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Role of forested land for natural flood management in the UK: A review

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Abstract

Natural flood management (NFM) is the use of natural processes and environments to mitigate flood risk by reducing and delaying peak flood. This review introduces the concept and history of NFM and looks at the current state of research into the potential for using different types of woodland to fulfill the aims of NFM. Four woodland types (catchment, cross-slope, floodplain, and riparian) are discussed with reference to studies carried out, mainly in the United Kingdom, to determine the relative merits of each type and their effectiveness in mitigating flood risk. We then discuss how trees interact with the hydrological cycle, along with a discussion of modeling methods which seek to determine the amount of water intercepted by different types of forest cover. We find that while there is some evidence that carefully planned and managed woodland can mitigate flood risk, the published data for this evidence base is somewhat sparse. This may be either due to the long timescales needed for comprehensive studies or the relative infancy of the research on NFM. More research needs to be carried out in each of the four woodland types, especially in the UK, as policy makers are increasingly looking towards nature based solutions to mitigate the potential impacts of climate change. The concept of a combined canopy/hydrological model which can be scaled from stand to watershed level and incorporate different types of woodland is suggested as it would be beneficial in guiding woodland creation policy in the future, both at the local and regional scales.

This article is categorized under:
    Science of Water > Water Extremes
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KEYWORDS

canopy modeling, catchment modeling, hydrological modeling, interception loss, natural flood management

1 | INTRODUCTION

The threat of flooding has been ever present throughout human civilization, and it is inevitable that, given the need for settlements to be close to a water source, a flood will occur at some stage. The risk of fluvial flooding has always been a threat to communities; it is an unfortunate fact that the most productive lands are those whose soils are periodically rejuvenated and renourished by deposition of nutrient rich sediments by floods, the River Nile in Egypt being a classic example of this. There is evidence of agriculture dating back to 5200 BP on the Nile floodplain (Said, 1993) and the annual cycle of inundation and retreat led to the founding of one of the earliest great civilizations (Brookfield, 2011). Jump forward thousands of years and the human race is still utilizing floodplains in order to drive civilization forward, and in the early 21st century some of the most densely populated areas of the planet are in the alluvial floodplains (Sultana, 2017). However, new research suggests that this perceived exposure to flood risk may be overestimated (Smith et al., 2019). What is certain is that the economic impact of flood damage is increasing. In the period 1980–2011, reported flood losses globally increased from $7 billion per year in the 1980s to $24 billion per year in 2001–2011 (adjusted for inflation) (Kundzewicz et al., 2014). Data from the United Nations Office for Disaster Risk Reduction 2020 report "Human cost of disasters" show that 44% of all disasters which occurred worldwide from 2000 to 2019 were floods, more than double the previous 20-year period and affecting 1.65 billion people (United Nations, 2020). The UK government Foresight project reported in 2004 that the annual cost of flooding is £2.2 billion each year, of which £800 million is spent on flood and coastal defenses, and £1400 million is damage (Evans et al., 2004a, 2004b). Since 2015 £2.6 billion will have been invested in flood defenses, and this figure is set to rise to £5.6 billion in the period 2021–2027 (National Audit Office, 2020). Individual events have a dramatic influence on the damage figures, with the summer floods of 2007 incurring a cost of £3.2 billion, and the winter storms of 2015–2016 costing £1.3 billion (ABI, 2016; Ward, 2016).

Traditional methods of flood defense and mitigation require the construction of hard infrastructure such as dams, weirs, sluices, and barriers, or by changing the profile of river channels, straightening, or deepening to increase capacity (Wheater, 2006), or by the building of levees or embankments such as the work carried out on the Mississippi in the United States (Alexander et al., 2012). All these methods carry high costs for construction and maintenance, have other drawbacks such as adverse effects on the environment and can often be aesthetically displeasing. There has been a recent groundswell of opinion that natural approaches to flood management can help mitigate the flood risk in a more environmentally friendly and cost effective way, and crucially can be more targetable to areas which fall outside the scope of large infrastructure projects due to the anticipated benefits being outweighed by the cost (Nesshöver et al., 2017; Waylen et al., 2018).

Natural flood management (NFM) has many definitions in the literature (Lane, 2017); the overall essence of the concept is to holistically apply general flood management and hydrological principles to develop techniques at any scale within the catchment, which either replicate or enhance natural processes to demonstrably reduce flood risk. Some of the NFM techniques classified by the Environment Agency in England are: river restoration, floodplain restoration, leaky barriers, offline storage areas, catchment woodland, cross slope woodland, floodplain woodland, riparian woodland, soil and land management, headwater management, and runoff management (Environment Agency, 2018). As the overall aim of NFM is to achieve a catchment wide effect through smaller scale interventions, a holistic approach will inevitably encompass a variety of, if not all, these categories. Of particular interest to this review is the use of either existing woodland, or the creation of new woodland features, to support NFM strategies and actions. Our goal is to determine the knowledge gaps in the understanding of the potential role that forests can play to achieve NFM, with primary focus on the UK. While the concept of NFM, and the potential use of forests to achieve it, is not exclusive to the UK, we think that our focus on the UK is justified based on: (1) the unique challenges faced by the UK due to a combination of its climate, geographical location, and lack of forest cover (which is one of the lowest in Europe; Forest Research, 2019), and (2) the UK government's increasing emphasis on seeking nature based solutions for flood mitigation, largely driven by the increasing flood related losses in recent years (DEFRA, 2018).

2 | WOODLAND IN THE UK

The story of the UK's forests begins with the retreat of the last glaciation and the beginning of the Holocene epoch, approximately 12,000 years ago. The extent to which the land was covered by trees is a matter of debate, the apocryphal story of the squirrel who could travel from Land's End in England to John O'Groats in Scotland without touching the

ground (as per Tansley's closed canopy model) was challenged in 2000 by Francis Vera in his book "Grazing Ecology and Forest History" (Vera, 2000). The "Vera model" has been equally challenged (Mitchell, 2005; Szabó, 2009) and there is no real record of the amount of tree cover until the Domesday Book was collated in 1086 (Rackham, 2000). It has been suggested that by the Bronze age (2nd millennium BC) England was half woodland and that by 1086 only 15% of England was covered in forest (Rackham, 2006). The proliferation of human settlement and the rise of forest product using industries such as coal mining, ship building, and the leather trade led to a steady decline in the percentage of forest land cover. This deforestation reached its peak at the end of the 19th century when woodland accounted for only 5% of the land area of the UK (Forestry Commission, 2017). Since the inception of the Forestry Commission in 1919, this figure has slowly rebounded; currently 13% of the UK (15% of Wales) is covered by forest (Forest Research, 2019).

The devolved UK governments have individual aspirations for increasing forest cover; England 12% from 10% by 2060 (DEFRA, 2018), Scotland 21% from 17% by 2032 (Environment and Forestry Directorate, 2019) and Wales aims to plant "at least 2000 hectares per annum from 2020 to 2030 and beyond" (Welsh Government, 2018). Many upland areas have been kept free of forest to facilitate animal, primarily sheep, grazing and free up lower, more fertile land for arable agriculture. These upland areas are often steeply sloped, with poor quality soil and form the upper catchment areas of streams and becks that flow into the main rivers. The upland forest landscape in the UK is dominated by coniferous plantations as a result of the reforestation schemes in the second half of the 20th century, when Sitka Spruce (*Picea sitchensis*) became the most common species in British forests. Many of these plantations are reaching commercial maturity and there is now a regulatory requirement to manage these resources for multiple benefits (Forestry Commission, 2017). Therefore, more emphasis is being placed on diversifying forests to deliver a wider range of ecosystem services than simply timber production. More native woodland is increasingly being planted and, as a result, the arboreal landscape is slowly changing back to a picture which may resemble the 18th century more than the 20th century (Mason, 2007).

3 | FORESTS AND WATER

Forests have been known to play a key role in controlling water since the time of Pliny the Elder (Andréassian, 2004), and even mediaeval France issued a decree in 1219 which recognized the relationship between water and forests (Kittredge, 1948). Andréassian (2004) suggests that the earliest hydrological monitoring was carried out in France in the mid to late 1800s. However, it is generally accepted that the first "modern" experiments were the paired catchment studies at Wagon Wheel Gap in Colorado, USA, from 1910 to 1926 (Bates & Henry, 1928) and the Bernese Emmental region of Switzerland (from 1900 onwards, but the period from 1927 to 1956 has been shown to be the most useful; McCulloch & Robinson, 1993). As the importance of the global hydrological cycle has risen higher in the overall consciousness of the scientific community, the role of the global forest as a key factor in this cycle has led to the creation of a wide variety of monitoring and experimental investigations worldwide, such as the Long Term Ecological Research network in the United States (www.lternet.edu) and the Coalburn (Birkinshaw et al., 2014) and Plynlimon (Kirby et al., 1991) sites in the UK. In terms of hydrological modeling for flood prediction and mitigation, the amount of rainfall which reaches the watercourse and the time it takes to do so are critical components of the equations (Beven, 2012). Trees have distinct characteristics that set them apart from other types of vegetation, especially in terms of water use, owing to their size and longevity. Morris and Benyon (2005) identified three main factors influencing the water use by trees: (1) climatic factors—humidity, solar radiation, air temperature, and wind, (2) water availability—rainfall, irrigation, soil water, and groundwater, and (3) tree factors—leaf area, rooting depth, maturity, and size. The species age and spatial distribution of the trees in any given area of the forest will have a significant impact on the hydrological fluxes of that area. It should be noted that in addition to directly influencing the hydrological flux, trees will also indirectly affect water runoff and flood flows by changing the physical properties of the soil (therefore affecting infiltration and soil water storage), changing the surface and hydraulic roughness of the area which will affect flows in times of flood, and aiding in reducing erosion and therefore downstream siltation (Calder, 1996; Granier et al., 2000; Harding et al., 1992; Martin et al., 1997). When discussing the use of trees to mitigate flood flows generated by surface runoff, it should also be remembered that while the soil beneath a canopy is likely to be drier than that under shorter vegetation, prolonged periods of rainfall, such as the winters of 2013–2014 and 2015–2016 can lead to saturation of the entire catchment soil layer, with no reserve under the canopy. Figure 1 shows the processes by which trees influence the hydrological balance of a forest.
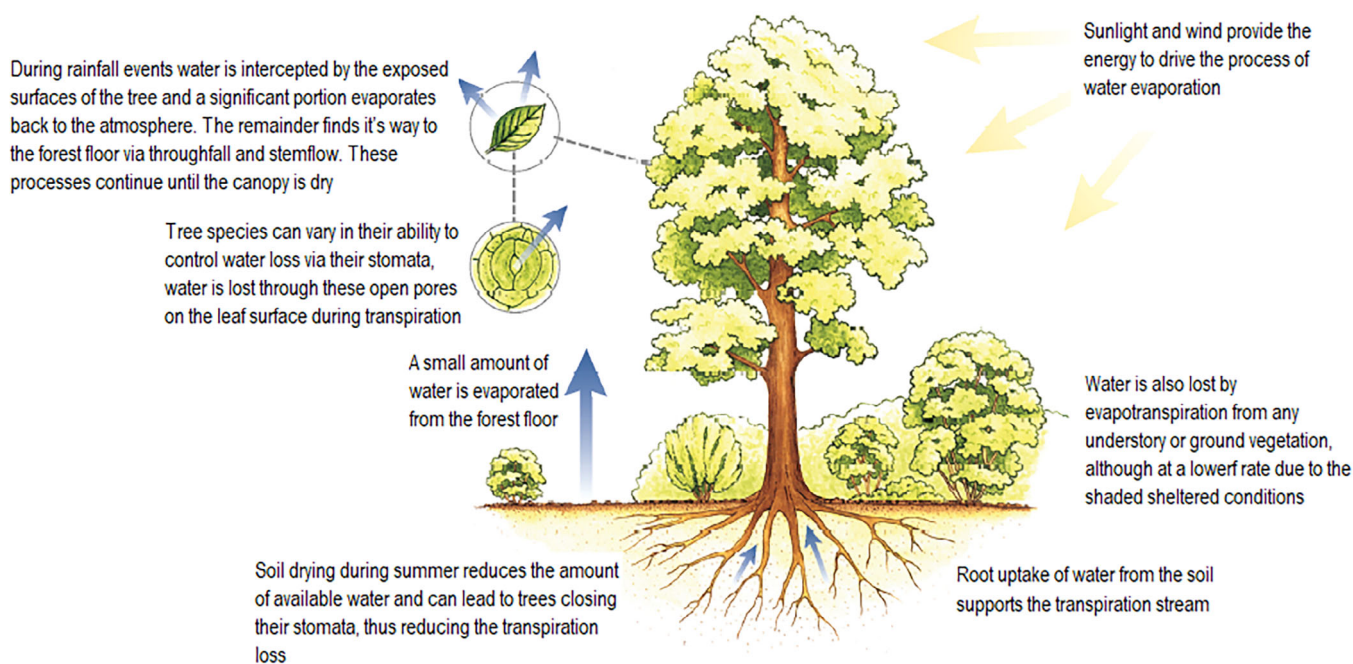
During rainfall events water is intercepted by the exposed surfaces of the tree and a significant portion evaporates back to the atmosphere. The remainder finds it's way to the forest floor via throughfall and stemflow. These processes continue until the canopy is dry

Tree species can vary in their ability to control water loss via their stomata, water is lost through these open pores on the leaf surface during transpiration

A small amount of water is evaporated from the forest floor

Soil drying during summer reduces the amount of available water and can lead to trees closing their stomata, thus reducing the transpiration loss

Sunlight and wind provide the energy to drive the process of water evaporation

Water is also lost by evapotranspiration from any understory or ground vegetation, although at a lowerf rate due to the shaded sheltered conditions

Root uptake of water from the soil supports the transpiration stream

FIGURE 1 How trees use water. Adapted from an original illustration published in Forestry Commission Information Note "Water use by Trees" with the permission of Forest Research. © Crown Copyright

Hydrological investigations at the catchment scale frequently use a combined value for the environmental water flux between the forest and the atmosphere, called evapotranspiration. This value is derived from the interception loss and transpiration, and there is an ongoing debate about which of these is the primary component in the land/atmosphere interaction (Germer et al., 2010; Jasechko et al., 2013; Loustau et al., 1992; Savenije, 2004; Schlesinger & Jasechko, 2014). Jasechko et al. (2013, p. 347) claim that transpiration is "by far the largest water flux from Earth's continents", whereas Savenije (2004, p. 1507), drawing on the work of Calder (1990, 2005) and Shuttleworth (1993), maintains that "evaporation from interception is a considerable proportion of total evaporation". Indeed, Savenije (2004, p. 1507) states that "[Evapotranspiration] is, therefore, an awkward and wholly superfluous term, the use of which should be avoided". Setting this debate aside, we deal with interception loss and transpiration loss as two separate entities.

Interception loss is precipitation that collects on leaves, stems, and branches and is evaporated back into the atmosphere before reaching the ground. The rate at which this occurs is driven by the climatic factors referred to above, as well as the surface area available for interception. Several studies have shown that evergreen conifer species have greater annual interception losses than deciduous broadleaf species (Carlyle-Moses & Gash, 2011; Llorens & Domingo, 2007). UK studies have shown that between 25% and 45% of annual rainfall is intercepted by the conifers, while the interception loss for broadleaf trees is approximately half of that, at 10%–25% (Nisbet, 2005). This is calculated by measuring the amount of precipitation which reaches the ground for a given area of tree covered land and comparing with rainfall measurements from a nearby open area. The models developed by Rutter and Gash (Gash, 1979; Rutter et al., 1971) have been instrumental in allowing for stand (and larger) scale predictions of interception loss, and are constantly being refined and reviewed (Cui & Jia, 2014; Muzylo et al., 2009; Pereira et al., 2009), while new models continue to be developed (Alavi et al., 2001; Jiagang, 1988; Liu, 1997; Massman, 1980; Mulder, 1985; Vegas Galdos et al., 2012; Xiao, 2000). The relationship between interception loss and rainfall amount is still not fully understood and, since the days of Horton (1919), the debate about the amount of water that can be intercepted during storm events has been ongoing (Calder, 1977; Gash, 1979; Leyton et al., 1967; Page et al., 2020; Rutter et al., 1971). Not only is the duration of a precipitation event a factor, but also the intensity and the amount of time since the last event have a marked effect on the amount of water stored within the canopy and therefore available for evaporation. All models partition the intercepted portion of precipitation to varying degrees, but they all struggle to account for the actual processes that occur during a period of rainfall. Determination of the canopy storage capacity (generally referred to as S) is key in

all models as when the precipitation exceeds S, any further precipitation becomes throughfall and, depending on the soil moisture conditions, either flows over the ground surface or infiltrates the soil. For interception and S, a model must also account for the intercepted precipitation which evaporates during the rainfall period, as well as which may be dislodged from the surface of the canopy by wind or by the action of larger droplets which have collected on leaves at the higher levels of the canopy and then dripped down, either by gravity alone or by the movement of the canopy generated by wind (Horton, 1919). In their review of 122 modeling studies, Muzylo et al. (2009) concluded that while the Gash and Rutter models are by far the most widely used, this may be more a function of the ease of use of these models than their appropriateness. They also suggest that the development of more user-friendly modeling software would increase the use of the more complex models. Since the publication of Muzylo et al. (2009) review, more studies have incorporated remote sensing data to reduce the reliance on field derived parameters (Cui & Jia, 2014; Miralles et al., 2010; Vegas Galdos et al., 2012; Verbeiren et al., 2016).

Transpiration is the physiological process whereby water taken up by the tree's roots evaporates via the stomata, or pores in the leaves. This can be quantified by experimental means at the individual tree scale by sap flow measurements (see Flo et al., 2019 for a discussion of different methods) and at the stand level by extrapolating from individual values, utilizing a gauged watershed and the eddy flux method. These approaches are described in detail in Vose et al. (2005). Transpiration loss has been shown to be broadly similar between broadleaf and conifer species, certainly within areas of similar climate (Roberts et al., 1980, 1982; Tan & Black, 1976), although Roberts (1983) cautioned that the understory more typical of broadleaved woodland could have a marked influence on total values for transpiration loss at the stand level.

4 | IMPACT OF WOODLAND TYPE ON NFM POTENTIAL

For NFM, the Environment Agency Evidence Directory (Environment Agency, 2018) has categorized woodland into four distinct types: catchment, cross-slope, floodplain, and riparian. A brief description of each is given in Table 1 and Figure 2 shows a schematic representation of the different woodland types.

4.1 | Catchment woodland

Catchment woodland is defined as the total area of all woodland within a catchment, comprising general woodland cover of all types and species, including plantations, plus specific forms where present, such as cross-slope, riparian, and floodplain woodland (Ngai et al., 2017). The influence of forest cover in a catchment on the hydrological cycle has been of close interest to the forest industry for over a century, as is shown in the Bosch and Hewlett (1982) review, which assessed data generated from paired catchment studies performed across the world dating back to 1912 and covering timescales up to 38 years. Paired catchment studies are considered to be quite rigorous, as they provide a control (forested) and a treated (i.e., thinned, planted, or clear-felled) area with similar climatic and topographical conditions. The overwhelming evidence is that reduction in vegetative cover increases water yield and afforestation

TABLE 1 Types of woodland as defined by UK Environment Agency Working with Natural Processes—Evidence Directory 2018

| Woodland type	Extent	Main features
Catchment	Total area of woodland within a catchment	Encompasses all types of woodland
Cross-slope	Smaller belts of woodland across hill slopes and along contours	Acts to provide shelter for animals and slow down surface runoff, increasing infiltration into the ground
Floodplain	Woodland within the fluvial floodplain which is subject to regular flooding	Useful for increasing hydraulic roughness, slowing flood flows, and increasing floodplain storage
Riparian	Woodland adjoining a river or stream channel	Narrow and linear, helps to protect watercourses from erosion, can provide "large woody debris" which helps to slow the flow and induce bank overtopping and floodplain storage. Also increases surface roughness
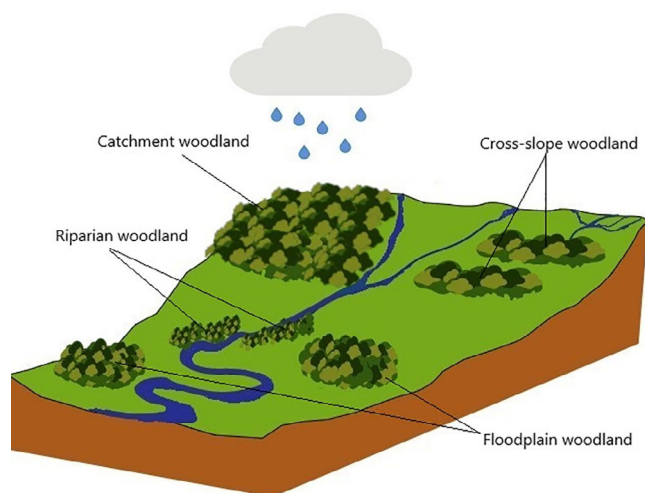
FIGURE 2 A schematic representation of the different types of woodlands as defined by the Environment Agency

decreases it, especially for conifer forest (Bosch & Hewlett, 1982). The review by Best et al. (2003) added a further 56 paired catchment studies to the established canon of data without dramatically changing Bosch and Hewlett's initial outlook. They suggested, however, that "while the effect of vegetation change on a mean annual basis is well understood, research on seasonal water yield reported in the literature is limited and confusing and is primarily of a descriptive nature" (Best et al., 2003, p. 24).

While paired catchments have the advantage of one of the fundamental principles of the scientific method (control vs. treatment), it must be remembered that, due to the necessary scale of catchment studies, the usual criteria of controls may not be possible. The soil type in each location will not be identical, nor will the topography, and as catchments often comprise valley locations, the aspect of the valley slope may directly influence the precipitation and evapotranspiration levels even within a very small geographical footprint (Birkinshaw et al., 2014). If a paired catchment study is not feasible, then the alternative is a single study site with as long a temporal data series as possible. This also gives the benefit of the data encompassing the entire forestry cycle; from initial land use, through cultivation, drainage, and planting to crop maturity. The major drawbacks of this "single site" type of study are that variations in precipitation on an annual scale are harder to detect than with a paired catchment study (McCulloch & Robinson, 1993) and that a study can take decades before any meaningful "before and after" results can be gained.

The Coalburn Catchment study, which is Britain's longest running forest hydrology research catchment, has been widely cited and written about during its 53-year history (Bathurst et al., 2018, 2020; Birkinshaw et al., 2014; Kay et al., 2019; Page et al., 2020; Robinson, 1986). Contrary to the accepted norm, the first 5 years of the Coalburn study (post planting) showed an increase in the order of 20% of peak flows and the time to peak decreased by about a third, while 10 years later drainage peak flows were still 10% above pre drainage values (Robinson, 1986). Continued data collection and analysis of the Coalburn catchment have shown that while the initial effects of this type of management increase the flood risk downstream of the catchment, the long term benefits are apparent, as now that the plantation has reached maturity the annual streamflow is around 250–300 mm less than that for the original vegetation (Birkinshaw et al., 2014). It should be noted that the cultivation methods used at Coalburn in the late 60s and early 70s were very different to modern practices; for example, the deep ploughing increased the density of drainage channels in the catchment to approx. 200 km/km^2 (a more than threefold increase). This has been shown to be instrumental in changing the shape of the hydrograph recession to such an extent that even after 40 years it has not reverted back to the original shape, with low flows remaining around 50% above baseline levels (Birkinshaw et al., 2014; Robinson et al., 1998).

Multidecadal data have also been collected from the Plynlimon catchment area in mid Wales, mainly focusing on water quality, but also on the water balance of the area throughout felling and re growth cycles, offering further insight into the relationship between forest cover and evaporation (Blackie & Robinson, 2007; Marc & Robinson, 2007; Neal et al., 2011) The Plynlimon study did not show any significant changes to peak flows after clear felling of forested areas (Robinson & Dupeyrat, 2005). Similar results were shown at Balquhidder in mid Scotland (Johnson, 1995), but it has been suggested that this may be due to the smaller scale of the catchment and the extended time period of the felling, where a maximum of 20% of the catchment was felled in a single year and the felling was carried out over many years (Ngai et al., 2017). The amount of a catchment which has to be harvested before a demonstrable increase in water yield was shown to be above this value of 20% in the majority of the 95 studies reviewed by Stednick (1996) in his paper

reviewing paired catchment studies in the United States. A more recent study (Abdelnour et al., 2011), however, did show that the location of the clearfelled area within a catchment could have more influence on the increase in streamflow than the size of the clearfell, stating that "... streamflow response is strongly sensitive to harvest distance from the stream channel" (Abdelnour et al., 2011, p. 1).

4.2 | Cross-slope woodland

Cross-slope woodland is the placement of smaller areas, typically belts, of woodland across hill slopes and includes all tree species. It can be managed as either productive or unproductive woodland. Planting cross-slope woodland provides a way of reducing the impact of livestock on soil conditions and the risk of rapid runoff (Elliott et al., 2002; Heathwaite et al., 1990; James & Alexander, 1998; Nguyen et al., 1998). Soil infiltration rates have been shown to be lowered by the constant traffic of sheep due to compaction of the soil (Lunka & Patil, 2016). The increased density of stock levels over the past century (between 1950 and 1990 the national flock more than doubled in size; Fuller & Gough, 1999) has raised the pressure on the available grazing land leading to much higher runoff values for these steep pasture lands (Wheater et al., 2008). One of the measures which has allowed this increase in stocking density is the removal of hedgerows to create larger fields (Marshall et al., 2014). A study of the Skell catchment in Yorkshire showed that hedgerows have a positive effect on soil properties, reducing bulk density and altering surface and subsurface water balances within 1–3 m either side of the boundary (Coates, 2018).

The altitude and exposure of upland pastures also have implications for animal welfare. This concern, in addition to a desire to farm sustainably, led to the creation of the "Pontbren Group," a consortium of 10 farming families with land in the Nant Pontbren catchment in Wales (Keenleyside, 2013). As part of their holistic approach to land management the farmers fenced off and planted trees on small areas of land, initially to provide shelter for livestock. An added advantage of this was that coppice harvesting of the trees provided a supply of animal bedding. It was noticed in 2001 that rainwater moving as over ground flow across the sheep pastures disappeared when it reached the cross-slope shelter belts. The group invited the Centre for Ecology and Hydrology to investigate this. The resulting study showed that within the shelterbelt areas soil infiltration rates were greatly increased (up to 60 times greater under wooded areas than open grazed pasture), and that these increases occurred very rapidly (within 2–6 years). The infiltration rate increases were also seen around the perimeters of the shelter belts, but decreased with increasing distance away from the boundary (Carroll et al., 2004).

The Pontbren Group was adopted by the Flood Risk Management Research Consortium in 2004 to carry out a much wider program of experimentation and instrumentation in order to quantify the impacts of rural land management on the interaction of water, soils, slope, and vegetation at varying scales (Ford et al., 2016; Henshaw, 2005, 2009; Jackson et al., 2008; Marshall et al., 2009, 2014; Reynolds et al., 2010, 2012; Wheater et al., 2008). One study in particular, which combined field data with simulations of different land use and rainfall events at the hill-slope and catchment levels showed that optimally placed woodland shelter belts could reduce peak flows for frequent events by 29%, compared to a 50% reduction for complete tree cover across the catchment. Extreme events (140 mm rainfall over 2 days) were also simulated and the corresponding reductions were 5% and 36%, respectively (Wheater et al., 2008).

A smaller scale study, at Eddleston water in Scotland showed that infiltration rates under broadleaved woodland are between five and six times higher than that of adjacent grazed grassland (Archer et al., 2013), although it should be noted that this study looked at established woodland between 180 and 500 years old. A modeling study of the same catchment area demonstrated that afforestation of >15% of the catchment area had the potential to significantly reduce peak flows at the catchment outlet (Sharp, 2014).

Other than the Pontbren study, there is very little in the literature regarding the hydrological effects of cross slope woodland planting in the UK, and almost none outside the UK (Ngai et al., 2017). Some work was done on Tebay Common in Cumbria, North West England, where the effects of tree planting and sheep exclusion on the hydrological properties of an area have been measured. The preliminary report into this study shows that tree planting increases infiltration rates and improves soil drainage within a few months of planting, indicating a likely reduction in the generation of overland flows in such areas (Mawdsley et al., 2017).

4.3 | Floodplain woodland

Floodplain woodland comprises all woodland lying within the fluvial floodplain that is subject to a regular or natural flooding regime. By its nature, the floodplain will encompass the riparian zone, but this subarea of the floodplain will

be discussed individually in Section 4.4. The floodplain typically comprises broadleaved woodland and can transition from productive woodland on drier parts, often higher or further away from the channel, to unmanaged, native wet woodland in wetter areas (Vanneuville et al., 2016). Floodplains are often subjected to the most development and deforestation due to the high agricultural value of the soil and the perceived social benefit of "living by the river" and as such, it is estimated that up to 90% of floodplains can be classed as "cultivated" and therefore functionally extinct (Tockner & Stanford, 2002). The Environment Agency's Working With Natural Processes literature review found no measured data on the effects of floodplain woodland at the catchment scale, primarily due to the absence of any large scale floodplain woodland in the UK and the fact that many lowland floodplains are already disconnected from their rivers by pre-existing hard infrastructure such as embankments and other flood defenses (Ngai et al., 2017). There are larger areas of floodplain woodland in mainland Europe, but the centuries of control and "improvement" have left a similar level of disconnectedness. Studies have tried to quantify the extent and condition of Europe's floodplains (Wenger et al., 1990), but no comprehensive dataset is available. The same difficulties are found when trying to determine the type of land use on floodplains in Europe. It has been suggested that only about 10% of the original European floodplain forest remains, much of which is in Eastern Europe (Vanneuville et al., 2016).

Empirical studies investigating the impact of floodplain woodland on flood peaks at either the reach or catchment level are rare in the literature. One study which does stand out though is by Piegay and Bravard (1997) on the 1 in 400 year flood that occurred on the Ouveze river in France in September 1992. This major event has provided an important insight into the behavior of both floodplain and riparian responses to a catastrophic flood and suggests that while a truly catastrophic event may be exacerbated by the presence of floodplain and riparian woodland, the benefits gained during events of a lower magnitude and higher frequency may be enough to outweigh this negative effect (Piegay & Bravard, 1997).

Modeling exercises investigating the effect of floodplain woodland regeneration in the UK have been carried out on rivers in Somerset (Thomas & Nisbet, 2007), Yorkshire (Nisbet & Thomas, 2008), and mid Wales (O'Connell, 2008). These studies showed that, at the smaller scale, restoration of floodplain woodland would decrease the flow rate of water within the planted area, raising the water level, and delay peak discharges as well as desynchronize the flood peaks from adjacent tributaries. Thomas and Nisbet (2007) used the 1D HEC-RAS model developed by the United States Army Corps of Engineers (https://www.hec.usace.army.mil/software/hec-ras/) and the River2D model developed by the University of Alberta, Canada (Steffler & Blackburn, 2002). O'Connell (2008) also used the River2D model, and Nisbet and Thomas (2008) used the Infoworks RS model developed by Wallingford Software Ltd. These studies suggested that increasing the scale of woodland planting would further increase their beneficial effects. While it would be expected that modeling larger scale planting interventions should reinforce this hypothesis, other studies in the literature do not fully support this. Park and Cluckie (2006) found that converting a 200 m wide zone of floodplain grassland to woodland would have no effect on flood risk, and studies of the rivers Laver (JBA Consulting, 2007) and Enrick (Babtie, 2006) catchments showed that large scale planting (upwards of 25%) of the catchment would have minimal effects on a 0.5%–1% annual exceedance probability (AEP) flood, although the Enrick flood peak was delayed by an hour. Pattison et al. (2014) showed that changing the relative timing of sub-catchment responses in the Eden watershed in Cumbria could significantly decrease downstream peak flow magnitudes, while Dixon et al. (2016) warn that positive effects in a sub-catchment (attenuating or delaying the flood peak) could increase the flood risk at the catchment level by synchronizing the flows from different sub-catchments. Dixon et al. (2016) argue that, if managed correctly, a planting program covering 10%–15% of the Lymington River catchment would reduce the 3% AEP flood by 6% 25 years after planting, and this benefit would increase with the age of the trees.

When considering the time for restoration measures to become effective, a slight shift in the concept of "natural" can be made. When most people think of natural woodland, the image is that of trees left to their own devices that naturally develop into mature trees which can eventually be harvested for timber with no human intervention until then. Rackham (2006) points out that for much of the UK forest's history most of the woodland was carefully managed, by either pollarding or coppicing trees in order to provide wood products. Willow, if regularly coppiced will grow relatively quickly, has a potentially very high evapotranspiration rate (Guidi et al., 2013) and has been shown to increase flood depth by >20 cm upstream of the planted area and reduce downstream flood velocity by >40% (Environment Agency, 2015). The Environment Agency modeling study investigated the potential of using a fast growing biofuel crop to enhance flood mitigation for two floodplains (River Severn at Uckinghall, West Midlands UK, and River Isle at Ashford Mill, in south-west England, UK) and a third, theoretical site (purely numerical model without local floodplain subtleties). One interesting finding was that the introduction of a new NFM measure, that of an extended "green leaky dam" could act to hold back and slow the flow of water across the floodplain. A potential drawback of this silvicultural system is that immediately after coppicing the floodplain would have no protection to offer, depending on the frequency of coppicing, which could be as often as one out of every 3 years.

4.4 | Riparian woodland

Riparian woodland is woodland located within the riparian zone, defined as the land immediately adjoining a river channel and influenced by it. This zone tends to be relatively narrow, often extending <5 m on either side of water-courses, and typically comprises native broadleaved woodland that is often unmanaged. In the past, conifer plantations extended into riparian zones but most of these areas have now been cleared and are being restored to native woodland.

There is very little evidence in the literature of empirical studies on the effects of riparian woodland on flooding at the catchment scale. Indeed, the Working with Natural Processes review states that as of 2017 "No [Before-After Control-Impact] (BACI) type catchment studies could be found that have measured the effects of riparian woodland planting or removal on flood flows" (Ngai et al., 2017). The study of the effects of riparian buffer zones (including, but not limited to forested zones) on water quality at the catchment level however, is an area which saw a dramatic increase in the last three decades of the 20th century, rising from a pre-1970 level of <2.5 papers per year to about 35 papers per year by 1995(Correll, 1997). The general focus of these papers is the effect of the riparian forest as a buffer zone to mitigate the effects of management activities on the adjacent land or climate change, such as: reducing diffuse pollution by trapping fine sediment runoff generated by agricultural practices (Cooper et al., 1987; Daniels & Gilliam, 1996; Lowrance et al., 1997); enhancing stream metabolism (Blaen et al., 2018); and controlling/cooling stream water temperature through solar shading and evapotranspiration (Brown & Krygier, 1970; Peterjohn & Correll, 1984; Sinokrot & Stefan, 1993). The effect of clear cutting in forested catchments has been discussed earlier with regard to its hydrological effects, but a few paired catchment studies have been carried out where a riparian strip has been left in situ, with a general trend in findings that only small increases in suspended sediments, nutrients and streamflows occurred in cases where the buffer strip was left intact compared with an entire clearcut (Aubertin & Patric, 1974; Borg et al., 1988; Lynch & Corbett, 1990).

Many studies which have modeled the effects of riparian woodland have looked at the potential of these areas to mitigate or exacerbate flood risk through the process of reducing the rate at which water flows through the area by physically obstructing the over ground or in streamflow (Gurnell et al., 2002; Nisbet et al., 2015; Syversen, 2005; Thomas & Nisbet, 2016; Wilkinson et al., 2019). Reduction in streamflow can be achieved by installing or allowing "Large Woody Debris" to accumulate in watercourses. This can be a contentious issue, as in large flood events the volume of water can overwhelm such measures if not fixed into place and lead to greater problems downstream, as bridges and culverts can become blocked by large debris (Dadson et al., 2017). There is certainly a dearth of numerical models of riparian forest growth, with none applicable to the UK environment (Dixon et al., 2019). Although species, geomorphology, and climatic conditions undoubtedly vary across continental scales, and smaller variations in soil type and land use can occur within catchment boundaries, it is fair to assume that widely parameterized, more general, models can be applied to give a conceptual understanding of the processes involved.

The Northeastern Coarse Woody Debris model was developed in the early years of the century by the United States Department of Agriculture and the University of Massachusetts, which uses a wide suite of growth, decay rate, and dead wood dynamic parameters in combination with riparian dynamics based on values derived from studies in North America (Lester et al., 2003). Dixon et al. (2019) used this model with parameters re-specified for typical lowland second and third order streams in the UK to forecast riparian forest development over 200 years at five yearly stages. Their results showed that there is a lag of 40–50 years between the establishment of forest growth and the natural delivery of large woody debris to the watercourse that is large enough to resist fluvial transport, anchor logjams and have a measurable effect on hydrological dynamics (Dixon et al., 2019).

The "Slowing the flow" project in Pickering, North Yorkshire saw the installation of 167 Large Woody Debris (LWD) dams within the Pickering Beck and River Seven catchments as part of a wider program of NFM interventions with the aim of protecting this small rural town from a 1 in 25 year flood. In addition, 29 ha of riparian woodland was planted, and 5.9 ha restored (Nisbet et al., 2011, 2015). These measures were guided by a modeling study (Odoni & Lane, 2010) which had identified suitable locations for various NFM interventions, which included LWD dams, riparian planting and restoration and the construction of two flood storage bunds. This project merits particular attention, as shortly after the construction phase had finished there was a large flood event (Boxing Day 2015) which, while outside the scope of the two official reports into the project, has subsequently been analyzed and it has been shown that the NFM measures put in place reduced the peak flow by 15%–20% and did prevent flooding of a small number of downstream properties. Due to the variety of mitigation measures in place at Pickering it is difficult to determine an individual measure's contribution to the peak flow reduction values, but it is estimated that the upstream land management measures contributed around half of the reduction (Slowing the Flow Partnership, 2016). A more recent study, which

has not yet been reported in peer reviewed literature, is the Eddleston Water Project. This project, on a tributary of the River Tweed in Scotland, has taken a holistic approach to flood mitigation and management with a variety of measures employed. Woodland planting, river re-meandering, and the construction of leaky dams have been implemented at a large number of sites, and early results have suggested that the time to peak flood has been reduced, as well as a reduction in peak flows (Tweed Forum, 2019; Spray, 2016).

5 | CONCLUSION AND FUTURE OUTLOOK

Of the four different types of woodland covered in this review it has been shown that the most work has been done at the catchment scale, and least in the riparian setting. All woodland types need more research to effectively guide the future development of planting proposals and enable the most effective use of forested lands in contributing to NFM. This review has shown that, when applied with due diligence and measured consideration, appropriately planted and managed woodlands can mitigate flood risk and delay flood peaks, both temporally and spatially. Further improvements are required in modeling before a generalized conceptual model is available that accounts for the variation in controlling factors at the stand, hillslope, and watershed level. The growing accuracy of remote sensing will add a further level of resolution to modeling studies, and when combined with field observations, can be used to further refine model parameters. This will aid the validation of models and can only lead to a greater understanding of the inherent processes. A model which incorporates canopy characteristics with streamflow response at varying temporal and spatial scales, and can be adapted to account for the different types of woodland cover found in "real world" scenarios would be very beneficial in guiding planning of afforestation and the management of land currently covered by trees.

CONFLICT OF INTEREST
The authors have declared no conflicts of interest for this article.

DATA AVAILABILITY STATEMENT
Data sharing is not applicable to this article as no new data were created or analyzed in this study.

AUTHOR CONTRIBUTIONS
Matt M. D. Cooper: Writing-original draft. **Sopan D. Patil:** Supervision. **Thomas R. Nisbet:** Supervision. **Huw Thomas:** Supervision. **Andrew Smith:** Supervision. **Morag A. McDonald:** Supervision

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