measurements supports hydrological research

to soil consolidation bellow 50 cm. Soil thickness is thin in high altitude areas (~1–3 m), but increases towards the catchment outlet. The landscape varies from coniferous forests to various types of mires: open fens, treed mires with typical poorly growing trees, and paludified forest areas. The mires are characterized by hummock and hollow microtopography and can be considered 'pristine', although there are some old ditches in the catchment area in one of the upslope mires. Manual peat thickness measurements were conducted in some mire parts in different catchment locations and the maximum peat thickness found was 3.85 m and median 1.35 m. The average degree of humification of peat (depth 0–3 m) in the area is H4 (range H1–H7 in the top 80 cm of peat), based on the von Post scale (Hobbs, 1986). Hydraulic conductivity of the peat, determined using a direct-push piezometer with a falling head, varies between $1{\cdot}10^{-3}$ and $1{\cdot}10^{-8}$ m/s from the surface (10 cm) to deeper layers (1.6 m). Hydraulic conductivity is relatively high (>$1{\cdot}10^{-5}$ m/s) for the top 60 cm of peat, indicating that the structure of the peatland matrix can promote lateral subsurface flow in the upper part of the peat profile. The Pallas site does not have permafrost but nearby areas have palsa mire formations containing permafrost layers.

2.1 | Climate and precipitation data

The climate of Pallas is characterized as subarctic with persistent snow cover during winter. The mean annual temperature at

Kenttärova weather station is 0.4°C (2003–2019), ranging from +13.9°C (July) to −11.3°C (January). Mean annual precipitation is 647 mm (2008–2019) and ~42% falls as snow, with maximum snow depth in April. Seasonal soil frost occurs within peatlands and uplands and is up to ~0.5 m deep. The mean annual maximum snow depth, measured by depth sensor, was 105 cm for the period 2007–2019. The mean annual snow water equivalent (SWE) at the nearby Pulju station was 200 mm in the period 1967–2020. Snowmelt occurs typically in May and the first snow appears in mid-October. Long-term snow depth and SWE at the snowline are measured at Raattama and Pulju (located 16 and 34 km away from the catchment, respectively). During 2017 a new snow course was established in the catchment, and snow depth and SWE are measured along a 2-km transect from Kenttärova to the stream gauging station at 2 week intervals. Snow depth is also recorded with an automated ultrasonic snow depth sensor (SR50-45H, Campbell Scientific Inc.) with an accuracy of ±1 cm at the Kenttärova meteorological station and in Lompolonjänkkä mire.

2.2 | Field measurements and active data collection

2.2.1 | Hydrological data and water geochemistry

Since summer 2013, the Finnish Environment Institute (SYKE) has monitored streamflow at 15-min intervals in the lower reaches of the catchment using a 120-degree V-notch weir (Figure 1). Soil moisture is measured by the Finnish Meteorological Institute (FMI) using time-domain reflectometry (TDR, Stevens Water Monitoring Systems Inc.) sensors at two locations and depths (5, 20 cm) in the Kenttärova forest area. Soil moisture is also measured by SYKE at four depths (10, 30, 50, 70 cm) at the Matorova hill slope since June 2014, and using Soil Scout (Soil Scout, SoilScout Oy, Finland) sensors at three locations and three depths (5, 30, 60 cm) since June 2018. Groundwater (GW) level (depth range 1–5.7 m) and temperature is recorded every 15 min interval in nine groundwater wells and peat piezometric head using three piezometers with water level loggers (Solinst levelogger, Solinst Canada Ltd., ON, Canada). Chemical monitoring of groundwater has been carried out by SYKE in one GW well (GW8) and in one natural spring since June 2018. Since 2015, stream water geochemistry is sampled at points PL1, PL2, PL3, PL4, PL5, PL6, and lake (L); (see Figure 1), and analysed for dissolved organic carbon (DOC), dissolved inorganic carbon (DIC) and silica (SiO_2), and occasionally for other solutes. At the catchment outlet (PL6), water chemistry samples have been taken as part of national and international monitoring programs since May 2017. High-resolutions DOC as fluorescent dissolved organic matter (fdom), pH, turbidity, and water temperature measurements are made (using YSI-EXO sensors, YSI Inc, OH) and pCO_2 and dissolved oxygen (O_2) concentrations are measured at one stream gauging location (PL6). O_2 is measured every 15 min using the RDO PRO-X Dissolved Oxygen Probe (In Situ, Inc. UK) submerged in water at depth of ca. 50 cm. The sensor window is cleaned weekly in the summertime. The pCO_2 is measured with a bespoke system following Hari et al. (2008).

2.2.2 | Eddy covariance flux measurements at Lompolojänkkä mire, Kenttärova, and Pallaslompolonniemi

Ecosystem-atmosphere GHG exchange and meteorological conditions (precipitation, air temperature, potential evaporation, incoming and reflected solar radiation) are measured by the FMI at the Kenttärova forest site, Lompolojänkkä mire, and Pallasjärvi lake shore within the Pallas catchment, using eddy covariance flux stations (Table 1). The eddy covariance measurement systems consists of a 3-D sonic anemometers (USA-1, METEK Gmbh, Elmshorn, Germany) and closed-path fast-response CH4 analyzers (RMT-200, Los Gatos Research, Inc., CA), for which air is sucked through a 14-m heated inlet tube mounted at the top of a 3 m high mast located in the middle of the fen. The CO_2 fluxes are measured with a closed-path LI-7000 (Li-Cor, Inc.) CO_2/H_2O analyzer at the same height using an 8-m long heated inlet tube and a flow rate of 5–6 L min^{-1}. Synthetic air without CO_2 is used as a reference gas. The fluxes are calculated as 30-min averages from the 10 Hz data following standard protocols including coordinate rotation, peak removal, data signal synchronization, compensation for water vapour fluctuations, and correction for high-frequency attenuation (Aurela et al., 2009; Aurela et al., 2015; Lohila et al., 2015). Supporting meteorological measurements including air temperature and humidity at 3 m height (HMP 35, Vaisala Oyj, Helsinki, Finland), soil temperature at 0.07, 0.30, and 0.60 m depth (PT100, Pentronic, Gunnebo, Sweden), GW level (PDCR1830, Campbell Scientific Ltd., Loughborough, UK), and snow depth (SR-50, Campbell Scientific Ltd., Loughborough, UK), are collected by a QLI-50 datalogger (Vaisala Oyj, Helsinki, Finland) as 30-min averages.

2.2.3 | Peat and stream water CH_4 concentration measurements at Lompolojänkkä mire

Daily mean concentration of methane (CH_4) in the peat was monitored at Lompolojänkkä mire. Measurements were obtained using two PTFE tubes (length 50 m, internal diameter 8 mm, external diameter 10 mm) buried in the peat to a depth of ~0.1–0.15 m, in two areas ~500 m^2 north and west of the eddy covariance tower, respectively. The tubes were automatically sampled once a day, with a flow rate of 2 L min^{-1}. It was assumed that the concentration in the tubes equilibrated with that in the peat during the 24 h after sampling. During the 3-min sampling, the CH_4 concentration was analysed with an Agilent 6890 N gas chromatograph (Agilent Technologies, Inc., Santa Clara, CA). For a more detailed description see Lohila et al. (2010). The concentration of CH_4 in stream water was monitored 17 times during the snowmelt period (April 27 to May 132 009) near gauging station PL6, using the headspace technique (Ding et al., 2002). In brief, immediately after sampling of three parallel stream water samples collected

TABLE 1 Summary of active measurements conducted at the Pallas study site, 2002–present

Variable	Location in Figure 1	Started	Time resolution	Data contact	Data used in present study
Meteorology	Kenttärova[a] and Lompolojänkkä[b] stations				
Wind speed	Eddy covariance flux stations	2002	1–30 min	FMI	
Air temperature	Eddy covariance flux stations	2002	1 min	FMI	[a]
Relative humidity	Eddy covariance flux stations	2002	1 min	FMI	
Short- and long-wave radiation balance	Eddy covariance flux stations	2002	1 min	FMI	
Precipitation	Kenttärova[a] and Lompolojänkkä[b] stations	2007[a] and 2018[b]	1 min	FMI	[a]
Snow depth	Kenttärova[a] and Lompolojänkkä[b] stations	2005[a] and 2018[b]	10 min	FMI	[a]
Soil temperature	Eddy covariance flux stations	2002	30 min	FMI	[a]
Hydrology					
Streamflow	PL6 (gauging station)	2013	15 min	SYKE	[a]
Snow water equivalent	Snowline	2018	2 weeks	UniO	[a]
Soil temperature and moisture at 5, 30, 60 cm	Kenttärova station	2018	20 min	UniO	[a]
Soil temperature and moisture at 5, 20 cm	Kenttärova station	2002	30 min	FMI	
Soil moisture at 10, 30, 50, 70 cm	Matorova station	2014	30 min	SYKE	
Soil temperature at 0.5, 10, 20, 30, 50, 100 cm	Lompolojänkkä	2002	30 min	FMI	
Groundwater level and temperature	GW1–GW11	2016	15 min	UniO	[a]
Peatland water table	PZ1–PZ3		15 min	UniO	[a]
Unmanned Aerial System: SfM snow depth	Snowline	2018	Several campaigns	UniO	[a]
Unmanned Aerial System: SfM snow depth, infrared and multispectral imaging	Catchment area	2018	Several campaigns	UEF	[a]
Biogeochemistry					
Net ecosystem CO_2 and CH_4 exchange by the EC method	Eddy covariance flux stations. Kenttärova CO_2 since 2002, CH_4 since 2018; Lompolojänkkä CO_2 and CH_4 since 2005; Pallaslompolonniemi CO_2 since 2013, CH_4 since 2020	Variable	30 min	FMI	[a]
Peat pore space CH_4	Lompolojänkkä station	2009 only	1 day	FMI	[a]
Stream CH_4	PL6 (gauging station)	2009 only	1 day	FMI	
Groundwater chemistry (∼50 parameters)	GW8	2018	6 months	SYKE	
Stream water (DOC, DIC, SiO_2)	PL1-PL5	2015	2 weeks	FMI	
Lake water	LAKE1	2015	2 weeks	FMI	
Stream water (∼40 parameters)	PL6 (gauging station)	2017	2 weeks	LUKE	
TOC (fDOM)	PL6 (gauging station)	2018	30 min	SYKE	[a]
pH	PL6 (gauging station)	2018	30 min	SYKE	
Turbidity	PL6 (gauging station)	2018	30 min	SYKE	
Stream water temperature	PL6 (gauging station)	2018	30 min	SYKE	
Stream CO_2	PL6 (gauging station)	2018	30 min	FMI	
Stream O_2	PL6 (gauging station)	2018	30 min	FMI	

(Continues)

TABLE 1 (Continued)

Variable	Location in Figure 1	Started	Time resolution	Data contact	Data used in present study
Isotope hydrology					
Precipitation	4 km north-west from PL6	2018	1 day	UniO	[a]
Snowpack	Snowline, 12 locations	2018	14 days	UniO	[a]
Snowmelt	Snowline, 11 locations	2019	1–3 days	UniO	
Groundwater	GW1–GW11, PZ1–PZ3	2014	14–30 days	UniO	[a]
Soil water (5, 30, 60 cm)	Kenttärova	2018	~30 days, or opportunistically	UniO	
Tree xylem water	Kenttärova	2018	~30 days, or opportunist-ically	UniO	
Stream	PL1–PL6	2014	14–30 days	UniO	[a]
Stream	PL6 (gauging station)	2019	6–24 h	UniO	[a]
Continuous vapour[b]	Sammaltunturi station	Dec 2017	1 s	UniO	
Continuous stream[b]	Gauging station	Summer 2018	1 s	UniO	

[a]Data used in present study.
[b]Picarro instruments L2130-I (Picarro Inc. CA) have been installed at the Sammaltunturi fell Atmospheric Research Laboratory for atmospheric water vapour isotope (δ18O, δ2H, d-excess) measurements in 1 s interval (Bailey et al., 2021) and a second liquid water Picarro has been installed at the Lompolojängänoja stream hut for stream water isotope measurements in 1 s interval. Both these perform high frequency measurements.

at the same time, 50 mL of water was flushed with 50 mL of synthetic air for 2 min, and the concentration in the headspace gas was analysed using the same gas chromatograph as above. The CH_4 concentration in water was calculated by applying Henry's law (Ding et al., 2002).

2.2.4 | Stable water isotope data

Precipitation samples for stable isotope ($\delta^{18}O/\delta^{2}H$) analysis are collected at fortnightly to monthly intervals at Matorova using an International Atomy Energy Association (IAEA) sampler (IAEA, 2014). Since 2018, event-based precipitation samples have been collected manually and using an automatic ISCO sampler (Model 6712, Teledyne ISCO, NE). Precipitation samples are also collected at the official Global Network of Isotopes in Precipitation (GNIP, IAEA NUCLEUS Portal) station at Rovaniemi (177 km to the south-east) and at Sodankylä Tähtelä (123 km to the east). Surface water samples for isotope analysis are also collected at six locations within the Lompolojängänoja stream (PL sites), in boreholes (GW and PZ sites), springs (SP sites), and from Lake Pallasjärvi (L1). All water grab samples for stable isotope analysis are collected by filling 15- or 50-mL bottles with no headspace. An automated ISCO sampler is used to sample stream water at the outlet (PL6). Zero-tension lysimeters and suction lysimeters at Kenttärova are used to sample the soil water component. The snowcourse is regularly sampled for snowpack isotopes, and snow lysimeters are used to monitor snowpack and snow meltwater isotope concentrations. All water isotope samples are stored in darkness at $+4^{\circ}C$ until analysis. Dual isotope ratios of water samples, $^{2}H/^{1}H$ and $^{18}O/^{16}O$, are determined using cavity ring-down spectroscopy with a Picarro L1102-i, L2130-i, or L2140-i spectrometer at the University of Oulu, Finland, and calibrated using in-house standards calibrated to Vienna Standard Mean Ocean Water (VSMOW). All isotope ratios are expressed in δ notation relative to VSMOW, with precision for $\delta^{18}O$ and $\delta^{2}H$ values of ±0.1‰ and ±1.0‰, respectively. Additionally, the secondary parameter deuterium (d)-excess is utilized and calculated as $\delta^{2}H - 8 \times \delta^{18}O$ (Dansgaard, 1964).

2.2.5 | Spatial UAS measurements at Pallas

Several unmanned aerial system (UAS) campaigns have been carried out in the Pallas catchment to characterize the spatiotemporal variation in snow depth and snow accumulation/melt patterns, and to investigate groundwater seepage to stream and peatland areas. Georeferenced wall-to-wall UAS multispectral and RGB data covering the entire Lompolonjängänoja catchment have been collected in both summer and winter. Snow-free data collection has been conducted in early summer immediately after the snowmelt growing season peak in July.

Four different multicopters (DJI Mavic Pro, DJI Phantom 4 Advanced, DJI Phantom 4 RTK, and DJI Matrice 210) and an eBee Plus RTK fixed-wing UAS have been used in surveying snow depth in the area. The basic approach has been to utilize UAS and Structure from Motion photogrammetry (Westoby et al., 2012) to produce a time series of digital surface models (DSM) throughout winter and spring, and then compare winter DSM with snow-free summer DSM to extract snow depth. The data are georeferenced using ground control points measured by a real-time kinematic Global Navigation

Satellite System (with RTK GNSS) receiver and/or using RTK solution to improve the positioning accuracy of the UAS (DJI Phantom 4 RTK and eBee Plus RTK). The accuracy of the DSM and resulting snow depth maps are assessed with comparison to the "ground-truth" checkpoints collected with the RTK GNSS receiver and snow course measurements collected during field campaigns.

2.3 | Data analysis

We focus on reporting and analysis of meteorological, hydrological, and biogeochemical datasets, with the aim of identifying the dominant ecohydrological processes in the Pallas catchment. For stable water isotope analysis, we use only results obtained from spatial grab samples (2014–2018), while other isotope measurements will be documented in detail in future studies. Isotope samples were used to identify and delineate the pathways and sources of water in the Lompolonjänganoja stream by calculating proportions of groundwater and new water fractions, following Kirchner (2016a, 2016b). In addition, young water fraction (Fyw) and short-term aquifer volume (STS, mm) were calculated. Young water, defined as the proportion of catchment outflow younger than approximately 2–3 months, can be estimated directly from the amplitudes of seasonal cycles of stable water isotopes in precipitation and streamflow, while short-term aquifer volume is the aquifer volume from which young streamflow is derived. End-member mixing and end-member splitting analyses were used for streamflow quantification as a mixture of two isotopically distinct precipitation sources (snow and rain) and the seasonal proportioning of precipitation contributing to streamflow (Kirchner & Allen, 2020). Details of the calculations are provided in the Supporting Information, Appendix. The snowy and rainy seasons are based on a rain-snow threshold temperature of 1°C (Jennings et al., 2018).

We used peat and streamwater CH_4 concentration and eddy covariance measurements at Lompolojänkkä mire to examine the role of hydrological processes on biogeochemistry in subarctic conditions during the spring freshet. We assessed dominant in-stream carbon processes using fdom (a surrogate for TOC, measured in 15 min intervals) datasets and wavelet analysis (Crawford et al., 2017; Riml et al., 2019; Schmidt et al., 2019). Wavelet transform is a form of spectral decomposition that transforms time-series into time-dependent spectral series. The transform localizes the time series in time and frequency and allows the identification of periodicities at different time frequencies and locations. Wavelet coherence was used to examine the relationship between TOC and streamflow. Wavelet coherence combined the wavelet transforms of the TOC and streamflow time series to identify the local correlation of variables at different time frequencies. Further details of coherence calculation can be found in Grinsted et al. (2004). We used fine-resolution UAS-based datasets to assess the importance of spatial analysis and hydrological connectivity for processes and to explore the possibilities for data analysis with UAS datasets.

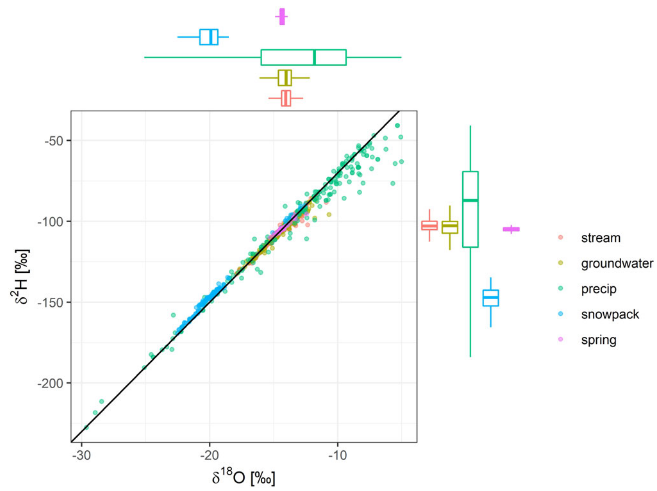

FIGURE 2 Stable water isotope values in stream water, groundwater, precipitation, snowpack, and natural springs in the Pallas catchment during 2014–2018. Boxplots indicate variation in different isotope categories

3 | RESULTS AND DISCUSSION

3.1 | Seasonality dominates the ecohydrological regime

In the Pallas area, the observed seasonal variability in precipitation $\delta^{18}O$ values ranges between −23‰ and −8‰, and in-stream water $\delta^{18}O$ values range between −14‰ and −10‰ (Figure 2), and exhibit strong seasonal fluctuation and variation along the stream continuum (Figure 3). Groundwater (GW) isotope values (mean $\delta^{18}O = -13.8‰$) are similar in all GW wells and springs. GW wells show some seasonal isotope variation, especially during the snowmelt period, indicating direct recharge. Spring isotope values show smaller variability compared with groundwater samples, indicating hydrological mixing along the hillslope transect from recharge to discharge.

Sampling sites PL1 and PL2 represent headwater locations with strong GW input, but moving downstream the isotope composition of stream water (locations PL3-PL6) remains relatively stable during the summer season. Some variation in isotopic composition is dominated by summer precipitation that enters the stream via overland flow paths. The consistency in average isotope values highlights the importance of GW inputs along the stream continuum, while surface water sources via overland flow paths only cause some subtle temporal variation in $\delta^{18}O$ and *d-excess* values, mainly during the summer period (Figure 3). Distinct changes in isotopic composition during the snowmelt period show the importance of spring sampling in understanding the dynamics of groundwater (GW) and snowmelt water dominance. For example, in 2014, the winter baseflow at PL4 and several isotope samples from the stream outlet (PL6) show snowmelt-related depletion of $\delta^{18}O$ and δ^2H values.

To the contrary, stream water *d-excess* values remain relatively consistent (~10‰) through time and are similar to the measured precipitation *d-excess* values. There is some evidence that evaporation is

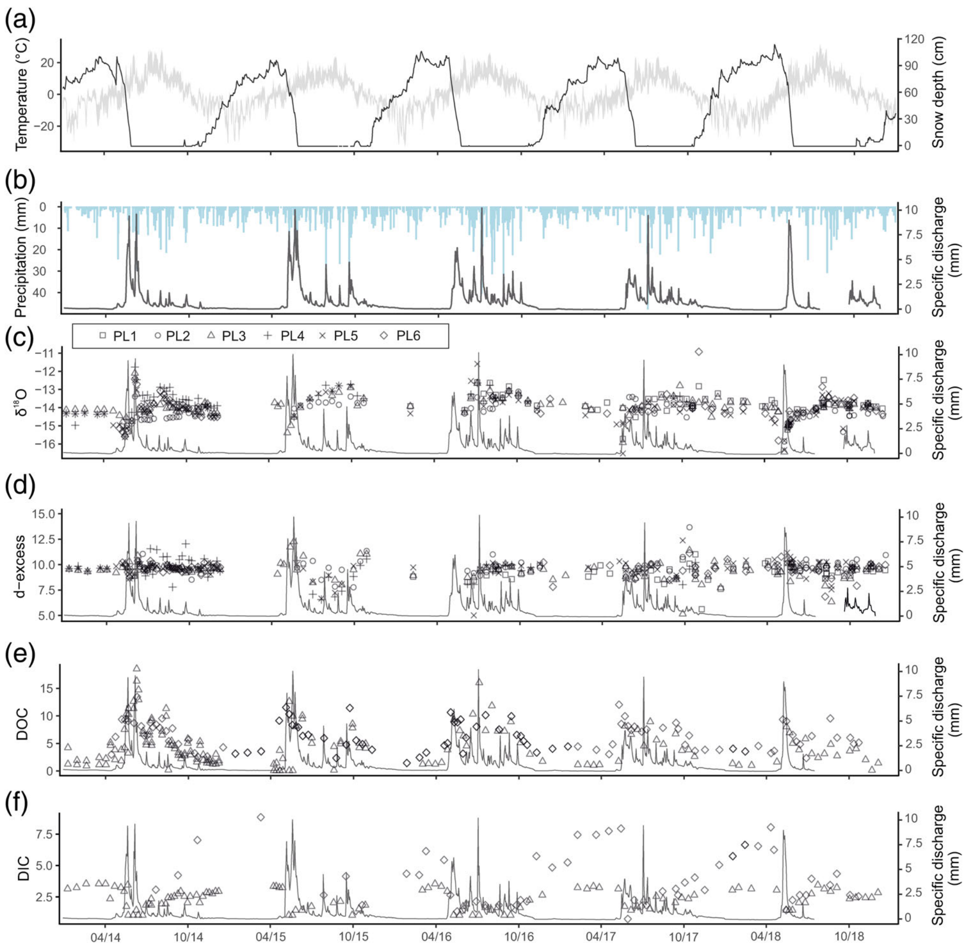

FIGURE 3 (a) Daily variation (min, max) in air temperature (grey) and snow depth (black), (b) daily precipitation (blue) and specific discharge (black), (c) $\delta^{18}O$, (d) deuterium (d-)excess in different stream continuum sites at Pallas, and (e) dissolved organic carbon (DOC) and (f) dissolved inorganic carbon (DIC) at sites PL3 and PL6

an important process in water fluxes in the Pallas catchment, as evidenced by the isotopic enrichment in stream water values in the dry summer of 2015. Evaporation rates are typically low in subarctic conditions, but increasingly dry summer periods are expected in arctic areas (Bring et al., 2016). Thus isotopes can provide a tool to assess evaporative influence also in sub-arctic conditions. In other years, evaporation from the wetlands appears to be minimal based on *d-excess* values, possibly due to the cooler summer temperatures, cold-air drainage at night, and high levels of water transported from the surrounding forest, through the wetlands and into the stream.

Values of DOC and DIC increase along the stream continuum from PL3 until PL5 (Figure 3). It is typically assumed that DIC is primarily controlled by GW inputs, whereas DOC is linked to surface water connections such as overland flow and runoff patterns (Giesler et al., 2014; Nydahl et al., 2020), as seen in the data (Figure 3). Accumulation of carbon along the stream indicates increased connectivity within the catchment (DOC from soils and peatlands), but also the progressive increase of GW seepage to the stream network (i.e., DIC from GW). Headwater stream locations (PL1–PL3) drain uphill forest areas with more limited contact with stream-side peatlands, but downstream increased DOC concentration is evidence of connectivity between the stream and riparian peatlands Additionally, downstream locations also receive more groundwater seepage, as indicated by DIC concentration levels and the presence of natural springs near to stream channels in the downstream locations. An inverse relationship between DOC and DIC in stream discharge is evident during all major peak flow events, indicating a change in flow regime from GW-dominated to surface water (SW)-dominated overland flow. This observation is further supported by *d-excess* values, where variability increases in the stream continuum (as in Sprenger et al., 2017), but values are not stable during summer (Figure 3). Our stream DOC data indicate that DOC-rich water from peatlands flushes mainly when the peatland is hydrologically connected to the stream, typically during a wet year such as in 2016. The DOC-DIC relationship shows strong seasonality in shifting from GW to surface water dominance in the Pallas catchment when overland flow paths activate. The data from periodic sampling at Pallas show considerable temporal variation in water quality parameters, suggesting a need to study the Pallas catchment and similar catchments by using high-resolution timeframes to identity event-scale patterns in ecohydrological processes (Tunaley et al., 2016).

Shifts in seasonality due to climate change are emerging (Bintanja & van der Linden, 2013), yet understanding their impacts at the landscape level and how these changes are linked to variations in atmospheric circulation, precipitation, and/or extreme weather patterns (Klein et al., 2015; Puntsag et al., 2016), remains uncertain. Several studies indicate increasing atmospheric humidity as a result of reduced sea ice concentration and longer open water periods in the

Arctic Ocean (Stroeve & Notz, 2018). These changes were recently quantified using the Pallas water vapour isotope monitoring program (Bailey et al., 2021), which showed a direct link between extreme snowfall in northern Europe and increasing atmospheric moisture sourced from ice-free Arctic seas. However, the current understanding of how shifts in precipitation (timing and volume) and moisture sources affect Arctic hydrological processes at the catchment-scale is limited. Meteoric and stream water isotope forensics (Bailey et al., 2021; Mellat et al., 2021) and measurements of plant water sources (Brooks et al., 2010; Jespersen et al., 2018; Welker et al., 2005) provide a valuable tool for quantifying atmosphere-cryosphere-hydrosphere-ecological interactions. Future shifts in seasonal patterns of synoptic climate, weather, snow, and sea ice in the Arctic region will shape moisture sources (Bailey et al., 2019; Kopec et al., 2016) as some regions gain more precipitation but also summer evaporation rates increases. Shifts in temporal and spatial precipitation patterns (Kopec et al., 2016) also transform ecohydrological processes (Biskaborn et al., 2019), and call for integrated high-resolution measurements to detect and trace these changes and link them to landscape-level ecohydrological processes. Quantifying these processes requires further investigation, and we stress the continued requirement for well-equipped and integrated research catchments such as Krycklan in Sweden (Laudon et al., 2021) and Toolik Field Station in Alaska (Medvedeff et al., 2021) to have uninterrupted and ongoing monitoring for detection of change in the northern high-latitudes. In particular, integrating spatial mapping with UASs, high-resolution element concentration (e.g., DOC) measurements in the stream continuum and physical-based modelling provides a novel and strong toolbox for further assessment. The holistic measurement concept including traditional grab sampling, high-frequency monitoring and spatial mapping can reveal seasonal changes and also sub-daily variation in the ecohydrological process in these highly responsive subarctic catchments. Stable water isotope measurements, and the latest technology for high-frequency measurements in particular, provide new ways forward to better understand high-latitude catchments.

3.2 | Limited catchment dynamic storage controls hydrological responses

Overall, the Pallas catchment streamflow shows fast responses (<1 h) to precipitation events (Figure 3), indicating rather limited dynamic storage in the catchment. Stream hydrographs are flashy, indicating rapid responses to rainfall events, limited soil storage, and active surface runoff generation from landscape units. Young water fraction (F_{yw}) at the site (0.22) matches median values globally (Jasechko et al., 2016), but is slightly above the median found in snow-influenced alpine catchments (0.16:von Freyberg et al., 2018). Compared to local annual precipitation amounts of 647 mm, mean short-term aquifer volume (STS) values as low as 14 mm support limited catchment storage in Pallas. Furthermore, observations of two isotopically-distinct precipitation types (rain and snowfall) allows direct seasonal partitioning of streamflow inputs using end-member mixing and splitting analyses (Kirchner & Allen, 2020), revealing that only small percentages of rain (8 ± 1%) and snowfall (5 ± 1%) are discharged from the Pallas catchment during the snowy season (Nov-early May). Conversely, 40 ± 6% of rainfall and 24 ± 8% snowfall leave the catchment during the rainy season (late May–Oct), whereby season demarcation uses a rain-snow threshold of 1°C (Jennings et al., 2018, described in details in Dai, 2008). Based on these analyses, 69 ± 9% of streamflow during the snowy season originates from rainfall and 31 ± 9% from snowfall. During the rainy season, 70 ± 9% of streamflow comes from rainfall and 30 ± 9% from snowfall, which is similar to the snowy season. In these calculations, the isotope data and the precipitation data were used from the years 2014–2018. These values are in accordance with the general water balance for Pallas. Despite the rapid catchment response and small STS storage, end-member splitting analysis indicated the dependency of the Lompolonjänganoja stream on inter-seasonal water storages in the catchment. Based on Kirchner and Allen (2020), the rate of evapotranspiration (ET) of precipitation differs from season to season. For instance, 71 ± 9% of snowy season precipitation is lost as evapotranspiration, while 24 ± 8% and 5 ± 1% contribute to rainy and snowy season discharge, respectively. In the rainy season, a smaller fraction of precipitation (52 ± 7%) is lost to evapotranspiration, while 40 ± 6% and 8 ± 1% contribute to rainy and snowy season discharge, respectively. Annual ET derives almost equally from snowy season precipitation (48 ± 7%) and rainy season precipitation (52 ± 7%). Similar trends are also evident in the dual-isotope plot (Figure 2). For example, the stream data for spring and early summer 2014 show relatively low $\delta^{18}O$ values during peak flow from snowmelt, followed by a rapid increase from −15.5‰ to −12‰ coincident with a large rainfall event (Figure 3(c)), and indicative of limited STS catchment storage capacity and an extensive network of rapid surface flow paths. Indeed, the Pallas hillslope is dominated by till with declining hydraulic conductivity to a depth of 30 cm, thus promoting overland strong flow formation as seen in stream discharge and isotopic data. Additionally, shallow soil structures maintain only limited soil and groundwater storage. Our study thus support previous findings conducted in boreal and sub-arctic sites (Sterte et al., 2021) and highlight the utility of stable water isotopes as hydrologic tracers in high-latitude catchments (Lyon et al., 2018).

Subsurface soil was fully saturated during the snowmelt runoff period, but moisture content declined markedly afterward (data not shown), indicating that the majority of snowmelt inputs produce runoff or generate groundwater recharge. In contrast, only large summer precipitation events (>20 mm) increased soil moisture content, indicating that summer precipitation either evapotranspired or produced direct runoff through preferential flow. Following larger rainfall events, catchment soils drain quickly (within days), indicating that soils in the upper hills do not store moisture between precipitation events. Soil moisture measurements indicate that the upper layer (top 5 cm) responds more quickly than lower layers (30 cm) to snowmelt or rainfall inputs, demonstrating flow through the till layers' (cf. Bishop et al., 2011), and enabling quick flow along with the upper more permeable soil layer in the forest areas. These observations are further supported by the minimal lag (within minutes) between rainfall events and water level rise in peatland piezometers, as well as the simultaneous increase in stream discharge due to rapid rainfall runoff from the hills and peatlands directly into the stream. Hence, these data further support that Pallas catchment storage is limited by the relatively shallow, young soil deposit layers. Similar findings have also been observed in previous studies which emphasize how shallow soil deposits exert a strong influence on catchment-scale hydrological and geochemical responses (Laudon et al., 2021; Peters & Driscoll, 1987; Verry & Timmons, 1982). However, to our knowledge this study is one of the few to demonstrate such storage processes in sub-arctic or arctic conditions (Lyon et al., 2018; Sterte et al., 2021; Tetzlaff et al., 2018) and by utilizing multi-year stable water isotope data. In future studies, coupling with local geology and climate change should be further explored and their influence separated. Whilst the climate is changing, local geology is not, and the impact of climate change in subarctic catchments will likely be different depending on the local geological setting. For example, warmer winters might alter water flow paths through peatlands during snowmelt but may not impact flow paths through the forest. Thus, changing climate conditions and impacts calls for a diverse suite of different catchment types and habitats to monitor across the pan-arctic region.

Interestingly, although snowmelt contributes more than one-third of the catchment water input, meltwater isotope values only shift temporarily during the main spring flood peak towards snow isotope values. These data suggest that there is minimal dynamic snowmelt water storage in the catchment, due to highly permeable flow paths through the top peat layer (especially at the fen site), facilitating ephemeral snowmelt water presence in the stream. Short storage during snowmelt is further supported by the observation that the stream water isotope values exhibit only a short period of depletion (i.e., snow-like) and then within weeks become enriched and much more similar to those of GW. Relatively modest, short-lived responses of stream isotope values to snowmelt have been observed previously in other snow-influenced catchments with peat soils (Ala-aho et al., 2018; Tetzlaff et al., 2018). However, the overall isotope values in the stream, groundwater, and springs are depleted relative to precipitation, and gravitate towards depleted snowmelt isotope values (Figure 2), suggesting a dominant role of snowmelt in recharging groundwater reservoirs, as seen globally (Jasechko et al., 2014).

3.3 | The hydrological state of the system regulates GHG and stream carbon fluxes

3.3.1 | High-frequency in-stream TOC monitoring

High-frequency in-stream measurements show that TOC concentrations in the stream are strongly influenced by the onset of snowmelt (Figure 4) and activation of overland flow pathways in the catchment. The TOC concentrations remain relatively steady during winter (less than 5 mg l^{-1}), as discharge remains stable and is dominated by groundwater inputs (see parts 3.1 and 3.2), indicating minimal inputs of TOC to the stream during the winter months due to reduced connectivity with the wider catchment. Similar observations of groundwater influence on TOC have been made e.g., at permafrost sites (Lamontagne-Halle et al., 2018). However, as snowmelt proceeds, TOC concentrations increase substantially with increasing discharge (Figure 4(a)). Snowmelt dominates carbon fluxes in subarctic streams, and is estimated to be responsible for 55% of DOC flux in Arctic rivers (Finlay et al., 2006). Snowmelt leads to activation of carbon-rich flow paths, causing substantial increases in terrestrially derived in-stream organic and inorganic carbon (Giesler et al., 2014). Export of terrestrial carbon to the stream has a strong causal link with aquatic CO_2 emissions, with increased processing of terrestrially derived DOC linked to increased CO_2 emissions in northern systems (Rocher-Ros et al., 2019; Lapierre et al., 2013; Duvert et al., 2018).

The high-frequency in-stream monitoring efforts at the Pallas catchment enable the use of new methods of data analysis such as wavelet transform (Crawford et al., 2017; Riml et al., 2019; Schmidt et al., 2019), which can improve knowledge of carbon sources and related hydrological connectivity in subarctic catchments (Figure 4(b)–(d)). For example, Figure 4(b) shows the development of diurnal periodicity in TOC dynamics after snowmelt begins, which likely reflects the onset of increased microbial activity and greater in-stream processing of TOC as stream temperatures become warmer. Longer-term periodicities over a 128- to 256-h period also occur from early May onwards, and indicate the rising trend in TOC across the snowmelt season. Increasing TOC throughout the snowmelt season may be caused by increasing activation of flow paths in the catchment as snowmelt progresses, which causes increasing transportation of TOC from the catchment to the stream. The theory of increased transport of DOC in snowmelt is supported by the wavelet coherence of the discharge and TOC time series, showing a significant in-phase relationship between discharge and TOC at periodicities between 128 and 256 h (Figure 4(c)). This relationship between discharge and TOC suggests that discharge and TOC increase concurrently in snowmelt season at longer-term periodicities, thereby indicating that the process which increases flow across this timescale may be linked to the process which increases TOC. However at periodicities of 16–32 h, an anti-phase relationship between discharge and TOC emerges and the anti-phase relationship suggests that as discharge increases during the diurnal cycle, TOC decreases, possibly relating to a dilution effect between flow and TOC. Combining high-frequency monitoring with high-frequency data analysis thus has strong potential to identify carbon pathways, timing and controls on carbon fluxes at multi-temporal scales for long time series (Riml et al., 2019).

Future climate change with increasing temperature and precipitation is expected to have a substantial impact on stream carbon fluxes (Parmentier et al., 2017). Changes in winter conditions such as snow depth directly influence soil frost condition, i.e. more snow, less soil frost (Ala-Aho et al., 2021a, 2021b). Additionally, soil freezing controls the biogeochemical activity in the soil, infiltration possibilities and thus impacts the amount of carbon available for export to streams during snowmelt (Haei et al., 2010). High-frequency monitoring efforts for catchments like Pallas, where carbon fluxes are dominated

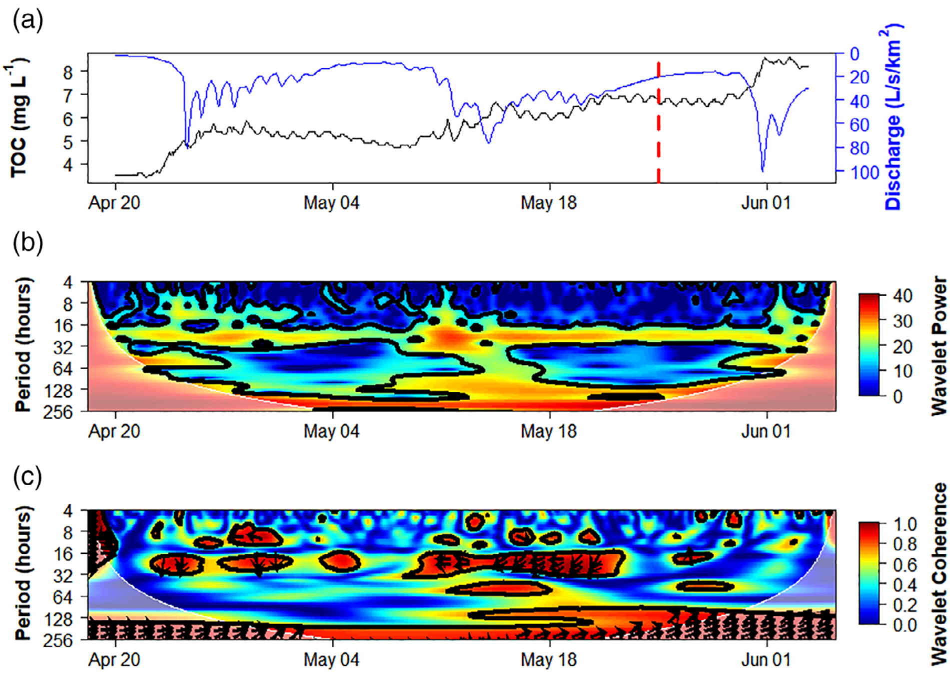

FIGURE 4 Measurements and wavelet transform of data from hourly in-stream monitoring of total organic carbon (TOC) and discharge in the Pallas catchment during the 2019 snowmelt season. (a) Time series of TOC and discharge, (b) continuous wavelet transform of TOC, and (c) wavelet coherence of TOC and discharge. The vertical red dotted line in (a) indicates the end of the snowmelt season in the catchment. Black contours in (b) and (c) demarcate areas of significant high-power periodicity. The wavelet coherence graphs show the phase relationship between the TOC and flow time series, which can be interpreted as the lead/lag relationship between the variables. The phase relationship between two time series is indicated by arrows on the coherence plot. Left facing arrows indicate an in-phase relationship, right facing arrows an anti-phase relationship, up facing arrows indicate that flow leads TOC, while down facing arrows indicate that TOC leads flow

by snowmelt regimes, are therefore critical for documenting current carbon processes such as fluxes and sources and identifying how shifts in climate will impact future carbon fluxes in subarctic streams (Campbell & Laudon, 2019).

3.3.2 | High-frequency monitoring of CO_2 and CH_4 in peatland

Hydrological processes play a dominant role in connecting terrestrial and aquatic CO_2 and CH_4 pools. At the landscape level, a variety of hydrological factors and flow paths control bio-physiochemical processes that substantially influence sources and sinks of GHG. For example, recent analyses of the controls on spatial variability in CH_4 fluxes at the mire site (Zhang et al., 2020) and in the larger Pallas catchment (Räsänen et al., 2021) suggest that hydrological pathways strongly controls the exchange rate and direction of CH_4 exchange. At the mire site, distance to the stream, which controls the area of oxic/anoxic zone in the peat by bringing O_2-rich water to the mire, is reported to be the most important factor explaining the spatial variability (Zhang et al., 2020). For the whole catchment, CH_4 fluxes are reported to be best predicted by topographical wetness indices, Sentinel-1 SAR soil moisture data, and the digital terrain model (Räsänen et al., 2021).

While the strength and variability of CH_4 fluxes are known to be strongly related to hydrology (Knox et al., 2019; Räsänen et al., 2021; Zhang et al., 2020), the seasonal dynamics in CO_2 and CH_4 fluxes typically follow the patterns in vegetation activity and, both directly and indirectly (through phenology), the patterns in temperature. On the other hand, the non-growing season fluxes can be more directly related to hydrological processes, particularly at sites dominated by active surface flow patterns, such as Lompolojänkkä mire. Eddy covariance measurements at Lompolojänkkä show direct interactions between -snow melt period and CH_4 fluxes. In the example of spring 2009, the first warm spell in mid-April, which resulted in depletion in snow cover of approximately 10 cm in a few days, caused a significant CH_4 emissions pulse from the snowpack (Figure 5). An effect of the first warm spell was not seen in any other GHG-related variables, so it was evident that the first peak of CH_4 was released from the snowpack during the first melting period. In CO_2, no such peak was observed, which might be related to the strong interaction between CO_2 and water, based on complex inorganic chemical processes including dissolution of CO_2 and subsequent dissociation of CO_2 into other carbonic species, while CH_4 is much less soluble in water.

The first melting peak was followed by a temporarily colder period (below zero temperatures in day and night) which ended on April 23–24, 2009, after which the temperature mainly stayed above zero. This period of above zero temperatures initiated a second

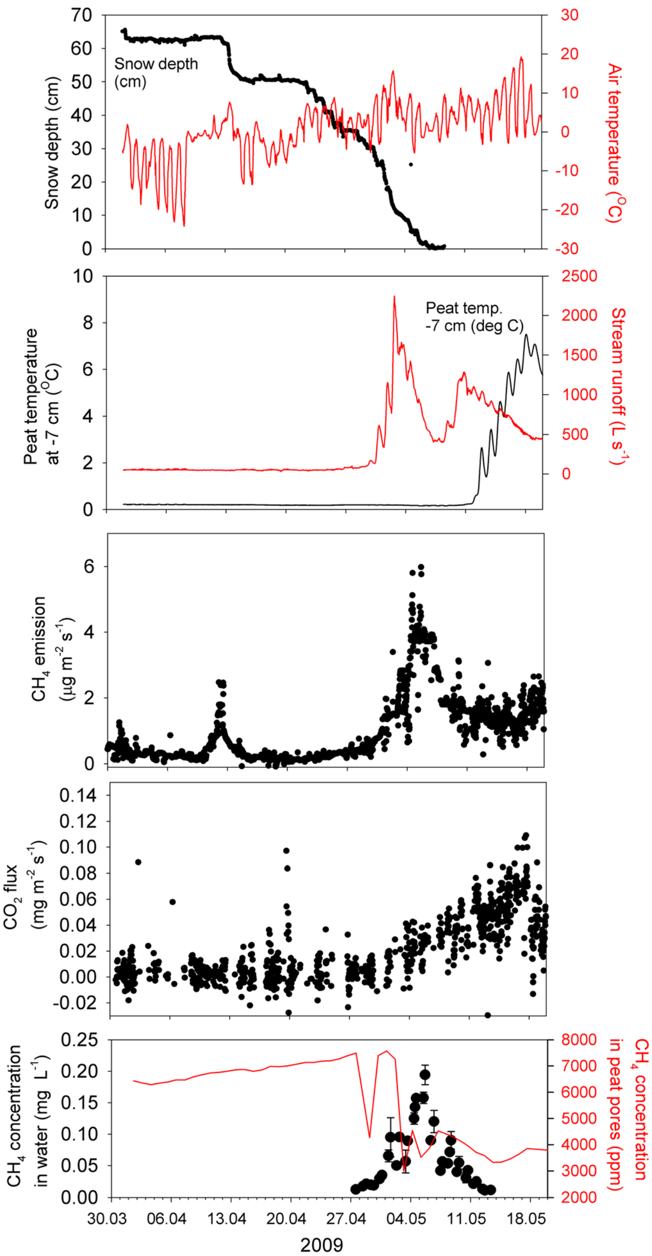

FIGURE 5 (a) Snow depth and air temperature, (b) peat temperature at 7 cm depth and stream runoff, (c) methane (CH_4) emissions, (d) carbon dioxide (CO_2) flux, and (e) CH_4 concentration in peat and concentration of dissolved CH_4 in stream water at Lompolojänkkä mire in spring 2009

melting period, during which the snow melted quickly, but CH_4 emissions increased only slightly. An intensive melting phase with clearly increased CH_4 and CO_2 emissions started on April 30, when streamflow and stream CH_4 concentrations also increased rapidly, with a simultaneous decrease in peat CH_4 concentration (Figure 5). A CH_4 emission spike was two times higher and longer-lasting than the earlier spike, and the CH_4 apparently originated from the peat, having accumulated there during the period when the soil surface was frozen. Notably, the soil at 7 cm depth never showed signs of freezing, but there was a clear ice cover on top of the peat and inside the snowpack, created by the groundwater seepage to add water in the snow and on top of the ice throughout the winter. The soil temperature at 7 cm depth only started increasing after the spikes in CH_4 emissions and changes in peat and stream water CH_4 concentrations had ceased. This result suggests that the observed CH_4 emission peak was due to thawing of the surface peat as the accumulated CH_4 was released into the atmosphere. At the same time, CH_4 dissolved in the stream water, additionally causing a CH_4 concentration spike in stream water.

To our knowledge, these are the first direct observations of a thawing-related CH_4 peak from a peatland with contemporaneous peat and stream CH_4 concentration data measurements. Previously, thawing peaks have been reported from polygonal tundra in Alaska (Raz-Yaseef et al., 2017) and permafrost peatland in China (Song et al., 2012), while no peaks were observed at a Swedish mire with sporadic permafrost (Lakomiec et al., 2021). Similar to these studies, we also conclude that the thawing-related CH_4 peak was attributed to a release of CH_4 stored in peat under the ice and snow. In our data, the height of the spring thawing peak was at the same level with the summer maximum (30-min values, data not shown from the July–August). Quite divergent results were found by Song et al. (2012) and Raz-Yaseef et al. (2017), who reported that the thawing peak clearly exceeded or was lower, respectively, as compared to the summer maximum. It is likely that the size of the peak is greatly affected by e.g. the length of the winter, thickness of the ice cover and rapidness of the melting, and great year-to-year variation in the thawing peak size and even emergence can be expected.

The peak in emissions to the atmosphere observed for CH_4 was not recorded for CO_2, probably due to similar chemistry-related water-CO_2 interactions as observed for the first peak. However, CO_2 emissions gradually started to increase during the final melt, which is potentially attributable to microbial decomposition of organic matter in the peat. At the time of melting, the mire surface was brown as the vegetation had not sprouted after winter. Only later, around May 20, was the first sign of CO_2 uptake observed, after the emergence of the first green leaves. While it is generally acknowledged that hydrology and particularly GW level impose important controls on GHG dynamics, especially in wetlands (Heiskanen et al., 2021), the above example demonstrates the importance of short-term hydrological patterns for GHG emissions. It can be concluded that in the spring-time the connection between hydrology and GHG emissions is mainly related to transport of gases, while during the summer hydrology has direct influence on the microbial processes producing GHGs.

3.4 | Fine-resolution and catchment-scale spatial analysis reveals the importance of connectivity in ecohydrological studies

Our snapshot analysis of Pallas UAS data highlights the importance of fine-scale spatial analyses in high-latitude catchments. In particular, it reveals how snow accumulation and melting are spatially heterogeneous across the catchment and can be mapped in high-resolution using UAS methods. For instance, the results capture spatial differences in snow depth variability for the subarctic forest and peatland, and the increasing snow depth variability with the progress of the snow season, especially during snowmelt (Figure 6(a)). In forested areas, the analysis shows high variability inside forest openings depending on the orientation, with north-facing edges having lower melt speeds than south-facing edges. In addition to standard RGB sensors, infrared/thermal sensors are being used at Pallas. Thermal sensors can provide additional information about GW seepage locations and catchment-scale connectivity. At the Lompolonjänkä peatland at Pallas, thermal camera (flight at 17.6.2018) and ground-truthing seepage observation data reveals clear GW seepage patterns strongly influencing the fen-type ecohydrology of the area (Figure 6 (b)). At the south-east edge of the thermal image, only the narrow stream channel is highlighted as a region of cold water. Moving north (downstream), the cold water regions extend beyond the stream channel, revealing two distinct regions of areal groundwater seepage in the extended stream riparian zone. In Figure 6(b), bluish colour indicates the wettest parts of the peatland and groundwater seepage areas, as groundwater is colder than the surrounding environment. Such regions of GW seepage near streams can create biogeochemically distinct environments (Isokangas et al., 2019; Lupon et al., 2019) that act as hotspots for microbial activity and the carbon source to streams. When combined with water sampling and catchment modelling, thermal imaging analysis (in time and space) can reveal hydrological connectivity at the catchment scale.

These observations highlight the potential of UAS in high-resolution monitoring of snow depth, melt speed and their variability, and in identifying groundwater seepage locations in subarctic land cover types: that is, information that can be used to analyse their relationship to ecohydrological conditions in the subarctic. UAS data could be quantified and combined with more detailed information about snow cover (such as density, isotope composition, etc.) acquired from in-situ measurements to extend their coverage for catchment-scale analysis. Snow coverage and depth, spatial accumulation, melting and the timing of these factors are highly important for subarctic ecohydrological processes.

4 | WAYS FORWARD IN SUBARCTIC ECOHYDROLOGY

Northern ecosystems are highly sensitive to any changes in the cryosphere, and in particular to the loss of distinct temperature and precipitation regimes and the subsequent variation in ecohydrological conditions (Jyväsjärvi et al., 2015; Rolls et al., 2018). Even small changes in annual air temperatures or shifts in seasonal ranges can have drastic ecosystem-scale influences (Jennings et al., 2018) especially related to catchment hydrological responses and carbon processes. Additionally, an increasing proportion of precipitation falling as rain and/or changes in total volumes will rapidly shape eco-hydrological conditions (e.g., snow, soil moisture, carbon transport, stream processes) already in the near future (Campbell & Laudon, 2019; Meriö et al., 2019). Most existing high-latitude research infrastructure is located in temperate or boreal regions, with less permanent infrastructure situated in subarctic or arctic areas (Laudon et al., 2017), and despite an increasing requirement to document baseline conditions and changing processes in the North (Burt & McDonnell, 2015). The Krycklan catchment in Sweden (Laudon et al., 2021) has been a flagship for boreal hydrological and biogeochemical studies for decades. Yet, whilst the distance between the Krycklan and Pallas sites is less than 500 km, their climate, dominant vegetation, and geology types are markedly different. For instance, subarctic Pallas is located near the northern tree line, whereas Krycklan lies in the heart of the boreal landscape (Laudon et al., 2021). Similarly, other long-term, high-latitude research catchment sites such as Toolik Field Station and Bonanza Creek LTER in Alaska (Medvedeff et al., 2021) (http://www.lter.uaf.edu/) or Fuglebekken catchment in Svalbard (Wawrzyniak et al., 2021) are located in the permafrost region or mountainous areas (Finse Alpine Research Centre, Norway; https://www.finse.uio.no/), whereas the Pallas is northernmost existing research station without permafrost. Thus, Pallas bridges a critical gap in the global network of high-latitude catchment monitoring sites that are needed to improve current understanding of ecosystem changes and the hydrological and climatic processes driving them.

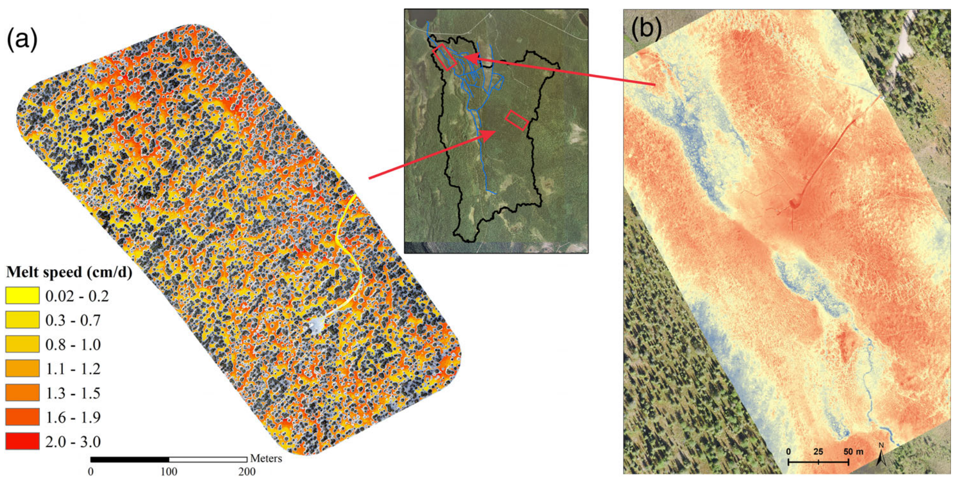

FIGURE 6 (a) Unmanned aerial system (UAS)-based analysis of snow depth and calculated average snowmelt rate over a three-week period, revealing high spatial variation in melting rates at Pallas catchment. UAS-based analysis can reveal spatiotemporal variation in the melting speed of snow layers. (b) UAS thermal camera data analysis can detect groundwater seepage locations and catchment scale connections (bluish colour shows wettest parts of the peatland and groundwater seepage areas)

We propose that future ecohydrological studies in subarctic regions focus on atmosphere-water-ecosystems interactions using combined measurements at broad spatial and temporal scales, and with linkages to physically-based catchment-scale and land-surface models. The novel technical capabilities emerging today allow a move from point measurements to spatial mapping (Figure 6), and from grab samples to high-resolution continuous monitoring in real-time (Figures 4 and 5). Systematic monitoring of coupled atmospheric, biogeochemical, and ecohydrological processes facilitate a better understanding and quantification of how these complex systems interact and function today, and how they may change in the future under shifting seasonal patterns of synoptic climate, weather, snow, and sea ice in the subarctic.

The complex challenges of climate change and associated transformation of subarctic ecosystems call for more holistic science to inform local communities and policy for adaptive management (Prowse et al., 2015). Comprehensive ecohydrological science is needed to improve understanding feedbacks between climate-hydrology-ecosystem boundaries in subarctic conditions. Our observations suggest that limited catchment dynamic storage in subarctic regions that are geologically similar to Pallas may have critical ecohydrological implications given future uncertainties in snowfall inputs (Bailey et al., 2021), and especially the timing of snowmelt processes. Simultaneously, ecohydrological connectivity strongly influences local and landscape processes in terms of carbon (DOC and DIC) export and GHG emissions (Harms et al., 2020). The latest sensor technologies and high-frequency measurements can reveal highly-detailed processes as shown by our snap-shot analysis. Thus, pronounced variations in spatial catchment connectivity, such as during snowmelt and groundwater-surface water connections (Duvert et al., 2018; McKenzie et al., 2021) should be given more consideration as hotspots in the ecohydrological system using the latest technological advances. In studies on subarctic ecohydrology, there is a need to acknowledge the value of long-term monitoring for anticipating future changes (Laudon et al., 2017). Based on the analysis from Pallas and recent findings in other studies, we suggest that future studies in subarctic catchments should focus on: (a) analysis of pronounced seasonality (Post et al., 2019) in the subarctic ecohydrological regime and processes, (b) water dynamic storage, pathways, and soil moisture controlled by ecohydrological processes (Kuppel et al., 2020), and (c) ecohydrological controls regulating GHG and stream fluxes, especially in GW-SW transition zones such as riparian wetland areas (Zhang et al., 2020).

ACKNOWLEDGEMENTS

Pallas studies are supported by the Maa- ja vesitekniikan tuki ry, K. H. Renlund Foundation, Academy of Finland (projects 316349, 316014, 308511, 316014, 312559), Hydro-RDI network (Academy of Finland funding 337523), the Strategic Research Council, JMW's UArctic Research Chairship, Kone Foundation (KRM's personal grant) and Kvantum Institute at the University of Oulu.

DATA AVAILABILITY STATEMENT

We gratefully acknowledge the Finnish Meteorological Institute (FMI), Finnish Environment Institute (SYKE), National Land Survey of Finland (MML), Geological Survey of Finland (GTK), and Natural Resources Institute of Finland (LUKE) for their efforts at the Pallas study site and for providing the open-access meteorological and land use data (Paituli: https://avaa.tdata.fi/web/paituli/latauspalvelu), hydrological data (Hertta: https://wwwp2.ymparisto.fi/scripts/hearts/welcome.asp), geological data (Hakku: https://hakku.gtk.fi/en/locations/search), and topographical data (MLL: https://tiedostopalvelu.maanmittauslaitos.fi/tp/kartta?lang=en). Other data are available from the authors, on request.

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How to cite this article: Marttila, H., Lohila, A., Ala-Aho, P., Noor, K., Welker, J. M., Croghan, D., Mustonen, K., Meriö, L.-J., Autio, A., Muhic, F., Bailey, H., Aurela, M., Vuorenmaa, J., Penttilä, T., Hyöky, V., Klein, E., Kuzmin, A., Korpelainen, P., Kumpula, T., … Kløve, B. (2021). Subarctic catchment water storage and carbon cycling – Leading the way for future studies using integrated datasets at Pallas, Finland. *Hydrological Processes*, *35*(9), e14350. https://doi.org/10.1002/hyp.14350