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Peatland hydrology in boreal Sweden: Modelling, long-term data analysis, and experimental rewetting

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Cover: The view of Trollberget mire (Stormyr), photo by Alejandro Gándara

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Abstract

Peatlands are the dominant type of wetland in boreal ecosystems and they are thought to play a major role in moderating hydrological extremes such as floods and droughts. Despite the valuable ecosystem services that they provide, a large proportion of peatlands around the globe has been degraded by human activity. Notably, in Sweden, peatlands have been subjected to drainage for the purposes of forestry. As awareness of the detrimental effects of climate change on boreal ecosystems has grown, the rewetting of drained peatlands has emerged as a nature-based solution for mitigating floods and droughts. However, the science behind this strategy is scant and the question of whether its potential benefits, in terms of alleviating extreme weather impacts, outweigh the costs of rewetting remains unanswered. Using a unique collection of hydrological field observations and modelling, this thesis provides a comprehensive analysis of the hydrological functioning of peatlands, at both local and stream network scale, within a heterogeneous boreal landscape (Paper I and Paper II) and addresses the question of whether peatland rewetting is more effective at mitigating both flooding events and low flow conditions than leaving historically drained peatlands as they are (Paper III and Paper IV). Our findings indicate that the moderating effect of peatlands on flow responses can primarily be found at the local scale. We also demonstrated that peatland rewetting successfully raised the groundwater table level, increased baseflow, and enhanced the overall storage capacity within the study site. During storm events, peatland rewetting effectively attenuated peak flow, reduced the runoff coefficient, and mitigated hydrograph flashiness. In conclusion, peatland rewetting is shown to be an effective tool for moderating hydrological extremes. However, given the dynamic nature of hydrological systems, continuous long-term monitoring of peatland processes following rewetting is required.

Keywords: peatland hydrology, rewetting, boreal landscape, floods and droughts

Torvmarkshydrologi i det boreala Sverige: Modellering, långtidsdataanalys och experimentell återvätning

Sammanfattning

Torvmarker är den dominerande typen av våtmarker i det boreala ekosystemet och har föreslagits spela en betydande roll i att mildra de hydrologiska effekterna av extremväder från uttorkning och översvämningar. Trots de värdefulla ekosystemstjänster som torvmarker erbjuder har en stor del av deras område globalt sett förstörts av mänskliga aktiviteter. Med ökad medvetenhet om klimatförändringarnas negativa effekter på boreala ekosystem har återställning av dränerade torvmarker lyfts fram som en naturbaserad lösning för att mildra effekten av extremväder. Vetenskapligt stöd för effektiviteten hos denna strategi saknas dock till stor del. Genom att använda en unik samling hydrologiska fältobservationer och modellering tillhandahåller denna avhandling en omfattande analys av torvmarkers hydrologiska funktion på både lokal och regional skala inom ett heterogent borealt landskap (Paper I och Paper II). Slutligen behandlar vi frågan om huruvida det, för att mildra effekten av översvämningar och låga flödesförhållanden, är mer effektivt med återvätning av torvmarker än att lämna historiskt dränerade torvmarker som de är (Paper III och Paper IV). Våra resultat indikerar att den reglerande effekt som torvmarker har på avrinningsresponsen främst sker på lokal nivå. Vi kunde också påvisa att återvätning av torvmarker framgångsrikt höjde grundvattennivån, ökade basflödet och förbättrade den totala lagringskapaciteten inom det undersökta området. Återvätning av torvmarker dämpar effektivt högflöden, minskar avrinningskoefficienten och responsen i flödesökningen. Sammantaget kan återvätning av torvmarker sägas vara ett effektivt verktyg för att mildra översvämningar. Men då hydrologiska system till sin natur är dynamiska och variabla finns ett behov av långsiktig och kontinuerlig övervakning av de processer som uppkommer i torvmarker till följd av återvätning.

Nyckelord: torvmarkshydrologi, restaurering, borealt landskap, översvämningar och torka

Trollberget mire, July 2023

Cloudberry (*Rubus chamaemorus*)

Dedication

To my mother

Trollberget mire outlet

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to in the text with the respective Roman numeral:

I. Karimi, S.*, Seibert, J. and Laudon, H. (2022). Evaluating the effects of alternative model structures on dynamic storage simulation in heterogeneous boreal catchments. Hydrology Research, 53(4), pp.562-583. https://doi.org/10.2166/nh.2022.121

II. Karimi, S.*, Leach, J., Karlsen, R.H., Seibert, J., Bishop, K. and Laudon, H. (2023). Local-and network-scale influence of peatlands on boreal catchment response to rainfall events. Hydrological Processes, 37(10), p.e14998. https://doi.org/10.1002/hyp.14998

III. Karimi, S.*, Hasselquist, E. M., Salimi, S., and Laudon, H. Rewetting impact on the hydrological function of a drained peatland in the boreal landscape (submitted)

IV. Karimi, S.*, Hasselquist, E. M., and Laudon, H. Does peatland rewetting mitigate extreme rainfall events? (manuscript)

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*corresponding author

Pooled surface water surrounding one of the dipwells

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Trollberget mire, September 2023

Trollberget mire, October 2023

1. Introduction

1.1 Definition of peatlands and their extent

Wetlands are unique ecosystems that are transitional environments between terrestrial and aquatic ecosystems. They therefore develop in areas that are inundated by water for most of the time and where oxygen deficiency (anaerobic conditions) prevails (Acreman et al., 2007). Wetlands cover a small proportion of the earth's land area (almost 6%) but represent one of its most important ecosystem types, providing essential hydrological, ecological, and biogeochemical functions. Wetland is a broad term, encompassing a wide range of ecosystem types including swamps, peatlands, sloughs, marshes, bogs, and fens. Peat-forming mires are the most common type of wetland found at northern latitudes. Peat-forming mires, or peatlands, form in waterlogged anaerobic conditions, where the rate of accumulation (1 mm per year) exceeds the rate of decomposition (Joosten, 2016). Peat is comprised of partially decomposed plant matter, typically sphagnum moss, and predominately occurs in boreal and temperate ecosystems (Joosten & Clarke 2002). The slow decomposition rate of organic material makes peatlands a significant source of terrestrial organic carbon. Sweden stands out as one of the most peat-rich countries in the world, with peatlands comprising 15% of its land area (Kellner and Halldin, 2002), mostly in the flatter environments in the north of the country (Vasander et al., 2003). In Sweden, an area is recognised as peatland or mire if it possesses a peat layer of 30 cm or more (Paavilainen and Päivänen, 1995). The most abundant peatland type in Sweden is poor fens (Kellner, 2003). Fens are peat-forming wetlands that receive water and nutrients from the surrounding watershed through drainage and surface runoff.

Important characteristics of peat are its high total porosity, low bulk density, and the ability to swell and shrink upon wetting and drying. Peat soil has a unique complex structure, with total porosity (the volume of soil that is filled with either water or air often surpassing 80% (Rezanezhad et al., 2016). The total porosity of peat is inversely correlated with bulk density. Bulk density is a fundamental soil characteristic and plays a crucial role in regulating peatland hydrology. Peatlands with lower bulk density have the capacity to store more water. Sphagnum mosses are the key component of peat soils (Rydin et al., 2006). The structure of Sphagnum moss, both alive and decomposed, contributes to peatlands' ability to expand and contract upon wetting and drying. In addition, its litter, which is more resistant to decay than that of other plants, plays a critical role in the hydrological function of peatlands. Changes in peat volume primarily arise from fluctuations in the groundwater table level (GWL) which significantly influences the hydraulic properties associated with peat's pore structure (Kennedy and Price, 2005). During dry periods, a falling GWL leads to subsidence of the peat surface, resulting in shrinkage and the closure of pore spaces in the peat. Conversely, a rising GWL leads to the expansion of the peat and pore spaces, resulting reduced moisture retention capability and greater potential for water loss through drainage and evapotranspiration (Kellner and Halldin, 2002).

1.2 Peatland ecosystem services

Boreal peatlands are important natural ecosystems with high value for biodiversity conservation, climate regulation and human welfare. Their distinct characteristics, including substantial water-holding capacity, peat content, expansive open surfaces, and unique plant communities, make a significant contribution to addressing current global sustainability issues. In particular, there is significant interest in peatlands in the context of climate change mitigation and adaptation. They actively participate in carbon sequestration, acting as essential sinks for carbon dioxide (CO2) and notable sources of methane (CH4) in the atmosphere. Despite covering only 3% of the Earth's land area (Lourenco et al., 2023) they account for 21% of the global soil carbon stock (Erwin, 2008; Leifeld and Menichetti, 2018; Loisel et al., 2014). In addition, peatlands are significant watershed features that play a major role in purifying water as it travels through wetlands from uplands to streams (Pelster et al., 2008). At the same time, peatlands are vital habitats and biodiversity hotspots, maintaining and protecting numerous rare and endangered species (Aapala et al., 2012). Furthermore, peatlands play a crucial role in regulating the regional water balance. They contribute to aquifer recharge, store and facilitate water transport, and sustain discharge into rivers and streams (Goodbrand et al., 2019; Lambert et al., 2022). It is commonly understood that peat soil plays an important regulatory role in flood attenuation, particularly by reducing peak flow. The high water storage capacity of peat soil allows peatlands to absorb and retain water, providing resilience against floods during high rainfall events. Conversely, during dry periods, peatlands release water slowly into streams and surrounding areas, helping to mitigate the impacts of droughts. However, our knowledge of the hydrological functions of boreal peatlands, especially in relation to human disturbance and restoration, is limited (Bring et al., 2020).

1.3 Peatland hydrology

The most extraordinary feature of peat soil is its great porosity, created by plant residues in different stages of decomposition. The network of macro and micro pores within peat soil facilitates the storage of substantial volumes of water. When saturated, peatlands can contain an impressive 90-98% water by mass (Holden, 2005). The popular analogy of blanket peatlands as a "sponge" has persisted for over two centuries, initially introduced by Turner in 1784 (Holden, 2005). The sponge analogy suggests that peatlands absorb rainfall during storms and then release it gradually, thereby contributing to the attenuation of floods. Contrary to this traditional perspective, recent studies have demonstrated that intact peatlands can exhibit flashy regimes with high runoff production (Burt et al., 1990; Price, 1992; Burt et al., 1997; Evans et al., 1999). It has been shown that whether a peatland behaves like a sponge or exhibits these flashy flow regimes depends on whether the initial storage, hereafter referred to as antecedent storage, is low or high (Acreman and Holden, 2013). The first rain after a long dry period may be effectively absorbed but, once the peat column is recharged, its ability to retain further water becomes limited. Moreover, the water storage capacity of peatlands and their impact on downstream flooding varies depending on the size of the peatlands in relation to the drainage network (Heathwaite, 1995; Edokpa et al., 2022). Where peatlands are positioned within the landscape has an important impact on their role in flood control urthermore, the position of peatlands in the landscape plays an important role for flood control. Upstream headwater peatlands can quickly fill during regular precipitation, reducing their capacity to buffer larger water volumes in extreme events. In contrast, downstream peatlands maintain a significant buffering capacity during severe flood events (Åhlén et al., 2022; Acreman and Holden, 2013; Ludden et al., 1983). Moreover, the hydraulic properties of peat depend strongly on its physical properties including compaction and vegetation composition (Evans et al., 1999; Edokpa et al., 2022; Rezanezhad, 2016). Until recently, there has been limited understanding of hydrological processes that either generate or attenuate storm runoff in peatlands.

1.4 Peatland degradation and drainage

Despite the valuable ecosystem services provided by peatlands, approximately 15–20% of their global area has been degraded by human activity (Joosten and Clarke, 2002). This degradation is responsible for 5–10% of annual global anthropogenic CO2 emissions (Joosten, 2015), transforming peatlands from carbon sinks into carbon sources. In Sweden, peatland drainage has been practiced since the early 18th century for agricultural purposes and the early 19th century for forest production (Paavilaine and Päivänen, 1995). Approximately 2 million hectares of peatlands have been drained (Holmen, 1964), with ditching activities peaking during the 1930s (Päivänen and Hånell 2012). In the forestry context, the purpose of ditching was to lower the GWL to promote the growth of existing slow growing trees or establishment of new tree seedlings. In many cases, draining peatlands has led to the successful growth of productive forests. However, in some instances the peatland remains unproductive, mainly due to nutrient-poor conditions. Draining peatlands has had many negative environmental impacts including carbon emissions (Harris et al., 2022), groundwater quality (Rodriguez et al., 2021), biodiversity loss (Fraixedas et al., 2017), sediment transport (Marttila and Kløve, 2010), and runoff production (Ballard et al., 2012). The impact of artificial drainage on the hydrological response of peatlands has been investigated in numerous studies. However, their results vary in terms of the impact of peatland drainage on runoff and peak flow changes (Lundin, 1994). Some studies concluded that runoff production in peatland was more rapid where artificial drainage had taken place (Menberu et al., 2018; Ballard et al., 2012; Conway, 1960; Ahti, 1980; Nicholson, 1989), possibly attributable to the channels provided by ditches which facilitate rapid and direct flow to the stream. Conversely, other studies reported that intact peatlands exhibit higher peak flows than drained ones (Burke, 1975), and some concluded that drainage has reduced peak flows (Berry et al., 1995; Lundin, 1994).

1.5 Peatland rewetting

With climate change, the frequency and intensity of drought events has increased over recent years and is expected to worsen in the future. Rewetting degraded peatlands is gaining attention as an effective nature-based strategy for mitigating the anticipated impacts of climate change. As water shortages escalate due to global warming and climate change, efforts to restore peatlands and thereby retain water in the landscape are likely to become more widespread. Meanwhile, floods are becoming increasingly common worldwide due to climate change (Arheimer and Lindström, 2015). Floods can cause significant damage to infrastructures and ecological systems (e.g., through sediment transport or uprooting trees along riparian zones) (Löfgren et al., 2014). In northern latitudes the frequency and magnitude of heavy precipitation events are also expected to increase, potentially leading to floods. For example, Arheimer and Lindström (2015) concluded that rain-driven floods are projected to become more common in northern Sweden. Recent dry summers in Sweden, particularly the 2018 drought, have increased interest in the hydrological functions of wetlands and whether rewetting can enhance groundwater storage and mitigate floods. In response, the Swedish government has committed over 30 million EUROs to wetland restoration initiatives. Nevertheless, there are persistent knowledge gaps concerning the potential impacts of peatland rewetting on mitigating hydrological extremes (Bring et al., 2020). Moreover, there is a lack of sufficient field data on the magnitude and spatial extent of these effects across various site and climatic conditions, particularly within the Swedish context.

Hydrology is fundamental to the development of peatlands. Therefore, it is believed that rewetting peatlands by blocking ditches to increase the GWL will allow them to resume their natural ecosystem functions (Fig. 1).

However, it has proven to be challenging to study the impact of ditch blocking on groundwater and runoff dynamics at the basin scale due to the substantial costs associated with the labour, equipment, and maintenance activities required for sustained, long-term monitoring. Nevertheless, a number of studies have identified positive hydrological effects from peatland rewetting. This includes GWL recovery (Menberu et al., 2018; Wilson et al., 2011; Schimelpfenig et al., 2014; Haapalehto et al., 2011), alterations in catchment runoff regimes (Acreman and Holden, 2013), reduction in peak flows (Wilson et al., 2010; Howson et al., 2023; Armstrong et al., 2010, Gatis et al., 2023; Ballard et al., 2011; Anderson et al., 2011), and natural flood management (Dadson et al., 2017), evidenced by both field and modelling studies. However, several studies have reported conflicting results, with some indicating no discernible effect on runoff production (Shuttleworth et al., 2019) or GWL change (Holden et al., 2011) and others reporting higher peak flow (Daniels et al., 2008; Spieksma, 1999). It is likely that the success of peatland rewetting depends on various factors including landscape location, configuration, soil characteristics, surface topography, and soil moisture status. All of these elements influence whether rewetting provides flood reduction services (Kløve et al., 2017). Given the significant investments and extensive efforts dedicated to peatland rewetting, there is an urgent need for comprehensive reports which address the spatial variability of GWL recovery and flood attenuation. This is particularly crucial within the context of the Swedish boreal ecosystem, as the existing literature relies largely on evidence from Finland, Canada, and the UK.

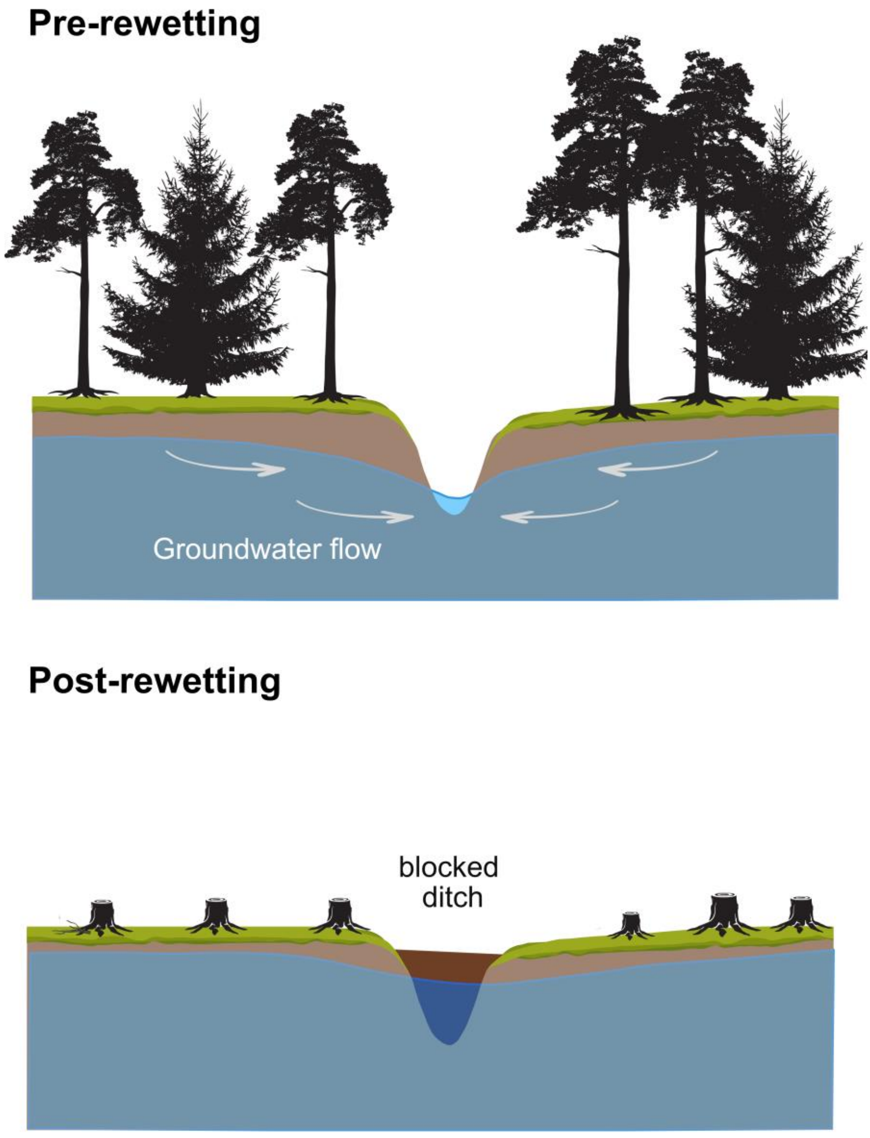

Figure 1. Schematic overview of groundwater table level (GWL) change after rewetting.

1.6 Monitoring approaches

1.6.1 Hydrological modelling

Rainfall-runoff models are used for a wide range of applications (Seibert and Bergström, 2021) and have gained popularity in water resources management due to the time and cost constraints on conducting comparative catchment studies. These models simplify the complex processes involved in rain becoming stream runoff at a catchment scale. They allow the different storage components in large basins to be estimated, based on the availability of meteorological and discharge data (Staudinger et al., 2017). Storage is the most important catchment function for buffering hydrological extremes. However, understanding the hydrological processes of peatlands through modelling remains challenging due to the complexity of these ecosystems, and the models themselves are constrained by the limited availability of empirical data. Hydrological modelling methods vary depending on whether the description of hydrological processes is conceptual, empirical, or fully physically based. Conceptual models offer advantages such as simplicity, limited input data requirements, and ease of implementation. An example of a conceptual model is HBV-light, a semi-distributed hydrological model which has been successfully applied to simulating discharge in Sweden (Seibert, 1999). However, modelling, while powerful, has its limitations. In HBV-light, there are three alternative model structures (one, two, and three groundwater boxes) for simulating discharge (see Uhlenbrook et al. in 1999). Although each structure can yield good model performance, the simulated groundwater outcomes may vary greatly, introducing uncertainty, as highlighted in my first paper (Paper I). Furthermore, although conceptual models are easy to implement and require fewer parameter sets than more complex physically based models, they still work best where long-term data sets already exist. Therefore, they may not be suitable for short-term rewetting studies.

1.6.2 Field observation

The primary objective of peatland rewetting is to raise the GWL, facilitating peat formation and the recovery of peat-forming vegetation such as Sphagnum (Bring et al., 2020). It is therefore essential to observe groundwater fluctuations in rewetted peatlands, to assess any changes in the hydrological characteristics that are critical to their resilience to climatic and hydrological shifts. Regular measurement of the GWL in peatlands would also contribute to an improved understanding of the temporal and spatial variations in water storage following rewetting efforts. Ensuring the accuracy of hydrological data is particularly important when evaluating the success of peatland rewetting. Peatland managers should have a solid understanding of the distribution and fluctuations of the GWL within the peatland. Because there is significant variability within individual sites this would involve installing multiple groundwater wells across each one. It would also be valuable to conduct side-by-side monitoring of groundwater tables in both managed and nearby natural peatlands, to yield deeper insights into their functions during extreme events. However, no such high-quality hydrological monitoring of GWL following rewetting has so far been carried out in Boreal Sweden. Peatland GWL can be determined manually using a measuring tape with a water-sensitive tip, or automatically using water level recorders. Typically, measurements are taken using dipwells, which are perforated pipes or wells extending from the base to the ground surface (Shaw, 2005). However, the frequency of manual measurements is limited by seasonal inundation and the inaccessibility of peatlands, which are very sensitive to any trampling. Automatic data loggers offer the advantage of recording data with whatever frequency is required, and the data can be retrieved when accessibility is good. Moreover, high-resolution data can help isolate the effects of individual rain events on rewetted peatlands, highlighting the necessity for detailed monitoring over time rather than relying solely on monthly or weekly measurements. Manual snapshot measurements are also limited in terms of determining the duration of specific GWLs, particularly during dry periods, or the extent and depth of flooding. Hence, continuous monitoring practices are essential for gaining a deeper understanding of the impacts of peatland rewetting.

1.7 Knowledge gaps

It is widely assumed that peatlands reduce floods by storing water during wet periods and sustaining baseflow during droughts. However, experimental studies have shown that the ability of peatlands to store excess rainfall water and prevent floods is limited (Acreman and Holden, 2013). Moreover, although numerous studies have characterised the hydrological function of individual peatlands in a watershed context, there is insufficient information about how peatlands operate in a heterogeneous boreal landscape dominated by other landscape features. This lack of understanding extends to the flood moderation ability of peatlands during short rainfall-runoff events. Although rewetting peatlands is widely assumed to be a beneficial strategy for mitigating extreme hydrological events like floods and droughts, the scientific evidence supporting this assumption is insufficient, particularly in the Swedish context. This raises concerns about the allocation of financial resources for such rewetting initiatives.

2. Research objectives

The primary objective of the research presented in this thesis is to contribute to a deeper understanding of peatland hydrology within a heterogeneous boreal landscape, and assess the effectiveness of peatland rewetting as a strategy for alleviating hydrological extremes. The thesis includes four papers (Paper I-IV). The specific objectives of this thesis are to:

- Investigate the performance of the three model structures in HBV-light for estimating different storage components across a heterogeneous boreal catchment, including peatlands, lakes, and forests, and to explore the relationship between dominant catchment characteristics and storage variability (Paper I);

- Investigate the role of natural peatlands in flood attenuation when scaling from headwaters to larger catchments under different antecedent moisture conditions (Paper II);

- Investigate how peatland rewetting impacts the groundwater table, discharge variability, and water storage capacity (Paper III);

- Investigate the impact of peatland rewetting on flood attenuation during rainfall-runoff events (Paper IV).

To fulfil the above research objectives, the following hypotheses are tested:

- Peatland coverage is positively correlated with higher storage characteristics (Paper I);
- Higher peatland and lake coverage is associated with lower peak flow, a reduction in runoff coefficient and discharge increase, and increased lag time (Paper II);
- Peatland rewetting results in a significant rise in GWL, increased baseflow, less variable GWL, and discharge reflective of a more natural condition, as well as increased water storage capacity (Paper III);
- Peatland rewetting leads to a reduction in peak flow, runoff coefficients, hydrograph flashiness, and an increased lag time (Paper IV).

3. Study sites, data, and methods

3.1 Study sites

Papers I and II were based on the Krycklan Catchment Study (KCS), while Papers III and IV were carried out in the Trollberget Experimental Area (TEA) (Fig. 2). In the latter two papers, natural peatlands at KCS and Degerö Stormyr were utilised as controls to evaluate the effect of rewetting on achieving natural hydrological conditions.

3.1.1 The Krycklan Catchment Study (KCS)

The Krycklan Catchment Study (KCS, www.slu.se/Krycklan) is situated in the heart of the boreal zone (64° 23′ N, 19° 78′ E), approximately 50 km northwest of the city of Umeå in northern Sweden (Laudon et al., 2021) (Fig. 2). The KCS spans 6790 hectares and encompasses elevations ranging from 114 to 405 meters above sea level. Like other boreal regions, KCS consists of a mosaic of forests, lakes, and peatlands. The landscape is dominated by forests which cover 87% of the total area. Mires occupy 9% and lakes 1% of the catchment area (Laudon et al. 2013). Scots pine (*Pinus sylvestris*) dominates the forest cover (63%), and is mostly found on the dry uplands. Norway spruce (*Picea abies*) covers 26% of wetter low-lying areas. Deciduous trees, particularly birch (*Betula* spp.), make up around 10% of the forest cover. The geological composition varies across altitudes, with quaternary deposits dominated by till and peat at higher elevations and postglacial sedimentary deposits prevailing at lower altitudes. Iron podzols dominate the forest floor soils in till areas, while organic content increases near stream channels, forming a riparian peat zone along the watercourses. KCS experiences a cold temperate humid climate with continuous snow cover in winter. At Svartberget station in KCS, the 30-year average for precipitation between 1991 and 2021 was 636 mm, and for mean air temperature was 2.4 0C (Lopez and Laudon, 2023). Snow accumulates from early November to late April, and constitutes approximately 40% of annual precipitation. Quaternary deposits consist of till (51%) and sorted sediments (30%). KCS includes 14 nested sub-catchments of varying sizes, ranging between 12 and 6790 hectares, all drained and connected by a network of streams and rivers, and all of which have been continuously monitored.

3.1.2 The Trollberget Experimental Area (TEA)

The Trollberget Experimental Area (TEA) is a headwater stream situated in the same region as KCS (64° 10′ N, 19° 51′ E). The TEA includes six treated experimental catchments which make the BACI design for this study possible (Laudon et al. 2023). Two catchments (R1 and R2 with drainage areas of 47 and 60 hectares, respectively) were used for peatland rewetting. The average peat depth at the site is 2.41 m. The open peatland in TEA is an oligotrophic minerogenic fen which was drained approximately 100 years ago. The peatland is dominated by Sphagnum spp. together with a sparse covering of sedges and dwarf shrubs and some slow-growing pine trees. The climate is similar to that of KCS, being characterised as a cold temperate humid type with relatively short and cool summers followed by long dark winters. Peatland rewetting took place in November 2020 using conventional practices determined by the authorities. Twenty-ton crawling excavators were employed to transport on-site peat and trees to fill in the ditches (Fig. 3). The sparse tree canopy on the restored peatland site was cut and removed, except where it was used as filling material, leaving only minimal slash behind.

3.1.3 Degerö stormyr

The nearby natural peatland of Degerö Stormyr is an oligotrophic minerogenic mire (i.e. a nutrient-poor fen) located approximately 24 km from the TEA at the Kulbäcksliden Experimental Forest (64°11′ N, 19°33′ E) (Noumonvi et al., 2023). Degerö Stormyr encompasses an area of 273 hectares and the average peat depth is between 3 and 4 m (Nilsson et al., 2008). It has a similar biotope to that of the peatland at Trollberget covered by this study. The site is dominated by lawn and carpet plant communities (e.g. tussock cottongrass, tufted bulrush, bog cranberry, bog-rosemary, and Sphagnum spp.). The bedrock in the area is gneiss, and the 30-year average (1991-2020) for precipitation is 645mm, and for temperature 3 0C, measured at the SLU reference climate station at Kulbäcksliden. The catchment landscape consists of 70 % mire and 30 % coniferous forest.

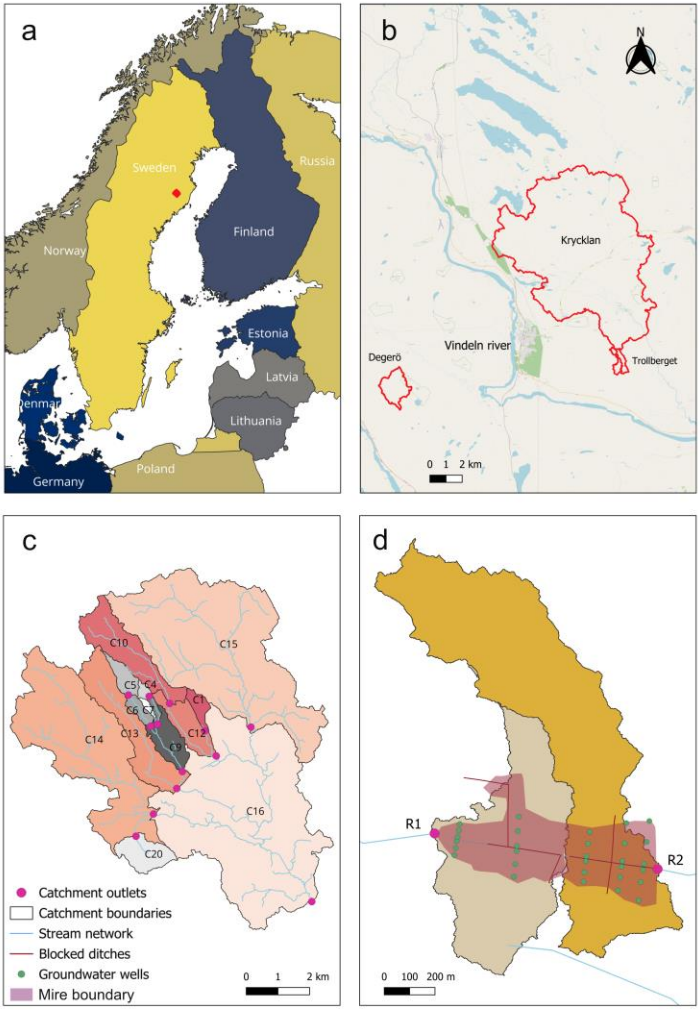

Figure 2. Geographic location of the study sites within Sweden (a), the location of the three sites in relation to each other (b), location of catchment outlets and stream network in the Krycklan Catchment Study (c), and location of groundwater wells (dipwells) and mire outlets in the Trollberget Experimental Area (d).

Figure 3. Restoration of Trollberget mire by filling the old ditches, November 2020.

3.2 Data

3.2.1 Climate data

The daily meteorological data needed for calculating potential evapotranspiration (PET) using the Penman equation were collected at the Svartberget research station in the middle of the Krycklan catchment (Paper I). The variables measured at the meteorological station are air temperature, humidity, net radiation, and wind speed. These measurements follow the standard guidelines and requirements of the World Meteorological Organisation (WMO) (Laudon et al. 2021). All climate data were assumed to be the same for the entire catchment area. Precipitation data from Svartberget station were used (64°14′ N, 19°46′ E, 225 m a.s.l) for all catchments (Paper I-IV) as the Swedish Meteorological and Hydrological Institute (SMHI) observes no significant elevation gradient in the region. Rainfall was measured at 10-minute intervals using a tipping-bucket gauge during the growing season and resampled to hourly (paper II and paper IV) and daily (Paper I and Paper III) values for this thesis. All these data were retrieved from the ICOS Carbon Portal (https://www.icos-cp.eu/).

3.2.2 Discharge data

At KCS, the monitoring programme began in 1981 inside a heated hut (at an hourly resolution) and, in 2003, gauging began in all 14 sub-catchments using V-notch weirs, flumes, or well-defined cross sections with road culverts. Water levels were measured using automatic stage loggers at five gauging stations in heated houses where year-round measurement is possible (C2 and C4 have been heated since 2011, C5 and C13 since 2012, and C7 since 1981). Frequent manual water-level measurements were taken (monthly during winter and at least bi-weekly during the rest of the year) to calibrate the automatic water-level data, and stage-discharge relationships were defined using manual flow gauging (Karlsen et al. 2019). Specific discharge, defined as discharge per unit drainage area, was calculated for each catchment. The catchment areas were determined using the D8 algorithm (O'Callaghan and Mark, 1984) based on a 5m resolution digital elevation model (DEM) derived from airborne Light Detection and Ranging (LiDAR) measurements. Catchment boundaries were adjusted using field mapping, and modifications were applied as needed, with any questionable sections further assessed using a 0.5 m resolution LiDAR DEM. Daily specific discharge data for 2011 to 2017 from 14 sub-catchments within the Krycklan catchment were used for paper I. For paper III, daily specific discharge data for 2020 to 2023 from peatland-dominated catchments (C4) were used. For paper II and paper IV, hourly specific discharge data were used.

At TEA, since 2019, stream discharge measurements have been recorded at the outlet of each sub-catchment (R1 and R2, see Fig. 2d). Stage height was recorded hourly at each catchment using pressure transducers (Expert 3400, MJK A/S, Denmark). The transducers were placed in the stilling ponds of 90-degree sharp-crested V-notches. In contrast to KCS, stream locations at TEA are not heated, meaning that limited data are available during winter low flow periods. The automatic water height time series for the two outlets were corrected to account for logger offset using manual measurements of reference water height. These manual readings were performed at biweekly intervals during snow-free conditions. The stage height time series from each logger was quality-controlled manually and corrected for the influence of ice and unrealistic values due to occasional downstream damming. Independent stage-discharge rating curves were derived using volumetric methods. Specific discharge (mm/day) was calculated using the measured discharge and the catchment area. Catchment areas were obtained using the D8 algorithm on a 0.5m resolution digital elevation model (DEM), derived from airborne Light Detection and Ranging (LiDAR) measurements (Laudon et al. 2021).

At Degerö Stormyr, stream discharge at the catchment outlet (C18) has been monitored since 2018. The weir at the C18 catchment is located inside a small house set up on a flume, allowing for continuous stage height measurements throughout the year (Noumonvi et al., 2023). Discharge calculations were performed by applying a stage height-discharge rating curve to hourly water level measurements. The C18 rating curve was calibrated using manual discharge measurements taken during different flow conditions with salt dilution (Leach et al., 2016).

3.2.3 Groundwater table level monitoring

At the peatland site located in TEA, GWL were measured using 30 dipwells, extending 6 meters below the ground surface (paper III and paper IV) (Fig. 4). Dipwells were distributed along 5 transects perpendicular to the main ditch. Each transect consisted of 6 wells at increasing distances of approximately 10, 50 and 100 m from the ditch. Half of these dipwells were continuously monitored for GWL from October 2019 to November 2023, using data loggers (Solinst Levelogger 5), while the remainder were manually measured every two weeks during the snow-free season. All manual measurements of GWL were made relative to the ground surface using a measuring tape with a water-sensitive tip (Weiss Bandmab Measuring Tape). The barometric compensation process was carried out automatically using the Levelogger Software 4.5.1 Data Wizard. For this conversion, the manual GWL measurements were used to calibrate and check the automated measurements. At the end of this processing, our data set included a GWL time series one-year pre-rewetting (October 2019 to November 2020) and three years post-rewetting (November 2020 to October 2023).

At Degerö Stormyr, the time series of GWL from four dipwells that are part of the ICOS-Svartberget system (https://www.icos-sweden.se/data) were used as our control for GWL change. Due to technical issues with the groundwater loggers, no groundwater data for recent years were available for the C4 control catchment at KCS.

Figure 4. The author measuring groundwater table level (GWL) in one of the dipwells within Trollberget mire, autumn 2023.

3.3 Methods

3.3.1 HBV-light model (Paper I)

In this study, our objective was to estimate and compare dynamic storage across 14 sub-catchments with contrasting landscape characteristics (e.g., lake, peatland, forest on till soils, and forest on sorted sediments). To achieve this objective, my co-authors and I employed a modified version of the bucket-type, semi-distributed hydrological model known as the HBV model (Lindström et al., 1997), specifically the HBV-light version (Seibert & Vis, 2012). In our methodology, dynamic storage is defined as the difference between minimum and maximum amount of water stored within a specific zone during a given time period, exerting direct control over streamflow dynamics (Fig. 5). The HBV model is a widely used bucket-type model for simulating runoff and was originally developed and extensively applied in the Nordic region. Its simplicity, minimal input data requirements, and robust performance, means it has been used in numerous catchments around the world (Scheepers et al., 2018; Girons Lopez et al., 2020). Input data for the model are rainfall, air temperature, and derived potential evapotranspiration (PET) and are usually calibrated based on discharge data. The HBV-light model consists of four commonly used routines which represent: (1) snow, using a degree-day method; (2) soil moisture and (3) groundwater, using three linear reservoir equations; and (4) channel routing, using a triangular weighting function. In the snow method, a threshold temperature is used to distinguish between rainfall and snowfall, and snowmelt is considered using a degree-day approach. The details of the model structure can be found in Seibert & Vis (2012). The HBV-light model includes three alternative structures which differ in the number of conceptual reservoirs (one, two, or three) and the shape of the storage-discharge relationship (linear versus nonlinear). In our study, the HBV-light model was utilised to simulate dynamic storage at a daily time step within the catchment, with water storage represented by distinct buckets. In order to assess whether notable differences exist in dynamic storage estimates derived from different model structures, we implemented all three model structures of the response routine in this study. This included: i. a one-bucket structure with a single groundwater reservoir and three linear outflows (Q0, Q1, and Q2) at three different thresholds; ii. a two-bucket structure with two reservoirs in parallel with a nonlinear outflow (Q1) in an upper bucket and one linear outflow (Q2) in a lower bucket (basic version); and iii. a three-bucket structure with three parallel reservoirs and one linear outflow in each reservoir. It should be noted that the snow and soil routines are consistent across all model variants. We used the built-in Genetic Algorithm followed by a Powell optimisation to calibrate the models using the observed daily discharge at each of the catchment outlets. For calibration, warm-up periods of at least one year were used for each catchment based on data availability. The possible parameter ranges we initially chose were adapted from Uhlenbrook et al. (1999) where preliminary simulations indicated that suitable parameter values were close to the limits. To consider parameter uncertainty, each calibration trial was repeated 100 times (5000 iterations each) and the best 100 parameter sets were selected according to the Nash-Sutcliffe model efficiency. The Nash–Sutcliffe efficiency (NSE) coefficient, here called Reff (Equation 1), is calculated using the following equation (Uhlenbrook et al. 1999):

$$R_{eff} = 1 - \frac{\sum(Q_{obs} - Q_{sim})^2}{\sum(Q_{obs} - \overline{Q_{obs}})^2} \qquad \text{(Equation 1)}$$

Where Qobs and Qsim are the measured (observed) and modelled (simulated) flows, respectively. We considered parameterisations that resulted in good runoff simulations in terms of Nash–Sutcliffe efficiencies (Reff) to be plausible. From the 100 calibration trials, we thus derived an ensemble of plausible simulations that resulted in a range of storage estimates for the upper (SUZ) and lower storage (SLZ) reservoirs. In the next step, the estimated storage from all reservoirs was combined and the difference between the minimum and maximum values was considered to represent dynamic storage. To examine the correlation between landscape characteristics and simulated dynamic storage, we employed non-parametric Spearman rank correlations.

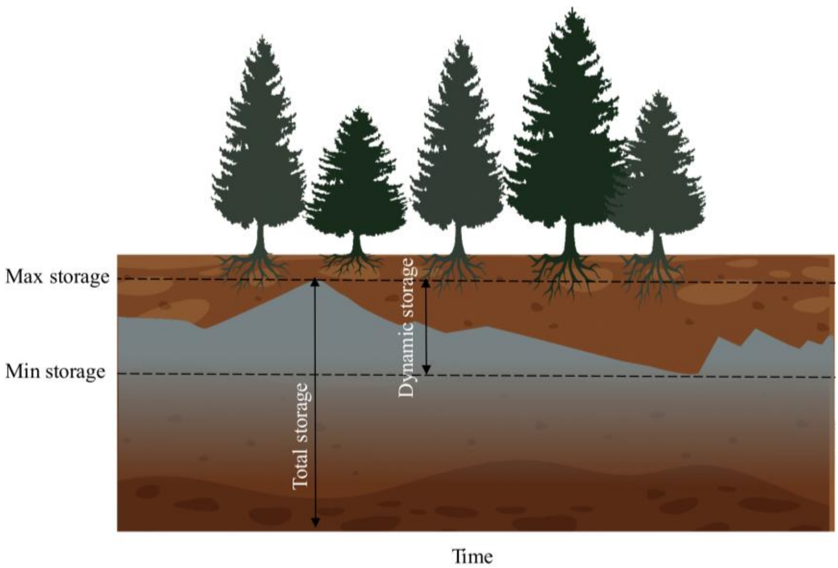

Figure 5. Schematic explanation of dynamic storage within a catchment. The area shaded blue represents the groundwater table level (GWL) fluctuations.

3.3.2 Rainfall events (Paper II)

Paper II focused on evaluating the influence of natural peatlands on flood attenuation at both local and stream network scales. We hypothesised that a larger area of peatlands would be associated with reduced peak flow magnitudes, runoff ratios, and delayed peak flow lag time. Individual rainfall events were extracted from hourly rainfall time series using the 'IETD' R package (https://cran.r-project.org/web/packages/IETD/index.html). An event was considered distinct if at least 2 mm of rainfall occurred within 1 hour and it was separated from other events by at least 14 hours without additional rainfall. Following Jones et al. (2004), rainfall events were categorised as low, medium, or high if the total event magnitude was below the first quartile (<7.5 mm), between the first and third quartile (7.5 to 21.2 mm), or above the third quartile (>21.2 mm), respectively. This analysis resulted in 18 high rainfall events, 56 medium rainfall events, and 30 low rainfall events with mean rainfall volumes of 34.4, 12.4, and 5.1 mm, respectively. To evaluate the impact of antecedent wetness on hydrograph response, we calculated the antecedent precipitation index (API) (Equation 2) for 1 and 5 days before events following the approach set out by Kohler and Linsley (1951):

$$\text{API} = \sum_{t=-1}^{-i} P_t \; K^{-t} \qquad \text{(Equation 2)}$$

Where i is the number of antecedent days, Pt is the rainfall during day t, and K is the decay constant. The value of K is generally determined arbitrarily and empirically, with values in the literature ranging between 0.80 and 0.98 at daily time steps. We adopted the value of 0.98 for K when applying this equation to hourly rainfall data. Antecedent conditions were categorised as low, moderate, and high, similar to our classification of rainfall events. We used the median value as the threshold for classifying API1 into either low or high antecedent conditions. This choice was made because the first quartile of API1 resulted in a value of zero. A runoff event was defined to start when rainfall began and last until 12 hours after it had stopped. Streamflow metrics were computed for each event to characterise the hydrograph response. These metrics included the runoff coefficient (unitless), calculated as total runoff divided by rainfall depth for each event; peak flow (mm/h); discharge increase (Δ mm/h), calculated as the difference between peak flow and discharge at the event's onset; and lag time (hours), representing the time difference between peak rainfall and peak flow. The values were then categorised into three groups: low, moderate, and high, using the quartile approach mentioned earlier. Furthermore, antecedent storage was assessed using observed discharge at the C7 station (Fig. 2c), recorded 5 hours prior to each rainfall event (Hudson et al., 2021; Wilson et al., 2011). Specific discharge from this station was used because it lies centrally within Krycklan. This sub-catchment drains a mix of mire and forest land cover and has a mean specific discharge comparable to that of all the other sub-catchments (Tiwari et al., 2022). This provides a consistent and standardised measurement approach across all sites. To assess the local impact of natural peatlands on flood response, linear models were employed to identify relationships between runoff coefficient, peak flow, and total rainfall in three small sub-catchments that are dominated by forest, peatland, and lake (C2, C4, and C5). Boxplots were utilised to illustrate runoff-event metric variability across these sub-catchments under various rainfall conditions. The paired Wilcoxon test was used to test whether any of these metrics varied significantly between these groups. A Spearman rank correlation test was used to identify catchment characteristics that related to hydrological responses.

3.3.3 BACI experimental design (Paper III and Paper IV)

In Papers III and IV, we used a BACI experiment to assess the impact of peatland rewetting on groundwater and discharge responses. In this analysis, we accounted for the effect of rainfall by calculating the relative difference from the control site (treatment minus control). Our control sites in these papers were the natural mires located in KCS (C4) and Degerö (Fig. 2). The study focused on assessing the effects of rewetting on hydrological responses during summer and autumn, excluding winter and spring months due to data gaps caused by snow cover, deep soil frost, and general frozen conditions that affected automated GWL monitoring. We also anticipated significant variations in GWL, and drought conditions are more likely to occur during the summer.

In Paper III, we asked whether rewetting has led to elevation and stabilisation in the GWL, increased baseflow, and enhanced water storage capacity. The effects of peatland rewetting on GWL were estimated using linear mixed-effects models and post-hoc analysis (pairwise comparison between each year) was done using a Wilcoxon test with Bonferroni Correction. A P-value of 0.05 was considered statistically significant. The Flow Duration Curve (FDC) was used to analyse the streamflow regime and the effect of rewetting on low flow. To assess whether peatland rewetting has increased water storage capacity, the GWL and discharge time series were regressed using an exponential model. The inflection points, representing the GWL threshold at which stream runoff is generated, were then extracted for both control and rewetted sites, both pre- and post-rewetting. In addition, the monthly runoff coefficient (calculated as total runoff divided by total rainfall) was determined for both control and rewetted sites (R1 and R2). The relative difference with the control sites was then calculated to assess the impact of rewetting.

In Paper IV, we assessed whether peatland rewetting is beneficial in reducing floods during rainfall-runoff events. To achieve this, we extracted rainfall events from the 2020–2023 summer-autumn rainfall time series using the inter-event time definition (IETD) (Duque, 2020). The IETD establishes a minimum dry period between independent rainfall events as a criterion for grouping them. To distinguish independent rainfall events from continuous precipitation, we set a minimum threshold of 0.1 mm h^{-1} at the start of an event. Events were considered distinct if they were separated from others by at least 12 hours without rainfall. The methodology for identifying runoff events was based on the framework outlined by Luscombe et al. (2014) and was further adapted to the specific characteristics of our study area. Runoff events were defined as periods during which the observed streamflow exhibited significant deviations from the baseflow. This was achieved by considering both the rate of change in streamflow and its magnitude. Peaks in streamflow exceeding predefined thresholds were classified as runoff events. Rainfall and runoff events were paired within a specified time window. A final, visual inspection of the time series with detected events was used to quality control these data and ensure that all significant rainfall and flow events were extracted from the dataset. Finally, for all rainfall-runoff events identified, a set of stormflow metrics comprising event duration, rainfall volume, rainfall intensity, lag time, peak flow, Hydrograph Shape Index (HSI), and runoff coefficients were calculated for both control and two rewetted sites. HSI, defined as the ratio of peak storm discharge to total storm discharge, serves as a simple measure of the overall hydrograph shape (Shuttleworth et al., 2019). For the other rewetted catchment (R2) and the control site, stormflow metrics were calculated based on the rainfall-runoff events extracted using the rewetted catchment (R1).

4. Results and discussion

4.1 Relationship between catchment characteristics and dynamic storage (Paper I)

In Paper I, we addressed uncertainties arising from different model structures within the HBV-light model that was used to estimate dynamic storage. The primary goal was to investigate the relationship between estimated storage components and different catchment characteristics. To achieve this, 14 heterogeneous boreal catchments were categorised into four distinct groups using k-means clustering, following the framework outlined by Karlsen et al. (2019). These categories were determined by dominant landscape types, including forest on till, forest on sorted sediments, wetlands and lakes, and mixed catchments. The results showed that the three-bucket structure performed better in larger catchments characterised by deeper sorted sediment soils. Conversely, a single reservoir structure proved sufficient for predicting storage-discharge behaviour in a lake-influenced catchment at lower elevation above the stream network. A possible explanation for this is that, with increasing elevation above the stream, the spatial heterogeneity of flow paths and processes within the respective catchments increases. Therefore, models that treat catchments as a single unit might have difficulty representing the hydrological functioning of these diverse landscapes. Our results also indicated that the large catchments dominated by sorted sediments mainly stored water in the lower zone, while catchments dominated by peatlands exhibited higher storage in the upper zone during periods of high flows, a finding which aligns with those from previous studies (Peralta-Tapia et al., 2015; Laudon et al., 2007). Contrary to our hypothesis that peatland coverage would be associated with higher dynamic storage, our analysis revealed that the largest mean storage estimates were found in larger catchments and those with a higher proportion of sorted sediments (Fig. 6). We also found a strong negative correlation between catchment tree volume and dynamic storage, which is in line with the findings of Barrientos & Iroumé (2018) who explored the impacts of forest management on dynamic storage in 15 forested catchments and concluded that catchments with lower forest cover (biomass volume and plantation density) have higher storage volumes. This might be caused by the higher evapotranspiration rates associated with deep-rooted trees taking up water from sub-surface storage areas, thereby reducing the amount of dynamic storage available.

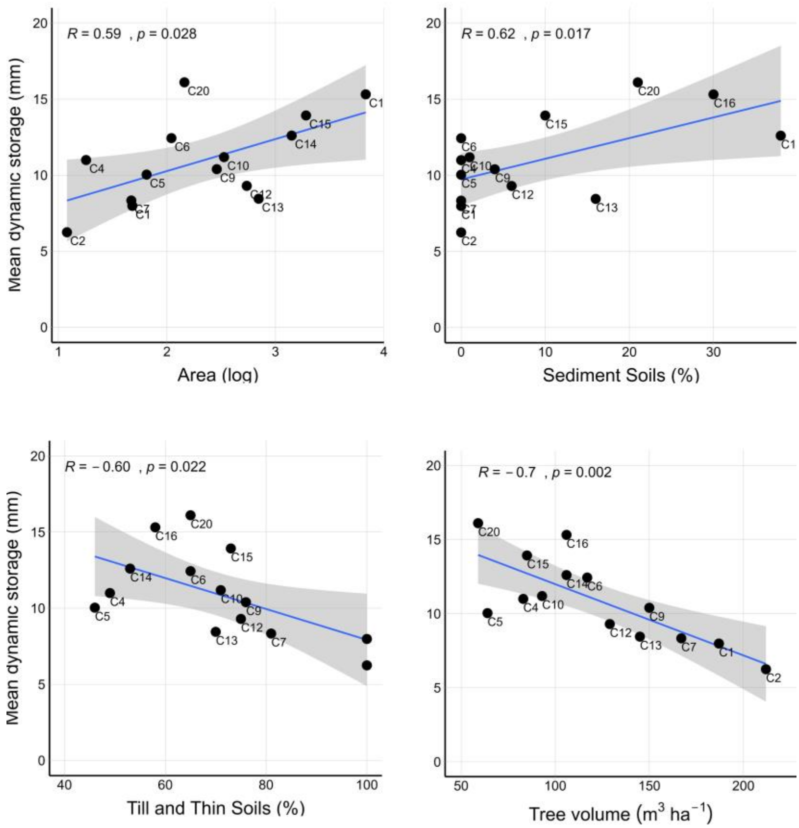

Figure 6. Scatter plots showing the relationship between dynamic storage estimated for each sub-catchment (see Fig. 2c) and different catchment characteristics. The grey bands around the line represent the 95% confidence interval for predictions from a linear model.

4.2 Local- and network-scale influence of peatlands on flood attenuation (Paper II)

In Paper II, we used nine years of hourly hydrometric data from 14 catchments within the KCS to investigate the contribution of peatlands to flood attenuation at both local and stream network scales, under different antecedent conditions. At the local scale, we investigated how event peak flow response and runoff coefficient were related to event rainfall under different antecedent conditions for the three end-member catchments: C5 (the lake-influenced catchment), C4 (the peatland-dominated catchment), and C2 (the forest-dominated catchment). In general, the peatland-dominated catchment showed responses that were more dampened than those in the forested catchment of similar size. During periods of low antecedent conditions, runoff coefficients for small rainfall events were similar in lake-influenced and peatland-dominated catchments, but they diverged with increased rainfall intensity. For all catchments, the highest runoff coefficients occurred with high antecedent conditions. Notably, the impact of antecedent conditions on peak flow and runoff response was more pronounced during small rainfall events for all end-member catchments. Moreover, the runoff-event metrics for the peatland-dominated catchment, including peak flow, discharge increase, runoff coefficient, and lag time, generally lay between those for the forest-dominated and lake-influenced catchments during all rainfall event types (Fig. 7). To investigate the role of peatlands in moderating runoff responses at the network scale, we conducted a Spearman rank correlation test on all 14 catchments. The objective was to examine potential correlations between runoff-event metrics and catchment characteristics at this broader scale. Our results revealed that factors such as catchment area, sorted sediment, and soil depth were positively correlated with lag times. In contrast, they showed negative correlations with peak flow magnitude, runoff coefficient, and discharge increase (Fig. 8). However, contrary to our hypothesis, we found no significant effect of peatlands on the attenuation or amplification of floods at the network scale even though our analysis using the end-member catchments, and findings from other studies, showed that they can decrease peak flow locally. This may be attributed to the effect of runoff characteristics from other land cover types overshadowing the influence of peatlands on a larger spatial scale.

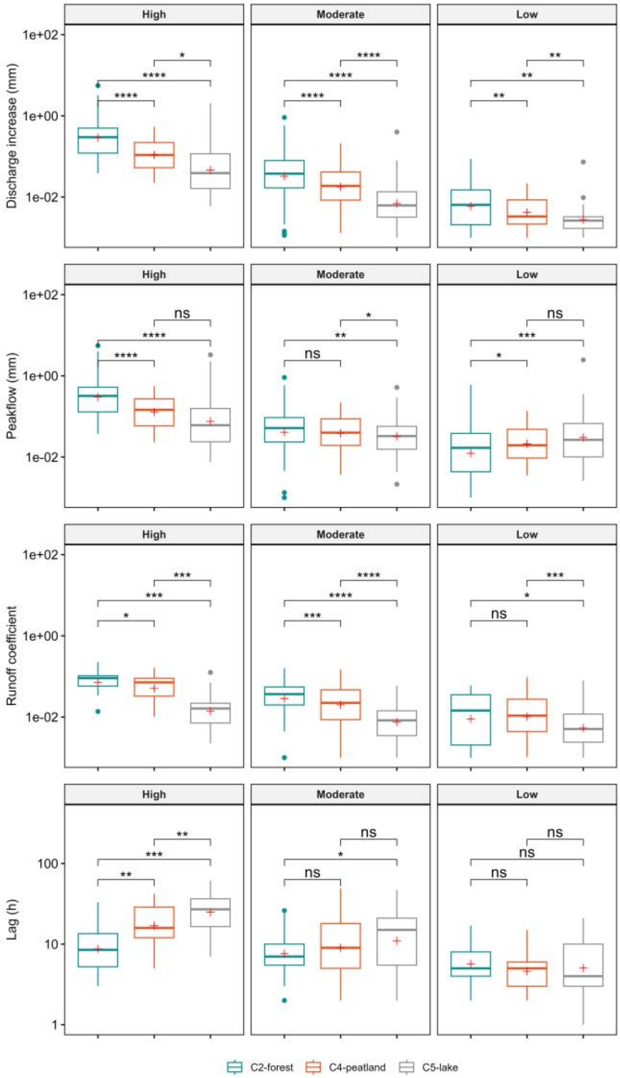

Figure 7. Event-based stormflow characteristics of the forest (blue-green), peatland (red), and lake (grey) dominated catchments during high, moderate, and low rainfall conditions. The stars indicate the levels of significance per Wilcoxon test (*p ≤ 0.05; **p ≤ 0.01; ***p ≤ 0.001; ****p ≤ 0.0001; 'ns' = not significant).

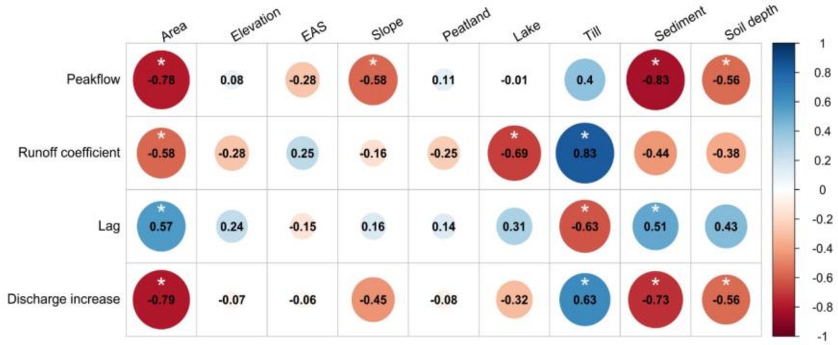

Figure 8. Spearman rank correlations between catchment characteristics and hydrological response variables. The colours correspond to the values of the correlation coefficient; blue indicates positive correlations, while red indicates negative correlations. White stars indicate correlations that are significant at the p<0.05 level.

4.3 Peatland rewetting effect on groundwater and discharge responses (Paper III)

In Paper III, we tested the hypothesis that the rewetting of drained peatlands would result in a significant rise in GWL, increased baseflow, less variable GWL and discharge reflective of a more natural condition, and increased water storage capacity. The results showed that rewetting significantly raised the GWL compared to the pre-rewetting period (Fig. 9). Overall, the mean GWL at the rewetted site rose 64 mm over the three years (2020-2023) post-rewetting, while the mean GWL at the control site decreased by 30 mm over the same period. These results align with previous studies which have shown that rewetting creates shallower GWL in the surrounding peat, and the rise of GWL is generally rapid after rewetting (Haapalehto et al., 2011; Menberu et al., 2018; Menberu et al., 2016; Wilson et al., 2010; Shantz and Price, 2006). The flow duration curve analysis provided support for the second hypothesis, indicating that rewetting has resulted in a substantial increase in baseflow (Fig. 10). At the rewetted site, R1, there was a 100% increase at the high flow threshold (from 0.58 to 1.16 mm/day) and a 157% increase at the low flow threshold (from 0.14 to 0.36 mm/day). In the catchment R2, a 69%

increase in high flow (from 0.56 to 0.95 mm/day) and a 120% increase in low flow (0.05 to 0.11 mm/day) was observed. For comparison, the control site displayed an 87% increase in high flow (from 0.83 to 1.56 mm/day) and an 85% increase in low flow (from 0.14 to 0.26 mm/day) thresholds, respectively. These results suggest that the rewetting had a significant impact on maintaining baseflow and preventing streams from drying up during drought. The substantial increase in baseflow at the rewetted site may be attributed to a combination of factors, including higher storage capacity during drier periods and an elevated GWL resulting from the rewetting activities. These results are consistent with other studies that have shown an increase in baseflow as a result of peatland rewetting (Holden et al., 2017; Howson et al., 2021; Norbury et al., 2021). Our results also support the hypothesis that peatland rewetting increases water storage capacity. This is demonstrated by the distinct threshold behaviour in the relationship between the GWL and discharge (Fig. 11). Our data suggest that flow initiation occurred in the drainage ditch when the GWL was within approximately 100 mm of the pre-rewetting peat surface. Post-rewetting, higher flows were observed when the GWL was close to the surface, typically within 20 mm of the peat. This increase is presumably linked to the positive impact of rewetting activities on the peatland storage capacity, as storage thresholds play a crucial role in regulating a catchment's ability to transfer water to its outlet and thereby regulate hydrological stream processes (Spence, 2007).

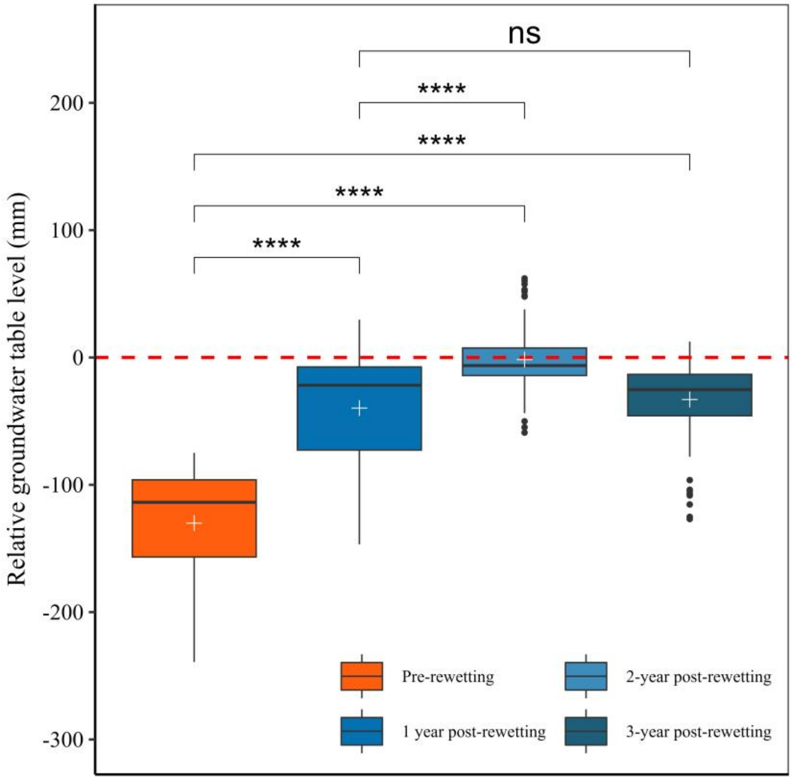

Figure 9. Differences in groundwater table level (GWL) between the rewetted and control sites for pre- and post-rewetting. The difference is computed as treatment minus control, thus positive values indicate that GWL is greater at the treatment site than at the control site, while negative values indicate the opposite. The white plus sign (+) indicates the mean value. The stars indicate the levels of significance per Wilcoxon test (*p $\leq$ 0.05, **p $\leq$ 0.01, ***p $\leq$ 0.001, ****p$\leq$0.0001) between individual years, while "ns" stands for not significant.

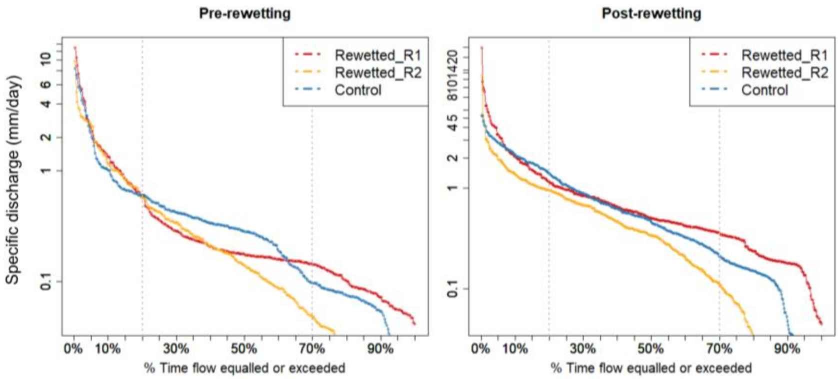

Figure 10. Flow duration curve showing exceedance probability of specific discharge for rewetted (R1 and R2) and control sites during 2020 (pre-rewetting) and 2021-2023 (post-rewetting). The vertical dashed lines represent transitions between high flow, mid flow and low flow periods.

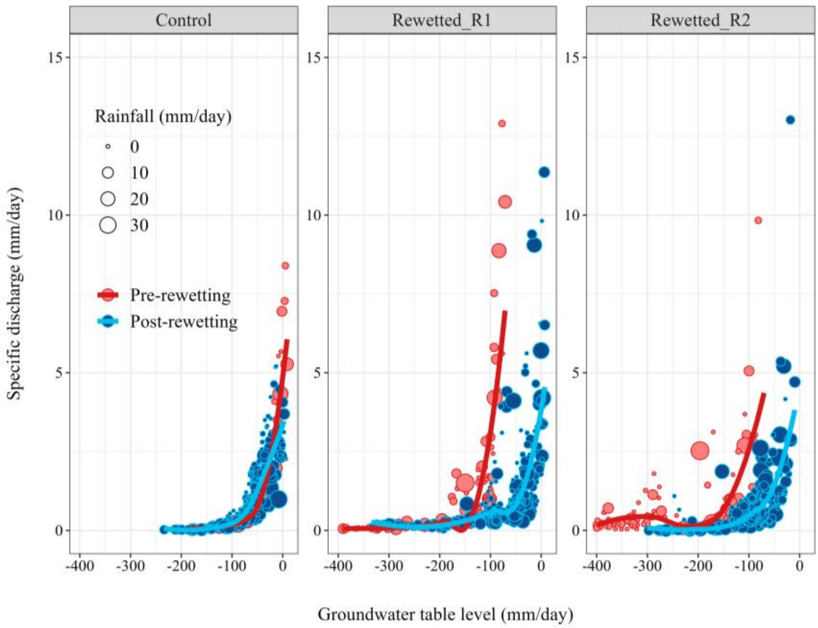

Figure 11. Scatter plots of daily specific discharge versus groundwater table level (GWL) during 2020 (pre-rewetting) and 2021-2023 (post-rewetting) for rewetted and control sites. Smoothed lines are a visual aid only.

4.4 The effect of peatland rewetting on flood attenuation during rainfall-runoff events (Paper IV)

In Paper IV, we investigated the effects of peatland rewetting on runoff responses for 50 rainfall-runoff events using a BACI approach. Consistent with our hypotheses, our results showed that peatland rewetting led to a significant reduction in peak flow, runoff coefficients, and hydrograph shape index (flashiness) (Fig. 12), findings which align with many previous studies (Wilson et al., 2011; Shantz and Price, 2006; Ketcheson and Price, 2011; Gatis et al., 2023; Shuttleworth et al., 2019). Specifically, the median peak flow at R1 experienced a decrease from 0.14 to 0.11 mm/h post-rewetting, while at R2 it increased from 0.03 to 0.08 mm/h ($p < 0.05$). However, compared to non-drained control sites, the median peak flow significantly decreased in both rewetted catchments ($p < 0.05$) (Fig. 12a). These results suggest that, despite the influence of other factors such as intensified precipitation leading to more pronounced responses post-rewetting, the rewetting seems to have played a mitigating role in reducing flood occurrences in the rewetted catchment. The median runoff coefficient at the rewetted sites increased from 0.22 to 0.4 and from 0.1 to 0.18 at R1 and R2, respectively, after rewetting. Similarly, in relation to the control site, the runoff coefficients at both rewetted sites decreased significantly ($p < 0.05$) by 0.12 (Fig. 12b), as the control catchment decreased from a median runoff coefficient of 0.14 to 0.41 during the post-rewetting period. Moreover, contrary to our expectation, the median lag at R1 remained unchanged after rewetting (from 14 to 15 h), and there was no statistically significant difference between it and the control site following rewetting (Figure 12c). Conversely, at R2, the median lag actually decreased from 17 to 10 h post-rewetting. This reduction was significant compared to the control site, where the lag increased from 14 h to 23 h ($p < 0.05$). Further, our results showed that the median HSI at R1 decreased from 0.035 to 0.025 after rewetting. This reduction was statistically significant ($p < 0.0001$), as the median HSI at the control site only changed from 0.024 to 0.021. Similarly, at R2, there was a slight reduction in the median HSI from 0.027 to 0.026 after rewetting. However, this decrease was not significant when compared to the control site (Fig. 12d). In summary, our findings highlight the beneficial effect of peatland rewetting on flood mitigation, but peatland managers should be aware of other potential consequences such as a decreased lag time accelerating water transport to the catchment outlet.

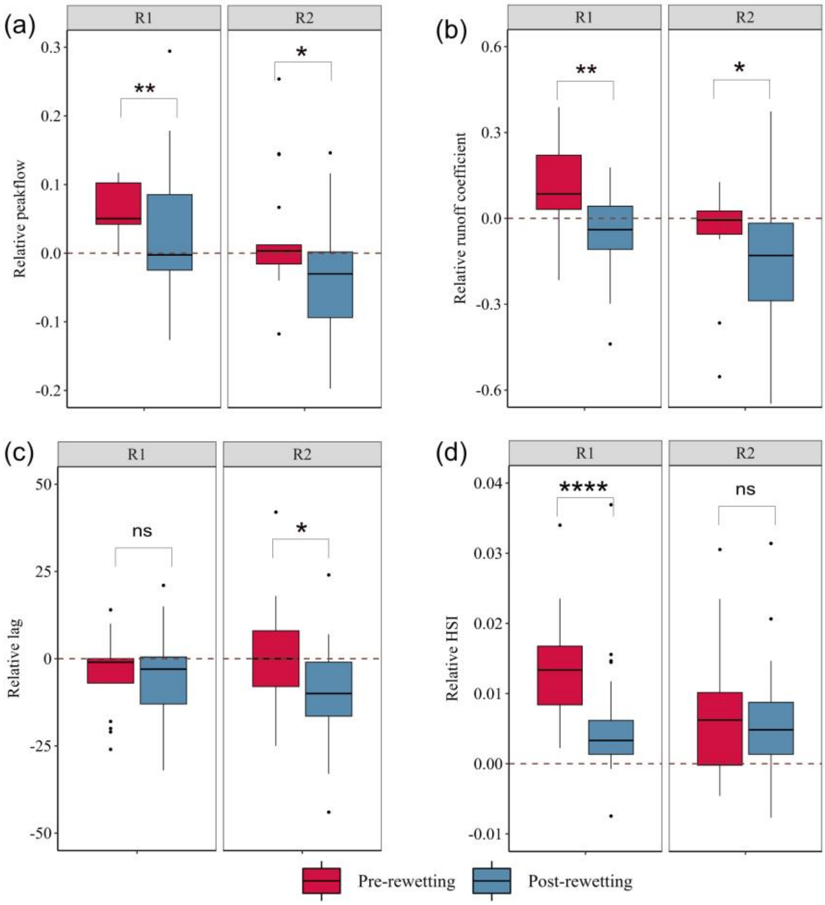

Figure 12. Differences between the rewetted and control sites pre- and post-rewetting period for (a) peak flow, (b) runoff coefficient, (c) lag, and (d) HSI. The difference was computed as treatment minus control, thus positive values indicate that the solute is greater at the treatment site than at the control site, while negative values indicate the opposite. The stars indicate the levels of significance per Wilcoxon test (*p ≤ 0.05; **p ≤ 0.01; ***p ≤ 0.001; ****p ≤ 0.0001; ‘ns’ denotes not significant.).

5. Conclusion

The findings of this thesis provide a robust baseline for understanding the hydrological function of both managed and unmanaged peatland ecosystems in a boreal environment. The use of high-quality hydro-meteorological data over an extended monitoring period has effectively filled several knowledge gaps. This information is particularly crucial for those involved in managing these landscapes in the Swedish context. The findings indicate that natural peatlands contribute to flood mitigation at the local scale. Further, rewetting peatlands has the potential to significantly reduce runoff generation during rainfall events, attenuating peak flows and the overall flashiness of the system.

The main conclusions of the thesis are as follows:

- In Paper **I,** we estimated dynamic storage using the three model structures within the HBV-light hydrological model across various catchments with different dominant landscape characteristics. We concluded that the three-bucket model performs best for estimating dynamic storage across all catchments, especially in large catchments dominated by sorted sediments. Further, contrary to our initial hypothesis that peatland proportion is linked to larger catchment storage, our results showed that dynamic storage is more strongly associated with other landscape characteristics such as catchment area, slope, soil type, and tree volume, rather than peatland coverage.

- In Paper II, we assessed the flood moderation ability of natural peatlands at both local and network scales during rainfall events with varying antecedent conditions. Our findings highlight the significant impact of antecedent conditions on hydrological responses. At the local scale, the peatland-dominated catchment exhibited more dampened responses than the similarly sized forest-dominated catchment on till soil. Contrary to our hypothesis, we did not observe a significant effect of peatlands on flood attenuation at the network scale.

- In Paper III, in light of the growing interest in peatland rewetting, we provided insight into the effect of rewetting a drained boreal peatland on the GWL and runoff dynamics. Based on the field data collected one year pre-rewetting and three years post-rewetting, we concluded that the hydrological functioning of the peatland is progressing towards a more natural state, characterised by a higher and more stable GWL. Further, in support of our hypothesis, significant increases in baseflow and a higher GWL threshold for runoff initiation served as indications of enhanced storage capacity within the peatland.

- In Paper IV, we advanced our understanding of how peatland rewetting contributes to natural flood management (NFM). We observed a gradual yet positive change in runoff responses after rewetting. In addition, we conducted a BACI analysis on 50 rainfall-runoff events and concluded that rewetting led to flood attenuation by significantly reducing peak flow, runoff coefficients, and hydrograph flashiness.

6. Final remarks and future perspectives

This thesis addressed a significant knowledge gap concerning hydrological processes in peatlands, especially within boreal ecosystems. Despite being such valuable ecosystems, little long-term hydrological data is available and the functioning of peatlands in general remains inadequately understood. This thesis benefitted greatly from the unique research infrastructure and the long data series provided by the Krycklan Catchment Study which offers insights into the hydrological functioning of natural peatlands at both local and stream network scales, in combination with other landscape characteristics. Moreover, growing concerns over the impacts of climate change on boreal ecosystems have heightened interest in peatland rewetting as a tool for mitigating hydrological extremes such as drought and flood. However, the effectiveness of these management strategies is not well-proven and further evidence is required. This thesis has thus made a significant contribution to addressing this knowledge gap in providing valuable empirical findings about the impact of rewetting on the hydrological functioning of a boreal peatland in the Swedish context. While our findings suggest successful outcomes in terms of groundwater table level recovery and moderated stormflow responses after rewetting, it is crucial to note that this success was evaluated over a relatively brief post-rewetting period of three years. Consequently, a certain level of uncertainty persists, particularly concerning the sustainability of flood mitigation under more extreme hydrological events. We also observed that, despite its seemingly rapid hydrological recovery, the rewetted site responded differently to the extreme drought in early summer 2023, showing a more pronounced drop in groundwater table level than the control site. However, the groundwater table level and discharge data records indicated a gradual progress toward a more favourable hydrological state. Therefore, we highly recommend continuous and long-term post-rewetting monitoring to better understand the sustained impact of restoration efforts. We further recommend integrating field data into process-based hydrological modelling to better understand the long-term effects of rewetting on hydrological responses, and ultimately predict the potential moderating effects of rewetting under different future climate scenarios.

References

Åhlén, I., Thorslund, J., Hambäck, P., Destouni, G. and Jarsjö, J., 2022. Wetland position in the landscape: Impact on water storage and flood buffering. Ecohydrology, 15(7), p.e2458.

Aapala, K., Kettunen, M., Haltia, E., Silvennoinen, S., Heikkilä, R., Hokkanen, T.J., Horne, P., Jäppinen, J.P., Lilja-Rothsten, S., Luotonen, H. and Maanavilja, L., 2012. Ecosystem services of boreal mires and peatlands. In 14th International Peat Congress. Stockholm, Sweden.

Acreman, M.C., Fisher, J., Stratford, C.J., Mould, D.J. and Mountford, J.O., 2007. Hydrological science and wetland restoration: some case studies from Europe. Hydrology and Earth System Sciences, 11(1), pp.158-169.

Acreman, M. and Holden, J., 2013. How wetlands affect floods. Wetlands, 33, pp.773-786.

Anderson, P., Worrall, P., Ross, S., Hammond, G. and Keen, A., 2011. United Utilities sustainable catchment management programme. Vol. 2: Restoring drained, burned and grazed moorlands. Report to United Utilities by Penny Anderson Associates.

Ahti, E.R.K.K.I., 1980. Ditch spacing experiments in estimating the effects of peatland drainage on summer runoff. International Association of Hydrological Sciences Publication, 130, pp.49-53.

Arheimer, B. and Lindström, G., 2015. Climate impact on floods: changes in high flows in Sweden in the past and the future (1911–2100). Hydrology and Earth System Sciences, 19(2), pp.771-784.

Armstrong, A., Holden, J., Kay, P., Francis, B., Foulger, M., Gledhill, S., McDonald, A.T. and Walker, A., 2010. The impact of peatland drain-blocking on dissolved organic carbon loss and discolouration of water; results from a national survey. Journal of Hydrology, 381(1-2), pp.112-120.

Bacon, K.L., Baird, A.J., Blundell, A., Bourgault, M.A., Chapman, P.J., Dargie, G., Dooling, G.P., Gee, C., Holden, J., Kelly, T.J. and McKendrick-Smith, K.A., 2017. Questioning ten common assumptions about peatlands. Mires and Peat, 19, pp.1-23.

Ballard, C.E., McIntyre, N. and Wheater, H.S., 2012. Effects of peatland drainage management on peak flows. Hydrology and Earth System Sciences, 16(7), pp.2299-2310.

Barrientos, G. and Iroumé, A., 2018. The effects of topography and forest management on water storage in catchments in south-central Chile. Hydrological Processes, 32(21), pp.3225-3240.

Berry, G.J., Jeglum, J.K. and Crook, G.W., 1995. Hydrological Responses of Drained Peatland Forests in Ontario. Natural Resources Canada, Canadian Forest Service-Ontario, Great Lakes Forestry Centre.

Breeuwer, A., Robroek, B.J., Limpens, J., Heijmans, M.M., Schouten, M.G. and Berendse, F., 2009. Decreased summer water table depth affects peatland vegetation. Basic and Applied Ecology, 10(4), pp.330-339.

Bring, A., Rosén, L., Thorslund, J., Tonderski, K., Åberg, C., Envall, I. and Laudon, H., 2020. Groundwater storage effects from restoring, constructing or draining wetlands in temperate and boreal climates: a systematic review protocol. Environmental Evidence, 9, pp.1-11.

Burke, W., 1975. Aspects of the hydrology of blanket peat in Ireland.

Conway, V.M., 1960. The hydrology of some small peat-covered catchments in the N. Pennines. Journal of the Institute of Water Engineers, 14, pp.415-424.

Dadson, S.J., Hall, J.W., Murgatroyd, A., Acreman, M., Bates, P., Beven, K., Heathwaite, L., Holden, J., Holman, I.P., Lane, S.N. and O'Connell, E., 2017. A restatement of the natural science evidence concerning catchment-based 'natural'flood management in the UK. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 473(2199), p.20160706.

Daniels, S.M., Agnew, C.T., Allott, T.E.H. and Evans, M.G., 2008. Water table variability and runoff generation in an eroded peatland, South Pennines, UK. Journal of Hydrology, 361(1-2), pp.214-226.

Duque, L.F., 2020. IETD: Inter-Event Time Definition. R package version 1.0. 0.

Edokpa, D., Milledge, D., Allott, T., Holden, J., Shuttleworth, E., Kay, M., Johnston, A., Millin-Chalabi, G., Scott-Campbell, M., Chandler, D. and Freestone, J., 2022. Rainfall intensity and catchment size control storm runoff in a gullied blanket peatland. Journal of Hydrology, 609, p.127688.

Erwin, K.L., 2009. Wetlands and global climate change: the role of wetland restoration in a changing world. Wetlands Ecology and management, 17(1), pp.71-84.

Evans, M.G., Burt, T.P., Holden, J. and Adamson, J.K., 1999. Runoff generation and water table fluctuations in blanket peat: evidence from UK data spanning the dry summer of 1995. Journal of Hydrology, 221(3-4), pp.141-160.

Fraixedas, S., Lindén, A., Meller, K., Lindström, Å., Keišs, O., Kålås, J.A., Husby, M., Leivits, A., Leivits, M. and Lehikoinen, A., 2017. Substantial decline of Northern European peatland bird populations: Consequences of drainage. Biological Conservation, 214, pp.223-232.

Gatis, N., Benaud, P., Anderson, K., Ashe, J., Grand-Clement, E., Luscombe, D.J., Puttock, A. and Brazier, R.E., 2023. Peatland restoration increases water storage and attenuates downstream stormflow but does not guarantee an immediate reversal of long-term ecohydrological degradation. Scientific Reports, 13(1), p.15865.

Girons Lopez, M., Vis, M.J., Jenicek, M., Griessinger, N. and Seibert, J., 2020. Assessing the degree of detail of temperature-based snow routines for runoff modelling in mountainous areas in central Europe. Hydrology and Earth System Sciences, 24(9), pp.4441-4461.

Goodbrand, A., Westbrook, C.J. and van der Kamp, G., 2019. Hydrological functions of a peatland in a Boreal Plains catchment. Hydrological Processes, 33(4), pp.562-574.

Harris, L.I., Richardson, K., Bona, K.A., Davidson, S.J., Finkelstein, S.A., Garneau, M., McLaughlin, J., Nwaishi, F., Olefeldt, D., Packalen, M. and Roulet, N.T., 2022. The essential carbon service provided by northern peatlands. Frontiers in Ecology and the Environment, 20(4), pp.222-230.

Haapalehto, T.O., Vasander, H., Jauhiainen, S., Tahvanainen, T. and Kotiaho, J.S., 2011. The effects of peatland restoration on water-table depth, elemental concentrations, and vegetation: 10 years of changes. Restoration Ecology, 19(5), pp.587-598

Heathwaite, A.L., 1995. Overview of the hydrology of British wetlands.

Holden, J. and Burt, T.P., 2003. Runoff production in blanket peat covered catchments. Water resources research, 39(7).

Holden, J., 2005. Peatland hydrology and carbon release: why small-scale process matters. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 363(1837), pp.2891-2913.

Holden, J., Wallage, Z.E., Lane, S.N. and McDonald, A.T., 2011. Water table dynamics in undisturbed, drained and restored blanket peat. Journal of Hydrology, 402(1-2), pp.103-114.

Holden, J., Green, S.M., Baird, A.J., Grayson, R.P., Dooling, G.P., Chapman, P.J., Evans, C.D., Peacock, M. and Swindles, G., 2017. The impact of ditch blocking on the hydrological functioning of blanket peatlands. Hydrological Processes, 31(3), pp.525-539.

Holmen, H., 1964. Forest ecological studies on drained peat land in the province of Uppland, Sweden.

Howson, T., Evans, M., Allott, T., Shuttleworth, E., Johnston, A., Rees, J., Milledge, D., Edokpa, D., Lockyer, C., Kay, M. and Spencer, T., 2023. Peatland gully restoration with stone and timber dams (Kinder Plateau, UK). Ecological Engineering, 195, p.107066.

Howson, T., Chapman, P.J., Shah, N., Anderson, R. and Holden, J., 2021. The effect of forest-to-bog restoration on the hydrological functioning of raised and blanket bogs. Ecohydrology, 14(7), p.e2334.

Hudson, D.T., Leach, J.A., Webster, K. and Houle, D., 2021. Streamflow regime of a lake-stream system based on long-term data from a high-density hydrometric network. Hydrological Processes, 35(10), p.e14396.

Jones, C., Waliser, D.E., Lau, K.M. and Stern, W., 2004. Global occurrences of extreme precipitation and the Madden–Julian oscillation: Observations and predictability. Journal of Climate, 17(23), pp.4575-4589.

Joosten, H. and Clarke, D., 2002. Wise use of mires and peatlands. International mire conservation group and international peat society, 304.

Joosten, H.A.N.S., 2016. Peatlands across the globe. In Peatland restoration and ecosystem services: Science, policy and practice (Vol. 2016, pp. 19-43). Cambridge, UK: Cambridge University Press.

Joosten, H., 2015. Peatlands, climate change mitigation and biodiversity conservation: An issue brief on the importance of peatlands for carbon and biodiversity conservation and the role of drained peatlands as greenhouse gas emission hotspots (Vol. 2015727). Nordic Council of Ministers.

Kellner, E., 2003. Wetlands-different types, their properties and functions.

Kellner, E. and Halldin, S., 2002. Water budget and surface-layer water storage in a Sphagnum bog in central Sweden. Hydrological Processes, 16(1), pp.87-103.

Kennedy, G.W. and Price, J.S., 2005. A conceptual model of volume-change controls on the hydrology of cutover peats. Journal of Hydrology, 302(1-4), pp.13-27.

Ketcheson, S.J. and Price, J.S., 2011. The impact of peatland restoration on the site hydrology of an abandoned block-cut bog. Wetlands, 31, pp.1263-1274.

Kløve, B., Berglund, K., Berglund, Ö., Weldon, S. and Maljanen, M., 2017. Future options for cultivated Nordic peat soils: Can land management and rewetting control greenhouse gas emissions?. Environmental Science & Policy, 69, pp.85-93.

Kohler, M.A. and Linsley, R.K., 1951. Predicting the runoff from storm rainfall (Vol. 30). US Department of Commerce, Weather Bureau.

Lambert, C., Larocque, M., Gagné, S. and Garneau, M., 2022. Aquifer-Peatland Hydrological Connectivity and Controlling Factors in Boreal Peatlands. Frontiers in Earth Science, 10, p.835817.

Laudon, H., Sjöblom, V., Buffam, I., Seibert, J. and Mörth, M., 2007. The role of catchment scale and landscape characteristics for runoff generation of boreal streams. Journal of Hydrology, 344(3-4), pp.198-209.

Leach, J.A., Larsson, A., Wallin, M.B., Nilsson, M.B. and Laudon, H., 2016. Twelve year interannual and seasonal variability of stream carbon export from a boreal peatland catchment. Journal of Geophysical Research: Biogeosciences, 121(7), pp.1851-1866.

Leifeld, J. and Menichetti, L., 2018. The underappreciated potential of peatlands in global climate change mitigation strategies. Nature communications, 9(1), p.1071.

Liu, L., Chen, H., Jiang, L., Hu, J., Zhan, W., He, Y., Zhu, D., Zhong, Q. and Yang, G., 2018. Water table drawdown reshapes soil physicochemical characteristics in Zoige peatlands. Catena, 170, pp.119-128.

Loisel, J., Yu, Z., Beilman, D.W., Camill, P., Alm, J., Amesbury, M.J., Anderson, D., Andersson, S., Bochicchio, C., Barber, K. and Belyea, L.R., 2014. A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. the Holocene, 24(9), pp.1028-1042.

Lopez, J.G. and Laudon, H., 2023. Water balance in boreal forests: the role of season-specific responses in a warming climate.

Ludden, A.P., Frink, D.L. and Johnson, D.H., 1983. Water storage capacity of natural wetland depressions in the Devils Lake Basin of North Dakota. Journal of Soil and Water Conservation, 38(1), pp.45-48.

Lundin, L., 1994. Impacts of forest drainage on flow regime (No. 192).

Luscombe, D.J., 2014. Understanding the ecohydrology of shallow, drained and marginal blanket peatlands. University of Exeter (United Kingdom).

Löfgren, S., Grandin, U. and Stendera, S., 2014. Long-term effects on nitrogen and benthic fauna of extreme weather events: Examples from two Swedish headwater streams. Ambio, 43, pp.58-76.

Nicholson, I.A., 1989. Effects of drainage on the hydrology of a peat bog. International Peat Journal, 3, pp.59-83.

Niedermeier, A. and Robinson, J.S., 2007. Hydrological controls on soil redox dynamics in a peat-based, restored wetland. Geoderma, 137(3-4), pp.318-326.

Nilsson, M., Sagerfors, J., Buffam, I., Laudon, H., Eriksson, T., Grelle, A., Klemedtsson, L., Weslien, P.E.R. and Lindroth, A., 2008. Contemporary carbon accumulation in a boreal oligotrophic minerogenic mire–a significant sink after accounting for all C-fluxes. Global Change Biology, 14(10), pp.2317-2332.

Norbury, M., Phillips, H., Macdonald, N., Brown, D., Boothroyd, R., Wilson, C., Quinn, P. and Shaw, D., 2021. Quantifying the hydrological implications of pre-and post-installation willowed engineered log jams in the Pennine Uplands, NW England. Journal of Hydrology, 603, p.126855.

Noumonvi, K.D., Ågren, A.M., Ratcliffe, J.L., Öquist, M.G., Ericson, L., Tong, C.H.M., Järveoja, J., Zhu, W., Osterwalder, S., Peng, H. and Erefur, C., 2023. The Kulbäcksliden Research Infrastructure: a unique setting for northern peatland studies. Frontiers in Earth Science, 11, p.1194749.

Marttila, H. and Kløve, B., 2010. Dynamics of erosion and suspended sediment transport from drained peatland forestry. Journal of hydrology, 388(3-4), pp.414-425.

Menberu, M.W., Haghighi, A.T., Ronkanen, A.K., Marttila, H. and Kløve, B., 2018. Effects of drainage and subsequent restoration on peatland hydrological processes at catchment scale. Water Resources Research, 54(7), pp.4479-4497.

Menberu, M.W., Tahvanainen, T., Marttila, H., Irannezhad, M., Ronkanen, A.K., Penttinen, J. and Kløve, B., 2016. Water-table-dependent hydrological changes following peatland forestry drainage and restoration: Analysis of restoration success. Water Resources Research, 52(5), pp.3742-3760.

O'Callaghan, J.F. and Mark, D.M., 1984. The extraction of drainage networks from digital elevation data. Computer vision, graphics, and image processing, 28(3), pp.323-344.

Moore, T.R. and Knowles, R., 1989. The influence of water table levels on methane and carbon dioxide emissions from peatland soils. Canadian Journal of Soil Science, 69(1), pp.33-38.

Paavilainen, E. and Päivänen, J., 1995. Peatland forestry: ecology and principles (Vol. 111). Springer Science & Business Media.

Paavilainen, E. and Päivänen, J., 1995. Peatland forestry: ecology and principles (Vol. 111). Springer Science & Business Media.

Pelster, D., Burke, J.M., Couling, K., Luke, S.H., Smith, D.W. and Prepas, E.E., 2008. Water and nutrient inputs, outputs, and storage in Canadian boreal forest wetlands: a review. Journal of Environmental Engineering and Science, 7(S1), pp.35-50.

Peralta-Tapia, A., Sponseller, R.A., Ågren, A., Tetzlaff, D., Soulsby, C. and Laudon, H., 2015. Scale-dependent groundwater contributions influence patterns of winter baseflow stream chemistry in boreal catchments. Journal of Geophysical Research: Biogeosciences, 120(5), pp.847-858.

Rodriguez, A.F., Daroub, S.H., Gerber, S., Jennewein, S.P. and Singh, M.P., 2021. Water management effect on soil oxidation, greenhouse gas emissions, and nitrogen leaching in drained peat soils. Soil Science Society of America Journal, 85(3), pp.814-828.

Rydin, H., Gunnarsson, U. and Sundberg, S., 2006. The role of Sphagnum in peatland development and persistence. Boreal peatland ecosystems, pp.47-65.

Seibert, J., 1999. Regionalisation of parameters for a conceptual rainfall-runoff model. Agricultural and forest meteorology, 98, pp.279-293.

Seibert, J. & Vis, M. J. 2012 Teaching hydrological modeling with a user-friendly catchment-runoff-model software package. Hydrology and Earth System Sciences 16 (9), 3315–3325

Seibert, J. and Bergström, S., 2021. A retrospective on hydrological modelling based on half a century with the HBV model. Hydrology and Earth System Sciences Discussions, 2021, pp.1-28.

Serk, H., Nilsson, M.B., Figueira, J., Wieloch, T. and Schleucher, J., 2021. CO2 fertilisation of Sphagnum peat mosses is modulated by water table level and other environmental factors. Plant, Cell & Environment, 44(6), pp.1756-1768.

Scheepers, H., Wang, J., Gan, T.Y. and Kuo, C.C., 2018. The impact of climate change on inland waterway transport: Effects of low water levels on the Mackenzie River. Journal of Hydrology, 566, pp.285-298.

Schimelpfenig, D.W., Cooper, D.J. and Chimner, R.A., 2014. Effectiveness of ditch blockage for restoring hydrologic and soil processes in mountain peatlands. Restoration Ecology, 22(2), pp.257-265.

Shantz, M.A. and Price, J.S., 2006. Characterisation of surface storage and runoff patterns following peatland restoration, Quebec, Canada. Hydrological Processes: An International Journal, 20(18), pp.3799-3814.

Shaw, E., 2005. Hydrology in practice. CRC press.

Shuttleworth, E.L., Evans, M.G., Pilkington, M., Spencer, T., Walker, J., Milledge, D. and Allott, T.E., 2019. Restoration of blanket peat moorland delays stormflow from hillslopes and reduces peak discharge. Journal of Hydrology X, 2, p.100006.

Spence, C., 2007. On the relation between dynamic storage and runoff: A discussion on thresholds, efficiency, and function. Water Resources Research, 43(12).

Spieksma, J.F.M., 1999. Changes in the discharge pattern of a cutover raised bog during rewetting. Hydrological processes, 13(8), pp.1233-1246.

Staudinger, M., Stoelzle, M., Seeger, S., Seibert, J., Weiler, M. and Stahl, K., 2017. Catchment water storage variation with elevation. Hydrological Processes, 31(11), pp.2000-2015.

Tiwari, T., Sponseller, R.A. and Laudon, H., 2022. The emerging role of drought as a regulator of dissolved organic carbon in boreal landscapes. Nature communications, 13(1), p.5125.

Turner, N., 1784. An Essay on Draining and Improving Peat Bogs: In which Their Nature and Properties are Fully Considered. By Mr. Nicholas Turner, Dennett Jaques. And sold by Baldwin and Bew in London.

Uhlenbrook, S., Seibert, J.A.N., Leibundgut, C. and Rodhe, A., 1999. Prediction uncertainty of conceptual rainfall-runoff models caused by problems in identifying model parameters and structure. Hydrological Sciences Journal, 44(5), pp.779-797.

Vasander, H., Tuittila, E.S., Lode, E., Lundin, L., Ilomets, M., Sallantaus, T., Heikkilä, R., Pitkänen, M.L. and Laine, J., 2003. Status and restoration of peatlands in northern Europe. Wetlands ecology and management, 11, pp.51-63.

Vitt, D.H. and Short, P., 2020. Peatlands. In Wetlands and Habitats (pp. 27-36). CRC Press.

Lourenco, M., Fitchett, J.M. and Woodborne, S., 2023. Peat definitions: A critical review. Progress in Physical Geography: Earth and Environment, 47(4), pp.506-520.

Walsh, J.E., Ballinger, T.J., Euskirchen, E.S., Hanna, E., Mård, J., Overland, J.E., Tangen, H. and Vihma, T., 2020. Extreme weather and climate events in northern areas: A review. Earth-Science Reviews, 209, p.103324.

Wilson, L., Wilson, J., Holden, J., Johnstone, I., Armstrong, A. and Morris, M., 2011. The impact of drain blocking on an upland blanket bog during storm and drought events, and the importance of sampling-scale. Journal of Hydrology, 404(3-4), pp.198-208.

Wilson, L., Wilson, J., Holden, J., Johnstone, I., Armstrong, A. and Morris, M., 2010. Recovery of water tables in Welsh blanket bog after drain blocking: discharge rates, time scales and the influence of local conditions. Journal of Hydrology, 391(3-4), pp.377-386.

Popular science summary

Peatlands provide various ecosystem services such as carbon (C) storage, water purification, and maintaining biodiversity. Peatlands also play an important role in enhancing ecosystem resilience by mitigating the impacts of both droughts and floods. It's generally believed that peatlands behave like sponges by storing large quantities of water during high rainfall (flood attenuation) and releasing it slowly into rivers, contributing to drought moderation. Despite performing these useful ecosystem services, peatlands around the world have been severely degraded. Northern Sweden's boreal peatlands have not been exempt from such degradation as they have been drained for forest production. With growing awareness of the adverse effects of climate change on boreal ecosystems, there is increasing interest in rewetting peatlands to regain their important ecosystem functions. In Sweden, particularly after the extreme drought of 2018, the government allocated large sums of money to peatland rewetting for drought moderation. However, as peatland rewetting is a relatively new strategy, the scientific foundation for this approach is not solid. In fact, the few scientific studies on the impact of peatland rewetting mostly originate from Finland, Canada, and the UK, where climatic and/or drainage conditions differ significantly from those found in Sweden. Therefore, in Papers I and II of my thesis, I examined the hydrological role of peatlands at both a local scale (comparing them to a similarly sized forested catchment) and a stream network scale (considering the influence of other dominant soil characteristics in the landscape). My results indicated that, at the local scale, peatlands exhibit greater water storage capacity and a moderating impact on flow responses. However, at the network scale, their ability to moderate flow is diminished due to the presence of other landscape characteristics. In Papers III and IV, I investigated the impact of peatland rewetting, specifically through ditch blocking, on the hydrological dynamics of a previously drained peatland. The findings of my research indicate that peatland rewetting has been successful, as evidenced by the elevation of the groundwater table level and the augmentation of water storage capacity within the peatlands. The results of the rainfall-runoff analysis also indicate that peatland rewetting has significantly reduced peak flow, runoff coefficient, and mitigated flashy hydrograph responses. Thus, peatland rewetting, possibly combined with other measures, can be an effective flood mitigation strategy. However, due to the evolving nature of the hydrological system, continuous long-term monitoring of peatland processes following rewetting is required.

Populärvetenskaplig sammanfattning

Myrar påverkar ett flertal viktiga ekosystemtjänster, såsom inlagring av kol (C), vattenrening och upprätthållande av biodiversitet. Dessutom spelar myrar en viktig roll i arbetet med att förbättra ekosystemens motståndskraft mot både torka och översvämningar. Det är en allmän uppfattning att myrar, vid kraftig nederbörd, kan lagra stora vattenmängder, för att sedan långsamt släppa ut det till intilliggande vattendrag. Trots dessa viktiga ekosystemtjänster har myrar kraftigt degraderats globalt, en trend som den borela skogsregionen, vilken omfattar betydande myrområden, inte har undgått. I norra Sverige har myrar historiskt dränerats för att öka skogsproduktion. Med en ökad medvetenhet om klimatförändringarnas ogynnsamma effekter på boreala ekosystem växer nu intresset för att återväta myrar för att återfå deras viktiga ekosystemfunktioner. I Sverige, i synnerhet efter den extrema torkan 2018, har regeringen avsatt stora summor pengar för återvätning som ett sätt att mildra effekterna vid torrperioder. Men eftersom återställning av myrar är en relativt ny strategi saknas den vetenskapliga grundvalen för tillvägagångssättet. I själva verket kommer de få vetenskapliga studierna om effekterna av återvätning huvudsakligen från Finland, Kanada och Storbritannien, där klimat- och/eller dräneringsförhållanden skiljer sig betydligt från hur det ser ut i Sverige. Därför undersökte jag i min avhandling (uppsats I och II) myrarnas hydrologiska roll både på lokal nivå (jämfört med ett skogsbeklätt avrinningsområde i jämförbar skala) och på en mer regional skala. Mina resultat indikerade att på lokal nivå har myrar större vattenlagringskapacitet och en mildrande effekt på flödesresponsen. Deras förmåga att, på ett mer regionalt perspektiv, mildra flödet begränsas dock på grund av närvaron av andra viktigare landskapskaraktärer. I uppsats III och IV genomförde jag en undersökning av Stormyren i Trollberget och återvätningens effekter på den hydrologiska dynamiken i den tidigare dränerade myren. Resultaten från min forskning indikerar en lyckad återställning, vilket visas genom höjningen av grundvattennivån och ökningen av vattenlagringskapaciteten inom myrarna. Dessutom indikerade resultaten från avrinningsanalysen att återvätningen ledde till minskade maximala flöden och andel avrunnet vatten. Således kan återvätning, eventuellt kombinerat med andra åtgärder, vara en effektiv strategi för att mildra översvämningsrisken nedströms. Men på grund av den ständigt föränderliga naturen och stora variationen hos hydrologiska system finns ett behov av kontinuerlig och långsiktig övervakning av de processer som följer i torvmarker till följd av återvätning.

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I

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Evaluating the effects of alternative model structures on dynamic storage simulation in heterogeneous boreal catchments

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ABSTRACT

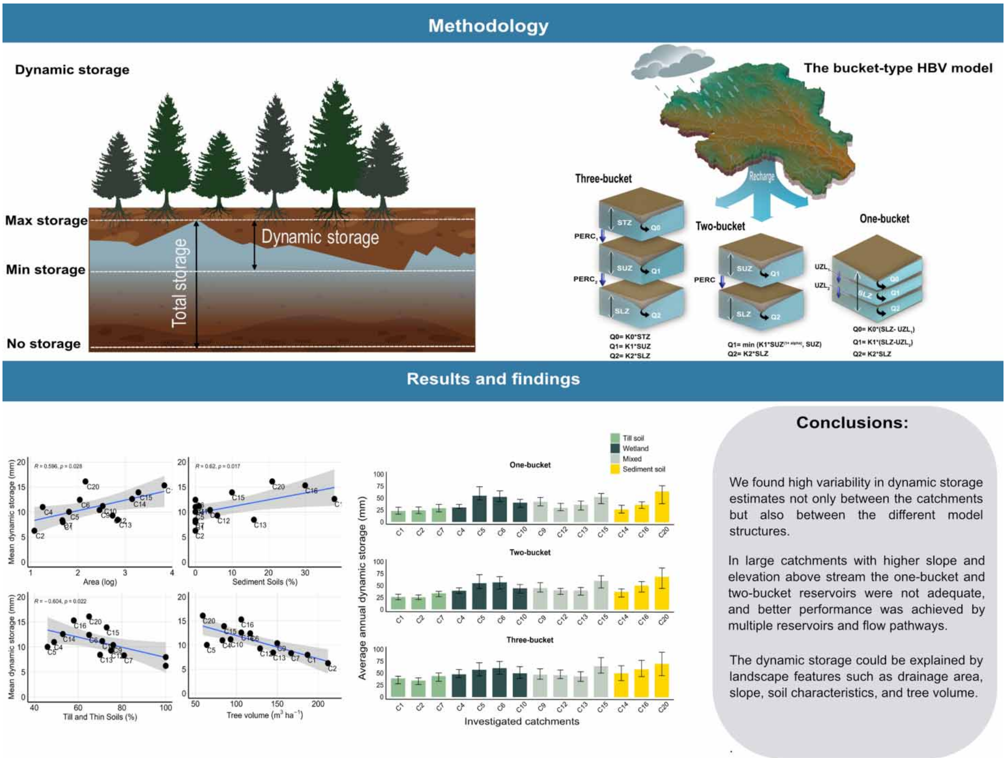
Estimating dynamic storage as a metric can be used to make an overall assessment of catchment resilience to extreme weather events such as droughts and floods. Because of the complexity of direct empirical measurements, bucket-type hydrological models can be a suitable tool to simulate the catchment storage across a broad range of scales as they require minimal input data. However, these models consist of one or more conceptual structures based on several linear or nonlinear reservoirs and connections between these reservoirs. Therefore, choosing the most appropriate model structure to represent storage-discharge functioning in catchments is difficult. To bridge this gap, this study evaluated the performance of three different HBV model structures on 14 heterogeneous boreal catchments classified into four distinct catchment categories. The results showed that the three-bucket structure performed better in larger catchments with deeper sediment soils. In contrast, a single reservoir structure is sufficient to predict the storage-discharge behavior for a lake-influenced catchment with lower elevation above the stream network. Moreover, our results indicate that while the estimates of mean catchment storage varied between the different model structures, the ranking between the catchments largely agreed for the different structures. Hence, our results suggest that instead of a single model structure, using an ensemble averaging approach would not only better address the structural uncertainty but also facilitate further storage comparison between different catchments. Finally, based on Spearman rank correlation results, we found that catchment size and sediment soil were positively correlated with dynamic storage estimation.

Key words: boreal, bucket-type, dynamic storage, ensemble, HBV, hydrological models, storage-discharge

HIGHLIGHTS

- Differences were found in storage estimates between the different model structures.
- Three-bucket structure performed well for all catchments.
- Lake-influenced catchments were well represented by one-bucket structure.
- One-bucket structure performed poorly in the large catchments with deep sediment soils.
- An ensemble averaging approach can be used as a point of comparison between hydrological functioning of catchments.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Storage and release of water are essential catchment functions, with large effects on modulating hydrological extremes such as drought and floods (Creutzfeldt *et al.* 2012). Water entering catchments is stored in different forms, including snow, ice, lakes, soil moisture, and groundwater (Riegger & Tourian 2014). Depending on soil physical properties, water can be retained in the unsaturated zone, move through the soil column and percolate to saturated layers as groundwater recharge. Accordingly, there are various pathways that water can take when it flows between unsaturated and saturated zones before leaving the catchment, depending on soil physical properties, catchment characteristics, and climate (Jutebring Sterte *et al.* 2021).

The temporal dynamics of stream discharge depend largely on catchment storage (Kirchner 2009; Creutzfeldt *et al.* 2012; Brauer *et al.* 2013). In periods when evapotranspiration and precipitation are negligible, it can be assumed that the only driver of discharge is the amount of water stored in the catchment (Moore 1997; Kirchner 2009). Water content freely available for drainage and flow is known as 'mobile storage' (Farrick & Branfireun 2014; Staudinger *et al.* 2017). However, not all catchment storage contributes to the runoff generation process, which is sometimes referred to as 'hydraulically decoupled storage' (Dralle *et al.* 2018). Changes in the amount of these hydrologically decoupled storages can have a negligible effect on runoff generation, at least in the short term, because of deep groundwater storage, or have no effect, such as canopy interception that leaves the basin through evaporation without entering the soil.

In many previous studies, catchment storage at different spatial scales has been quantified using a range of different methods: water balance approaches (Sayama *et al.* 2011; Wang & Alimohammadi 2012), hydrometric analysis (Kirchner 2009; McNamara *et al.* 2011; Brauer *et al.* 2013; Amvrosiadi *et al.* 2017a, 2017b), analysis of stable isotope tracers (Soulsby *et al.* 2009; Sprenger *et al.* 2018), gravimeter measurements (Creutzfeldt *et al.* 2012; Kennedy *et al.* 2014), and application of hydrological models (Staudinger *et al.* 2017; Sterte *et al.* 2018; Karlsen *et al.* 2019). One of the most common methods for direct estimation of catchment water storage involves using a network of piezometer wells and soil moisture probes to provide detailed information on whether a sufficient number of sensors has been installed (Kalbus *et al.* 2006). However, due to the high spatiotemporal variability, collecting massive hydrological data across a broad range of scales is time-consuming and costly (Kirchner 2009). Hence, efforts to reduce field investigations have resulted in various modeling attempts to understand better the complexities of the hydrological behavior in heterogeneous catchments.

There are several definitions of catchment water storage (Staudinger *et al.* 2017). Here, we focus on the part of the storage that is relevant for catchment discharge. This leads to an operational definition where the storage is zero when streamflow ceases completely. Various terms have been proposed for this discharge-generating storage; these include 'dynamic storage' (Kirchner 2009; Sayama *et al.* 2011; Staudinger *et al.* 2017), 'active storage' (McNamara *et al.* 2011), and 'direct storage' (Dralle *et al.* 2018). Here we use the term dynamic storage as a critical metric to assess the sensitivity of a catchment to extreme weather events such as flooding or its resistance to drought by maintaining low flows (McNamara *et al.* 2011). Revealing the dynamic storage-discharge relationship can also help make more accurate predictions of streamflow changes in response to global warming.

Bucket-type models, also called conceptual models, are suitable tools for simulating runoff and water availability based on storage–discharge relationships and represent in general terms how precipitation results in groundwater recharge, evapotranspiration, and discharge (Hrachowitz & Clark 2017; Sitterson *et al.* 2018). These models consist of several reservoirs, which can be linear or nonlinear and be connected in serial or parallel (Stoelzle *et al.* 2015; Parra *et al.* 2019a). The most important advantage of these bucket-type models, compared to more detailed and complex fully physically-based models, is a lower number of free parameters, which means that the parameter values of the models can, in principle, be estimated by calibration only. However, even for such models, model parameter uncertainty has to be considered when deriving storage estimates by modeling. Furthermore, there is model structure uncertainty as there are usually various possible alternatives to arrange the different buckets. For example, the proper choice of linear and nonlinear storage-discharge relationships has been debated for a long time (Stoelzle *et al.* 2015). Some researchers have concluded that groundwater release is a linear process (Chapman 1999; Fenicia *et al.* 2006), while others have demonstrated that nonlinear relationships are more appropriate (Wittenberg 1999; Mishra *et al.* 2003; Botter *et al.* 2009; Maneta *et al.* 2018; Rezaei-Sadr 2019). These findings show that choosing appropriate model structures is challenging and uncertain. In other words, the mathematical formulation of hydrological functions that control the transformation of rainfall to runoff might vary by type of catchment and climate, and that a 'one size fits all' is not easily found (Hogue *et al.* 2006; Ajami *et al.* 2007).

Many studies have used bucket-type models to improve the understanding of hydrological functioning in catchments, such as estimation of water storage (Krasnostein & Oldham 2004; Mendoza-Sanchez *et al.* 2013; Staudinger *et al.* 2017) as well as streamflow signatures (Hailegeorgis & Alfredsen 2015; Ledesma & Futter 2017; Teutschbein *et al.* 2018). These studies have also demonstrated that bucket models can provide suitable representations of catchment hydrology and result in good runoff simulations for both calibration and validation periods. However, as pointed out in previous studies, achieving an acceptable value of model performance based on a good agreement between modeled and observed streamflow data does not necessarily correspond to a good simulation for other hydrological functioning (Gupta *et al.* 2012; Teutschbein *et al.* 2015; Lane *et al.* 2019; Seibert *et al.* 2019). Therefore, choosing a model structure with an appropriate degree of complexity is a crucial step in catchment modeling.

Hence, despite a good model performance for a certain calibration or validation period, model outputs can still be unreliable when extrapolated beyond calibration conditions (Seibert 1997). Therefore, a proper analysis of how the model parameters and the model structures are correlated and a detailed assessment of their effects on the model output can improve the model reliability. To our knowledge, few previous studies have comprehensively analyzed the most important parameters controlling the amount of storage in the catchment reservoirs (Tetzlaff *et al.* 2015; Teutschbein *et al.* 2015; Ledesma & Futter 2017). This is especially true in northern latitude catchments defined by long-lasting winters and snowmelt-dominated hydrological conditions.

The main purpose of the approach lies in the evaluation of the performance of different model structures, which only differ in the number of storage reservoirs, in estimating dynamic storage using a bucket-type model for a large number of catchments with contrasting landscape characteristics but similar climatic conditions. In addition, we aimed to better understand the relationship between dominant catchment characteristics and dynamic storage variability across a heterogeneous boreal landscape. We addressed the following research questions: (1) How does the uncertainty of parameters in the response routine of a bucket-type model affect the dynamic storage estimation? (2) Is there a major difference between dynamic storage estimates obtained using different model structures? If yes, which model structure is most reliable at different catchment scales? We then used this approach to evaluate how simulated dynamic storage varies in both time and space for different subcatchments. Furthermore, we studied potential relationships between the different types of storage zones and dominant catchment characteristics.

2. MATERIALS AND METHODS

2.1. Study site

The study was conducted in the Krycklan catchment located in northern Sweden, about 50 km west of the Baltic Sea coast (64°25′ N, 19°46′ E), with an area of approximately 68 km^2. The catchment area comprises 14 nested subcatchments with elevation ranging from 130 to 370 meters above sea level, as shown in Figure 1. The higher elevations of the catchment are dominated by till (58% of total area) and peat soil, and lower elevations are covered by sediment soils (Laudon *et al.* 2021). Forests cover 87% of the entire catchment and are dominated by Scots pine (Pinus sylvestris) and Norway spruce (Picea abies).

The hydrological characteristics of the catchment are well studied and are monitored by 14 streamflow gauging stations (named C1-C20, with some of the original stations abandoned for various reasons) (Table 1). The climate in this area is characterized by relatively cold winters with consistent snow coverage for four to six months of the year, between November to April. The annual average precipitation was 614 mm for 1981–2010, and the average daily mean temperature was 1.8 °C. The mean temperature was −9.5 °C in January and +14.7 °C in July (Laudon *et al.* 2013).

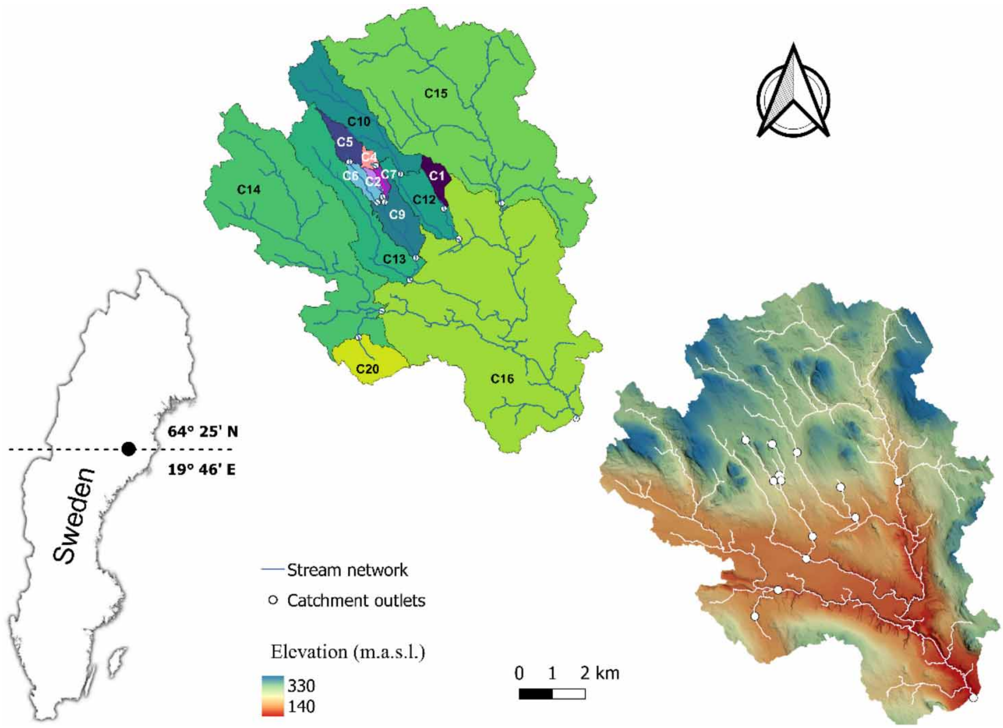


Figure 1 | Topography and subcatchments of the Krycklan catchment and its location in Sweden.

Table 1 | Catchment gauging set up and mean specific discharge values over the study period

Catchment	Gauge type	Mean specific discharge (mm d^{-1})	Water level logger
C1	90° V-notch weir	0.83	PT, TT
C2	90° V-notch weir[a]	0.63	PT, TT
C4	90° V-notch weir[a]	1.03	PT, TT
C5	120° V-notch weir, H-flume[b]	1.12	PT, TT
C6	Culvert	1.05	PT, TT
C7	90° V-notch weir[c]	0.84	PT, TT, Float
C9	Culvert	0.91	PT, TT
C10	Culvert	0.90	PT, TT
C12	Venturi flume	0.93	TT
C13	Trapezoidal flume	0.78	PT, TT
C14	Natural section	0.71	TT
C15	Natural section	1.03	PT, TT
C16	Natural section (bridge)	0.90	TT,RLS
C20	Culvert	0.97	TT

[a]Heated weir since 2011.
[b]Heated flume since 2012.
[c]Heated weir since 1981.
PT, Pressure transducer (MJK 3400, with Campbell Scientific CR1000); TT, TruTrack capacitance rods (WTHR 1000); Float, OTT model X float strip chart recorder; RLS, OTT RLS Radar.

2.2. Input data

2.2.1. Hydrological data

Discharge observations from 14 subcatchments within the Krycklan catchment were used (Karlsen *et al.* 2019). Water levels, measured using automatic stage loggers, were possible year-round for five gauging stations in heated houses (C2 and C4 have been heated since 2011, C5 and C13 since 2012, and C7 since 1981). The monitoring program began in 1981 inside a heated hut (with an hourly resolution), and in 2003, gauging started in all 14 subcatchments. The lengths of all hydro-climatic data series in our study were adjusted to match the span of subcatchments with the least amount of data, covering a period of seven hydrologic years (1 October–30 September) from 2011 to 2017. Frequent manual water-level measurements (monthly during winter, minimum bi-weekly during the rest of the year) were made to calibrate automatic water level data, and stage-discharge relationships were defined using manual flow gauging (Karlsen *et al.* 2019). Specific discharge, defined as streamflow per unit drainage area, was calculated for each catchment.

2.2.2. Meteorological data

Air temperature, humidity, net radiation, and wind speed for estimating potential evapotranspiration (PET) via the Penman equation were measured in the central part of the Krycklan catchment at the Svartberget research station (Laudon *et al.* 2021). All climate data were assumed to be uniform for the whole catchment area. Precipitation from one centrally placed weather station was used (64°14′ N, 19°46′ E, 225 m a.s.l) for all catchments as there is no significant elevation gradient observed for the region by the network of the Swedish Meteorological and Hydrological Institute (SMHI) (Karlsen *et al.* 2016).

2.2.3. Catchment characterization

A LiDAR DEM with 2 m resolution was created from a point cloud with a point density of 15–25 points/square meter. This DEM was hydrologically corrected by burning streams and culverts across roads as described in Lidberg *et al.* 2017. Catchment areas were delineated from the hydrologically correct DEM using Deterministic-8 (D8) (O'Callaghan & Mark 1984). The Swedish property map (1:12,500, Lantmäteriet Gävle, Sweden) was used to calculate forest, lake and, wetland coverage for each catchment. The proportion of soil type cover was calculated for sediment soils, till, and thin soils using the

Table 2 | Catchment characteristics of the entire Krycklan catchment (in bold) and its subcatchments (sorted from left to right by increasing catchment area)

Properties	Unit	C02	C04	C01	C07	C05	C06	C20	C09	C10	C12	C13	C14	C15	C16
TOPOGRAPHY															
Area	[km^2]	01	0.2	0.5	0.5	0.7	1.1	1.5	2.9	3.4	5.4	7.0	13.8	19.1	**67.9**
Median catchments area[a]	[km^2]	0.1	0.2	0.1	0.2	0.7	0.8	1.0	0.3	2.0	1.7	0.5	2.2	0.7	**1.4**
Elevation above sea level	[m]	275	287	279	275	293	282	211	252	297	277	251	229	278	**239**
Elevation above stream[b]	[m]	10.1	9.0	10.9	7.5	2.3	4.2	13.5	4.4	8.3	7.4	6.3	10.2	9.6	**10.0**
Slope	[%]	9	8	9	9	5	9	11	8	10	9	9	12	12	**12**
Aspect	[°]	139	146	177	149	168	164	164	161	161	164	156	171	180	**172**
GEOLOGY/SOIL															
Sediment	[%]	16	27	8	15	30	26	42	20	19	20	29	47	27	**42**
Till	[%]	84	22	92	65	16	39	45	62	52	61	57	43	56	**47**
LAND COVER															
Wetlands	[%]	0	44	2	18	40	25	10	14	26	17	10	5	15	**9**
Agricultural land	[%]	0	0	0	0	0	0	3	0	0	0	1	3	0	**2**
Lakes	[%]	0	0	0	0	6	4	0	1	0	0	1	1	2	**1**
Tree volume[c]	[m^3 ha^{-1}]	212	83	187	167	64	117	59	150	93	129	145	106	85	**106**
Forest	[%]	100	56	98	82	54	71	88	84	74	83	88	90	82	**87**

[a]Median catchment area from 5 m LiDAR DEM, calculated similar to McGuire *et al.*(2005).
[b]Catchment mean elevation above stream from 5 m LiDAR DEM, calculated similar to McGuire *et al.*(2005).
[c]Calculated for the entire catchment using correlations between a forest inventory (from 110 plots) and LiDAR measurements (Laudon *et al.* 2013).
Note: Values in bold refer to the Krycklan catchment outlet (C16).

quaternary deposits map (1:100,000, Geological Survey of Sweden, Uppsala, Sweden). Landscape characteristics of all catchments, including the main outlet (C16, in bold), are summarized in Table 2.

2.3. HBV model description

A modified version of a bucket-type, semi-distributed hydrological model, namely the HBV model (Lindström *et al.* 1997) in the version HBV light (Seibert & Vis 2012) was used to simulate dynamic storage at a daily time step in the catchment. The HBV model is a widely used bucket-type model for simulating runoff. One advantage of HBV is the limited demand for input data. The input data for the HBV model were rainfall, air temperature data, and derived PET. The observed streamflow data were used for the calibration of the model. In general, the model consists of four commonly used routines which represent: (1) snow by a degree-day method; (2) soil moisture, and (3) groundwater by three linear reservoir equations; and (4) channel routing by a triangular weighting function. In the snow routine, a threshold temperature is used to distinguish between rainfall and snowfall, and snowmelt is considered by a degree-day approach.

A more detailed description of HBV's routines can be found in Seibert & Vis (2012). HBV-light includes three alternative model structures based on a varying number of conceptual reservoirs (one, two, or three) and different shapes of the storage-discharge relationship (linear versus nonlinear).

We implemented the three model structures of the response routine. This included a one-bucket structure with a single groundwater reservoir and three linear outflows (Q0, Q1, and Q2) at three different thresholds; a two-bucket structure with two reservoirs in parallel with a nonlinear outflow (Q1) in an upper bucket and one linear outflow (Q2) in a lower bucket (basic version); and a three-bucket structure with three parallel reservoirs (STZ, SUZ, and SLZ) and one linear outflow in each reservoir (Figure 2). It should be noted that these model structures differ only in the response routine, i.e., the same snow and soil routines were used in all model variants.

The built-in Genetic Algorithm followed by a Powell optimization (GAP, Seibert 2000) was used to calibrate the models for each catchment. For calibration, warm-up periods of at least one year were used for each catchment based on data availability. The initially chosen possible parameter ranges were adapted from Uhlenbrook *et al.* (1999) where preliminary simulations indicated that suitable parameter values were close to the limits.

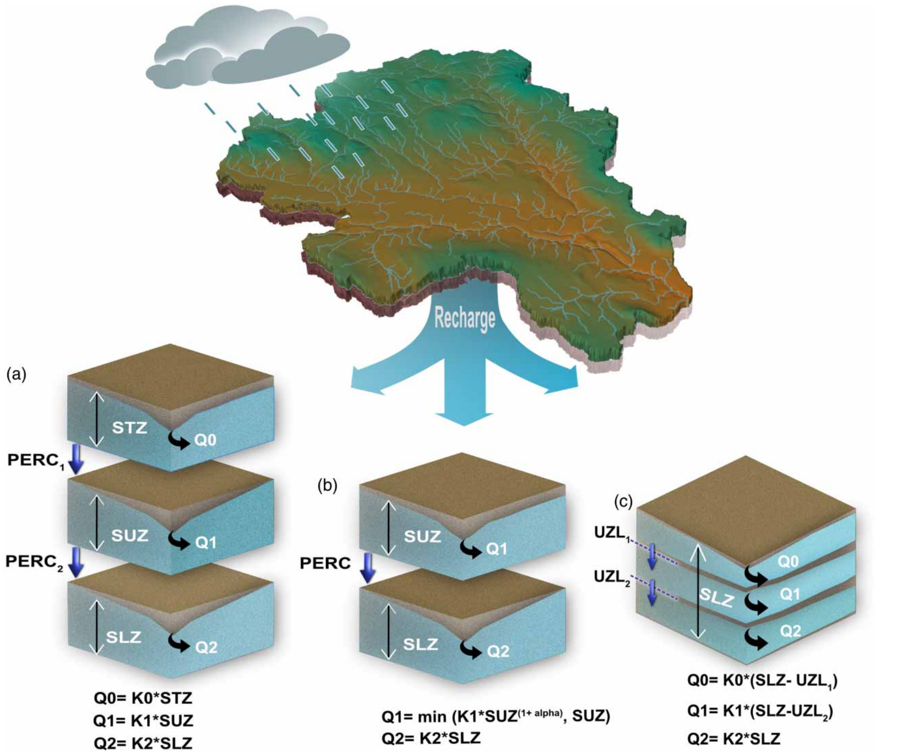


Figure 2 | Groundwater routines considered in this study. Three-bucket (a); two-bucket (b) and one-bucket (c). Recharge = Input from soil routine (mm/d); STZ = Storage in soil top zone (mm/d); SUZ = Storage in upper groundwater zone (mm/d); SLZ = Storage in lower groundwater zone (mm/d); UZL_i = Threshold parameter (mm/d); $PERC_i$ = Maximum percolation to the lower zone (mm/d); Alpha = Non-linearity coefficient; K_i = Recession coefficient (d^{-1}); Q_i = Runoff component (mm/d).

To consider parameter uncertainty, each calibration trial was repeated 100 times (5000 iterations each) and the best 100 parameter sets were selected according to the Nash Sutcliffe model efficiency. The Nash–Sutcliffe efficiency (NSE) coefficient, here called R_{eff}, is calculated with the following equation (Uhlenbrook *et al.* 1999):

$$R_{eff} = 1 - \frac{\sum (Q_{obs} - Q_{sim})^2}{\sum (Q_{obs} - \overline{Q_{obs}})^2} \quad (1)$$

where Q_{obs} and Q_{sim} are the measured (observed) and modeled (simulated) flows, respectively.

We considered parameterizations resulting in good runoff simulations in terms of Nash–Sutcliffe efficiencies (R_{eff}) as plausible. From the 100 calibration trials, we thus derived an ensemble of plausible simulations that result in a range of storage estimates for the upper (SUZ) and lower storage (SLZ) reservoirs. In the next step, the estimated storage from all reservoirs was combined and the difference between the minimum and maximum values was considered as dynamic storage.

A qualitative preparatory evaluation of parameter sensitivity indicated that automatic calibration could sometimes result in very small values for K2 (baseflow recession coefficient) with tiny model performance improvements for these very small K2 values (Figure 3 and Supplementary Material, Figure A). These very small K2 values, in turn, resulted in extremely large estimates of the derived catchment storage for some of the catchments. This optimization issue, which greatly affected the storage

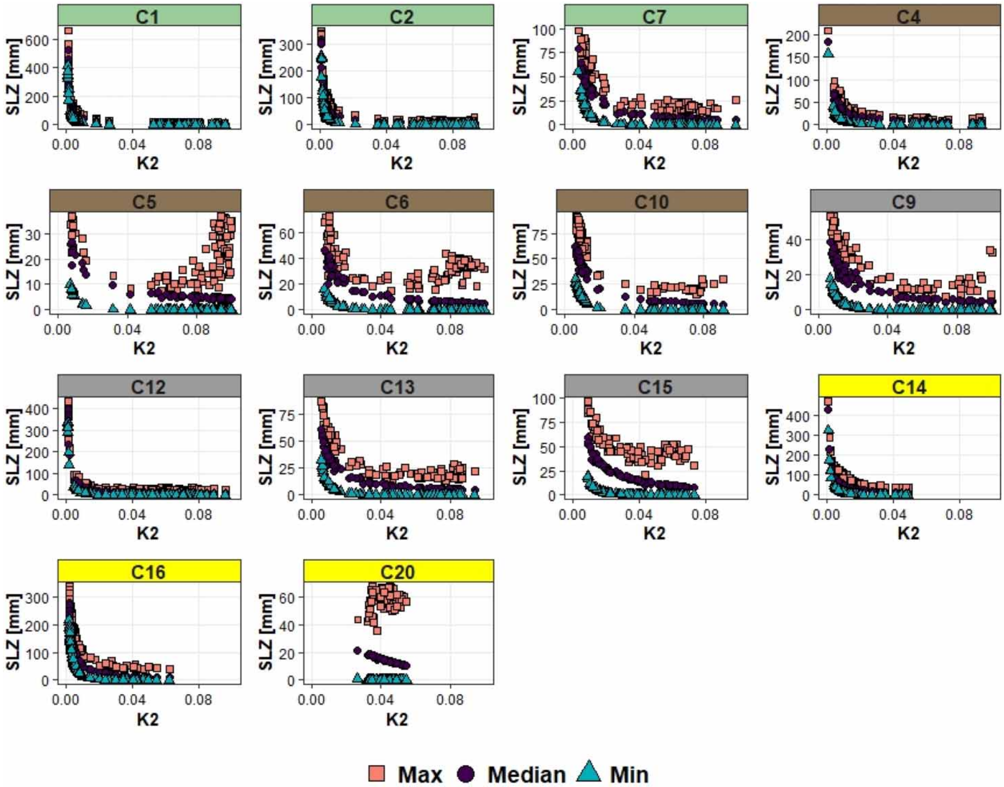


Figure 3 | Scatter plots of recession coefficient values for the lower groundwater zone (K2) versus the minimum, maximum, and median simulated lower groundwater storage (SLZ) derived from the first 100 calibration trials for each of the subcatchments. Plots are colored based on different dominant landscape types (green = forest on till, brown = wetland, gray = catchments with mixed characteristics, yellow = forest on sedimentary deposits). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2022.121.

simulation results, occurred mainly with the three-bucket model structure. All but one of the catchments (C20) showed a strongly nonlinear relationship between K2 and storage in the lower zone. To avoid artefacts like this, we limited the lower range of K2 to 0.02. The summary statistics (min, max, and mean) of calibrated parameter values with limited K2 parameter values are summarized in Table 3.

2.4. Water balance method

Based on simple water balance accounting (Equation (2)), time series of catchment water storage were obtained for each catchment.

$$V(t) = V_0 + \Delta t \sum_{i=1}^{t} (P_i - Q_i - E_i) \tag{2}$$

where P is the precipitation, E is the evapotranspiration, Q is the streamflow, and V(t) and V_0 are the storage at time step t and t = 0, respectively. We then calculated the total water storage, ΔV as the difference between the minimum and maximum of the estimated storage volumes over the observation period (Staudinger *et al.* 2017).

Table 3 | Calibration results with limited K2 parameter for the catchment outlet, C16

Parameter	Description	Calibration range	Min	Max	Median
One-bucket					
PERC	Maximum flow from upper to lower zone (mm/d)	0–4	3.07	3.99	3.94
UZL	Threshold parameter (mm)	0–70	20.31	60.47	24.17
K0	Recession coefficient of fast runoff (d^{-1})	0.1–0.5	0.10	0.37	0.18
K1	Recession coefficient of upper box (d^{-1})	0.01–0.2	0.01	0.10	0.04
K2	Recession coefficient of lower box (d−1)	0.02–0.1	0.02	0.07	0.03
Two-bucket					
PERC	Maximum flow from upper to lower zone (mm/d)	0–4	0.93	4.00	3.04
Alpha	Nonlinearity coefficient	0–1	0.14	0.60	0.31
K1	Recession coefficient of upper box (d^{-1})	0.01–0.2	0.02	0.19	0.11
K2	Recession coefficient of lower box (d^{-1})	0.02–0.1	0.02	0.07	0.05
Three-bucket					
PERC	Maximum flow from upper to lower zone (mm/d)	0–4	0.80	3.56	1.66
UZL	Threshold parameter (mm)	0–70	4.08	11.43	7.15
K0	Recession coefficient of fast runoff (d^{-1})	0.1–0.5	0.30	0.49	0.43
K1	Recession coefficient (d^{-1})	0.01–0.2	0.07	0.18	0.11
K2	Recession coefficient of lower box (d−1)	0.02–0.1	0.02	0.06	0.02

2.5. Correlation analysis between landscape characteristic and dynamic storage

To investigate the relationship between landscape characteristics and simulated dynamic storage, we used non-parametric Spearman rank correlations (Spearman 1904). The storage metrics used in this analysis were dynamic storage (the difference between the minimum and maximum storage), mean storage (mean value during the entire analysis period), storage in the upper and lower zone separately (SUZ and SLZ), and mean storage for each season. Instead of using a single model output, we used the average of all three model structures to calculate these storage metrics and then examined their relationship with landscape characteristics.

3. RESULTS

3.1. Model performance analysis

Based on the results, differences in model performance were found between catchments with different landscape characteristics. There are also performance differences between the different model structures. The range of the best 100 model performances (R_{eff}) of the three model structures for each subcatchment is shown in Figure 4. The plot suggests that model performance decreases as the mean elevation above the streams increases ($r = -0.85$, $p < 0.05$). Moreover, the three-bucket model gave good agreement between the simulated and observed streamflow in all the catchments (R_{eff} between 0.76 and 0.87). The one-bucket model performed well in the lake-influenced catchments, C5 and C6 ($0.80 < R_{eff} < 0.87$), while it performed worse for large catchments with deep soils, C14 and C16 ($0.68 < R_{eff} < 0.75$). This indicates that the one-bucket model could not represent the hydrological functioning as well as the three-bucket model in the large catchments with deep sediment soils. The one-bucket model resulted in the poorest simulations in C14 and the best simulation in C6 with maximum R_{eff} values of 0.74 and 0.87, respectively. Additionally, the two-bucket model with two storage reservoirs and only two outflows (intermediate and baseflow) performed similarly to the one-bucket model for C2, C4, C9, and C20. The highest model performances were obtained for C5, C6 and, C9, which have a high lake percentage and lower elevation above their stream network. The simulated discharge time series derived from the three model structures calibrated against observed discharge, for four representing catchments including C4, C5, C7, and C16, are shown in supporting information Figure B1–4. These catchments are also representing the highest (C4 and C5), average (C7), and lowest NS values (C16). We also provided a detailed analysis of snow water equivalent and soil moisture estimated using the three model structures for the above-

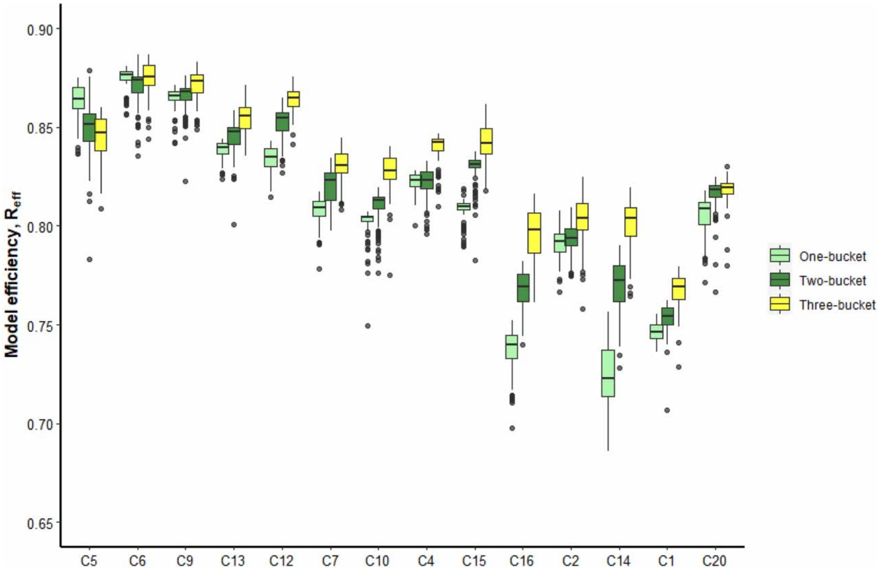


Figure 4 | Boxplots represent the variation of model performance during the calibration period. The catchments are sorted from left to right in ascending order of their mean elevation above the stream network. The lower and upper endpoints of the boxes represent the 25th and 75th percentiles of model performance over 100 parameterizations. The whiskers show the range of model performance between the minimum and maximum values. The horizontal bar and dots show the median value and outliers, respectively.

mentioned catchments. Results showed that all model structures simulated snow water equivalent relatively similar for the four representing catchments, though C4 and C5 had a slightly higher amount (supporting information Figure C1-4).

3.2. Flow characteristics

The contribution (as a fraction of the total discharge) of outflow from the surface (Q0), upper (Q1), and the lower (Q2) flow paths for all the model structures are shown in Figure 5 (note that the standard version of HBV has only two outflows, Q1 and Q2). The boxplots are based on 100 streamflow characteristic values derived from 100 different parameter sets. When comparing the runoff components calculated by all three model structures, remarkable differences were seen between different subcatchments and the three HBV model structures. For example, the difference in the contribution of different Q components between the sediment and till-dominated catchments was apparent. It can be seen in Figure 5 that the calibrated contribution of discharge from the lower groundwater bucket (baseflow) was higher in larger catchments with more sediment soils (e.g., C14, C15, and C16). In contrast, in catchments C5 and C4, the fast flow (Q1) showed a more significant contribution to total runoff generation.

3.3. Comparisons of dynamic storage within and between catchments

Simulation results from the three-bucket structure, which showed reasonably good performance across all catchments, demonstrate differences in storage components between catchments. The simulated maximum storage in the upper and lower groundwater bucket are plotted in Figure 6. It can first be noted that in wetland-dominated catchments, the maximum storage in the upper groundwater zone was higher than the other subcatchments. In contrast, catchments dominated by sediment soils retained a higher amount of water in their lower groundwater bucket. It should also be noted that the upper reservoir (SUZ) is nearly empty during long periods and the mean value is, therefore, small. The simulated daily storage in upper and lower reservoirs estimated by each model structure was then aggregated to compare changes in dynamic storage estimated by different model structures.

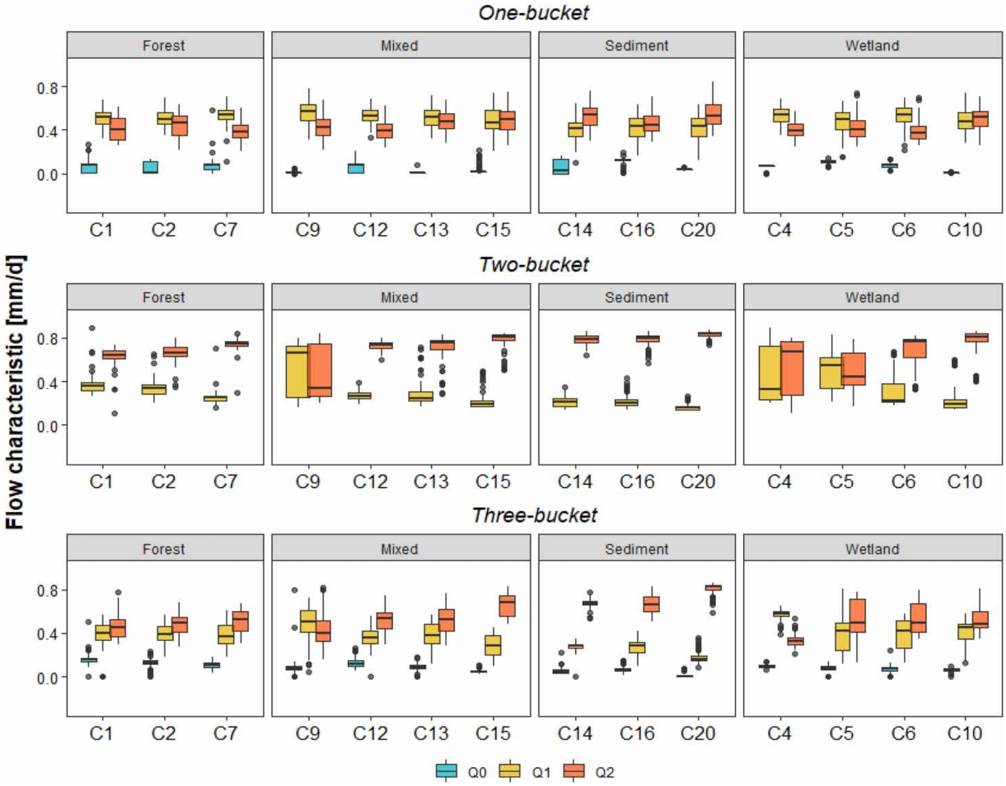


Figure 5 | Fraction of fast runoff (Q0), delayed runoff (Q1), and slow runoff (Q2) to catchment outflow derived from different model structures.

The dynamic storage estimates calculated as the difference between the maximum and minimum groundwater storages from the different model structures are presented in Figure 7. While the estimated storage volumes varied, a consistent overall pattern among the catchments could be observed. In general, the forested catchments had lower storage estimates than the catchments with a lake or large wetlands, and storage estimates were even larger for the sediment catchments. For some of the catchments (C5, C6, and C9), the estimated dynamic storages were similar for the different model structures. In contrast, the differences were higher for others (C14, C15, and C16).

In contrast to the overall range of dynamic storage, the mean storage value calculated by each model structure showed large variation among catchments (Figure 8, Table 4).

For most of the catchments there was only a slight increase in estimated dynamic storage from the one-bucket to the two-bucket structure, but a significant increase from the two-bucket to the three-bucket in most of the catchments (Figure 8). This pattern was opposite for the lake dominated-catchment (C5).

Simulated dynamic storage, however, exhibited more variation both within and among the catchments on shorter time-scales (Figure 9). The variation in dynamic storage between catchments was highest in spring with a minimum value of 9 mm for C1 and a maximum value of 30.9 mm for C20, and lowest in winter with a range of 5 mm. According to the three-bucket model, C5 had the largest seasonal variation with the mean storage approximately 5 times greater in spring compared to winter. Additionally, we quantified the similarity degree between the mean seasonal storage estimates by the three model structures using the Spearman correlation coefficient (Table 5). The comparison of similarity metrics revealed that the

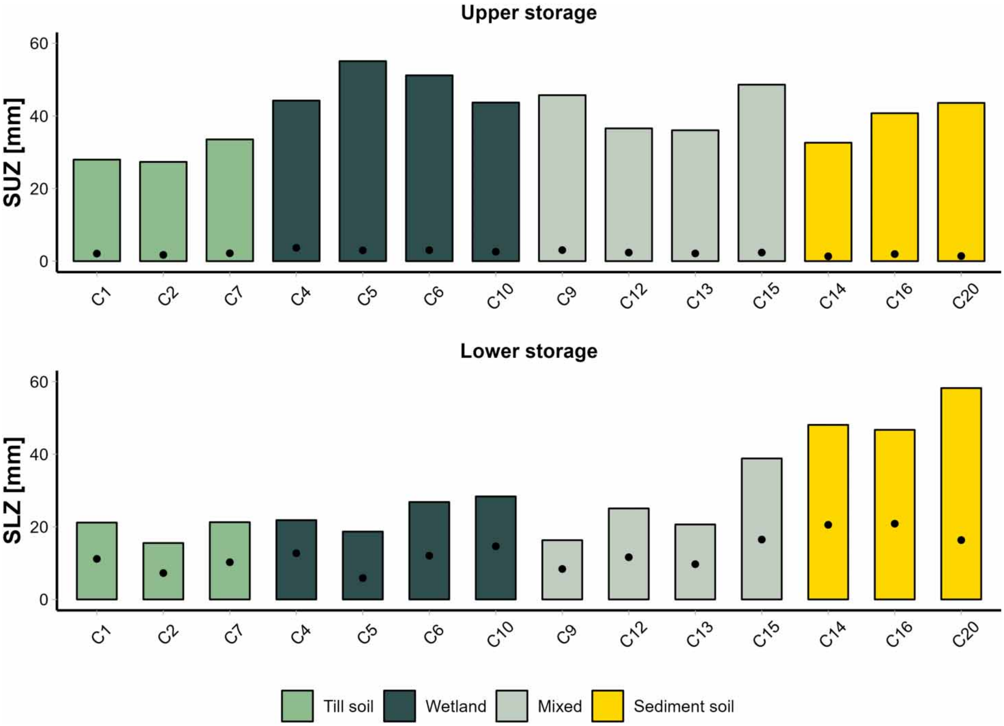


Figure 6 | The maximum amount of storage (mm) in the upper (SUZ) and lower (SLZ) groundwater zones estimated by the three-bucket model structure over the whole study period. The black dots show the mean storage over the entire period.

correlation between the mean storages estimated by the three model structures was highest for spring and lowest for winter. Moreover, the one-bucket and three-bucket structures had the largest differences in estimating dynamic storage during all seasons. These differences were highest for C14 and lowest for C5.

3.4. The role of landscape characteristics

The results of Spearman's correlation analysis between catchment storage and dominant landscape characteristics are summarized in Table 6. The test showed a positive relationship between catchment tree volume, till soils, and total water storage, ΔV. This indicates that as the amount of tree volume and till soils increase, the total water storage, ΔV also increases ($r = 0.60$, $p < 0.05$). In contrast, with increasing wetland percentage, the amount of total water storage, ΔV decreased ($r = -0.59$, $p < 0.05$). Dynamic storage (HBV), on the other hand, showed a negative correlation with tree volume ($r = -0.77$, $p < 0.05$) and till soil ($r = -0.60$, $p < 0.05$). It also showed a positive correlation with lake percentage. Positive correlations were also found between catchment area, mean storage during the entire period, and mean seasonal storage (winter, spring, and summer). Elevation above stream (EAS) and slope both showed a negative relationship with storage in the upper zone (SUZ) and a positive relationship with storage in the lower zone (SLZ). In contrast, there was no correlation between mean catchment elevation and any of the storage metrics.

Catchment area and sediment soil were positively correlated to mean SLZ, which means that catchments with a larger area, higher EAS, larger amounts of sediment soil, and steeper slope would have higher storage in the lower groundwater bucket. For the mean storage over the whole study period, a positive relationship was observed with the mean catchment area and the proportion of sediment soil. However, the mean storage was inversely affected by till soils and tree volume

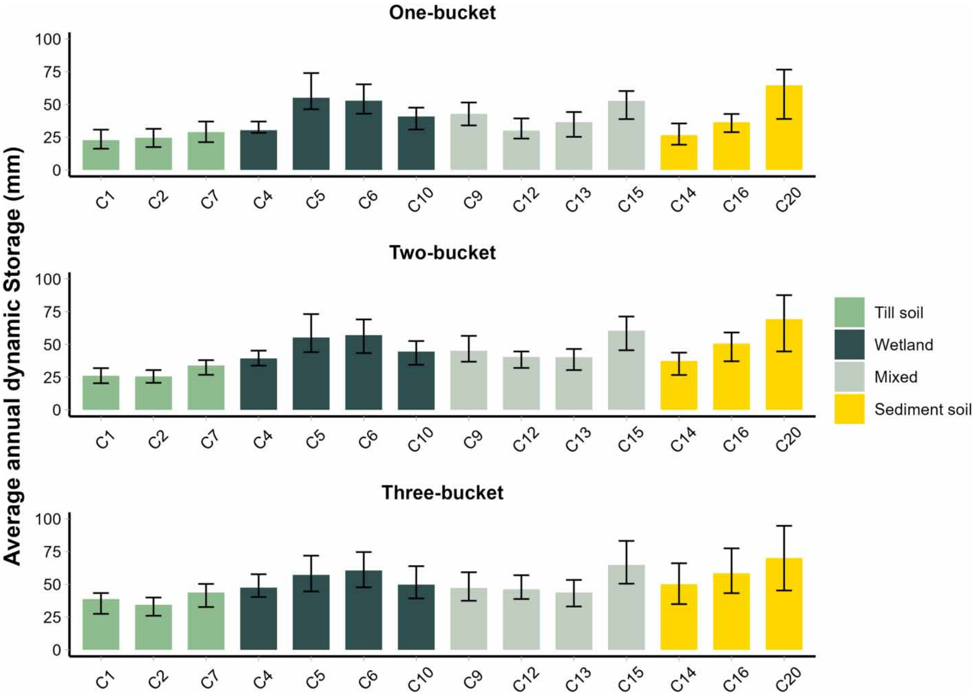


Figure 7 | Dynamic storage estimated by the three HBV model structures. The error bars represent the intra-annual variability of dynamic storage for the study period (2011–2017).

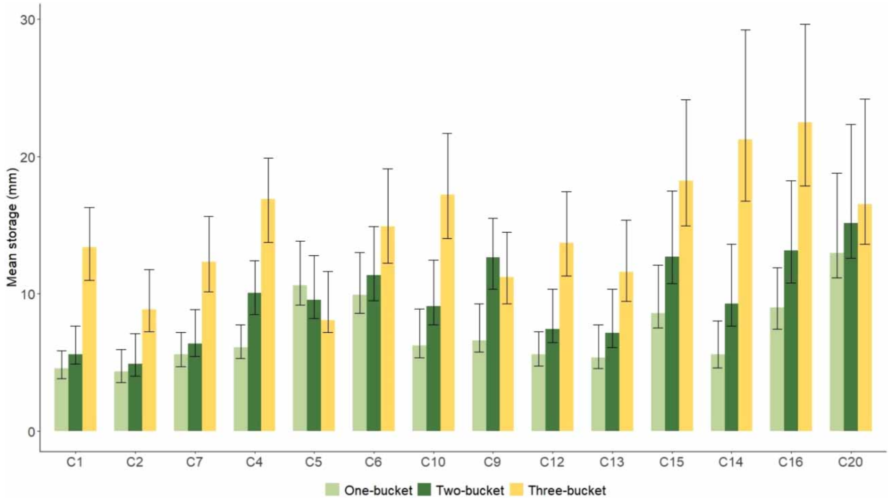


Figure 8 | Mean storage estimates by all model structures. The error bars represent the intra-annual variability of mean storage for the study period (2011–2017).

Table 4 | Dynamic storages as estimated by the three model structures

	C2	C4	C1	C7	C5	C6	C20	C9	C10	C12	C13	C14	C15	C16
One-bucket														
Min	0.01	0.00	0.01	0.02	0.10	0.13	0.19	0.02	0.01	0.01	0.00	0.03	0.05	0.09
Max	31.37	37.03	30.76	37.04	74.25	65.82	77.32	51.61	47.62	39.44	44.24	35.56	60.48	43.11
Mean	4.48	6.38	4.66	5.73	11.16	10.47	14.17	7.20	6.75	5.82	5.77	5.92	9.38	9.29
Two-bucket														
Min	0.01	0.35	0.03	0.01	0.10	0.27	0.04	0.67	0.22	0.00	0.08	0.13	0.14	0.23
Max	30.41	45.61	31.91	37.99	73.21	69.43	87.91	58.24	53.09	44.58	46.73	44.13	71.61	59.80
Mean	5.27	10.18	6.01	6.84	10.06	11.75	16.39	12.53	9.58	8.07	7.74	9.99	13.53	13.83
Three-bucket														
Min	0.29	0.98	0.73	0.46	0.04	0.50	0.13	0.38	0.89	0.41	0.43	1.22	0.52	1.22
Max	40.78	60.25	44.37	51.52	71.95	76.14	95.25	60.32	66.34	58.14	54.57	69.89	84.72	80.90
Mean	9.00	16.43	13.26	12.43	8.89	15.08	17.76	11.45	17.23	14.00	11.84	21.89	18.86	22.82

Catchments are sorted from left to right by increasing their area. Values with darker colors correspond to larger values.
Note: The color scale shows the range of data in each row (e.g. the max value in the range has the darkest color).

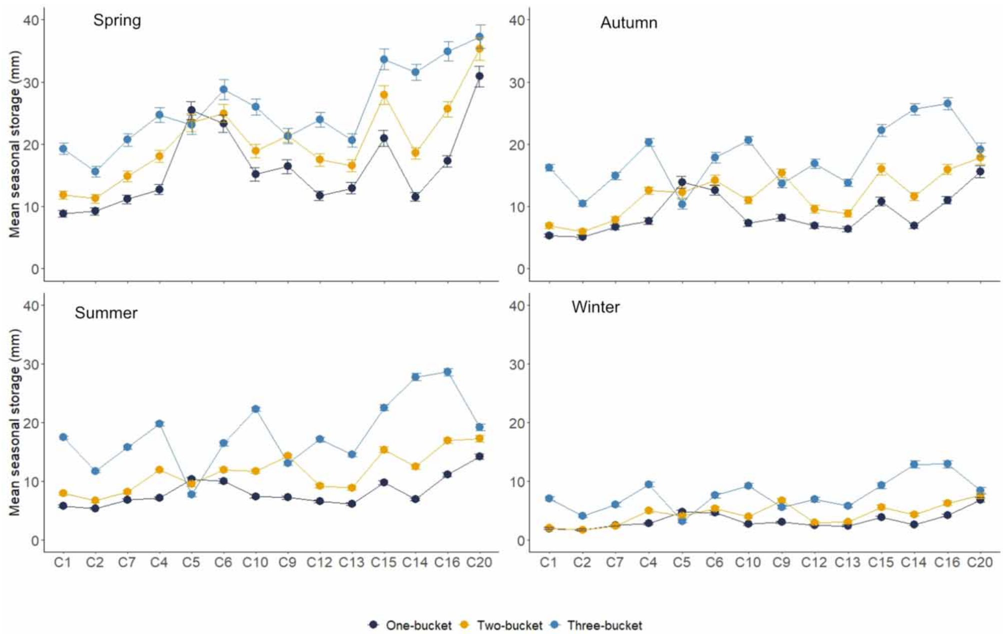


Figure 9 | Mean seasonal water storage estimated by the three model structures. Seasons were divided into four seasons: winter (NDJFM), spring (AM), summer (JJA) and autumn (SO).

Table 5 | Spearman proximity matrix between mean seasonal storages calculated using the three different model structures

	One-bucket	Two-bucket	Three-bucket
Spring			
One-bucket	**1**	0.916	0.657
Two-bucket	0.916	**1**	0.864
Three-bucket	0.657	0.864	**1**
Summer			
One-bucket	**1**	0.824	0.319
Two-bucket	0.824	**1**	0.565
Three-bucket	0.319	0.565	**1**
Autumn			
One-bucket	**1**	0.895	0.284
Two-bucket	0.895	**1**	0.486
Three-bucket	0.284	0.486	**1**
Winter			
One-bucket	**1**	0.846	0.266
Two-bucket	0.846	**1**	0.442
Three-bucket	0.266	0.442	**1**

Table 6 | Spearman rank correlation coefficients between physical catchment properties and storage metrics

Variables	ΔV [mm]	Dynamic storage	Mean storage	Summer	Autumn	Winter	Spring	SUZ	SLZ
Area (log)	0.042	0.437	**0.596**	**0.596**	0.534	**0.618**	**0.543**	−0.231	**0.604**
Elevation	−0.015	−0.044	−0.073	−0.112	−0.079	−0.073	−0.040	0.385	0.002
EAS	0.332	−0.187	0.213	0.429	0.165	0.262	0.029	**−0.749**	0.525
Slope	0.226	0.124	0.513	**0.670**	0.469	0.509	0.374	**−0.670**	**0.783**
Mire	**−0.590**	0.306	0.130	−0.002	0.187	0.057	0.222	**0.816**	−0.084
Lake %	−0.265	**0.633**	0.307	0.033	0.326	0.272	0.503	0.298	−0.085
Till	**0.615**	**−0.601**	**−0.604**	−0.388	**−0.604**	**−0.617**	**−0.619**	−0.148	−0.361
Sediment	0.032	0.371	**0.624**	**0.636**	0.531	**0.657**	0.499	−0.524	**0.631**
Tree volume ($m^3\ ha^{-1}$)	**0.603**	**−0.770**	**−0.750**	**−0.576**	**−0.719**	**−0.689**	**−0.796**	−0.158	−0.475
Soil depth (m)	0.011	0.383	0.432	0.383	0.374	0.471	0.407	−0.476	0.306
ΔV [mm]	**1**	−0.534	−0.393	−0.169	−0.433	−0.336	−0.490	−0.292	−0.125
Dynamic storage	**1**	**0.793**	**0.538**	**0.767**	**0.697**	**0.938**	0.138	0.332	
Mean storage		**1**	**0.921**	**0.982**	**0.978**	**0.938**	−0.081	**0.811**	
Summer				**1**	**0.912**	**0.938**	**0.763**	−0.156	**0.934**
Autumn					**1**	**0.969**	**0.925**	−0.002	**0.802**
Winter						**1**	**0.877**	−0.103	**0.855**
Spring							**1**	0.007	**0.618**
SUZ								**1**	−0.310
SLZ									**1**

Values in bold are different from 0 with a significance level alpha = 0.05.
Note: Mean storage is the average of model-based storage for the whole period of 2011–2017. Dynamic storage is the difference between min and max model-based storage.

(Figure 10(c) and 10(d)). For the mean seasonal storage, an inverse correlation was found between till soils and the mean storage in autumn, spring, and winter, with a much weaker correlation in summer ($r = -0.388$, $p < 0.05$).

Tree volume also revealed a negative correlation with all seasonal storage, although this relationship was stronger in winter and summer. Furthermore, a positive correlation was observed between sediment soil and the mean storage in summer and winter. This highlighted the role of sediment soils in maintaining a relatively high flow, mainly during the dry periods. The mean slope showed a significant correlation only to the mean storage during summer. Contrary to what was expected, the mean catchment soil depth did not correlate with any storage metrics.

4. DISCUSSION

4.1. Model performance comparison

The analysis of model performances showed that the three-bucket model captures the hydrological behavior best in all catchments. This finding is similar to Stoelzle *et al.* (2015), who suggested the simple structures of one or two reservoirs are less efficient in simulating catchment baseflow. Fenicia *et al.* (2014) also found that single-reservoir models are too simplistic to identify the different runoff-generating processes and that models with multiple parallel flow paths performed better. In addition, for all model structures, the best model performances were achieved in catchments with lower slope and mean elevation above streams (EAS) (Figure 4). A possible explanation is that with increasing elevations above the stream, the spatial heterogeneity of flow paths and processes within the respective catchments increases. Therefore, models that treat catchments as a single unit might have difficulties in representing the hydrologic functioning of these catchments.

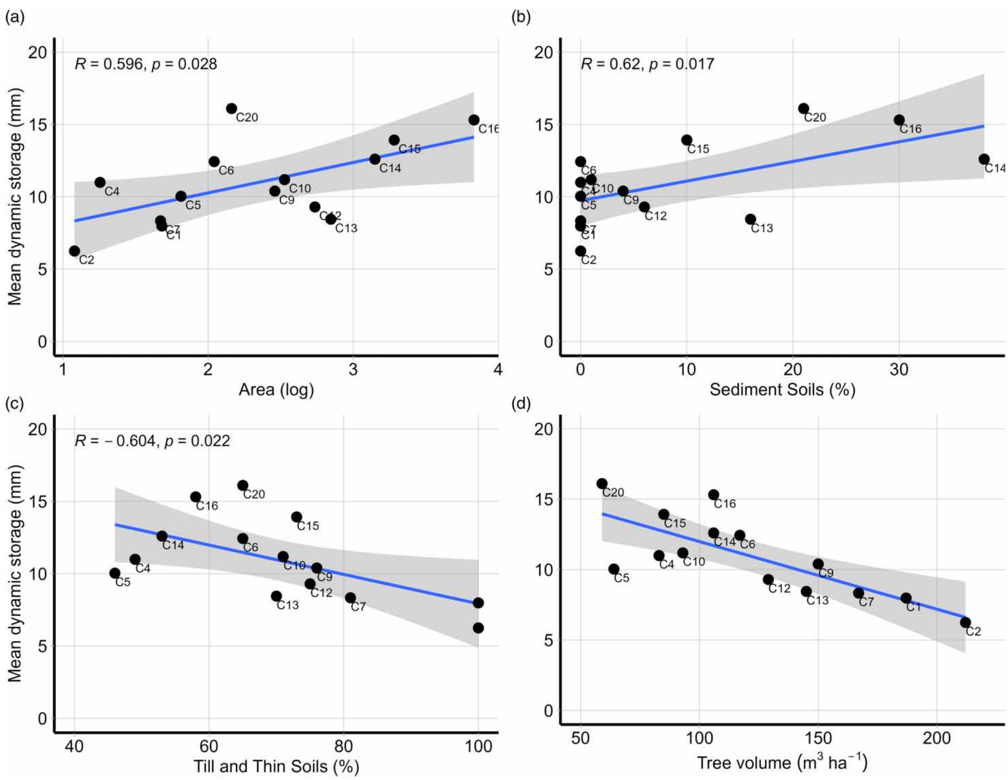


Figure 10 | Scatter plots illustrating the correlations between dynamic storage and dominant catchment characteristics.

Our results also suggest that in large catchments with higher slope and EAS, the one-bucket and two-bucket reservoirs were not adequate, and better performance was achieved by multiple reservoirs and flow pathways. The underlying reason could be that for the larger catchments there also is a higher percentage of sediment cover and deeper soils, which both can increase spatial variability within a catchment and, as a result, affect model performance. Furthermore, the relatively poor performance of all three model structures in large sediment catchments suggests that capturing the storage–discharge functioning is more challenging than the other catchments, likely because of more complex hydrological responses (Jutebring-Sterte *et al.* 2021). However, our results contradict the findings of other studies. For example, Broderick *et al.* (2016) used the NSE criterion and found higher model performance for catchments with greater storage capacity and baseflow as they are less sensitive to storm events, and therefore produce a less variable flow series. Additionally, Van Esse *et al.* (2013) tested 12 different conceptual model structures on 237 catchments in France and found that conceptual models have higher efficiency in larger catchments.

4.2. Runoff components differences

The analysis of simulated runoff components suggests various dominant hydrological functioning in different catchments that can potentially be attributed to the spatial heterogeneity of soil properties in the studied catchment. The results of 100 calibration trials showed the importance of baseflow in sustaining runoff generation, especially in sediment soil catchments. This is in line with findings from Karlsen *et al.* (2019), Teutschbein *et al.* (2015), and Peralta-Tapia *et al.* (2015) that also demonstrated that the amount of baseflow draining into the streams has a positive correlation with increasing catchment area and sediment cover.

Conversely, in wetland-dominated catchments (C4 and C5), overland flow from peat soils dominates storm runoff generation. Laudon *et al.* (2007) and Seibert *et al.* (2003) have also pointed out that in peatlands, groundwater levels reach the soil surface and, combined with overland flow from snowmelt, results in higher specific discharge compared to other catchments. In contrast, larger catchments with deep sediment soils have deeper flow paths and higher contribution to baseflow.

4.3. Partitioning of storage between upper and lower reservoirs

We also illustrated and compared the differences in the simulated storage components and flow paths among the catchment categories. We observe differences in dynamic storage at various locations (upper and lower storage zones) within the catchment between different landscape classes. Since the studied catchments are partially nested and have a similar climatological regime, the variability in storage behavior should be mainly due to different physical attributes such as soils, landform, and vegetation cover.

The large sediment catchments in the lower part of Krycklan had a higher infiltration rate and deeper subsurface flow paths. This suggests that water is stored mainly in the lower storage zone and thus can help maintain baseflow during dry periods. Our results are consistent with those obtained by Peralta-Tapia *et al.* (2015), who used stable isotopes to show that the contribution of deeper groundwater flow paths to catchment discharge increases with the catchment size. Conversely, the wetland-dominated catchments had more storage volume in the upper groundwater zone during high flows. This supports the finding of Laudon *et al.* (2007) that in wetland-dominated catchments, the proportion of new or event water was much higher than forest on till catchments. Using isotopic data, they also concluded that there is a shallow pathway in wetland catchments close to the surface, which might be formed by a concrete frost layer inhibiting the infiltration of rain and meltwater.

4.4. Influence of different model structures on dynamic storage

The different model structures had a varying number of storage reservoirs, which could partly explain differences in model performance as they capture hydrological catchment functioning differently. However, our main question was how much the estimated storages differed between these structures. As expected, using multiple storage reservoirs, even with the same number of parameters (one-bucket and three-bucket structures), makes a large difference in some catchments. Typically, for the most lake-influenced catchments (C5, C6, and C9), as well as the sediment dominated catchment C20, the modeling results were similar for all model structures, which implies that regardless of the high model performance value, model structures with only one reservoir can adequately represent the dynamic storage behavior. The explanation for C20, which was an outlier of sediment categories, could be due to its smaller drainage area compared to other sediment-dominated catchments (C14 and C16).

Although applying different model structures resulted in different estimates of dynamic storage for each catchment, all dynamic storage estimates calculated for different model structures ranked similar among the catchments. For instance, all model structures resulted in less dynamic storage for till catchments, while a higher amount of dynamic storage was obtained for those most influenced by lakes. These results are in line with Karlsen *et al.* (2019), who calculated dynamic storage, as the difference between the observed daily minimum and maximum specific discharge for each catchment and found the lowest dynamic storage for C2 (20 mm), and the highest for C6 (75 mm).

Moreover, we found that the spatial variability of dynamic storage is higher in spring, possibly due to differences in soil frost extent during snowmelt, depending on the vegetation cover and soil type. The difference between the two dominant soil groups (till and sediment) in transferring snowmelt water inflow within the catchment may also account for this difference. Catchments with sediment soil have deeper, or probably more groundwater paths, while catchments with till soils are less permeable so that most of the snowmelt leaves the catchment as overland flow and through the upper storage box.

As mentioned above, the boreal ecosystems are characterized by long winter and large snow accumulation. Therefore, spring snowmelt has a dominant contribution to the annual storage-discharge magnitude in northern regions (Laudon & Ottosson Löfvenius 2016). The simulation results determined that although the precipitation and temperature were similar across all catchments, the differences in catchment topography, soil, and land cover resulted in differences in the snow accumulation among catchments. Compared to other forested similar size catchments, the higher amount of discharge and dynamic storage of lake and wetland-dominated catchments (C5 and C4) during spring snowmelt can be explained by the larger snowpacks in these open canopy catchments (Kozii *et al.* 2017). In seasons when rainfall has the dominant effect on runoff, the lake catchment, C5, had the smallest amount of dynamic storage compared to other catchments. This agrees with previous findings suggesting that deep glacial till soils, wetlands, and forests on sediment soils have more storage during low flow conditions, while shallower till soils and open-water wetlands have been shown to sustain less water as they already contain a lot of water and their storage capacity (active storage) is small (Meriö *et al.* 2019).

The three different model structures showed that although the pattern of dynamic storage (the difference between the minimum and maximum annual storage values) estimates among catchments were similar, the catchments ranking for mean storage values differed greatly. However, for every model structure, catchments with higher tree volume and more till soils had a lower amount of dynamic storage compared to sediment catchments with less tree volume. This is likely due to transpiration and interception losses that reduce groundwater recharge (Ilstedt *et al.* 2016; Bonnesoeur *et al.* 2019), or soil water uptake within the tree root zone (Allen & Chapman 2001).

4.5. Importance of using an ensemble average of different model outputs in the final prediction

To consider parameter uncertainty and to ensure that results are not affected by it, as a first step we calculated the conceptual dynamic storage using an ensemble average taken over 100 best simulations, to have more robust storage estimations. Second, the results revealed that although the three-bucket model performed relatively better for all catchments, for some catchments the one-bucket model with less complexity also yielded a high model performance. Additionally, our findings indicated that the three-bucket model, despite its high performance, had more uncertainty in simulating dynamic storage than the one-bucket model, which gained the lowest model performance. Most studies, on the other hand, have focused on the impacts of model structures on discharge simulation (Uhlenbrook *et al.* 1999; Van Esse *et al.* 2013; Fenicia *et al.* 2014; Parra *et al.* 2019a), and considered the performance criteria to determine the predictive power of a model. With our focus on estimating a fraction of total storage that is actively controlling discharge release, and using it as a comparison of hydrological functioning across contrasting boreal catchments, makes the validation more difficult.

Therefore, we argue that using a simple ensemble averaging method that combines the prediction of each model equally would decrease the weakness of every single model in representing the hydrological functioning. This approach will also reduce the biases resulting from modelers' personal preferences

4.6. Dependence of dynamic storage on catchment characteristics

The results from the Spearman rank correlation tests suggest that the largest mean storage estimates were found in larger catchments, and catchments characterized by a large proportion of sedimentary soil, especially during winter. This finding is in accordance with other studies in Krycklan. For example, Karlsen *et al.* (2016), who applied partial least square regression to quantify the linkage between recession characteristics and catchment properties found that with increasing catchment size, the relative contribution of groundwater, especially during winter baseflow, increased. This is also in agreement with Tiwari *et al.* (2014) and Peralta-Tapia *et al.* (2016), who have shown that deep groundwater contribution in the catchment increases with catchment size.

When comparing our findings with Jutebring Sterte *et al.* (2021), a similar pattern was seen between travel time and dynamic storage among the catchments. For example, the modeled mean travel time (MTT) increased with increasing slope, sediment soil proportion, and catchment size. In their study, C20 was seen as an outlier in most of the correlation analyses, and the longest MTTs were found for that catchment despite its relatively small size. A direct association of sedimentary soil on prolonged groundwater storage-release processes has also been found in a study conducted in south-central Chile (Parra *et al.* 2019b), while Staudinger *et al.* (2017) found no correlation between catchment area and any of the storage metrics in alpine catchments.

We also found a strong correlation between catchment tree volume and dynamic storage, which is in line with findings of Barrientos & Iroumé (2018), who explored the impacts of forest management on dynamic storage in 15 forested catchments and concluded that catchments with lower forest cover (biomass volume and plantation density) have higher storage volumes. This might be due to the increasing evapotranspiration rate by deep-rooted trees with water uptake in sub-surface storage and therefore results in reducing the available amounts of dynamic storage. Furthermore, we assumed that the positive association between the total water storage (estimated by the water balance method) and till soils could be because densely forested catchments store significant amounts of input water, and this large quantity of immobile storage was included in the calculations of the water balance method.

5. CONCLUSION

In this study, we used the HBV model with three model structures, each with a different number of storage reservoirs, to evaluate differences in dynamic storage simulation. First, we found that there is a high variability among different parameterizations. This means that to achieve robust results for further analyses, it is important to consider parameter uncertainty, for instance, by an approach such as the 100 calibration trials used in our study. Second, we found high variability in dynamic storage estimates not only between the catchments but also between the different model structures.

Moreover, this study highlighted the importance of a three-bucket conceptual model that generates runoff using multiple storage reservoirs, especially in large groundwater-dominated catchments with deeper sediment soils. In contrast, for the lake-influenced catchments, a single-reservoir structure performed equally well, indicating that these simple structures can adequately represent the hydrological functioning in such catchments due to the lower storage capacity and shallow groundwater levels.

We also concluded that an ensemble average of simulations can be used as a point of hydrological functioning comparison between different catchments. Considering that the model validation using real data in these large-scale heterogeneous catchments is not possible in practice, this can reduce the time, cost, and risk associated with uncertainty of each single model structure.

Finally, as demonstrated by our results, the dynamic catchment storage could be explained by landscape features such as drainage area, slope, soil characteristics, and tree volume.

DATA AND CODE AVAILABILITY

The GIS and hydroclimate data are publicly available from (https://www.slu.se/Krycklan). The HBV-light software and its tutorial are freely available from (https://www.geo.uzh.ch/en/units/h2 k/Services/HBV-Model.html). The source code of the different response routine model structures can be requested from the second author.

COMPETING INTERESTS

The authors declare that they have no conflict of interest.

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REFERENCES

Ajami, N. K., Duan, Q. & Sorooshian, S. 2007 An integrated hydrologic Bayesian multimodel combination framework: confronting input, parameter, and model structural uncertainty in hydrologic prediction. *Water Resources Research* **43** (1), W01403.

Allen, A. & Chapman, D. 2001 Impacts of afforestation on groundwater resources and quality. *Hydrogeology Journal* **9** (4), 390–400.

Amvrosiadi, N., Bishop, K. & Seibert, J. 2017a Soil moisture storage estimation based on steady vertical fluxes under equilibrium. *Journal of Hydrology* **553**, 798–804.

Amvrosiadi, N., Seibert, J., Grabs, T. & Bishop, K. 2017b Water storage dynamics in a till hillslope: the foundation for modeling flows and turnover times. *Hydrological Processes* **31** (1), 4–14.

Barrientos, G. & Iroumé, A. 2018 The effects of topography and forest management on water storage in catchments in south-central Chile. *Hydrological Processes* **32** (21), 3225–3240.

Bonnesoeur, V., Locatelli, B., Guariguata, M. R., Ochoa-Tocachi, B. F., Vanacker, V., Mao, Z., Stokes, A. & Mathez-Stiefel, S. L. 2019 Impacts of forests and forestation on hydrological services in the Andes: a systematic review. *Forest Ecology and Management* **433**, 569–584.

Botter, G., Porporato, A., Rodriguez-Iturbe, I. & Rinaldo, A. 2009 Nonlinear storage-discharge relations and catchment streamflow regimes. *Water Resources Research* **45** (10), W10427.

Brauer, C. C., Teuling, A. J., Torfs, P. J. J. F. & Uijlenhoet, R. 2013 Investigating storage-discharge relations in a lowland catchment using hydrograph fitting, recession analysis, and soil moisture data. *Water Resources Research* **49** (7), 4257–4264.

Broderick, C., Matthews, T., Wilby, R. L., Bastola, S. & Murphy, C. 2016 Transferability of hydrological models and ensemble averaging methods between contrasting climatic periods. *Water Resources Research* **52** (10), 8343–8373.

Chapman, T. 1999 A comparison of algorithms for stream flow recession and baseflow separation. *Hydrological Processes* **13** (5), 701–714.

Creutzfeldt, B., Ferré, T., Troch, P., Merz, B., Wziontek, H. & Güntner, A. 2012 Total water storage dynamics in response to climate variability and extremes: inference from long-term terrestrial gravity measurement. *Journal of Geophysical Research: Atmospheres* **117** (D8), D08112.

Dralle, D. N., Hahm, W. J., Rempe, D. M., Karst, N. J., Thompson, S. E. & Dietrich, W. E. 2018 Quantification of the seasonal hillslope water storage that does not drive streamflow. *Hydrological Processes* **32** (13), 1978–1992.

Farrick, K. K. & Branfireun, B. A. 2014 Soil water storage, rainfall and runoff relationships in a tropical dry forest catchment. *Water Resources Research* **50** (12), 9236–9250.

Fenicia, F., Savenije, H. H. G., Matgen, P. & Pfister, L. 2006 *Is the Groundwater Reservoir Linear? Learning From Data in Hydrological Modelling*.

Fenicia, F., Kavetski, D., Savenije, H. H., Clark, M. P., Schoups, G., Pfister, L. & Freer, J. 2014 Catchment properties, function, and conceptual model representation: is there a correspondence? *Hydrological Processes* **28** (4), 2451–2467.

Gupta, H. V., Clark, M. P., Vrugt, J. A., Abramowitz, G. & Ye, M. 2012 Towards a comprehensive assessment of model structural adequacy. *Water Resources Research* **48** (8), W08301.

Hailegeorgis, T. T. & Alfredsen, K. 2015 Comparative evaluation of performances of different conceptualisations of distributed HBV runoff response routines for prediction of hourly streamflow in boreal mountainous catchments. *Hydrology Research* **46** (4), 607–628.

Hogue, T. S., Bastidas, L. A., Gupta, H. V. & Sorooshian, S. 2006 Evaluating model performance and parameter behavior for varying levels of land surface model complexity. *Water Resources Research* **42** (8), W08430.

Hrachowitz, M. & Clark, M. P. 2017 HESS opinions: the complementary merits of competing modelling philosophies in hydrology. *Hydrology and Earth System Sciences* **21** (8), 3953–3973.

Ilstedt, U., Tobella, A. B., Bazié, H. R., Bayala, J., Verbeeten, E., Nyberg, G., Sanou, J., Benegas, L., Murdiyarso, D., Laudon, H. & Sheil, D. 2016 Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics. *Scientific Reports* **6** (1), 1–12.

Jutebring Sterte, E., Lidman, F., Lindborg, E., Sjöberg, Y. & Laudon, H. 2021 How catchment characteristics influence hydrological pathways and travel times in a boreal landscape. *Hydrology and Earth System Sciences* **25** (4), 2133–2158.

Kalbus, E., Reinstorf, F. & Schirmer, M. 2006 *Measuring Methods for Groundwater, Surface Water and Their Interactions: A Review*.

Karlsen, R. H., Grabs, T., Bishop, K., Buffam, I., Laudon, H. & Seibert, J. 2016 Landscape controls on spatiotemporal discharge variability in a boreal catchment. *Water Resources Research* **52** (8), 6541–6556.

Karlsen, R. H., Bishop, K., Grabs, T., Ottosson-Löfvenius, M., Laudon, H. & Seibert, J. 2019 The role of landscape properties, storage and evapotranspiration on variability in streamflow recessions in a boreal catchment. *Journal of Hydrology* **570**, 315–328.

Kennedy, J., Ferré, T. P., Güntner, A., Abe, M. & Creutzfeldt, B. 2014 Direct measurement of subsurface mass change using the variable baseline gravity gradient method. *Geophysical Research Letters* **41** (8), 2827–2834.

Kirchner, J. W. 2009 Catchments as simple dynamical systems: catchment characterization, rainfall-runoff modeling, and doing hydrology backward. *Water Resources Research* **45** (2), W02429.

Kozii, N., Laudon, H., Ottosson-Löfvenius, M. & Hasselquist, N. J. 2017 Increasing water losses from snow captured in the canopy of boreal forests: a case study using a 30 year data set. *Hydrological Processes* **31** (20), 3558–3567.

Krasnostein, A. L. & Oldham, C. E. 2004 Predicting wetland water storage. *Water Resources Research* **40** (10), W10203.

Lane, R. A., Coxon, G., Freer, J. E., Wagener, T., Johnes, P. J., Bloomfield, J. P., Greene, S., Macleod, C. J. & Reaney, S. M. 2019 Benchmarking the predictive capability of hydrological models for river flow and flood peak predictions across over 1000 catchments in Great Britain. *Hydrology and Earth System Sciences* **23** (10), 4011–4032.

Laudon, H., Sjöblom, V., Buffam, I., Seibert, J. & Mörth, M. 2007 The role of catchment scale and landscape characteristics for runoff generation of boreal streams. *Journal of Hydrology* **344** (3-4), 198–209.

Laudon, H., Taberman, I., Ågren, A., Futter, M., Ottosson-Löfvenius, M. & Bishop, K. 2013 The Krycklan catchment study – a flagship infrastructure for hydrology, biogeochemistry, and climate research in the boreal landscape. *Water Resources Research* **49** (10), 7154–7158.

Laudon, H. & Ottosson Löfvenius, M. 2016 Adding snow to the picture–providing complementary winter precipitation data to the Krycklan catchment study database. *Hydrological Processes* **30** (13), 2413–2416.

Laudon, H., Sponseller, R. A. & Bishop, K. 2021 From legacy effects of acid deposition in boreal streams to future environmental threats. *Environmental Research Letters* **16** (1), 015007.

Ledesma, J. L. & Futter, M. N. 2017 Gridded climate data products are an alternative to instrumental measurements as inputs to rainfall–runoff models. *Hydrological Processes* **31** (18), 3283–3293.

Lidberg, W., Nilsson, M., Lundmark, T. & Ågren, A. M. 2017 Evaluating preprocessing methods of digital elevation models for hydrological modelling. *Hydrological Processes* **31** (26), 4660–4668.

Lindström, G., Johansson, B., Persson, M., Gardelin, M. & Bergström, S. 1997 Development and test of the distributed HBV-96 hydrological model. *Journal of Hydrology* **201** (1-4), 272–288.

Maneta, M., Soulsby, C., Kuppel, S. & Tetzlaff, D. 2018 Conceptualizing catchment storage dynamics and nonlinearities. *Hydrological Processes* **32**, 3299–3303.

McGuire, K. J., McDonnell, J. J., Weiler, M., Kendall, C., McGlynn, B. L., Welker, J. M. & Seibert, J. 2005 The role of topography on catchment-scale water residence time. *Water Resources Research* **41**, 5.

McNamara, J. P., Tetzlaff, D., Bishop, K., Soulsby, C., Seyfried, M., Peters, N. E., Aulenbach, B. T. & Hooper, R. 2011 Storage as a metric of catchment comparison. *Hydrological Processes* **25** (21), 3364–3371.

Mendoza-Sanchez, I., Phanikumar, M. S., Niu, J., Masoner, J. R., Cozzarelli, I. M. & McGuire, J. T. 2013 Quantifying wetland–aquifer interactions in a humid subtropical climate region: an integrated approach. *Journal of Hydrology* **498**, 237–253.

Meriö, L. J., Ala-aho, P., Linjama, J., Hjort, J., Kløve, B. & Marttila, H. 2019 Snow to precipitation ratio controls catchment storage and summer flows in boreal headwater catchments. *Water Resources Research* **55** (5), 4096–4109.

Mishra, A., Hata, T., Abdelhadi, A. W., Tada, A. & Tanakamaru, H. 2003 Recession flow analysis of the Blue Nile River. *Hydrological Processes* **17** (14), 2825–2835.

Moore, R. D. 1997 Storage-outflow modelling of streamflow recessions, with application to a shallow-soil forested catchment. *Journal of Hydrology* **198** (1–4), 260–270.

O'Callaghan, J. F. & Mark, D. M. 1984 The extraction of drainage networks from digital elevation data. *Computer Vision, Graphics, and Image Processing* **28** (3), 323–344.

Parra, V., Arumí, J. L. & Muñoz, E. 2019a Identifying a suitable model for low-flow simulation in watersheds of south-central Chile: a study based on a sensitivity analysis. *Water* **11** (7), 1506.

Parra, V., Arumí, J. L., Muñoz, E. & Paredes, J. 2019b Characterization of the groundwater storage systems of south-central Chile: an approach based on recession flow analysis. *Water* **11** (11), 2324.

Peralta-Tapia, A., Sponseller, R. A., Ågren, A., Tetzlaff, D., Soulsby, C. & Laudon, H. 2015 Scale-dependent groundwater contributions influence patterns of winter baseflow stream chemistry in boreal catchments. *Journal of Geophysical Research: Biogeosciences* **120** (5), 847–858.

Peralta-Tapia, A., Soulsby, C., Tetzlaff, D., Sponseller, R., Bishop, K. & Laudon, H. 2016 Hydroclimatic influences on non-stationary transit time distributions in a boreal headwater catchment. *Journal of Hydrology* **543**, 7–16.

Rezaei-Sadr, H. 2019 Flood hydrograph simulation in ungaged basins: modeling linear–nonlinear storage-discharge relationships in a semiarid mountain region. *Physical Geography* **40** (1), 52–70.

Riegger, J. & Tourian, M. J. 2014 Characterization of runoff-storage relationships by satellite gravimetry and remote sensing. *Water Resources Research* **50** (4), 3444–3466.

Sayama, T., McDonnell, J. J., Dhakal, A. & Sullivan, K. 2011 How much water can a watershed store? *Hydrological Processes* **25** (25), 3899–3908.

Seibert, J. 1997 Estimation of parameter uncertainty in the HBV model: paper presented at the Nordic Hydrological Conference (Akureyri, Iceland-August 1996). *Hydrology Research* **28** (4-5), 247–262.

Seibert, J. 2000 Multi-criteria calibration of a conceptual runoff model using a genetic algorithm. *Hydrology and Earth System Sciences* **4** (2), 215–224.

Seibert, J. & Vis, M. J. 2012 Teaching hydrological modeling with a user-friendly catchment-runoff-model software package. *Hydrology and Earth System Sciences* **16** (9), 3315–3325.

Seibert, J., Bishop, K., Rodhe, A. & McDonnell, J. J. 2003 Groundwater dynamics along a hillslope: a test of the steady state hypothesis. *Water Resources Research* **39** (1), 1014.

Seibert, J., Staudinger, M. & van Meerveld, H. I. 2019 Validation and over-parameterization - experiences from hydrological modeling. In: *Computer Simulation Validation: Fundamental Concepts, Methodological Frameworks, and Philosophical Perspectives* (C. Beisbart & N. J. Saam, eds). Simulation Foundations, Methods and Applications. Springer International Publishing, Cham, Switzerland, pp. 811–834.

Sitterson, J., Knightes, C., Parmar, R., Wolfe, K., Avant, B. & Muche, M. 2018 *An Overview of Rainfall-Runoff Model Types*.

Soulsby, C., Tetzlaff, D. & Hrachowitz, M. 2009 Tracers and transit times: windows for viewing catchment scale storage? *Hydrological Processes* **23** (24), 3503–3507.

Spearman, C. 1904 The proof and measurement of association between two things. *The American Journal of Psychology* **15** (1), 72–101.

Sprenger, M., Tetzlaff, D., Buttle, J., Carey, S. K., McNamara, J. P., Laudon, H., Shatilla, N. J. & Soulsby, C. 2018 Storage, mixing, and fluxes of water in the critical zone across northern environments inferred by stable isotopes of soil water. *Hydrological Processes* **32** (12), 1720–1737.

Staudinger, M., Stoelzle, M., Seeger, S., Seibert, J., Weiler, M. & Stahl, K. 2017 Catchment water storage variation with elevation. *Hydrological Processes* **31** (11), 2000–2015.

Sterte, E. J., Johansson, E., Sjöberg, Y., Karlsen, R. H. & Laudon, H. 2018 Groundwater-surface water interactions across scales in a boreal landscape investigated using a numerical modelling approach. *Journal of Hydrology* **560**, 184–201.

Stoelzle, M., Weiler, M., Stahl, K., Morhard, A. & Schuetz, T. 2015 Is there a superior conceptual groundwater model structures for baseflow simulation? *Hydrological Processes* **29** (6), 1301–1313.

Tetzlaff, D., Buttle, J., Carey, S. K., Van Huijgevoort, M. H., Laudon, H., McNamara, J. P., Mitchell, C. P., Spence, C., Gabor, R. S. & Soulsby, C. 2015 A preliminary assessment of water partitioning and ecohydrological coupling in northern headwaters using stable isotopes and conceptual runoff models. *Hydrological Processes* **29** (25), 5153–5173.

Teutschbein, C., Grabs, T., Karlsen, R. H., Laudon, H. & Bishop, K. 2015 Hydrological response to changing climate conditions: spatial streamflow variability in the boreal region. *Water Resources Research* **51** (12), 9425–9446.

Teutschbein, C., Grabs, T., Laudon, H., Karlsen, R. H. & Bishop, K. 2018 Simulating streamflow in ungauged basins under a changing climate: the importance of landscape characteristics. *Journal of Hydrology* **561**, 160–178.

Tiwari, T., Laudon, H., Beven, K. & Ågren, A. M. 2014 Downstream changes in DOC: Inferring contributions in the face of model uncertainties. *Water Resources Research* **50** (1), 514-525.

Uhlenbrook, S., Seibert, J. A. N., Leibundgut, C. & Rodhe, A. 1999 Prediction uncertainty of conceptual rainfall-runoff models caused by problems in identifying model parameters and structures. *Hydrological Sciences Journal* **44** (5), 779–797.

Van Esse, W. R., Perrin, C., Booij, M. J., Augustijn, D. C., Fenicia, F., Kavetski, D. & Lobligeois, F. 2013 The influence of conceptual model structures on model performance: a comparative study for 237 French catchments. *Hydrology and Earth System Sciences* **17** (10), 4227–4239.

Wang, D. & Alimohammadi, N. 2012 Responses of annual runoff, evaporation, and storage change to climate variability at the watershed scale. *Water Resources Research* **48** (5), W05546.

Wittenberg, H. 1999 Baseflow recession and recharge as nonlinear storage processes. *Hydrological Processes* **13** (5), 715–726.

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RESEARCH ARTICLE

WILEY

Local- and network-scale influence of peatlands on boreal catchment response to rainfall events

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Abstract

Boreal catchments are composed of different land covers, such as forests, peatlands and lakes, which differ in their runoff response to rainfall events. Understanding the individual and combined responses to rainfall events of these different land cover types is crucial for predicting potential impacts of future climate conditions on boreal water cycling. A common assumption is that peatlands attenuate peak flows, which is used as a motivation to restore drained boreal wetlands. However, it remains unclear how and to what extent peatlands can affect peak flow response. Only a few previous studies have looked at the hydrologic dynamics of peatlands in response to specific rainfall events across a wide range of nested sub-catchments with varying peatland cover. In this study, we use nine years of hourly hydrometric data from 14 catchments within the Krycklan Catchment Study in northern Sweden to examine how peatlands contribute to flood attenuation at both local and stream network scales. Our analysis at the local scale demonstrated that during large events with low antecedent wetness conditions, peatland-dominated catchment exhibited more muted responses compared to the similar-sized forest-dominated catchment. However, during events with high antecedent wetness conditions, the peatland-dominated catchment exhibited flood magnitudes similar to the forest-dominated catchment, although the elevated flow condition at the peatland-dominated catchment persisted for longer periods. Finally, our analysis revealed no significant influence of peatlands on the attenuation or amplification of floods at the stream network scale.

KEYWORDS

antecedent conditions, boreal landscapes, peak flow, peatlands, rainfall events

1 | INTRODUCTION

Flood events are characterized by a rapid increase in stream discharge occurring over relatively short periods and are often generated by large rainfall events or rapid snowmelt combined with high antecedent soil moisture conditions (Acreman & Holden, 2013; Baker, 2006; Brunner et al., 2021). Floods can cause considerable destruction to property and infrastructure and result in large sediment, nutrient, and contaminant export (Dyson et al., 2011; Marttila et al., 2010; Qiu et al., 2021; Räsänen et al., 2014; Zwart et al., 2017). Because climate change projections suggest a general increase in large precipitation events at high latitudes, we can expect future increases in the magnitude and frequency of flooding with potentially catastrophic implications to both natural and human environments in boreal landscapes

(Arheimer & Lindström, 2015; Ducharme et al., 2021; Favaro & Lamoureux, 2014; Pörtner et al., 2019; Walsh et al., 2020). Given these concerns, efforts should be made to adopt improved flood mitigation measures in places where they are most needed.

The magnitude and timing of catchment event response are highly dependent on rainfall characteristics (e.g., rainfall volume, intensity and duration) as well as catchment physical attributes such as topography, land cover and soil types (Devito et al., 2017; Edokpa et al., 2022; McGuire et al., 2005; Phillips et al., 2011). Numerous studies have also highlighted the impact of land use and land cover changes, particularly deforestation, on peak flow (Brath et al., 2006; Guillemette et al., 2005). Based on an extensive literature review conducted by Rogger et al. (2017), it has been consistently observed through multiple experimental studies that forested areas are associated with lower peak flow magnitudes compared to grasslands. This has been attributed to factors such as increased rates of rainfall interception and transpiration, but soil infiltration can also be enhanced by forest cover in some circumstances (Bargués Tobella et al., 2014). Furthermore, several studies have demonstrated the significant role of lakes in moderating peak flow and reducing the occurrence of floods (Arp et al., 2006; Hudson et al., 2021; Leach & Laudon, 2019; Nakayama & Watanabe, 2008).

In addition, antecedent soil wetness conditions can be an important factor influencing peak flow dynamics (Acreman & Holden, 2013; Biron et al., 1999; McKillop et al., 1999; Penna et al., 2011). Specifically, in peatlands, it has been shown that when the soil is already at or near saturation due to previous rainfall events, overland flow can become the dominant mechanism for delivering water rapidly to the stream network and thus contributing to flood risk (Branfireun & Roulet, 1998; Haque et al., 2018; Peralta-Tapia et al., 2015). Furthermore, a study conducted by Wells et al. (2017) investigated runoff generation dynamics of a wetland-dominated headwater catchment in northeastern Alberta, Canada, revealed that during wet antecedent conditions, storms of various magnitudes were capable of generating significant runoff, with water tables approximately 6 cm below the ground surface. James and Roulet (2009) conducted a comprehensive analysis of ten storm events in eight nested forest catchments located within the glaciated landscape of Mont Saint-Hilaire, Quebec, Canada, highlighting the significant influence of antecedent moisture conditions on shaping the spatial patterns of runoff generation.

Many recent studies have investigated the response of runoff in northern regions, but the focus has been mostly on snowmelt events or mean seasonal runoff (Buttle et al., 2018; Ide et al., 2013; Mack et al., 2021; Schelker et al., 2013; Wu et al., 2020). This emphasis arises from the hydrological regime in northern regions being dominated by long winters where large proportions of annual precipitation fall as snow. As a result, the variability in the annual flow patterns is primarily controlled by the impact of snow accumulation and melt, often on frozen soils. Fewer studies have examined event-scale runoff response during summer and autumn, when runoff is predominantly driven by rainfall events (Haque et al., 2022; Hudson et al., 2021; Wilson et al., 2011). Therefore, studying event-scale runoff response during summer and autumn offers new insights into how catchment characteristics, antecedent wetness conditions, and rainfall events influence runoff generation during unfrozen conditions.

Most approaches for studying rainfall response at event scales are based on characterizing hydrographs. Studies have used descriptions of runoff-event metrics, such as the event runoff coefficient, peak flow, lag time and discharge increase rate (Bullock & Acreman, 2003; Palleiro et al., 2014; Rodríguez-Blanco et al., 2012; Seibert et al., 2016; Tarasova et al., 2018) to explore how landscape features influence runoff dynamics. Characterizing catchment responses during short-term rainfall events can provide insight into how runoff generation depends on catchment characteristics, rainfall events and antecedent wetness conditions (Lyon et al., 2008). For instance, Tarasova et al. (2018) quantified event runoff coefficient, lag, discharge increase and peak discharge for more than 220,000 rainfall-runoff events across 185 German catchments. They found that rainfall amounts had a more pronounced effect on runoff-event metrics in catchments with lower water storage capacity than in catchments with higher capacity.

The boreal landscape is characterized by a mosaic of forests, lakes and wetlands and each of these land cover types may exhibit unique hydrologic response to rainfall events (Buffam et al., 2007; Petrone et al., 2007; Wells et al., 2017). Most wetlands in the boreal ecosystem are peat-forming, such as bogs, fens and mixed mires, where a peat layer accumulates due to organic matter storage under saturated and anaerobic conditions (Holden, 2006). These peatlands have the capacity to significantly impact the timing, volume and duration of streamflow owing to their substantial water-holding capacity (Holden et al., 2004). While forests and lakes have been studied to some extent (Hudson et al., 2021; Ide et al., 2013; Leach & Laudon, 2019; Schelker et al., 2013), less work has focused on the role of boreal peatlands in how they influence event-scale hydrologic response.

Studies have shown that the impact of peatlands on flood magnitude can vary. While some studies have shown that peatlands reduce peak flood magnitudes (Acreman et al., 2003; Kadykalo & Findlay, 2016; Mitsch et al., 1977; Wu et al., 2020) others have indicated that they instead increase flood magnitude depending on their available storage (Acreman & Holden, 2013; Bay, 1969; Bullock & Acreman, 2003; Burt, 1995; Holden & Burt, 2003). For example, a recent study conducted by Wu et al. (2023), investigated how different types and locations of peatlands affect their efficiency in regulating floods and droughts in the Nenjiang River Basin, China. By using a hydrological modelling platform, they found that wetlands have the capability to mitigate extreme floods and alleviate severe droughts within the basin. Consequently, they proposed wetlands as an efficient nature-based solution for enhancing the resilience of basins to hydrological extremes. In contrast, Bay (1969) presented findings indicating that peatlands were efficient in storing short-term runoff by exhibiting low annual peak discharge rates and long recessions, but they proved ineffective for long-term storage purposes. These contrasting findings suggest that peatland influence on peak flow likely depends on multiple factors such as landscape configuration, topography, soil moisture conditions, management history (e.g., peatland restoration and ditch cleaning) and climate conditions (Bring et al., 2022; Heathwaite, 1995; Sun et al., 2002; Tardif et al., 2009).

Given the uncertain role of peatlands in peak flow regulation, more research is needed on their hydrologic functions. Detailed studies on event scale regulation have been limited due to the lack of high-resolution hydro-climatic data (Haque et al., 2022; Manus et al., 2009; Menberu et al., 2018). Existing studies have typically been conducted at either small spatial scales that focus more on individual catchments (McKillop et al., 1999; Palleiro et al., 2014; Streich & Westbrook, 2020; Wilson et al., 2011), or captured a relatively limited number of rainfall events (Haque et al., 2022; Ketcheson & Price, 2011; Lana-Renault et al., 2014; Sun et al., 2002; Viglione et al., 2010; Wu et al., 2020). These studies have highlighted the important role of factors such as initial conditions and antecedent moisture in influencing hydrological responses, demonstrating a higher responsiveness of streamflow to rainfall events under higher antecedent wetness conditions. Additionally, these studies have emphasized the importance of employing larger spatial scales and high-resolution datasets when evaluating how catchments respond to rainfall events. There may be limitations in extending these previous findings to larger spatial scales, such as stream networks, that vary in peatland cover or for a broader range of rainfall event conditions (Edokpa et al., 2022; Gao et al., 2018; Rodríguez-Blanco et al., 2012). Moreover, explicitly accounting for the influence of antecedent storage (i.e., the amount of water stored in a watershed before a rainfall event occurs) on peak flow response has often not been accounted for in many previous studies.

The main objective of this study was to understand the role of peatlands on flood regulation when scaling from headwaters to larger catchments in a boreal ecosystem. To address this, we used hourly measurements of discharge data from 14 nested catchments (with varying land cover configurations comprised of peatland, lake and forest) within a well-studied boreal experimental forest in northern Sweden. We specifically asked the following questions: how important are peatlands for regulating hydrologic events compared to other landscape characteristics and does the hydrological response depend on the spatial scale? We hypothesized that a higher areal peatland and lake coverage would be associated with reduced peak flow magnitudes, runoff ratios, and delayed peak flow lag time. We also expected that antecedent wetness conditions would modify the relationships between peatland and lake coverage and peak flow response, with elevated antecedent conditions associated with greater relative peak flow magnitudes.

2 | MATERIALS AND METHODS

2.1 | Study area description

The 14 partially nested sub-catchments are located within the 68 km^2 Krycklan Catchment Study (Laudon et al., 2021) in the northern part of Sweden (Lat. 64°, 23 ′N, Long. 19°, 78 ′E) (Figure 1). The catchment has an elevation range from 127 to 372 masl. The climate at the site is characterized by cold winters (with a mean temperature of −9.1°C in January) with seasonal snow cover that typically accumulates starting from early November and persists until late April. Based on the period of 1991–2020, the mean annual air temperature is 2.1°C, and the average annual precipitation is 630 mm, where approximately 40% of the annual precipitation falls as snow (Laudon et al., 2021). The seasonal snow cover typically starts in mid-November, and snowmelt begins in April or the beginning of May. Of the 68 km^2 catchment, almost 87% is forested, with 9% covered by peat-dominated wetlands, 1% by lakes and 3% by arable land (Table 1). Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) dominate the forests. The bedrock in the catchment consists primarily of metagraywacke and metasediments (94%). Lower parts of the catchment comprise post-glacial sorted sediments, while the upper part mainly comprises till and thin soils.

2.2 | Rainfall event identification

Rainfall data were obtained from the Svartberget Research Station, located in the centre of the Krycklan catchment (64°14′ N, 19°46′ E, 225 m a.s.l). The rainfall was recorded using a tipping bucket (ARG 100, Campbell Scientific, USA) with a temporal resolution of 10 min and summed to hourly intervals for this study.

Individual rainfall events were extracted from hourly rainfall time series. An event was considered distinct if at least 2 mm of rainfall fell within 1 h and was separated from other events by at least 14 h without any additional rainfall. Following Jones et al. (2004), rainfall events were categorized as low, medium and high if the total event magnitude was below the first quartile (<7.5 mm), between the first and third quartile (7.5–21.2 mm), and above the third quartile (>21.2 mm), respectively. The cumulative probability of rainfall events is shown in Figure S1. This analysis resulted in 18 high rainfall events, 56 medium rainfall events and 30 low rainfall events with mean volume rainfall of 34.4, 12.4 and 5.1 mm, respectively. We used the 'IETD' R package (https://cran.r-project.org/web/packages/IETD/index.html) for identifying rainfall events.

2.3 | Analysis of the antecedent precipitation index

To evaluate the effect of antecedent wetness conditions on hydrograph response, the antecedent precipitation index (API) for 1 and 5 days before the events were quantified following the approach by Kohler and Linsley (1951).

$$\mathrm{API} = \sum_{t=-1}^{-i} P_t K^{-t},$$

where i is the number of antecedent days, P_t is the rainfall during day t, and K is the decay constant. The value of K for a given region is generally selected empirically, with literature values ranging between 0.80 and 0.98 at daily time steps (Brocca et al., 2009; Li et al., 2021). Larger values of K lead to larger APIs. Here, we adopted the value of 0.98 for K when applying this equation to hourly rainfall data.

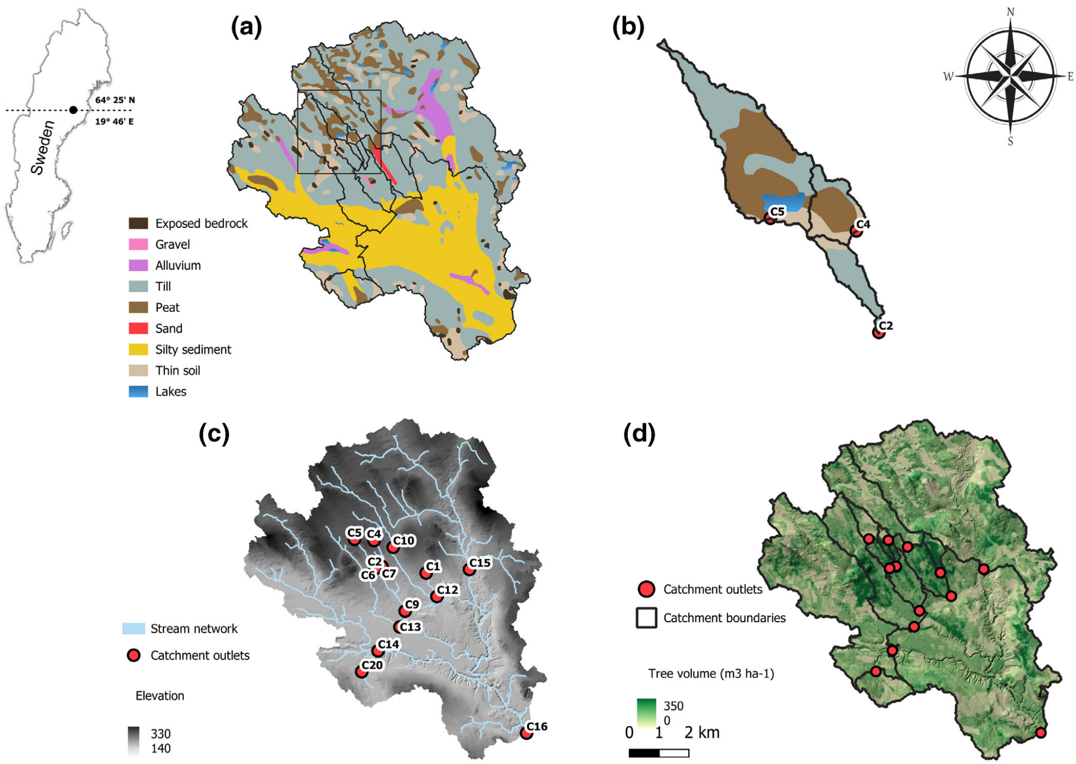

FIGURE 1 Maps of the Krycklan catchment, indicating (a) soil type, (b) magnified view of the three end-member catchments: c5 (the lake-influenced catchment), c4 (the peatland-dominated catchment), and c2 (the forest-dominated catchment) from map (a), (c) elevation, stream network and sub-catchments and (d) tree volume.

Moreover, we observed that changes in the *K* value primarily affect the absolute value of the API within catchments, as we used the same climate/rainfall data for all catchments. Therefore, selecting *K* becomes more crucial when comparing catchments across different climate regions.

It should be noted that our study focused exclusively on periods where all precipitation occurred as rainfall. We classified the antecedent rainfall index for each event into three categories: low, moderate and high, using the first and third quartiles, similar to the classification of the rainfall events outlined above. However, we used the median value as the threshold for classifying API1 into either low or high antecedent conditions as the first quartile of API1 resulted in a value of zero.

2.4 | Runoff-event metrics analysis

Hourly discharge from the 14 sub-catchments was estimated from water level observations and station-specific stage-discharge rating curves developed by Karlsen et al. (2016). Data were extracted from 2009 to 2017 since records were available for all catchments during this period. For the present study, we defined the start of a runoff event as the beginning of rainfall, and we considered the event to continue until 12 h after the rain had stopped. This time frame was chosen to ensure that the peak flow response resulting from the storm event was captured. For each rainfall event, streamflow metrics were calculated to characterize the hydrograph response for each catchment. The streamflow variables include (1) runoff coefficient (unitless) calculated as total runoff divided by rainfall depth for each event; (2) peak flow (mm/h); (3) discharge increase (Δ mm/h) calculated as the difference between peak flow and discharge at the start of the event and (4) lag time (hours) as the time difference between the peak rainfall and peak flow (Beven, 2011; Haque et al., 2022) (Figure 2, Table 2).

Moreover, we used observed streamflow recorded at the C7 station 5 h before the start of each rainfall event as another indicator of antecedent storage (referred to as antecedent reference discharge) (Hudson et al., 2021; Wilson et al., 2011). We used specific discharge

TABLE 1 Main characteristics of all 14 monitored sub-catchments in Krycklan.

	Topography					Quaternary deposit		Landcover		
	Area (ha)	Elevation (m a. s.l.)	EAS[a] (m)	Slope (°)	Soil depth[b] (m)	Sediment (%)	Till (%)	Peatland (%)	Lakes (%)	Forest (%)
C2	12	273	10.1	4.7	9.9	0	100	0	0	100
C4	18	287	9.0	4.2	10.1	0	49	44	0	56
C7	47	275	7.5	5.0	11.4	0	81	18	0	82
C1	48	279	10.9	4.9	12.2	0	100	2	0	98
C5	65	292	2.3	2.9	12.3	0	46	40	6	54
C6	110	282	4.2	4.5	9.8	0	65	25	4	71
C20	145	214	13.5	6.0	15.9	21	65	10	0	88
C9	288	251	4.4	4.3	14	4	76	14	1	84
C10	336	296	8.3	5.1	9.5	1	71	26	0	74
C12	544	277	7.4	4.9	12.2	6	75	17	0	83
C13	700	251	6.3	4.5	13.5	16	70	10	1	88
C14	1410	228	10.2	6.4	17.3	38	53	5	1	90
C15	1913	278	9.6	6.4	12.3	10	73	15	2	82
C16	6790	239	10	6.4	16	30	58	9	1	87

Note: Sub-catchments are ordered by catchment area.
[a]EAS: Catchment mean elevation above stream network calculated similarly to Seibert and McGlynn (2007).
[b]Soil depth: Mean catchment soil depth, calculated from the SGU soil depth model map (Daniels & Thunholm, 2014). Soil depth is here equivalent to the depth of bedrock.

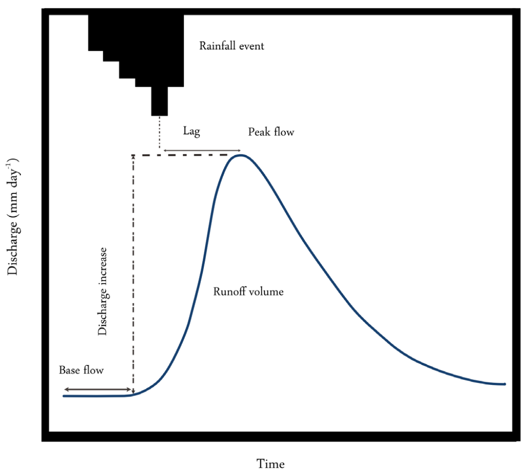

FIGURE 2 Flood hydrograph characteristics.

TABLE 2 Names, abbreviations and units for the variables used to characterize rainfall–runoff events.

	Abbreviation	Unit
Runoff-event metrics		
Peak flow	Qmax	mm/h
Discharge increase	ΔQ	mm
Lag time	Lag	h
Runoff coefficient	Rc	-
Antecedent reference discharge	Q_b	mm/h
Rainfall metrics		
Rainfall volume	P	mm
Intensity	IP	mm/h
Antecedent precipitation index	API	mm
Rainfall duration	Rd	h

at C7 sub-catchment, following Tiwari et al. (2022), as it is located in the central part of Krycklan, drains a mix of mire and forest land covers, and has a mean specific discharge comparable to that of all other sub-catchments; therefore, the use of C7 allows for a consistent and standardized measurement across all sites. The antecedent reference discharge values were then categorized into three groups, low, moderate and high based on the abovementioned quartile approach.

3 | STATISTICAL ANALYSIS

To evaluate the local influence of peatlands on flood response, we fitted linear models to identify possible relationships between total rainfall and peak flow responses across three small sub-catchments: C2 (forest-dominated catchment), C4 (mire-dominated catchment) and C5 (lake-influenced catchment) under varying antecedent conditions (Peralta-Tapia et al., 2015). These catchments represent three end-members of the land cover types typically found in boreal landscapes. In addition, these three catchments are of comparable size and experience similar weather events, facilitating inter-comparisons.

C2 consists mainly of forested areas overlying mineral soils and C4 and C5 are dominated by peatland and lake cover, respectively.

Boxplots were also used to illustrate the variability of runoff-event metrics across these end-member catchments for different rainfall conditions. In addition, a paired Wilcoxon test with a Holm correction on the p values was utilized to determine whether the observed differences between the runoff-event metrics were statistically significant.

The second purpose of the study was to determine which catchment characteristics may be related to differences in hydrological responses among all 14 catchments. A principal component analysis (PCA) was performed on the landscape characteristics in Table 1 using the XLSTAT statistical software to account for the strong covariance between landscape characteristics. The relationships between catchment characteristics and mean runoff-event metrics were investigated using non-parametric Spearman rank correlation tests. All the correlation analysis and graphics, except for the PCA, were performed using the R software, version 4.1.2 (https://www.r-project.org/). Statistical significance was determined using a 5% significance level ($p < 0.05$).

4 | RESULTS

4.1 | Rainfall event identification

We identified 114 individual rainfall events from 2009 to 2017 for which hourly streamflow records were available for all sites (Table 3). The rainfall events exhibited a wide range in rainfall totals (2.8–75 mm) and antecedent rainfall during the previous 1 and 5 days.

4.2 | Rainfall-runoff responses for the end-member examples

To show the variability in streamflow response across the end-member catchments, four hydrograph examples (out of the 114 in total) for different event rainfall amounts and antecedent conditions were compared (Figure 3). These hydrographs include events with high *P* and low antecedent reference discharge (A), low *P*, and high antecedent reference discharge (B), moderate *P* and high antecedent reference discharge (C) and moderate *P* and low antecedent reference discharge.

The first event on the upper left (21–23 July 2008, Figure 3a) was generated by a rainfall amount of 66 mm that followed a dry period during the previous five days (0.47 mm) and low antecedent reference discharge (0.003 mm/h). For the lake-influenced catchment (C5), the event hydrograph had a slow and prolonged rising limb. In contrast, the forest-dominated catchment (C2) showed a flashier and more rapid response to rainfall inputs with a shorter lag to the peak. The response of the peatland-dominated catchment (C4) was more delayed and had a lower peak magnitude than the forest-dominated catchment (C2).

The rainfall event of 12 mm (20–23 August 2008) (Figure 3, top right) followed a high antecedent rainfall period (7.7 mm during the

TABLE 3 Statistic summary of the main characteristics of rainfall–runoff events.

	Minimum	Maximum	Mean	1st quartile	3rd quartile
Rainfall duration (h)	1.00	92	22	8	29.75
Rainfall depth (mm)	2.84	75	15.38	6.75	18.47
Intensity (mm/h)	0.15	6.1	1.07	0.49	1.28
AP1 (mm)	0.00	10	0.35	0	0.96
AP5 (mm)	0.00	22	3.5	0.14	8.2
Q_b (mm/h)	0.002	0.13	0.02	0.003	0.05
Peak flow (mm/h)					
C1	0.003	1.16	0.11	0.019	0.113
C2	0.000	5.55	0.20	0.020	0.124
C4	0.003	0.55	0.07	0.018	0.105
C5	0.002	3.32	0.13	0.014	0.081
C6	0.005	3.6	0.16	0.025	0.092
C7	0.003	0.79	0.09	0.024	0.104
C9	0.003	0.62	0.08	0.019	0.106
C10	0.006	0.55	0.07	0.023	0.085
C12	0.007	0.49	0.08	0.024	0.093
C13	0.003	0.47	0.06	0.020	0.075
C14	0.006	0.44	0.04	0.020	0.049
C15	0.011	0.29	0.06	0.029	0.075
C16	0.015	0.31	0.05	0.026	0.059
C20	0.007	0.43	0.07	0.035	0.085

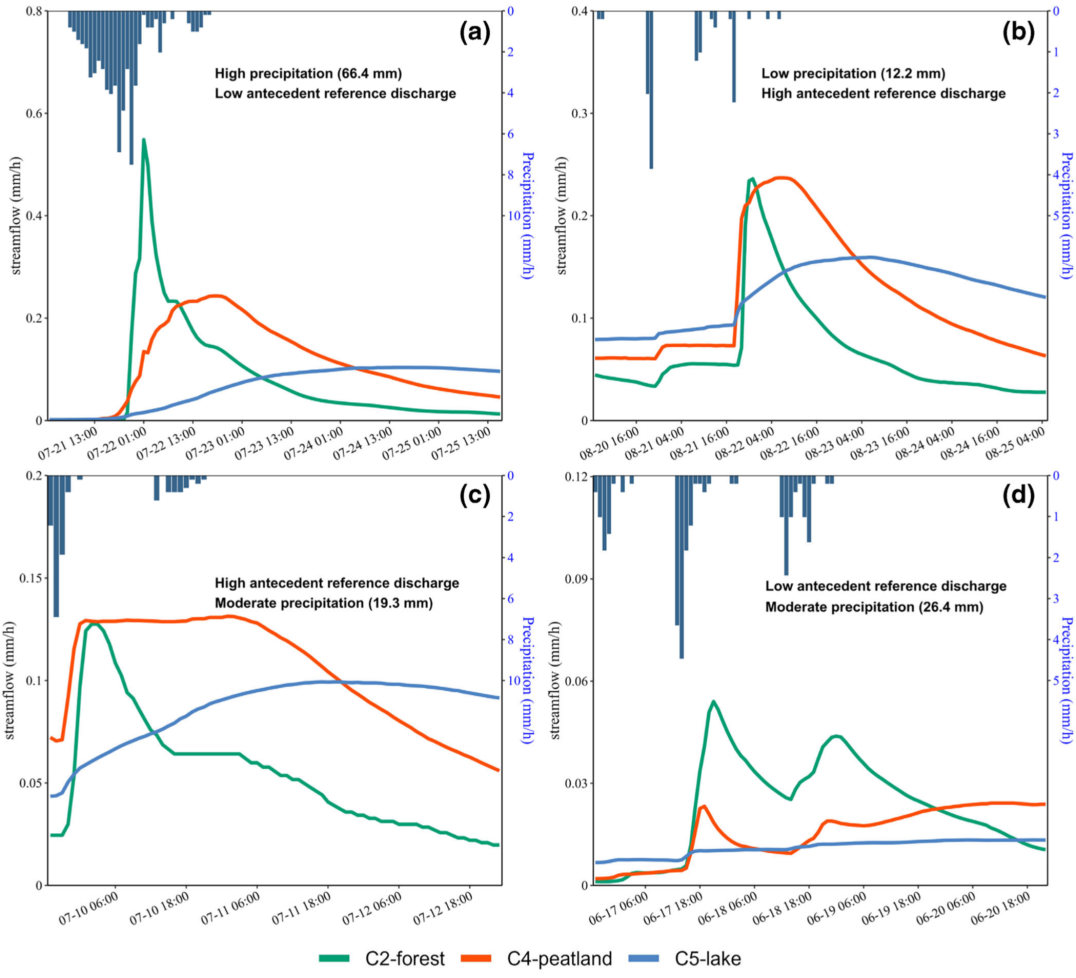

FIGURE 3 Examples of event scale hydrographs for the end-member catchments.

previous five days) and high antecedent reference discharge (0.05 mm/h). The forested and peatland-dominated catchments showed relatively similar initial hydrograph rise but the peatland-dominated catchment had a more delayed recession limb. Also, the lake-influenced catchment (C5) had a relatively higher response than the event with low antecedent conditions, but the peak occurred later than the other two catchments.

The event of 9–12 July 2009 (Figure 3c) was generated by a rainfall amount of 20 mm but under high antecedent conditions (AP5 = 19 mm and $Q_b = 0.05$ mm/h). When the antecedent rainfall was relatively high, the forest and peatland-dominated catchments showed a relatively rapid response to rainfall. The response of the lake-influenced catchment was slightly higher than during the other events. However, the peak flow response of the forested catchment was much higher and steeper than peatland and lake catchments for the event with a similar amount of rainfall (Figure 3d), but occurring after a dry period (AP5 = 0.0 mm). Furthermore, two peak flows were observed in forest and peatland-dominated catchments due to another high-intensity rainfall during the event. In the forest-dominated catchment, the second peak was higher than in the peatland-dominated catchment.

We also investigated how event peak flow response and runoff coefficient were related to event rainfall with different antecedent conditions for the forest, peatland and lake catchments (Figure 4). Overall, peak flows for all end-member catchments were higher during events with high antecedent conditions. The forest-dominated catchment generally experienced the highest and lowest peak flows during high and low rainfall events, respectively, regardless of

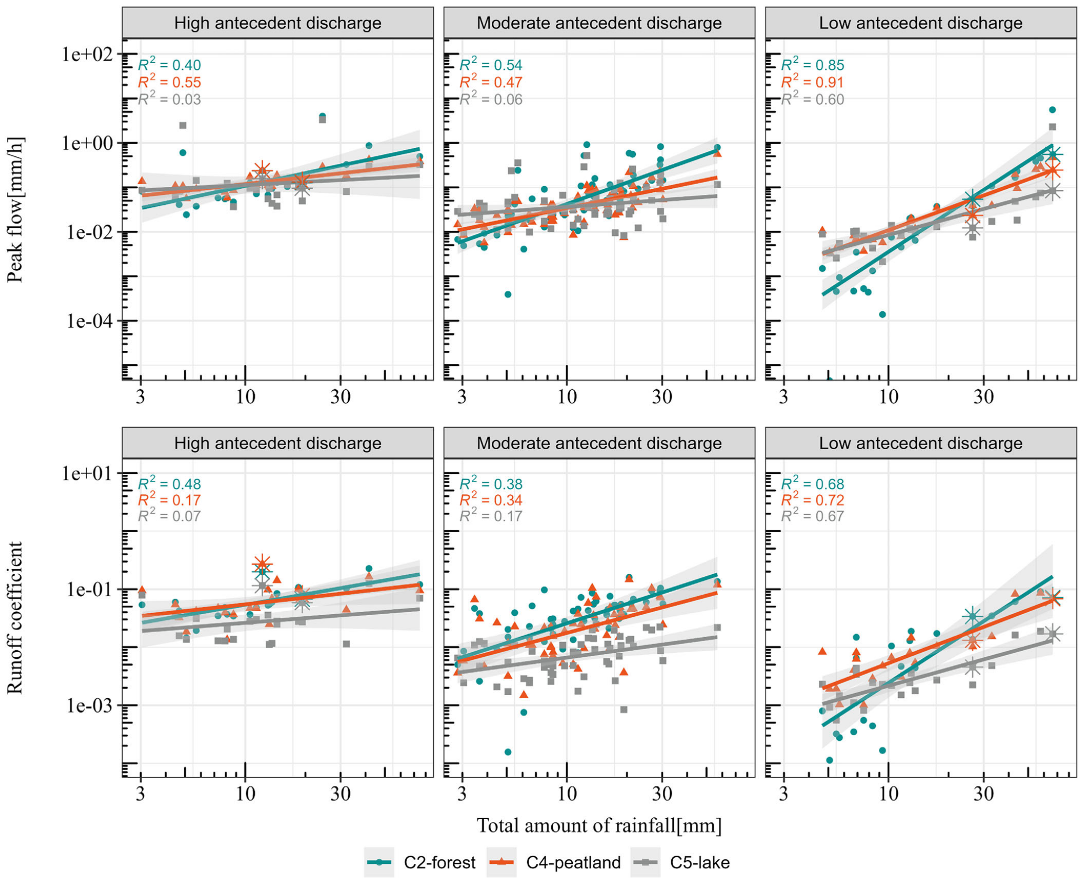

FIGURE 4 Peak flow response and runoff coefficient plotted against rainfall events (log scale). The solid lines show the best-fit regression lines. The grey band is a 95% confidence interval for the regression line. 'High', 'Moderate' and 'Low' denote high, medium and low antecedent reference discharge, respectively. The stars show the four events analyzed in Figure 3.

antecedent conditions. Moreover, peak flow response in the forest-dominated catchment showed a steeper response to rainfall, particularly during the moderate and low antecedent conditions. During periods of low antecedent conditions, we observed similar runoff coefficients for the lake-influenced and peatland-dominated catchments, particularly during small rainfall events. However, as the rainfall intensity increased, the coefficients of the runoff events diverged between the two catchment types. The runoff coefficients were largest during the high antecedent conditions for all end-member catchments. Moreover, runoff coefficient responses for each catchment were more scattered during low and moderate antecedent conditions. It is worth noting that the impact of antecedent conditions on peak flow and runoff response was more pronounced during small rainfall events for all end-member catchments.

The analysis of runoff-event metrics (e.g., peak flow, discharge increase, runoff coefficient and lag) in different rainfall groups revealed that high rainfall events exhibited greater differences among the end-member catchments, whereas the variations were relatively small during low rainfall events (Figure 5).

The mean increase in discharge varied significantly among the end-member catchments (C2, C4 and C5) during all rainfall events. In general, the forest-dominated catchment exhibited a significantly higher discharge increase than the peatland and lake catchments, while the lake-influenced catchment showed the lowest increase.

Furthermore, during high rainfall events, the forest-dominated catchment showed significantly higher peak flow values compared to the peatland and lake-influenced catchments, while no statistically significant difference was identified between the peak flows influenced by the lake and peatland. During moderate rainfall events, no statistically significant differences were found between the forest and peatland-dominated catchments. Nevertheless, the mean peak flow in the lake-influenced catchment was significantly lower than that of

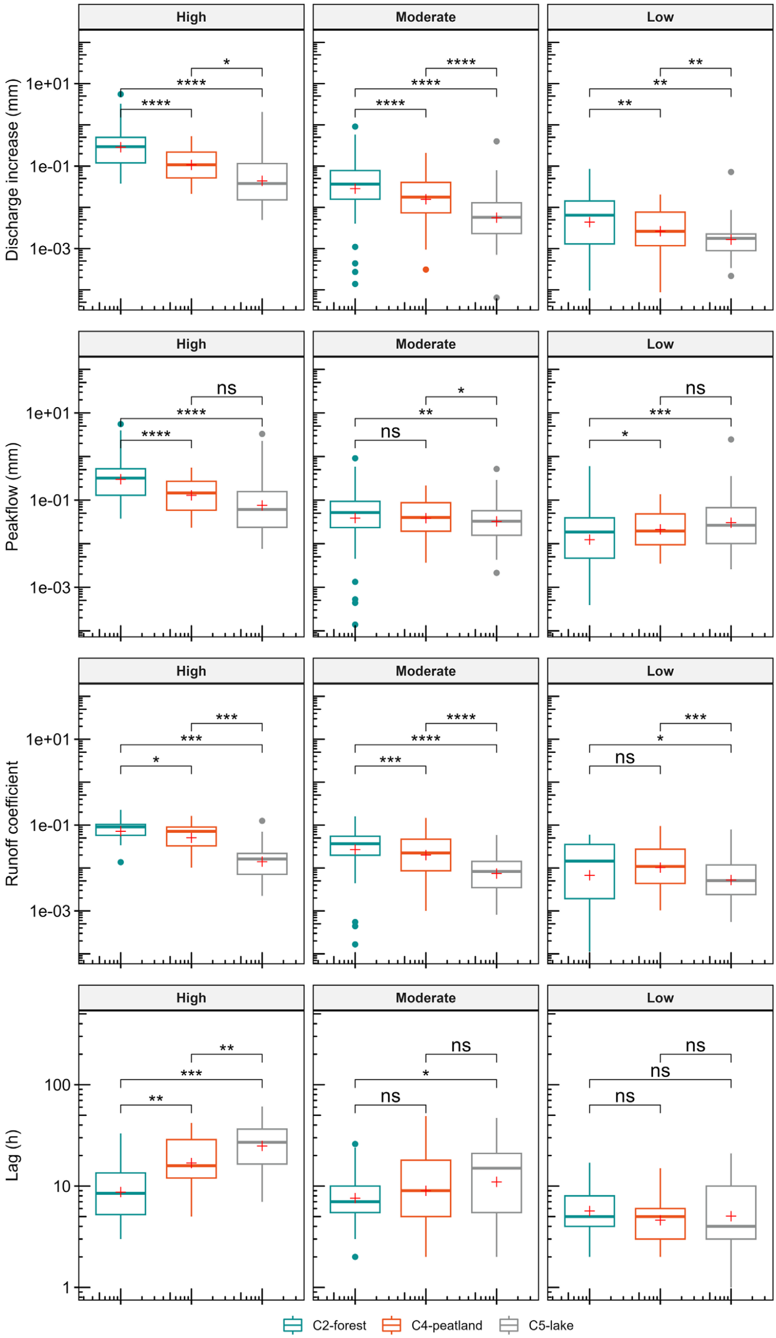

FIGURE 5 Event-based stormflow characteristics of the forest (green), peatland (red) and lake (grey) dominated catchments during high, moderate and low rainfall conditions. Ns denotes not significant. The stars indicate the levels of significance in Wilcoxon test (*$p \le 0.05$; **$p \le 0.01$; ***$p \le 0.001$; ****$p \le 0.0001$).

forest and peatland-dominated catchments. Conversely, during low rainfall events, the forest-dominated catchment showed a significantly lower peak flow compared to the lake and peatland catchments.

The result of the pairwise comparision test for the runoff coefficient indicated that the forest-dominated catchment had significantly higher runoff coefficients compared to the peatland and lake catchments during high and moderate rainfall events. During low rainfall events, there was no significant difference between the forest and peatland-dominated catchments while the lake-influenced catchment exhibited a significantly lower runoff coefficient than both forest and peatland-dominated catchments.

In terms of the lag time, the catchment influenced by the lake exhibited the longest mean lag time, while the forest-dominated catchment had the lowest mean lag time. These differences were particularly distinct and significant during high rainfall events. While the forest-dominated catchment had a significantly shorter lag time than the peatland during high rainfall events, these differences were not significant during moderate and low rainfall events. No significant differences were observed in lag times among the three end-member catchments during low rainfall events.

4.3 | Rainfall-runoff response and catchment characteristics

PCA applied to these landscape characteristics showed that the first two principal components (PCs) explained 42% and 30% of the variance, respectively (Figure 6). Some catchment characteristics are strongly correlated. For example, the catchment area was positively correlated with soil depth and percent sediment soil. In addition, tree volume and percent till soil had a strong positive correlation. Thus, we excluded tree volume from the rest of the analysis. A Spearman rank correlation test was then conducted on all 14 catchments to investigate whether any runoff-event metrics were correlated with catchment characteristics at the network scale (Figure 7). Results indicated negative associations between peak flow ($r = -0.78$, $p < 0.05$), discharge increase ($r = -0.79$, $p < 0.05$), and runoff coefficient ($r = -0.58$, $p < 0.05$) with drainage area. Conversely, till-soil-cover catchments showed positive correlations with discharge increase ($r = 0.63$, $p < 0.05$) and runoff coefficient ($r = 0.83$, $p < 0.05$). Furthermore, the data revealed significant inverse correlations between lake percentage and runoff coefficient ($r = -0.69$, $p < 0.05$). Similarly, percent sediment soil exhibited inverse correlations with peak flow ($r = -0.83$, $p < 0.05$) and discharge increase ($r = -0.73$, $p < 0.05$). There were inverse correlations between peak flow ($r = -0.56$, $p < 0.05$) and discharge increase ($r = -0.56$, $p < 0.05$) with soil depth. In terms of lag time, it was found to positively correlate with catchment area ($r = 0.57$, $p < 0.05$) and percent sediment soil ($r = 0.51$, $p < 0.05$), while showing a negative correlation with percent till soil ($r = -0.63$, $p < 0.05$). However, no statistically significant relationship was observed between peatland percentage and peak flow, runoff coefficient, lag time, or discharge increase. Additionally, neither elevation nor elevation above stream (EAS) exhibited strong correlations with any of the runoff-event metrics.

4.4 | Rainfall-runoff responses and antecedent conditions

The correlation analysis between peak flow and catchment characteristics exhibited varying degrees of strength under specific antecedent conditions (Figure 8). At the network scale, catchment area and

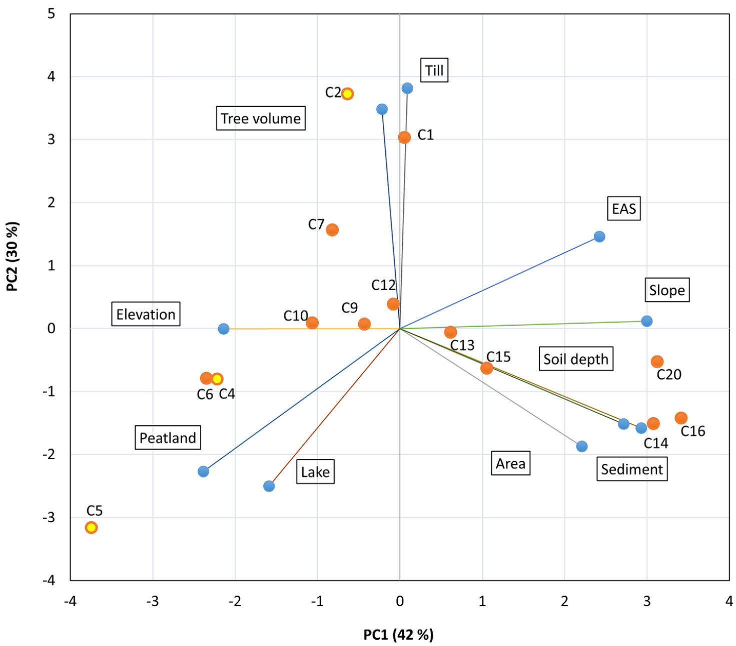

FIGURE 6 Principal components analysis (PCA) for the landscape characteristics (labelled arrows). The three end-member catchments are highlighted in yellow.

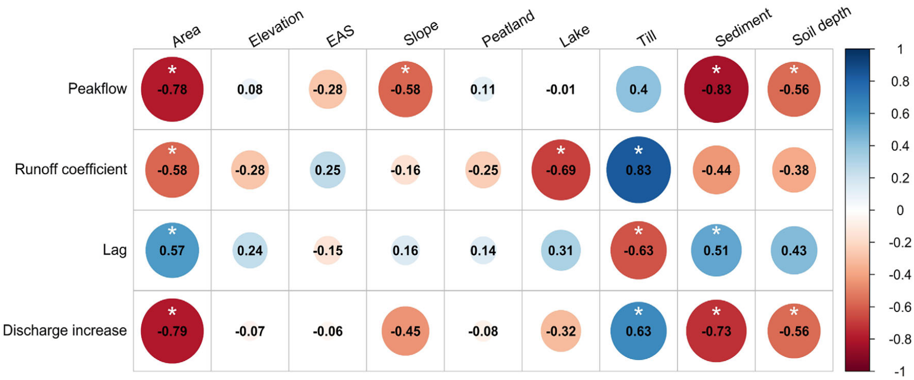

FIGURE 7 Spearman rank correlations between catchment characteristics and hydrological response variables. The colours correspond to the values of the correlation coefficient (blue and red indicate positive and negative correlations, respectively). White stars indicate significant correlations at the 5% level.

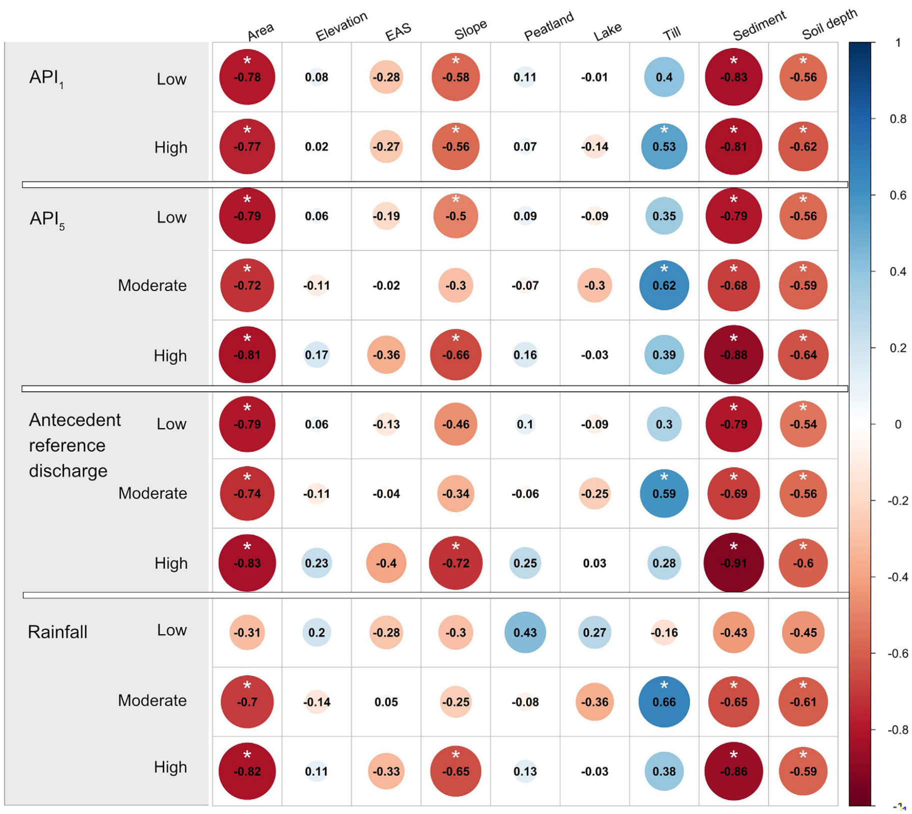

FIGURE 8 Spearman rank correlation analysis between peak flow and catchment characteristics calculated for groups based on different antecedent conditions. The colours correspond to the values of the correlation coefficient (blue and red indicate positive and negative correlations, respectively). White stars indicate significant correlations at the 5% level.

percent sediment soil were found to exhibit the most pronounced negative correlation with peak flow across a wide range of antecedent moisture conditions. This correlation was notably strengthened during periods of high antecedent conditions. Subsequently, soil depth and slope were also found to be negatively correlated with peak flow. Specifically, the negative correlation with slope was stronger and statistically significant, primarily during high antecedent conditions. On the other hand, soil depth exhibited a significant negative correlation with peak flow in almost all of the examined conditions. However, in contrast to catchment area and percent sediment soil, the results showed that peatland and lake percentages did not display any significant correlation with peak flow. Interestingly, the correlation between till and peak flow was found to be non-significant when antecedent conditions were not considered. However, after considering different antecedent conditions, a statistically significant positive correlation between percent till and peak flow emerged under moderate antecedent conditions.

Correlation analyses were performed to investigate the relationship between discharge increase rate and catchment characteristics under various antecedent moisture conditions (Figure S2). Regardless of the antecedent moisture conditions, larger drainage areas were associated with decreased rates of discharge increase. Similarly, a negative correlation was identified between the discharge increase rate and both percent sediment soil and soil depth. This implies that catchments with higher proportions of sediment soil and deeper soil exhibited lower rates of discharge increase. Additionally, the correlation analysis revealed a significant negative correlation between slope and peak flow, but only under low antecedent conditions and during high rainfall events. Moreover, we found that the positive relationship between till soil content and peak flow was stronger during moderate antecedent moisture conditions. In contrast, this correlation became insignificant during low antecedent moisture conditions. Interestingly, percent till soil was consistently associated with increased rates of discharge increment across all rainfall events.

We also investigated the relationship between the runoff coefficient and catchment characteristics under various antecedent conditions (Figure S3). Regardless of antecedent conditions, lake percentage consistently exhibited the largest negative correlation with the runoff coefficient among all the catchment characteristics examined. Conversely, percent till soil demonstrated a consistent positive correlation with the runoff coefficient under all antecedent conditions. Furthermore, our study identified significant correlations between the runoff coefficient and other catchment characteristics, including EAS, percent sediment soil and soil depth. However, these relationships were contingent upon specific antecedent conditions. Specifically, we found that EAS had a significant positive correlation with the runoff coefficient, but only under the low antecedent discharge. Regarding soil depth, a significant correlation was observed during high antecedent rainfall over the past five days. Furthermore, increased percent sediment soil was associated with a higher runoff coefficient, particularly during high antecedent conditions.

A similar analysis was performed for lag time and catchment characteristics by accounting for antecedent moisture conditions (Figure S4). Percent till soil displayed the most pronounced negative correlation with lag time, particularly under high antecedent rainfall conditions ($r = -0.78$, $p < 0.05$). Conversely, the analysis indicated that area exhibited the strongest positive correlation with lag time, specifically during low antecedent conditions. Furthermore, the study identified a significant positive correlation between the lake percentage and lag time during high antecedent rainfall conditions ($r = 0.52$, $p < 0.05$) and high antecedent discharge ($r = 0.56$, $p < 0.05$). Similarly, percent sediment soil had a significant positive correlation with lag time during both low and moderate antecedent rainfall conditions. Soil depth displayed a significant positive correlation with lag time, specifically during low antecedent rainfall conditions.

5 | DISCUSSION

5.1 | The local influence of peatland on runoff-event metrics

The event hydrographs of the end-member catchments (C2, C4 and C5) suggest that antecedent conditions play an important role in the hydrological response of lake-, peatland- and forest-dominated catchments. The peatland-dominated catchment response was higher, compared to the lake-influenced catchment, but lower than the forest-dominated catchment (Figure 3). However, at high antecedent conditions, even low rainfall amounts caused relatively large hydrograph responses in all catchments.

In general, the peatland-dominated catchment showed more dampened responses than the forested catchment of similar size. An illustrative example is an event with complex rainfall patterns resulting in two peaks, where the second peak at the forest site was noticeably higher than that at the peatland-dominated catchment (Figure 3d). This suggests that the peatland-dominated catchment may have been able to store and delay a larger proportion of the event runoff following the first peak. However, during events following high antecedent conditions, there is limited storage capacity in the lake and peatland, resulting in relatively higher flood peaks.

During high antecedent conditions, hydrograph analysis demonstrated that the peatland (C4) and forest-dominated (C2) catchments experienced flood events of similar magnitude. However, a notable difference was observed in the duration of high flow periods between the two catchments, with the peatland-dominated catchment exhibiting longer periods of elevated flow compared to the forest-dominated catchment (Figure 3). To explain this discrepancy, one potential factor could be the swelling mechanism of the peat layer. This mechanism suggests that peatlands can retain water for an extended period, even when they have reached their maximum water storage capacity during high antecedent wetness conditions (Howie & Hebda, 2018; Kellner & Halldin, 2002). The swelling mechanism is a short-term change in the pore structure of peatlands caused by high water absorption capacity during wet conditions. This extra peat soil storage capacity could contribute to sustaining streamflow for an extended period following a rainfall event. Our comparison between events with high and low antecedent conditions demonstrated that peatlands do not always reduce peak flows. This finding is supported by Acreman and Holden (2013), who stated that, in order to mitigate floods in headwater catchments, the water table level at the wetlands must be sufficiently low to possess the capacity to absorb water at the onset of the rainfall event. In a study by Bay (1969) on runoff response in four forested bog watersheds in northern Minnesota, they found that the ability of peatlands to reduce peak flows, especially at short time scales, is influenced mainly by their available storage capacity. Wetlands, which are usually recognized for their role in mitigating peak flows, might contribute to amplified flood peaks when they become fully saturated, thus potentially enhancing flood peaks.

Low-magnitude hydrological response (with no clear peak flows) at the lake catchment can be associated with the large storage capacity of lakes. This is also consistent with Spence (2006) who showed that peak flow response to rainfall events can be attenuated by lake storage. Although some peatlands may not always have persistent standing water, they share common characteristics with lakes regarding their large potential storage capacity that can store and delay water delivery to the downstream network. During snowmelt, peatlands and lakes have relatively high peak flows since the available storage capacity is limited because ice limits the water pathways (Laudon et al., 2007). However, during summer, when water losses from lakes and peatlands are increased due to evapotranspiration, these waterbodies can exert a greater attenuating effect (Bay, 1969; Phillips et al., 2011; Roulet & Woo, 1986).

Based on our analysis presented in Figure 4, we found that the responses of peak flow and runoff coefficient to event rainfall varied considerably among the end-member catchments and under different antecedent conditions. Furthermore, it became evident that the same rainfall magnitude, occurring under different antecedent conditions, could lead to a wide range of peak flows within each catchment. In general, we observed that under high antecedent wetness conditions, catchments exhibited higher peak flow and runoff events with the same amount of rainfall. This suggests that even a relatively small amount of rainfall could result in significant runoff responses when the catchment is already saturated.

The influence of antecedent moisture conditions became less pronounced when intense rainfall events occurred. This observation aligns with the study conducted by Ran et al. (2022), which examined the relative importance of antecedent soil moisture and rainfall in flood generation within the middle and lower Yangtze River basin. That study revealed that the dominance of these factors varies depending on the size of the watershed. In larger catchments, floods (which were calculated as the maximum daily discharge of each year) tend to occur when the soil is already saturated, even with relatively small rainfall amounts. Conversely, floods in small to medium-sized watersheds are usually linked to intense rainfall events. When comparing peatland, forest and lake catchments, we observed that the relationship between peak flow and event rainfall had a slightly lower slope in the peatland-influenced catchment compared to the forested-dominated catchment, but a higher slope compared to the lake-influenced catchment, suggesting a greater sensitivity to rainfall events in the forest-dominated catchment. In contrast, the lake-influenced catchment showed the lowest sensitivity, with a smaller increase in stormflow despite the same amount of rainfall.

The study findings indicated that during high and moderate rainfall events, the differences between catchment stormflow responses became more pronounced (Figure 5). This could be attributed to the fact that during low-intensity rainfall events, catchments accumulate and retain rainfall without releasing it to the streams, resulting in minimal or even no observable response at the outlet. In contrast, during periods of high rainfall events, some catchments reached their storage capacity faster, activating more hydrological pathways. This would lead to rapid delivery of rainfall to the catchment outlet, causing high peak flows.

The activation of the hydrological pathways depends on local spatial heterogeneity, including differences in physical properties and land cover. The contrasting land covers are important in determining spatial differences in soil storage, evapotranspiration and subsequent stormflow responses within each catchment (Devito et al., 2017). Despite these catchments experiencing the same climatic conditions, the forest-dominated catchment demonstrated statistically significant and higher responses than the peatland and lake-influenced catchments. The lake-influenced catchment exhibited the lowest stormflow responses. Catchments influenced by lakes and peat have a higher capacity to store rainfall and delay runoff. For forested areas, stormflow responses were higher, primarily attributed to the relatively small amount of water storage capacity, compared to a lake or peatlands. In addition, forested hillslopes have greater slope gradients that facilitate more rapid transfer of rainfall to the stream network. The absence of differences in low rainfall events can be explained by the forested catchment's ability to delay responses through rainfall interception by leaves and trees (Levia et al., 2011).

Results from this study indicate that stormflow responses of the peatland-dominated catchment, including discharge increase, peak flow, runoff coefficient and lag, generally fall between the responses observed in lake and forested catchments, as seen in Figures 3–5. These findings suggest that the peatland-influenced catchment has a more moderating effect on peak flows than the forested catchment but less than the lake catchment. It is crucial to account for variations in drainage basin features within these end-member catchments, as these variations could contribute to the observed stormflow responses. As previously mentioned, the flashier hydrologic response of the forest and peatland-dominated catchments, in comparison to the lake-influenced catchment, may potentially be due to their steeper slope of the drainage area as well. Nonetheless, it is noteworthy that the lake-influenced catchment also contains 40% peat soil, making it difficult to determine whether the effect is solely due to the presence of the lake or the combined effect of the lake and peatland. Additionally, our analysis primarily focused on total event rainfall, and we did not consider differences in rainfall intensity and duration, which can also affect soil infiltration and, consequently, response lag, runoff coefficient and peak flow magnitude (Castillo et al., 2003; Guan et al., 2016; Joel et al., 2002).

5.2 | What role do peatlands play at stream network scales?

We found no significant effect of peatlands on the attenuation or amplification of floods at the network scale even though our analysis using the end-members catchments, as well as findings from other studies, have shown that they can decrease peak flow locally (Bourgault et al., 2014; Holden et al., 2006). It is important to note that this lack of effect is seen at larger spatial scales with heterogeneous land cover composition. A reason why percent peatland cover was not statistically significant in moderating stormflows could be that the composition and configuration of land cover and soil types influence the flood moderation ability of peatlands (Gao et al., 2018). This is probably due to the runoff characteristics of the other land cover types overwhelming the peatland influences at a larger spatial scale.

Although peatland cover did not emerge as an important predictor of runoff response at network scales, our analysis suggests that some other landscape characteristics strongly correlate with storm runoff in our study area. In particular, catchment area, percent sediment soil, and soil depth were positively correlated with lag time. This means that larger catchment areas and more significant proportions of deeper, especially sediment soils lead to longer lag times, which is an indication of the time it takes for water to flow from the catchment to the outlet. On the other hand, these factors negatively correlated with peak flow magnitude, runoff coefficient, and discharge response. This suggests that larger catchments with more sediment and deeper soil tend to have lower peak flow magnitudes, reduced runoff coefficients (ratio of runoff to rainfall), and slower discharge responses.

McGlynn et al. (2004) investigated how catchment size and landscape organization affect runoff generation in New Zealand. By analyzing both hydrometric and tracer data, they found a systematic increase in the lag times of tracer responses as the catchment size increased. However, these relationships can be spurious as the largest catchments in our study exhibit a strong correlation with higher proportions of sediment, greater soil depth, and steeper slopes (see Figure 6). However, based on physically based modelling, Jutebring Sterte et al. (2021) showed that the larger catchments with more sediment cover are linked to longer hydrological travel times, supporting our empirical evidence. The reason for this relationship could be that large catchments with more percent sediment soils have a greater capacity to store water, resulting in longer subsurface flow paths.

Lake percentage was also an important landscape feature in reducing runoff coefficient. During short rainfall events, lakes control streamflow response by storing much of the rainfall input, resulting in lower runoff volumes during rainfall events. The results are similar to those obtained by Hudson et al. (2021), who found that catchments that have larger lake percentages can reduce the peak flow magnitude and delay peak flow occurrence, especially during short rainfall events. Arp et al. (2006) also investigated how stream-lake landscapes contribute to flood reduction by analysing the timing and magnitude of peak flow during snowmelt and storm events. Interestingly, their findings revealed that the lake did not significantly impact flood reduction during spring snowmelt, while during summer rainstorms, the lake consistently reduced downstream runoff. In another study examining lake influence on streamflow, Leach and Laudon (2019) found that the large storage capacity of lakes reduces downstream peak flows and delays runoff peaks several km down in the stream network. High storage capacity in the lakes during summer could be attributed to the water loss from surface evaporation. Furthermore, Rouse et al. (2003) studying a catchment in northern latitudes, also pointed out that lakes in these regions have the highest evaporation rates of any surface.

Although some studies have discussed the similarities between lakes and peatlands in reducing peak flow (Novitzki, 1979), our results show that lakes have a greater peak flow dampening effect than wetlands at local scales. At network scales, the influence of both lakes and peatlands on event response was negligible. A reason could be that hydrological responses are affected by the catchment configuration, that is, the position of lakes and peatlands in the catchment. Similar conclusions were reported by Tardif et al. (2009), who compared hydrological responses among fens and lakes. Their results indicated that fens that become more aquatic (merging with adjacent ponds due to vegetation loss) would tend to have more consistent hydrological responses to rain events, meaning that they will be characterized by frequent, but smaller, runoff fluctuations.

5.3 | Importance of antecedent wetness conditions

In the correlation analysis, we observed that certain catchment characteristics, including drainage area and till soil composition, play a significant role in generating stormflow responses. However, the dominance of each factor varied when antecedent conditions were considered, which helped to understand the relative importance of antecedent soil moisture and rainfall in flood generation in the study catchment. Incorporation of antecedent wetness conditions into the analyses also helps to disentangle how runoff response might be related to other landscape characteristics beyond peatland cover. For instance, soil depth was one of the factors that had no significant moderating effect on increasing lag before considering different catchment moisture conditions. Previous studies reported that shallow soils result in a flashier response, while deeper soils result in a more moderate peak flow response (Birkinshaw et al., 2011; Lee et al., 2015). Nonetheless, the significance of soil depth on lag time became evident primarily during low antecedent moisture conditions. When the soil is relatively dry, a deeper soil layer can absorb and retain more water. This leads to a longer lag time as the water slowly infiltrates through the soil layers before reaching the stream.

Finally, based on our findings, we can infer that lakes play a significant role in delaying peak flow within the stream network during high antecedent discharge conditions (Figure S4). Lakes act as a buffer that effectively delay the occurrence of peak flow and mitigate the potentially adverse effects of rapid runoff response. Conversely, during low antecedent discharge conditions, the influence of lakes on delaying the occurrence of peak flow becomes less pronounced. Instead, other factors may have a greater influence, such as percent sediment soil and soil depth.

6 | CONCLUSIONS

Our study provides insights into the moderating effect of peatlands on runoff-event metrics, specifically at the local scale. Additionally, we observed a significant impact of antecedent wetness conditions on both the local and network scales, further emphasizing their role in shaping catchment stormflow responses. Our study primarily served as an exploratory investigation, and future research should expand on these correlation analyses by incorporating additional process-based methods to understand how landscape organization affects hydrological event dynamics at network scales. These advancements will be important for flood prediction in boreal catchments altered by a changing climate, and how interventions, such as peatland and forest management, may help mitigate hydrological risks to infrastructure and aquatic systems.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The GIS and Meteorological data are publicly available from (https://www.slu.se/en/departments/forest-ecology-management/environment/krycklan/data/). The R code and discharge data used in this study are available at https://data.mendeley.com/datasets/6rb2sfz8dk/1.

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REFERENCES

Acreman, M., & Holden, J. (2013). How wetlands affect floods. *Wetlands*, *33*(5), 773–786.

Acreman, M. C., Riddington, R., & Booker, D. J. (2003). Hydrological impacts of floodplain restoration: A case study of the River Cherwell, UK. *Hydrology and Earth System Sciences*, *7*(1), 75–85.

Arheimer, B., & Lindström, G. (2015). Climate impact on floods: Changes in high flows in Sweden in the past and the future (1911–2100). *Hydrology and Earth System Sciences*, *19*(2), 771–784.

Arp, C. D., Gooseff, M. N., Baker, M. A., & Wurtsbaugh, W. (2006). Surface-water hydrodynamics and regimes of a small mountain stream–lake ecosystem. *Journal of Hydrology*, *329*(3-4), 500–513.

Baker, V. R. (2006). Palaeoflood hydrology in a global context. *Catena*, *66*(1-2), 161–168.

Bargués Tobella, A., Reese, H., Almaw, A., Bayala, J., Malmer, A., Laudon, H., & Ilstedt, U. (2014). The effect of trees on preferential flow and soil infiltrability in an agroforestry parkland in semiarid Burkina Faso. *Water Resources Research*, *50*(4), 3342–3354.

Bay, R. R. (1969). Runoff from small peatland watersheds. *Journal of Hydrology*, *9*(1), 90–102.

Beven, K. J. (2011). *Rainfall-runoff modelling: The primer*. John Wiley & Sons.

Birkinshaw, S. J., Bathurst, J. C., Iroumé, A., & Palacios, H. (2011). The effect of forest cover on peakflow and sediment discharge—an integrated field and modelling study in central–southern Chile. *Hydrological Processes*, *25*(8), 1284–1297.

Biron, P. M., Roy, A. G., Courschesne, F., Hendershot, W. H., Côté, B., & Fyles, J. (1999). The effects of antecedent moisture conditions on the relationship of hydrology to hydrochemistry in a small forested watershed. *Hydrological Processes*, *13*(11), 1541–1555.

Bourgault, M. A., Larocque, M., & Roy, M. (2014). Simulation of aquifer-peatland-river interactions under climate change. *Hydrology Research*, *45*(3), 425–440.

Branfireun, B. A., & Roulet, N. T. (1998). The baseflow and storm flow hydrology of a precambrian shield headwater peatland. *Hydrological Processes*, *12*(1), 57–72.

Brath, A., Montanari, A., & Moretti, G. (2006). Assessing the effect on flood frequency of land use change via hydrological simulation (with uncertainty). *Journal of Hydrology*, *324*(1-4), 141–153.

Bring, A., Thorslund, J., Rosén, L., Tonderski, K., Åberg, C., Envall, I., & Laudon, H. (2022). Effects on groundwater storage of restoring, constructing or draining wetlands in temperate and boreal climates: A systematic review. *Environmental Evidence*, *11*(1), 38.

Brocca, L., Melone, F., Moramarco, T., & Singh, V. P. (2009). Assimilation of observed soil moisture data in storm rainfall-runoff modeling. *Journal of Hydrologic Engineering*, *14*(2), 153–165.

Brunner, M. I., Slater, L., Tallaksen, L. M., & Clark, M. (2021). Challenges in modeling and predicting floods and droughts: A review. *Wiley Interdisciplinary Reviews: Water*, *8*(3), e1520.

Buffam, I., Laudon, H., Temnerud, J., Mörth, C. M., & Bishop, K. (2007). Landscape-scale variability of acidity and dissolved organic carbon during spring flood in a boreal stream network. *Journal of Geophysical Research: Biogeosciences*, *112*(G1), G01022.

Bullock, A., & Acreman, M. (2003). The role of wetlands in the hydrological cycle. *Hydrology and Earth System Sciences*, *7*(3), 358–389.

Burt, T. P. (1995). The role of wetlands in runoff generation from headwater catchments. *Hydrology and Hydrochemistry of British Wetlands*, 21–38.

Buttle, J. M., Beall, F. D., Webster, K. L., Hazlett, P. W., Creed, I. F., Semkin, R. G., & Jeffries, D. S. (2018). Hydrologic response to and recovery from differing silvicultural systems in a deciduous forest landscape with seasonal snow cover. *Journal of Hydrology*, *557*, 805–825.

Castillo, V. M., Gomez-Plaza, A., & Martınez-Mena, M. (2003). The role of antecedent soil water content in the runoff response of semiarid catchments: A simulation approach. *Journal of Hydrology*, *284*(1-4), 114–130.

Daniels, J., & Thunholm, B. (2014). Rikstäckande jorddjupsmodell. SGU rapport, 14.

Devito, K. J., Hokanson, K. J., Moore, P. A., Kettridge, N., Anderson, A. E., Chasmer, L., Hopkinson, C., Lukenbach, M. C., Mendoza, C. A., Morissette, J., & Peters, D. L. (2017). Landscape controls on long-term runoff in subhumid heterogeneous Boreal Plains catchments. *Hydrological Processes*, *31*(15), 2737–2751.

Ducharme, A. A., Casson, N. J., Higgins, S. N., & Friesen-Hughes, K. (2021). Hydrological and catchment controls on event-scale dissolved organic carbon dynamics in boreal headwater streams. *Hydrological Processes*, *35*(7), e14279.

Dyson, K. E., Billett, M. F., Dinsmore, K. J., Harvey, F., Thomson, A. M., Piirainen, S., & Kortelainen, P. (2011). Release of aquatic carbon from two peatland catchments in E. Finland during the spring snowmelt period. *Biogeochemistry*, *103*(1), 125–142.

Edokpa, D., Milledge, D., Allott, T., Holden, J., Shuttleworth, E., Kay, M., Johnston, A., Millin-Chalabi, G., Scott-Campbell, M., Chandler, D., & Freestone, J. (2022). Rainfall intensity and catchment size control storm runoff in a gullied blanket peatland. *Journal of Hydrology*, *609*, 127688.

Favaro, E. A., & Lamoureux, S. F. (2014). Antecedent controls on rainfall runoff response and sediment transport in a High Arctic catchment. *Geografiska Annaler: Series A, Physical Geography*, *96*(4), 433–446.

Gao, J., Kirkby, M., & Holden, J. (2018). The effect of interactions between rainfall patterns and land-cover change on flood peaks in upland peatlands. *Journal of Hydrology*, *567*, 546–559.

Guan, M., Sillanpää, N., & Koivusalo, H. (2016). Storm runoff response to rainfall pattern, magnitude and urbanization in a developing urban catchment. *Hydrological Processes*, *30*(4), 543–557.

Guillemette, F., Plamondon, A. P., Prévost, M., & Lévesque, D. (2005). Rainfall generated stormflow response to clearcutting a boreal forest: Peak flow comparison with 50 world-wide basin studies. *Journal of hydrology*, *302*(1-4), 137–153.

Haque, A., Ali, G., & Badiou, P. (2018). Hydrological dynamics of prairie pothole wetlands: Dominant processes and landscape controls under contrasted conditions. *Hydrological Processes*, *32*(15), 2405–2422.

Haque, A., Ali, G., & Badiou, P. (2022). Event-based analysis of wetland hydrologic response in the Prairie Pothole Region. *Journal of Hydrology*, *604*, 127237.

Heathwaite, A. L. (1995). Overview of the hydrology of British wetlands. In J. M. R. Hughes & A. L. Heathwaite (Eds.), *Hydrology and Hydrochemistry of British Wetlands* (pp. 11–20). John Wiley.

Holden, J. (2006). Peatland hydrology. *Developments in Earth Surface Processes*, *9*, 319–346.

Holden, J., & Burt, T. P. (2003). Runoff production in blanket peat covered catchments. *Water Resources Research*, *39*(7), 1191. https://doi.org/10.1029/2002WR001956

Holden, J., Chapman, P. J., & Labadz, J. C. (2004). Artificial drainage of peatlands: Hydrological and hydrochemical process and wetland restoration. *Progress in Physical Geography*, *28*(1), 95–123.

Holden, J., Evans, M. G., Burt, T. P., & Horton, M. (2006). Impact of land drainage on peatland hydrology. *Journal of Environmental Quality*, *35*(5), 1764–1778.

Howie, S. A., & Hebda, R. J. (2018). Bog surface oscillation (mire breathing): A useful measure in raised bog restoration. *Hydrological Processes*, *32*(11), 1518–1530.

Hudson, D. T., Leach, J. A., Webster, K., & Houle, D. (2021). Streamflow regime of a lake-stream system based on long-term data from a high-density hydrometric network. *Hydrological Processes*, *35*(10), e14396.

Ide, J. I., Finér, L., Laurén, A., Piirainen, S., & Launiainen, S. (2013). Effects of clear-cutting on annual and seasonal runoff from a boreal forest catchment in eastern Finland. *Forest Ecology and Management*, *304*, 482–491.

James, A. L., & Roulet, N. T. (2009). Antecedent moisture conditions and catchment morphology as controls on spatial patterns of runoff generation in small forest catchments. *Journal of Hydrology*, *377*(3-4), 351–366.

Joel, A., Messing, I., Seguel, O., & Casanova, M. (2002). Measurement of surface water runoff from plots of two different sizes. *Hydrological Processes*, *16*(7), 1467–1478.

Jones, C., Waliser, D. E., Lau, K. M., & Stern, W. (2004). Global occurrences of extreme precipitation and the Madden–Julian oscillation: Observations and predictability. *Journal of Climate*, *17*(23), 4575–4589.

Jutebring Sterte, E., Lidman, F., Lindborg, E., Sjöberg, Y., & Laudon, H. (2021). How catchment characteristics influence hydrological pathways and travel times in a boreal landscape. *Hydrology and Earth System Sciences*, *25*(4), 2133–2158.

Kadykalo, A. N., & Findlay, C. S. (2016). The flow regulation services of wetlands. *Ecosystem Services*, *20*, 91–103.

Karlsen, R. H., Grabs, T., Bishop, K., Buffam, I., Laudon, H., & Seibert, J. (2016). Landscape controls on spatiotemporal discharge variability in a boreal catchment. *Water Resources Research*, *52*(8), 6541–6556.

Kellner, E., & Halldin, S. (2002). Water budget and surface-layer water storage in a Sphagnum bog in central Sweden. *Hydrological Processes*, *16*(1), 87–103.

Ketcheson, S. J., & Price, J. S. (2011). The impact of peatland restoration on the site hydrology of an abandoned block-cut bog. *Wetlands*, *31*(6), 1263–1274.

Kohler, M. A., & Linsley, R. K. (1951). Predicting the runoff from storm rainfall (Vol. 30). US Department of Commerce, Weather Bureau.

Lana-Renault, N., Nadal-Romero, E., Serrano-Muela, M. P., Alvera, B., Sánchez-Navarrete, P., Sanjuán, Y., & García-Ruiz, J. M. (2014). Comparative analysis of the response of various land covers to an exceptional rainfall event in the central Spanish Pyrenees, October 2012. *Earth Surface Processes and Landforms*, *39*(5), 581–592.

Laudon, H., Hasselquist, E. M., Peichl, M., Lindgren, K., Sponseller, R., Lidman, F., Kuglerova, L., Hasselquist, N. J., Bishop, K., Nilsson, M. B., & Ågren, A. M. (2021). Northern landscapes in transition: Evidence, approach and ways forward using the Krycklan Catchment Study. *Hydrological Processes*, *35*(4), e14170.

Laudon, H., Sjöblom, V., Buffam, I., Seibert, J., & Mörth, M. (2007). The role of catchment scale and landscape characteristics for runoff generation of boreal streams. *Journal of Hydrology*, *344*(3–4), 198–209.

Leach, J. A., & Laudon, H. (2019). Headwater lakes and their influence on downstream discharge. *Limnology and Oceanography Letters*, *4*(4), 105–112.

Lee, J. Y., Lee, M. J., & Han, M. (2015). A pilot study to evaluate runoff quantity from green roofs. *Journal of Environmental Management*, *152*, 171–176.

Levia, D. F., Carlyle-Moses, D., & Tanaka, T. (Eds.). (2011). Forest hydrology and biogeochemistry: Synthesis of past research and future directions (Vol. 216). Springer Science & Business Media.

Li, X., Wei, Y., & Li, F. (2021). Optimality of antecedent precipitation index and its application. *Journal of Hydrology*, *595*, 126027.

Lyon, S. W., Desilets, S. L., & Troch, P. A. (2008). Characterizing the response of a catchment to an extreme rainfall event using hydrometric and isotopic data. *Water Resources Research*, *44*(6), W06413. https://doi.org/10.1029/2007WR006259

Mack, M., Connon, R., Makarieva, O., McLaughlin, J., Nesterova, N., & Quinton, W. (2021). Heterogenous runoff trends in peatland-dominated basins throughout the circumpolar North. *Environmental Research Communications*, *3*(7), 075006.

Manus, C., Anquetin, S., Braud, I., Vandervaere, J. P., Creutin, J. D., Viallet, P., & Gaume, E. (2009). A modeling approach to assess the hydrological response of small mediterranean catchments to the variability of soil characteristics in a context of extreme events. *Hydrology and Earth System Sciences*, *13*(2), 79–97.

Marttila, H., Vuori, K. M., Hökkä, H., Jämsen, J., & Kløve, B. (2010). Framework for designing and applying peak runoff control structures for peatland forestry conditions. *Forest Ecology and Management*, *260*(8), 1262–1273.

McGlynn, B. L., McDonnell, J. J., Seibert, J., & Kendall, C. (2004). Scale effects on headwater catchment runoff timing, flow sources, and groundwater-streamflow relations. *Water Resources Research*, *40*(7), W07504. https://doi.org/10.1029/2003WR002494

McGuire, K. J., McDonnell, J. J., Weiler, M., Kendall, C., McGlynn, B. L., Welker, J. M., & Seibert, J. (2005). The role of topography on catchment-scale water residence time. *Water Resources Research*, *41*(5), W05002. https://doi.org/10.1029/2004WR003657

McKillop, R., Kouwen, N., & Soulis, E. D. (1999). Modeling the rainfall-runoff response of a headwater wetland. *Water Resources Research*, *35*(4), 1165–1177.

Menberu, M. W., Haghighi, A. T., Ronkanen, A. K., Marttila, H., & Kløve, B. (2018). Effects of drainage and subsequent restoration on peatland hydrological processes at catchment scale. *Water Resources Research*, *54*(7), 4479–4497.

Mitsch, W. J., Dorge, C. L., & Wiemhoff, J. R. (1977). Forested wetlands for water resource management in southern Illinois.

Nakayama, T., & Watanabe, M. (2008). Role of flood storage ability of lakes in the Changjiang River catchment. *Global and Planetary Change*, *63*(1), 9–22.

Novitzki, R. P. (1979). Hydrologic characteristics of Wisconsin's wetlands and their influence on floods, stream flow, and sediment. *Wetland Functions and Values: The State of Our Understanding*, *377*, 385.

Palleiro, L., Rodríguez-Blanco, M. L., Taboada-Castro, M. M., & Taboada-Castro, M. T. (2014). Hydrological response of a humid agroforestry catchment at different time scales. *Hydrological Processes*, *28*(4), 1677–1688.

Penna, D., Tromp-van Meerveld, H. J., Gobbi, A., Borga, M., & Dalla Fontana, G. (2011). The influence of soil moisture on threshold runoff generation processes in an alpine headwater catchment. *Hydrology and Earth System Sciences*, *15*(3), 689–702.

Peralta-Tapia, A., Sponseller, R. A., Tetzlaff, D., Soulsby, C., & Laudon, H. (2015). Connecting precipitation inputs and soil flow pathways to stream water in contrasting boreal catchments. *Hydrological Processes*, *29*(16), 3546–3555.

Petrone, R. M., Silins, U., & Devito, K. J. (2007). Dynamics of evapotranspiration from a riparian pond complex in the Western Boreal Forest, Alberta, Canada. *Hydrological Processes: An International Journal*, *21*(11), 1391–1401.

Phillips, R. W., Spence, C., & Pomeroy, J. W. (2011). Connectivity and runoff dynamics in heterogeneous basins. *Hydrological Processes*, *25*(19), 3061–3075.

Pörtner, H. O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., & Weyer, N. M. (2019). The ocean and cryosphere in a changing climate. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Qiu, J., Shen, Z., Leng, G., & Wei, G. (2021). Synergistic effect of drought and rainfall events of different patterns on watershed systems. *Scientific Reports*, *11*(1), 1–18.

Ran, Q., Wang, J., Chen, X., Liu, L., Li, J., & Ye, S. (2022). The relative importance of antecedent soil moisture and precipitation in flood generation in the middle and lower Yangtze River basin. *Hydrology and Earth System Sciences*, *26*(19), 4919–4931.

Räsänen, N., Kankaala, P., Tahvanainen, T., Akkanen, J., & Saarnio, S. (2014). Short-term effects of phosphorus addition and pH rise on bacterial utilization and biodegradation of dissolved organic carbon (DOC) from boreal peatlands. *Aquatic Ecology*, *48*(4), 435–446.

Rodríguez-Blanco, M. L., Taboada-Castro, M. M., & Taboada-Castro, M. T. (2012). Rainfall–runoff response and event-based runoff coefficients in a humid area (northwest Spain). *Hydrological Sciences Journal*, *57*(3), 445–459.

Rogger, M., Agnoletti, M., Alaoui, A., Bathurst, J. C., Bodner, G., Borga, M., Chaplot, V., Gallart, F., Glatzel, G., Hall, J., & Holden, J. (2017). Land use change impacts on floods at the catchment scale: Challenges and opportunities for future research. *Water Resources Research*, *53*(7), 5209–5219.

Roulet, N. T., & Woo, M. K. (1986). Hydrology of a wetland in the continuous permafrost region. *Journal of Hydrology*, *89*(1-2), 73–91.

Rouse, W. R., Blyth, E. M., Crawford, R. W., Gyakum, J. R., Janowicz, J. R., Kochtubajda, B., Leighton, H. G., Marsh, P., Martz, L., Pietroniro, A., & Ritchie, H. (2003). Energy and water cycles in a high-latitude, north-flowing river system: summary of results from the Mackenzie GEWEX Study—Phase I. *Bulletin of the American Meteorological Society*, *84*(1), 73–88.

Schelker, J., Kuglerová, L., Eklöf, K., Bishop, K., & Laudon, H. (2013). Hydrological effects of clear-cutting in a boreal forest–Snowpack dynamics, snowmelt and streamflow responses. *Journal of Hydrology*, *484*, 105–114.

Seibert, J., & McGlynn, B. L. (2007). A new triangular multiple flow direction algorithm for computing upslope areas from gridded digital elevation models. *Water Resources Research*, *43*(4), W04501. https://doi.org/10.1029/2006WR005128

Seibert, S. P., Jackisch, C., Ehret, U., Pfister, L., & Zehe, E. (2016). Exploring the interplay between state, structure and runoff behaviour of lower mesoscale catchments. *Hydrology and Earth System Sciences Discussions*, *2016*, 1–51. https://doi.org/10.5194/hess-2016-109

Spence, C. (2006). Hydrological processes and streamflow in a lake dominated watercourse. *Hydrological Processes*, *20*(17), 3665–3681.

Streich, S. C., & Westbrook, C. J. (2020). Hydrological function of a mountain fen at low elevation under dry conditions. *Hydrological Processes*, *34*(2), 244–257.

Sun, G., McNulty, S. G., Amatya, D. M., Skaggs, R. W., Swift, L. W., Jr., Shepard, J. P., & Riekerk, H. (2002). A comparison of the watershed hydrology of coastal forested wetlands and the mountainous uplands in the Southern US. *Journal of Hydrology*, *263*(1-4), 92–104.

Tarasova, L., Basso, S., Zink, M., & Merz, R. (2018). Exploring controls on rainfall-runoff events: 1. Time series-based event separation and temporal dynamics of event runoff response in Germany. *Water Resources Research*, *54*(10), 7711–7732.

Tardif, S., St-Hilaire, A., Roy, R., Bernier, M., & Payette, S. (2009). Statistical properties of hydrographs in minerotrophic fens and small lakes in mid-latitude Québec, Canada. *Canadian Water Resources Journal*, *34*(4), 365–380.

Tiwari, T., Sponseller, R. A., & Laudon, H. (2022). The emerging role of drought as a regulator of dissolved organic carbon in boreal landscapes. *Nature Communications*, *13*(1), 1–11.

Viglione, A., Chirico, G. B., Komma, J., Woods, R., Borga, M., & Blöschl, G. (2010). Quantifying space-time dynamics of flood event types. *Journal of Hydrology*, *394*(1-2), 213–229.

Walsh, J. E., Ballinger, T. J., Euskirchen, E. S., Hanna, E., Mård, J., Overland, J. E., Tangen, H., & Vihma, T. (2020). Extreme weather and climate events in northern areas: A review. *Earth-Science Reviews*, *209*, 103324.

Wells, C., Ketcheson, S., & Price, J. (2017). Hydrology of a wetland-dominated headwater basin in the Boreal Plain, Alberta, Canada. *Journal of Hydrology*, *547*, 168–183.

Wilson, L., Wilson, J., Holden, J., Johnstone, I., Armstrong, A., & Morris, M. (2011). The impact of drain blocking on an upland blanket bog during storm and drought events, and the importance of sampling-scale. *Journal of Hydrology*, *404*(3-4), 198–208.

Wu, Y., Sun, J., Hu, B., Zhang, G., & Rousseau, A. N. (2023). Wetland-based solutions against extreme flood and severe drought: Efficiency evaluation of risk mitigation. *Climate Risk Management*, *40*, 100505.

Wu, Y., Zhang, G., Rousseau, A. N., & Xu, Y. J. (2020). Quantifying streamflow regulation services of wetlands with an emphasis on quickflow and baseflow responses in the Upper Nenjiang River Basin, Northeast China. *Journal of Hydrology*, *583*, 124565.

Zwart, J. A., Sebestyen, S. D., Solomon, C. T., & Jones, S. E. (2017). The influence of hydrologic residence time on lake carbon cycling dynamics following extreme precipitation events. *Ecosystems*, *20*(5), 1000–1014.

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In this thesis, I investigated the hydrological functions of natural and rewetted peatlands in a boreal ecosystem. To do this, I used a combination of hydrological modeling and field observations to quantify these functions. The findings indicated that restoring drained peatlands through rewetting leads to notable improvements in groundwater table levels, baseflow, and storage capacity. Furthermore, rewetted peatlands showed potential in mitigating hydrological extremes by lowering peakflow, runoff coefficient, and hydrological flashiness.

Shirin Karimi received her PhD education at the Department of Forest Ecology and Management, SLU, Umeå. She holds a Master of Science degree in Environmental science from University of Tehran, Iran.

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