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Original Article

Catchment woodland planting and the benefits to flood reduction

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Abstract

Tree planting is considered to be an effective, low maintenance approach for reducing flood risk in catchments, primarily by interception, increasing water infiltration and surface roughness. Identifying optimal tree planting scenarios for hydrological benefits is an important aspect of developing wider and long-term woodland planting strategies in relation to natural flood management and nature-based solutions interventions. In this study, we apply a spatially distributed hydrological model to explore six different woodland planting scenarios that are limited to between 10% and 2% of the catchment area. We evaluate which approach is the most effective in reducing overland flow, reducing downstream flow volumes and flood peaks and delaying those peaks for three UK catchments: the Lowther, Ennerdale, and Colne valleys. We further explore whether the possibility of identifying target areas for tree planting can be achieved by exploring the physical properties of the areas of woodland that individually achieve the greatest flood attenuation. Large randomly located areas of planting are shown to have the highest overall benefit (10% peak flow reduction); however, planting schemes that focus on river corridors are more effective when considering the hydrological benefit per hectare (∼2–3 times more effective). No single underlying characteristic or combination of characteristics are found to define better performing regions of planting, indicating that designing optimized planting schemes will be location specific, and require detailed modeling.

Keywords: catchments; woodlands; hydrology

Introduction

Flooding is a complex and devastating hazard that is predicted to increase due to climate change (Lowe et al. 2018). Natural Flood Management (NFM) is seen as critical tool in the development of flood mitigation strategies (Environment Agency 2018, Wren et al. 2022). NFM is a broad term that involves the creation of interventions that work with and promote natural processes to slow the flow in critical parts of the catchment to create a cumulative benefit to downstream regions and communities (Environment Agency 2018). These approaches include land cover and management changes to encourage overland flow to be stored, slowed, or infiltrated, thus reducing the risk of flooding (Lane 2017). A key part of this land management approach is to increase tree coverage (Burgess-Gamble et al. 2017, Dadson et al. 2017), which can help reduce flood impact by increasing soil water holding capacity, increasing ground surface roughness and enhancing infiltration and wet canopy evaporation (Page et al. 2020). As the UK attempts to increase the coverage of woodland from 10% to 16.5% in England by 2060 and in Scotland from 17% to 21% as part of the Environmental Improvement Programme (GOV.UK 2023), developing effective strategies that target flood benefits from tree planting will be critical (UK Government 2021). This is particularly important in the North of England, where tree coverage is below the UK national average (7.3%) and significant efforts are being made to increase tree coverage through programs such as the Northern Forest (thenorthernforest.org.uk).

The effects of tree planting on river discharge and overland flow have been demonstrated in a variety of settings and are well documented. For example, Revell et al. (2021) used observed infiltration rates to parametrize a 2D hydraulic model and to demonstrate the benefits of tree planting for a variety of storms. Dixon et al. (2019) analysed the evolution of the benefit of tree planting in the riparian zone demonstrating the increasing reduction in peak values over the development of the tree canopy while Monger et al. (2022a) demonstrated the reductions to flood peaks in a modeling exercise that used extensive tree planting in a small upland catchment in the UK. Further studies have also demonstrated that these observed benefits are location dependent: i.e. different parts of the catchment will bring different benefits to flood risk reduction from woodland planting. For example, Thomas and Nisbet (2007) and Nisbet and Thomas (2008) demonstrated the potential benefits of floodplain planting, while Dixon et al. (2019) demonstrated the potential benefits of riparian planting. Kingsbury-Smith et al. (2023) evaluated catchment wide woodland planting plans including riparian planting and opportunity mapping based woodland planting in the Bishopdale

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catchment noting a reduction to flood peaks in the 1 in 10 and 1 in 100-year floods. Monger et al. (2022a) demonstrated the combined benefits of broadleaved woodland and bracken plants by studying the impact on soil conductivity and overland flow velocity, noting a 20% reduction in overland velocities compared to pasture based woodland. Monger et al. (2024) also found benefits to reducing flood peaks between 2%–15% for a 1 in 50-year storm event for various types of woodland planting in an small (2.4 km) uphill catchment in the UK, depending on the configuration of woodland planting. Overall, these studies tend to focus on location specific planting schemes and in single catchments which provide insights into the effects of woodlands for individual catchments and events, but provide limited opportunity to understand the wider implications of these schemes. There has been limited research to evaluate the benefits of different woodland planting scenarios in different events and catchments. Further, understanding how the spatial configuration of a woodland planting scenario could be optimized for multiple benefits, beyond approaches of planting that are typically used for flood risk management such as cross slope and contour planting, are not widely explored.

While the role of woodlands and tree planting in mitigating flood effects is widely appreciated, determining general strategies for woodland creation schemes with targeted and priority planting areas is difficult (Cooper et al. 2021). Further, devising planting approaches that optimize multiple benefits around increasing woodland cover such as ecological and diversity improvements are also difficult to determine (Burton et al. 2018). Future planting schemes will inevitably have to include wider considerations as part of dealing with the impacts of climate change. There is a current gap to understanding if ecological and flood reduction benefits can be achieved in the same planting scheme, and if locations for woodland creation that achieve both these benefits exist in catchments with limited planting opportunities (Cooper et al. 2021). Evidence beyond single site modeling studies is fragmented and more work is required to determine these joint impacts (Carrick et al. 2019).

In this study, we aim to understand the impacts of potential woodland planting scenarios across three catchments and across a series of observed storm events in order to provide a comprehensive view of the potential benefits of various woodland creation approaches. By assessing multiple approaches to woodland planting with a focus on the wider benefits of woodland planting, the results can be used to identify broad catchment management strategies and plans which are not location dependent. The woodland planting scenario will represent a different overall strategy for planting in a catchment, which could be applied within any catchment in a temperate climatic region. Each woodland planting scenario is designed with broad strategic considerations, including ecological connectivity, rather than a specific application, such as flood risk reduction. As such, woodland planting schemes that include cross-slope tree planting (where trees are planted across slopes, at the same elevation, effectively creating a barrier for water flowing down the hill slope) are not included and instead each woodland has wider potential benefits and impacts, rather than explicit reduction of overland flow which are considered in other approaches (Nisbet 2022). The results should then provide some insight into general guidance on tree planting that can be used to inform management strategies.

The study is based on developing these woodland planting scenarios and testing the benefits using the spatially distributed hydrological model SD-TOPMODEL (Gao et al. 2015), which has been used to assess the benefits of woodland creation in other catchment settings (Monger et al. 2021), to determine the impact of the change of land cover on the hydrology of the catchment. This impact is evaluated across a portfolio of storms, each grouped into different fundamental characteristics, including synthetic storms, large events, and seasonal storms. This approach of using multiple events with different characteristics overcomes some of the issues relating to studies where single events are used (Pham and Alila 2024), and where conclusions may be limited to the few events that have been modeled or observed. The study catchments are located in the north of England (Fig. 1 where the development of the Northern Forest will represent a significant increase in woodland coverage in the next decade, with the results providing general conclusions that can help landowners in the development of tree planting plans and strategies.

Methodology

Study site

Three catchments are used to assess the potential tree planting scenarios, the Lowther and Ennerdale catchments, both located in Cumbria and the Colne catchment, located in West Yorkshire. Each catchment has similar topographic and land cover characteristics, but with variations in the distribution of land cover types that collectively provide insights into the potential impacts of woodland planting on catchment hydrology. As is common in Northern England, extensive parts of the catchments are used for sheep grazing (Cooper et al. 2021). All three catchments are characterized by steep upland hills that are predominately covered in moorland and cover extensive areas. The catchments are relatively large with Ennerdale and Colne measuring 70 and 75 km^2, while the Lowther is more extensive (155 km^2), with an average elevation of 357 m for Lowther, 283 m for Ennerdale and 297 m for Colne. Within each catchment are significant reservoirs and lakes each of which have an attenuating effect on flow, notably the Haweswater reservoir in Lowther, and Enner Water in Ennerdale. The Colne valley contains multiple reservoirs in the upper reaches of the river. The Lowther and Ennerdale catchments are predominately rural, with 60%–80% being covered with grasslands, which dominate the lower slopes of those valleys, while the lower reaches of the Colne are dominated by the urban area of Huddersfield, as illustrated in Figure 1. The river channel has been partially modified in the urban areas of the Colne, with culverting and straightening evident in these regions. All three catchments have a history of flooding, with the Colne valley most notably affected by the wide-ranging Boxing Day 2015 floods (26 December 2015) that impacted large parts of the north of England. Existing woodland varies between each catchment. While the Lowther and Colne have relatively low woodland cover (14% and 7%, respectively), Ennerdale contains significant areas of mainly commercial timber in the upper reaches (25%). The three catchments are typical of catchments in the north of England, and can be further characterized as being rural with limited woodland (Lowther), rural with extensive upper catchment woodland (Ennerdale), and urban with limited woodland (Colne).

Baseline hydrological model

We implemented the tree planting scenarios using SD-TOPMODEL, a spatially distributed version of the hydrological model TOPMODEL that has been used previously to assess the impact of changing land cover and management practices on catchment hydrology (Gao et al. 2017, Gao et al. 2016, Bond et al. 2023, Kingsbury-Smith et al. 2023, Monger et al. 2024). The model

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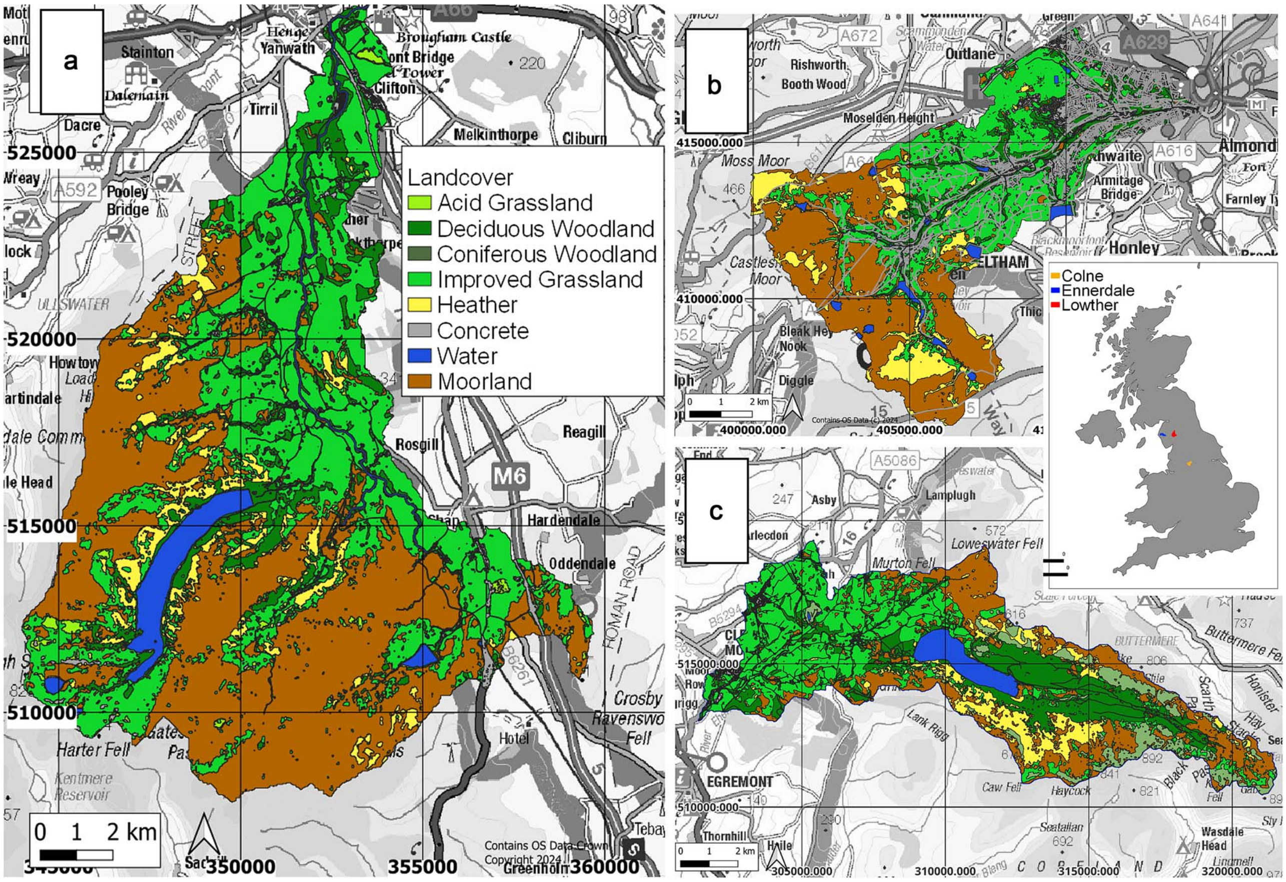

Figure 1. Location and existing landcover of the three catchments, Lowther (a), Colne (b), and Ennerdale (c), with location in the UK (inset) and with EPSG 27700 coordinates. Land cover classes are determined from UK CEH LandCover 2022 data, and based on the processing of sentinel 2 data described in section 3.1.

provides an ideal modeling approach for comparing land cover change through woodland planting schemes. The model uses a soil moisture deficit approach for determining subsurface water volume (Beven and Kirkby 1979) coupled to a subsurface connectivity module to represent subsurface flow and a stochastic overland flow module to represent surface flow. The equations are disaggregated to a 2D cell approach which allows land cover and flow processes to be represented at the model cell level. The model requires three inputs: a notional hydraulic conductivity of the soil, K (m hr-1); active depth of subsurface flow m (a scaling parameter, normally described as depth, m); and overland flow conveyance Kv (a dimensionless coefficient factor, analogous to the inverse of the Darcy Weisbach friction factor) (Gao et al. 2015, Boisgontier 2018). A full overview of the model is given in Gao et al. (2015). For each of the three test catchments, a baseline model is developed with the underlying land cover of the catchment being represented by spatial distributing the three key parameters of SD-TOPMODEL. This is achieved by using the land scaling factor approach that has been used in previous studies using SD-TOPMODEL (Kingsbury-Smith et al. 2023). In this approach the parameters for the largest land cover type (improved grassland) are determined in a calibration exercise (which are typically the events that will be used in the study, for example in this study the 1 in 10 year return period synthetic events), while other land use values are fixed according to the relative difference in parameter values between the largest land cover type and the other land covers. This approach has been used in previous studies (Kingsbury-Smith et al. 2023, Bond et al. 2023) and allows a high model performance to be achieved, while retaining key information about the relative differences in land cover types, and accepting the uncertainty that will be inherent in the simplified physics approaches of TOPMODEL. These values are summarized in Table 1, and show how the model parameters are used to represent different land cover types. These values are determined from literature and field data, a fully summary of which is provided in Kingsbury-Smith et al. 2023.

Table 1. Relative land cover parameter values for the eight land cover classes used in the models.

Land classification	*K* (mm/hr) Scale	*Kv* (–) Scale	*m* (mm) Scale
Acid grassland	1	1	1
Improved grassland	0.5	0.8	1
Deciduous woodland	0.9	2.4	1.5
Coniferous woodland	0.9	2.4	1.5
Heather	1	0.5	1.5
Moorland	1	1.6	1.5
Concrete	0.1	5	0.1
Water	1	2	0.1

The baseline model was developed using major land cover type maps derived from 10 m Sentinel-2 imagery (Fig. 1). The major land cover types are divided into eight land use classes, including deciduous and coniferous woodland areas (which were determined from comparison with UK CEH Land Cover data).

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Sentinel 2 image capture was taken on 25/06/2020 for Colne and 10/08/2022 for Ennerdale and Lowther, with <5% cloud cover and downloaded from the Copernicus Data Space Ecosystem hub in a pre-processed form (Copernicus 2024 https://dataspace.copernicus.eu/). We applied a pixel based supervised classification which takes a shapefile of polygons of known land types, and samples all pixels from within the polygon to represent the land class (this can be several 1000 per class) for training the model, which is then used to create prediction rasters. A neural network model within the R caret package (Kuhn 2008) was used for creating prediction rasters at each catchment. The validity of the data was confirmed with a visual inspection of satellite imagery with the proposed land classification. Full details of the process, including R code, can be found at https://github.com/andyspeak/landclass.

Woodland areas also have an additional fixed parameter from other land use types—rainfall interception, which is represented in the model as a fixed percentage reduction of rainfall. For deciduous woodland this is represented as 0.8, and for coniferous as 0.6 (Boisgontier 2018). It should be noted that an important assumption is that this rainfall is lost in the system, and transpiration is not considered. We accept this as an assumption in the context of the modeling which is concerned with looking at the impact of extreme rainfall events. Concrete surfaces are represented as near impervious surfaces with low friction surface, with buildings represented as small blockages, while watercourse and reservoirs are represented as shallow subsurface layers, with a similar low energy loss surface. The terrain data is derived from OS Terrain 5 data (Ordnance Survey 2022), and resampled to 10 m for the Colne and Ennerdale catchments and 20 m for the Lowther. This was primarily to ensure that watercourse sinks were removed from the terrain data and can be used in the hydrological model. For Ennerdale, further terrain data was collected using a DJI Mavic 3 Enterprise RTK UAV data in July 2023 to improve the resolution of terrain in the upper catchment. This survey was limited to the eastern most extent, covering the top 1 km^2 of the catchment, which is predominantly grassland or rocky landcover. The results from the survey were then resampled and incorporated into the 10 m terrain data.

As part of the development of the baseline models, a suite of rainfall events was selected which represented different storm conditions and profiles from each catchment. In total 13 simulations were created which are a combination of synthetic storm events and observed events (Table 2). The motivation for this selection is to understand the impacts in different storm conditions, where storm profiles, initial conditions and rainfall intensity vary thus giving more insight into the hydrological implications of the tree planting scenarios. Three categories were defined: (i) synthetic storm events with increasing return period values for fixed duration events; (ii) observed annual maximum (AMAX) events, which are the largest observed events in each catchment; and (iii) seasonal storms, representing specific storms conditions, as described below.

To derive 'synthetic events' for each catchment, the estimated outflow for five return periods (based on a 12-hour storm) were calculated using Flood Estimation Handbook and Revitalized Handbook methods and FEH22 rainfall data (Institute of Hydrology 1999, Kjeldsen 2007). Assessing across 5 return periods (5, 10, 20, 50, 100 years) provides an insight into the effectiveness of the woodland planting scenarios for different intensities and magnitude of storms.

Using the National River Flow Archive database gages within each catchment (NRFA 2024), we analysed the discharge data to determine storm events in the catchment. The 'AMAX' event selection was based on determining the largest events on record, and selecting corresponding 15-minute rainfall data using the Hydrological Data Explorer to locate rainfall gages (https://environment.data.gov.uk/hydrology/explore). For Ennerdale, where the only river gage occurs in the middle of the catchment, and Colne where the only data available is daily average discharge, estimations of the assumed discharge were based on using the statistical approach of the Flood Estimation Handbook (FEH, Institute of Hydrology 1999). The selected events consisted of the five largest events for each gage record (~40 years for all gages), referred to as Observed AMAX event, and three additional events that combined events of smaller magnitude but contrasting rainfall characteristics; namely, a summer storm characterized with periods of intense rainfall (>5 mm/hr-1 for some period of the event) and two winter storms derived from frontal systems. These final three storm types are referred to as 'seasonal storms'. Each storm was added as a rainfall boundary condition to the model with a 15-minute timestep to match the simulation. Each simulation would begin with a 2 or 3 hour warm up period, followed by a 6–12 hour drying phase to allow flow to return to near normal baseflow rates (~10% of initial flow rates). An example of the types of profiles generated from this approach are displayed in Fig. 2, which show the eight observed events for the Lowther catchment. The profile for all the storms and for all three catchments are provided in Supporting information, Section 1.

For each baseline a calibration and validation exercise were undertaken in which the model outputs were compared to the FEH estimated flow for the 1 in 20 year and 1 in 100 year flood events, using Nash-Sutcliffe efficiency as a comparison of the difference in peak value as performance metrics. Calibration was undertaken by sampling 120 parameter sets from a range of values for the three key parameters (Kv: 10–50, K: 200–300, m: 0.008–0.03), for each catchment. The range of parameters provide a wide range of results with which to select an optimal set of parameters. The baseline was parametrized by selecting the single parameter set that provided the highest NSE and difference in peak values, and also provided reasonable metrics for a second validation event to confirm that these values could be used to sufficiently model other events (where values of NSE > 0.7, difference in peak <0.3 m were considered to be adequate).

Afforestation scenarios

We examined six tree planting scenarios representing broad strategies for tree planting with multiple benefits in the catchment (Fig. 3). The landscape was first divided into polygon, with each polygon assigned a modal land cover from the underlying land classification raster. The polygons were created using a novel approach based on real-world land divisions from the UK government INSPIRE dataset (INSPIRE 2023, Speak et al. in press). Larger polygons were subdivided into smaller 'patches' with a mean average size of 1.3 ha which is the median size of existing National Forestry Inventory woodland patches (Forestry Commission 2024) utilizing k-means clustering to create Voronoi polygons. This was achieved with a custom R function (see aforementioned GitHub page) and the resulting subdivided polygon vector files served as input for woodland creation simulation models based on six scenarios. Each tree planting scenario assumes a fully developed and closed canopy. The changes that are made to the spatially distributed parameters for each land cover type to represent these new woodland creation scenarios are summarized in Table 3.

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Table 2. Summary of the range of events for each catchment. The return period for each observed event is referenced in brackets next to each event.

Simulation number	Event type	Lowther	Ennerdale	Colne
1	Synthetic	12-hour, 1 in 5 year	12-hour, 1 in 5 year	12-hour, 1 in 5 year
2	Synthetic	12-hour, 1 in 10 year	12-hour, 1 in 10 year	12-hour, 1 in 10 year
3	Synthetic	12-hour, 1 in 20 year	12-hour, 1 in 20 year	12-hour, 1 in 20 year
4	Synthetic	12-hour, 1 in 50 year	12-hour, 1 in 50 year	12-hour, 1 in 50 year
5	Synthetic	12-hour, 1 in 100 year	12-hour, 1 in 100 year	12-hour, 1 in 100 year
6	Observed AMAX	4–6 October 2015 (1 in 48 year)	18–20 November 2009 (1 in 50 year)	20–22 January 2008 (1 in 44 year)
7	Observed AMAX	18–21 November 2009 (1 in 24 year)	10–12 October 2017 (1 in 25 year)	15–17 March 2019 (1 in 22 year)
18	Observed AMAX	6–8 January 2005 (1 in 14 year)	25–26 October 2008 (1 in 16 year)	18–22 January 2021 (1 in 15 year)
9	Observed AMAX	8–10 February 2020 (1 in 10 year)	15–17 November 2015 (1 in 12 year)	6–7 July 2012 (1 in 7 year)
10	Observed AMAX	10–12 January 2009 (1 in 8 year)	25–26 December 2003 (1 in 7 year)	9 February 2012 (1 in 5.5 year)
11	Observed Seasonal	2–4 February 2004 (1 in 8)	9–11 January 2006 (1 in 4 year)	6–7 November (1 in 5 year)
12	Observed Seasonal	1–3 February 2002 (1 in 8 year)	19–20 February 2020 (1 in 4 year)	25–27 December 2015 (1 in 5 year)
13	Observed Seasonal	9–10 August 2004 (1 in 7 year)	21–23 June 2012 (1 in 3 year)	24–26 June 2007 (1 in 2.75 year)

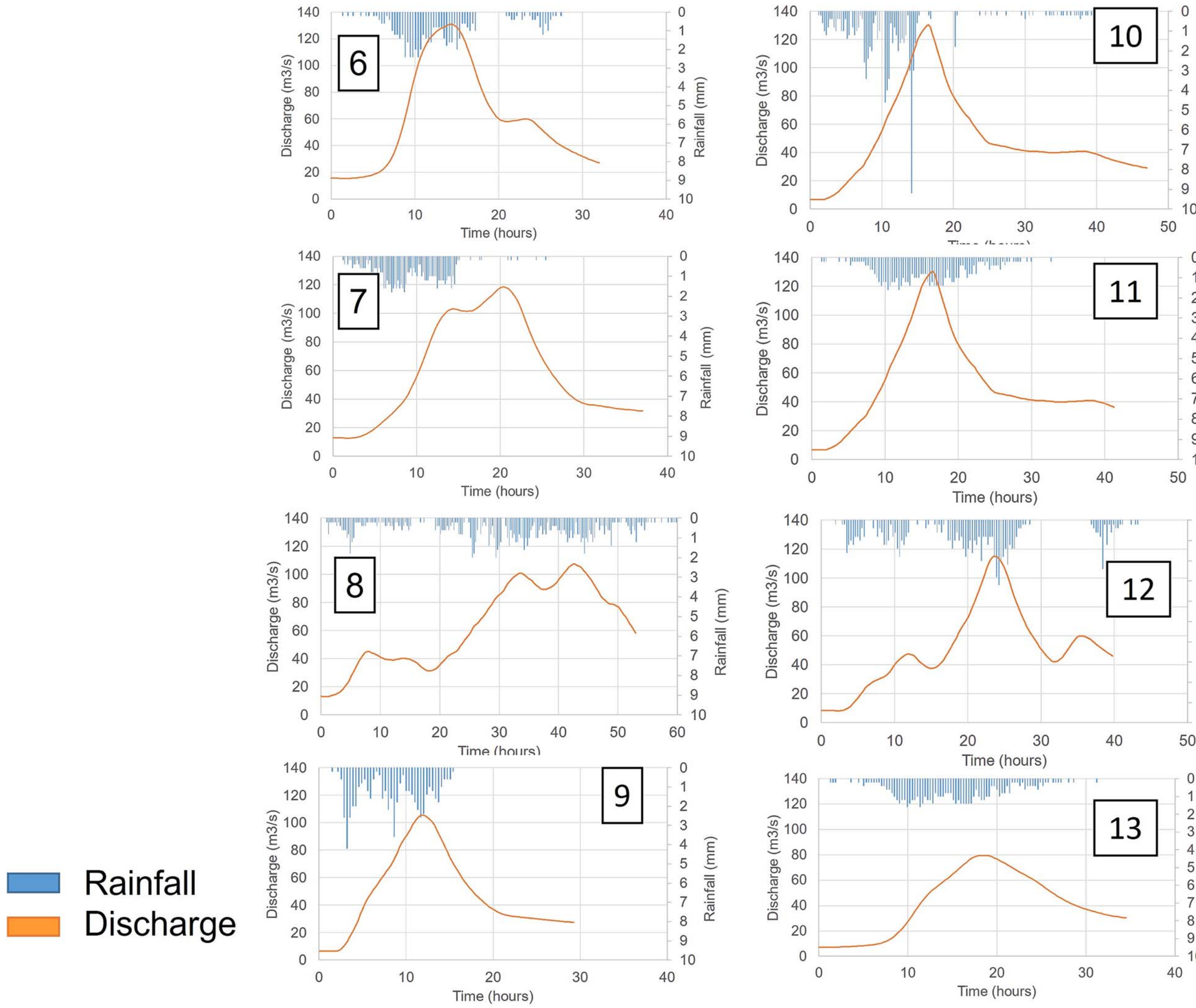

Figure 2. Storm event hydrographs for the Lowther catchment with each event from Table 2 numbered for each hydrograph.

The first scenario is to create a riparian zone woodland planting scenario, using a 20 m buffer (10 m each side of the river) along the main river network in each catchment ('Riparian Planting'). The second and third scenarios involve increasing the area of existing woodland patches adjacent to the river network (i.e. within 20 meters of the river) by 10% and 40% by adding new woodland patches in a proximal growth fashion, expanding each woodland from the center of the polygon, excluding areas that coincide with the river. Unlike the riparian buffer, this scenario does not cover the entire river network with a level of woodland planting but rather aims to expand existing woodland areas. The fourth and fifth scenarios were based on creating random patches

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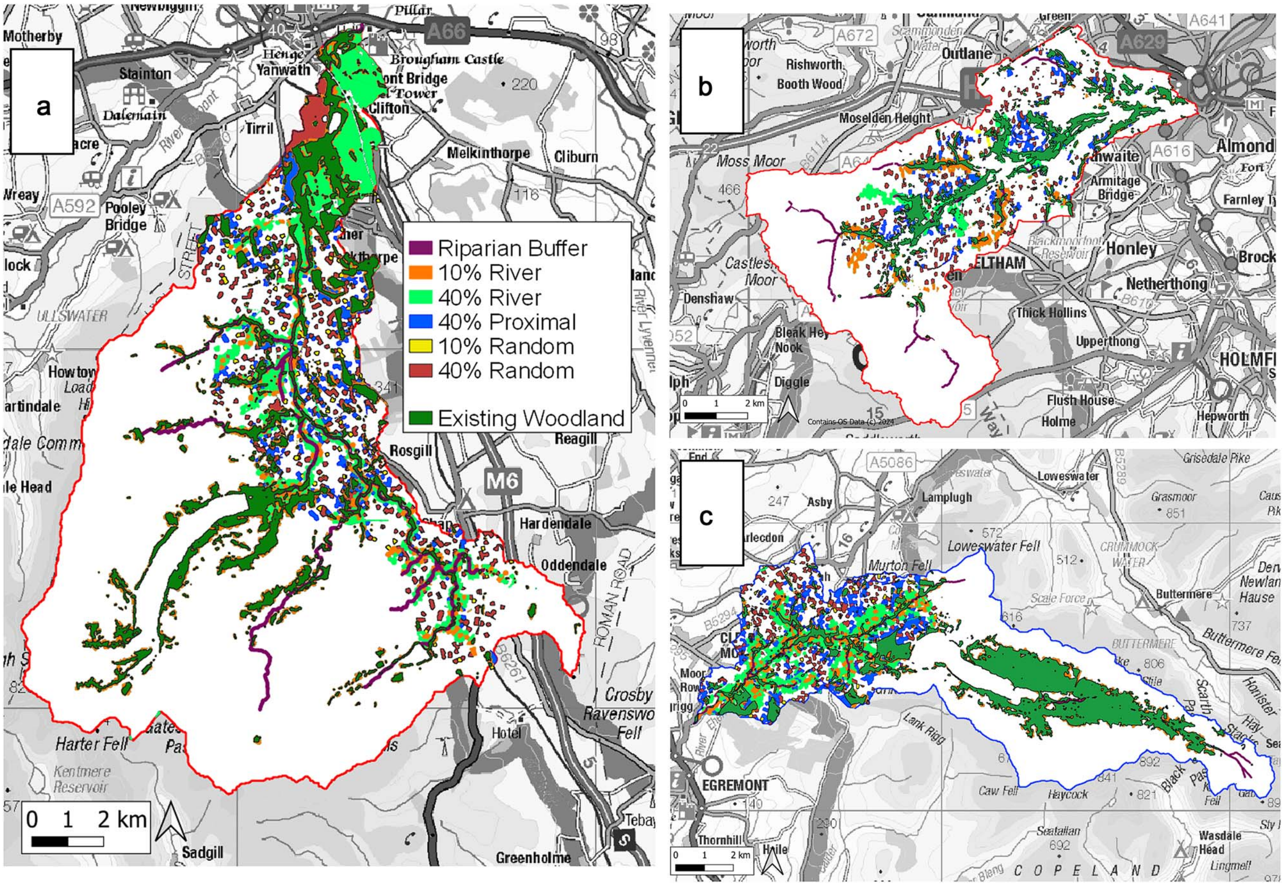

Figure 3. Woodland planting scenarios for the three catchments: Lowther (a), Colne (b), and Ennerdale (c).

Table 3. Summary of the tree planting scenarios and changes to catchment landcover.

	Increase in woodland coverage km^2 (percentage increase)					
	Ennerdale		Lowther		Colne	
Planting scenario	km^2 (percent change of woodland)	Total catchment area change	km^2 (percent change of woodland)	Total catchment area change	km^2 (percent change of woodland)	Total catchment area change
Existing woodland	15.1	20%	15.01	9%	5.43	8%
Riparian	0.3 km (2%)	20%	0.6 km (4%)	9%	0.8 km (15%)	8%
10% River	0.47 (3%)	21%	3.9 (12%)	12%	1.7 (31%)	10%
40% River	6.42 (43%)	29%	12.6 (84%)	18%	2.3 (44%)	11%
Small random	1.78 (12%)	23%	3.9 (26%)	12%	2.75 (51%)	11%
Large random	5.99 (40%)	28%	13.6 (91%)	19%	2.95 (54%)	12%
40% Proximal	5.99 (40%)	28%	13.2 (88%)	19%	3.54 (65%)	12%
Optimal	3.32 (22%)	25%	4.2 (28%)	13%	1.38 (25%)	9%

of woodland throughout the catchment again. Each patch has a similar size of ∼1–2 km^2, with the two scenarios aiming to cover 10% and 40% of available land (i.e. grassland and ignoring moorland or existing urban and woodland areas). As these areas vary between catchments and the planting scenarios create different percentage of landcover change, we refer to them as the Small and Large random planting scenarios. These random patches create more of a mosaic effect across the catchment compared to the other scenarios with no large single area of woodland being reintroduced. The final scenario involved increasing the size of existing woodland areas by 40%, regardless of location in the catchment. Broadly, each catchment has similar levels of land cover change for each category of planting (for example, Ennerdale has a 40% increase of woodland for the 40% river, large random scenario and 40% proximal planting), even though the inter-catchment variability is higher. This still allows us to understand the difference in each planting approach based on these relative land cover changes.

All tree planting scenarios were modified to ensure that tree planting occurred only in low grade agricultural or grassland and

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did not coincide with protected areas. The woodland planting scenarios for each catchment are illustrated in Fig. 3 and in Section 2 of the supporting information.

The performance of tree planting scenarios was assessed by comparing discharge at the catchment outlet against the baseline model. Three key metrics are identified: (i) peak flow magnitude (m3/s); (ii) the time to the peak (minutes); and (iii) the total storm outflow (m3, volume). Differences between baseline and planting scenario results for these hydrograph metrics were calculated and scaled by the area of woodland planting to identify the most efficient tree planting scenario.

To gain further understanding of the effectiveness of each tree planting scenario, the spatially distributed model outputs were used to assess overland flow in each model cell. For each hour of model simulation, SD-TOPMODEL indicates if a cell is producing overland flow. By comparing the length of time that a cell produces overland flow between the baseline model and the woodland creation planting scenarios, a determination can be made of exactly which parts of the catchment are responding to the planting scenario. Further, using these outputs it can be determined how each cell and patch of woodland respond across the range of storms, by using distributed likelihood plots (Aronica et al. 2002). These maps are created by converting the time that overland flow is generated into binary plots, where a cell that has any reduction in overland flow as a result of land cover change is given a value of 1 and a cell that has the same or an increased amount of overland flow a value of 0. The likelihood value is then determined from the average value for each cell from each of the 13 simulations, where values of 1 would indicate that the cell has reduced overland flow in all simulations, while values closer to 0 indicate infrequent on no change to overland flow. By comparing these likelihood values for each tree planting scenario across all the storms, it can be seen where patches of land are consistently providing a benefit, as the value of these cells will be close to 1. Cells where an increase in overland flow occurred were also considered, but these regions were small and spatially incoherent in comparison to the regions where a benefit was considered, so a greater focus is placed on understanding the regions where a reduction on overland flow has occurred. Future studies should focus on hydrological models that may provide more insight into this.

Using these outputs, the effectiveness of each area of woodland was determined by comparing changes to overland flow against a set of physical properties associated with the woodland areas (slope, aspect, contributing area, topographic wetness index, slope length, and total area) using scatter plots and basic correlation statistics. This analysis offers insight into any physical properties that define these patches, that can then be used to inform priority woodland creation areas.

Using the outputs from this comparison, a final optimal planting scenario was created using the patches of woodland from each scenario that provided the greatest reduction in overland flow. This 6th planting scenario is created to understand if an optimal planting scenario can be achieved and if the same reduction in discharge can be achieved with less land cover change.

Results

Each catchment was calibrated and validated against FEH/ReFH estimated 1 in 20 and 1 in 100-year events. For the Lowther catchment, a NSE of 0.84 and 0.72 were achieved with a parameter set of K = 0.014(m hr-1) Kv = 250(m/s-1), and m = 0.22, for Ennerdale a NSE of 0.72 and 0.76 and for Colne a NSE of 0.82 and 0.67 were achieved with a parameter set of K = 0.012, Kv = 200 and m = 0.012. These parameters form the baseline values for the improved grassland as the dominant land class from which the land scaling factors for each land class in Table 1 are derived.

Outflow analysis

The hydrological variations between the baseline and the tree planting scenarios for each of the three catchments are displayed in Table 3. The full set of results are provided in the Supplementary Information Section 3. All tree planting scenarios have a positive benefit; that is a reduction in one of the three discharge metrics, with an overall reduction to peak values of ~4%–8% across all scenarios and for all catchments. The 40% random tree planting scenario has the greatest impact in reducing peak discharge in all three catchments and is at least 0.5%–1% more effective at reducing peak flow than the other tree planting scenarios. The 40% random planting scenario is also most effective for reducing the overall total runoff volume in Lowther and Colne, while the 40% river-based planting scenario is more effective in Ennerdale.

The difference between the three 40% woodland coverage scenarios (i.e. random, riverine and proximal) are relatively small, with each scenario demonstrating similar peak decreases, time of peak delays and reduction in overall volumes. The 40% scenarios are all shown to have a greater impact than the smaller tree planting scenarios. Difference in the change of time of peak are more modest, with average delay being in the order of 10 to 20 minutes. This is particularly noticeable in Ennerdale and Colne, where the average delay across all events for each scenario is ~5–10 minutes, and for some of the more complex AMAX and Seasonal storm profiles, a reduction in the time to peak is noted.

By comparing the changes as a proportion of the increase in planting, a different pattern is noted (Fig. 4). In this analysis, the most effective scenarios (i.e. reduction in peak flow volume per hectare of planting) are the smaller, targeted river-based planting schemes, (Riparian and 10% River Planting), which are 2–3 times more effective per hectare than the larger planting schemes (right hand side graphs, Fig. 4). This is particularly noticeable for the Ennerdale catchment, where the 10% River planting has an median benefit of 0.5 peak reduction compared to 0.1–0.2 for other planting scenarios. In general, the reduction in peak flows for each planting scenario is similar for different return periods for each catchment. This is probably due to the impact that the planting has on reducing or disrupting overland flow, rather than the total volume.

Analysis of distributed outputs

Comparing the distribution of overland flow across each scenario allows the impact of individual sections of woodland to be evaluated in more detail, by analysing the overland flow for each cell within the footprint of a woodland planting area. For each tree planting scenario, the effect is similar in each catchment, and an example for the Large random tree planting scenario is given in Fig. 5.

As highlighted in the Fig. 5a, the majority of the regions where overland flow is reduced occur within the footprint of the woodland cells. These are represented by the blue regions. The length of time that overland flow is reduced varies across the footprints, with longer time differences noted across the upper slope of the woodland areas (the yellow to green regions located around the green woodland planting areas), with a reduced effect moving downstream. An effect of reducing overland flow within some areas is the increase of overland flow in adjacent cells, as more

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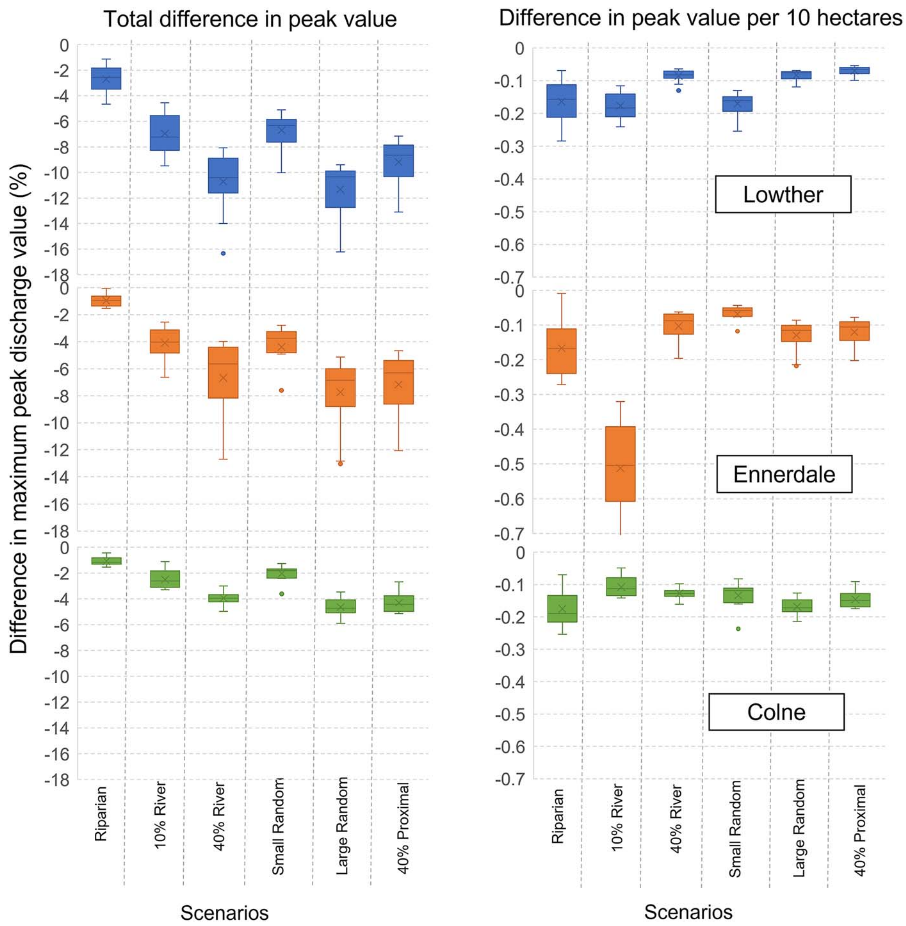

Figure 4. Box plot comparison of the difference in peak as a percentage for each planting scenario (left hand side), and the difference in peak per 10 hectares of planting (right hand side) for Lowther (top), Ennerdale (middle), Colne (bottom).

water moves through the near sub-surface layer as a result of the greater infiltration in the woodland area, but re-emerges downslope from these areas, represented by the red regions in Fig. 5a. These regions are relatively small in comparison to the regions of reduced runoff in each catchment. Table 4 summarizes these variations across all the simulations for each catchment and each tree planting scenario. For Ennerdale and Colne, the number of cells of increased runoff are limited in comparison with the Lowther catchment. For all three catchments, the large random planting pattern produces the highest number of cells with reduced overland flow time.

A comparison of the likelihood maps, which show the number of cells where overland flow occurs for less time as a result of the woodland planting scenarios compared to the baseline for all the events, demonstrates the spatial impact of each woodland planting. An example of these outputs for the 40% random tree planting scenario for the lower catchment of Ennerdale is given in Fig. 5b. In this figure, cells with values of ∼1 are represented by darker regions which are regions that in every scenario have less overland flow than the same cells in the baseline model. The patterns highlighted in Fig. 5b are similar to the differences in time, with higher likelihood regions near the upper slopes of the woodland areas, and lower likelihood values in the lower slopes of the woodland areas.

By comparing the likelihood values generated for each catchment, it can be seen how the tree planting scenarios compare across all events (Fig. 6). The high number of cells with a likelihood value of 0.1–0.3 indicate that a reduction in runoff occurs infrequently across all the scenarios. These lower frequency values are typically associated with the summer storm scenarios and higher intensity rainfall (i.e. a reduction in overland flow for a cell is noted during the summer storm events, and not for AMAX or winter-based events) where higher total values of overland flow are generated. In these events the tree planting is highly effective at reducing the time of runoff generation, leading to more extensive areas of reduced overland flow across the catchment. It should be noted as well, that these events are higher frequency, with a lower return period than the winter events, indicating a higher modeled benefit for more frequent events. For longer duration events, this is less likely and the generation of runoff is restricted to the footprint of the polygon. Comparing between each catchment, it can be seen that the 40% riparian planting scenario produces higher frequency likelihood values (0.7–1) for all catchments, while the riparian planting produces the greatest number of lower frequency values (0.1–0.3).

Analysis of woodland area characteristics and reduction in overland flow

By determining if an area of woodland planting has reduced the overall catchment flood peaks and volumes, through modifying peaks or decreasing the likelihood value of the cells in an area, we attempt to derive a relationship between these values and the underlying physical characteristics of these areas. The aim of this analysis is to determine if a relationship between particular areas

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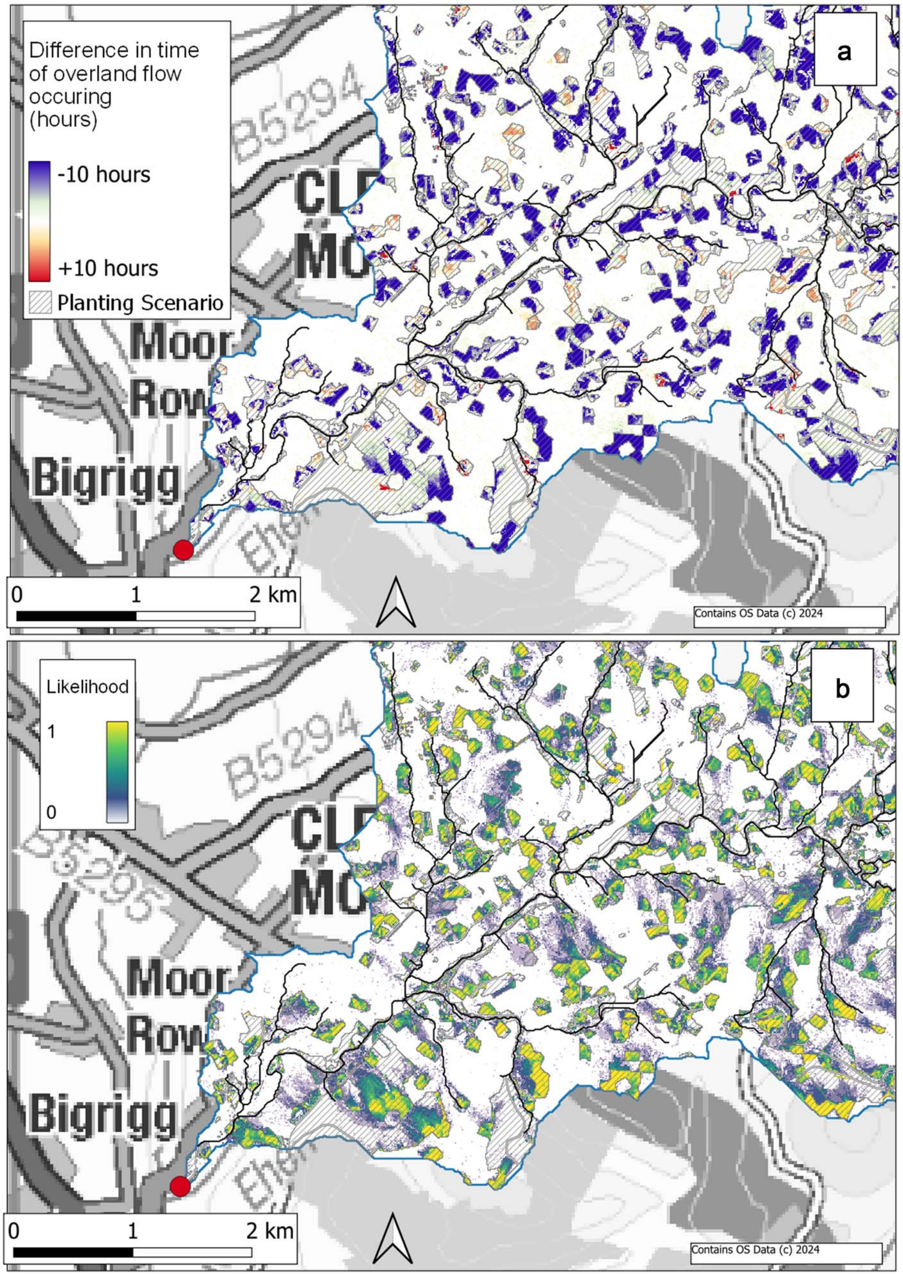

Figure 5. (a) Comparison of difference in overland flow for the 40% random tree planting scenario at the catchment outlet of the Ennerdale catchment, where decreased length of time of runoff is represented by the blue areas and increased length of time by the red areas. (b) Likelihood map for the same scenario where cells that have decreased overland flow observation time in all cells are given values of 1 (yellow regions) and cells that have no change are given values of 0 (white regions). The black line represents the water course, and the red dot is the catchment outlet.

of each planting scenario provide a higher impact at reducing flood peak and volume values. The results indicate that no clear relationship exists between values of high likelihood/high average reduction in time of overland flow generation cells and four of the catchment characteristics tested. The only catchment characteristic that appears to have a significant relation is the polygon area and the average change in time of overland flow occurrence (Fig. 7), which shows that for larger areas of woodland planting there is a greater reduction in the time of overland flow occurring during a storm event. Combinations of these parameters also failed to indicate any multivariate or multivariable relationships that could also be used to prioritize regions.

Although the area of individual planting has a benefit to the reduction of peak flow, as can be seen in Fig. 7, this does not provide any significant insight into if the spatial configuration of the planting scheme can be modified. In the absence of a set, or range, of underlying physical attributes that define the areas that provide a greater benefit of flood peak reduction, a combination of the best performing polygons from each tree planting scenario are combined to create a 'optimal' scenario, to test if the polygons that provided the most significant reductions in overland flow from each scenario could be combined to create a similar level of benefit, but with less land cover change (Fig. 8). The 10 best performing areas, defined as the areas that had the highest

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Table 4. Summary of difference in peak (peak %), difference in time to peak (delay min), and difference in total runoff (volume %) for each of the tree planting scenarios, for the three catchments and divided for each category of storm. The highlighted (bold) values represent the highest reduction/increase in peak and volume/peak time delay for each category of storm.

Scenario	ALL			SYNTHETIC			AMAX			SEASONAL		
	Peak (%)	Delay (min)	Volume (%)	Peak (%)	Delay (min)	Volume (%)	Peak (%)	Delay (min)	Volume (%)	Peak (%)	Delay (min)	Volume (%)
Lowther												
Riparian buffer	−2.7	−5.4	−1.4	−2.6	−11.3	−1.6	−2.1	7.5	−1.2	−3.1	−5.0	−1.3
10% River	−6.9	−1.1	−5.0	−7.4	−18.8	−5.3	−5.8	18.8	−4.8	−7.3	0.0	−4.1
40% River	−10.7	**−28.9**	−8.7	**−10.7**	**−22.5**	−9.5	−9.1	**−22.5**	−8.2	−12.1	**−40.0**	−7.6
Small random	−6.7	−9.6	−5.2	−6.5	−15.0	−5.6	−6.3	3.8	−5.1	−7.0	−5.0	−4.3
Large random	**−11.3**	−18.2	**−9.6**	−10.4	−18.8	**−10.3**	**−10.5**	−3.8	**−9.3**	**−13.0**	−25.0	**−8.3**
40% Proximal	−9.2	−21.4	−8.7	−8.5	−18.8	−9.3	−8.7	−22.5	−8.4	−9.7	−25.0	−7.4
Ennerdale												
Riparian buffer	−0.9	−2.1	−0.9	−1.0	−3.8	−0.8	−0.8	−3.8	−1.0	−-1.4	7.5	−1.1
10% River	−3.8	−1.1	−3.7	−3.6	−7.5	−3.3	−4.6	−3.8	−3.9	−4.8	15.0	−4.1
40% River	−6.2	−8.6	**−7.9**	−4.9	−11.3	**−7.0**	−8.7	−15.0	**−8.4**	−7.1	0.0	**−8.6**
Small random	−4.1	−4.3	−4.1	−4.0	−7.5	−3.6	−5.4	−11.3	−4.4	−3.8	7.5	−4.6
Large random	**−7.2**	**−17.1**	−7.5	−6.2	−11.3	−6.8	**−9.5**	**−33.8**	−7.9	**−8.5**	0.0	−8.3
40% Proximal	−6.7	−10.7	−7.6	**−6.3**	**−11.3**	−6.9	−8.4	−15.0	−7.9	−8.3	**−7.5**	−8.3
Colne												
Riparian buffer	−1.0	−5.0	−0.5	−1.1	−11.3	−0.5	−1.3	0.0	−0.6	−0.9	**−10.0**	−0.6
10% River	−2.5	3.8	−1.6	−2.0	−3.8	−1.5	−2.8	3.8	−1.7	−2.8	5.0	−1.8
40% River	−3.9	**−10.0**	−3.0	**−3.9**	**−26.3**	−2.7	−4.0	0.0	−3.2	−4.0	−5.0	−3.2
Small random	−2.0	−5.0	−1.6	−1.9	−15.0	−1.4	−2.4	**−7.5**	−1.7	−2.0	10.0	−1.7
Large random	**−4.6**	−2.5	**−3.5**	−4.4	−3.8	**−3.2**	**−5.3**	−3.8	**−3.8**	**−4.4**	0.0	**−3.8**
40% Proximal	−4.3	−2.5	−3.1	−3.9	−11.3	−2.8	−4.7	3.8	−3.3	−3.9	0.0	−3.3

average reduction in the timing of overland flow, from each scenario were combined to create the ‘optimal planting’ scenario using the selection of best performing polygons come from a variety of locations within the catchment illustrated in Fig. 8. The area of the polygons selected were ∼2–4 hectares in size, with each catchment containing a few larger single area ∼20–30 hectares in size, leading to a planting scenario of 4.2km^2 (Lowther), 1.38km^2 (Colne), 3.32km^2 (Ennerdale).

Table 6 contains a summary of the results for all tree planting scenarios, including the optimal planting scenario. In general, Lowther has the highest level of reductions and delays, although this can be understood because of the large changes to woodland for each scenario in comparison to the other catchments (Table 3). This can also be seen in the relative performance of Colne and Ennerdale. The Optimal Planting scenario produces variable results in each catchment. For the Colne valley, the optimal selection produces the second highest reduction in overland flow peak and is the most effective in terms of area planted (i.e. the benefit to the reduction of flooding in terms of hectares planted). For the Lowther catchment the results are the opposite, and it is the least effective in terms of area planted, although the overall reduction in peak flow is similar to the 10% cases. In the Ennerdale catchment, it is shown to be more effective than the 10% scenarios, but less effective than the 40% scenarios.

Table 5. Percentage of cells in a catchment where total runoff time is reduced against the number of cells where runoff is increased, as an average across all storm scenarios for each catchment. Bold values indicate the scenario with the highest reduction in percentage of cells.

	Scenario	Lowther (%)	Ennerdale (%)	Colne (%)
Reduction	Riparian buffer	5.2	0.6	0.7
	10% River	9.6	4.6	2.5
	40% River	14.4	9.6	**5.8**
	Small random	10.6	5.8	4.2
	Large random	**17.5**	10.1	5.7
	40% Proximal	16.0	**10.1**	5.2
Increase	Riparian buffer	**3.2**	0.2	0.6
	10% River	2.3	0.4	0.6
	40% River	2.6	**0.7**	**0.8**
	Small random	2.2	0.4	0.4
	Large random	2.7	0.6	**0.8**
	40% Proximal	2.6	0.6	0.7

Discussion

The aim of this work has been to explore the hydrological benefits of a series of woodland planting schemes, and to identify if any overall strategies for woodland planting can be determined. The scenarios we have investigated are beyond typical setups considered in ‘flood focused’ planting schemes, and to explore more generic schemes that will have benefits including better ecological connectivity and increased biodiversity through the creation of other types of woodland, including wet woodland. Across all the catchments there is a clear benefit in terms of reducing flow by increasing the coverage of woodland, regardless of the size or configuration of the planting scenario. All the planting scenarios tested here provided a benefit of some kind. Based on the assessment of the hydrographs at the catchment outlet (Table 1), the larger and more extensive planting schemes produce the largest reduction in peak flow values, reduction in total overland flow and introduces the largest increase to the time

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Table 6. Summary results with scenario tree planting for all simulations. The highlighted values represent the highest reduction/increase in peak and volume/peak time delay for each category of storm. The last column is difference in peak as a percentage of each km of planting.

	Lowther				Ennerdale				Colne			
	Peak (%)	Delay (min)	Volume (%)	Peak (km/(%)	Peak (km/%)	Delay (min)	Volume (%)	Peak (km/(%)	Peak (km/%)	Delay (min)	Volume (%)	Peak (km/(%)
Riparian buffer	−2.69	−5.36	−1.42	**−0.16**	−0.87	−2.14	−0.93	−0.17	−1.05	−5.00	−0.54	−0.17
10% River	−6.95	−1.07	−4.96	−0.18	−3.79	−1.07	−3.67	**−0.51**	−2.51	3.75	−1.64	−0.16
40% River	−10.7	**−28.9**	−8.69	−0.08	−6.19	−8.57	**−7.91**	−0.10	−3.85	−10.0	−2.97	−0.08
Small random	−6.69	−9.64	−5.22	−0.17	−4.07	−4.29	−4.12	−0.07	−2.03	−5.00	−1.57	−0.13
Large random	**−11.3**	−18.2	**−9.64**	−0.08	**−7.19**	**−17.1**	−7.54	−0.13	**−4.64**	−2.50	**−3.54**	−0.17
40% Proximal	−9.19	−21.4	−8.70	−0.07	−6.65	−10.7	−7.58	−0.12	−4.32	−2.50	−3.11	−0.15
Optimal	−6.85	−12.8	−6.10	−0.06	−5.66	−12.8	−6.07	−0.13	−4.58	**−7.50**	−3.54	**−0.34**

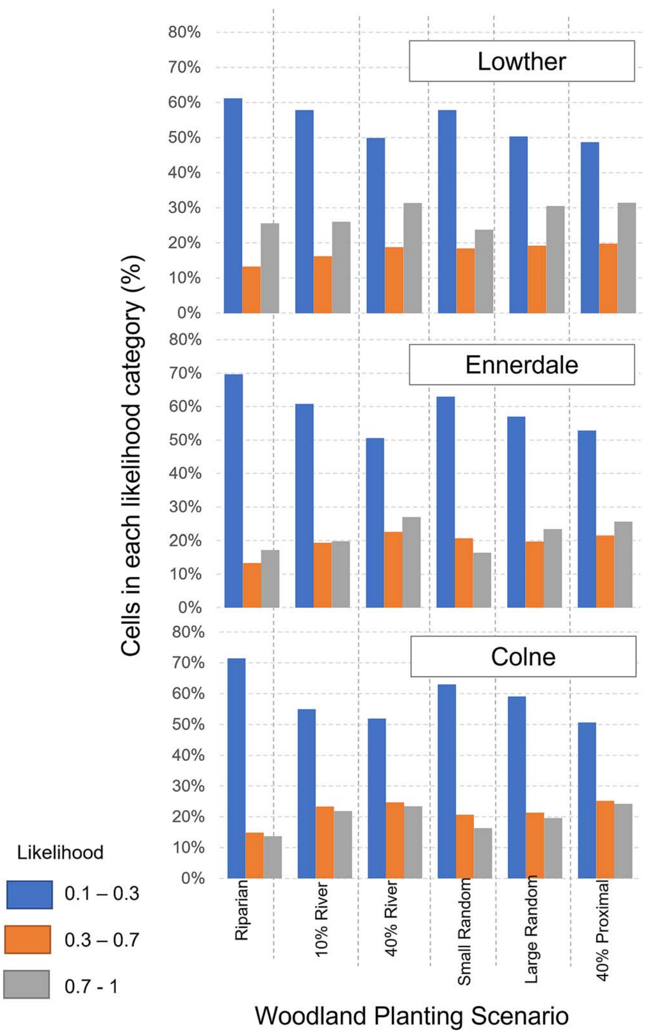

Figure 6. Comparison of likelihood values for each tree planting scenario and for each catchment (Lowther top, Ennerdale middle, Colne bottom).

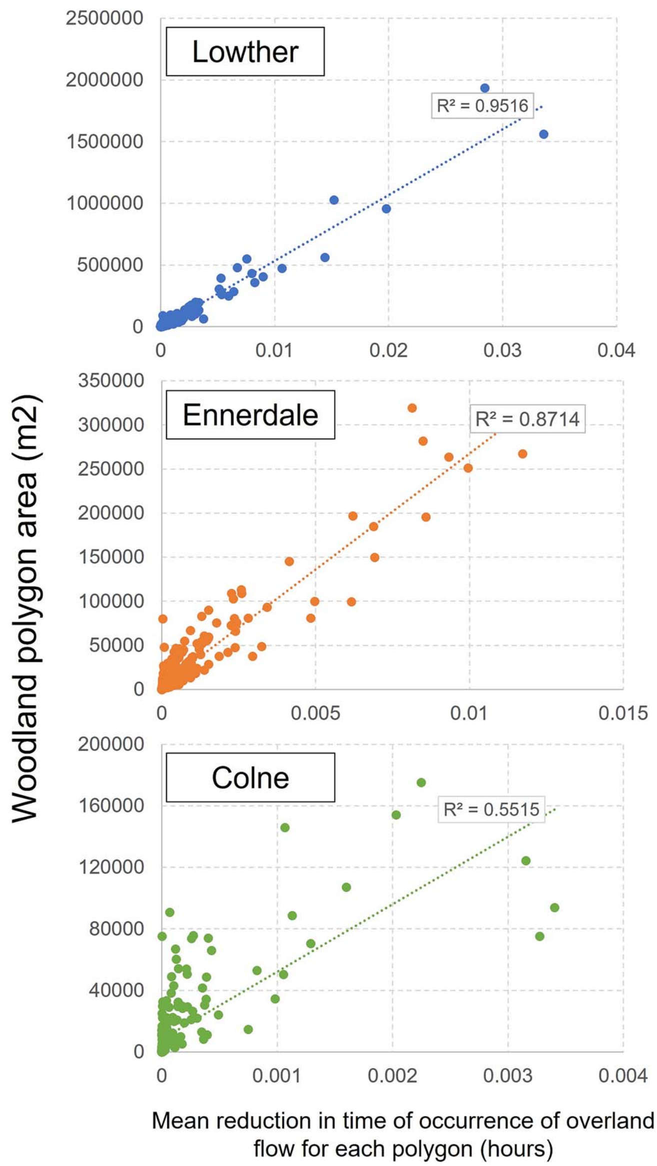

Figure 7. Regression plots for catchment characteristics against difference in time values for each polygon for the 40% random sampling tree scenario for each catchment.

of the peak, which is similar to results reported in Kingsbury-Smith et al. (2023). The peak reductions are higher for Lowther, although this appears to be related to the large amount of planting in each of the scenarios, as can be seen in Table 3. However, in terms of efficient and effective broadleaf tree planting, planting schemes close to rivers and the riparian zone are demonstrated to be the most effective per hectare of planting. It should be noted that we have only considered broadleaf woodland planting in these scenarios, and this benefit maybe reduced during winter

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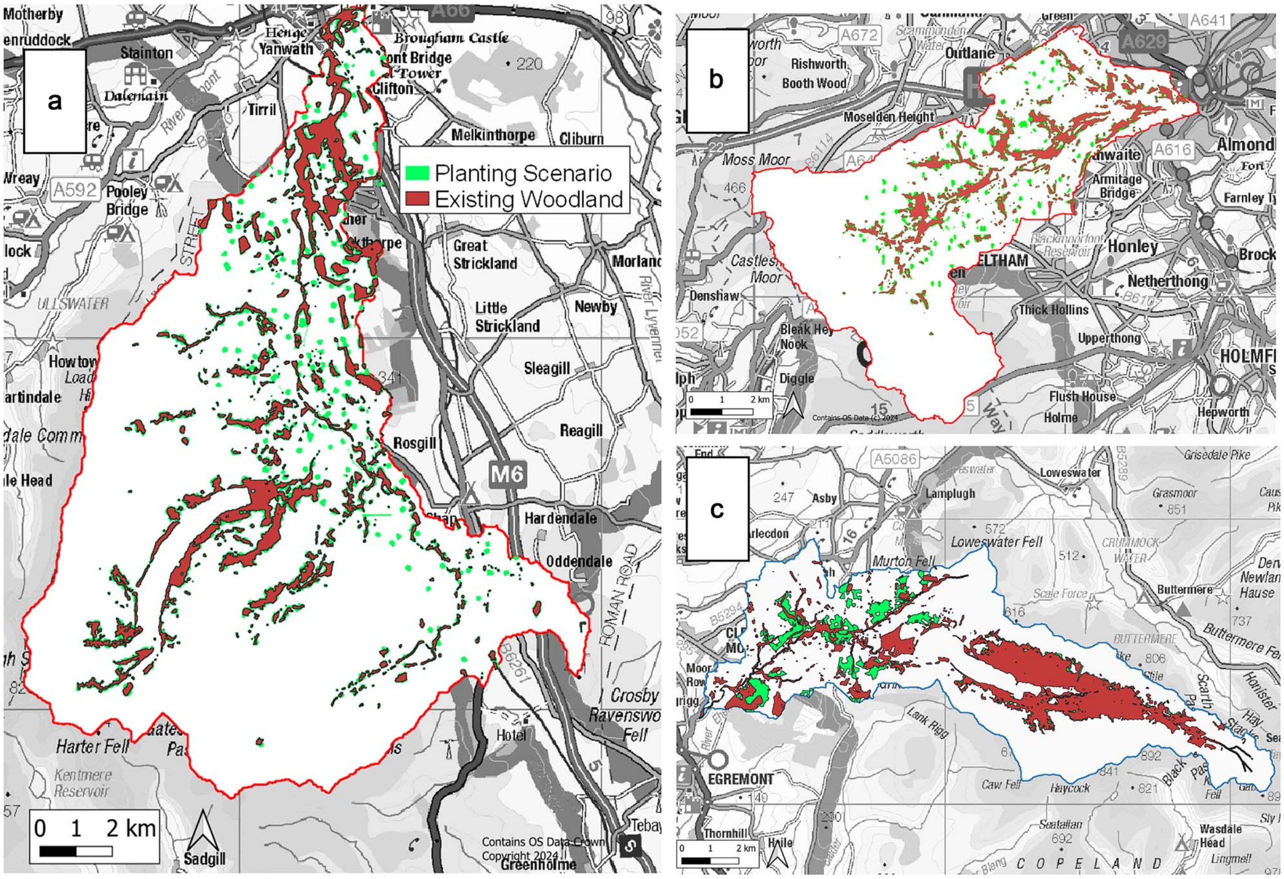

Figure 8. Combined best polygon planting scheme layout (green area) for Lowther (a), Colne (b), and Ennerdale (c).

storms, where broadleaf cover will be significantly less. Further, the planting scenarios only consider a total increase of woodland of 9%–10%, indicating that with more extensive woodland planting in the catchments, greater reductions in flood peak could be achieved.

These overall changes to peak flow values confirm previous findings about the most effectiveness of planting schemes (Cooper et al. 2021) and more general riparian restoration schemes (Gao et al. 2017, Kingsbury Smith et al. 2023). This is an important consideration in prioritizing planting areas and woodland creation strategies in catchments, and would suggest that these regions should be considered first, particularly where the type of trees being considered for planting is broadleaf and the overall goal is a reduction in flood risk. These areas are often marginal in terms of agricultural outputs and grazing opportunities, and could therefore be a useful compromise between farmers, land owners and catchment managers looking to increase woodland coverage in catchments. It should be noted that while this is the most effective type of woodland planting in terms of reduction in flood peak per hectare, these scenarios only achieved a maximum flood peak reduction of 1%–2%. Future work should look at co-partnership woodland planting developments that incorporate multiple requirements to see if a single design for a catchment can be achieved within a single plan. Conversely, further work should also determine where changing land cover to woodland would not be appropriate by considering additional factors such as the potential increase in localized flooding as a result of higher groundwater and slower overland flow, or debris from woodland during storms may also cause other impacts during flood events. For example, locations near urban areas while they may provide an overall reduction in the catchment overland flow, may create localized impacts that are detrimental to local communities.

Our study also confirms that the findings are applicable in a wide variety of storm events, demonstrating that the benefits from woodland planting are broadly observed for all types of storms. However, the benefit is not uniform, and the response of individual areas of woodland planting vary depending on the nature of the storm. For longer duration events, the benefits tended to be more localized, and within the footprints of woodland areas, compared to the shorter duration and more intense rainfall events, which lead to a wider range of benefits (i.e. more cells are shown to have a reduction in overland flow). These local impacts will be important when considering how to develop woodland creation in catchments, and understanding how this might impact the survival of trees will be important to establish.

In addition to the overall effectiveness of woodland creation in reducing overland flow in a variety of storm events, it can also be noted that the impact across different return periods is largely similar. This demonstrates that the benefit of tree planting should remain largely consistent across similar storm profiles of different intensities, and is not return period specific (Carrick et al. 2019, Zhu et al. 2024). In terms of developing economic cases for increasing woodland coverage, this may be an important consideration in justifying the outlay and change in landcover within catchments. Further modeling efforts should focus on understanding the link between reduction of peak flow and economic damages from flooding to further develop this conclusion.

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While the changes to peak flow values appear to be larger than the overall difference to volume and changes in the timing of peak flow, there are still important changes to the latter metrics. For the storm runoff volume, an overall reduction can be seen. Broadly this follows a similar pattern to the changes in peak (similar relative scores between each catchment), and is mostly the result of increased losses from interception, as well as increased infiltration. Changes to the time of the peaks are relatively modest. This is potentially at odds with wider reviews which indicate that the impact to the timing of the peak maybe more substantial (e.g. Cooper et al. 2021), but reflect that for the catchments considered in this study, the types of storms that lead to flooding are typically ~12–20 hours of rainfall. The response of these catchments reduction in time is likely to be less significant due to the underlying catchment properties.

While reductions have been demonstrated in all three catchments and across all the different storm types, the reduction in peak flow is larger in the Lowther and Ennerdale catchment than in the Colne (−7.8% and − 4.9% of baseline peak flow vs scenario peak flow vs −3.0% in the Colne catchment). This difference is primarily due to the relative changes in land use in each catchment but will also be influenced by the current configuration of woodland in the catchments. Lowther and Ennerdale have more opportunities for planting throughout the catchment, whereas the Colne with more extensive urban areas in the catchment, woodland planting is limited to the upper parts of the catchment. The types of catchments examined here are similar in broad characteristics, such as size and location in the UK, as well as overall configurations. Applying similar approaches to catchments in the south and for smaller catchment sizes will also provide insights for UK wide woodland creation.

Establishing a clear link between the physical properties of woodland areas and reduced overland flow to prioritize planting for hydrological benefits could not be determined, except those indicating that larger areas had a higher average reduction in runoff. The methods here have only considered linking the results from each region of woodland planting and the physical characteristics. Another, more intensive, approach could be to first identify hydrological similarly parts of the catchment and compare across ensembles of planting. Although no physical characteristics could be determined, by selecting the combination of best performing areas of planting an ‘Optimal Selection’ was developed. This planting scheme did not achieve a similar level of effectiveness in the Lowther and Ennerdale compared to the more extensive 40% planting schemes in those catchments. By comparison in the Colne valley, where larger areas of planting were used in the Optimal Selection, a more comparative score was achieved. This indicates that such approaches may have merit. In the Colne valley scenario, most of the selected tree planting regions in the selection-based approach are in the headwaters of the tributaries and in the near river environment, which again emphasize the importance of these environments reducing the impact of overland flow.

Numerical modeling continues to form an essential tool in the analysis of catchment scale NFM interventions. These models, while useful, contain a number of uncertainties and assumptions that will impact the results. For example, in this study, the treatment of interception, which is relatively simple, and the lack of evaporation data used in the simulations (considered to be too small in the course of 12–24 hour simulation time), will have some impact. This is not only a consideration in this work, but a general problem in the development of hydrological models to assess the impacts of woodland creation (Cooper et al. 2021). Further to this, antecedent conditions have not been fully considered in this study. These might be critical in the initial phases of storms, when the capacity of soil to absorb rainfall could influence flood risk. Further quantification and consideration of the parameters used to represented process in physical based and spatially distributed models, particularly of the infiltration rates of trees and woodland areas more broadly and antecedent conditions during extreme events are required to improve the confidence of these results, and to develop a common set of forest hydrology processes to include in hydrological models. Land surface models such as JULES (Best et al. 2011), contain approaches that consider these processes more explicitly, but at the cost of detailed hydrological processes. Finding further modeling approaches that combine these effects will be critical to further developing the case for woodland creation.

An additional consideration beyond the specifics of the numerical model is the application of the model, and what approaches would be suitable for establishing the hydrological benefits of tree planting. The method presented here is essentially deterministic, applying a planting scenario to a baseline and a series of events, creating a before and after effect that we have analysed. This approach allowed us to evaluate each woodland type in turn, to isolate and understand the impact to overland flow from each. However, ensemble approaches, where many thousands of planting scenarios are considered and evaluated in turn may help identify statistical patterns relating areas of woodland with reduced flood risk. These approaches would require considerable modeling efforts, but would improve on the limited approach presented here.

This work also assumes that all created and existing woodland are broadleaved, deciduous trees with a common overland flow resistance parameter given for all the woodlands. Consideration of species types or precise locations of trees in these planting schemes is not given. In reality, the woodland area will be more heterogeneous with more variety in species used in both the development of new woodland and in existing woodland. How to represent this within a simulation in a deterministic way will also require further development of modeling techniques, and in general they are not considered in wider modeling studies.

As well as the representation of woodland in models, understanding how woodland will behave in evolving hydrological conditions, as well as determining the species that may be suited to current hydrological conditions will be an important consideration in the development of woodland creation schemes. In our modeling approach we assumed that the new woodland areas are mature, with a fully developed canopy. The impact of the age of woodland has shown to be an important factor in the overall benefit of tree planting has not been considered (Dixon et al. 2019). In this regard, the results can be considered the optimal result for a catchment and would be achieved once a complete canopy has formed (~20–30 years in the UK). Further, this work does not consider the evolution of the tree canopy over time, or how the final canopy coverage compares to the original tree planting scheme. As well as the broad planting strategies considered here, more detailed catchment specific planting and other strategic planting approaches, such as cross slope woodland creation should also be explored. Hydrological modeling could be used to understand the evolving nature of runoff generation as land cover and woodlands change and mature over time. Furthermore, as the focus of this work has been studying the impact of woodland creation on flooding and peak discharge, other impacts in the hydrological cycle, including prolonged saturation of ground and droughts have not been considered. These hazards, while lowering the impact in

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terms of damages and potential loss of life, could have a significant impact on agricultural processes and on economic activity in catchments. In order to understand these risks, continuous simulations and simulation of longer duration events could be used to provide more insights into the impact of tree planting in less extreme, but perhaps more persistent conditions that will have long-term implications for local communities and businesses. Developing modeling approaches that combine detailed spatial distributions of land cover and continuous simulations will be essential for future catchment management.

Conclusions

The authors of this paper have modeled the impact of catchment wide tree planting schemes to understand if any underlying properties of the area of planting can be used to define more definitive guidance to woodland creation. Across the three catchments, the overall results indicate that while random patches provide the largest impact, the most efficient approach, in terms of reducing flood peaks as a percentage of changed land cover is targeted planting in the riparian zone. This impact occurs for a range of storm types, providing consistent benefit in most storm events, although only provides a small overall reduction in flood peaks. Increased coverage of woodland planting will have a positive benefit for reducing flood risk, regardless of configuration of location of tree planting, and a 9%–10% increase in woodland in Ennerdale and Lowther, led to 6%–10% reduction in peak flood values beyond the riparian zone, defining broad strategies for maximizing the multiple benefits from woodland planting will be location specific, and require detailed modeling to achieve either targeted reductions or to quantify the hydrological benefits of opportunistic planting.

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Author contributions

Tom Willis (Conceptualization, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing—original draft, Writing—review & editing), Mark Smith (Conceptualization, Investigation, Methodology, Writing—review & editing), Andrew Speak (Conceptualization, Formal analysis, Investigation, Methodology, Writing—review & editing), Matthew Dennis (Funding acquisition, Methodology, Project administration, Writing—review & editing), Phillip James (Methodology, Project administration, Writing—review & editing), and Megan Klaar (Conceptualization, Funding acquisition, Methodology, Project administration, Writing—review & editing)

Conflict of interest

None declared.

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Data availability

The hydrological data underlying this article are available from the Environment Agency Hydrology Data Explorer (https://environment.data.gov.uk/hydrology). The FEH and ReFH derived 'synthetic events' hydrological data used in this article were provided by WHS under licence/by permission. Data will be shared on request to the corresponding author with permission of WHS. The terrain data used is provided from the Ordnance Survey under license (https://www.ordnancesurvey.co.uk/products/os-terrain-5). The land cover data underlying the model can be found at https://github.com/andyspeak/landclass.

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