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The impact of semi-natural broadleaf woodland and pasture on soil properties and flood discharge

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Abstract

Woodlands can reduce the risk of rainfall-generated flooding through increased interception, soil infiltration and available storage. Despite growing evidence, there is still low confidence in using woodlands as a flood mitigation method due to limited empirical data, particularly for broadleaf woodlands. We measured soil properties and streamflow for nine small (<0.2 km^2) upland catchments and compared mature semi-natural broadleaf woodland where no stock grazing occurs to pasture with varied grazing intensity. We compared streamflow across 28 storm events including a 1 in 10-year event, two 1 in 4-year events and five 1 in 1.5-year events, identified over a 13-month period. We found that semi-natural broadleaf woodlands reduce specific peak discharge by 23%–60% and peak run-off coefficients by 30%–60% compared with pasture. Response to storm events took 14–50% longer in woodland compared to pasture. These differences in flood response are partly explained by more permeable woodland soils, 11–20 times greater than pasture soil. The more muted response of wooded catchments to storm events is consistent across the storms investigated, including Storm Ciara, a 1 in 10-year event. Our analysis strengthens the argument that semi-natural woodlands can reduce rainfall-generated flooding contributing to the evidence base for natural flood management.

KEYWORDS
catchment-based flood management, natural flood management, pasture, soil permeability, woodland

1 | INTRODUCTION

Over the past three decades the frequency of flood events has increased across the UK (Rogger et al., 2017) and worldwide (Hall et al., 2014; Kundzewicz et al., 2014; Wingfield et al., 2019). In England, floods cause damages of £1.1 billion annually with one in six properties at risk from flooding (Priestley, 2017). This risk is expected to further increase under future climate change (Iacob et al., 2017).

Because of recent floods, there is a growing interest in the use of 'soft-engineered' flood mitigation schemes (Dadson et al., 2017; Stevens et al., 2016). Natural Flood Management (NFM), also referred to as working with natural processes or nature-based solutions (Seddon et al., 2020), is an approach to flood management that seeks to work with natural processes to enhance the flood regulatory capacity of a catchment. Often these approaches also provide ecosystem services such as pollution assimilation, habitat creation and carbon storage (Hankin et al., 2017). NFM approaches may include the

development of built water storage (Nicholson et al., 2020; Quinn et al., 2013), river restoration (Dixon et al., 2016), leaky debris dams (Ashbrook, 2020; Thomas & Nisbet, 2012) and land-use management (Spray et al., 2016).

Land-use management can influence the generation of overland flow, through hydrological processes such as interception, infiltration into soils, and available water storage, making it a potentially impactful NFM approach (Stratford et al., 2017). However, there is limited empirical data regarding the impact of land-use management as an effective NFM strategy (Burgess-Gamble et al., 2017). Furthermore, the size of a storm event is an important variable influencing the effectiveness of NFM (Archer, 2007; Beschta et al., 2000; Gallart & Clotet, 1987; Kirby, Newman, & Gilman, 1991).

In the UK and across northern Europe, NFM is often used in headwater catchments of the uplands, which receive high volumes of precipitation and are ideally placed for schemes which aim to 'slow the flow' of water down-slope (Bronstert et al., 2002; Marshall et al., 2009; Wheater & Evans, 2009). These areas are often dominated by grasslands used as permanent pasture (Marshall et al., 2009; Murphy et al., 2020), grazed by livestock, predominantly sheep. Grazing alters vegetation and can lead to soil compaction, loss of macro-porous soil structure and increased flood risk (Alaoui et al., 2018; Holden et al., 2007; Murphy et al., 2020; Palmer & Smith, 2013; Sansom, 1999). Exclusion of livestock has been observed to alter vegetation structure and soil structure, leading to an increase in infiltration rates and a reduction in surface runoff (Gifford & Hawkins, 1978; Greenwood et al., 1997; Marshall et al., 2009; Marshall et al., 2014; Nguyen et al., 1998).

Forested catchments have a different hydrological response compared to un-forested catchments due to greater interception, soil infiltration and available storage. Woodland soils typically have higher permeability rates than other vegetation types (Agnese et al., 2011; Archer et al., 2013; Mawdsley et al., 2017; McCulloch & Robinson, 1993; Zimmermann et al., 2006). This is attributed to a more open structure found in woodland soils as a result of increased organic matter and the action of tree roots (Nisbet & Thomas, 2006). Wooded catchments also have higher evapotranspiration and interception rates compared with other vegetation types, as trees are usually taller and have greater leaf area (Calder & Aylward, 2006; Nisbet, 2005). This means woodlands can produce lower annual runoff compared to other land cover types, as demonstrated in numerous catchment-based studies including Stocks Reservoir (Law, 1956), Plynlimon (Hudson et al., 1997; Kirby et al., 1991); Coalburn (Birkinshaw et al., 2014; Robinson, 1998) and Balquhidder (Johnson, 1995), depending on hydrological regime and climate (Brown et al., 2005; Farley et al., 2005; Zhang et al., 2017). In addition to altering annual runoff, woodland tends to reduce and delay flood peaks (Dadson et al., 2017; Stratford et al., 2017). However, the benefit of woodlands in providing smaller peak flows is typically less for larger storms and larger catchments (Archer, 2007; Beschta et al., 2000; Gallart & Clotet, 1987; Gallart & Llorens, 2003).

Historically, UK catchment-scale hydrological studies have investigated the influence of conifer afforestation (Marshall et al., 2009).

UK forest cover increased from 5% in 1920 to 13% in 2020 (Forestry Commission, 2020), largely due to expansion of conifer plantations, which now account for 51% of UK woodland area (Forestry Commission, 2020). Relatively few UK studies have focused on broadleaf woodlands, which are the natural vegetation type in much of the UK. Broadleaf woodlands are likely to have a different impact on hydrological processes. For example, evergreen conifers retain leaves all year and intercept 25%–40% of annual rainfall compared with 10%–25% for broadleaf deciduous woodland (Ahmad-Shah & Rieley, 1989; Nisbet & Broadmeadow, 2003; Roberts & Rosier, 2005). In addition, broadleaf trees typically have deeper root systems and higher soil infiltration rates compared with conifers (Archer et al., 2013). Differences in woodland management are also likely to alter hydrology, with the drainage ditches and forest roads that are more likely to be present in a productive conifer plantation, contributing to increases in downstream peak flows (Bathurst et al., 2018; Bathurst et al., 2020; Robinson et al., 2003; Stratford et al., 2017). Furthermore, the occurrence of periodic felling in a productive conifer plantation removes the canopy and causes soil disturbance which may contribute to an increase in localized flood risk (Nisbet & Thomas, 2006) and increased annual flows (Robinson & Dupeyrat, 2005). In a study focused on China, Tembata et al. (2020) found that broadleaf and mixed forests mitigate flooding, but conifer forests do not.

There have been few comparisons between upland permanent pasture and broadleaf woodland, particularly studies that have measured both soil properties and streamflow response. Previous studies of broadleaf woodland creation (Marshall et al., 2014) have focused on the short-term impacts, as soon as 18-months after tree planting (Mawdsley et al., 2017). Research at Pontbren, one of the limited broadleaf woodland studies, found median soil infiltration rates were 67 times greater in newly (<5 years) planted broadleaf woodlands compared with grazed pasture, with runoff volume reduced by 78% (Carroll et al., 2004; Marshall et al., 2014). As areas of newly planted broadleaf woodland mature, it will be increasingly important to understand how established broadleaf woodlands impact both soil properties and streamflow, to better understand the potential for flood mitigation (Murphy et al., 2020).

In this study we report results from a research catchment consisting of mature broadleaf woodland and grazed pasture in the UK uplands. The aims of the study were to:

1. Quantify the impact of pasture and mature semi-natural broadleaf woodland on soil properties.
2. Analyse streamflow response, including peak flow and runoff coefficient, of catchments dominated by pasture and mature semi-natural broadleaf woodland.

Our study is one of the first studies to investigate the impact of a mature broadleaf woodland in the UK, contributing to the evidence base around the benefits of broadleaf woodlands in the UK uplands.

2 | METHODS

2.1 | Study area

This study took place around Haweswater reservoir (54°31′50.9"N, 2°45′37.3"W) in the Lake District National Park, UK (Figure 1). The land is owned by United Utilities and managed in partnership with the Royal Society for the Protection of Birds (RSPB) (RSBP, 2015). Elevations across the study area range from 243 to 720 m. The site experiences mild winters and cool summers (Kenworthy, 2014), with mean monthly temperatures ranging from −0.3°C to 18.3°C. Mean annual precipitation is 1779 mm, with monthly totals ranging from 88 to 231 mm (1981–2010 mean, derived from the Shap weather station at 255 m AoD) (Met Office, 2020). Average potential evapotranspiration (1961–2017) is 1.3 mm·d^{-1}, with a summer average of 2.4 mm·d^{-1} and a winter average of 0.3 mm·d^{-1} (Robinson et al., 2020).

Soils in the study area are upland organo-mineral soils, predominately Malvern 611a (Chromic Endoleptic Umbrisol), a free draining acid loamy soil and Bangor 311e (Dystric Epileptic Histosol) soils, ordinarily described as very acidic peaty soil underlined by igneous rock (Cranfield University, 2019). Land use includes semi-natural broadleaf woodland and unimproved permanent pasture grazed at a variety of densities. In recent years, United Utilities and RSPB have trialled a number of upland land management strategies, including tree planting, moorland drain blocking and changes to grazing (RSBP, 2015).

2.2 | Study design

We identified nine small (<0.2 km^2) catchments with different land covers but similar elevation, slope, geology and soil type (Table 1). We compared mature semi-natural woodland (W) and permanent pasture under either commons grazing (CG) or low-density grazing (LG). Woodland catchments consisted of mixed broadleaf species, predominantly oak, ash, alder, birch and hazel, with no stock grazing. Permanent pasture sites were unimproved (i.e., no drainage, ploughing or fertilizer application has occurred). Sheep grazing in CG occurs all year round at a maximum ewe intensity of 0.12 livestock units, LU·ha^{-1}, whereas grazing intensity in LG never exceeded 0.10 LU·ha^{-1}, with no grazing in winter and scattered tree planting. Red and roe deer occurred at all sites.

2.3 | Soil properties

Soil properties were analysed on a monthly basis during a 12-month period (July 2018–July 2019) and sampled randomly across each catchment. Soil cores ($n = 30$) were taken at 0–5 cm depth, just below the vegetation layer using Eijelkamp soil sample rings. Top-soil permeability (saturated hydraulic conductivity, Kfs or Ksat) was measured in an Eijelkamp 25 place Permeameter, from the collected soil cores. Subsoil permeability (Kfs or Ksat, 0.15 m depth) was determined in-field using a constant head well permeameter (CHWP, Engineering Technologies Canada Ltd. [ETC] pask, $n = 13$) (Elrick & Reynolds, 1986; Reynolds, 2008). A pre-wetting phase was included to reduce the time to reach steady state flow and ensure saturation. The Eijelkamp Permeameter was unsuitable for the subsoil measurements due to the rocky nature of the ground. Bulk density (ρ, g·cm^{-3}) was calculated after oven drying (105° for a minimum of 16 h) the soil cores to constant weight. Soil moisture content was measured using a Delta-T Ltd 'theta probe' ($n = 225$). The 'theta probe' uses a simplified time-domain reflectometry (TDR) technique to derive values of volumetric moisture content (Delta-T, 1999).

2.4 | Hydrological monitoring

Hydrology was monitored over a 13-month period (January 2019–February 2020). A 90° v-notch weir was established within each catchment, with a pressure transducer installed to collect stream depth data every 5 min (see Supplementary material 1 for details). Flow was calculated using the Kindsvater-Shen equation (Supplementary material 2). Locations for data collection within the streams were based on suitability of the channel bed; approximately 1.5 m between channel banks and accessibility for monthly equipment checks. Rainfall data (5 min resolution) was collected using a HOBO RG3 data logging tipping bucket rain gauge (Figure 1).

2.5 | Storm response

Storm events were defined when more than 20 mm of rain occurred during a 24-hr period. The end of the event was defined as 6 hours with no rain. During a 13-month period (January 2019–February
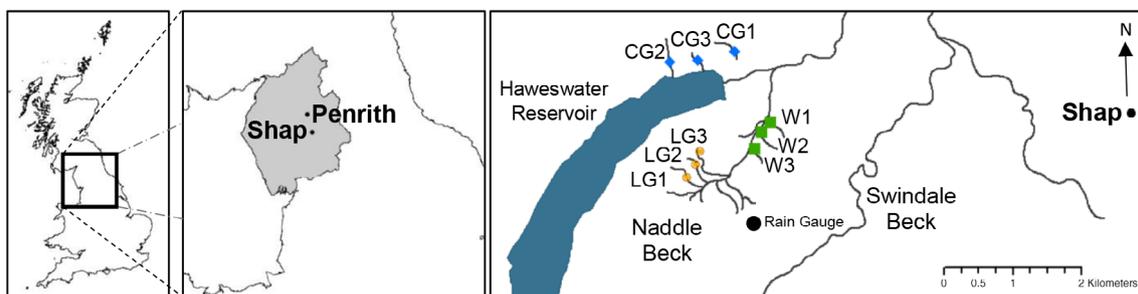

FIGURE 1 Map of field sites, RSPB Haweswater within the UK and location of rain gauge and woodland (W), commons grazing (CG) and low-density grazing (LG) pasture

TABLE 1 Summary information for the nine field catchments. Elevation (m) is recorded where streamflow measurements are taken.

Land-use		Field site	Catchment size (km²)[a]	Average elevation (m)	Average slope (°)	Aspect	Location	Ground vegetation cover (dominant species)	Land management and grazing intensity
Pasture	Commons Grazing	CG1	0.05	260	19.3	S-SE	54°32'19 N2°45'58 W	Deschampsia flexuosa, Digitalis sp., Galium saxatile, Molinia caerulea, Nardus stricta, Potentilla erecta, Pteridium aquilium, Ranunculus sp. Rubus sp., Sphagnum sp., Ulex europaeus	All year round grazing at a maximum intensity of 0.12 LU·ha^{-1}.
		CG2	0.08	260	20.2	SE-E	54°32'90 N2°47'40 W		
		CG3	0.14	270	16.0	S	54°32'14 N2°46'44 W		
	Low-Density Grazing	LG1	0.10	360	12.0	SE	54°31'12 N2°46'12 W	Carduus sp., Cirsium vulgare, Deschampsia flexuosa, Equisetum arvense, Juncus sp., Molinia caerulea, Nardus stricta, Potentilla erecta, Pteridium aquilium, Ranunculus sp., Sphagnum sp., Veronica sp.	Maximum grazing intensity of 0.10 LU·ha^{-1} with no stock grazing from 1st November - 30th April.
		LG2	0.12	370	8.5	SE-E	54°31'20 N2°46'39 W		
		LG3	0.11	390	4.6	SW-W	54°31'30 N2°46'28 W		
Woodland		W1	0.06	280	21.8	NW	54°31'33 N2°45'39 W	Deschampsia flexuosa, Euphrasia sp., Mercurialis perennis, Molinia caerulea, Nardus stricta, Pteridium aquilium, Sphagnum sp., Trifolium repens	Semi-natural upland woodland (NVC classification W7, W9, W11–upland mixed woodland and wet woodland) designated as a site of special scientific interest (SSSI). The woodlands are fenced to exclude livestock.
		W2	0.05	310	24.0	N-NW	54°31'30 N2°45'44 W		
		W3	0.03	270	17.7	NW	54°31'40 N2°45'33 W		

Abbreviation: LU, livestock units.

[a]Calculated as the median of the estimate from OS (Digimap, 2021) and the water balance method (December data assuming zero evapotranspiration).

2020), 28 storms were identified including both winter and summer storms (Supplementary material 3). Storm durations ranged from 9.5 to 96.25 hours. Storm intensity, defined as total rainfall divided by storm duration, ranged from 0.62 to 5.3 mm·hr^{-1}.

We used rainfall data from Wet Sleddale, 8 km from the site, to establish storm return periods as there was insufficient data available from the nearest rain gauge (Naddle). Rainfall at Wet Sleddale was highly correlated with records from Naddle (see Supplementary material 4). An IDF (intensity-duration-frequency) curve was used to calculate return periods.

Catchment response to each storm was analysed in four ways: The specific peak discharge, peak runoff coefficient, volume runoff coefficient and time to flow response. The specific peak discharge (SPD, mm·hr^{-1}) indicates the highest discharge during the storm event with the influence of catchment area removed (Supplementary material 5). Both the peak runoff coefficient and volume runoff coefficient are dimensionless coefficients relating the amount of runoff to the amount of precipitation received and useful for catchment comparisons to understand how different landscapes impact runoff (Young et al., 2009). A larger runoff coefficient can indicate a catchment with lower infiltration rates that is more susceptible to flooding, whilst a smaller value suggests a more permeable catchment. Peak runoff coefficient (C) is calculated by dividing the peak rate of runoff by the maximum rainfall intensity (Supplementary material 5). To determine the volume runoff coefficient (V) for each storm, baseflow was removed from the storm hydrograph and the total storm runoff calculated. The volume runoff coefficient was then calculated as the ratio of total storm runoff to total storm rainfall (Merz et al., 2006). The time to flow response is the time, in hours, between the initiation of rainfall and a significant water level rise (Gonzalez-Sosa et al., 2010), defined in our analysis as three times streamflow at the start of the event.

2.5.1 | Influence of storm size and seasonality

We analysed the impact of storm size by two different methods. Firstly, we used the classification of Kirby et al. (1991) with smaller storms classified as discharge peaks <1 mm·hr^{-1} and larger storms as discharge peaks >1 mm·hr^{-1}, allowing for direct comparison with previous studies (Kirkby et al., 1991; Meyles et al., 2003). Secondly, we divided storms by storm return periods. Storms were divided into those with a return period less than 1.5 years and those with a return period longer than 1.5 years, with this threshold reflecting the average reoccurrence of bankfull stage (Wolman & Miller, 1960). Our storm return periods are based on rainfall data, likely leading to longer return periods compared to return periods based on discharge data. There were insufficient large storm events in our study period to fully characterize the impact of land cover as a function of storm size.

We also identified whether the storms occurred during winter or summer and re-calculated the mean SPD, peak runoff coefficient, volume runoff coefficient and time to flow response. Finally we calculated the cumulative sum of flow above two different thresholds

(1 and 2 mm·hr^{-1}) between 03 March 2019 and 17 March 2019, a period when data was available at all sites and evapotranspiration can be assumed to be minimal.

2.5.2 | Hydrograph form and flashiness

We identified the 97.5% flow threshold and analysed each consecutive period of higher flow. The hydrograph within each of these peak periods was normalized relative to the peak flow in the period, allowing us to compare the relative rates of rise and fall around the peak, thereby providing an indication of the flashiness of the response. This procedure was followed for each measurement site. Since the sites are all close together (within 3.5 km^2), the incidence of storm events was considered comparable, revealing the inherent differences in flashiness between the sites.

2.6 | Statistical analysis

Shapiro–Wilks tests were employed to deduce normality of soil properties and storm responses. Non-parametric Kruskal–Wallis and post-hoc tests were used to determine a significant difference (significance determined at $p < 0.05$) between land covers (significant differences between individual catchments can be found in Supplementary material 6 & 8). Statistics were performed using the Python matplotlib (Barrett et al., 2005), SciPy (Virtanen et al., 2019) and scikit-posthocs (Terpilowski, 2019) packages.

3 | RESULTS

3.1 | Soil properties

Woodland sites had significantly ($p < 0.05$) higher topsoil permeability compared with the pasture sites. Median topsoil permeability was 11 times higher in the woodland sites compared with CG sites, and 20 times higher than the LG sites (Figure 2a). There was no significant ($p > 0.05$) difference between subsoil permeability at the different sites (Figure 2b). The highest mean soil moisture occurred at the woodland sites (49%), compared with LG (46%) and CG (33%) with significant ($p < 0.05$) differences between the soil moisture at the different sites (Figure 2c). The lowest bulk density soils were measured at the LG sites (0.36 g·cm^{-3}) compared with CG (0.46 g·cm^{-3}) and W sites (0.50 g·cm^{-3}) (Figure 2d). Details of the measurements for the nine catchments are given in Supplementary material 6 and 7.

3.2 | Storm response

Figure 3 compares SPD, runoff coefficients and time to flow response across all the storms analysed. SPD and peak runoff coefficient were significantly lower at woodland sites compared with CG and LG sites
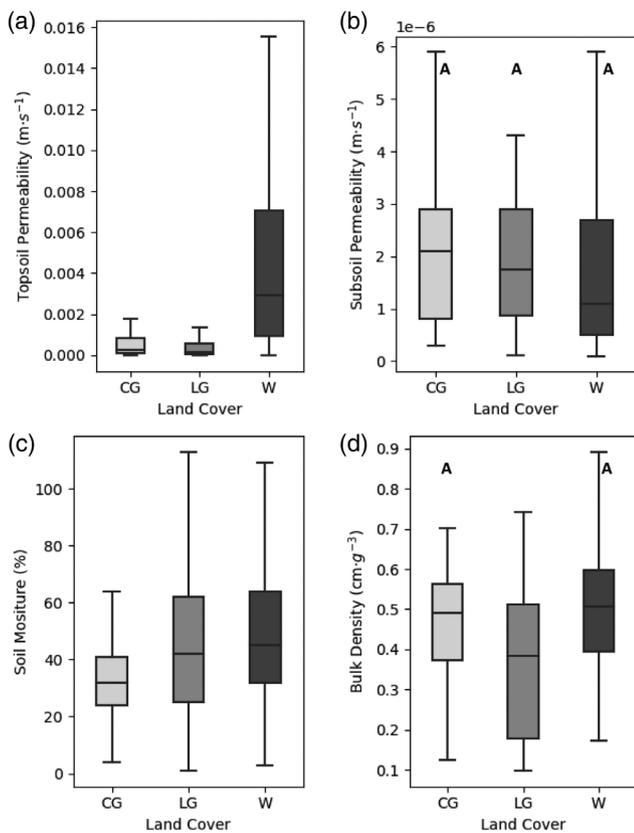
FIGURE 2 Distribution of (a) topsoil permeability (m·s^{-1}), (b) subsoil permeability (m·s^{-1}), (c) soil moisture (%), (d) bulk density (g·cm^{-3}) for woodland (W), commons grazing (CG) and low-density grazing (LG) pasture shown as median (line), 25% and 75% (box), and 5% and 95% (whiskers). Sites which are not statistically different share a letter

FIGURE 3 Distribution of (a) specific peak discharge (mm·hr^{-1}), (b) peak runoff coefficient, (c) volume runoff coefficient, (d) time to flow response (hr) for woodland (W), commons grazing (CG) and low-density grazing (LG) pasture shown as median (line), 25% and 75% (box), 5% and 95% (whiskers). Sites which are not statistically different share a letter

($p < 0.05$). Woodland sites median SPD was 23% less than CG and 60% less than LG sites (Figure 3a). Woodland sites had a peak runoff coefficient 30% less compared with CG sites and 60% less LG sites (Figure 3b). Volume runoff coefficients were not significantly different between land covers (Figure 3c). The median time to flow response in woodland was 14% longer than CG sites and 50% longer compared with LG sites (Figure 3d). Woodland sites had significantly different time taken to flow response compared with the LG ($p < 0.05$), but not CG sites. Details of the measurements for the nine catchments are given in Supplementary material 8 and 9.

3.2.1 | Influence of storm size and seasonality

We identified 28 storms during our analysis period; including a 1 in 10-year storm event, two 1 in 4-year storm events and five 1 in 1.5-year events (Figure 4a). Two of these storms met requirements to be named by the UK Met Office, Storm Ciara (1 in 10-year event) and Storm Dennis (1 in 4-year event) (Parry et al., 2020). Both storms displayed characteristics of storms with longer return periods (Storm Ciara up to a 1 in 50-year event and Storm Dennis a 1 in 10-year event) (Figure 4b).
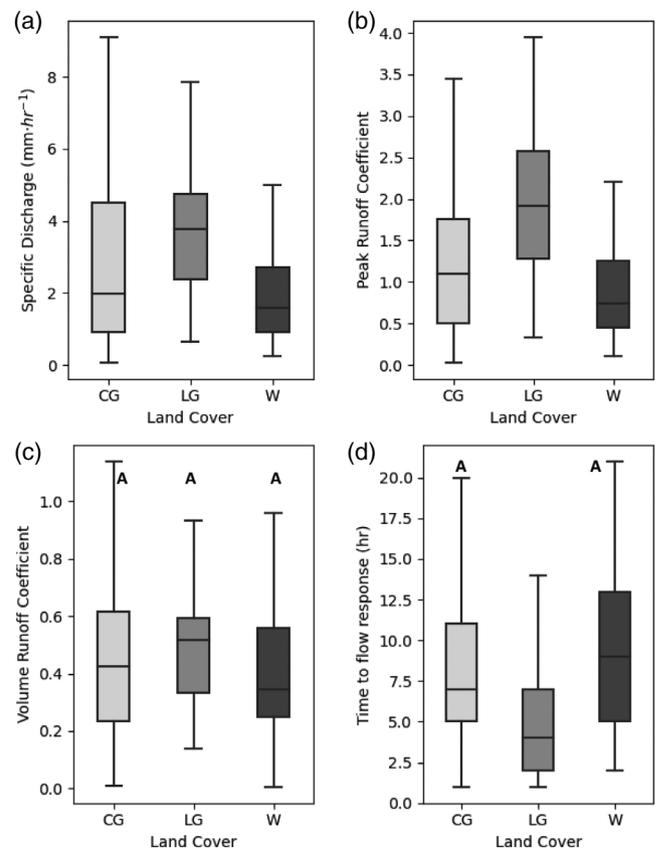
We divided storms into those with a return period more than 1.5 years ($n = 8$ storms) and storms with a return period less than 1.5 years ($n = 20$ storms). For storms with a return period more than 1.5 years, woodlands exhibited significantly different ($p < 0.05$) SPD (Figure 5a) and peak runoff coefficient (Figure 5b) compared with pasture: median SPD was 53% lower than for CG sites and 58% lower than LG sites, peak runoff coefficient was 48% lower than CG sites and 58% lower than LG sites. For storms with a return period more than 1.5 years, the median volume runoff coefficient for woodland sites was 26% lower than CG sites and 41% lower than LG sites ($p < 0.05$) (Figure 5c). Woodland catchments also exhibited lower SPD and peak runoff coefficients than pasture during Storm Ciara (Supplementary material 10 and Supplementary material 11).

Using the same storm classification as Kirby et al. (1991), we found woodland exhibited a significantly lower mean SPD (2.35 mm·hr^{-1}) compared with pasture (3.67 mm·hr^{-1}) for larger storms. However, there was no significant difference in mean SPD between woodland (0.68 mm·hr^{-1}) and pasture (0.51 mm·hr^{-1}) for smaller storms. We found woodlands had lower SPD and runoff coefficients compared with pasture in both summer and winter, with the largest differences in winter (Table 2). We found the cumulative flow above a certain threshold during a 14-day period in winter was lower at the woodland sites compared with pasture (Table 3).
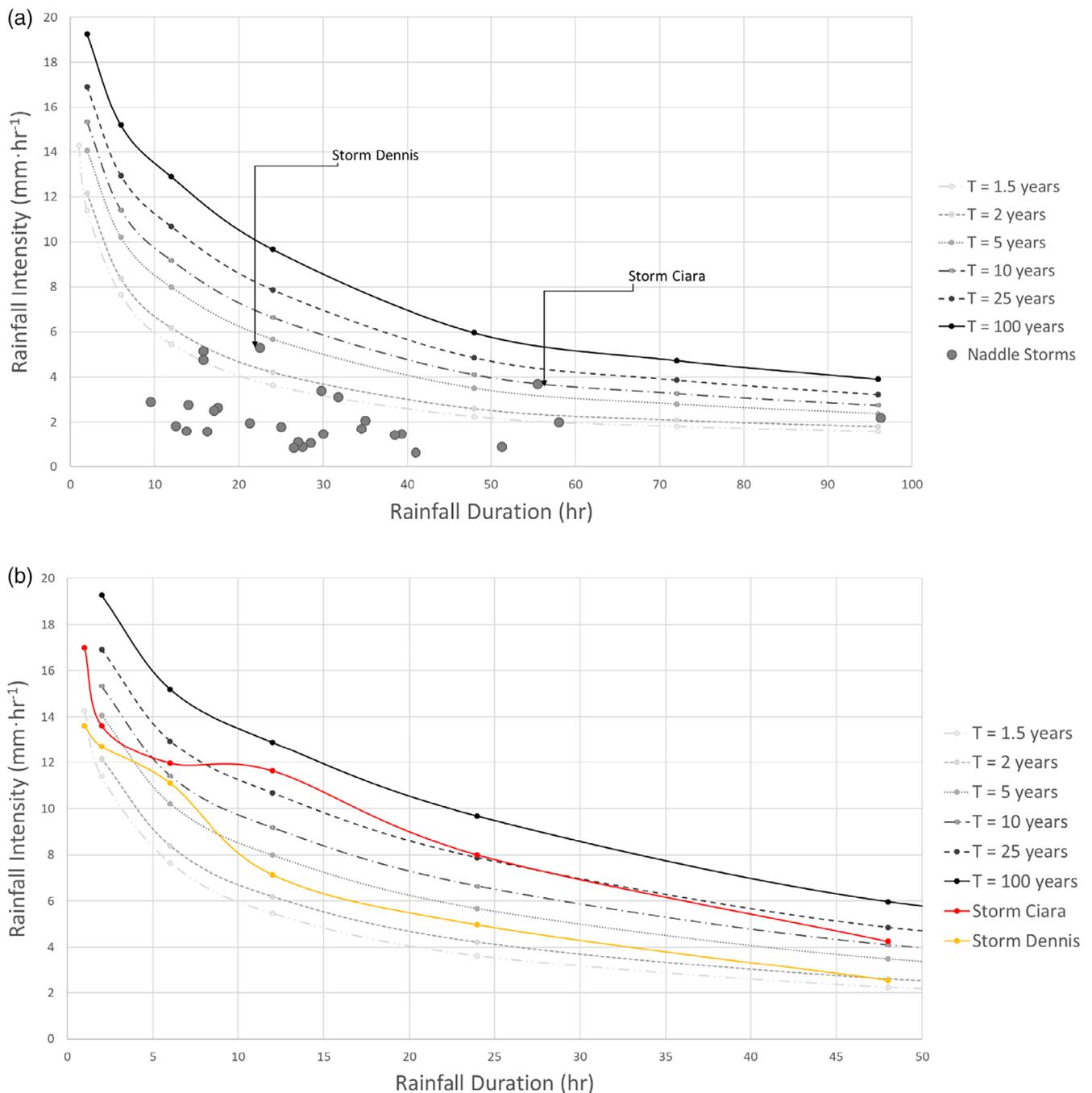
FIGURE 4 Intensity-duration-frequency (IDF) curve of wet Sleddale rainfall data from 1997 to 2021 for return periods, T = 1.5, 2, 5, 10, 25, 100 years. (a) 28 storms identified at the Naddle rain gauge overlaid with grey circles. (b) Met office named storms, Ciara & Dennis overlaid to show the range of storm intensities throughout each event

3.2.2 | Hydrograph form and flashiness

Figure 6 shows the medians of normalized hydrograph peaks for all storms exceeding the 97.5% frequency threshold. These medians are derived from individual storm data for each site, shown in full in Supplementary material 12. Steeper rising and falling limbs indicate a flashier response, generally associated with more severe flooding from storm rainfall. It is evident that woodland sites are the least

flashy, and pasture sites (particularly low-density pasture) the most flashy.

4 | DISCUSSION

Our study provides some of the first information of the impacts of mature semi-natural broadleaf woodlands in the UK on streamflow in
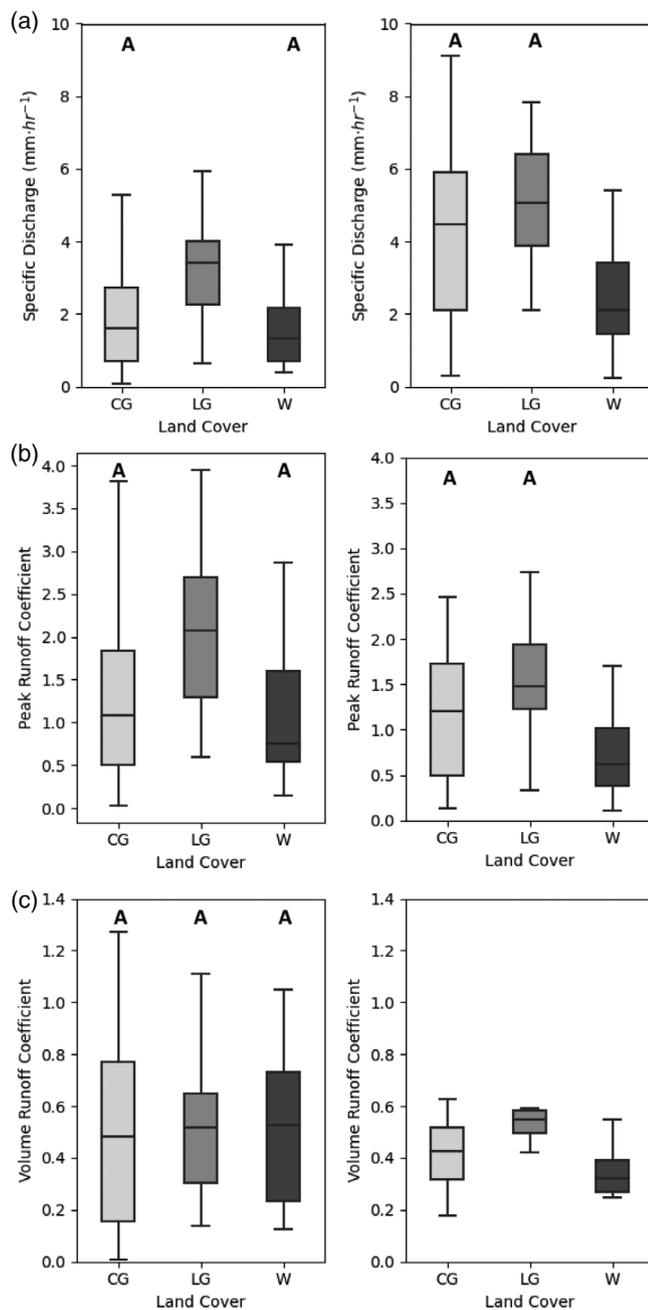
FIGURE 5 Comparison of streamflow for storms with return periods of less than (left hand panels) and more than (right hand panels) 1.5 years for woodland (W), commons grazing (CG) and low-density grazing (LG) pasture. (a) Specific peak discharge (mm·hr^{-1}), (b) peak runoff coefficient), (c) volume runoff coefficient shown as median (line), 25% and 95% (box), 5% and 95% (whiskers). Shown for sites which are not statistically different share a letter. Supplementary material 10 reports tabulated data

small (<0.2 km^2) catchments. The lower specific peak flow, lower run-off coefficient and longer response time of mature semi-natural broadleaf woodlands compared with pasture will contribute to reduced peak flow downstream. In contrast to some previous studies, we found mature broadleaf woodland can reduce peak flow for larger storms (>1 mm·hr^{-1}) and for storms with >1.5-year return periods.

Together this demonstrates the effectiveness of mature semi-natural broadleaf woodlands as a NFM method.

4.1 | Comparison of streamflow response in semi-natural woodland and wood pasture

Across all the storms analysed, we found that woodland sites typically had lower SPD, peak and volume runoff compared with grazed pasture sites by 23%–60%, 30%–60%, and 21%–35% respectively. Peak runoff coefficients can be strongly influenced by characteristics of the storm event (Figure 5b), but in our analysis shows consistent behaviour with other streamflow metrics. Sriwongsitanon and Taesombat (2011) reported lower runoff coefficients for a forested area in comparison with an agricultural area. We found that the average time taken for flow to respond to storm events was 14%–50% longer in the woodland compared with pasture sites. Lana-Renault et al. (2011) found a forested catchment took 171% longer to respond than a formerly agricultural catchment, subsequently left to naturally regenerate. As in previous studies (e.g., Carroll et al., 2004; Chandler et al., 2018; Mawdsley et al., 2017; Wahl et al., 2003) we compared small catchments which are as similar as possible in all respects except land cover and assume differences in land cover drive difference in hydrological response (McCulloch & Robinson, 1993). Flow response is dependent on antecedent conditions, which will be similar for our sites as they are closely located to each other. We note that it is not possible to identify catchments that are identical in all aspects, so it remains possible that catchment differences drive some of the observed differences in flow response (Lana-Renault et al., 2011; López-Ramírez et al., 2020). Establishing measurements in multiple small catchments (here three woodland and six pasture catchments) will help to reduce these uncertainties. Future work is needed to track changes in soil properties and streamflow as newly established broad-leaf woodlands mature.

4.2 | Impact of storm size

Previous studies have reported that forests reduce peak discharge during small flood events but not always during larger events (Dadson et al., 2017; Stratford et al., 2017). For example, Kirby et al. (1991) showed lower peak flows in a wooded catchment compared with a grassland catchment during smaller storms (discharge peaks <1 mm·hr^{-1}), but little difference during larger storms (discharge peaks >1 mm·hr^{-1}). Using the same storm classification, we found woodland exhibited a lower mean SPD (2.35 mm·hr^{-1}) compared with pasture (3.67 mm·hr^{-1}) for larger storms.

We also explored whether land use had different impacts for different storm return periods. Woodlands had a median volume runoff coefficient that was 26%–41% lower and peak runoff coefficient that was 48%–58% lower than pasture for storms with a return period greater than 1.5 years. Our study focused on mature, semi-natural woodlands consisting of native broadleaf tree species without any

TABLE 2 Summer and winter streamflow properties for woodland and pasture (commons grazing (CG) and low-density grazing (LG) combined due to data availability)

	Specific peak discharge (SPD) (mm·hr^{-1})				Peak runoff coefficient				Volume runoff coefficient				Time to flow response (hr)			
	Summer		Winter		Summer		Winter		Summer		Winter		Summer		Winter	
	n	μ	n	μ	n	μ	n	μ	n	μ	n	μ	n	μ	n	μ
Woodland	12	0.0013	43	0.0019	12	0.80	42	0.89	10	0.50	37	0.42	12	9	45	10
Pasture	36	0.0020	103	0.0035	36	1.15	99	1.64	40	0.37	83	0.61	36	6	106	8

TABLE 3 Cumulative sum of flow above 1 mm·hr^{-1} and 2 mm·hr^{-1} flow thresholds

Land cover	Cumulative flow (mm)	
	1 mm·hr^{-1}	2 mm·hr^{-1}
Commons Grazing	283	102
Low-density Grazing	270	189
Woodland	131	21

drainage. In contrast, most previous UK studies have focused on conifer plantation with drains established prior to afforestation (Dadson et al., 2017; Kirby et al., 1991; Stratford et al., 2017) which may partly explain the difference in response to larger storms. Tembata et al. (2020) confirms that forest type is important, with broadleaf and mixed forests mitigating flooding whereas conifer forests did not.

Importantly, we found that the response to the largest storm event recorded in our study period, Storm Ciara, remained consistent with the response to other storm events. SPD, peak and volume runoff coefficients were lower in the wooded catchments compared to pasture. The hydrograph response shows the wooded catchments were less flashy during Storm Ciara with a slower rising and falling hydrograph with a smaller and later peak (Supplementary material 11). However, the impact of land cover on storm response during more extreme storm events, for example, 100 year return period, remain unquantified and are likely to show lesser effects than those demonstrated here. Longer data records are needed to capture such large storm events and allow for a more detailed analysis of the impacts of land cover as a function of storm size.

4.3 | Seasonal differences in flood response

We analysed the impacts of land cover during both winter and summer storms (Table 2).

Woodlands had lower SPD and runoff coefficients compared with pasture in both summer and winter, with the largest differences in winter. We found the cumulative flow above a certain threshold during a 14-day period in winter was lower at the woodland sites compared with pasture (Table 3). An increase in heavy wintertime rainfall across Northern England in recent decades highlights the need for flood management during winter months (Burt & Ferranti, 2012; Orr & Carling, 2006).

4.4 | Soil properties

The difference in streamflow response between woodland and pasture sites, particularly in winter when differences in evapotranspiration will be more limited (Blyth et al., 2019; Robinson et al., 2020), can in part be explained by differences in their soil properties. Lower peak flows, lower runoff coefficients and longer times to flow response in woodland sites all indicate a more permeable catchment. This is confirmed by differences in topsoil permeability with our woodland sites having a median topsoil permeability 11–20 times greater than the pasture sites. Previous studies have also found woodland catchments to have more permeable soils, with topsoil (< 20 cm) permeability 1.8–8 times greater than that of grazed permanent pasture (Table 4). The median topsoil permeability we measured for pasture sites (1.47×10^{-4}–2.78×10^{-4} m·s^{-1}, 529–1000 mm·hr^{-1}) overlap previously reported values for pasture and field margins in Northern England: Wallace and Chappell (2019) reported median topsoil permeability of 21–2794 mm·hr^{-1} whereas Wallace et al., (2021) reported 317–8780 mm·hr^{-1}. Hedgerows can also increase permeability, with topsoil permeability 20–30 times higher than pasture (Wallace & Chappel, 2021; Holden et al., 2019). Individual trees within pasture have been shown to increase soil permeability up to 13 m from the tree (Chandler & Chappell, 2008), though we did not observe this effect at our LG pasture sites.

A range of mechanisms have been proposed to explain the greater permeability of woodland and hedgerow soils compared with pasture. The root networks of trees and shrubs can generate macropores within the soil matrix that enhance permeability (Chandler & Chappell, 2008; Wallace et al., 2021). The lower permeability of pasture soils can be due to topsoil compaction caused by livestock grazing (Carroll et al., 2004). Our pasture sites were only lightly grazed and we did not find pasture soils had higher bulk density that would be consistent with compaction. Wallace and Chappell (2019) found that aeration of pasture soils can increase saturated hydraulic conductivity and reduce overland flow. The lower permeability of pasture soils is known to increase runoff and contribute to downstream flooding (Alaoui et al., 2018). Conifer forests soils can have lower permeability compared with both broadleaf woodland and permanent pasture (Chappell et al., 1996; Gonzalez-Sosa et al., 2010), contributing to greater overland flow (Tembata et al., 2020). Many previous studies also found higher subsoil permeability in woodland soils, whereas we found no significant difference in soil permeability at 15 cm depth between woodland and pasture soils. This is likely due
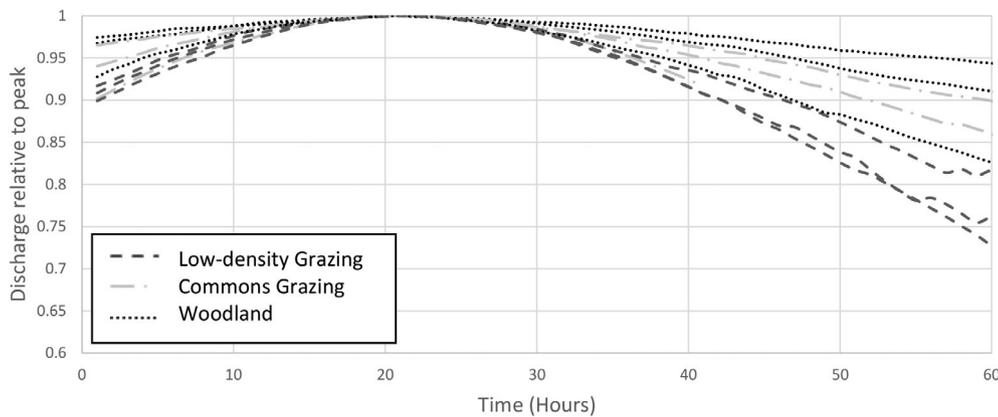
FIGURE 6 Median form of hydrograph peaks for all events exceeding the 97.5% threshold. Data normalized to 100% for the peak flow. Data from all storms shown in Supplementary material 12

TABLE 4 Ratio between permeability (Kfs) of woodlands and grazed soils, comparing data from previous studies

References	Vegetation	Ratio of Kfs woodland compared with grazed land	Depth (cm)
Agnese et al. (2011)	40–50 year-old broadleaf	3.4	10–20
Archer et al. (2013)	180 year-old broadleaf500 year-old broadleaf	65	4–154–15
Mawdsley et al. (2017)	18 month-old saplings	2.3	10–30
Marshall et al., (2009)	7 year-old broadleaf	2.4	18–30
Murphy et al. (2020)	7–15 year-old broadleaf	1.8	6
Zimmermann et al. (2006)	Tropical forest	4 8	12.5 20
López-Ramirez et al. (2020)	Tropical montane	4.8	20
This study	Mature broadleaf	11–20	5

to the relatively thin soils in our upland sites, with the action of tree roots in the development of open pores more limited below 15 cm.

We found LG pasture and woodland sites had significantly higher soil moisture when compared with CG pasture sites. The sparse tree planting in the LG sites may have contributed to the higher soil moisture in this area. Mawdsley et al. (2017) found tree planting can increase soil moisture within 18 months. Furthermore, higher levels of soil moisture are often attributed to lower levels of grazing (Xu et al., 2014). Wallace and Chappell (2020) found that application of fertilizer and slurry to agriculturally improved pasture resulted in reduced summer soil moisture but increased autumn soil moisture potentially increasing downstream flood risk.

Some previous studies have found woodland soils to have 10%–30% lower bulk density than other vegetation types (Agnese et al., 2011; Sharrow, 2007; Wahren, 2009). In contrast, Upson et al. (2016) found woodland soils had greater bulk density compared with pasture. We found woodlands exhibited the highest bulk density values, with a significant difference between woodland soils and LG soils. Our pasture sites were lightly grazed, possibly explaining the lack of compaction and lower bulk density.

In our study, livestock grazed the pasture sites whereas the woodland sites did not have any livestock grazing. The number of sheep in the UK has changed substantially in recent decades, increasing from 19.7 million in 1950 to 44.5 million in 1990 (Fuller &

Gough, 1999), before declining around the turn of the century to 33.5 million in 2019 (DEFRA, 2020). Sheep numbers in the nearby Lune catchment (Cumbria) increased by a factor of five from 100 000 in 1860 to 500 000 in 1990 (Orr & Carling, 2006). These large changes in livestock numbers are likely to have caused substantial impacts (O'connell et al., 2007). Stock grazing changes vegetation structure and composition (Milligan et al., 2016; Orr & Carling, 2006) and can lead to soil compaction, a reduction in soil permeability (Alaoui et al., 2018) and soil water storage (Meyles et al., 2006). Loss of vegetation and soil compaction can increase flood risk, with simulated flood peaks in a UK upland catchment increased by 33% under light grazing and 82% under heavy grazing (Gao et al., 2017). The lower grazing levels found in our LG sites would be anticipated to lead to higher soil permeability and lower peak flow compared with CG sites. In contrast, we found lower rates of permeability and higher SPD and runoff coefficients at the LG compared with CG sites. Overall grazing pressures across both the CG and LG pasture sites in our study were relatively similar at around 0.1 livestock unit per hectare (Table 1), with the main difference being less wintertime grazing in the LG sites. Our study does not provide any information on the impacts of higher grazing pressure that is found across much of the UK uplands, exceeding four sheep per hectare in some locations (Orr & Carling, 2006). Variability in grazing pressure within a site can result in areas favoured for grazing experiencing more compaction (Orr & Carling, 2006)

reducing the downward mixing of organic material, decreasing permeability. The recovery of vegetation after a reduction in grazing should reduce rates of overland flow (Bond et al., 2020), with impacts on downstream flooding. In our study reduced grazing was introduced fairly recently (∼ 7 years ago) and whilst relatively little is known about the effects of reducing stock grazing pressures, it may take 48–62 years to see the benefits of reduced grazing due to the long-term soil degradation caused by intensive sheep-grazing and slow rates of recovery (Marrs et al., 2018; Marrs et al., 2020).

4.5 | Implications for policy

Our analysis demonstrates the importance of semi-natural broadleaf woodlands in modifying soil properties and reducing flood peaks in small (<0.2 km^2) catchments, even for larger storm events. A key challenge remains to assess the impacts of woodland at larger scales (Dadson et al., 2017). Data collected here can be used to inform parameter choice in flood prediction models, which can then be used to upscale results to understand the impacts of semi-natural woodlands on downstream flooding in larger catchments (Gao et al., 2017; Jackson et al., 2008; McIntyre et al., 2013). Our analysis includes a number of large storms, including two storms that met the UK Met Office criteria for a named storm (Storm Dennis and Storm Ciara). Storm Ciara resulted in widespread disruption and flooding within Northern England, so our results are relevant for flood risk management. However, the smaller number of recorded peak flows with increasing peak size makes it difficult to demonstrate a statistically significant change in flow response for the largest events (Burgess-Gamble et al., 2017).

We show that semi-natural broadleaf woodland has more permeable soils resulting in lower peak flood discharge compared with pasture grazed by sheep, the dominant land use in much of the UK uplands. All the pasture sites in our study had relatively low grazing intensity (∼0.1 sheep/hectare)—the difference in soil permeability and streamflow between woodland and pasture may be even greater for pasture with the higher grazing intensity more typical of the UK uplands (DEFRA, 2020). Our study suggests that restoring or converting upland pasture to semi-natural woodland would help reduce downstream flood risk. Previous studies have found that soil permeability can increase rapidly after tree planting (Mawdsley et al., 2017) so the benefits to reduced flooding could be realized quickly. In contrast, reductions in grazing without tree planting may result in relatively slow changes in soil properties suggesting tree planting may be necessary in many locations if rapid changes are needed.

In the UK, agricultural subsidies have supported upland sheep farming in recent decades (Hardaker, 2018). Planned changes in agricultural subsidy and the need to mitigate climate change and reach net-zero carbon emissions (Paris Agreement, 2015) may increase future interest in woodland creation in the UK uplands. The UK government has committed to creating 30 000 hectares of new woodland per year (DEFRA, 2018; Jordan & Wentworth, 2021), which would increase UK woodland cover to about 18% in 2050. A large proportion of these new woodlands will likely be established in the uplands (Murphy et al., 2020). Broadleaf woodland accounted for 43% of the new woodland created in the UK in 2019–2020 (Forestry Commission, 2020) and is likely to make up a substantial component of future woodland creation under the UK's 25 Year Environment Plan (DEFRA, 2018). Our work suggests creation of new broadleaf woodlands will help to reduce flood risk. As changes to upland land-use and management occur, it is essential that the influence of those changes to flood risk is monitored and understood (Pender, 2006). An integrated policy perspective combining climate and flood mitigation alongside the additional benefits of woodlands is required to maximize the societal benefits of new woodlands. Future work is needed to identify the most beneficial locations for woodland creation in terms of flood mitigation and to understand how climate and flood mitigation vary for different woodland types.

5 | CONCLUSION

Most previous work on the hydrological impacts of forests, especially the impacts on flooding, has been based on conifer forests, typically plantations. The aim of this study was to explore the potential flood mitigation impacts of semi-natural broadleaf woodlands. We established an experimental correlation catchment study in northwest England, to identify differences in streamflow and soil properties between semi-natural broadleaf woodland and permanent pasture. Catchments were selected with similar size, elevation, soil type and geology but different land use.

We found that semi-natural broadleaf woodlands can reduce specific peak discharge by 23%–60%, peak runoff coefficients by 30%–60% and volume runoff coefficient by 21%–35%, compared with pasture. Woodland sites take 14%–50% longer to respond to storm events than pasture sites. Crucially, we found woodlands reduced runoff for both small and large storms. For storms with a return period of more than 1.5 years, woodlands reduced peak runoff coefficient by 48%–58% and volume runoff coefficient by 26%–41%. Differences in flood response can be explained by the more permeable woodland soils, 11–20 times greater than pasture soil irrespective of the higher bulk density measured.

Our study demonstrates that semi-natural broadleaf woodlands in the uplands can reduce rainfall-generated flooding, strengthening the case for broadleaf woodland creation as a land use management method of NFM. Our study is based on small catchments (<0.2 km^2) and relatively short (≤10 year) storm return periods. Data from our study needs to be used within models to predict the impacts of broadleaf woodlands on downstream flooding in larger catchments and for bigger storm events. Empirical studies are now needed to monitor the long-term impact of reduced grazing levels, tree planting and woodland creation on streamflow and soil properties.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the University of Leeds repository at https://doi.org/10.5518/950.

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