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ORIGINAL ARTICLE

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Investigating the impact of woodland placement and percentage cover on flood peaks in an upland catchment using spatially distributed TOPMODEL

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Abstract

Woodlands can reduce downstream flooding, but it is not well known how the extent and distribution of woodland affects reductions in peak flow. We used the spatially distributed TOPMODEL to simulate peak flow during a 1 in 50 year storm event for a range of broadleaf woodland scenarios across a 2.6 km^2 catchment in Northern England. Woodland reduced peak flow by 2.6%–15.3% depending on the extent and spatial distribution of woodland cover. Cross slope and riparian woodland resulted in larger reductions in peak flow, 4.9% and 3.3% for a 10-percentage point increase in woodland cover respectively, compared to a 2.7% reduction for woodland randomly located across the catchment. Our results demonstrate that increased woodland cover can reduce peak flows during a large storm event and suggest that targeted placement of woodland can maximise the effectiveness of natural flood management interventions.

KEYWORDS

flood mitigation, modelling, natural flood management, rainfall-runoff

1 | INTRODUCTION

Flooding is one of the most costly and widespread climate-related natural hazards (Jonkman, 2005), accounting for 44% of all disaster events from 2000 to 2019 and affecting 1.6 billion people worldwide (UNDRR, 2020). Anthropogenic climate change is predicted to increase the frequency of extreme precipitation events, subsequently increasing the risk of flooding (Tabari, 2020). This has increased interest in natural flood management (NFM) as a means to mitigate flood risk. NFM approaches aim to mitigate against flood risk using natural processes (Cooper et al., 2021) and can complement other flood management methods.

Woodland creation, is increasingly seen as an important way to deliver flood mitigation (Murphy et al., 2020). Forested catchments have a different hydrological response compared to un-forested catchments due to greater interception, evaporation, soil infiltration, surface roughness and available storage (McCulloch & Robinson, 1993; Monger et al., 2022; Nisbet, 2005; Page et al., 2020; Stratford et al., 2017). For the purposes of NFM, woodland can be divided into four types (Cooper et al., 2021):

- *Catchment woodland*—defined as the total area of all woodland within a catchment, comprising woodland cover of all types.

- *Cross-slope woodland*—the placement of smaller areas of woodland across hill slopes, broadly following the contours.
- *Floodplain woodland*—comprised of all woodland lying within the fluvial floodplain that is subject to a regular or natural flooding regime.
- *Riparian woodland*—woodland located within the riparian zone, defined as the land immediately adjoining a river channel and influenced by it (Burgess-Gamble et al., 2017; Cooper et al., 2021).

The impacts of catchment woodland on the hydrological cycle have long been studied (Best et al., 2003; Bosch & Hewlett, 1982; Law, 1956). Catchment woodland 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 et al., 1998) and Balquhidder (Johnson, 1995). Peak flows are also found to be reduced in catchment woodlands (Monger et al., 2021); however, this can be dependent on the size of the storms (Archer, 2007; Dadson et al., 2017; Fahey & Payne, 2017; Soulsby et al., 2008; Xiao et al., 2022). The potential for afforestation to reduce runoff peak flows during large storm events is still not clear (Burgess-Gamble et al., 2017; Peskett et al., 2021; Stratford et al., 2017) particularly for larger catchments (Rogger et al., 2017). Cross-slope woodland has been investigated at the Pontbren experiment with the construction of shelter-belts, resulting in increased soil infiltration rates (up to 60 times greater under wooded areas than open grazed pasture) within 2–6 years (Carroll et al., 2004). Modelling studies of floodplain woodland regeneration (Connell, 2008; Thomas & Nisbet, 2007) report reductions in flow velocity and increases in water levels. Floodplain woodland restoration could also lead to delays in peak flow as well as desynchronizing the flood peaks from adjacent tributaries (Cooper et al., 2021). Modelling studies of riparian woodland often focused on the impacts of in-channel wood and installation of 'Large Woody Dams' within watercourses (Burgess-Gamble et al., 2017; Thomas & Nisbet, 2012). However, there is a dearth of numerical models of riparian forest growth, with none applicable to the UK environment (Cooper et al., 2021; Dixon et al., 2019). More work is needed to understand how these different woodland management strategies may impact downstream flood peaks.

Hydrological modelling tools can be used to simulate the impacts of different land covers on peak flow (IHACRES [Jakeman et al., 1990]; TOPMODEL [Beven & Kirkby, 1979]; ReFH [Kjeldsen, 2009]). More recently, models have been developed that allow investigation of different spatial land cover patterns (HBV [Bergström, 1976]; SD-TOPMODEL [Gao et al., 2015]; SWAT [Arnold et al., 1998]). These models allow the potential outcomes of NFM interventions to be simulated before they are implemented offering insight to practitioners and policy makers (Gao et al., 2017). A modelling study by Gao et al. (2017) found that revegetating areas of bare peat with *Sphagnum* in riparian zones altered flow peaks up to three times as much as those same changes in headwater areas. This suggests that the location of land cover interventions is an important consideration when developing strategies to reduce flood risk (Murphy et al., 2020), as the effect of land cover change is influenced by a catchment's soils, topography, slope (Suecker et al., 2000), as well as the geology (Peskett et al., 2021). However, little is known about how the spatial distribution of woodland impacts flood risk.

In recent years, the UK has also experienced notable flood events (Chatterton et al., 2016; Marsh et al., 2016; Schaller et al., 2016) causing significant economic and environmental damage (Murphy et al., 2020; Priestley, 2017) and increasing interest in woodland creation as NFM. The UK is one of the least densely wooded countries in Europe (Forestry Commission, 2021b). At present woodland covers 13.2% (3.2 million ha) of the UK's land surface, up from 12% cover in 1998 (Reid et al., 2021). In England, woodland covers 10%, compared with 15% in Wales, 19% in Scotland and 9% in Northern Ireland (Forestry Commission, 2021a). The interest in woodland creation is growing, as woodlands are being increasingly viewed as key to simultaneously mitigating both the climate and nature crises (Reid et al., 2021). The UK Government pledged to increase tree planting rates across the UK to 30,000 ha per year by May 2024 (UK Government, 2021). In addition, DEFRA published the England Trees Action Plan 2021–2024 in May 2021 (UK Government, 2021), the Welsh government published 'Woodlands for Wales' (Welsh Government, 2021) and Scotland published a 'Forestry Strategy 2019–2029' (Reid, 2018). With plans for woodland cover to increase throughout the UK, it is important we understand what impact this could have on catchment hydrology and where to focus new plantings to provide the maximum benefits.

In this study, we used the spatially distributed TOPMODEL (SD-TOPMODEL) (Gao et al., 2015; Gao et al., 2016) to investigate how changes in woodland cover alter flood peak within an upland catchment in northern England. Spatially distributed TOPMODEL simulates the 2D heterogeneity of the catchment in terms of topography and land cover allowing us to explore how different spatial configurations of woodland cover impact flood peaks. We use this model framework to provide the first consistent comparison of the impacts of catchment, riparian and cross-slope woodland on peak flow.

2 | STUDY SITE

We selected the upland catchment, Naddle, in Cumbria, UK (54°31′50.9″ N, 2°45′37.3″ W) as the study site for this investigation (Figure 1a). The catchment area covers 2.62 km^2 with elevations ranging from 268 to 502 m (Figure 1b). The land is managed by the RSPB (The Royal Society for the Protection of Birds) on behalf of the landowners, United Utilities.

The catchment experiences mild winters and cool summers (Kenworthy, 2014), with mean monthly temperatures ranging from −0.3 to 18.3°C and mean annual precipitation of 1779 mm, with monthly rainfall ranging from 88 to 231 mm (1981–2010 mean, Shap weather station at 255 m AoD) (Met Office, 2020).

The catchment consists of unimproved permanent pasture, grazed at a variety of densities, and woodland (RSPB, 2015) (Figure 1c). The woodland is predominantly semi-natural ancient woodland designated as a site of special scientific interest (SSSI) that is fenced to exclude livestock and a small conifer plantation which has been recently felled to allow for natural regeneration. Soils in the study area are upland organo-mineral soils, predominately Malvern 611a (Chromic Endoleptic Umbrisol), a free draining acid loamy soil (Cranfield University, 2019).

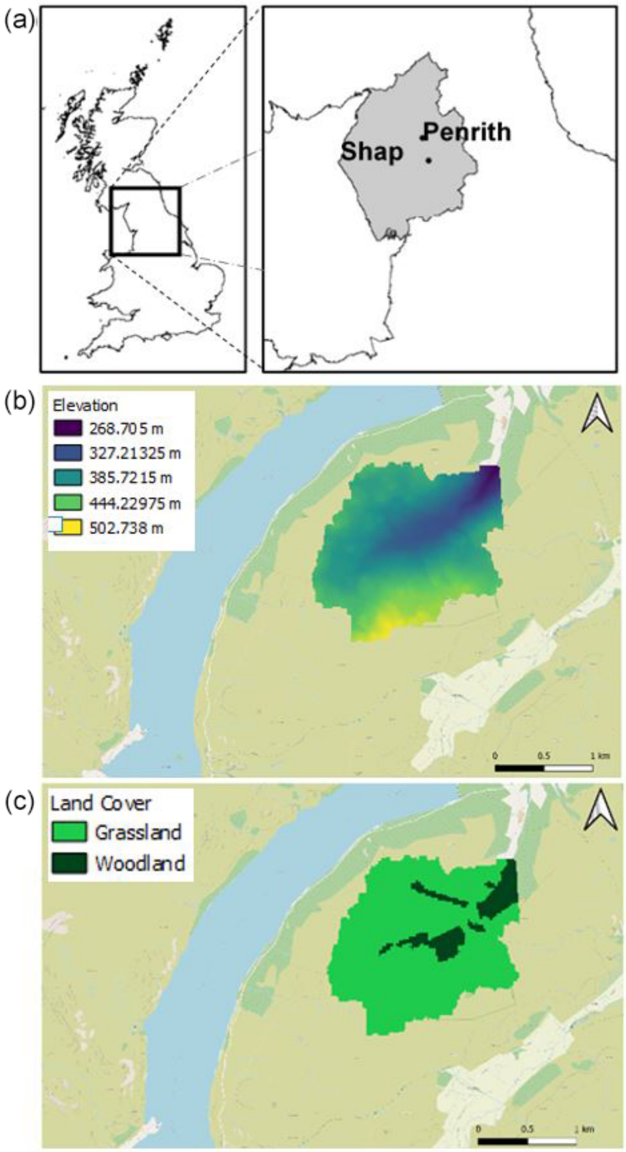

FIGURE 1 (a) Map of the Naddle catchment location within the UK, (b) Elevation (m) across the Naddle catchment and (c) Current land cover in Naddle simplified into two classifications, 12.9% woodland and 87.1% grassland.

3 | METHODOLOGY

3.1 | SD-TOPMODEL

TOPMODEL is a rainfall-runoff model originally developed by Beven and Kirkby (1979) as the lumped or semi distributed TOPMODEL. We use a spatially distributed version of TOPMODEL (SD-TOPMODEL) (Gao et al., 2015). In this version, the TOPMODEL equations are applied in a typical 2D model setup, using Digital Elevation Model (DEM) cells to define the calculation elements in the numeric model. In this approach, the hydrological behaviour of each cell in the DEM data is calculated individually, solving subsurface and overland flow volumes and rates, which are treated separately, for each cell and at each time step. The spatially distributed approach removes the requirements to define Hydrological Response Units within the catchment, at which the TOPMODEL equations are applied in a semi-distributed setup and are typically defined using measures such as the Topographic Wetness Index. This allows a model setup that explores more of the catchment heterogeneity than is possible with a lumped or semi-distributed model setup, making it a useful tool to examine the impact of land cover on flow (Gao et al., 2015). SD-TOPMODEL has been used to simulate the impact of land-cover change in peatlands (Gao et al., 2016), agricultural practices (Bond et al., 2022; Gao et al., 2017) and landscape features, such as stone walls and hedges (Willis & Klaar, 2021) on flood peaks in upland catchments.

A 25 m × 25 m DEM, derived from photogrammetry and LiDAR data sources (Ordnance Survey, 2020) and delineated in QGIS is used to represent the catchment boundaries and provide elevation data to the model (Figure 1b). Land cover data at the same resolution was from the UK Centre for Ecology and Hydrology Land Cover Map for 2017 (Morton et al., 2020) (Figure 1c).

Land cover in SD-TOPMODEL is represented using four key parameters; hydraulic conductivity of the soil (K), interception (i), a scaling parameter representing the active water storage in soil (m) and an overland flow velocity parameter related to surface roughness, and equal to $1/n$ where n is Manning's roughness (K_v). Model parameters, excluding m, can vary spatially based on the land cover in the simulations, and the map of each parameter can be used to describe the heterogeneous properties of the catchment (Gao et al., 2017). m is calculated for each catchment and therefore used as a lumped parameter and unsuitable for spatial distribution.

3.2 | Representing land cover in SD-TOPMODEL

Representation of different land covers in SD-TOPMODEL is based on empirical data collected from the Naddle catchment (Monger et al., 2021, 2022), see Table 1. For grassland, the median Ksat from low-density grazing (pasture) (Monger et al., 2021) and median overland flow velocity for wood pasture dominated by grassland (Monger et al., 2022) were used. For woodland, the median overland flow velocity from established semi-natural woodland (Monger et al., 2021) and median Ksat (Monger et al., 2022) values were used. The most conservative estimate for an Oak woodland in winter was used to represent interception (Dolman, 1987).

SD-TOPMODEL parameters K and Kv are based on Ksat and overland flow, respectively. Values for parameters K, Kv and I are spatially variable in the model based on land cover. Woodland values are relative to grassland values as shown in Table 2, with the scalings based on the empirical data in Table 1. For example, woodland has a K value 20 times that of grassland. Sensitivity analysis of spatial distribution of parameters shown in Supplementary Material 1.

3.3 | Model calibration

Due to limited (less than 18 months) runoff and rainfall data available for the Naddle catchment, the Revitalised Flood Hydrograph (ReFH) rainfall-runoff model (Kjeldsen et al., 2005) was used to create synthetic storms with specific return periods. This method is used widely in the UK to estimate discharge values for return periods in ungauged catchments using catchment characteristics derived from the Flood Estimation Handbook (FEH). In this approach, rainfall in a catchment is taken from the FEH2013 dataset, that combines multiple gauge records from across the UK to determine rainfall depth duration frequency curves. A flood frequency curve is determined based on broad, catchment characteristics. This approach is used to provide an indication of the expected discharge values for the study site, rather than a definitive value associated with a storm. A 1 in 50 year event for a 6 h time frame, over a 24 h period, was produced and used for model calibration.

As in previous work (Bond et al., 2022; Gao et al., 2017) the Nash–Sutcliffe efficiency coefficient (NSE) was used to evaluate SD-TOPMODEL and to select the best performing model. The NSE is a widely used indicator of model performance (Ritter & Munoz-Carpena, 2013) and was chosen as it assesses the shape of the hydrograph and to be consistent with previous work. We used 48 simulations of SD-TOPMODEL to identify the best performing set of parameters ($m = 6$ mm, $K = 6.9$ m·h^{-1}, $k_v = 40$, see Supplementary Material 2). There was good correspondence between this best fit model and observed flow in the calibration period (NSE was 0.85) (Figure 2) with similar NSE to previous work (Bond et al., 2022; Gao et al., 2017).

3.4 | Model validation

A 1 in 10 year event for a 6 h time frame, over a 24 h period, was produced using ReFH in order to validate the model (Figure 3), in the absence of gauged data. A lower return period is selected to validate the model compared to the calibration event, to ensure that the model performance is retained over different rainfall rates and volumes for the same length of event. This provides an independent test of the model parameters in comparison

TABLE 2 Relative land cover values used in SD-TOPMODEL.

	K	Kv	i
Grassland	1	1	1
Woodland	20	0.9	0.87

TABLE 1 Empirical values used to represent different land covers.

	Saturated hydraulic conductivity, Ksat (m h^{-1})	Overland flow velocity (m s^{-1})	Interception, i (%)
Grassland	1.47×10^{-4} (Monger et al., 2021)	0.031 (Monger et al., 2022)	0
Woodland	2.94×10^{-3} (Monger et al., 2021)	0.028 (Monger et al., 2022)	13 (Dolman, 1987)

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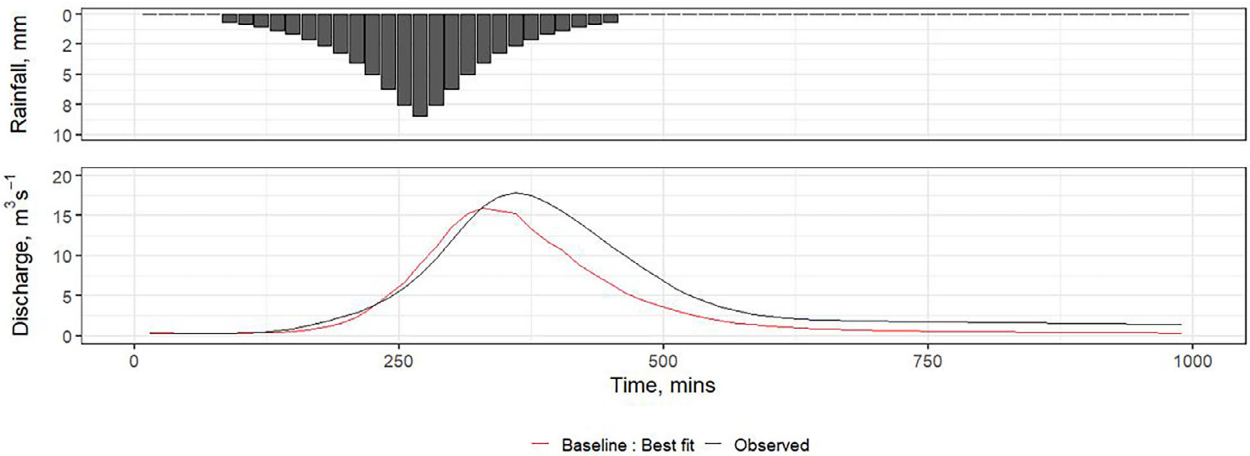

FIGURE 2 Hydrograph response to the 1 in 50-year ReFH storm, observed discharge and SD-TOPMODEL modelled discharge. A Nash–Sutcliffe efficiency (NSE) of 0.85, the best fit model.

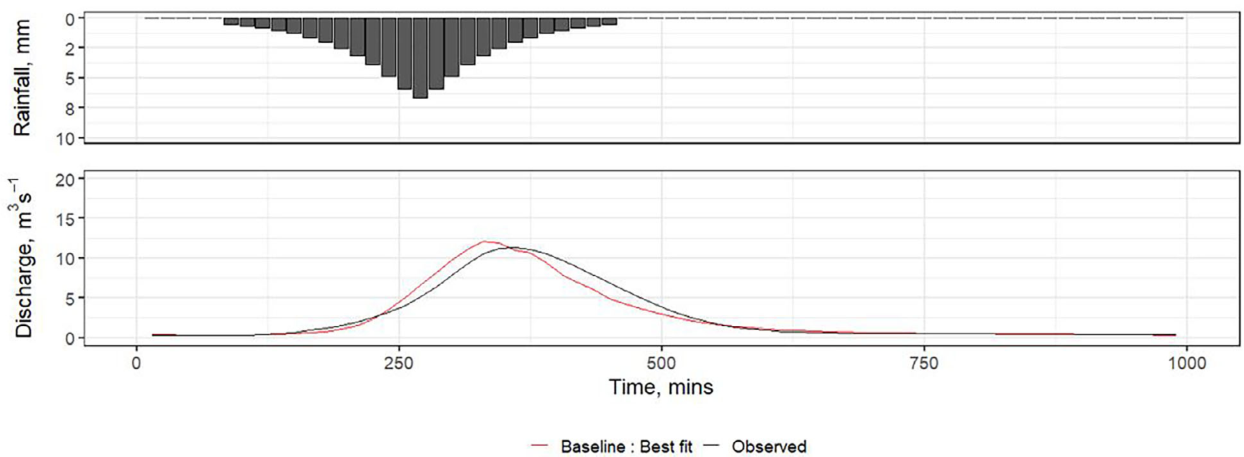

FIGURE 3 Hydrograph response to the 1 in 10-year ReFH storm, observed discharge and SD-TOPMODEL modelled discharge. A Nash–Sutcliffe efficiency (NSE) of 0.95, the best fit model.

to the calibration phase. A NSE of 0.95 was achieved by the best fit model for this storm. This best fit version of SD-TOPMODEL is then used for the rest of the analysis.

3.5 | Modelled woodland scenarios

We used the best fit version of SD-TOPMODEL to investigate 28 land cover scenarios with different woodland cover as described in Table 3 (scenario land cover maps included in Supplementary Material 3). Land cover was varied at the same resolution as SD-TOPMODEL (25 × 25 m). Our woodland scenarios were intended to assess the impact of different woodland covers as well as the potential of the different classes of woodland creation options in NFM interventions, including catchment, riparian and cross slope woodland.

We simulated the current land use in the catchment based on CEH land cover data for 2017 (Morton et al., 2020), which was 12.9% woodland and 87.1% grassland (Scenario name: Naddle; Figure 1c). Whilst we calibrated the model to fit the current Naddle land use, we compared the scenarios against a *no woodland* scenario (0% woodland cover), where current woodland in the Naddle catchment was replaced with grassland. This allowed us to calculate the impacts of a 10-percentage point increase in woodland cover for each NFM woodland type.

We explored three different sets of catchment woodland scenarios. In each set of catchment scenarios, areas of woodland cover were added randomly as 25 m × 25 m squares across the catchment, to replicate natural regeneration or random planting. For each catchment woodland cover scenario, we repeated five replicates with

TABLE 3 Simulated peak discharge ($m^3 \cdot s^{-1}$) for woodland scenarios.

Scenario	Description	Woodland cover (%)	Peak discharge ($m^3\ s^{-1}$)			Change in peak discharge compared to no woodland (*reference*) scenario (%)			Time to peak (mins)	Change in time to peak (%)
			μ	σ	SEM	μ	σ	SEM		
No woodland (*reference scenario*)	Naddle catchment if completely grassland (*All other scenarios compared to the reference scenario*)	0	17.17			0			330	
Catchment woodland	Randomised increased catchment-wide woodland cover	10	16.50	0.214	0.107	−3.88	1.248	0.624	330	0
		20	15.98	0.084	0.042	−6.95	0.488	0.244	330	0
		30	15.70	0.156	0.078	−8.55	0.909	0.455	315	−4.55
		40	15.16	0.071	0.036	−11.71	0.415	0.208	315	−4.55
		50	14.98	0.079	0.039	−12.75	0.459	0.229	315	−4.55
		60	14.71	0.050	0.025	−14.30	0.291	0.146	315	−4.55
		70	14.76	0.043	0.022	−14.05	0.251	0.125	285	−13.64
		80	15.23	0.030	0.015	−11.28	0.175	0.088	285	−13.64
Riparian	Increased woodland cover along the watercourse	10	16.73			−2.56			330	0
		20	15.76			−8.21			330	0
		30	15.49			−9.78			330	0
Cross-slope	Cross slope plots of woodland cover	10	15.98			−6.92			330	0
		20	15.68			−8.68			330	0
		30	15.41			−10.24			330	0
Naddle	Current woodland cover in Naddle	12.9	15.93			−7.22			330	0
Naddle + catchment woodland	Current woodland cover in Naddle plus randomised increased catchment-wide woodland cover	20	15.97	0.207	0.104	−7.01	1.207	0.603	330	0
		25	15.77	0.180	0.090	−8.17	1.049	0.524	330	0
		35	15.46	0.236	0.118	−9.96	1.375	0.688	330	0
		45	15.00	0.086	0.042	−12.64	0.500	0.250	315	−4.55
		55	14.64	0.083	0.041	−14.74	0.483	0.242	315	−4.55
		65	14.55	0.059	0.030	−15.27	0.346	0.173	300	−9.09
		75	14.89	0.035	0.018	−13.27	0.206	0.103	285	−13.64
		85	15.45	0.045	0.022	−10.04	0.262	0.131	285	−13.64
Naddle + upland catchment	Current woodland cover in Naddle plus randomised increased woodland above 400 m	25	15.97	0.228	0.114	−6.98	1.326	0.663	330	0
		35	15.66	0.186	0.093	−8.82	1.083	0.542	330	0
		45	15.26	0.115	0.058	−11.11	0.672	0.336	315	−4.55
Naddle + RSPB	Current woodland cover in Naddle plus randomised planting based on soil properties	23	15.53			−9.55			330	0

Note: All catchment woodland scenarios are repeated five times and mean (μ), standard deviation (σ) and standard error (SEM) are reported. Change in peak discharge (%) and change in time to peak (%) are percentage change for each scenario compared to no woodland (reference) scenario. Results for all model runs including repeats can be found in Supplementary Material 4.

different random allocations of woodland cover and we report the mean and standard error across the replicates. In the first set of catchment woodland scenarios, we increased woodland cover across the catchment from 0% to 80% at 10% intervals (Table 3, *Catchment*).

In the second set of catchment woodland scenarios, we increased woodland cover from the current Naddle woodland (Table 3, *Naddle* + *Catchment*). Woodland cover in the *Naddle* + *Catchment* scenarios increased from 25% to 85% at 10% intervals. In the third set of scenarios, we increased woodland cover above 400 m from 25% to 45% at 10% intervals, including the current Naddle woodland (Table 3, *Naddle* + *Upland Catchment*).

To simulate riparian woodland, we created a set of scenarios where woodland planting was expanded out from the riparian zone along the watercourse (Naddle beck), increasing woodland cover from 10% to 30% at 10% intervals (Table 3, *Riparian*).

To represent cross-slope woodland, we created scenarios where woodland was established across the slope from 10% to 30% at 10% intervals (Table 3, *Cross-slope*). Finally, we created a scenario based on the current plans for tree planting and expected natural regeneration in the Naddle catchment by the RSPB, increasing woodland from the current Naddle woodland to 23% (Table 3, *RSPB*).

3.6 | Modelled scenario analysis

For each scenario the peak total discharge ($m^3 \cdot s^{-1}$) recorded during the storm was calculated and the relative change in peak total discharge (%) compared to no woodland scenario is reported. The timing of the peak, as 15-min intervals, was also recorded.

For each type of NFM woodland, we calculate the reduction in peak flow for a 10-percentage point increase in woodland cover as the average reduction in peak flow compared to the baseline (no woodland scenario) divided by percentage woodland cover then multiplied by 10. We report values as the mean ± the standard deviation.

The peak subsurface flow ($m^3 \cdot s^{-1}$) and peak overland flow ($m^3 \cdot s^{-1}$) for each scenario are also simulated.

4 | RESULTS

4.1 | Changes to peak total discharge

We found that the peak discharge during the modelled 1 in 50 year storm event was greatest for the un-forested catchment (Table 3; Figure 4). Woodlands reduced peak discharge by 2.6%–15.3% depending on the extent and spatial placement of woodland cover.

For all NFM interventions, increased woodland cover typically led to larger reductions in peak discharge. For catchment woodland scenarios, larger reductions in peak discharge occurred until woodland cover reached 60%. When woodland cover increased beyond 60% peak discharge started to increase (Figure 4) due to simulated increases in subsurface flow (see Section 4.3). For woodland cover up to 60%, peak discharge was reduced by 2.7% for each 10-percentage point increase in catchment woodland.

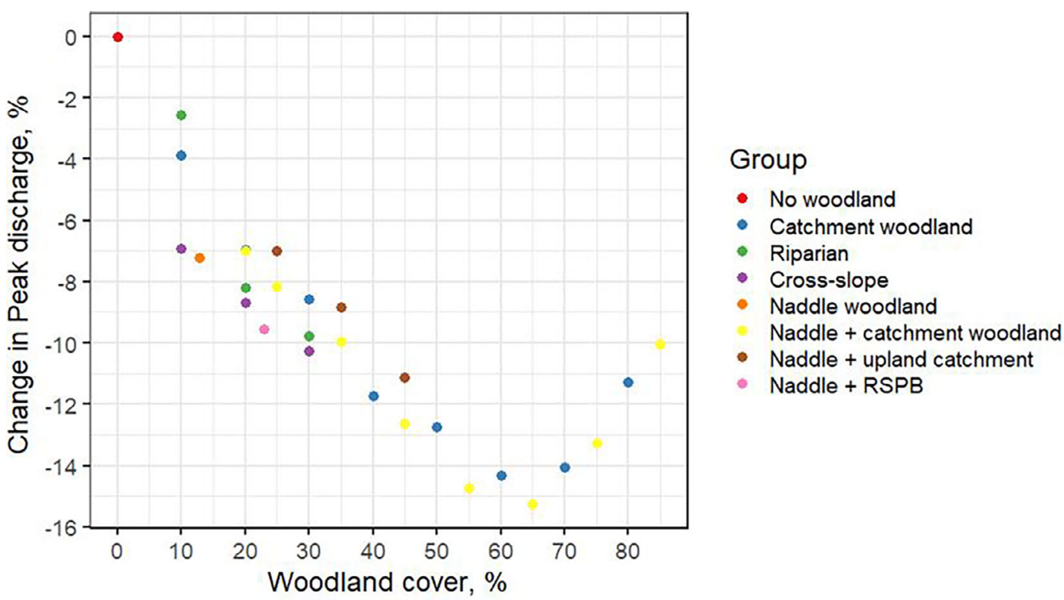

FIGURE 4 Simulated change in peak discharge (%) as a function of woodland cover for modelled land cover scenarios.

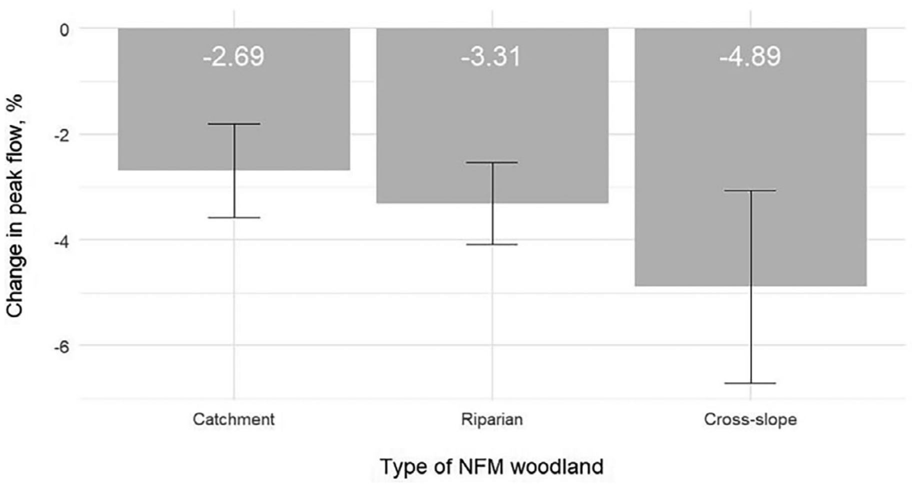

FIGURE 5 Simulated change in peak flow for a 10-percentage point increase in woodland cover, grouped by type of natural flood management (NFM) woodland.

The riparian and cross-slope woodland scenarios resulted in larger decreases in peak discharge compared with catchment scenarios of the same woodland cover, for example, riparian scenario with 30% woodland resulted in reduction in peak flow of 9.78%, whilst the catchment scenario with the same woodland cover reduced peak flow by 8.55%. For woodland cover up to 30%, peak discharge is reduced by 3.3% for each 10-percentage point increase in riparian woodland and by 4.9% for each 10-percentage point increase in cross-slope woodland (Figure 5).

The current woodland in the Naddle catchment (12.9% woodland cover) results in a reduction of peak flow of 7.2% compared to the scenario without woodlands. The potential RSPB management strategy scenario, increasing woodland cover to 23%, reduced peak discharge by 9.55%.

4.2 | Peak timing

A number of catchment woodland scenarios peaked by between 15 and 45 min (1–3 model timesteps) earlier than the 'no woodland' scenario. As catchment woodland scenarios increased in woodland cover, from 30% upwards, the peak occurred earlier. There was no change in peak timing for 'riparian' and 'cross-slope' scenarios. An earlier simulated peak was due to increased soil permeability (see Section 5.2).

4.3 | Subsurface flow and overland flow

As woodland cover increased, peak overland flow decreased whilst peak subsurface flow increased (Figure 6). Overland flow is the primary runoff method for scenarios with woodland cover up to approximately 35%, after which subsurface flow becomes dominant.

Figure 7 demonstrates peak overland flow is higher for a scenario with 25% woodland cover (Naddle + catchment) compared to 75% woodland cover. Peak subsurface flow is higher in the 75% woodland scenario.

5 | DISCUSSION

This study used SD-TOPMODEL to investigate the impact of a range of land cover scenarios on peak discharge for a 1 in 50 year storm event. The modelled scenarios showed that increased woodland cover decreased peak total discharge when compared to a no woodland scenario. Increases in woodland were represented by increasing the soil permeability, interception and surface roughness (decreasing overland flow velocity) in the model.

5.1 | Impact of woodland type on peak total discharge

We found that catchment woodland reduced peak flow by 4%–15% depending on the extent of woodland cover. These findings are consistent with our understanding of woodlands reducing flood peaks (Dadson et al., 2017; Kirby et al., 1991; Stratford et al., 2017) due to the increased interception, permeability and water storage of woodland soils compared to other land covers (Archer et al., 2013; Calder et al., 2008; Carroll et al., 2004; McCulloch & Robinson, 1993; Murphy et al., 2020). For catchment scale afforestation (80% woodland cover), simulated peak discharge was reduced by 11.3%, broadly in agreement with previous studies. Wheater et al. (2008) modelled catchment wide afforestation in the Pontbren catchment (5.77 km^2) in Wales and found a reduction in peak flow during an extreme event of 10% to 54% (mean 36%). Fraser et al. (2013) simulated conifer afforestation

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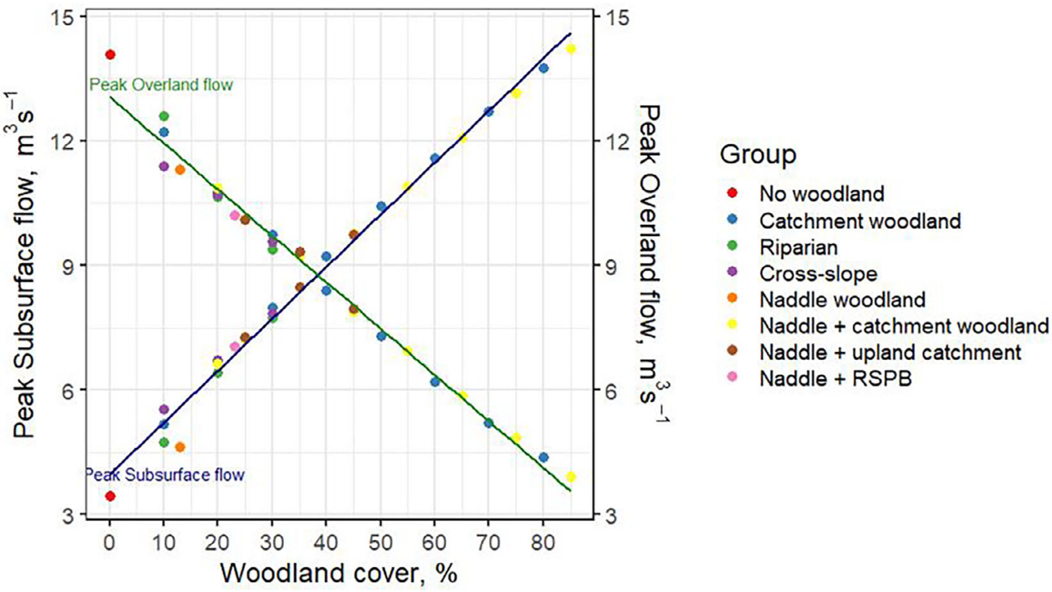

FIGURE 6 Comparison of peak subsurface flow ($m^3\ s^{-1}$) and peak overland flow ($m^3\ s^{-1}$) as a function of woodland cover for modelled land cover scenarios.

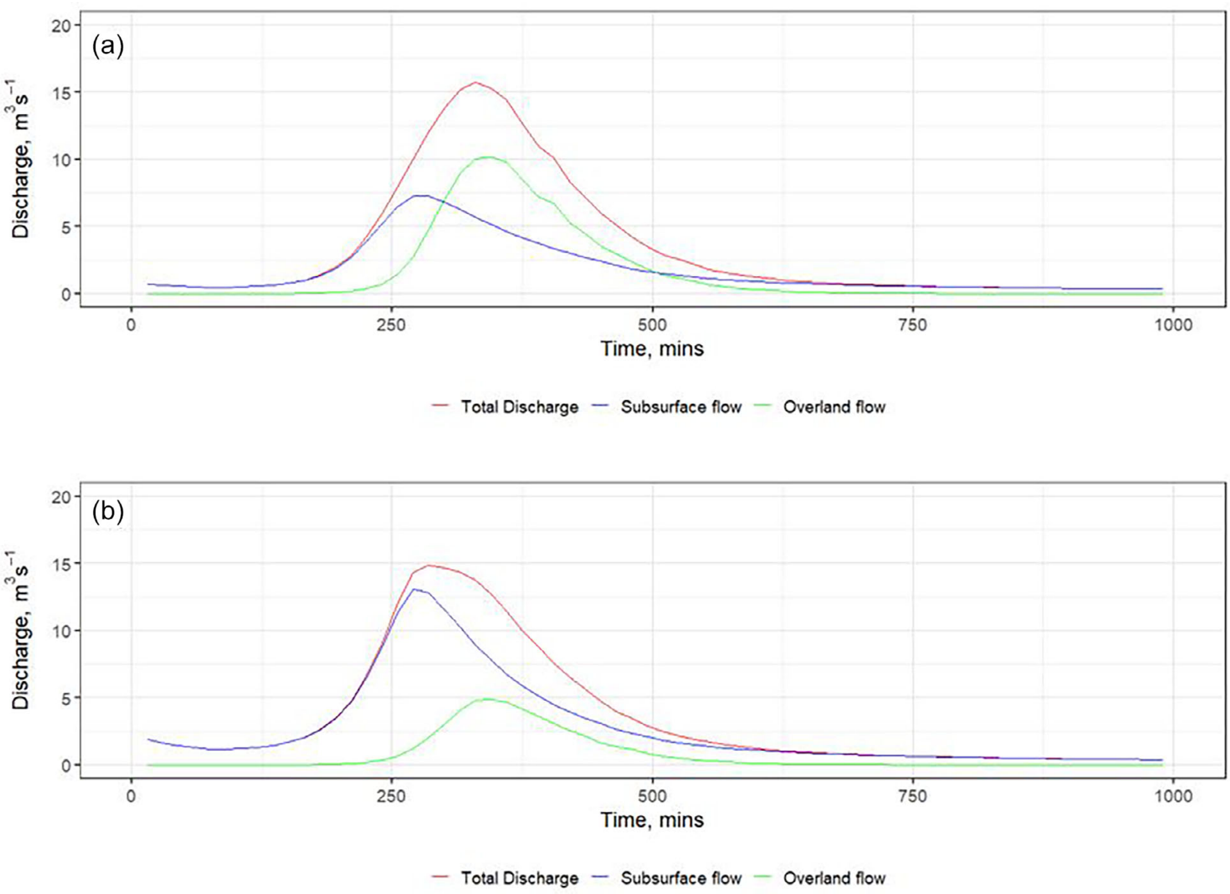

FIGURE 7 Total flow, subsurface flow and overland flow ($m^3\ s^{-1}$) for scenarios (a) Naddle + catchment, 25% woodland and (b) Naddle + catchment, 75% woodland.

of mineral soils in the Hodder catchment (25.3 km^2) and simulated a 5% to 7% reduction in mean catchment peak flow.

Our simulations of catchment-wide afforestation reduced peak flow by an average of 2.7% for each 10-percentage point increase in woodland cover (Figure 5). For larger UK catchments (500–10,000 km^2), Buechel et al. (2022) used the JULES model at 1 km^2 resolution to show that afforestation reduced the top 1% of flows by 1.4% ± 0.6 for each 10-percentage point increase in woodland.

We find that not only the amount of woodland is important in reducing peak total discharge, but that location within the catchment can play a vital role (Figure 5). In comparison to our catchment-wide afforestation scenarios, a 10-percentage point increase in cross-slope woodlands reduced peak flow by 4.9% (Figure 5). This supports previous findings by Wheater et al. (2008), who found that cross slope woodland in the Pontbren catchment could reduce peak flow during an extreme event by 5% (range 2%–11%). We found riparian woodland scenarios reduced peak total discharge by 3.3% for a 10-percentage point increase in woodland cover. However, the simulated response of peak discharge to riparian woodland cover was relatively non-linear. The 10% riparian woodland cover scenario resulted in the smallest reduction in peak discharge, whilst the 20% and 30% riparian scenarios exceeded catchment woodland reductions in peak flow. This suggests that there may be an optimum distance from the river channel at which increased permeability and roughness is most influential. Further work is needed to explore this in more detail. Our simulations are likely to underestimate the NFM benefits of riparian woodland as we do not simulate the impacts of in-channel woody debris, runoff attenuation features or the greater roughness of riparian woodland (Cole et al., 2020; Cooper et al., 2021; Thomas & Nisbet, 2012). It is important to note, that catchment characteristics, such as slope, also have a role to play in determining the hydrological response to land use change. For example, land cover change on steeper slopes may not 'slow the flow' of overland flow to the same extent as shallower slopes (Bond et al., 2022; Maske & Jain, 2014).

5.2 | Impact of woodland on peak timing

We found that increases in catchment woodland cover above 30% resulted in simulated flood peak occurring earlier. Woodland soils are represented in the model as 20 times more permeable than grassland, based on empirical data from the studied catchment (Monger et al., 2021, 2022). Therefore, as woodland cover increased within Naddle so did the percentage of the catchment with more permeable soil and consequently, the portion of total flow moving as subsurface flow rather than overland flow increased.

The potential for changing the timing of peak flow during storms needs to be considered when planning woodland creation for NFM. Changing the land cover in one part of catchment may alter the hydrograph in such a way to create synchronicity with another part of the wider catchment, potentially increasing the potential flood risk (Guse et al., 2020; Pattison et al., 2014). Our woodland soil permeability is based on established (mature) broadleaf woodlands (Monger et al., 2021, 2022), whereas newly planted woodlands may have soil permeability that is only 5–10 times larger than grassland (Archer et al., 2013) which may in turn lead to different impacts on peak timing.

5.3 | Impact of woodland on subsurface flow and overland flow

We found a catchment woodland cover of 65% resulted in the greatest reductions in peak flow. When woodland cover increased beyond 65% smaller reductions in peak total flow were simulated. We also found that increased catchment woodland cover also resulted in an earlier time to peak between 15 and 45 min (Table 3). Both of these factors may be explained by the change in dominant flow from overland flow to subsurface flow (Figure 6).

When the Naddle catchment is predominately grassland, the soils are less permeable and overland flow dominant. Increases in woodland cover lead to increased surface roughness, reducing overland flow and it takes longer for overland flow to reach the Naddle Beck. However, increasing woodland cover also increases the permeability of the soils with simulated subsurface flow becoming dominant at 40% woodland cover. Further increases in woodland cover result in reductions in peak total discharge until 65% woodland cover, due to the greater roughness of woodland 'slowing the flow' of overland flow. Furthermore, a portion of the subsurface flow will be actively stored in the more permeable woodland soils. For woodland cover greater than 65%, peak total peak discharge is no longer reduced by the same extent. When soils storage is full, more permeable soils can result in increased subsurface flow converting to total flow. In addition, if less overland flow is being produced, there is no benefit of increased surface roughness.

However, it is worth considering whether this shift in dominant flow may be an artefact of the parameters chosen or the model set up. In this study we assume woodland and grassland have the same storage (Table 2). If woodland soils have greater storage than grassland soils, as suggested in some studies (Geris et al., 2015; Stratford et al., 2017), it is likely that woodlands would result in larger reductions in peak flow than simulated here. Whilst parameters used were directly calculated from field evidence, catchments naturally vary in their permeability, roughness and storage. Future work, repeating this work for additional catchments would identify whether the same patterns are replicated.

5.4 | Future work

All our model scenarios are based on a 1 in 50 year storm event for a relatively small (2.6 km^2) upland catchment. Storm size, catchment size and antecedent conditions can all impact the extent to which woodlands impact flood response (Bathurst et al., 2020; Dadson et al., 2017). This study should be repeated in the future for other catchments, with varying characteristics, particularly larger catchments and those with a higher baseflow index which would allow for a more diverse range of events to be investigated. Climate change will increase flood risk through increased frequency of storm events and increased peak river flows (Kay et al., 2021). Under high future carbon emissions (e.g., RCP8.5) climate change is projected to cause at least 20%–40% increases in peak flow by 2100 (Kay et al., 2021), greater than the reduction in peak flow due to woodland creation that we simulate here. This emphasises the urgent need for rapid emission reductions to minimise future climate change. In the absence of strong emission reductions, NFM interventions will not be capable of adapting to future increased flood events. Future work using a consistent modelling framework is needed to investigate how the impact of woodland varies for different storm frequencies and profiles, antecedent conditions and different catchment sizes in both current and future climate conditions.

We studied the impact of ungrazed, semi-natural broadleaf woodland compared to pasture grazed at relatively low grazing intensity based on empirical data collected in Northern England. Future work is needed to assess how the hydrological response varies with woodland age, woodland type (conifer, broadleaf, mixed) (Peskett et al., 2021), planting design (e.g., planting density) and with varying grazing intensity in pasture and woodland areas. New woodland creation schemes can be tailored to maximise NFM benefits. However, there are likely to be some tradeoffs: increased planting density may increase interception and soil permeability but reduce surface roughness due to canopy closure and reduced ground vegetation.

Our paper provides additional evidence of the magnitude of the reduction in peak runoff possible through woodland creation. However, the impact of other NFM methods such as woody debris dams (Thomas & Nisbet, 2012), grazing management (Bond et al., 2022; Gao et al., 2017), floodplain reconnection and peatland restoration (Gao et al., 2016) needs to be investigated alongside woodland creation to identify the combined benefits and limitations of NFM. Climate change creates urgency to implement NFM to help adaptation to increasing flood risk. Through providing more evidence of the magnitude of flood reduction provided by woodland, our work highlights both the potential and the limitations of NFM, with a combination of NFM and traditional flood management likely needed in many situations.

6 | CONCLUSION

We used a rainfall-runoff model to investigate how broadleaf woodland cover altered peak flow during a 1 in 50 year storm event in a small upland catchment. Woodland cover reduced peak flow by as much as 16%, with maximum reductions in peak flow for woodland cover of 65%. For woodland cover above 65%, lower reductions in peak flow were simulated due to increases in subsurface flow. Simulated reductions in peak flow depend on the placement of woodlands within the catchment. Larger reductions in peak flow were simulated for cross-slope and riparian woodland compared to catchment woodland with reductions in peak flow of 4.9%, 3.3% and 2.7% respectively for a 10-percentage increase in woodland cover. Our results confirm that increased woodland cover can be an effective method of reducing peak flow even in large storm events and suggest that location of new woodland within the catchment can be targeted to maximise flood reduction benefits.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available; Information regarding the land cover within the Naddle catchment are available from the CEH datasets (https://www.ceh.ac.uk/ukceh-land-cover-maps). Elevation data used is available from https://digimap.edina.ac.uk/roam/download/os. Rainfall data for the 1 in 50 year and 1 in 10 year storm events were generated using https://fehweb.ceh.ac.uk and the runoff data from https://www.hydrosolutions.co.uk/software/refh-2/. Preparation of model files were carried out using QGIS (https://qgis.org/en/site/), python (https://www.python.org/) and R (https://www.r-project.org/).

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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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