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Modelling the effectiveness of land-based natural flood management in a large, permeable catchment

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Abstract
In the United Kingdom, woodland planting and soil and crop management are being promoted as approaches to tackling flooding. Although evidence is limited, it is thought tree planting and regenerative agriculture practices such as crop–herbal ley pasture rotations increase infiltration, soil water storage and evapotranspiration, potentially reducing flooding. A process-based soil–water–vegetation model was coupled with a semi-distributed groundwater model to explore the impact of these interventions on peak and low flows in a large, groundwater-dominated catchment. Land use change and management were found to have limited potential to reduce flooding in this setting. Herbal ley–crop rotations produced a <1% reduction in flow for return periods >2 years, and levels of woodland planting judged to be the realistic maximum produced reductions of 0.2%–2.6%, depending on tree species. Broadscale spruce planting was the only scenario to produce significant reductions in peak flow (16.0%–24.7% at return periods 1–15 years); however, the level of spruce planting required to achieve these reductions was estimated to reduce Q95 flow by ~39%, which would likely have negative implications for water security and ecological river flows. The impact of land-based natural flood management interventions for flood prevention in large, permeable catchments should not be overstated.

KEYWORDS
flood mitigation, groundwater, land use, nature-based solutions

1 | INTRODUCTION

With increasing global concern over the impact of flooding (Kreibich et al., 2022; Ward et al., 2017; Willner et al., 2018), and a focus on nature-based solutions (NBS) to environmental problems (Cohen-Shacham et al., 2016; Faivre et al., 2017; Maes & Jacobs, 2017), interest has grown in the efficacy of natural flood management (NFM) as a means to reduce flood risk. NFM aims to reduce flood hazard, while also enhancing other potentially significant co-benefits such as biodiversity, soil and water quality, carbon sequestration, reduced soil erosion and agricultural productivity (Dadson et al., 2017). NFM measures have been classified as those that reduce the rate of rapid runoff generation on hillslopes, create storage of water during high river flows, and slow flow by reducing the connection between runoff sources and zones of potential flood inundation (Lane, 2017). As well as in-channel and riparian measures, such as leaky dams, offline storage areas and floodplain woodlands and hedgerows (e.g., Hankin et al., 2020; Lavers et al., 2022; Lavers & Charlesworth, 2017; Nicholson et al., 2020), NFM includes diffuse land management that reduces runoff generation by increasing surface infiltration, enhancing soil storage, increasing evapotranspiration and inhibiting lateral surface flow (Burgess-Gamble et al., 2017; Martin et al., 2020). Diffuse land management NFM measures focus on the conversion of farming land to woodland, crop choice and rotation, and soil management (Archer et al., 2013; Cooper et al., 2021; Koschke et al., 2013).

However, the effects of these diffuse land management measures on reducing flooding are unclear (Bathurst et al., 2020; Carrick et al., 2019; Stratford et al., 2017). Whereas modelling studies tend to support the hypothesis that increasing tree cover reduces flood peaks, results from observation-based studies are more mixed (Stratford et al., 2017). It is likely that the effect of woodland planting is dependent on a range of local factors including soils and geology (Peskett et al., 2021), catchment size (Ewen et al., 2015), the land use being replaced (Revell et al., 2021), and forest age, type and management (Archer et al., 2013, 2015; Chandler et al., 2018; Lunka & Patil, 2016; Xiao et al., 2022). The effect of regenerative agriculture (RA) on flooding is even less clear than that of afforestation. RA is an approach to farming that focuses on soil conservation, potentially producing a range of ecosystem services, including improving soil health and fertility, soil organic carbon, water quality and soil water retention (Rhodes, 2017; Schreefel et al., 2020). One form of RA is to rotate crops with a herbal ley pasture, comprising a mixture of grasses, legumes and herbs. We found no modelling or observational studies on the impact of RA on flood risk; this tends to be inferred from a limited number of plot-scale studies on changes in soil properties (e.g., Berdeni et al., 2021; Rhodes, 2017).

Groundwater-dominated lowland catchments are characterised by a significant proportion of high permeability underlying bedrock and high levels of baseflow in associated rivers (Bloomfield et al., 2009). Soils derived from these bedrocks tend to have naturally high effective porosity and surface infiltration rates (Boorman et al., 1995). These soil properties mean that significant soil moisture deficits (SMD) can form during summer periods; persistent, high-volume rainfall is required before SMDs are overcome, with substantive groundwater recharge generally only occurring during winter and spring (Jasechko et al., 2014; Rushton et al., 2006). High soil infiltration rates mean that runoff generation is generally limited in these landscapes (Martínez-Mena et al., 1998), although there are settings where runoff can be significant, for example, where small outcrops of low permeability bedrock or superficial deposits occur (Jencso & McGlynn, 2011). Although direct runoff is one of the forms of flooding in permeable catchments (Bradford, 2002), flood events are typically groundwater driven. Flooding is most commonly the result of groundwater-fed fluvial flooding and abnormally high groundwater levels (gwls) away from the perennial river channel that cause inundation of subsurface infrastructure or the discharge of groundwater at surface (Collins et al., 2020; Gotkowitz et al., 2014; Hughes et al., 2011; Macdonald et al., 2008, 2012; Naughton et al., 2018).

The application of conceptual hydrological models in simulating the effect of afforestation or land management on flooding generally relies on speculative shifts to model parameters representing routing or soil storage (e.g., Ferguson & Fenner, 2020; Packman et al., 2014; Rose & Rosolova, 2007). While some authors have studied these 'parameter shifts' for well-monitored micro-catchments (Goudarzi et al., 2021; Hankin et al. 2021a; Hankin et al. 2021b), it would be difficult to directly apply their results to other catchments, and impossible where geology and hydrological processes or climate vary significantly. Process-based models, alternatively, allow physical changes in measurable soil and vegetation properties to be directly incorporated in scenarios of land use change (Buechel et al., 2022; Bulygina et al., 2013; Iacob et al., 2017; Milkovic et al., 2019; Wahren et al., 2012). The limitation of this approach is that a significant amount of data is required to define these properties, and these data, particularly with regard to soils, may not exist.

Shifts in routing parameters are unlikely to be relevant for groundwater-driven long-duration flood peaks. Instead, vegetation and soils need to be simulated with sufficient complexity to understand their impact on antecedent soil moisture and gwls as well as subsurface routing to streams. Whereas a number of studies have used process-based models to simulate afforestation (e.g., Buechel et al., 2022; Bulygina et al., 2013; Milkovic et al., 2019), to our knowledge none has incorporated a groundwater model to estimate changes to flood risk in groundwater-dominated settings.

There is evidence that NFM measures can be effective locally in reducing flood risk from high-probability flood events, particularly in sub-catchments underlain by low-permeability soils and bedrock geology (Black et al., 2021; Wilkinson et al., 2010). However, the

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effectiveness of these measures at larger scales, for low probability flood events and in groundwater-dominated lowland catchments has been questioned (Barnsley et al., 2021; Dadson et al., 2017; Lane, 2017). In this study, we investigate the impact of two NFM measures, tree planting and herbal ley–crop rotations, on peak flows to address this question. We use a case study catchment in the southern United Kingdom, where the upscaling of NFM measures is being actively considered within schemes to manage downstream flood risk to large urban centres (e.g. Short et al., 2018). We do this by coupling a process-based soil–water–vegetation model with a groundwater model. We also analyse impacts of NFM on low flows.

2 | MATERIALS AND METHODS

2.1 | Study site

In the study, we focus on the catchment of the River Thames to the town of Eynsham (1616 km^2; Figure 1a). The catchment is dominated by the Cotswolds Hills (up to 280 masl), which dip gently, east−southeast towards the Thames floodplain (Neumann et al., 2003; Rushton et al., 1992). Land use within the catchment is predominately agricultural with 35% arable, of which 96% is cereal crops (Crop Map of England 2019), and 38% grassland/improved grassland; over the Cotswold Hills (Figures 1c and 4), 49% is arable and 33% grassland/improved grassland. At present, 20% of land is broadleaved woodland and 3% coniferous woodland within the Thames catchment to Eynsham, but much less over the Cotswold Hills (11% and 1%, respectively). Long-term mean precipitation across the catchment is 757 mm/a (1951–2017, National River Flow Archive 2022).

The hydrology of the catchment is controlled by its complex geology (Bricker et al., 2014). The Cotswold Hills comprise an alternating sequence of Jurassic Limestone and clays, the limestones forming two principal aquifers, the lower Inferior Oolite (IO) and upper Great Oolite (GO; Figure 2). Although two distinct aquifers separated by clays, the GO and IO are connected in places via faults (Maurice et al., 2008). The aquifers have low storage and high hydraulic conductivity (Morgan-Jones & Eggboro, 1981); and there is evidence of groundwater crossing surface water catchment divides via the IO (Allen et al., 1997). Superficial deposits, comprising sand and gravel, are found on the Thames floodplain, extending upwards in step-like terraces onto the hillsides (Bricker & Bloomfield, 2014; see Figure 4). The Cotswold Hills are predominately overlain by shallow, freely draining soils (30–50 cm; Figure 1b). More clay-rich soils are found towards the Thames floodplain, and in isolated areas along the river (Figure 1b).

Reports of historical flooding in the study area were infrequent in the second half of the 20th Century (Marsh & Harvey, 2012); however, in the 2000s and 2010s a series of major flood events occurred. These affected local towns, as well as causing substantial flooding to Oxford city, which sits partially on the Thames floodplain downstream (Macdonald et al., 2012, 2018). The flooding was primarily fluvial, although some flooding in the higher ground and in the floodplain of the River Thames was due to groundwater discharging away from the perennial water course (Macdonald et al., 2012), and, in the summer flood of July 2007, also included significant pluvial flooding (Marsh & Hannaford, 2007). The gwls and river flows within the catchment are highly vulnerable to sustained periods of low rainfall, with the droughts of the summers of 1976 and 1990 of particular note. Surface water and groundwater abstractions have been identified as impacting on ecological flows of streams sourced from the Cotswold Hills (Environment Agency, 2019).

NFM is being explored within the study area as a means to manage flood risk. Following a consultation exercise with local stakeholders, three NFM options from a list of 11 were selected as being both feasible and acceptable (Elwin et al., 2020): soil and land management, increased tree cover, and river restoration. The effectiveness of aspects of the former two is addressed here.

2.2 | Modelling framework

The modelling framework is outlined in Figure 3. The focus of this study is on land-based NFM interventions, that is, tree planting and herbal ley–crop rotations, on the freely draining soils and permeable geologies of the Cotswolds limestone. A pre-existing groundwater model of the Upper Thames catchment is used (Hutchins et al., 2018). We replaced the recharge component of this model, ZOODRM (Zooming Object Oriented Distributed Recharge Model; Mansour & Hughes, 2004), with SWAP (Soil Water Atmosphere Plant model) over the Cotswolds limestone (Figure 4; Kroes et al., 2017), as SWAP provides the necessary functionality to represent land-based interventions. The groundwater model simulates baseflow for each sub-catchment, which is summed with surface runoff to produce a river flow.

2.2.1 | Soil–land–vegetation model

We implemented soil–land use combinations for the Cotswold limestone via the SWAP model configuration

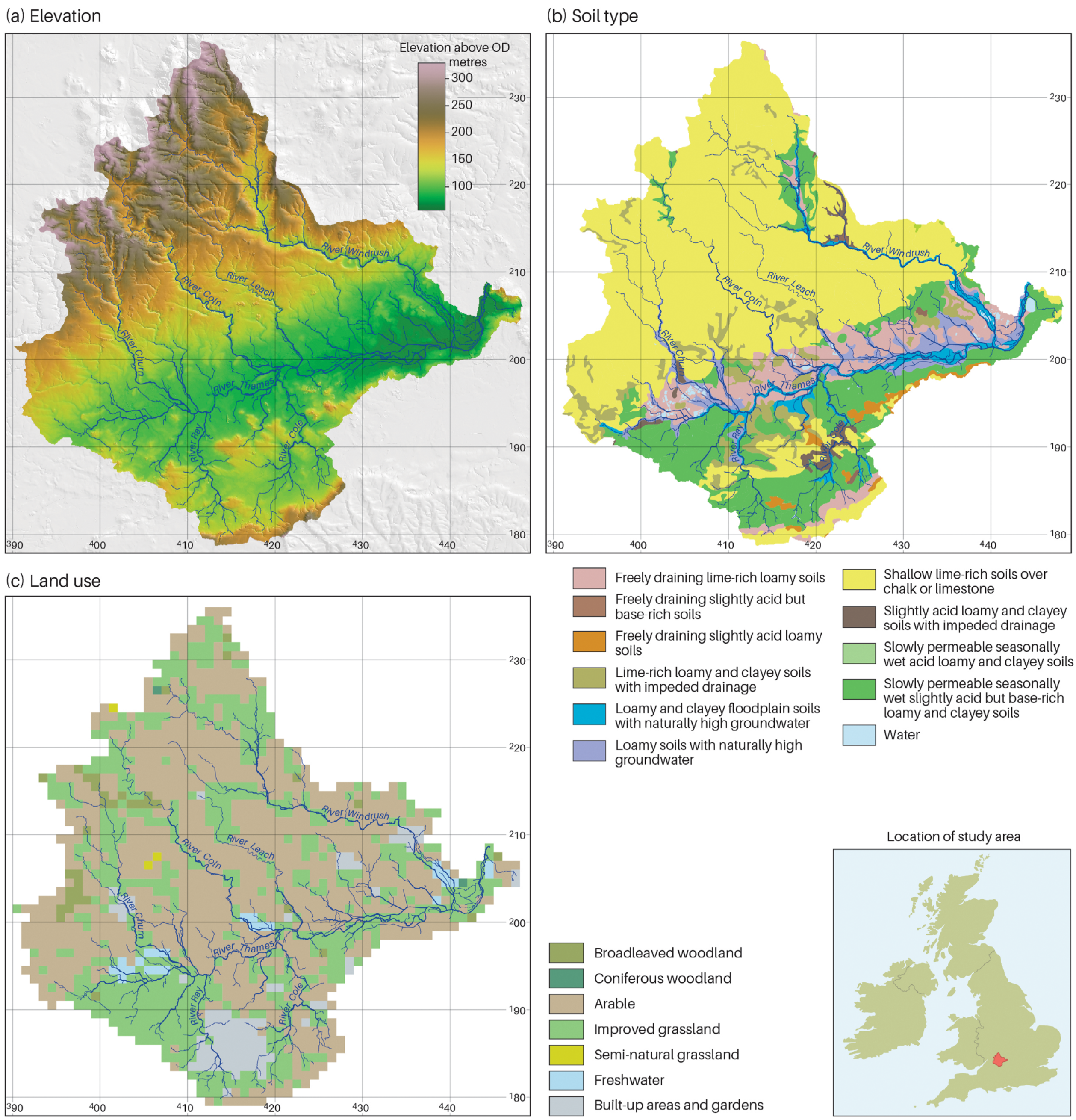

FIGURE 1 Thames at Eynsham catchment (a) elevation, (b) soil type, using Soilscapes descriptions (©Cranfield University (NSRI) and for the Controller of HMSO [2022]), (c) land use (Rowland et al., 2017). Contains NEXTMap Britain elevation data from Intermap Technologies.

(.swp) and crop files (.crp) (detailed in Verhoef et al., 2023). Soil information, such as soil hydraulic parameters and soil depth, was based on the UK NATMAP database (Cranfield Soil and Agrifood Institute, Cranfield University, L0070/01077). The measured soil water retention curves (WRCs) available from NATMAP were used to fit the parameters in the Van Genuchten–Mualem (VGM) equations, required in the .swp files. It was assumed that the WRCs had no hysteresis. VGM parameters were obtained for each soil horizon, and for each land use type. NATMAP WRC data are provided for arable, grass ley, permanent grass and other (unfarmed natural vegetation, used for forest model runs). For each soil series, the saturated hydraulic conductivity was also taken from the NATMAP dataset (and the VGM parameter L was set to 0.5 for all soil series). For the bottom boundary, we assumed free drainage for all soil series (but note that some soils had impeded drainage or water logging, see Table 1). After some preliminary test-runs it was decided to set the SWAP parameter 'drainage

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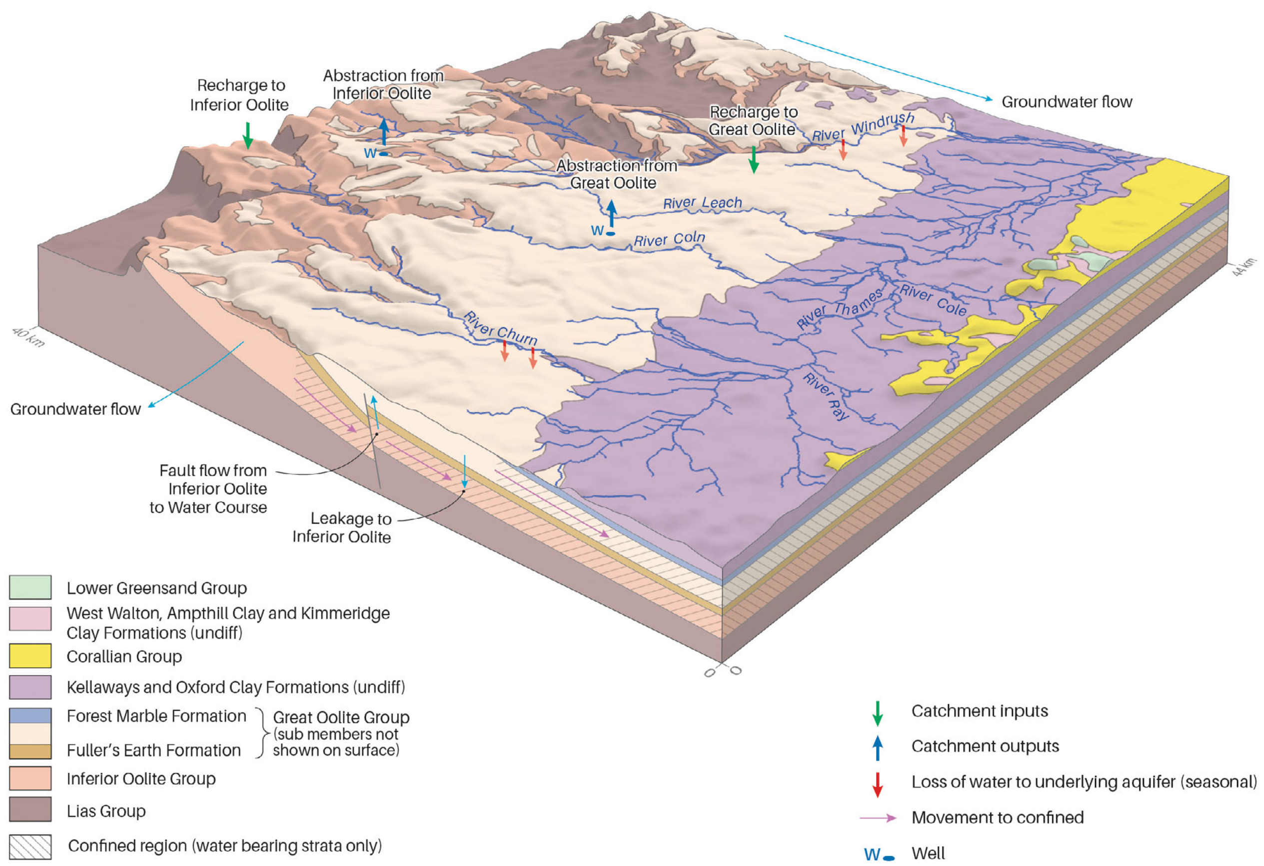

FIGURE 2 Schematic 3D geology of the Cotswold Hills. Contains NEXTMap Britain elevation data from Intermap Technologies.

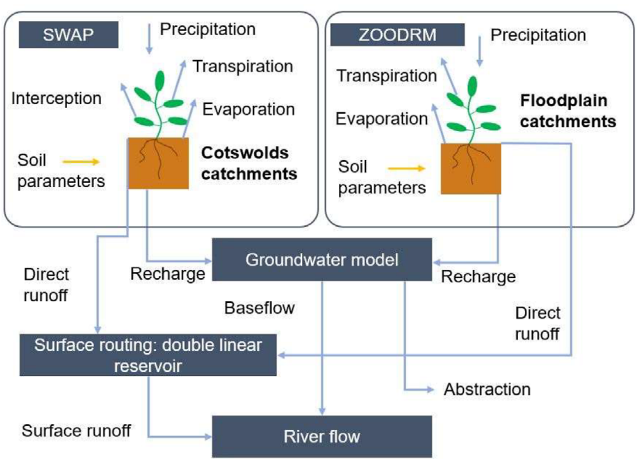

FIGURE 3 Modelling framework. SWAP, Soil Water Atmosphere Plant model; ZOODRM, Zoom Object Oriented Distributed Recharge Model.

resistance for surface runoff' to baseflow index (BFI)/100 (values for BFI, can be found in Table 1, also obtained from NATMAP), whereas the 'exponent in the drainage equation of surface runoff' was set to 1.0 for all soil series.

Vegetation parameters were largely derived from standard .crp files within SWAP. Some parameters in these files were changed slightly (e.g., to avoid the permanent grassland vegetation dying during extremely dry years). The crops used in the crop rotations, as well as the permanent grassland (improved grassland), were simulated using SWAP *detailed* crop files, whereby crop and root growth is based on carbon partitioning.

Two crop rotations were used: a winter wheat–winter oilseed rape (conventional crop) rotation, representing conventional agriculture (CA), as the base case; and a crop–herbal ley rotation representing RA. The RA rotation consisted of 4 years crops (winter wheat, winter oilseed rape, broad beans and spring barley) and 4 years herbal ley. Note that for the SWAP RA runs, the soil properties were represented by the permanent grass soil profiles to reflect the improved soil hydraulic properties resulting from the beneficial rooting systems of the plants in the grass–herb–legume mixtures. Although implementing just a single CA rotation is a simplification, winter wheat and winter oilseed rape constitute >50% of all crops grown over the Cotswold Hills (Crop Map of England 2019). The crop rotations were devised by local agricultural advisors.[1]

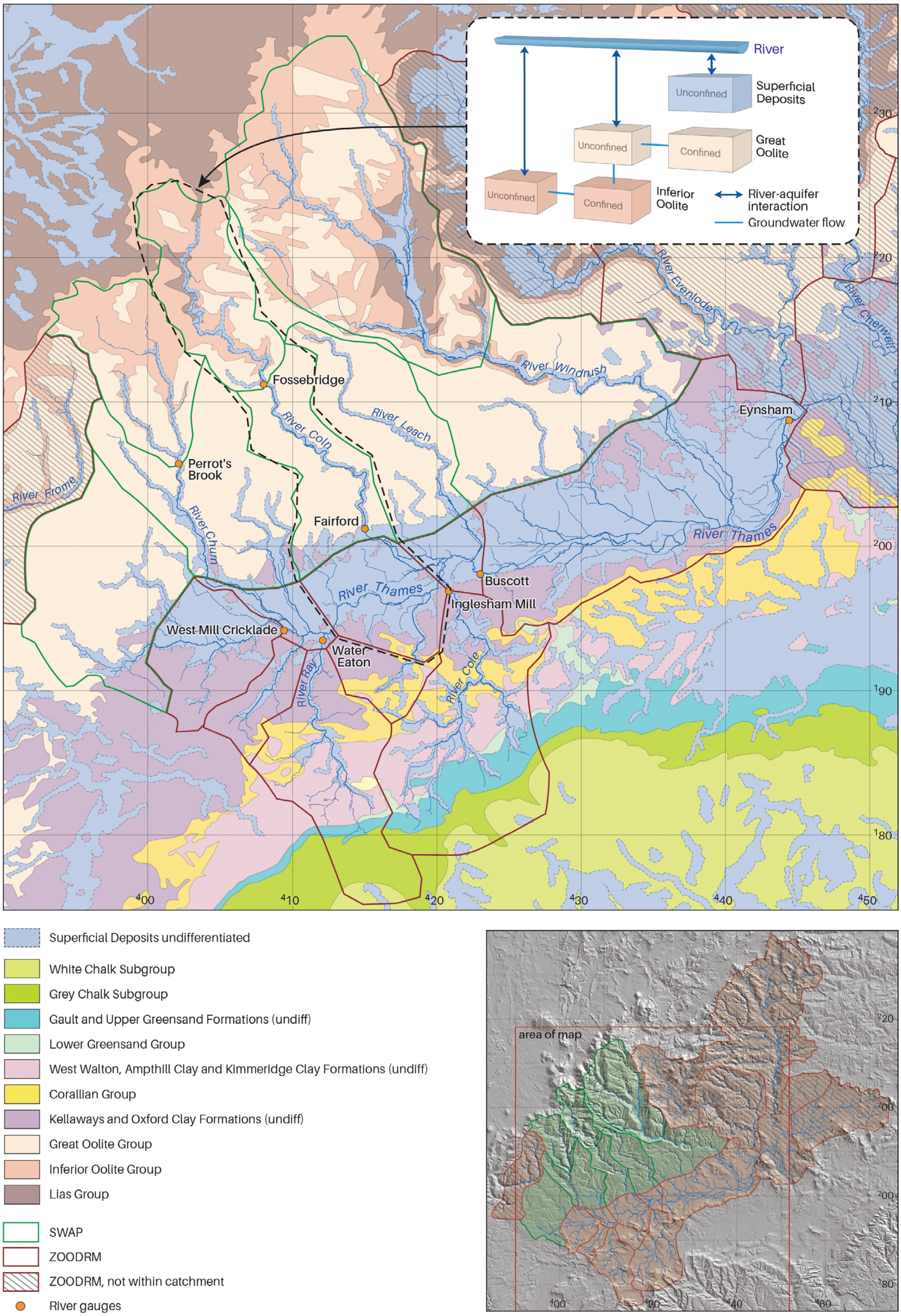

FIGURE 4 Groundwater model discretisation into cells and geological map. Hatched cells are not within the Thames at Eynsham study catchment. Inset (upper image) shows the interactions amongst model cells down the Coln catchment. Contains OS data © Crown Copyright and database right 2022. Contains NEXTMap Britain elevation data from Intermap Technologies. SWAP, Soil Water Atmosphere Plant model; ZOODRM, Zoom Object Oriented Distributed Recharge Model.

TABLE 1 Key soil series found in the Upper Thames Catchment and their texture and hydrological properties.

Soil series	Texture[a]	Drainage (DGLEY in cm)	Depth (cm)	BFI	Description
Elmton	ClLo	FD (999)	35	0.98	Shallow lime-rich soils over chalk or limestone
Sherborne	ClLo	FD (999)	30 (25 forest)	0.98	Shallow lime-rich soils over chalk or limestone
Aberford	ClLo	FD (999)	55	0.98	Freely draining lime-rich loamy soils
Badsey	ClLo	FD (999)	150	0.88	Freely draining lime-rich loamy soils
Moreton	ClLo	FD (999)	60	0.98	Freely draining lime-rich loamy soils
Evesham	Cl	ID (60)	150	0.22	Lime-rich loamy and clayey soils with impeded drainage
Wickham	ClLo	ID/WL (25)	150	0.17	Slowly permeable seasonally wet slightly acid but base-rich loamy and clayey soils
Denchworth	Cl	ID/WL (25)	150	0.17	Slowly permeable seasonally wet slightly acid but base-rich loamy and clayey soils

Abbreviations: BFI, base flow index; Cl, clay; ClLo, clay loam; DGLEY, depth to gleying; FD, freely draining; ID, impeded drainage; WL, water logging.
[a]Based on percentages in A horizon for arable soils, texture triangle: Soil Survey of England and Wales.

For the forests—one broadleaf forest and one needle leaf forest (spruce)—simple .swp files were used, with leaf area index, tree height and root depth prescribed. Here, it was assumed that the forests, and their root systems, grow exponentially over time (from 1 January 1971, for ∼30 years), after which their growth remains constant.

ZOODRM uses the simplified FAO soil moisture accounting scheme to estimate actual evapotranspiration, recharge and runoff (Griffiths et al., 2007). Its parameterisation over the United Kingdom is described in detail by Mansour et al. (2018).

ZOODRM is driven by daily gridded rainfall and potential evapotranspiration data and produces spatially distributed recharge and runoff, which are summed over the relevant model cells. As SWAP is a 1D model, its input and output data require processing so that they can be mapped onto cells. A set of meteorological data was created for each cell by a really averaging gridded meteorological variables: daily 1 km rainfall and maximum and minimum temperature (UK Met Office, 2022); and daily 1 km potential evapotranspiration and short-wave radiation (Robinson et al., 2020). Separate .swp files were created for each combination of soil type, land use type and meteorological dataset. The fractional cell cover of each soil type and land use combination was determined, and then used to create a weighted sum of recharge and direct runoff from the SWAP model outputs for each cell.

2.2.2 | Groundwater model

The extreme heterogeneity of the Cotswold limestone aquifers (Rushton et al., 1992) poses a significant challenge to modelling. Groundwater models of the GO and IO aquifers have ranged widely in complexity from an unsuccessful attempt to calculate river discharges by multiplying upstream area by a measure of river baseflow speed (Paul, 2014) to fully distributed groundwater models applying an equivalent porous medium approach (Environment Agency, 1997; Parades, 2012; Rushton et al., 1992). Hutchins et al. (2018) demonstrated that, despite the heterogeneity of these aquifers, they could be successfully modelled at a large scale with a semi-distributed model. In this study, the groundwater model we apply is an updated version of the Hutchins et al. (2018) model, the basis of which is described in detail in the Supplementary material S1.

In the groundwater model the groundwater system is divided into a series of cells (Figure 4). Horizontally the cells approximate groundwater sub-catchments. Vertically they are associated with an aquifer unit; either the IO, GO or superficial deposits (SD) in the Thames valley.

The model is composed of 35 cells, although only 28 cells are within the Thames at Eynsham catchment (see Figure 4). The cells are assigned to one of three layers, which have different lateral extents: the bottom layer represents the IO; the middle layer, the GO; and the top layer, the SD. Cells in each layer are connected laterally to their neighbours; along and across dip for the IO and GO, and along the valley for the SD cells. GO and SD cells are not connected because of the low hydraulic conductivity clay separating them.

Each cell is conceptualised as a lumped, homogeneous store for which a hydraulic conductivity, specific storage and specific yield are specified and calibrated. Groundwater storage in a cell is represented by a single head. Fluxes between cells depend on the difference in cell heads; the conductance between vertically connected cells is also calibrated. River networks within upper cells are connected to model river components; the riverbed conductance parameter is also calibrated. The flux between the aquifer and rivers depends on the groundwater head and river level, and on the flowing length of the rivers within the cell, which in unconfined IO and GO cells is dynamic (see Supplementary material S1).

The model simulates the period 1971–2017 on a daily timestep with the first 3 years discarded as spin-up. Time series of recharge from SWAP or ZOODRM are input to the related cells, and groundwater is pumped from six IO and GO cells. Annual groundwater pumping rates for the period 1971–1991, and monthly groundwater pumping rates for the period 1992–2003, have been provided by Thames Water Utilities Ltd. For the later period for which pumping rates have not been obtained average rates were applied. Groundwater pumping is equivalent to ~5% of simulated groundwater recharge.

2.2.3 | Runoff simulation

Surface runoff at each gauge was generated by applying direct runoff from ZOODRM and SWAP to a surface water routing model comprising a cascade of two linear reservoirs (Moore, 2007; Figure 3). The parameters of the linear reservoirs were calibrated by fitting simulated runoff to observed runoff at gauging stations (Figure 4) estimated by baseflow separation (Gustard et al., 1992). In total two sets of parameters were calibrated, for SWAP-related and ZOODRM-related cells.

2.2.4 | Model calibration

The groundwater model was calibrated against streamflow at eight gauging stations using the Kling–Gupta efficiency (KGE; Gupta et al., 2009), which is superior to Nash-Sutcliffe for high flow estimation (Knoben et al., 2019; Mizukami et al., 2019). Gauged flow records at the eight stations ranged from 17 to 46 years. There is wide variation in the literature with regard to setting the KGE threshold (Knoben et al., 2019). We took a pragmatic approach to model evaluation, setting thresholds prior to calibration somewhat arbitrarily but high considering the complex geology of the catchment (Table 2).

An initial Monte Carlo simulation of 60,000 runs sampling 39 parameters failed to produce a single acceptable model. Instead, to tackle the lack of parameter identifiability, the model was calibrated with PEST (Doherty, 2005) using singular value decomposition. Parameter ranges and initial values were set using expert knowledge. PEST was able to find an acceptable model instance, and a posterior parameter covariance matrix was produced to explore the uncertainty. The matrix was used, along with the optimum parameter values found by PEST, to generate 1000 random parameter sets, which were run through the model to find a range of acceptable model instances. All scenarios were run with all acceptable model instances to help quantify model prediction uncertainty.

2.3 | NFM scenarios

NFM interventions were applied only to the SWAP-modelled cells (Figure 4). Four woodland scenarios were created: two *broadscale* NFM scenarios that convert all grassland and arable land into either deciduous or spruce woodland; and two *refined* scenarios that convert 78 km^2 (~5% of the entire catchment, 9% of Cotswold limestone sub-catchments) into either. The refined scenarios were derived from discussions with local stakeholders, and

TABLE 2 Performance of acceptable models against thresholds set.

River	Gauging station	KGE threshold	Comments on threshold	KGE ranges for acceptable models (see Section 3.1)
Thames	Eynsham	0.7	Main stem and incorporating areas of proposed NFM interventions	0.75–0.92
	Buscot			0.81–0.91
Coln	Fossebridge	0.6	Areas of proposed NFM interventions	0.62–0.78
	Fairford			0.62–0.78
Churn	Perrot's Brook			0.60–0.67
Ray	Water Eaton	0.5	Not within the area of proposed NFM interventions	0.51
Cole	Inglesham Mill			0.66–0.70
Thames	West Mill, Cricklade	0.5	Gauged flows are affected by abstractions, which the authors were unable to obtain	0.52–0.63

Abbreviations: KGE, Kling–Gupta efficiency; NFM, natural flood man agement.

considered an absolute maximum of what would be feasible and acceptable in the landscape. These scenarios were created by putting a 25 m buffer around existing woodland (Forestry Commission, 2022) and a 20 m buffer along streams. Only grassland and arable land within the buffers were converted to woodland.

We represented RA through a crop–herbal ley rotation (see Section 2.2.1), which, although a limited definition of RA, incorporates the improvements in soil structure that many approaches to RA aim to achieve. Three RA scenarios were run, with 25%, 50% and 75% conversion of CA to RA, representing 12%, 25% and 37% of the limestone sub-catchments (or 10%, 19% and 29% of the Thames catchment at Eynsham), respectively.

2.4 | Analysis of peak and low flows

The period October 1987–2017 was used for analysis of flows to focus on more mature woodland, as the trees planted in the SWAP model in 1971 had grown to maturity at that stage. Each scenario was run with all acceptable model instances. For each scenario and acceptable model, empirical flood frequency analysis was used to assign return periods to annual maximum flows (hydrological year, October–September). Events were grouped by return period for comparison: 1–2, 2–3, 3–5 and 5–15 years.

Low flows were analysed by comparing the flow at Q95 for the base case and scenarios, for all acceptable models. We used the median Q95 flow of all acceptable models from the base case to characterise the drought threshold, and defined a drought as being any period in which river flow is below the drought threshold for 2 consecutive days or more. Droughts were identified for all scenarios and model instances, and their duration and intensity calculated. The intensity of a drought was defined as the mean difference between median base case Q95 and simulated flow throughout the duration of the drought.

3 | RESULTS

3.1 | Model performance

From the 1000 random parameter sets generated from the posterior parameter probability distribution, 47 acceptable model instances were found. Model performance (KGE) amongst the acceptable models is shown in Table 2. Figure 5 shows the observed daily flows at the eight gauging stations against simulated flows for a single acceptable model instance. As illustrated in Figure 5, the model performed well overall, matching the shape of the hydrograph and the baseflows. For those stations with higher KGE values (Table 2), such as the River Thames at Eynsham and Burcot, the model also did generally well in simulating the flow peaks; for those with relatively low KGE values, such as the River Ray at Water Eaton and the River Cole at Inglesham Mill, the model generally produced lower peaks than observed.

3.2 | Antecedent controls on the impact of interventions

The antecedent conditions prior to annual maximum flows are presented in Figure 6. Of the 30 annual maximum observed flows at Eynsham, 20 (67%) occurred either in January or February and 27 (90%) occurred in December–March. Figure 6a shows the mean antecedent accumulated precipitation prior to annual maximum peak flows, as well as the long-term mean (1987–2017), for different accumulation periods. Whereas the 1-day and 2-day accumulated event precipitation are 30% lower and 2% higher than the mean, respectively, 7-day and 1-month and 2-month accumulated precipitation indicate pro-longed wet periods (360%, 185% and 146% of mean, respectively).

Figure 6b shows the average soil water storage capacity (SWSC; saturated minus actual volumetric water content) throughout the Sherborne soil profiles—the most extensive soil over the Cotswolds limestone—in the month prior to annual maximum flows. Antecedent SWSC is lowest for CA (median 0.036 cm^3/cm^3); higher, and very similar, for broadleaved woodland, grassland and RA (medians 0.060, 0.061 and 0.062 cm^3/cm^3, respectively); and highest under spruce woodland (0.072 cm^3/cm^3). The spruce woodland–Sherborne combination has double the SWSC of the arable–Sherborne combination, and a change from CA to RA rotations results in a 72% increase in SWSC.

Figure 6c shows the average recharge under Sherborne soil for different land uses at the onset of the recharge season (September–December). Recharge is much reduced under spruce woodland, but very similar for all other land uses from November. The differences between antecedent gwls—defined as the average gwl in the month of the peak and the month prior to the peak—in the base case and NFM scenarios are shown in Figure 6d. Spruce woodland has the largest impact on antecedent gwl, followed by broadleaved woodland. However, the effect is much larger for broadscale conversion than in the refined scenario: −0.1 m versus −1.1 m reduction for broadleaved woodland and −0.6 m versus −5.9 m reduction for spruce woodland for the refined and broadscale scenarios, respectively (medians).

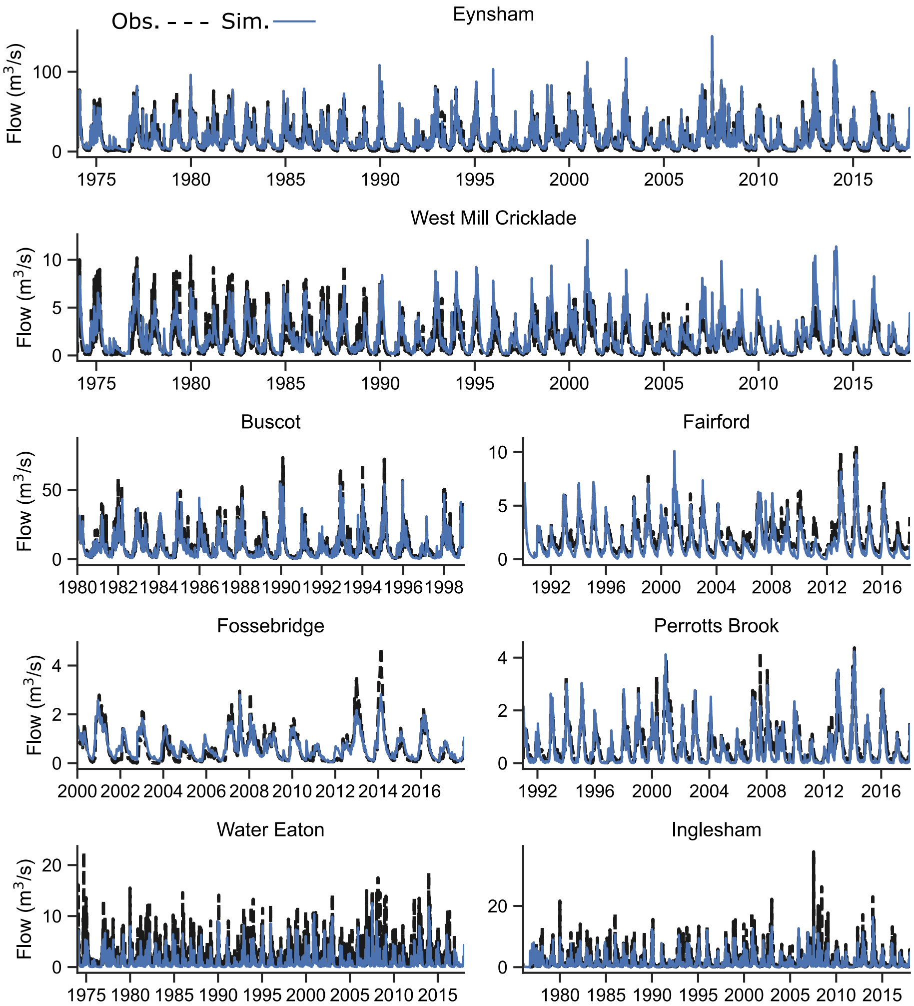

FIGURE 5 Simulated (sim.) versus observed (obs.) flow for one acceptable model instance at the eight gauging stations. Contains data from *UK National River Flow Archive*.

3.3 | NFM scenarios

The effect of the tree planting and RA scenarios on peak flows at Eynsham for various return periods is shown in Figure 7. The more realistic refined broadleaved and spruce woodland scenarios have only a limited impact on peak flows, with the greatest effect seen with spruce woodland for peak flows with return periods of 1–2 years (Figure 7a). Percentage reductions in median flows across the 30 annual maxima for these two scenarios are 0.2%–0.9% for broadleaved and 1.5%–2.6% for spruce woodland. The two broadscale woodland scenarios have a much greater effect on peak flows, although the effect of broadleaved woodland is still rather small considering the scale of the intervention. Percentage reductions in median peak flow for these two scenarios are 1.7%–6.7% for broadleaved and 16.0%–24.7% for spruce woodland, with the smallest reductions simulated for peak flows with return periods of 5–15 years, and the largest for return periods 1–2 and 2–3 years for broadleaved and spruce woodland, respectively.

The RA scenarios have a greater impact than the refined broadleaved scenario on peak flows with a 1–2 years return period: 1.7%, 2.9% and 4.1% reduction in median peak flow for 25%, 50% and 75% conversion to RA, respectively (Figure 7b). Percentage reductions in median peak flow for return periods 3–15 years are all below 1%.

With regard to low flows, all scenarios lead to a reduction in Q95 flow at Eynsham (Figure 8). The effect of the RA and refined woodland scenarios is small (<5%), particularly considering the uncertainty in the results (i.e., captured by the range of results from all acceptable models, 2.8–4.1 m^3/s for the base case). Broadscale broadleaved woodland produces a greater reduction in Q95 (12%), but broadscale spruce produces the largest reduction, with a 39% drop in median Q95 (Figure 8).

Figure 9 shows the number of hydrological drought periods (1987–2017), their length and their severity for the base case and all scenarios. Similar to Q95, the uncertainty in the number of drought periods for the base case is high, ranging from 7 to 51 (Figure 9a), although the majority of these drought periods last only a few days (median 14 days, Figure 9b). Whereas the range in the number of droughts simulated is a direct result of model uncertainty

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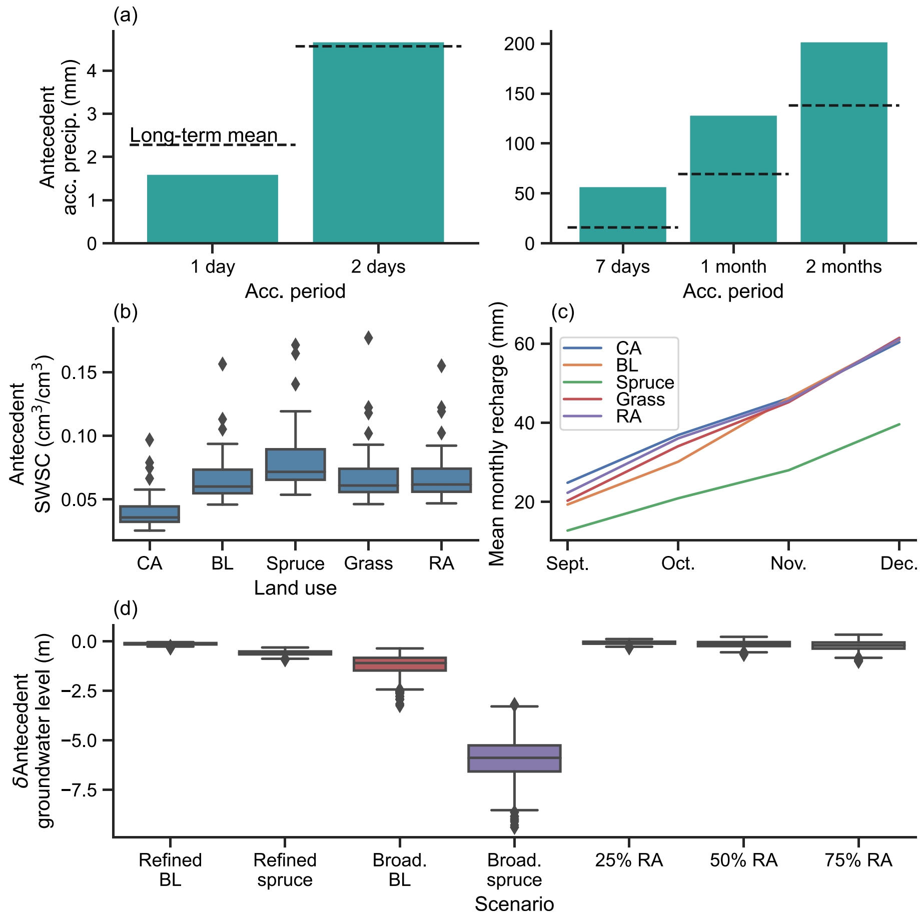

FIGURE 6 (a) Mean antecedent accumulated (acc.) precipitation before annual maximum flows. Precipitation is the areal average over the limestone sub-catchments. Black dashed lines show long-term means for each accumulation period. (b) Antecedent soil water storage capacity (SWSC) in month prior to annual maximum flows ($n = 30$) for Sherborne soil. (c) Mean monthly recharge for different land uses and Sherborne soil. (d) Mean difference between base case and scenario gwls in limestone sub-catchments in the month prior to and of annual maximum flows ($n = 30$). BL, broadleaved woodland; CA, conventional agriculture; RA, regenerative agriculture.

(Figure 9a), the range in the duration and severity of droughts (Figure 9b,c) is a combination of model uncertainty and the variation in different drought periods within a single model run, 1987–2017. The refined woodland and RA scenarios have very little impact on the number, duration or severity of drought periods. However, broadscale broadleaved and spruce woodland are estimated to increase the number of droughts considerably (by ~2 and ~ 5 times, respectively), and broadscale spruce is estimated to increase drought intensity by 134% (median). The duration of these droughts under the broadscale woodland scenarios is predicted to change little, although the most extreme droughts predicted in some of the base case model instances (8 produce a maximum duration >120 days) are predicted to lengthen considerably under broadscale spruce woodland (up to 59% longer).

4 | DISCUSSION

4.1 | Impact of land-based NFM on soil moisture, groundwater levels and river flows

In this large, permeable catchment, peak flows are not the result of individual storm events, but instead, follow weeks and months of high accumulated precipitation (Figure 6a). The overwhelming majority of peak flows occur between December and March. At this time of year and in the shallow soils over limestone, there is no additional SWSC under broadleaved woodland compared with grassland (Figure 6b), as broadleaved trees are neither transpiring nor intercepting much rainfall. Although evaporative losses from broadleaved woodland are generally higher than those from arable land and grassland through summer until late autumn (~mid-November), the shallow soil is quick to wet up in response to autumn rainfall, meaning that any additional rainwater storage potential gained under woodland during the summer can quickly disappear. As spruce woodland continues to transpire and intercept rainfall throughout the winter, it has the highest antecedent SWSC during this period. The RA rotation antecedent SWSCs are very similar to grassland and broadleaved woodland (Figure 6b), and greater than the CA rotations, as winter vegetation cover (and hence interception and transpiration) is increased.

Given that peak flows in permeable catchments are driven by high winter gwls, the effect of land use on recharge is key. Recharge is low for all land uses over the summer, and in September it increases more rapidly under arable and grassland than under woodland (Figure 6c). However, by November, with the loss of

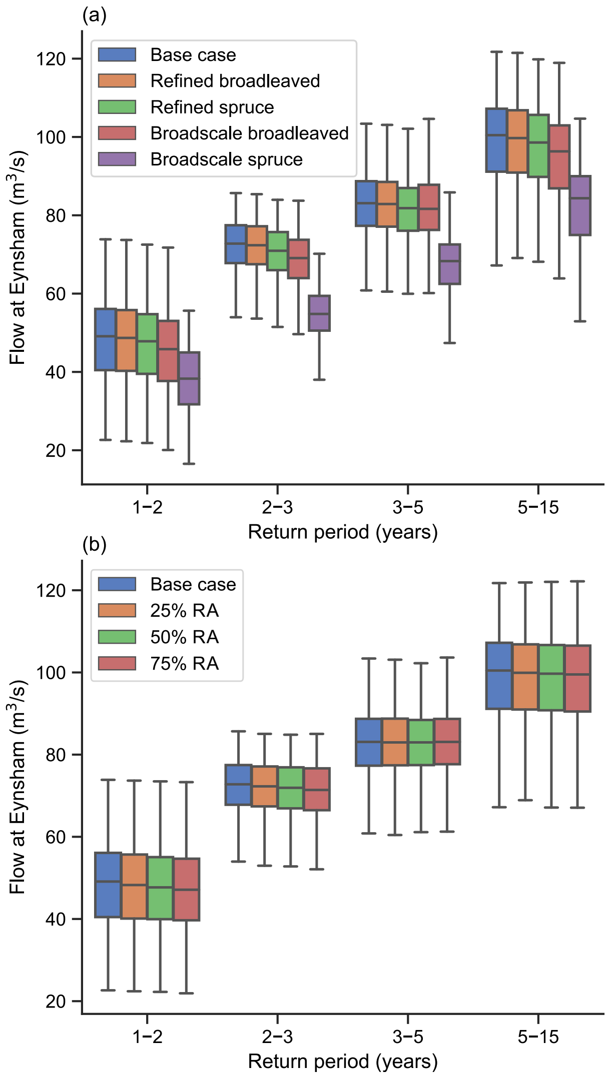

FIGURE 7 Annual peak flows grouped into associated return periods for (a) tree planting and (b) regenerative agriculture (RA) scenarios. Ranges include several floods within the given return period interval as well as the uncertainty derived from the range of acceptable model results.

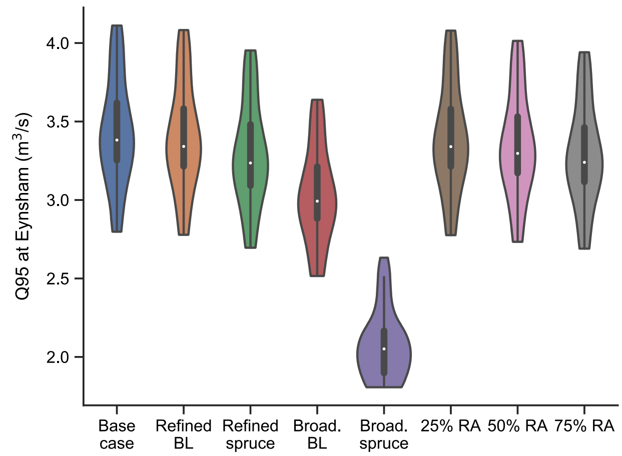

FIGURE 8 Q95 flow for the base case and scenarios for all acceptable models. BL, broadleaved; RA, regenerative agriculture.

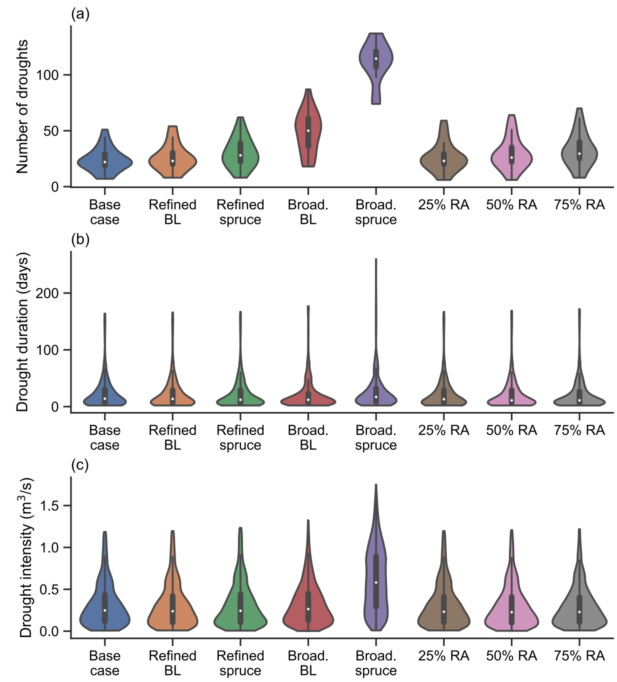

FIGURE 9 (a) Number of droughts—defined as flow on consecutive days below base case Q95—for the base case and scenarios for all acceptable models. (b) Duration of droughts for all acceptable models. (c) Drought intensity defined as the mean difference between base case Q95 and simulated flow during drought for all acceptable models. BL, broadleaved; RA, regenerative agriculture.

tree foliage, recharge under broadleaved woodland approaches that under arable and grassland, limiting the impact of woodland on winter gwls (Figure 6d). In contrast, evaporative losses not only remain significant for spruce woodland over the winter, but also exceed those of broadleaved woodland throughout the year, leading to lower recharge and lower antecedent gwls. For the shallow soils, the RA rotation shows only a small reduction in recharge versus the CA rotation.

The changes in recharge and antecedent gwl for different land uses are reflected in river flows. RA scenarios had very little impact on either high or low flows (Figures 7–9). Refined tree planting scenarios showed very limited potential to reduce peak flows (Figure 7), although spruce woodland does have a greater impact than broadleaved woodland. The refined woodland scenarios also showed little impact on low flows (Figures 8 and 9). Broadscale tree planting scenarios suggest that even extensive broadleaved woodland coverage has a minimal impact on peak flows in permeable catchments (Figure 7). Extensive spruce planting was the only land use change found to have significant benefits for reducing flood peaks (Figure 7), but also substantially reduces low flows (Figures 8 and 9).

4.2 | Implications for land-based NFM policy

Research on the acceptability and feasibility of NFM in the Thames Valley suggests there is strong support for soil and land use management measures amongst farmers and land owners (Elwin et al., 2020; Short et al., 2022). Woodland planting has also been found to be acceptable, although some issues have been highlighted with regard to the amount of land required and the expense of planting woodland on good arable land (Elwin et al., 2020).

In this study, we represent RA with a crop–herbal ley rotation, which is only one of the forms of RA being trialled in the catchment. In this study, we found that for these permeable catchments with shallow soils the RA rotation had little impact on reducing peak flows. Given that SWSC is affected more by land use type than recharge or gwls (Figure 6), crop–herbal ley rotations or similar RA interventions may be more effective in sub-catchments with impermeable geology and related soil types (see Verhoef et al., 2023). We do not find evidence to promote crop–herbal ley rotations as a form of flood prevention for catchments dominated by groundwater flow. However, if implemented to improve soil health (Faivre et al., 2017), we found no evidence to suggest they would have a negative impact on flooding or water resources.

Although the relative benefits of spruce woodland on peak flows have been shown, it contributes less to enhancing biodiversity and is considered to have negative impacts on landscape character (Cotswolds National Landscape, 2016). Climate projections suggest that the Thames Valley may become too warm and dry for spruce woodland by as early as the mid-century (Forest Research, 2022). Further, flood risk management benefits would have to be weighed up against reductions in low flows. In contrast, while broadleaved woodland planting within acceptable and feasible limits is unlikely to impact peak flows, if promoted within the context of biodiversity gains, it is unlikely to impact water security.

Although the selected NFM measures have been shown here to be largely ineffective in groundwater-dominated catchments, locally and in specific landscapes, for example where underlain by low permeability geology, some NFM measures can significantly reduce flood risk. Therefore, it is important that NFM measures are applied in the appropriate settings and combinations, so that resources are not wasted. The benefits of NBS can be substantial and wide ranging but risk being undermined if assumptions are wrongly made that these are universally effective in managing flood risk (Cook et al., 2016).

4.3 | Sensitivity to SWAP parameters and limitations

There is always uncertainty in parameterising soils and vegetation. Although NATMAP is the most comprehensive UK soils dataset, none can fully encompass the extreme heterogeneity of soils. There is also a degree of uncertainty involved in the parameterisation of vegetation in SWAP: for example, we assume all current agriculture is a rotation of winter wheat and winter oilseed rape. However, the goodness of fit of the base case scenario to the river flows suggests these simplifications and the soil parameterisations are fit for purpose.

Although it could be argued that there is a lot of uncertainty in how a herbal ley affects soil properties, any extra storage gained in the shallow soils overlying the Cotswold limestone is unlikely to be sufficient to buffer a prolonged period of heavy winter rainfall. It could also be argued that small changes in the parameterisation of broadleaved woodland, for example, its seasonal variation in leaf-area index, may have large impacts on its simulated effectiveness in terms of flood risk reduction. However, in groundwater-dominated catchments this is not the case. Flooding in these catchments is driven by high winter gwls, and groundwater recharge occurs predominantly in winter, when broadleaved woodland has little potential to intercept rainfall.

One limitation of this study is that there was a large convective storm that caused flooding in July 2007, which we exclude from Figure 7. The model simulates the largest reductions in peak flow for this event, as it occurred in summer, maximising the impact of both RA and woodland. However, the event was surface water driven, which is extremely rare for this catchment. We exclude the event from the results as the model framework was developed for groundwater-driven flooding events.

5 | CONCLUSIONS

In permeable catchments, flooding is driven by high gwls, resulting from high winter recharge. In the United Kingdom, land use change and management are being promoted as approaches to tackling flooding through NFM in these types of catchment. A process-based soil–water–vegetation model was coupled with a semi-distributed groundwater model to explore the impact of tree planting and crop–herbal ley rotations on peak and low flows in a large, groundwater-dominated catchment in the southern United Kingdom. Crop–herbal ley rotations, representing RA, were found to have limited potential to reduce flooding in this setting. Spruce and broadleaved woodland planting at levels judged to be the absolute maximum of what could be realistically achieved also showed very limited potential to reduce flooding. The only scenario that produced significant reductions in peak flow was broadscale spruce planting; however, this was also found to reduce low flows, with potential implications for water security and river ecology. Therefore, while RA practices and woodland have significant environmental and leisure benefits, their effect on flooding in groundwater-dominated catchments should not be overstated.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the National River Flow Archive at nrfa.ceh.ac.uk; in the CEDA Archive at catalogue.ceda.ac.uk; and at the Environmental Information Data Centre at catalogue.ceh.ac.uk. The soils data that support the findings of this study are available from Cranfield University. Restrictions apply to the availability of these data, which were used under license for this study. Data are available at landis.org.uk with licence from Cranfield University.

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ENDNOTE

[1] Through discussions as part of the LANDWISE project (https://landwise-nfm.org/).

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SUPPORTING INFORMATION

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

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