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Evaluating the effectiveness of land use management as a natural flood management intervention in reducing the impact of flooding for an upland catchment

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Abstract

Natural flood management (NFM) is a method for reducing flooding by using a catchment-based approach to managing flood risk. Understanding and quantifying the impact of implementing NFM at the catchment scale remains ambiguous with a clear need for robust empirical evidence. A combination of fieldwork, laboratory analysis and modelling was applied to quantify the impacts of land use management changes on catchment flood hazard. Soil hydraulic conductivity was measured under varying land management regimes and used to parameterize a physically based spatially distributed hydrological model (SD-TOPMODEL). A suite of stakeholder informed land management scenarios was modelled, permitting the quantification of the impact of NFM interventions on the timing and the intensity of the peak discharge at the catchment outlet. The findings support the implementation of NFM interventions as a means of reducing flood hazard within a rural upland catchment. Improved soil infiltration provided the greatest reduction in the intensity and delayed timing of the flood peak for a 10-year occurrence storm event (7% reduction in peak runoff and 8% increase in lag time) with similar reductions observed for a 100-year storm event. Catchment wide woodland planting reduced peak flow by 11% during the 100-year event but was not effective during the 10-year event. Riparian buffer strips provided consistent reductions in peak flow and in the timing of the peak across both storm events with no significant differences relating to vegetation age. Critically, we observed that the effect of implementing multiple NFM interventions was not additive and that efficiencies can be made in using this modelling approach to prioritize the most effective outcomes.

KEYWORDS

hydraulic conductivity, natural flood management, SD-TOPMODEL, uplands

1 | INTRODUCTION

Natural flood management (NFM) is a tool to help reduce flooding by using a catchment-based approach to managing flood risk and encompasses a number of approaches from flow attenuation features to land use management practices (Wren et al., 2022). The primary objective of NFM is to optimize the natural water retention processes within a river catchment to effectively delay or desynchronize the flood peak and reduce the impact of runoff on the rising limb of the storm hydrograph (Lane, 2017; CaBA., 2017; Metcalfe et al., 2018). Intervention methods can be categorized into three general groups: reducing rapid runoff via land use changes that reduce overland flow velocity and improve soil conditions to enhance infiltration; providing and increasing upstream water storage; and reducing flow conveyance within a catchment (Burgess-Gamble et al., 2017; Lane, 2017). Considering the first of these options, UK land management initiatives have included afforestation, establishment of riparian buffer zones and reducing grazing intensity (Burgess-Gamble et al., 2017).

The effects of afforestation have been studied extensively through a combination of field work and modelling studies. A combined experimental and modelling study identified that careful placement of tree strips can reduce flood peaks by 40% (Jackson et al., 2008; Parrott et al., 2009). Newly planted broadleaf woodland has been estimated to enhance soil infiltration rates and reduce runoff by 78% (Marshall et al., 2014) while Dixon et al. (2016) report though the use of a simplified physical model that mature forested floodplains can reduce peak discharges by up to 19% when catchments are forested between 20% and 35% of their total area through the desynchronization of flood waves. Iacob et al. (2017) found a greater reduction in high flows for woodland planted in lowland zones to replace agricultural land compared to the same proportion of planting in upland areas. Peskett et al. (2020) also demonstrated that cross slope forest strips increase sub-surface water storage up to a depth of 1.7 m below the forest strip, which can reduce flood risk in summer storm type events. An analysis of river gauge data by Monger et al. (2021) also identified that semi natural broadleaved woodlands reduced discharge by 20%–60% and runoff coefficients by 30%–60% compared to grazed pasture land for nine small catchments in the Lake District. However, to date, the relative effectiveness of these interventions on downstream flood risk has yet to be determined, preventing effective planning, siting and optimization of NFM interventions, and in particular understanding where in a catchment tree planting would be most efficient (Cooper et al., 2021). Whilst there has been significant work on establishing the benefits of tree planting in reducing flood risk, there have also been reviews that have highlighted the uncertainty and the extent of evidence in establishing the impacts of tree planting on flooding, and the influence and extent of 'modifiers' on discharge (Stratford et al., 2017).

Riparian buffer zones are vegetated belts of land adjacent to river networks (Tiwari et al., 2016) and are considered one of the best methods in providing pollution management and protection of surface water (Hénault-Ethier et al., 2017). The buffering capacity of these zones is strongly dependent upon antecedent conditions (Lane et al., 2007), thus they are most effective between storm events, during small events and in the early stages of larger events (McGlynn & McDonnell, 2003). Gao et al. (2016) modelled the impact of buffer strip position on the hillslope and found that land cover change in riparian buffer zones had a greater effect on peak flow than mid-slope and headwater strips. However, there may be a more complex mechanism driving the benefit of this intervention, and it has been demonstrated that riparian zone planting in isolation may not have as significant an impact on delaying the timing of the peak of a flood, compared to riparian zone planting in combination with other NFM interventions (Black et al., 2021). Other land management techniques, such as grazing management and adjusting livestock densities, influence overland flow generation and velocity and the resulting downstream flood hazard. For example, hydraulic conductivity and infiltration rates are lower in grazed fields than where grazing has been restricted (Evans, 1998; Holden et al., 2007), thereby increasing the probability of overland flow generation. Yet, these negative impacts, such as soil compaction and decreased permeability, may be reversed through careful management. The removal and exclusion of livestock leads to an improvement in the soil structure, particularly in the upper layers, enhancing infiltration and evaporation (Carroll et al., 2004; Greenwood et al., 1998; Nguyen et al., 1998).

As a bottom-up approach, NFM schemes provide opportunities for early stakeholder engagement that enable flood practitioners to establish positive relations with local communities, water companies, charities and local government organizations from an early stage; a critical element to the success of NFM schemes (Metcalfe et al., 2018). The ability to provide catchment-wide, multiple benefits has facilitated its adoption as part of UK policy for addressing flood issues (DEFRA, 2020). Extensive evidence suggests that land management practices affect runoff generation (Nicholson et al., 2012; Thomas & Nisbet, 2012); however, the majority of research has concentrated on local flooding with limited data for large catchment scale downstream flooding. This creates difficulties in attributing local land use change to wider catchment (>10 km^2) flooding during large-scale events with a return period of greater than 1 in 100 years (O'Connell et al., 2007; Parrott et al., 2009). The spatial variability and spatial connectivity of hydrological processes is widely recognized as a determinant of land use change effects (Rogger et al., 2017). Despite the many benefits associated with NFM schemes (e.g., Lo et al., 2021), there is still a requirement to model and assess the impacts of such localized schemes on the wider catchment scale (Metcalfe et al., 2018). There is a need to understand the problem of the varying spatiotemporal scales as it is possible that simplistic interventions designed to desynchronize flood peaks within sub-catchments could lead to unforeseen synchronizations (Blanc et al., 2012). To date, there is a clear evidence gap in the modelling of land use management at the catchment scale contributing to low confidence in land use management as a NFM technique (Burgess-Gamble et al., 2017; O'Connell et al., 2007).

This paper presents an integrated field and modelling approach to investigating the impacts of land management changes on flood hazard at the catchment scale. We aim to increase the efficacy of NFM techniques in reducing the impact of flooding and provide an evidence base to support the implementation of these methods as a means to reducing flood risk to downstream communities. First, field data collected provides a characterization of soil hydraulic conductivity under different land management regimes. Second, the field data is used to parameterize a SD-TOPMODEL baseline model of the catchment. Using the baseline model, varying distributions of stakeholder-informed NFM interventions have been assessed for reducing the intensity and timing of flood peaks at a catchment scale. The assessment of the interventions is made by comparing the model outputs at the catchment outlet, to understand the cumulative impact of the NFM interventions.

2 | FIELD SITE AND METHODS

2.1 | Field site and sampling

Bishopdale is a 38 km^2 predominantly rural upland catchment located within the Yorkshire Dales National Park, UK. The catchment is characterized by heavily gripped peat moorland and extensively grazed pastoral farmland (Figure 1). Elevations range between 652 m AOD (Above Ordinance Datum) in the south of the catchment towards Buckden Pike and 147 m AOD at the confluence where Bishopdale Beck meets the River Ure (Figure 1b). The bedrock is dominated by sedimentary limestone throughout the catchment with deposits of sandstone also present in the south-eastern extents of the catchment. Superficial geological deposits are dominated by glacial Devensian till, with peat deposits present in the uplands and alluvium deposits around the channel network where deep loam soils from the East Keswick series are formed from Palaeozoic sandstone and shale (BGS, 2019). Slight seasonal waterlogging is present due to low permeability subsoils. Upland areas are characterized by naturally wet thick acidic peaty soil. In the lowlands, the catchment is dominated by pastoral grassland used for grazing by sheep and cattle. Grassland covers 71.8% of Bishopdale, of which 26.3% is classified as improved (Figure 1d). There is a mixture of deciduous and coniferous woodland present in small pockets throughout the catchment.

Average annual rainfall at Bishopdale between 1961 and 1990 is 1337 mm with a maximum recorded daily rainfall of 86 mm (Environment Agency, 2018; NERC, 2012). Flood risk in Bishopdale is categorized as low-to-moderate due to the dispersed population and low flood risk to properties (Environment Agency, 2010); however, the combined risk of rapid runoff generated from upland areas within the broader Ouse catchment poses a significant risk to densely populated areas downstream. The York floods in 2000 were attributed to the rapid runoff of storm water from such upland areas (Environment Agency, 2010).

A catchment-based approach to reduce the impact of flooding in the local area, through involving a number of stakeholders within Bishopdale, has been adopted to slow the flow of water through the valley. The catchment is a beneficiary of a DEFRA (Department for Environment, Food and Rural Affairs) NFM funding initiative. Funding obtained by the Environment Agency, the UK public body with responsibility for environmental management and flood risk and in partnership with the Yorkshire Dales Rivers Trust (YDRT) and Yorkshire Dales National Park. This has enabled a number of NFM projects to be implemented, including the daylighting of 300 m of Bishopdale Beck to improve flood plain connectivity, and the construction of a mile of riparian fencing to reduce stock grazing (White, 2019). The

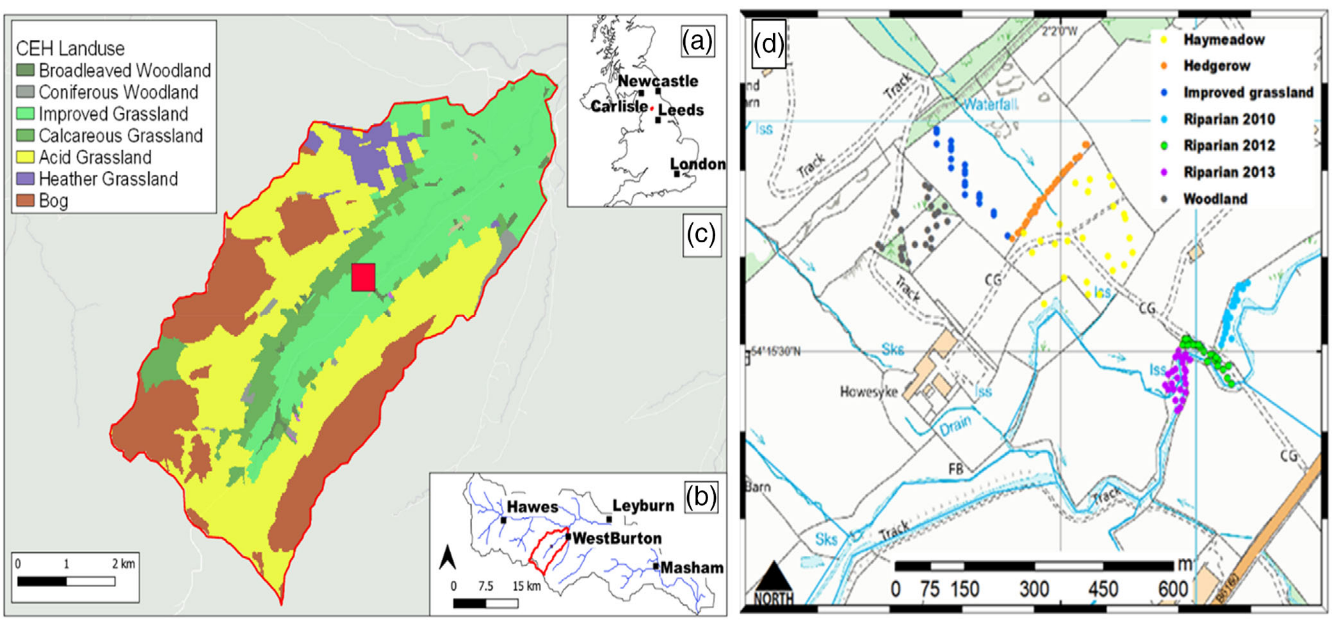

FIGURE 1 Location of the Bishopdale catchment: (a) within the United Kingdom; (b) relative location in relation to the Upper Ure catchment to Boroughbridge; (c) land cover within Bishopdale created using LCM2015 data (Rowland et al., 2017) and location of soil sampling sites (red square); (d) location of soil sampling within land cover classifications

low slope gradients around the main channel of Bishopdale Beck provide an ideal area to implement NFM interventions targeted at attenuating the flow and increasing water storage during storm events. A number of runoff management measures have been undertaken including targeted hedgerow planting (across overland flow paths), woodland creation, construction of earth bunds, riparian buffer strips and peatland restoration aimed at reducing runoff and increasing surface roughness.

To assess hydraulic conductivity of different land uses and cover types a total of 174 samples of the top 5 cm of the soil column were collected using 53 mm bulk density rings through random sampling of targeted land use covers in the Bishopdale catchment (outlined in Figure 1d). The sampled land use classifications include hay meadow (designated as land used for the production of hay followed by grazing), woodland (broadleaf), improved grassland (land used predominantly for the grazing of sheep), hedgerow (located between field boundaries) and riparian buffer strips (enclosed areas planted with a mixture of woody perennials). Three riparian buffer strips of varying ages planted in 2010, 2012 and 2013 respectively are located within the study area.

2.2 | Laboratory methods

The hydraulic conductivity of undisturbed soil samples was determined using a 25 ring Eijkelkamp permeameter (Eijkelkamp, The Netherlands). Soil samples were placed in water for 24 h prior to analysis to allow for complete saturation and calculation of saturated permeability (K_s). Sample permeability was assessed using a closed system, whereby water was pumped from a storage system to an adjustable water level regulator. Samples sat inside a ring holder within the tank and a siphon was used to connect the water collecting on top of the saturated sample into a burette. The rate of draining was measured and from this K_s (cm day^{-1}) was determined, based on Darcy's Law.

Two methods were used to determine saturated permeability based on the soil class and material. The constant head method, outlined in Equation (1), is the most widely employed and was used for all soils excluding low permeable clay and peaty soils:

$$K_s = \frac{VL}{Ath} \tag{1}$$

where V is the volume of water flowing through the sample (cm^3), L is the length of the soil sample (cm), A is the sample cross-sectional area (cm^2), t is the time (days) and h is the water level difference inside and outside the sample cylinder (cm).

The falling head method was used for samples that have low permeability where a siphon cannot be inserted due to low water levels inside the sample. The same setup is required as described above; however, no siphon is required. Water level was measured both in the tank and in the sample at regular intervals over the course of several days to establish the permeability coefficient. An adjusted Darcy's Law is required to calculate K_s:

$$K_s = \frac{VL}{Ath} \ln \frac{h_1}{h_2} + \frac{xaL}{A\sqrt{h_1 h_2}} \tag{2}$$

where h_1 and h_2 (both cm) are the water level differences and the start and end times respectively and x is an evaporation factor applied as the measurement may take several days (0.0864 cm day^{-1}, following Eijkelkamp, 2013).

Measured K_s values were assessed for normality using a Shapiro–Wilk test ($p < 0.05$). Following a non-normal distribution, data were analysed using Kruskal–Wallis ($p < 0.05$) followed by a post hoc Wilcoxon signed rank comparison to identify any significant differences between land use classifications. Average K_s values for each land use were used to determine the relative difference in hydraulic conductivity for each land use, which formed the basis for the parameter input to SD-TOPMODEL, as outlined below.

2.3 | Numerical modelling: An introduction to SD-TOPMODEL

TOPMODEL (Beven & Kirkby, 1979) was developed to provide a physically realistic, but simple rainfall-runoff model with the ability to simulate hydrologic fluxes including channel routing, saturation excess overland flow and overland flow through a catchment (Ambroise et al., 1996). As a semi-distributed model, specific land-use change interventions were challenging to represent within the computationally efficient model framework. Gao et al. (2015) developed a spatially distributed TOPMODEL (SD-TOPMODEL) specifically to assess changes in land cover. SD-TOPMODEL implements a distributed approach whereby hydrological processes are calculated within individual units (cells) whilst retaining the same conceptual approach from the original TOPMODEL (Gao et al., 2015, 2017). A significant change is the separation of subsurface and overland flow in the model, which allows cells to be defined with different parameter values which can be set to varying spatial arrangements of land use and cover types. The model requires three parameters in order to do this: a notional hydraulic conductivity of the soil, K (m/h); active depth of subsurface flow m (m, scaling parameter); and overland flow conveyance k_v (a dimensionless coefficient factor, analogous to the Darcy friction factor; Boisgontier, 2018; Gao et al., 2015). The model uses a soil deficit approach to model the saturated zone, similar to the original TOPMODEL formulation (Kirkby, 1997), where the rate of subsurface flow is related to the depth at which flow reduces to zero (defined by m). The overland flow module is based on a multi-direction flow dispersion approach, which allows explicit routing of surface runoff, although using a simplified physics approach to model this process. While the limited number of parameters reflects the reduced physical complexity of the model, the ability to spatially distribute these parameter values allows land cover and uses to be included in the model (Deng & Sun, 2010; Gao et al., 2015). For a full description of the model, readers are referred to Gao et al. (2015).

The model is required to be calibrated and validated by adjusting these parameters and comparing the model outputs against a reference discharge dataset. This process is chosen to help establish the reliability of the model. Further and more detailed uncertainty analysis will be required to mitigate potential equifinality issues and improve parameter identifiability (Beven, 2012; Her & Chaubey, 2015; Pechlivanidis et al., 2011). It should be noted that whilst the model parameter K is linked to the soil hydraulic conductivity value K_s, determined in the field data collection, the values of K_s are not used directly. The input to the model is an 'effective parameter', where the value given is designed to represent the impact of a number of processes, rather than linking to a direct physical property within the soil (Beven, 2012). Hence, in this paper we refer to these values separately, and each have separate units (K in m/h, K_s in cm/h).

SD-TOPMODEL has been applied previously to an upland peatland catchment to model the effects of typical upland management activities such as grazing, vegetation restoration and rotational burning (Bond et al., 2022; Gao et al., 2016, 2017). Previous SD-TOPMODEL applications have derived all parameter values primarily from literature values (Boisgontier, 2018). There has been little work establishing the spatial variation of hydraulic conductivity and surface roughness, with the exception of Bond et al., 2020, and implementing this variability in distributed models both within and between land use classes requires significant effort.

2.4 | Numerical modelling: Establishing the baseline model

A baseline model of Bishopdale was established which reflects the current land cover conditions in the catchment, determined from 2015 UK CEH land cover maps, and a OS Terrain 5m DTM for the terrain data (Ordanance Survey, 2018). Calibration of the baseline hydrological model was carried out using a synthetic storm based on catchment descriptors to provide a reference model as the catchment in the absence of discharge and rainfall data in Bishopdale. A 100-year 12-h design storm was generated from the ReFH (Revitalised Flood Hydrograph; Wallingford HydroSolutions, Wallingford, UK). Model simulations were evaluated by comparing the predicted hydrograph with the ReFH reference model hydrograph for the same period and quantified using the Nash-Sutcliffe efficiency (NSE) criterion. The ReFH reference model hydrograph may not be reflective of the actual peak flows in the catchment, but is used to provide an estimate of potential ranges of peak values. Whilst this approach relies on general relationships between catchment descriptors and peak flows, and is therefore unlikely to be representative of the complex flood generating processes present within the catchment (Faulkner & Barber, 2009), the approach still provides a reasonable calculation of flow in the absence of recorded data, although the uncertainty in this value can be as great as 55% for some catchments (Kjeldsen, 2015). As the primary purpose of this research is to understand the impact of land management changes on a baseline model, the relative values have a greater significance in our conclusions than the observed values.

For each model run (baseline and scenario), the model simulation time is 20 h with a time-step of 15 min, providing enough time for the catchment to drain sufficiently and the outflow to return to within 10% of the base flow value. For the calibration, 90 simulations with varying parameters inputs were tested using the range of parameter inputs highlighted in Table 1. The parameters set with the highest performing NSE and peak value were used for the lumped baseline model which best replicates the predicted hydrograph from the ReFH model.

In order to represent different land cover and uses in the model, each land class is represented as a variation of the three input parameters (Table 2). This is implemented in the model as a set of scaling factors from a set of base values. The base values are picked as reference positions from within the parameter values described in Table 1, and were selected as they gave good initial comparison between the model and the ReFH derived discharge, before a more comprehensive calibration was undertaken. It is important to note that in this approach, the observed field values of a given parameter are not used

TABLE 1 Parameter ranges used in model calibration

Parameter	Lower limit	Upper limit	Interval	Base value
k_v (−)	10	50	10	10
m (mm)	0.006	0.026	0.004	0.020
K (m/h)	100	300	100	200

TABLE 2 Final distributed parameter set for each land use cover for the baseline model

Land use	LCM number	K (m/h)	m (mm)	k_v (−)
Broadleaf woodland	1	0.9 (180)	1.5 (0.03)	0.8 (8)
Coniferous woodland	2	0.9 (180)	1.5 (0.03)	0.8 (8)
Improved grassland	4	0.55 (110)	1 (0.02)	2.4 (24)
Calcareous grassland	6	1 (200)	1 (0.02)	2.4 (24)
Heather/Heather grassland	9/10	1 (200)	1 (0.02)	1.6 (16)
Bog	11	1 (200)	1.5 (0.03)	1.6 (16)
Suburban	20/21	0.1 (20)	1.5 (0.03)	10 (100)

Note: The land use scaling factor (the relative value of each land use type compared to the lumped parameters presented in Table 1) are presented for each input, with the actual value used in the model presented in parentheses. LCM number relates to the land class number presented by Rowland et al. (2017).

directly in the model, but are used to maintain the relationship of a particular hydrological property of the soil between land cover types in the model. We refer to these values as the *land use scaling factor*. Land use and cover types are represented in the model by spatially distributing the three model parameters, using a 2015 UK CEH land cover map (resampled to the same 5 m resolution as the DEM) as the basis for the distribution of land cover parameters (LCM2015, Rowland et al., 2017). For each parameter, a land cover map (Figure 1c) is provided which describes the land use scaling factor and the parameter value for each land use class (Table 2). The validity of this approach was tested by comparing the spatially distributed model to the calibration event and evaluated again for performance.

The land use scaling factor for the hydraulic conductivity of the soil, K, was based on the analysis described in Section 2.2. Values for m and k_v were estimated from the literature. Due to the complexity and inherent uncertainty influencing the exponential rate at which flow reaches zero with soil depth (m), we made the assumption that m relates to soil depth only, although there are multiple physical properties and influences on this parameter (Beven, 2012). Values were derived from the National Soil Map descriptions of soil depth (UK Soil Observatory, 2019) and previous values applied by Gao et al. (2016). In this approach, Acid Grasslands were predominantly in shallow soil categories, whereas Improved Grasslands, which was the second largest land cover type, covered 'medium' soil depth categories. This was used as the baseline value from which the land use scaling factor took its values. Values for the overland flow conveyance parameter (k_v) were determined for each land use class calculated as the inverse of the associated Manning's n value obtained from Chow et al. (1988). For the land cover types used here, a typical value of typical value of Manning's n for woodland (0.1) is three times greater than that used for grassland (0.03–0.035), and around two times greater than a heather grassland surface (0.06) hence the values of 0.8, 1.6 and 2.4 used here as the land scaling factors (from a starting k_v of 10, which represent a sphagnum moss covering, similar to the approach used by Gao et al., 2015). The limited Suburban land cover is assumed to be concrete or tarmac surface, hence the high value of 10 (equivalent to a Manning's n value of 0.01).

For values of m, improved and calcareous grasslands are taken as the baseline value, and are given relative values of 1. Woodland soils are complicated by the presence of roots, which increase the active depth of the saturated zone. Studies by Archer et al. (2013) provide an indication of the changes to conductivity at depth from various woodland, where is it noted that for some species the change can be 5–6 times than grassland but this does not hold across all species and at all depths. The difference of infiltration between a 500 year old broadleaved woodland site and two grazed grassland sites was found to be about 3–5 times at a depth of 15–20 cm. Considering both the lack of wider studies, and the younger age of tree planting at this site, a value of 1.5 is used as a conservative estimate from the results of that study. For 'bog', which is a generic term in the land use classification for most upland peat based land covers, we retain a K value of 1 in the absence of more detailed data and to reflect the uncertainty in developing a definitive description of the hydraulic properties for this land cover which will change during the course of a flood event and as a result of antecedent conditions (Holden et al., 2007). An m value of 1.5 is used, derived from Holden et al. (2007) which demonstrated a difference between macro pore flow for surface of around 50% for grassland versus peatland, hence the use of 1.5 for m. For heather grassland, we assume that the development of macro pores are less developed as a result of the difference in vegetation types (predominantly grass), so retain a base m value of 1.

The estimation of these values represents the largest area of uncertainty in the model and whilst the effort has been made to find values that provide reasonable estimates of the parameters further work should consider understand the full impact of these values. From these parameters, a total of 90 model simulations were run to establish the best performing distributed model.

2.5 | NFM scenarios

Ten land management scenarios were designed based on the priorities stated by YDRT for the Bishopdale catchment (YDRT, 2014) (Table 3) which were informed by on-site land manager engagement assessments. For each scenario, an intervention is applied in the model by modifying the three input parameters within the footprint of the proposed intervention location to reflect a specific change to the land use. The location of the interventions for each scenario are highlighted in Figure 2, and the land use scaling factors that are used to represent an intervention are summarized in Table 3. The value of the land use scaling factor used to represent a particular intervention is based on the approach described above and using a combination of the conductivity values analysed in Section 3.1 and literature values. Further detail is provided in the Supporting Information. In addition to the 100-year recurrence interval storm event used to establish the model baseline, a 10-year (12-h duration) designed storm event was used to assess the effectiveness of the measures in smaller, more frequent storm events. Each scenario is analysed by comparing percentage change in peak flow and time to peak at the catchment outlet against the baseline model. The results are presented in a deterministic way, without ranges of potential values. This is due to the limited time to complete more comprehensive uncertainty analysis, and the conclusions are made with respect to this limitation.

3 | RESULTS

3.1 | Hydraulic conductivity in Bishopdale land classes

Descriptive statistics of measured absolute K_s values are presented in Table 4. Figure 3 indicates that K_s values (in m day^{-1}) vary significantly under different land use classes even at a local scale. A relatively high variability in K_s is observed within improved grassland, hedgerow and haymeadow land use classes. Lower variation is found

TABLE 3 Final parameter set for each scenario, with the land use scaling factor for each intervention (actual values presented in parenthesis)

Scenario	Figure	Intervention	Spatial distribution	K (m/h)	m (mm)	k_v (−)
1	A	Woodland planting	Based on mapped potential of catchment woodland provided by the Environment Agency (Hankin et al., 2017)	0.9 (180)	1.5 (0.03)	0.8 (0.8)
2	B	Hedgerow planting	Based on YDRT Farming plan	0.5 (100)	1.5 (0.03)	1.4 (14)
3	C	Riparian buffer (grass)	5 m buffer around main channel	4 (800)	1 (0.02)	2 (20)
4	C	Riparian buffer (young)	5 m buffer around main channel	1.3 (260)	1 (0.02)	1.4 (14)
5	C	Riparian buffer (developing)	5 m buffer around main channel	1 (200)	1.2 (0.024)	1.3 (13)
6	C	Riparian buffer (established woodland)	5 m buffer around main channel	0.8 (160)	1.3 (0.026)	1.2 (12)
7	C	Riparian buffer (mature woodland)	5 m buffer around main channel	0.8 (160)	1.5 (0.03)	1 (10)
8	D	Increased soil infiltration	Areas currently marked as Improved grassland on the floodplain converted to a lower grazing density	1 (200)	1.5 (0.03)	1.5 (15)
9	E	Moorland restoration	Based on YDRT Farming plan	1 (200)	1.5 (0.03)	1.5 (15)
10	F	All NFM interventions	-	-	-	-

Note: Scenario 10 incorporates all modelled scenarios see text in the Supporting Information for further details.
Abbreviation: NFM, natural flood management.

in land uses that promote greater infiltration within the top 0–5 cm of soil including woodland and riparian areas respectively.

There is a clear difference observed between land uses, including conventional pastoral land uses with higher K_s attributed to NFM techniques encompassing the hedgerow, woodland and riparian areas. A test of variance using the Kruskal–Wallis test ($p < 0.05$) calculated on the K_s values indicated significant differences between land management classes ($x^2 = 76.2$, $p = <0.01$, $df = 6$), with a post hoc pairwise Wilcoxon (Figure 3) indicating which land classes are significantly different from one another. Haymeadow exhibits the lowest mean K_s value (0.32 ± 0.46 m day^{-1}) and is significantly different to all other sampled land use classes. Significant differences between other land classes include differences between woodland and Riparian 2013 ($p = 0.00$) and between hedgerow and Riparian 2012 ($p < 0.01$) and Riparian 2013 ($p < 0.01$). Improved grassland was significantly different from Riparian 2012 ($p < 0.00$), riparian 2013 ($p < 0.00$) and woodland ($p < 0.01$).

3.2 | Modelled NFM scenario results

The baseline model was established by calibrating to the 100-year recurrence interval 12-h event, as described in Section 2.4. The best parameter set from 90 model runs with highest NSE value (0.84) was carried forward as the baseline parameter values ($K = 100$ (m/h), $m = 0.026$ mm and $k_v = 20(-)$). It was found that the FEH derived hydrograph fell within the largest and smallest hydrographs created from the 90 model runs, thus demonstrating that the range of values was appropriate in finding a suitable baseline model, and additional calibration runs were not required.

Table 5 and Figure 4 provide a summary of the impact of each scenario on the peak flow intensity and timing for the two simulated storm events. Hydrograph figures for all the model results can be found in the supporting Implementation of all NFM interventions resulted in only a 1% reduction in peak flows and no change in time to peak compared to the baseline conditions during a 100-year storm event; however, there was a greater impact on peak flows during the 10-year storm event (5% peak flow reduction and a 45-min (8%) delay to peak).

The five riparian buffer strip scenarios of varying maturity situated adjacent to Bishopdale Beck (Figure 2d–h) decreased peak flow by 1% in all instances compared to the baseline scenario during the 100-year rainfall event. The grass covered buffer strip (Scenario 3) and the young vegetated buffer strip (Scenario 4) resulted in no reduction in time to peak with both scenarios reaching peak flows 8.5 h after the start of the rainfall event. Conversely, the remaining scenarios representing mature vegetated riparian buffer strips delayed the time to peak by 3% (15-min) during the 100-year rainfall event. During the 10-year event, peak flow was reduced by 1% for all scenarios with the exception of the youngest riparian buffer strip (Scenario 5; Table 5). Riparian buffer strips had a greater impact on time to peak during the 10-year 12-h storm event with an observed increase of 3% (15-min) in all scenarios.

The implementation of woodland considerably reduced peak flow (−11%) during the 100-year storm event and resulted in a marginally earlier rising limb on the hydrograph (Figure 5). Woodland had a positive impact on time to peak with a 3% (15-min) increase observed during both storm intensities. During the 10-year storm event, catchment woodland was not effective at reducing peak flow with an increase of 3% observed.

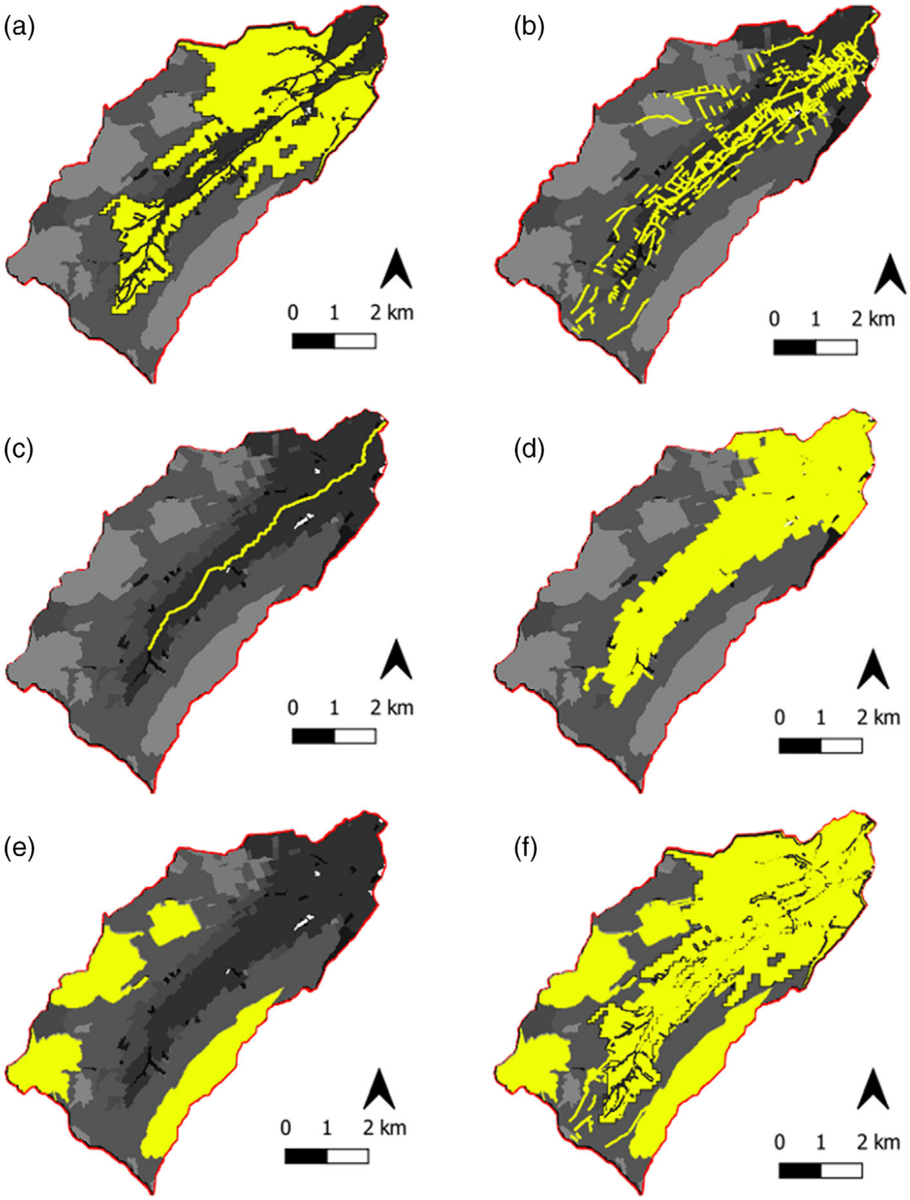

FIGURE 2 Locations of the interventions for the natural flood management (NFM) scenarios highlighted in yellow; (a) Scenario 1: woodland planting scenario; (b) Scenario 2: hedgerow scenario; (c) Scenarios 3–7: riparian buffer scenarios; (d) Scenario 8: increased soil infiltration scenario; (e) Scenario 9: moorland restoration scenario; (f) Scenario 10: all NFM interventions

TABLE 4 Descriptive statistics of measured hydraulic conductivity (K_s; cm day^{-1}) by land use class

Land use	Min K_s	Max K_s	Mean K_s	*SD*	CV
Improved Grassland	0.14	19.16	3.53	4.97	141.05
Hedgerow	0.09	45.42	8.09	12.23	151.2
Woodland	0.1	28.41	9.72	6.92	71.14
Haymeadow	0	1.59	0.32	0.46	143.76
Riparian 2010	0.05	36.75	13.43	11.58	86.28
Riparian 2012	1.9	59.62	22.34	17.23	77.11
Riparian 2013	1.43	157.33	44.87	42.14	93.9

Abbreviation: CV, coefficient of variation; *SD*, standard deviation.

The scenario simulating the planting of hedgerows across the catchment resulted in no significant changes in peak flows compared to other modelled NFM interventions. Conversely, improved soil infiltration within the floodplain had a strong positive impact on both the timing and the size of peak within in the catchment (Figure 5). The effectiveness of reduced grazing intensities (i.e., riparian buffer strips and woodland planting) had a greater impact during the 100-year storm event. The peak flow was significantly reduced with an 8%

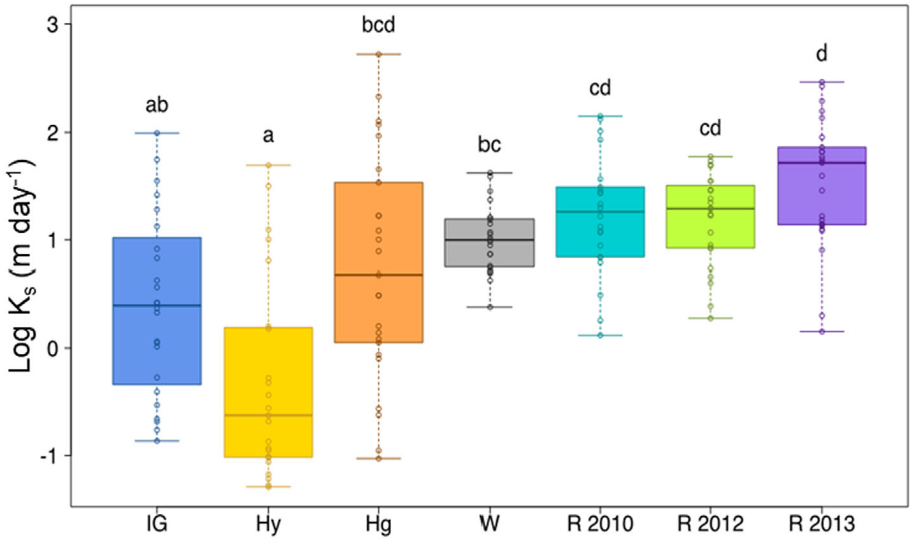

FIGURE 3 Saturated hydraulic conductivity measurements for the Bishopdale catchment by land use class (IG = Improved Grassland, Hy = Haymeadow, Hg = Hedgerow, W = Woodland, R 2010 = Riparian buffer 2010, R 2012 = Riparian buffer 2012 and R 2013 = Riparian buffer 2013). Plots sharing the same letter do not have significant differences in means

TABLE 5 Summary of natural flood management (NFM) scenario results by rainfall event compared to baseline conditions

		10-year 12-h				100-year 12-h			
Scenario	Intervention	Peak runoff (mm)	Relative peak diff (%)	Time to peak (h)	Time to peak diff (%)	Peak runoff (mm)	Relative peak diff (%)	Time to peak (h)	Time to peak diff (%)
	Baseline	26.88	-	9.25	-	122.77	-	8.50	-
1	Woodland planting	27.58	3	9.50	3	109.56	−11	8.75	3
2	Hedgerow	26.96	0	9.50	3	122.77	0	8.75	3
3	Riparian buffer (grass)	26.88	0	9.50	3	121.99	−1	8.50	0
4	Buffer strip (young)	26.65	−1	9.50	3	121.99	−1	8.50	0
5	Buffer strip (developing)	26.73	−1	9.50	3	121.99	−1	8.75	3
6	Buffer strip (established woodland)	26.65	−1	9.50	3	121.99	−1	8.75	3
7	Buffer strip (mature woodland)	26.50	−1	9.50	3	121.99	−1	8.75	3
8	Increased soil infiltration	24.94	−7	10.00	8	112.67	−8	9.00	6
9	Moorland restoration	27.20	1	9.25	0	121.22	−1	8.50	0
10	All NFM	25.64	−5	10.00	8	121.22	−1	8.50	0

reduction during the 100-year event and a 7% reduction during the 10-year storm event. The timing of each flow peak was delayed with a 30- and 45-min delay, respectively. Finally, moorland restoration had a greater impact on reducing peak flows during the large storm event compared to the smaller event with an observed decrease of 1% in peak flow. The impact of moorland restoration on peak flows during the 10-year event resulted in a 1% increase in causing an earlier rising limb on the hydrograph. During both storms, there was no observed change in the timing of the peak compared to baseline conditions.

4 | DISCUSSION

This study uses a spatially-distributed hydrological model (SD-TOPMODEL) combined with site-specific model parameters and NFM intervention scenarios to provide a detailed analysis of the impacts of proposed NFM interventions on the local scale (e.g., on soil properties) and on the large-scale catchment hydrological impact. Due to the fine-scale resolution of the model (5 m DEM), we were able to show how smaller NFM interventions, such as buffer strips are able to contribute to reduce flood peak and timing, and how these interventions will improve in performance as they develop. Woodland planting (in the large flood event) and improved soil condition were found to provide the best flood reduction, even when considering the 'all NFM scenarios' which implemented all possible NFM intervention measures identified at the site. The large variation in measured hydraulic conductivity (K_s) within and between land uses highlight the importance of field-based and site-specific model parameterization in model representation. Below, we discuss how our field data and local-scale NFM modelling can be further employed in future studies seeking to address the role of NFM in reducing flood risk at the catchment scale.

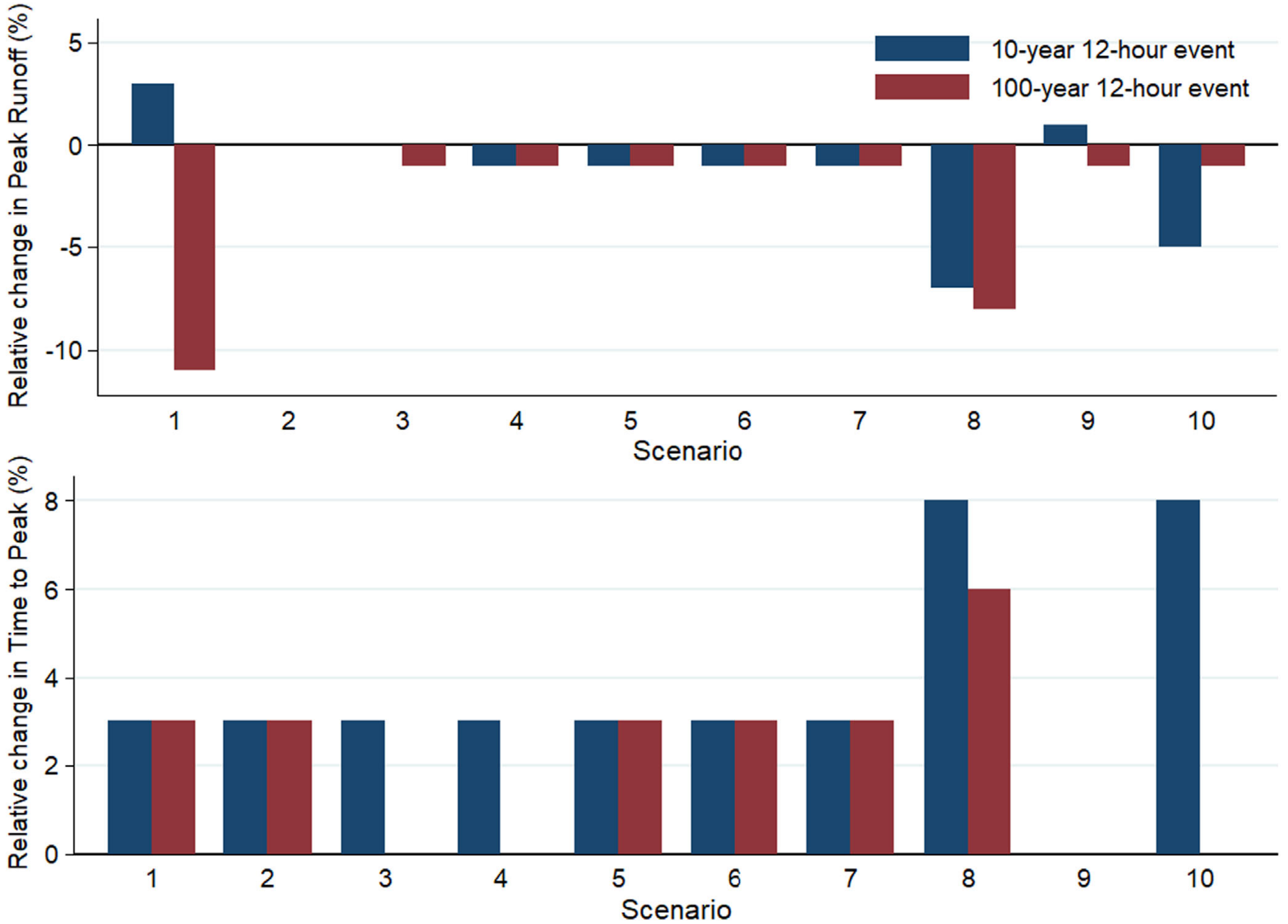

FIGURE 4 Comparison of the relative change to the peak runoff and the timing of the peak for each scenario compared to the baseline model

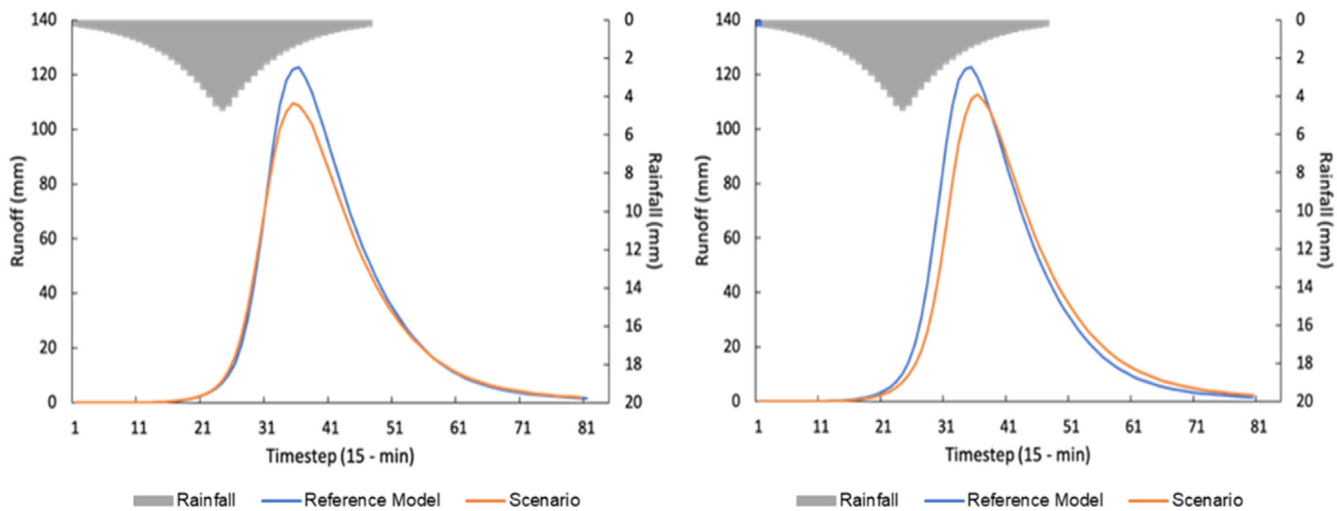

FIGURE 5 Modelled hydrograph from woodland natural flood management interventions (left) and soil improvement (right) within the Bishopdale catchment during a 100-year, 12-h storm event

4.1 | Impact of land management on hydraulic conductivity

Soil hydraulic conductivity plays a fundamental role in influencing catchment water budgets and directly affects the amount of surface runoff reaching the outlet (Hao et al., 2019; Zhao et al., 2013). K_s is influenced by a combination of physical soil characteristics including bulk density, porosity and chemical properties such as soil organic matter and carbon (Hao et al., 2019; Li & Shao, 2006). A clear influence of land use on hydraulic conductivity was observed, with a distinction between human-induced disturbances through cultivation and grazing compared to land uses that promote water retention and increased infiltration. The land use classes can be categorized into those comprising agricultural management practices (improved grassland, haymeadow) and the remaining land uses which can be classified as NFM-beneficial interventions. Similar findings have been reported by previous research (e.g., Chartier et al., 2011; Gonzalez-Sosa et al., 2010; Zhou et al., 2008; Zimmermann et al., 2006).

The effects of land use on K_s are strongly linked to the vegetation type. Vegetation properties have a strong influential role on soil characteristics and consequently are largely responsible for controlling the flow pathways of both surface and near surface runoff (Chaves et al., 2008). In this study, the vegetation types present within the NFM interventions are predominantly woody perennials. The introduction of shrubs and trees play a pivotal role in improving the soil structure by altering the root distribution and biomass (Hao et al., 2019; Li & Shao, 2006). A more stable soil structure is achieved through a dense root and macropore network under permanent vegetation and is associated with increased faunal activity, which can further enhance infiltration rates (Gonzalez-Sosa et al., 2010). Significant differences between K_s of grazed pastures and woodland have been well documented (Archer et al., 2013; Li & Shao, 2006; Price et al., 2010; Zimmermann et al., 2006). Although these differences are not replicated in this study, we did observe an increase in mean K_s under woodland compared to the grazed group, in the order woodland > improved grassland > haymeadow. The conversion of pastures to woodland changes the soil characteristics through increased root length density and distribution, which are important drivers in promoting infiltration (Hao et al., 2019; Kalhoro et al., 2018).

While there is a large support for the notion that the conversion of managed to natural vegetation leads to an enhancement in K_s, few studies compare K_s under different NFM interventions. Among the land use categories, the riparian buffer strips consistently maintain the highest mean K_s across the vegetation development groups. Similarly, Bharati et al. (2002) reported infiltration rates as being five times greater under an established riparian area than under cultivated fields and pasture. This study has shown that K_s is significantly enhanced in riparian areas that were previously grazed prior to 6–9 years of exclusion. However, vegetation maturity within the riparian buffer strips had no significant effect on K_s as no significant differences were observed between the different aged buffer strips (Riparian 2010 to Riparian 2013). K_s values were found to reduce as the age of vegetation increases with the oldest riparian buffer strip (Riparian 2010) having the lowest average infiltration rate across the three sampled age ranges. Results are inconsistent with similar research that has identified a positive trend of increasing K_s with increasing vegetation restoration age (Ren et al., 2016). The heterogeneity of hydraulic conductivity and the complex interactions with vegetation density may be responsible for these conflicting results. Further, the level of grazing on the land prior to the change in land use may also impact the results seen here. The role of vegetation age requires more comprehensive understanding and could have important implications on NFM efficacy in reducing flood risk; Archer et al. (2013) previously highlighted the temporal variability in forests reaching maturity and consequently improving K_s.

4.2 | NFM scenarios

Similar to the findings of Gao et al. (2016), riparian buffer strips had a positive impact on the timing and intensity of the flood peak within the catchment, by increasing the time to peak, and lowering the peak flow. The possible cause of this is the increased levels of hydraulic roughness of the vegetated strips, which would attenuate the upstream surface runoff and produces a reduction in peak flow and a delay in time to peak. The impact of grassland type on overland flow velocity and its associated roughness has been tested on a rural upland catchment by Bond et al. (2020) who observed that mean overland flow velocity was consistently lower in grassland types following a natural growth and decay cycle without additional management practices such as grazing. This provides further support for the implementation of grassland as a NFM method in achieving a delay in the time to peak (Bond et al., 2020). The model results indicate that the riparian zone is sensitive to changes in surface roughness. As the vegetation age increases, it is expected that hydraulic roughness exerts a greater impact on overland flow velocities as a result of increased leaf litter and stem density (Madi et al., 2013). The effects of vegetation age on hydraulic roughness, and therefore overland flow, were more pronounced during the large storm event with the establishment of woody perennials producing attenuation of overland flow compared to no observed change in time to peak under the younger vegetation (grass and young buffer strips). However, the effect is complex and dynamic as overland flow depths increase with increasing storm intensity, the influence of vegetation on overall hydraulic roughness can be reduced by flattening and be less effective at reducing overland flow velocity (Smith, 2014). Including this depth-dependent roughness into hydrological models will be important in understanding the evolving effectiveness of vegetation during storm events. During the 10-year event, all riparian scenarios resulted in a delay in time to peak flow, indicating that during high frequency and low intensity storm events vegetation in the riparian zone slows overland flow irrespective of vegetation age. The model results indicate that the establishment of woody perennials are more effective at attenuating surface runoff than grass covered buffer strips across a range of storm intensities.

These results are consistent with the assessment of Anderson et al. (2006) on the impact of vegetation roughness on the hydrograph during a 2-year and 100-year recurrence interval rainfall event. During the 2-year event, vegetation roughness was found to have a positive impact on the arrival time of peak discharge (i.e., increases the time between the start of the storm and the time of peak discharge) but was less consistent in delaying time to peak during the 100-year recurrence interval with the taller vegetation producing the greatest delay in time to peak. Vegetation age, or more specifically, the age of the intervention in the riparian zones, exerted no significant control on the size of peak at the catchment outlet. Based on the field data collected and on previous modelling studies, it was expected that the grass buffer strip would produce the greatest reduction in peak flow (Gao et al., 2016); however, the modelled reduction in peak discharge remains consistent irrespective of vegetation age. Due to the high concentration of overland flow in the riparian zone and the relative size compared to the total catchment area, it is likely that the width of the riparian zone is too narrow to attenuate flow and enable infiltration.

The woodland scenario was the most effective NFM technique during the large storm event, which is consistent with the findings of Boisgontier (2018). The reduction in peak flow can be attributed to the greater hydraulic roughness exerted by trees compared to the surrounding vegetation coupled with high infiltration rates under woodland soils (Broadmeadow et al., 2018; Calder & Aylward, 2006). Similarly, Thomas and Nisbet (2007) demonstrated the effects of floodplain woodland during a 100-yearflood event and found an area of 50 ha yielded a 15% increase in flood storage volume and resulted in a 30-min increase in time to peak.

The impact of hedgerows within the catchment had a minimal effect on flood risk during both storm intensities. This is despite the hedgerows being represented as being slightly larger in the model, due to the baseline cell size of 5 m against the proposed 2–2.5 m width. This is likely due to the low spatial distribution of hedgerows within the catchment with hedgerows placed in strategic locations identified as having high connectivity for overland flow routing rather than along individual field boundaries. Similarly, Peskett et al. (2020) found across slope forest strips had a marginal increase in catchment storage. Such NFM methods could be limited by their fragmented distribution and connectivity to surrounding impermeable land uses (e.g., grazed grassland) leading to the available storage becoming quickly overwhelmed during storm events (Peskett et al., 2020). The introduction of hedgerows had a positive impact on the time to peak producing a delay of 3% (15 min) in each storm event. Considering that the hydraulic conductivity of the hedgerows within the model was obtained from field data collected from a hedgerow established for 1 year, it would be interesting to observe if additional benefits can be derived under a mature hedgerow. Carroll et al. (2004) demonstrated the planting of shelter belts on previously grazed pastures can rapidly change soil properties leading to greater infiltration, indicating that the strategic placement of hedgerows has the capacity to reduce runoff rates.

Improved soil infiltration situated in the floodplain had the greatest impact on flood risk, illustrating the importance of agricultural management in the floodplain. These findings are consistent with previous studies (Boisgontier, 2018; Greenwood et al., 1998; Marshall et al., 2014). There is a substantial opportunity to reduce flood risk within the Bishopdale catchment through the exclusion of grazing animals to riparian areas leading to greater hydraulic roughness and enhanced infiltration, evaporation and interception of vegetation (Marshall et al., 2014). Conversely, the spatial distribution of peatlands across the Bishopdale catchment (located at the top of the catchment, but with limited extents) limits the impact on the timing and the size of the peak flow; only minor changes in the hydrograph response were observed in this study indicating that the additional area of moorland restoration would yield minimal additional benefits on catchment response during large storm events.

During the large storm event, the effectiveness of multiple NFM methods was restricted, producing only a 1% decrease in peak discharge and no change observed in time to peak compared to the 10-year event. The effectiveness of NFM interventions are often reliant upon the desynchronization of flood peaks within tributary watercourses (Dadson et al., 2017; Lane, 2017; Metcalfe et al., 2018). The application of multiple NFM methods across the catchment was not as efficient as implementing a single intervention (e.g., increased soil infiltration). It is important to consider the prospect of flood peak synchronicity (Metcalfe et al., 2018), where decreasing the conveyance of overland flow across the catchment using a combination of NFM methods can increase the likelihood of synchronization of flood peaks if interventions are inappropriately placed (Dadson et al., 2017). It is probable that this is occurring within the 'all NFM' modelled scenario in the Bishopdale catchment and is particularly evident during the large storm event where the reduction in the intensity and the timing of the peak flow are noticeably lower than the smaller storm event. Further investigation is required to identify the key regions of synchronicity within the catchment and to test additional spatial arrangements of NFM interventions on the hydrograph to maximize the effectiveness of NFM interventions.

4.3 | Implications and further research

This study emphasizes the importance of scenario testing to quantify the impacts of different NFM methods in other rural catchments. The different spatial distributions of land use cover presented in other rural catchments should also be studied to test the wider applicability of our results. Interventions such as improved soil infiltration in the Bishopdale catchment could substantially reduce flood hazard due to the large spatial distribution of improved grassland in the catchment. In other catchments where this is not the dominant land use cover contradictory results may be seen. Catchments are more likely to benefit from large catchment scale land use alterations; however, it is recognized that this is not financially viable due to the loss of highly productive agricultural land. Interventions should be targeted in areas of frequent flooding and concentrated in the floodplain and riparian zone where surface roughness exerts the greatest effect on the flood peak. This should be supported by detailed hydrological modelling to critically assess the impact of interventions on catchment response.

A clear limitation of this work has been the lack of river and rain gauge data with which to derive events to test and validate the model. In the United Kingdom, the FEH methods provide a standardized approach for determining flow in ungauged catchments, although the approach can contain a wide range of uncertainties. For this work, the exact value of discharge is less critical than understanding the difference to discharge from a baseline scenario that the NFM scenarios create. This issue is not unique to this catchment, as river monitoring network in the United Kingdom is sparse in these upland areas that now form an essential part of future flood and land management processes. This issue will continue to represent a significant obstacles to future studies, where the aim is quantify the impact, beyond the baseline versus scenario modelling testing demonstrated here. Alongside this, further modelling work should be used to establish the range of events and return periods that the interventions are effective for, as well as the nature of the events that should be tested. In this work, only two events have been considered, but higher frequency events such as the 2- and 5-year events, would also be worth considering. This approach presented here is 'Event-Based'—using individual storms in order to establish the impact of these features on river flow for events of different magnitudes. In order to assess the complete impact, a continuous modelling approach, or approaches that consider different initial conditions, storm profiles, durations and spatial distributions of rainfall are required to assess NFM interventions. This is also an important aspect in developing effective flood management using NFM.

Due to the time constraints of the project, it was not possible to obtain data relating to all the model parameters. The depth of subsurface flow (m) and overland flow conveyance (k_v) data are based on published estimates. This presents a high degree of uncertainty within model parameterization with insufficient detail on key model parameters. The development of a more robust method to determine the active depth of subsurface flow and overland flow velocity of varying land cover types is desirable (e.g., Bond et al., 2020) and will further improve the understanding of the effects of NFM methods on soil properties and improve model predictions by reducing the assumptions made on high level datasets. Data collection should also be extended to consider soils more generally, rather than by land use alone, as has been used in this study. As well as further data collection for model parameters, it is important to establish further quantification of the uncertainty associated with the data obtained and used in this study. Whilst the calibration used in this study has helped establish the validity of the model, further uncertainty analysis is required to understand the implication of these results, and in particular the sensitivity of the results to the parameters presented. These results should be considered as indicative of the potential benefits of NFM, rather than definitive.

5 | CONCLUSIONS

This study provided support for the implementation of NFM interventions to manage flood risk in a rural upland catchment and has highlighted the potential of using model scenarios to assess their effectiveness at the catchment scale. Analysis of soil hydraulic properties indicates that NFM-relevant land management methods exert a significantly strong influence on soil hydraulic conductivity and are beneficial for improving water retention and infiltration. The development of model scenarios in conjunction with the YDRT permitted the assessment of varying spatial arrangements of NFM methods across the Bishopdale catchment. Distributed hydrological modelling permitted the assessment of NFM methods at the catchment scale through the quantification of relative changes to the intensity and timing of peak discharge. Improved soil infiltration on the floodplain due to reduced grazing intensity leads to the amelioration of soil properties and has the capability to consistently mitigate downstream flooding across a range of storm intensities. The addition of widespread catchment woodland would further decrease flood risk during high intensity storm events.

A combination of all modelled NFM interventions was successful at reducing the flood peak during high frequency and low storm intensities. However, the problem of flood peak synchronicity is possibly identified with the combination of multiple NFM interventions less efficient as applying an individual method, indicating NFM is not an additive process in this catchment. This has important ramifications for practitioners and requires a comprehensive understanding of the catchment hydrology prior to implementing NFM across a catchment. While the modelling exercises were based on limited data and would benefit from catchment specific rainfall and discharge data, the initial evidence indicates that NFM interventions employed at the catchment scale can significantly reduce flood risk and can play a pivotal role in protecting rural communities.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

Ambroise, B., Beven, K., & Freer, J. (1996). Application of a generalized TOPMODEL to the small Ringelbach catchment, Vosges, France. *Water Resources Research*, *32*(7), 2147–2159.

Anderson, B. G., Rutherford, I. G., & Western, A. W. (2006). An analysis of the influence of riparian vegetation on the propagation of flood waves. *Environment Modelling and Software*, *21*, 1290–1296.

Archer, N. A. L., Bonell, M., Coles, N., MacDonald, A. M., Auton, C. A., & Stevenson, R. (2013). Soil characteristics and landcover relationships on soil hydraulic conductivity at a hillslope scale: A view towards local flood management. *Journal of Hydrology*, *497*, 208–222.

Basche, A. D., & DeLonge, M. S. (2019). Comparing infiltration rates in soils managed with conventional and alternative farming methods: A meta-analysis. *PLoS One*, *14*(9), e0215702.

Beven, K. (2012). *Rainfall-runoff modelling: The primer* (2nd ed.). Wiley-Blackwell.

Beven, K., & Kirkby, M. (1979). A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin*, *24*, 43–69.

British Geological Survey (BGS) (2019). *Geology of Britain viewer*. https://geologyviewer.bgs.ac.uk

Bharati, L., Lee, K. H., Senhart, T. M., & Schultz, R. C. (2002). Soil-water infiltration under crops, pasture, and established riparian buffer in Midwestern USA. *Agroforestry Systems*, *56*, 249–257.

Black, A., Peskett, L., MacDonald, A., Young, A., Spray, C., Ball, T., Thomas, H., & Werritty, A. (2021). Natural flood management, lag time and catchment scale: Results from an empirical nested catchment study. *Journal of Flood Risk Management*, *14*(3), e12717.

Blanc, J., Wright, G., & Arthur, S. (2012). *Natural flood management (NFM) knowledge system: Part 2—The effect of NFM features on the desynchronising of flood peaks at a catchment scale*. CREW Report.

Boisgontier, H. (2018). *Modelling the potential of natural flood management practices in an upland peatland catchment with the distributed TOPMODEL*. University of Leeds.

Bond, S., Kirkby, M. J., Johnston, J., Crowle, A., & Holden, J. (2020). Seasonal vegetation and management influence overland flow velocity and roughness in upland grasslands. *Hydrological Processes*, *34*, 1–15.

Bond, S., Willis, T., Johnston, J., Crowle, A., Klaar, M., Kirkby, M., & Holden, J. (2022). The influence of land management and season on flood mitigation in two UK upland catchments. *Hydrological Processes*, *32*, 12.

Broadmeadow, S., Thomas, H., Nisbet, T., & Valatin, G. (2018). Valuing flood regulation services of existing forest cover to inform natural capital accounts. *Forest Research*. https://www.forestresearch.gov.uk/publications/valuing-flood-regulation-services-of-existing-forest-cover-to-inform-natural-capital-accounts/

Burgess-Gamble, L., Ngai, R., Wilkinson, M., Nisbet, T., Pontee, N., Harvey, R., Kipling, K., Addy, S., Rose, S., Maslen, S., Jay, H., Nicholson, A., Page, T., Jonczyk, J., & Quinn, P. (2017). *Working with natural processes to manage flood and coastal erosion risk—A guidance document SC150005*. Environment Agency.

Calder, I., & Aylward, B. (2006). Forest and floods: Moving to an evidence-based approach to watershed and integrated flood management. *Water International*, *31*(1), 87–99.

Carroll, Z. L., Bird, S. B., Emmett, B. A., Reynolds, B., & Sinclair, F. L. (2004). Can tree shelterbelts on agricultural land reduce flood risk? *Soil Use and Management*, *20*(3), 357–359.

Catchment Based Approaches (CaBA). (2017). *Natural flood management measures—A practical guide for farmers*. Yorkshire Dales National Park Authority https://catchmentbasedapproach.org/wp-content/uploads/2018/11/North-West-NFM-handbook.pdf

Chartier, M. P., Rostagno, C. M., & Pazos, G. E. (2011). Effects of soil degradation on infiltration rates in grazed semiarid rangelands of northeastern Patagonia, Argentina. *Journal of Arid Environments*, *75*, 656–661.

Chaves, J., Neill, C., Germer, S., Neto, S. G., Krusche, A., & Elsenbeer, H. (2008). Land management impacts on runoff sources in small Amazon watersheds. *Hydrological Processes*, *22*, 1766–1775.

Chow, V. T., Maidment, D. R., & Mays, L. W. (1988). *Applied hydrology* (IV ed.). McGraw-Hill.

Cooper, M., Patil, S., Nisbet, T., Thomas, H., Smith, A., & McDonald, M. (2021). Role of forested land for natural flood management in the UK: A review. *WIREs Water*, *2021*(8), e1541.

Dadson, S. J., Hall, J. W., Murgatroyd, A., Acreman, M., Bates, P., Beven, K., Heathwaite, L., Holden, J., Holman, I. P., Lane, S. N., O'Connell, E., Penning-Rowsell, E., Reynard, N., Sear, D., Thorne, C., & Wilby, R. (2017). A restatement of the natural science evidence concerning catchment-based 'natural' flood management in the UK. *Proceedings of the Royal Society A—Mathematical Physical and Engineering Sciences*, *473*(2), 0160706.

Deng, H., & Sun, S. (2010). Extension of TOPMODEL applications to the heterogeneous land surface. *Advances in Atmospheric Sciences*, *27*(1), 164–176.

Department for the Environment and Rural Affairs DEFRA. (2020). Flood and coastal erosion risk management policy statement. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/903705/flood-coastal-erosion-policy-statement.pdf

Dixon, S. J., Sear, D. S., Odoni, N. D., Sykes, T., & Lane, S. N. (2016). The effects of river restoration on catchment scale flood risk and flood hydrology. *Earth Surface Processes and Landforms*, *41*(7), 997–1008.

Eijkelkamp. (2013). *Laboratory-permeameters: Operating instructions*. Eijkelkamp.

Environment Agency. (2010). *Ouse catchment flood management plan: Summary report*. Environment Agency.

Environment Agency. (2018). *Catchment data explorer*. https://environment.data.gov.uk/catchment-planning/

Evans, R. (1998). The erosional impacts of grazing animals. *Progress in Physical Geography*, *22*(2), 251–268.

Faulkner, D. S., & Barber, S. (2009). Performance of the revitalised flood hydrograph method. *Journal of Flood Risk Management*, *2*, 254–261.

Gao, J., Holden, J., & Kirkby, M. (2015). A distributed TOPMODEL for modelling impacts of land- cover change on river flow in upland peatland catchments. *Hydrological Processes*, *29*(13), 2687–2879.

Gao, J., Holden, J., & Kirkby, M. (2016). The impact of land-cover change on flood peaks in peatland basins. *Water Resources Research*, *52*(5), 3477–3492.

Gao, J., Holden, J., & Kirkby, M. (2017). Modelling impacts of agricultural practice on flood peaks in upland catchments: An application of the distributed TOPMODEL. *Hydrological Processes*, *31*(23), 4206–4216.

Gonzalez-Sosa, E., Braud, I., Dehotin, J., Lassabateere, L., Angullo-Jaramillo, R., Branger, F., Jacqueminet, C., Kermadi, S., & Michel, K. (2010). Impact of land use on the hydraulic properties of the topsoil in a small French catchment. *Hydrological Processes*, *24*, 2382–2399.

Greenwood, K. L., MacLeod, D. A., Scott, J. M., & Hutchinson, K. J. (1998). Changes to soil physical properties after grazing exclusion. *Soil Use and Management*, *14*(1), 19–24.

Hankin, B., Metcalfe, P., Johnson, D., Chappell, N. A., Page, T., Craigen, I., Lamb, R., & Beven, K. (2017). *Strategies for testing the impact of natural flood risk management measures*. InTech.

Hao, M., Zhang, J., Meng, M., Chen, H., Guo, X., Liu, S., & Ye, L. (2019). Impacts of changes in vegetation on saturated hydraulic conductivity of soil in subtropical forests. *Scientific Reports*, *9*, 8372.

Hénault-Ethier, L., Larocque, M., Perron, R., Wiseman, N., & Labrecque, M. (2017). Hydrological heterogeneity in agricultural riparian buffer strips. *Journal of Hydrology*, *546*, 276–288.

Her, Y., & Chaubey, I. (2015). Impact of the number of observations and calibration parameters on equifinality, model performance, and output and parameter uncertainty. *Hydrological Processes*, *29*(19), 4220–4237.

Holden, J., Grayson, R. P., Berdini, D., Bird, S., Chapman, P. J., Edmondson, J. L., Firbank, L. G., Helgason, T., Hodson, M. E., Hunt, S. F. P., Jones, D. T., Lappage, M. G., Marshall-Harries, E., Nelson, M., Prendergast-Miller, M., Shaw, H., Wade, R. N., & Leake, J. R. (2019). The role of hedgerows in soil functioning within agricultural landscapes. *Agriculture, Ecosystems and Environment*, *271*, 1–12.

Holden, J., Shotbolt, L., Bonn, A., Burt, T. P., Chapman, P. J., Dougill, A. J., Fraser, E. D. G., Hubacek, K., Irvine, B., Kirkby, M. J., Reed, M. S., Prell, C., Stagl, S., Stringer, L. C., Turner, A., & Worrall, F. (2007). Environmental change in moorland landscapes. *Earth-Science Reviews*, *82*(1), 75–100.

Iacob, O., Brown, I., & Rowan, J. (2017). Natural flood management, land use and climate change trade-offs: The case of tarland catchment, Scotland. *Hydrological Sciences Journal*, *62*(12), 1931–1948.

Jackson, B. M., Wheater, H. S., McIntyre, N. R., Chell, J., Francis, O. J., Frogbrook, Z., Marshall, M., Reynolds, B., & Solloway, I. (2008). The impact of upland land management on flooding: Insights from a multiscale experimental and modelling programme. *Journal of Flood Risk Management*, *1*(2), 71–80.

Kalhoro, S., Xu, X., Ding, K., Chen, W., Shar, A. G., & Rashid, M. (2018). The effects of different land uses on soil hydraulic properties in the Loess Plateau, Northern China. *Land Degradation and Development*, *29*(11), 3907–3916.

Kirkby, M. J. (1997). TOPMODEL: A personal view. *Hydrological Processes*, *11*, 1087–1097.

Kjeldsen, T. (2015). How reliable are design flood estimates in the UK? *Journal of Flood Risk Management*, *8*, 237–246.

Lane, S. L., Morris, J., O'Connell, E., & Quinn, P. F. (2007). Chapter 18: Managing the rural landscape. In C. R. Thorne, E. P. Evans, & E. C. Penning-Rowsell (Eds.), *Future flooding and coastal erosion risks* (pp. 297–319). Thomas-Telford.

Lane, S. N. (2017). Natural flood management. *Wiley Interdisciplinary Reviews: Water*, *4*, c1211.

Li, Y. Y., & Shao, M. A. (2006). Change of soil physical properties under long-term natural vegetation restoration in the loess plateau of China. *Journal of Arid Environments*, *64*, 77–96.

Lo, H. W., Smith, M., Klaar, M., & Woulds, C. (2021). Potential secondary effects of in-stream wood structures installed for natural flood management: A conceptual model. *WIREs Water*, *8*, e1546. https://doi.org/10.1002/wat2.1546

Madi, H., Mouzai, L., & Bouhadef, M. (2013). Plants cover effects on overland flow and on soil erosion under simulated rainfall intensity. *International Journal of Environmental and Ecological Engineering*, *7*(8), 561–565.

Marshall, M. R., Ballard, C. E., Frogbrook, Z. L., Solloway, I., McIntyre, N., Reynolds, B., & Wheater, H. S. (2014). The impact of rural land management changes on soil hydraulic properties and runoff processes: Results from experimental plots in upland UK. *Hydrological Processes*, *28*(4), 2617–2629.

McGlynn, B. L., & McDonnell, J. J. (2003). Quantifying the relative contributions of riparian and hillslope zones to catchment runoff. *Water Resources Research*, *29*(11), 1310.

Metcalfe, P., Beven, K., Hankin, B., & Lamb, R. (2018). A new method, with application, for analysis of the impacts on flood risk of widely distributed enhanced hillslope storage. *Hydrology and Earth System Sciences*, *22*(4), 2589–2605.

Monger, F., Spracklen, D., Kirkby, M., & Scofield, L. (2021). The impact of semi-natural broadleaf woodland and pasture on soil properties and flood discharge. *Hydrological Processes.*, *36*, e14453.

NERC. (2012). *Rainfall map based on met Office standard average annual rainfall 1961–1990*. https://nrfa.ceh.ac.uk/data/search

Nguyen, M. L., Sheath, G. W., Smith, C. M., & Cooper, A. B. (1998). Impact of cattle treading on hill land: 2. Soil physical properties and contaminant runoff. *New Zealand Journal of Agricultural Research*, *41*(2), 279–290.

Nicholson, A. R., Wilkinson, M. E., O'Donnell, G. M., & Quinn, P. F. (2012). Runoff attenuation features: A sustainable flood mitigation strategy in the Belford catchment, UK. *Area*, *44*(4), 463–469.

O'Connell, E., Ewen, J., O'Donnell, G., & Quinn, P. F. (2007). Is there a link between agricultural land-use management and flooding? *Hydrology and Earth System Sciences*, *11*(1), 96–107.

Ordnance Survey. (2018). *OS terrain 5*. https://digimap.edina.ac.uk

Parrott, A., Brooks, W., Harmar, O., & Pygott, K. (2009). Role of rural land use management in flood and coastal risk management. *Journal of Flood Risk Management*, *2*(4), 272–284.

Pechlivanidis, I. G., Jackson, B. M., McIntyre, N. R., & Wheater, H. S. (2011). Catchment scale hydrological modelling: A review of model types, calibration approaches and uncertainty analysis methods in the context of recent developments in technology and applications. *Global NEST Journal*, *13*, 193–214.

Peskett, L., MacDonald, A., Heal, K., McDonnell, J., Chambers, J., Uhlemann, S., Upton, K., & Black, A. (2020). The impact of across-slope forest strips on hillslope subsurface hydrological dynamics. *Journal of Hydrology*, *581*, 124427.

Price, K., Jackson, R. C., & Parker, A. J. (2010). Variation of surficial soil hydraulic properties across land uses in the southern blue Ridge Mountains, South Carolina, USA. *Journal of Hydrology*, *383*, 256–268.

Ren, Z., Zhu, L., Wang, B., & Cheng, S. (2016). Soil hydraulic conductivity as affected by vegetation restoration age on the Loess Plateau, China. *Journal of Arid Land*, *8*(4), 546–555.

Rogger, M., Agnoletti, M., Alaoui, A., Bathurst, J. C., Bodner, G., Borga, M., Chaplot, V., Gallart, F., Glatzel, G., Hall, J., Holden, J., Holko, L., Horn, R., Kiss, A., Kohnova, S., Leitinger, G., Lennartz, B., Parajka, J., Perdigao, R., … Bloschl, G. (2017). Land use change impacts on floods at the catchment scale: Challenges and opportunities for future research. *Water Resources Research*, *53*(7), 5209–5219.

Rowland, C. S., Morton, R. D., Carrasco, L., McShane, G., O'Neil, A. W., & Wood, C. M. (2017). Land cover map 2015 (vector, GB) NERC environmental information data centre. *Centre for Ecology and Hydrology*. https://doi.org/10.5285/6c6c9203-7333-4d96-88ab-78925e7a4e73

Smith, M. (2014). Roughness in the earth sciences. *Earth Science Reviews*, *136*, 202–225.

Stratford, C., Miller, J., House, A., Old, G., Acreman, M., Dueñas-Lopez, M. A., Nisbet, T., Newman, J., BurgessGamble, L., Chappell, N., Clarke, S., Leeson, L., Monbiot, G., Paterson, J., Robinson, M., Rogers, M., & Tickner, D. (2017). *Do trees in UK-relevant river catchments influence fluvial flood peaks?* (p. 46). NERC.

Thomas, H., & Nisbet, T. (2012). Modelling the hydraulic impact of reintroducing large woody debris into watercourses. *Journal of Flood Risk Management*, *5*(2), 164–174.

Thomas, H., & Nisbet, T. R. (2007). An assessment of the impact of floodplain woodland on flood flows. *Water and Environment Journal*, *21*, 114–126.

Tiwari, T., Lundstrom, J., Kuglerova, L., Laudon, H., Ohman, K., & Agren, A. M. (2016). Cost of riparian buffer zones: A comparison of hydrologically adapted site-specific riparian buffers with traditional fixed widths. *Water Resources Research*, *52*(5), 1056–1069.

UK Soil Observatory (UKSO) (2019). Accessed April 03 2023. https://www.landis.org.uk/soilscapes/

White, A. (2019). New natural flood defences will protect dales farms. *The Northern Echo*. https://www.thenorthernecho.co.uk/news/17403070.new-natural-flood-defences-will-protect-dales-farms/

Wren, E., Barnes, M., Janes, M., Kitchen, A., Nutt, N., Patterson, C., Piggott, M., Robins, J., Ross, M., Simons, C., Taylor, M., Timbrell, S.,

Turner, D., & Down, P. (2022). *The natural flood management manual, C802*. CIRIA.
Yorkshire Dales Rivers Trust (YDRT) (2014). https://www.ydrt.org.uk/what-we-do/projects/past-projects/bishopdale-nfm/
Zhao, Y., Wu, P., Zhao, S., & Feng, H. (2013). Variation of soil infiltrability across a 79-year chronosequence of naturally restored grassland on the Loess Plateau, China. *Journal of Hydrology*, *504*, 94–103.
Zhou, X., Lin, H. S., & White, E. A. (2008). Surface soil hydraulic properties in four soil series under different land uses and their temporal changes. *Catena*, *73*, 180–188.
Zimmermann, B., Elsenbeer, H., & De Moraes, J. M. (2006). The influence of land-use changes on soil hydraulic properties: Implications for runoff generation. *Forest Ecology and Management*, *222*, 29–38.

SUPPORTING INFORMATION

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

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