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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 postglacial 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.

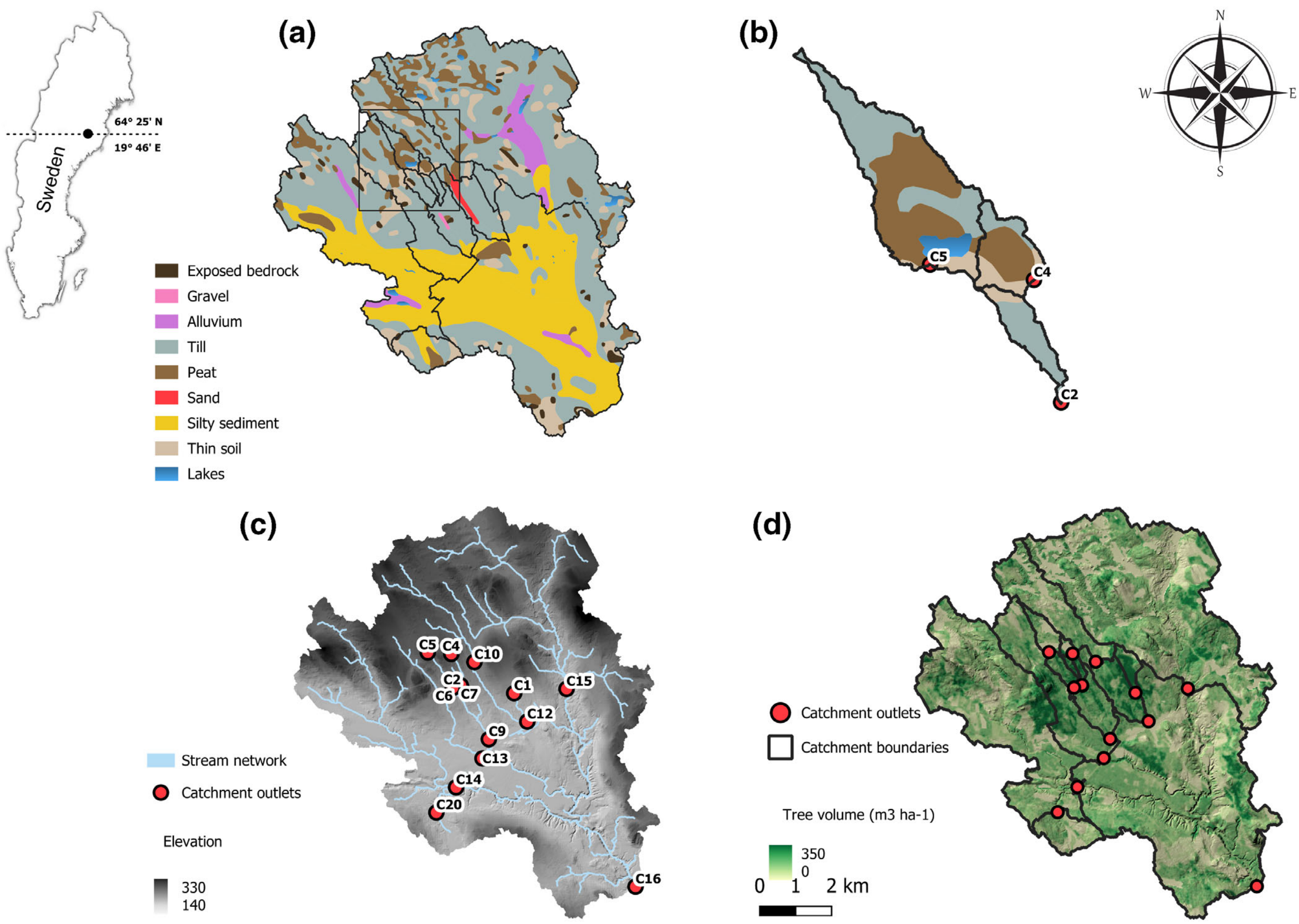

FIGURE 1 Maps of the Krycklan catchment, indicating (a) soil type, (b) magnified view of the three end-member catchments: c5 (the lake-influenced catchment), c4 (the peatland-dominated catchment), and c2 (the forest-dominated catchment) from map (a), (c) elevation, stream network and sub-catchments and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

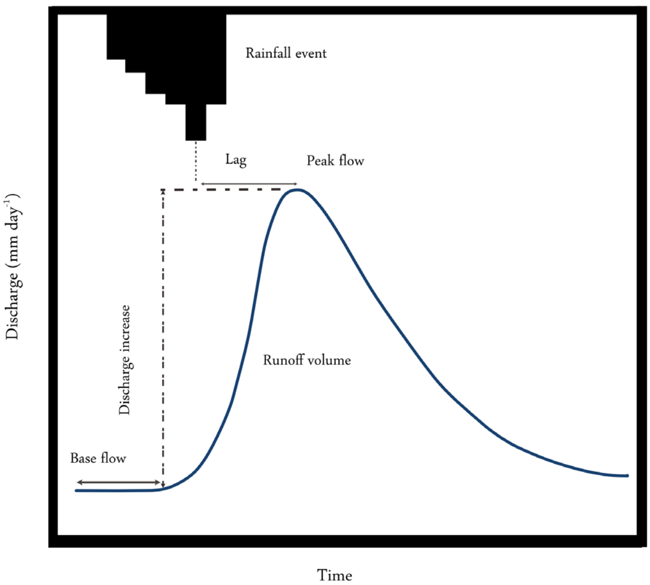

FIGURE 2 Flood hydrograph characteristics.

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.

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

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

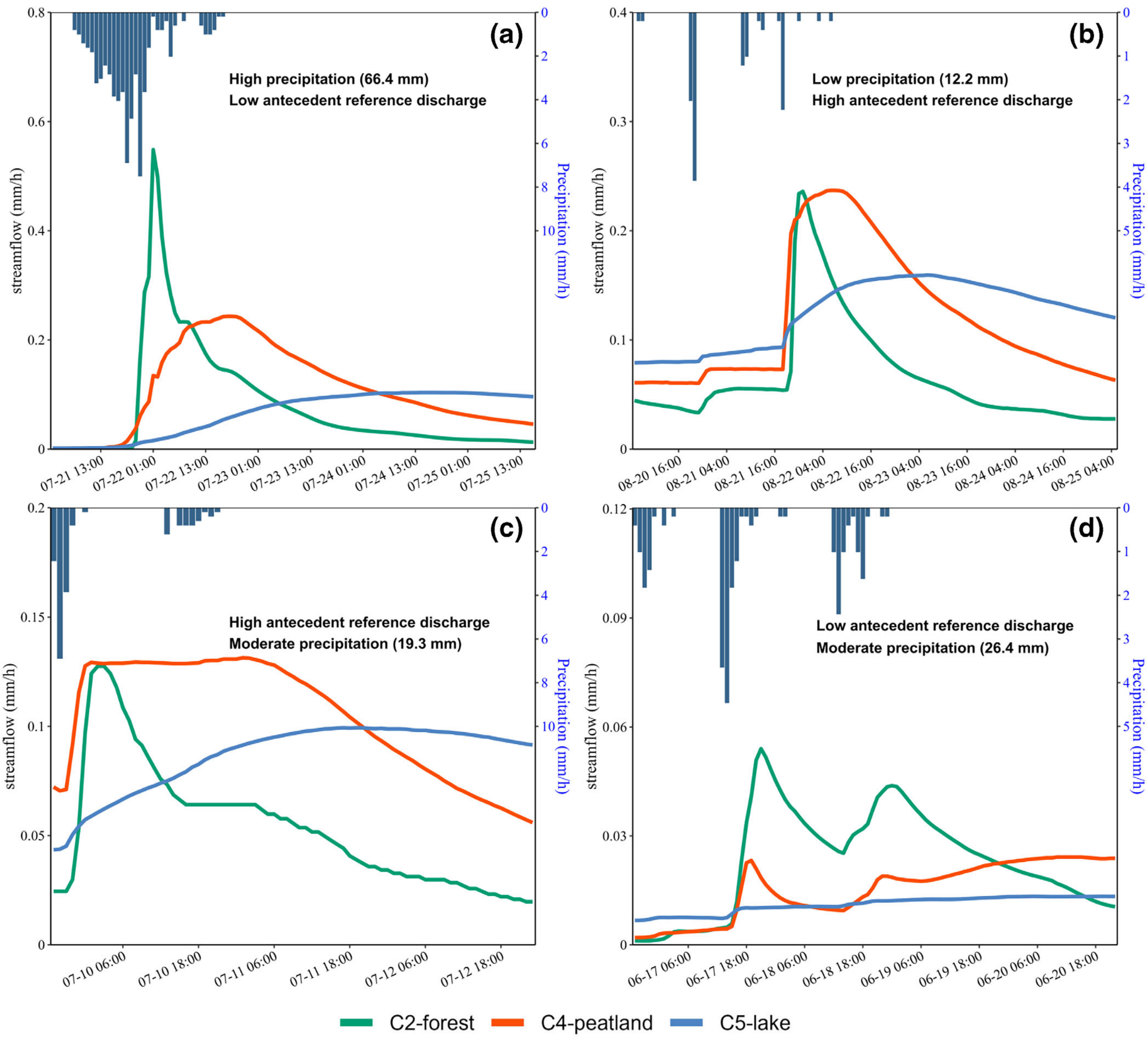

FIGURE 3 Examples of event scale hydrographs for the end-member catchments.

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

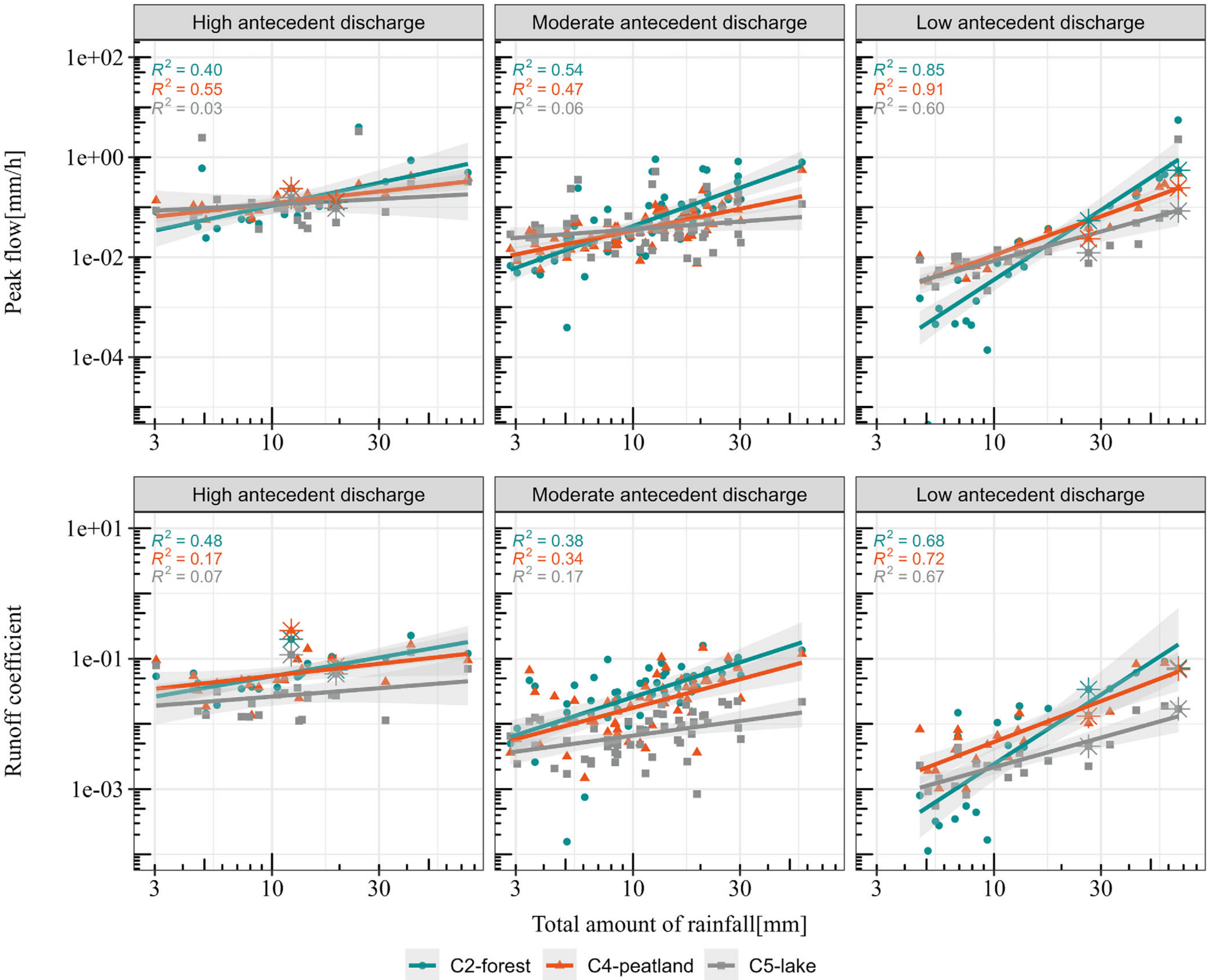

FIGURE 4 Peak flow response and runoff coefficient plotted against rainfall events (log scale). The solid lines show the best-fit regression lines. The grey band is a 95% confidence interval for the regression line. 'High', 'Moderate' and 'Low' denote high, medium and low antecedent reference discharge,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

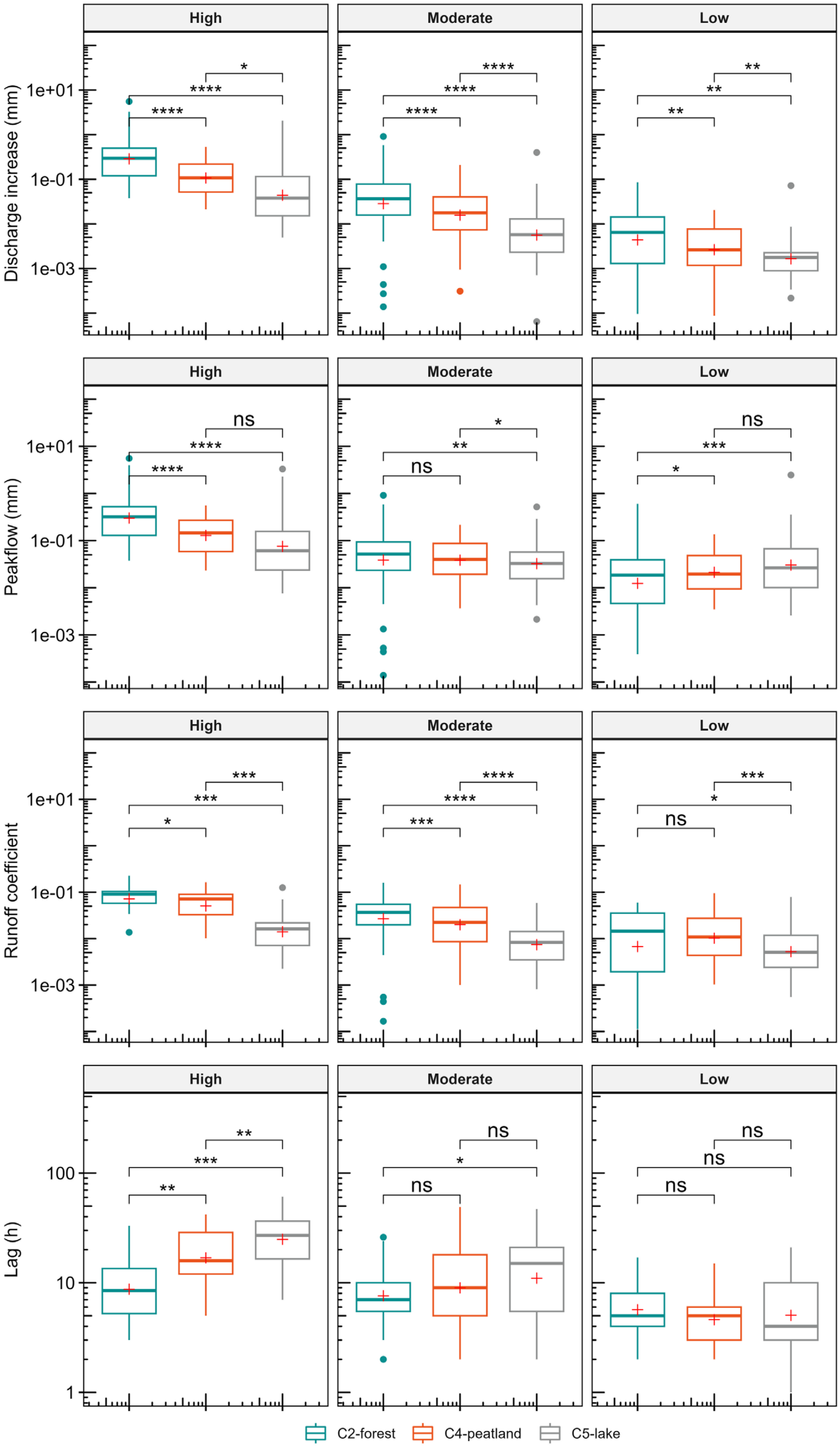

FIGURE 5 Event-based stormflow characteristics of the forest (green), peatland (red) and lake (grey) dominated catchments during high, moderate and low rainfall conditions. Ns denotes not significant. The stars indicate the levels of significance in Wilcoxon test (*$p \le 0.05$; **$p \le 0.01$; ***$p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

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

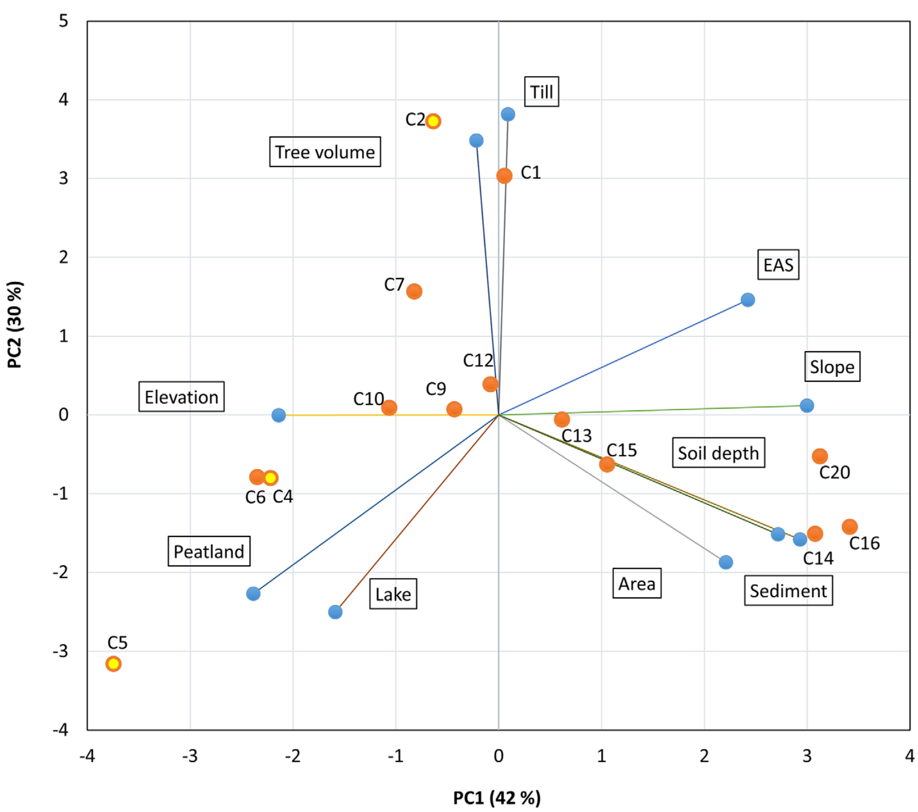

FIGURE 6 Principal components analysis (PCA) for the landscape characteristics (labelled arrows). The three end-member catchments are highlighted in yellow.

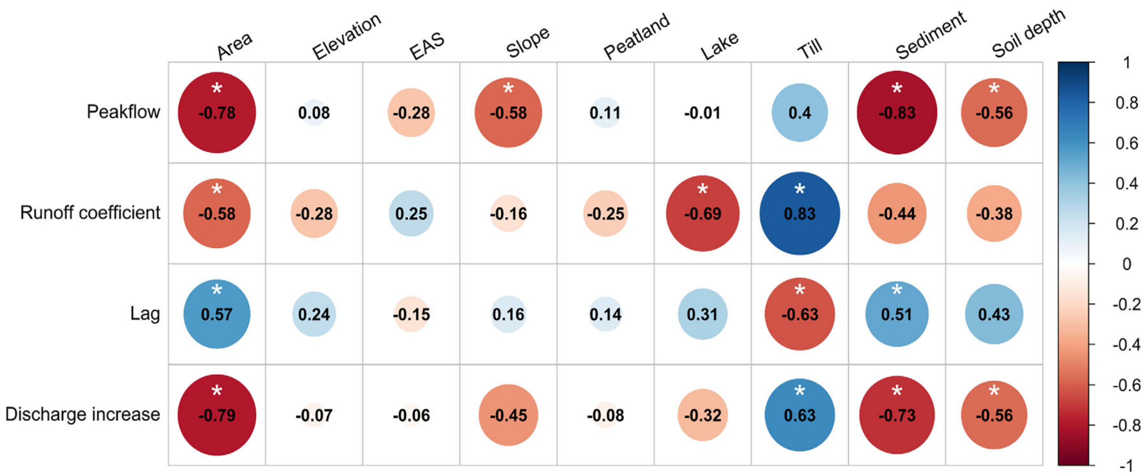

FIGURE 7 Spearman rank correlations between catchment characteristics and hydrological response variables. The colours correspond to the values of the correlation coefficient (blue and red indicate positive and negative correlations, respectively). White stars indicate significant correlations at the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

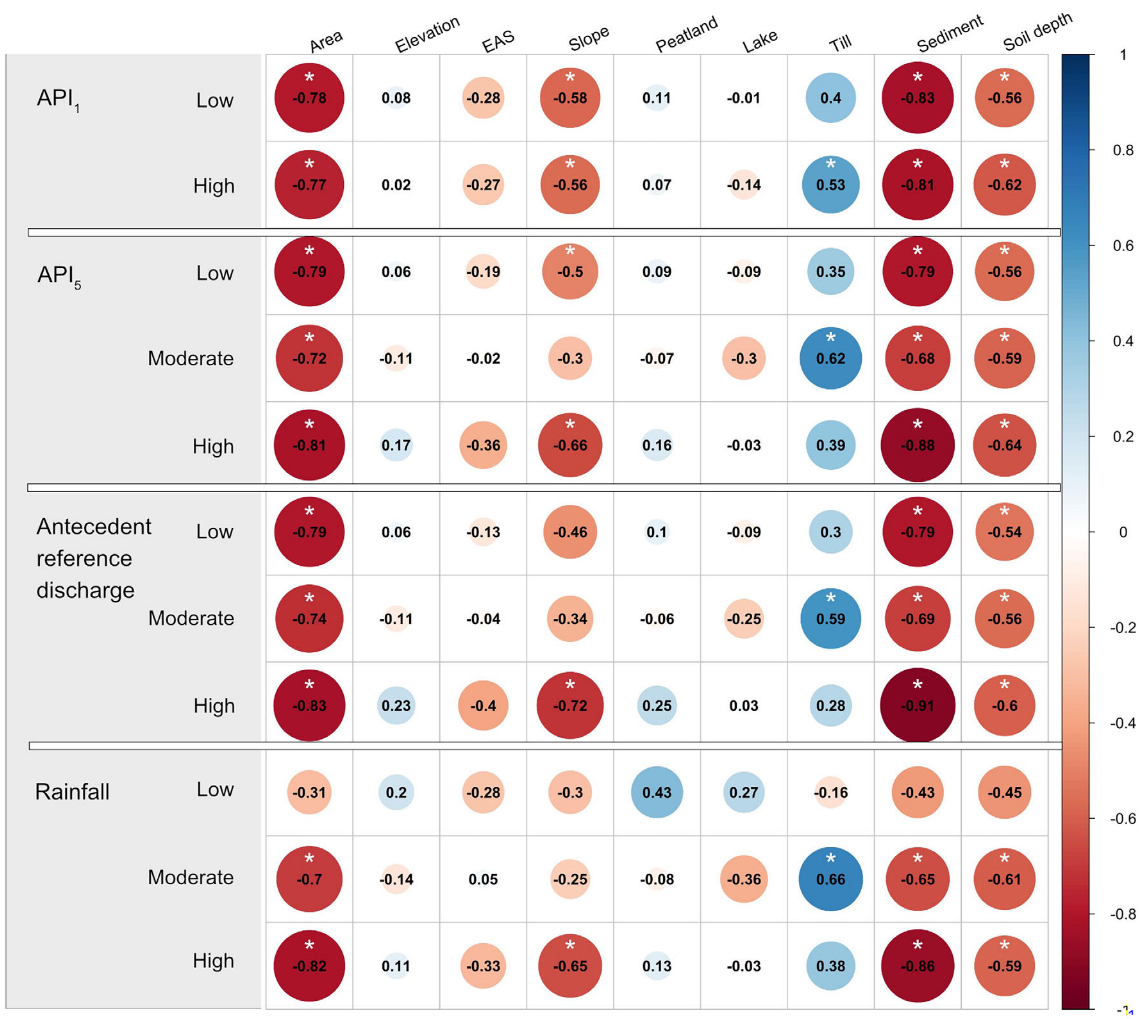

FIGURE 8 Spearman rank correlation analysis between peak flow and catchment characteristics calculated for groups based on different antecedent conditions. The colours correspond to the values of the correlation coefficient (blue and red indicate positive and negative correlations, respectively). White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

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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