

A national assessment of Natural Flood Management and its contribution to fluvial flood risk reduction

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Headline messages

- Woodland, soil, and surface storage features **provide flood alleviation services and are legitimate flood management infrastructure providing** Natural flood management (NFM)
- NFM has the potential to contribute significantly to **flood risk management**, contributing ~10-13% of the national adaptation benefit as part of a wider portfolio of flood risk management measures. **The NFM contribution reduces risk by £80-110m per year by the 2050s with an associated Benefit-Cost ratio of ~3 to 5.**
- The **benefits achieved by NFM vary spatially**, depending upon the scale of the opportunity to modify land use, the characteristics of the flow regime that influences downstream risk, and the role of other measures within the adaptation portfolio.
- Realising the benefits of **NFM relies upon a landscape approach to flood risk management planning.**

Abstract

The desire to promote Natural Flood Management (NFM) has not yet been matched by implementation. In part, this reflects the lack of scientific evidence regarding the ability of NFM measures to contribute to risk reduction at the national scale. Broad scale understanding, as exemplified for Great Britain in this paper, is necessary evidence for policy development and a prerequisite enabling implementation. This does not imply a lack of confidence in the wider benefits that NFM measures provide (for biodiversity, carbon sequestration, well-being and many others), but without credible quantified flood risk reduction evidence, progress has been slow. This paper integrates national scale hydrological models (using SHETRAN and HBV-TYN) and fluvial flood risk analysis (using the Future Flood Explorer, FFE) to quantify the flood risk reduction benefits of NFM across Great Britain under conditions of future climate and socio-economic change. An optimisation of these benefits is presented considering alternative NFM policy ambitions and other demands on land (urban development, agriculture, and biodiversity). The findings suggest NFM has the potential to make a significant contribution to national flood risk reduction when implemented as part of a portfolio of measures. An optimisation through to 2100 suggests investment in NFM achieves a benefit to cost ratio of ~3 to 5 (based on the reduction in Expected Annual Damage (EAD) to residential properties alone). By the 2050s, this equates to an ~£80m reduction in EAD under a scenario of low population growth and a 2°C rise in global warming by 2100. This increases to £110m given a scenario of high population growth and 4°C rise. Assuming current levels of adaptation continue in all other aspects of flood risk management, this is ~9-13% of the reduction in EAD achieved by the portfolio. By the 2080s, this contribution of NFM increases to ~£110 and ~£145m under these two scenarios. These figures are based flood risk reduction benefits alone, and do not include the substantial co-benefits that would also accrue.

Keywords

Great Britain, Natural Flood Management, flood risk reduction, climate change adaptation, sustainable development, landscape-scale planning, national assessment, Future Flood Explorer

Glossary

BCR - Benefit-Cost Ratio: A ratio used to compare the benefits of a project or investment to its costs. A BCR greater than 1 indicates that the benefits outweigh the costs.

EAD - Expected Annual Damage: A measure of the average annual economic damage caused by flooding. This metric is used to assess the benefits of flood risk management measures.

FFE - Future Flood Explorer: An exploratory tool used to quantify the flood risk reduction benefits of adaptation under conditions of future climate and socio-economic change.

Fluvial Flood Risk: The risk of flooding from rivers and streams, determined as a function of the probability of flooding and the associated consequences.

GMST – Global Mean Surface Temperature: Used to reflect the rise in global mean temperature since pre-industrial times.

Hydrological Models (SHETRAN and HBV-TYN): Models used to simulate the hydrological changes of NFM implementation scenarios under different population growth and climate change future.

NAP - National Adaptation Programme: A programme that outlines actions needed to adapt to climate change impacts in the UK, including the implementation of NFM measures.

NbS – Nature-based Solution: Actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, the simultaneously provide benefits for people and nature.

NFM - Natural Flood Management: A flood risk management approach that uses natural processes to reduce the risk of flooding. This includes methods such as restoring functional floodplains, enhancing soil infiltration, and modifying surface vegetation to increase roughness

SSP - Shared Socio-economic Pathway: Scenarios that describe different pathways of socio-economic development, including population growth and urban development, which influence future flood risk.

Introduction

In recent years, aspirations for Nature-based Solutions (NbS) have emerged as central to Sustainable Development (e.g., Seddon *et al.*, 2021, UNEA, 2022) and for fluvial flood management (Howarth *et al.* 2025). Recognising that NbS provides simultaneous benefits for both people and nature, Natural Flood Management (NFM) aligns with this objective (e.g., Environment Agency, 2018). Within the UK NFM, echoing similar international approaches like Engineering with Nature (Bridges *et al.*, 2014), includes methods such as restoring functional floodplains, enhancing soil infiltration, and modifying surface vegetation to increase roughness (Nicholson *et al.*, 2020, Black *et al.* 2021; Cooper *et al.*, 2021; Quinn *et al.*, 2022). In all its forms, NFM strives to work with natural processes to ‘*slow the flow*’ (WWF, 2007) and maintain the dynamic stability of landscapes essential for healthy ecosystems while providing wider benefits (e.g., Sayers *et al.*, 2025).

The notion of resilience and enhancing resilience is increasingly positioned at the heart of flood risk management (FRM), recognising that ‘*resilience*’ is not the same as ‘*protection*’ (HM Government, 2016). This reinforces the sentiment that to succeed as a society, we need to ‘*learn to manage risk and not simply seek to avoid it*’ (Walport and Craig, 2014). This context is crucial in promoting NFM, given that NFM does not equate to conventional ‘flood protection’ but contributes to the management of flood risk while simultaneously providing wider benefits (e.g., Evans *et al.*, 2004, Sayers *et al.*, 2013).

The heuristics of this narrative are well established and reflected in framing natural capital assets and the value they provide. However, measures to compare interventions, such as costs and benefits calculations, are important in making policy decisions (Brown *et al.*, 2018) and quantified evidence on the national-scale opportunity NFM affords remains elusive. In the absence of quantified evidence, progress towards implementation remains sporadic (e.g., Wells *et al.*, 2020). Pilot schemes (e.g., Defra, 2022) and Flood Risk Management (FRM) plans that seek to embed NFM alongside other measures (e.g., Jenkins *et al.*, 2025) continue to gather pace.

The lack of national-scale evidence on the flood risk reduction afforded by NFM continues to act as a brake on uptake. This in turn limits our ability to transform FRM from an approach that embeds a ‘bias to build’ flood defences to one that promotes flood risk management as a multiple objective endeavour supporting Sustainable Development (e.g., Sayers *et al.*, 2014, 2025). This paper addresses this important knowledge gap with a focus on fluvial flood risk in Great Britain. For the first time, the national scale flood risk reduction benefits of NFM across Great Britain under conditions of future change are presented. By focusing exclusively on NFM's role in economic flood risk reduction to residential properties, this paper deliberately excludes quantitative consideration of wider benefits such as biodiversity, carbon sequestration, and well-being. While these additional benefits are central to the philosophy of NFM, they are not considered here to maintain a clear focus on fluvial flood risk. If included, these additional benefits would add significantly to the case for implementation (Morris *et al.*, 2024).

Method

Flood risk responds to multiple drivers varying in space and time. This includes the existing pattern of land use and flood management measures but also climate change and development pressures. NFM will seldom be a complete solution in response to these risks but instead form part of a broader portfolio of measures that in combination seek to manage flood risk (e.g., Evans *et al.*, 2004, Sayers *et al.*, 2014). Equally, flood risk management choices are always influenced by, and influence, other sectors and their priorities. Any credible assessment of the benefits of NFM needs to reflect these

interactions. This is made difficult because of the continued challenges in representing the detail of any single NFM intervention on hydrological response (e.g., Dadson *et al.*, 2017), the interactions between NFM and other measures within a portfolio of flood risk management measures (e.g., Beven *et al.*, 2012), and the relative priority given to NFM and other land use demands. These difficulties are compounded when attempting to do so in the context of multiple future scenarios (e.g., Sayers *et al.*, 2016).

The method developed here addresses these challenges and provides new insight into the role NFM may play in managing future fluvial flood risk as part of a national adaptation portfolio. To do so, a series of NFM implementation scenarios for Great Britain are developed that reflect four levels of policy ambition (maximum, high, moderate and low). These are developed based on consideration of not only the physical suitability of a catchment for NFM but also competing land use demands (such as urban development, biodiversity (conservation and restoration), and agricultural production). Two national scale hydrological models (SHETRAN and HBV-TYN) are used to assess the hydrological changes of the NFM implementation scenarios under different population growth and climate change futures (details are given in the “Representation within the assessment of flood risk” section). The influence of NFM measures on flood flows are translated to a change in flood risk (using the Future Flood Explorer, FFE) and combined with an estimate of the whole-life implementation cost to support a spatial optimisation of the return on investment in NFM through to the 2080s (using the Adaptation Explorer). The FFE and associated Adaption Explorer toolset have been developed to provide an emulation of the national flood risk system (sources, pathways, and receptors) that faithfully reflects present day hazard, exposure and vulnerability data from across the Great Britain (Sayers *et al.*, 2015, 2020, 2022). The structure of the emulation has been specifically designed to enable a credible exploration of how present-day flood risk may change under a range of alternative climate and socioeconomic projections, and how effective different adaptation policies may be in offsetting these changes. The workflow is summarised in **Figure 1** and discussed in detail below.

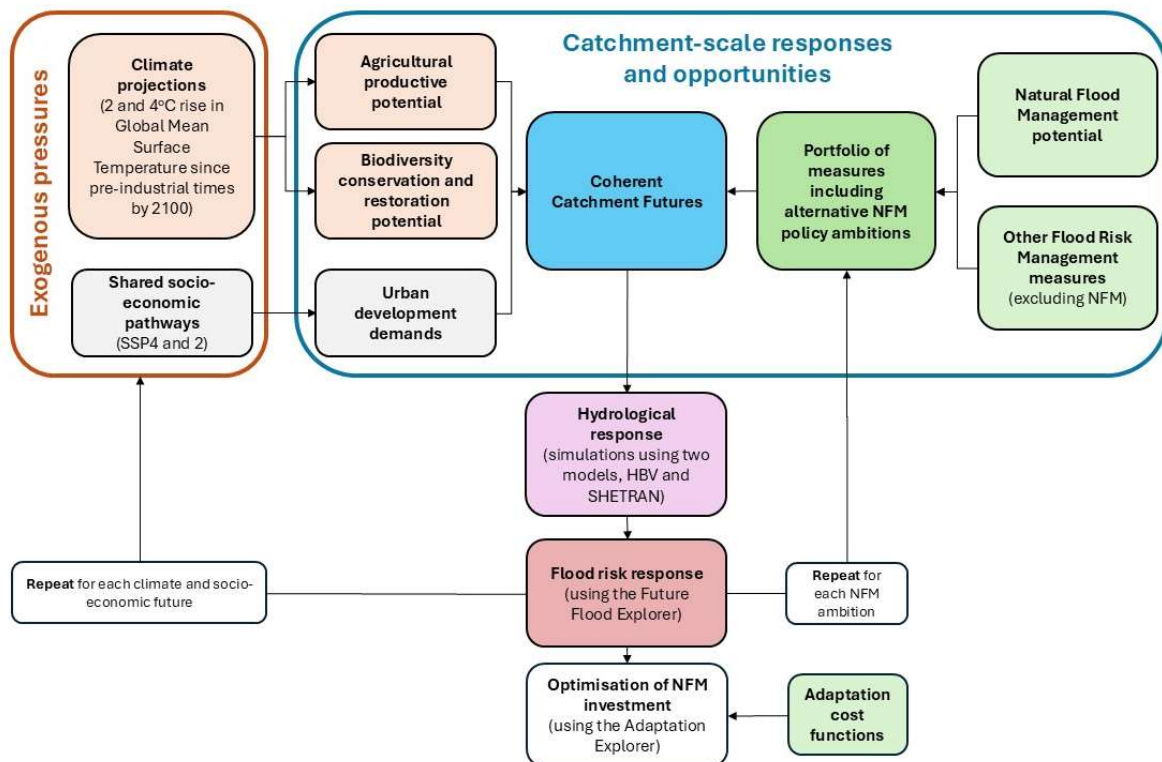


Figure 1 Analysis framework – Workflow of scenarios and models used to assess the NFM flood risk reduction benefits and investment costs

Exogenous pressures

Climate change and socio-economic development are considered here as external pressures not influenced by flood management choices. However, NFM at scale has the potential to significantly contribute to carbon sequestration and climate mitigation (e.g., Environment Agency, 2022). This paper focuses on climate adaptation and the role NFM plays in flood risk reduction.

Climate projections

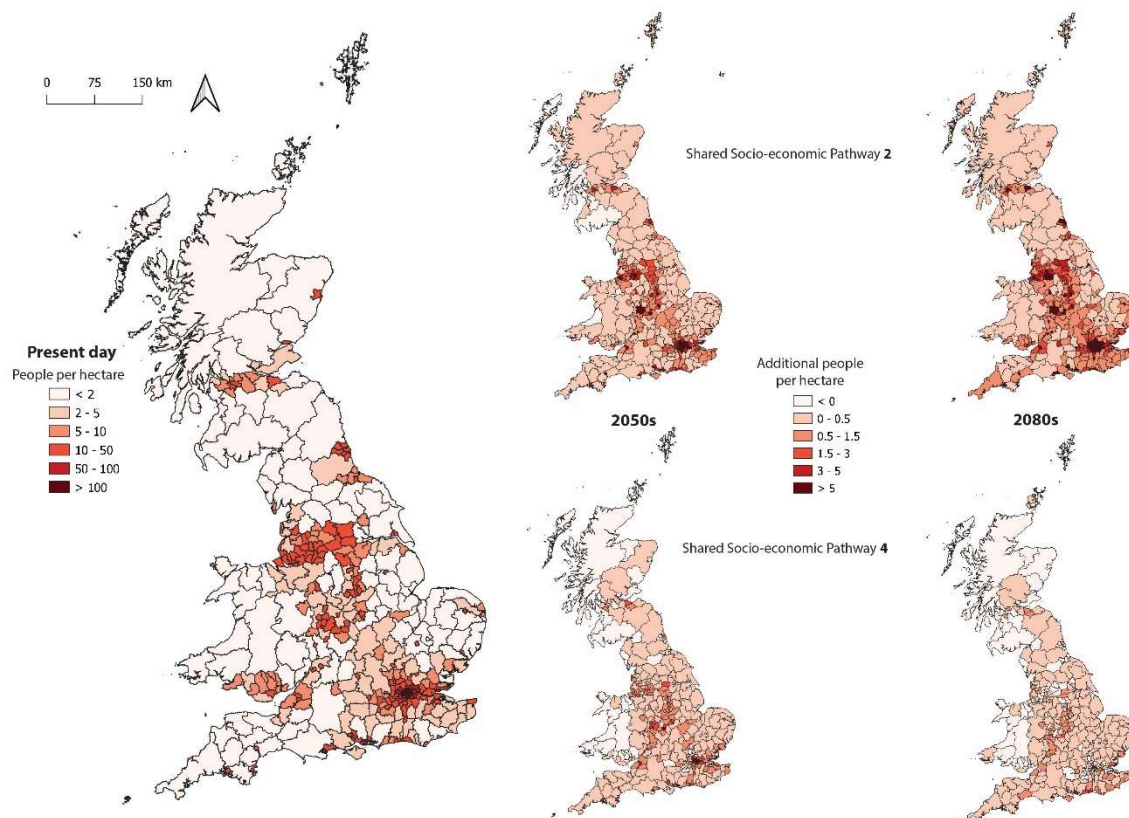
Two climate scenarios are considered: a 2°C and 4°C rise in Global-Mean-Surface-Temperature (GMST) from pre-industrial times by 2100. A two-step approach determines the change in peak fluvial flows. The ability of NFM to moderate these changes is modelled using two national scale hydrological models (see later). Each model has been driven by the same UKCP18 Regional Climate Model (RCM) ensembles (Murphy *et al.*, 2018), as detailed by Smith *et al.*, 2024. The RCMs provide continuous daily timeseries of meteorological variables at a 12km spatial resolution to provide a spatially coherence assessment of the change in river flows under a range of future land use assumptions as discussed later in this paper.

Population change

Two of the five UK-scale Shared Socio-economic Pathways (UK-SSPs) (Cambridge Econometrics, 2021) are used to determine future population growth and, by extension, urban development through to the 2080s. They are:

- **UK-SSP2** (*middle of the road*) – This scenario assumes a continuation of current trends without significant change. The UK's population is projected to increase from around 64.2 million (today, defined here as 2019) to 76.6 million by 2050, and 83.2 million by 2080. The growing population and development tend result in increasingly dense cities.
- **UK-SSP4** (*inequality*) – This scenario reflects a future with increased social and economic inequalities. The UK's population is expected to reach 71 million by 2050, then decline to 68.8 million by 2080. The development distribution is more disparate than in SSP2, reflecting increasing inequality across the UK in terms of investment and economic opportunity, with an increasing divide between wealthier and poorer regions. Development remains focused in and around densely populated urban areas.

The UK-SSP provides Local Authority scale population growth projections and is used here as the driver of residential development (**Figure 2**).



Left: Present-day distribution of population by local authority. **Right top:** Additional people per hectare by Local Authority - Shared Socio-economic Pathway 2 for a) 2050s and b) 2080s. **Right bottom:** Additional people per hectare by Local Authority - Shared Socio-economic Pathway 4 for a) 2050s and b) 2080s. Source: after Cambridge Econometrics, 2019

Figure 2 Present and future variation in population

Competing land use demands

NFM often competes for land with urban development and agriculture. Conservation and restoration also require land, sometimes in collaboration with NFM but not always. To understand these competing demands high-resolution spatial projections for each are combined with a spatial understanding of suitability for NFM measures to create a set of coherent catchment development futures that prioritise NFM to a greater or lesser extent. These high-resolution projections of competing demands on land and how they are used to create alternative land-use futures (that reflect different scales of NFM policy ambition) are discussed below.

Urban demand – Land for residential development

New development is assumed to be needed when the population is projected to increase. The spatial distribution of that development will respond to local ‘*attractors*’ (such as proximity to transport hubs) and ‘*constraints*’ (such as the protection of greenspace or floodplain development planning controls) of development. Both are included here within the coupled multi-criteria evaluation and cellular-automata Urban Development Model (UDM, Ford *et al.*, 2019, Lomax *et al.*, 2022) to downscale the population projections at a Local Authority District (LAD) scale associated with SSP2 and SSP4 to spatial patterns of development (using policies consistent with the SSP narratives). The UDM is run twice for each population projection, firstly assuming development is unconstrained by floodplain, and secondly assuming the floodplain (defined by the 1in100 year undefended event) is avoided. These results are then combined within the FFE to reflect realistic floodplain development

policies (as defined by Sayers *et al.*, 2020). This enables the significant differences in floodplain development contexts across Local Authorities to be considered. For example, the City of Hull lies in the floodplain of the Humber, and hence future development (as in the past) is likely to be in the floodplain. Other Local Authorities have a much greater opportunity to avoid the floodplain, with less than 10% of new developments in recent years taking place in the floodplain. This combination of the UDM and FFE results in a high-resolution (100m grid) spatial distribution of future residential development under each of the SSP scenarios (**Figure 3**).

We note that not all UK SSPs suggest an increase in population from present day; some suggest a significant decrease for some LADs. Trends other than population may also lead to reduced demand for housing (such as occupancy rates). The opportunity provided for reclassifying land in response to a reducing population are however excluded here. Expansion of non-residential property and municipal service infrastructure (rail, roads, power, schools, etc.) are also excluded.

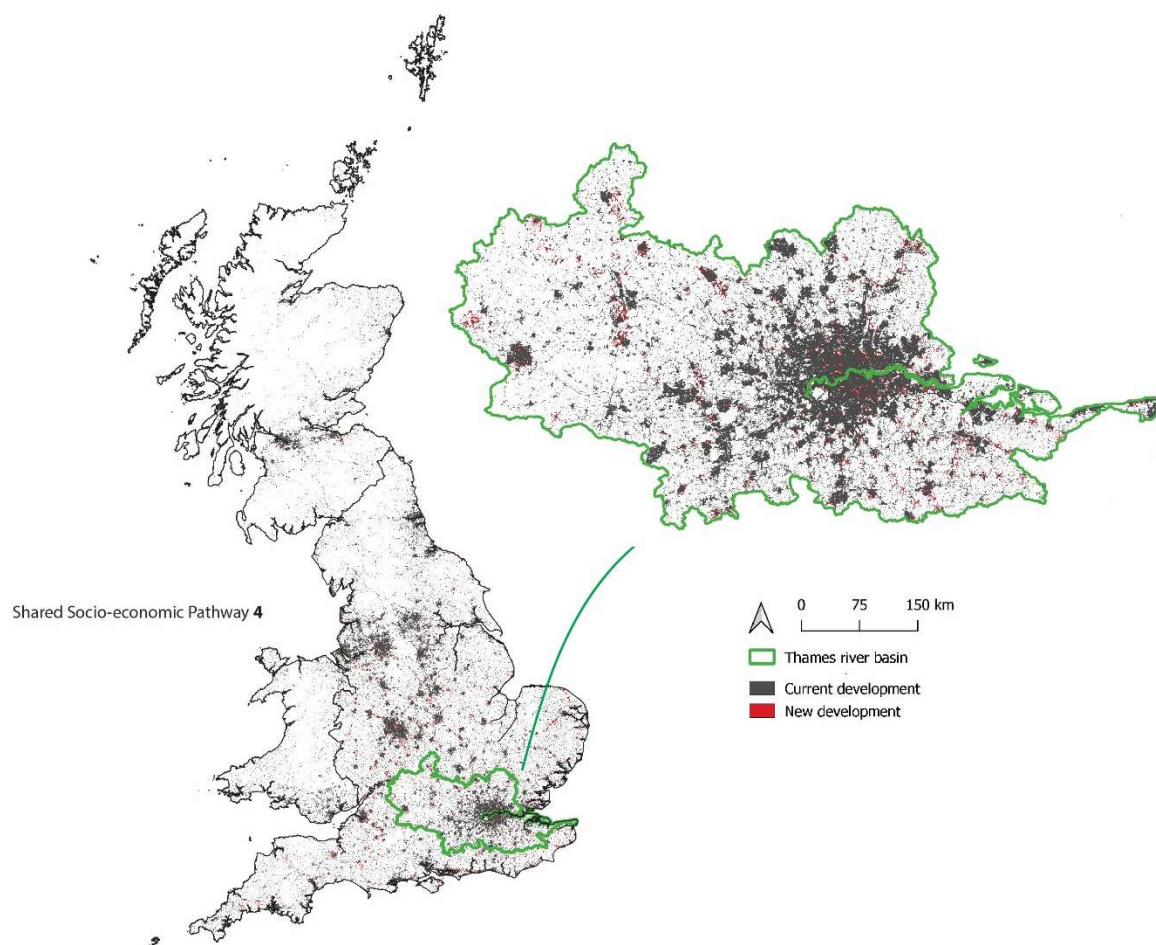
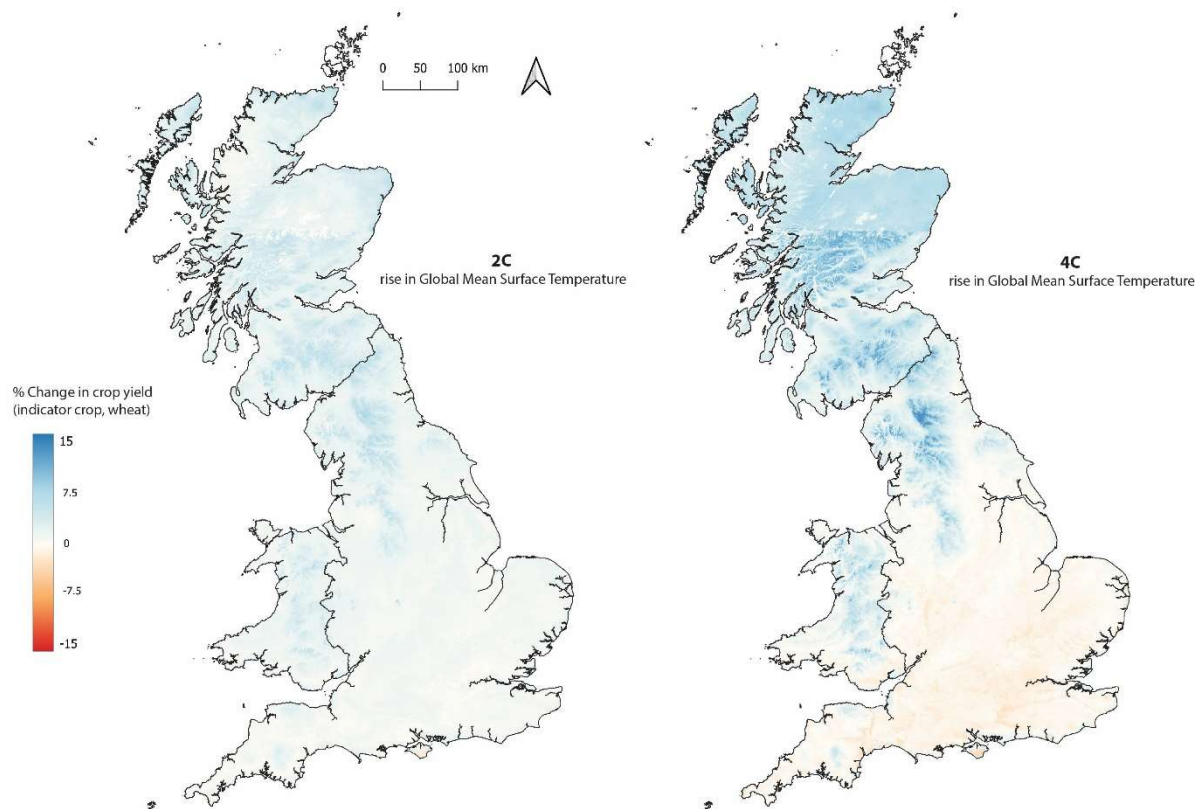


Figure 3 Present and future variation in urban development - Great Britain and to illustrate at a large scale the Thames basin

Agricultural demand – Land to maintain food production

Maintaining national food security is increasingly a significant influence within the debate on future land use (Defra, 2021). Climate change influences both temperature and precipitation patterns and impacts the suitability for crop growth and alters potential yields across the UK (Warren *et al.*, 2023). The results from the CropNet Wheat yield model (Hayman *et al.*, 2024) are used here to provide insights into spatial variation in potential wheat yields (grown under rainfed conditions and subject to ideal agricultural management) given climate driven changes in key meteorological inputs (*e.g.*, solar radiation, temperature, and precipitation). The wheat results are used to produce a high-resolution spatial indication (on a 1 km grid) of where yields are likely to increase and decrease in the future (**Figure 4**). The absolute increase in yield is not important here. Instead, the direction of change is used to determine where agricultural land may or may not be suitable for conversion to NFM (see later). Although individual crops may respond to climate change in different ways, wheat is the UK's dominant arable crop by both area and total production (Defra 2023), and its response is likely to be an important indicator of the viability of many current arable rotations. When the climatic suitability of many of the UK's other major crops has been examined, many show a similar north-south polarisation in the impacts of climate change (Redhead *et al.*, 2025), such that relative change in wheat yield is likely to be a reasonable proxy for future agricultural land priorities, outside of dramatic shifts in the type of crops the UK grows (Redhead *et al.* 2025).



Source: Image based on CropNet, Hayman *et al.*, 2024

Figure 4 Percentage change in the yield (tonnes/year) from one hectare of wheat (as an indicator crop). **Left:** given a 2°C rise in Global Mean Surface Temperature. **Right:** given a 4°C rise in Global Mean Surface Temperature

Biodiversity demand- Land to respond to conservation and restoration priorities

Climate change has already impacted the geographical range of many species (Warren *et al.*, 2023). Across Great Britain continued loss of species richness is projected due to the decline in suitable climate space for insect pollinators, such as bees, wasps, butterflies, moths, and hoverflies (Warren *et al.*, 2018). The location and size of refugia for terrestrial biodiversity (that is areas which remain climatically suitable for most taxa), including fungi, plants, invertebrates, and vertebrates, is also expected to change (and decrease) – Warren *et al.*, 2018. Securing the ‘right’ land for conservation and restoration will be central in seeking to arrest the decrease in biodiversity. High-resolution spatial projections of conservation and restoration suitability across Great Britain under conditions of climate change are used to influence the choices around NFM (see later). Each 1km grid is assigned a qualitative score of 1 to 100 reflecting its potential importance for conservation and restoration in each climate future (Warren *et al.*, 2023). The importance scores across GB are ranked from the lowest to highest relative opportunities. These results are then used to enable priority biodiversity land demand to influence the choices around NFM (see later).

Hydrological suitability of the catchment for NFM

In some areas the opportunity to influence flood flows through NFM is more limited than in others due to the geology and topography of a catchment. This spatial variation is reflected in the ‘*NFM suitability*’ maps developed by various national agencies across Great Britain (*e.g.*, based upon Environment Agency (EA), 2015, Scottish Environment Protection Agency (SEPA), 2014, and recent updates from Natural Resources Wales (NRW), 2022). These assessments focus on the physical hydrological suitability for storage (including riparian buffers) and afforestation (woodland) measures. The third UK Climate Change Risk Assessment future flood projections (Sayers *et al.*, 2020), integrated these data into the Future Flood Explorer (FFE) and it is this data that is used here to provide a map of the physical hydrological suitability for NFM on a 1km grid, with each grid attributed with the percentage opportunity for the creation of storage and the percentage opportunity for woodland planting.

Natural Flood Management- Land use trade-offs, policy ambitions, and associated implementation scenarios

Hydrological suitability of the catchment alone does not determine the implementation of an NFM measure. The relative priority given to other land uses (as introduced above) and varying levels of policy ambition for NFM used here together with considerations of hydrological suitability to determine four spatially explicit ‘*NFM implementation scenarios*’, namely:

- **NFM ‘Max ambition’** – The ‘*NFM Max*’ scenario implements all woodland and storage as defined by the ‘*NFM suitability*’ maps outside of existing and projected urban areas. No consideration is given to agricultural or conservation/restoration priorities. Broader flood risk management policy, including raising existing defences in response to climate change, forecasting and warning, and take-up of property-level measures, continue in a way that reflects current adaptation policies (as set out in Sayers *et al.*, 2020). The only change is the enhanced focus on NFM. Innovative hybrid interventions, for example, the creation of major flood storage areas using a combination of built and natural infrastructure, are excluded for the purposes here. Given this context, this ‘NFM Max Ambition’ represents a reasonable upper bound to the NFM opportunity to manage fluvial flood risk.
- **NFM ‘High ambition’** – The second scenario implements all woodland and storage opportunities (as in the *NFM Max* scenario) but avoid areas where agricultural yields are projected to increase (regardless of present-day agricultural potential) in addition to existing and projected urban areas.

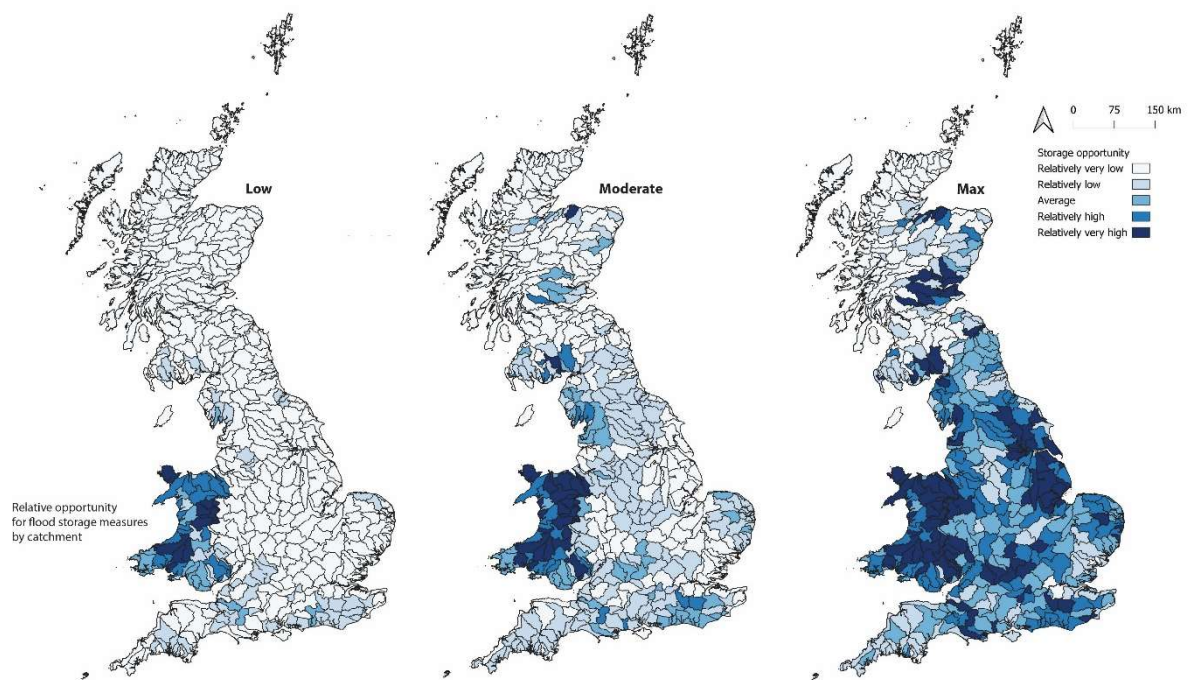
- **NFM ‘Moderate ambition’** - The third scenario adds a further constraint to the NFM implementation by avoiding all present-day *Best and Most Versatile Land* (BMV, Class 1), as well as lower-grade agricultural land (BMV Class 2 and 3) projected to experience stable or increasing yields. Priority areas of conservation and restoration are also avoided. This assumes conservation and restoration activities are undertaken without accruing additional flood management benefits. This is recognised as a conservative simplification. Often such efforts are designed to reduce flood flows, but this is not necessarily the case (for example, the recreation of permanent wetland areas may provide little additional flood storage during larger events compared to existing land use).
- **NFM ‘Low ambition’** – The fourth scenario adapts the ‘Moderate Ambition’ scenario to avoid all areas of the Best and Most Versatile Land (Class 1 and 2) regardless of changes in yield, as well as lower-grade agricultural land (BMV 3) where yields are projected to be stable or increasing.

Each ‘*NFM Implementation scenario*’ is translated to spatially explicit description (on a 1km grid across Great Britain) that reflects the location and extent of land area converted to storage (**Figure 5**) and woodland (

Figure 6). The variation in scale of NFM implementation between each level of ambition is significant, with the low ambition representing ~20% of the area of the max ambition (**Table 1**), These spatial narratives are taken forward to the assessment of flood risk (see later).

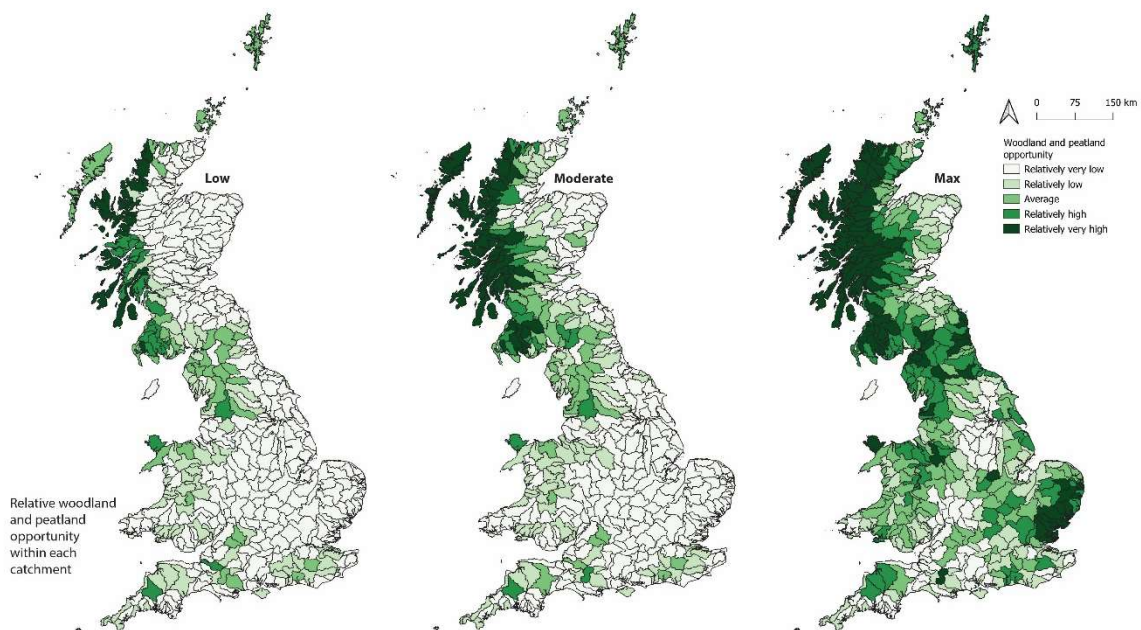
Table 1 Summary comparison of the scale of NFM measures within each level of ambition

Storage measures				
	Max	High	Moderate	Low
Area (km ²)	4,284	2,126	1,420	711
Percentage of Max		50%	33%	17%
Woodland and Peatland Restoration				
	Max	High	Moderate	Low
Area (km ²)	75,350	46,237	31,060	15,683
Percentage of Max		61%	41%	21%



Left: Low ambition scenario. **Middle:** Moderate ambition scenario. **Right:** Max ambition. The legend refers to the relative storage opportunity (by area) in each catchment area. The legend reflects the lowest to highest relative opportunities established by aggregating the areas of opportunity to a 1km grid under the Max ambition assumption and determining the lowest 20 percentile (Relatively very low), 21-40 (Relatively low), 41-60 (Average), 61-80 (Relatively high), and above 80 (Relatively very high) percentile values. The same values are then applied to all levels of NFM ambition to enable visual comparison. High ambition is not shown.

Figure 5 Natural Flood Management – The spatial variation in storage opportunities by river catchment



Left: Low ambition scenario. **Middle:** Moderate ambition scenario. **Right:** Max ambition. The legend refers to the relative NFM woodland opportunity (by area) in each catchment area. The legend reflects the lowest to highest relative opportunities established by aggregating the areas of opportunity to a 1km grid under the Max ambition assumption and determining the lowest 20 percentile (Relatively very low), 21-40 (Relatively low), 41-60 (Average), 61-80 (Relatively high), and above 80 (Relatively very high) percentile values. The same values are then applied to all levels of NFM ambition to enable visual comparison. High ambition is not shown.

Figure 6 Natural Flood Management – Spatial variation in woodland opportunities by river catchment

Representation within the assessment of flood risk

Hydrological influences of NFM measures

Hydrological modelling plays a crucial role in understanding how river catchments respond to change (He *et al.*, 2013, Peel and McMahon, 2020; Kumar, 2023). Broadly, hydrological models classify as empirical, conceptual, or physically-based. Here, one physically-based, spatially-distributed hydrological model (SHETRAN, Abbott *et al.*, 1986; Ewen *et al.*, 2000) and one spatially distributed conceptual model (HBV, Bergström 1992; Lindström *et al.*, 1997, with version used here referred to as HBV-TYN, He *et al.*, 2022) are used to determine the changes in fluvial floods in each future scenario. Both models represent critical catchment processes, such as snowmelt, evapotranspiration, infiltration, overland flow, interflow, etc.

To enable comparison and credibly capture model structure uncertainties, both models use the same CAMELS-GB catchments (Coxon *et al.*, 2020), the same spatial definition of NFM measures and development on the same 1km grid, and the same meteorological forcings. Three of the CAMELS-GB catchments were excluded due to them being either a single cell or having a diagonal channel flow direction that cannot be modelled by SHETRAN. To maintain consistency, HBV-TYN also excluded them. This allows comparisons between the results of the two models. SHETRAN spatial resolution: 1x1 km for catchments < 2000 km², otherwise 5x5 km. HBV-TYN uses 1x1 km for all CAMELS-GB catchments. Both models use the 1990-1999 discharge data for calibration and the 2000-2009 discharge data for validation with comparable results obtained compared with other models using the same datasets (Lane *et al.*, 2019). Although the spatial description of each future is common across both models, each represents the associated NFM measures differently as outlined below (and described in detail in Smith *et al.*, 2024).

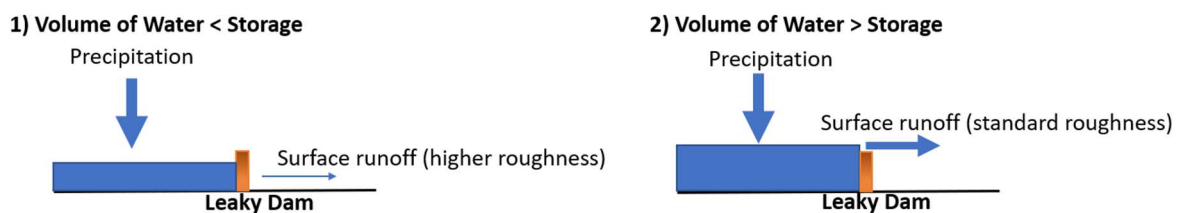
Characterising woodland measures

Woodland as an NFM measure involves establishing woodland on land not currently used for this purpose. Woodland is a legitimate NFM measure as trees tend to use more water than shorter types of vegetation, and hence have the potential to reduce run-off and by extension river flow. This is mainly due to the increased interception of rainwater by their aerodynamically rougher canopies (Nisbett, 2005). Large-scale hydrological models typically represent woodland measures by modifying interception, infiltration, and/or roughness to simulate land use changes like afforestation. Here, these techniques are applied as follows:

- **SHETRAN** - In SHETRAN, the main change in evapotranspiration in woodland is considered by increasing intercepted evaporation due to the taller canopy height, which promotes more turbulent airflows. The increase matches the fraction of woodland cover added under each NFM scenario for each 1km grid cell. For instance, a 100% increase in woodland cover results in a 100% rise in potential intercepted evaporation; a 50% increase corresponds to a 50% rise. However, the actual intercepted evaporation depends on water availability at any given time and is typically lower than the potential increase. The approach has been validated on data from research at Plynlimon and Coalburn in the UK, which compares evapotranspiration from grassland and mature coniferous forest (Marc and Robinson, 2007; Birkinshaw *et al.*, 2014).
- **HBV-TYN**– Woodland was expressed as a percentage within each 1km grid cell. Increase of woodland increases the interception amount and the roughness of the surface. The interception increase was implemented in the same way as described above for SHETRAN. The increase in the surface roughness is represented by linearly reducing the overland flow recession coefficient by the increase in the woodland.

Characterising storage measures

There are several NFM measures that can be used to add storage. This includes temporary attenuation ponds, reconnecting floodplain storage, riparian vegetation, and meanders. Temporary attenuation ponds make up 69% of all NFM measures in the UK (Quinn *et al.*, 2022). These allow flood water to be temporarily stored, with the stored water then gradually released through the leaky barrier when the flood wave has passed, so there is then storage available for the next rainfall event. Within both models NFM measures are accounted for by allowing specific volumes of surface water to be stored in each model cell (Metcalf *et al.*, 2018). Within each cell, a 'threshold volume' is assigned according to the NFM scenario to represent the process of a pond filling and storing water during a rainfall event and then, once filled, allowing the excess water to flow through or out of the cell as it would if the pond was not there. An upper bound threshold volume of 100,000m³ is assigned to align an extensive reconnected floodplain storage equivalent to a depth 0.2m across the cell or a large attenuation pond. This upper bound is then modified according to the fraction of additional storage specified for the 1km grid cell. If a 1km grid cell has 100% storage specified within a given NFM scenario, the total storage volume equals 100,000m³ a 50% storage means the total storage volume of 50,000m³. These large values are however usual. In the NFM max ambition scenario, 3.75% of cells with a storage volume between 10,000m³ and 100,000m³ with 0.2% of the 1km cells have a potential storage volume between 50,000m³ and 100,000m³. Stored water is then released slowly via surface runoff (which corresponds to a pipe or a leaky barrier, **Figure 7**) or via infiltration. In SHETRAN, we mimic this process by reducing the overland flow Strickler coefficient (the inverse of Manning's roughness coefficient) from 2.0 (m^{1/3}/s) to 0.2 (m^{1/3}/s) until the required specific volume of surface water is stored in the cell. Beyond this volume, water is routed through the cell using the original Strickler coefficient. In HBV-TYN, additional storage increases the roughness of the surface and the store capacity, which is represented through linearly reducing the overland flow and interflow recession coefficients by the increase in the storage. This approach, in both models, applies the increased roughness to the whole cell, scaling the depth threshold to generate the desired storage volume.



Left: The stored volume is based on a maximum depth and an area that reflects the percentage opportunity locally defined by the NFM ambition. **Right:** The residence time of the storage corresponds to that found by Metcalfe *et al.*, (2018) and if the volume of water in the cell exceeds that a standard roughness coefficient is applied.

Figure 7 Natural Flood Management representation of storage measures

Influence of urban development on exposure and run-off

The urban development projections (introduced earlier) are used to modify the residential exposure within the Future Flood Explorer. To provide a focus on NFM catchment-based measures (rather than urban NFM) it is assumed the new development takes place using good practice sustainable urban drainage methods and hence the pre-development run-off remains unchanged. In reality, the interaction between NFM measures and the management of surface water flows (through Sustainable urban Drainage, SuDs, and conventional piped drainage) is complex (e.g. Sayers *et al.*,

2022) and future research (beyond the scope here) will be necessary to take these interactions into account.

Influence of climate change

Each hydrological model is driven by the same climate model outputs. In both, the UKCP18 future climate scenarios are run for each of the 668 catchments for the period 1980-2080. Simulation results are presented in terms of changes from the baseline period using each of the 12 Regional Climate Models (RCMs) to provide a credible view of potential flow changes in response to NFM under conditions of climate change. These results are used to determine the change in the return period flows for the different warming levels and associated NFM ambition levels (as described for SHETRAN in Smith *et al.*, 2024,). The urban development and the climate change simulations were run for each RCM for the entire period from 1980-2080 in the absence of NFM measures to provide a comparative hydrological response assuming ‘no NFM adaptation’ (Table 2). These results are used later in this paper as the counterfactual against which risk reduction achieved by implementing NFM are compared.

Optimising the return on NFM investment

To maximise the return on investing in NFM requires an assessment of both costs (including capital and maintenance costs) and benefits (defined here narrowly in terms of the reduction in direct damage to residential properties). The approach to NFM that delivers the highest benefit to cost ratio varies from location to location. This reflects the spatial variation portfolio of flood risk management measures that exist as well as the performance of the NFM. For example, the benefit of an NFM measure will reflect the ability of NFM to influence the flow, the subsequent influence of any change in flow on the downstream hazard, the influence of that change on the performance of downstream flood defences (where they exist), and change in exposure in response to a change in the hazard (taking account of the spatial distribution of residential properties). A spatially explicit economic optimisation is adopted within the FFE to capture this system scale interaction. that assumes a continuation of current levels of adaptation associated with all measures other than NFM (as detailed in the next section). The approach to determining and optimising the contribution of NFM is described below.

Enabling reductions in flow achieved in one location to persist through the downstream catchment

Flow reductions achieved by NFM accrue both locally (within the area they are implemented) and persist through the downstream river network. The influence of local change on extreme water levels diminishes downstream as the flow reduction becomes an increasingly lower proportion of the river flow. The FFE tracks the connectivity and river discharge through the river network. This understanding of upstream to downstream connectivity enables the flow reduction achieved when NFM is implemented in one sub-catchment to be propagated through all downstream catchments. This enables the risk reductions accrued at a given location to be appropriately attributed to contributing NFM measures (including those implemented far upstream). This connectivity within nested catchments is illustrated in **Figure 8**.

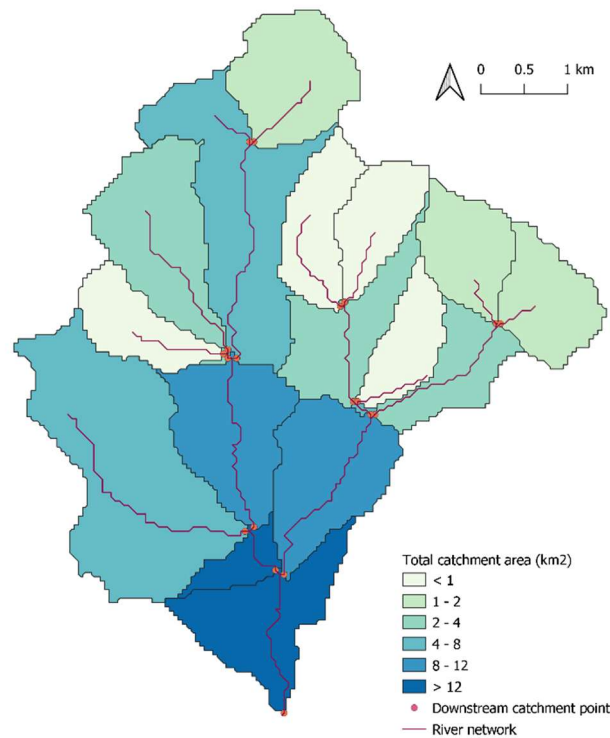


Figure 8 The FFE tracks flow connectivity and river discharge through the river network to determine the significance of flow reductions in one location on the downstream system. In doing so the effect of a local change on river flow diminishes downstream as the flow reduction becomes an increasingly lower proportion of the river flow.

Accruing risk reduction benefits and costs through the catchment

Quantifying the reduction in ‘risk’ achieved by NFM measures is of course dependent on the choice of risk lens. Here we described risk through the lens of Expected Annual Damages (EAD, based on direct property damage only). Focuses on the reduction in EAD is widely used to determine the worthwhileness of an investment and hence aligns with the focus here. In this context ‘risk’ is often driven by frequent events; events over which NFM has the greatest influence (e.g., Sayers *et al.*, 2015, Dadson *et al.*, 2017). To determine the change in EAD, the FFE translates the change in flow (due to the combined influence of upstream NFM measures, climate change, and development) to a change in the economic damage using a series of Impact Curves (constructed using the methods set out in Sayers *et al.*, 2015, 2020). These are manipulated within the FFE to determine the change in EAD for each sub-catchment across Great Britain (as defined by the catchment sections of the UKCEH Integrated Hydrological Unit, Fray and Dixon, 2015). This enables the benefits associated with a given NFM measure (either woodland or storage) both locally and downstream to be readily accrued.

The associated costs of implementing NFM measures are also accrued through the catchment using simplified cost functions for woodland and storage measures reused from the third Climate Change Risk Assessment (CCRA3) (**Table 2**). These cost functions enable an indicative capital cost (associated with initial creation of the measure) and revenue costs (of 5% of the capital cost) to be assessed. A further simplification is made here by assuming costs are incurred from year 1 (2025) through to year 10 and the benefits related to storage measures are accrued from the year of the investment. The benefits accrued from woodland measures are assumed to be delayed for 10 years from the year of investment, starting in 2035 onwards. This provides a basic adjustment to account for the time taken

for woodland measures to mature (recognising this would vary depending on tree species and the detail of the woodland restoration scheme). Although simplified, and not appropriate for local project appraisal (as NFM costs are always context specific, Environment Agency, 2015), this approach provides a useful first pass national assessment that is sensitive to the scale of the NFM ambition.

Table 2 Cost functions - Woodland and storage natural flood management measures

Woodlands				
Infiltration and roughness based	Lower	Central	Upper	Units
Capital	0.2	0.37	0.53	£/m ²
Revenue assumed 5% of the capital expenditure				£/m ² /year
Storage				
Storage ponds, reconnections etc	Lower	Central	Upper	
Capital	3.17	11.26	18.59	£/m ²
Revenue assumed 5% of the capital expenditure				£/m ² /year
Assuming storage provides an average depth of 0.2m				

Rates rebased to 2019 to be consistent with the baseline of the risk reduction benefits. The cost estimates here are indicative and will vary in each location. Source: Based on Sayers *et al.*, 2018

Determining the spatial variation in the utility of investment

The costs of implementing and maintaining the NFM measures vary by sub-catchment and so do the accumulated benefits of those actions. The costs and benefits over the chosen appraisal period (from 2025 to 2085) are then discounted using standard discount rates set out by HM Treasury (**Table 3**).

Table 3 Discount rates used to estimate Present Value Costs and Benefits

Discount Rate (%)	Year from Year 0
3.50%	0-30
3.00%	31-75
2.50%	76-125
2.00%	126-200
1.50%	>= 201

Source: HM Treasury, 2022

The discounted stream of costs and benefits are used to estimate the Net Present Value (NPV) associated with acting in any sub-catchment to be estimated as follows:

$$NPV = \sum_{t=2020}^{2100} \frac{B_t - C_t}{(1 + r)^t}$$

Where:

- B_t : Accumulated benefits in year t
- C_t : Costs in year t
- r : Discount rate
- t : Time in years

This process is repeated for each level of NFM ambition, climate, and development future. A ranking of the results (from those sub-catchments and ambition levels that achieve the highest NPV to the

lowest) reveals the preferred approach to NFM within each sub-catchment across Great Britain (conditional on a given climate and development future).

It is recognised that selection of the discount rate can have a material influence on the preferred investment approach. This is especially the case a long-term perspective is important, as is the case under climate change where damages have the potential to increase over time. This issue is not explored here, and the standard rates are used directly.

Placing NFM in the context of a portfolio of measures

It is widely accepted that flood risk is best managed through a portfolio of measures (e.g., Sayers *et al.*, 2014). A range of individual adaptation measures are typically used as part of this portfolio that relate to the management of the *sources* and *pathways* of the flood hazard, and the vulnerability of the exposed *receptors* (using the source-pathway-receptor framework set out in Sayers *et al.*, 2002). This whole risk system framework is reflected within the FFE enabling individual adaptations and their collective performance to be assessed under conditions of change. Within the FFE, the modelled changes in flow at each river confluence (as determined from the HBV-TYN and SHETRAN models are translated to a change in the return period of in-river water level (using the Flood Estimation Handbook (FEH) statistical method (Kjeldsen *et al.*, 2008) and catchment descriptors from the most appropriate 50m FEH pixel, Kay *et al.*, 2020, a method detailed in Sayers *et al.*, 2020). This in turn is used to infer a change in the standard of protection provided by flood defences and natural banks and hence the change in probability of a flood occurring at a given location. Exposure and vulnerability measures, such as spatial planning, forecasting and warning, and property level measures are also represented in the FFE and act to reduce the impact should a flood occur. The detail of the approaches used to represent these wider adaptation measures are well covered by previous publications and are not repeated here (Sayers *et al.*, 2020, 2022).

The FFE captures the benefits associated with each individual measure within a portfolio of measures through a hierarchical process of implementation. Here it is assumed NFM measures are given priority over conventional build flood defences. Other, non-structural, measures are implemented to manage the residual risk. This reflects the emerging rationale of using built infrastructure to supplement the performance of natural infrastructure and not vice versa (Sayers *et al.*, 2025). The extent to which these other measures are implemented is assumed to reflect a continuation of Current Level Adaptation (CLA) as previously defined (CCRA3, Sayers *et al.*, 2020). The '*portfolio benefit*' refers to the reduction in EAD achieved by this portfolio (including the varying scale of NFM ambition) when compared to the counterfactual of a low adaptation future (in which defences remain but are not raised with limited maintenance). The contribution of NFM measures to risk reduction is then determined by considering the change in risk as the hierarchy of measures are progressively implemented within the FFE.

Results

Changes in flood risk are assessed for ten alternative futures. Each future is defined by the scale of the NFM policy ambition, climate change and population growth (**Table 4**). To focus on the benefits of NFM flood risk, management policies (excluding NFM) are assumed to continue as in the recent past (as defined by the continuation of Current Levels of Adaptation defined by Sayers *et al.*, 2020) and the changing risks compared to a counterfactual assuming no NFM measures are implemented. At a national scale GMST and population growth can be considered decoupled (Sayers *et al.*, 2015). This assumption is made here and underpins the rationale of linking the 2°C rise in GMST with a lower population growth (SSP4) and a 4°C rise in GMST with a higher population projection (SSP2).

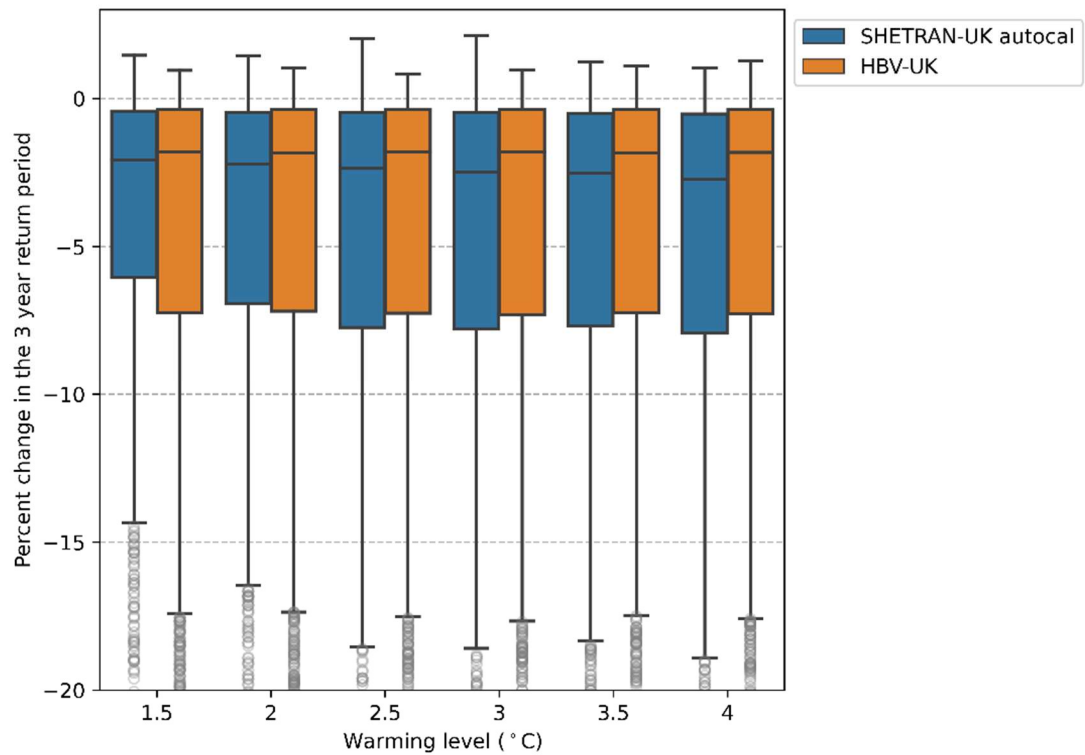
This helps capture some of the uncertainty in the exogenous pressures (although not all and the inclusion of additional combinations will be useful future extension).

Table 4 Future scenario definitions

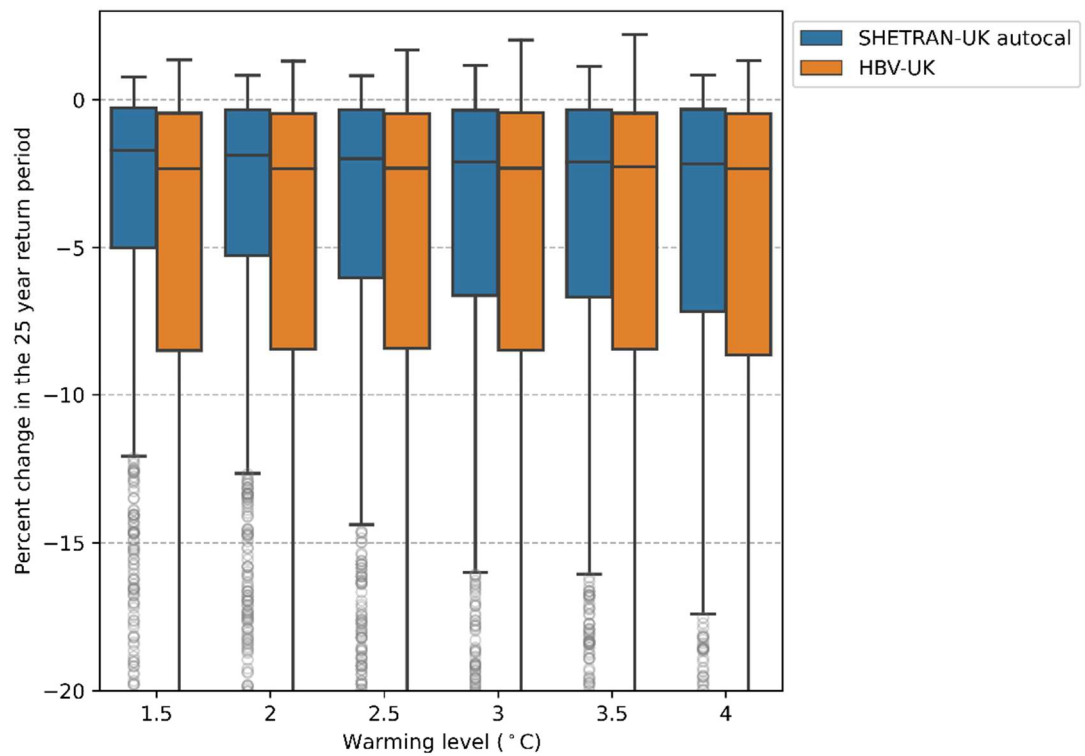
NFM policy ambition	Assumed approach to other flood risk management measures	Climate change (rise in GMST since pre-industrial times)	Shared Socio-economic Pathway (population growth)	Future
No NFM (counterfactual)	Continuation of current levels of adaptation (as defined in Sayers <i>et al.</i> , 2020)	2°C	UK-SSP4	1
		4°C	UK-SSP2	2
Max		2°C	UK-SSP4	3
		4°C	UK-SSP2	4
High (HBV-TYN only)		2°C	UK-SSP4	5
		4°C	UK-SSP2	6
Moderate		2°C	UK-SSP4	7
		4°C	UK-SSP2	8
Low (HBV-TYN only)		2°C	UK-SSP4	9
		4°C	UK-SSP2	10

Ability of NFM to reduce fluvial flows

SHETRAN and HBV-TYN suggest similar influences on flood flows with a reduction of between 0 and 10% in the 3-year return period. This compares well to (limited) available empirical evidence; representing an estimate that is smaller change than the 30% reduction in peak flows observed when a significant additional storage was added to the small (5.7km²) Belford catchment (Nicholson *et al.*, 2020), but similar to those reviewed in Roberts *et al.* (2023) that correspond to the similar volumes of additional storage represented here. Both models suggest an increase in the performance of NFM as climate change increases (**Figure 9**). There are some differences between the models, with SHETRAN suggesting a slightly higher effectiveness of NFM during very frequent events (1in3 year return period) than HBV-TYN, and vice versa at given slightly more extreme events (1in25 years). The similarity of the comparison however suggests a robust agreement on ability of NFM to influence (reduce) flows, particularly in more frequent events. Differences may reflect SHETRAN's explicit simulation of groundwater and unsaturated zone processes, which can enhance infiltration and storage under warming, attenuating peak flows. HBV-TYN, in contrast, is more responsive to surface runoff. Further work is needed to assess how model structure influences hydrological responses to climate change.



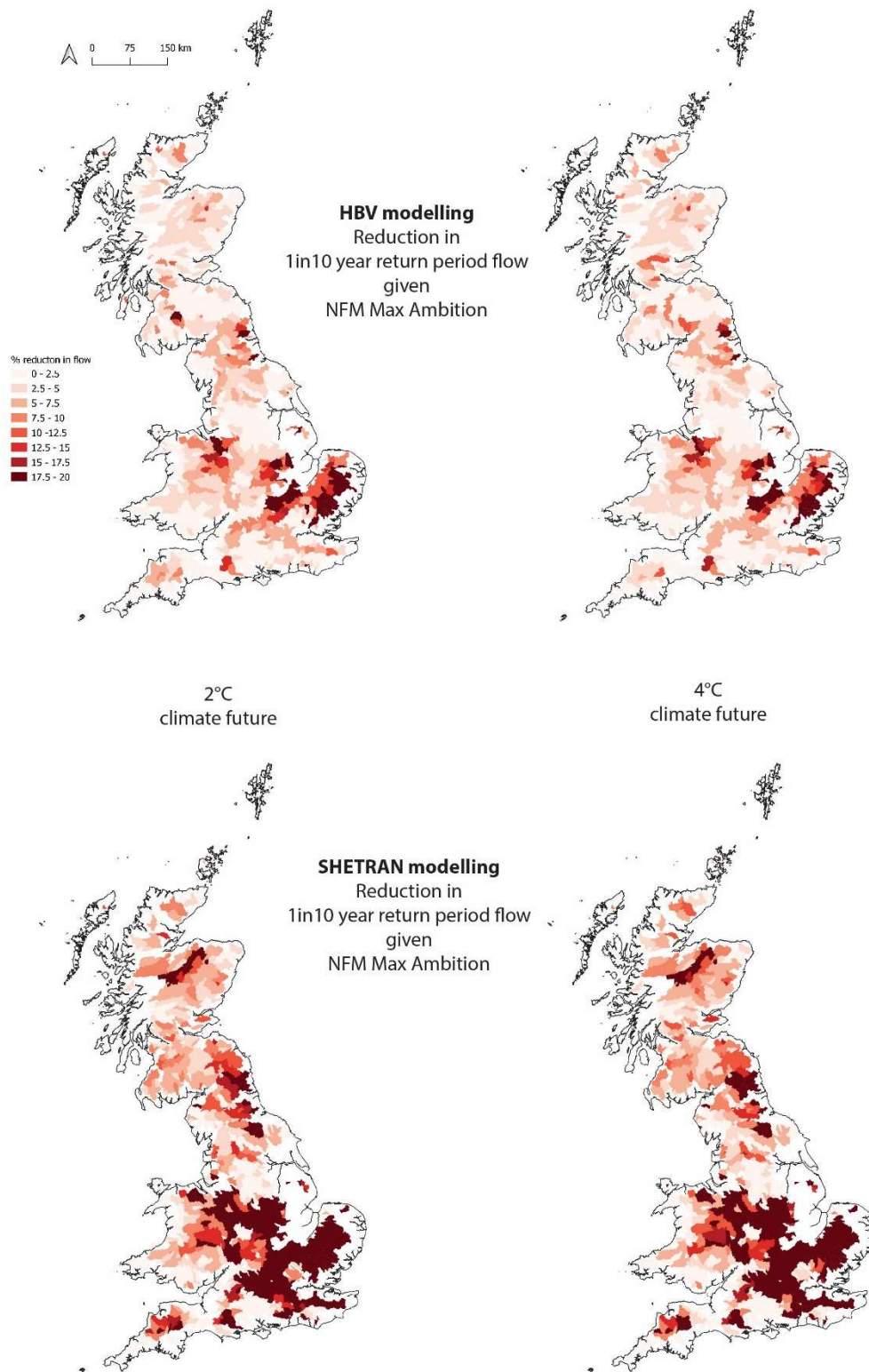
A comparison of the influence of NFM Max scenario on the 1in3 year return period flows across all CAMELS-UK catchments for SHETRAN and HBV-TYN. The Boxplots show the 25th, 50th and 75th quartiles of the data, with 'whiskers' stretching to the data point that is greatest or smallest but still within 1.5 times the interquartile range from its respective upper or lower quartiles, and points representing values beyond this range.



A comparison of the influence of NFM Max scenario on the 1in25 year return period flows across all CAMELS-GB catchments for SHETRAN and HBV-TYN. The mean change, and the X percentiles are shown

Figure 9 A comparison of the influence of NFM Max scenario on fluvial flows from SHETRAN and HBV-TYN

A spatial comparison of the influence of an '*NFM Max*' on the 1in10-year (using the ensemble mean outputs) highlights influences of NFM between the models and by return period (**Figure 10**). Both models project larger flow reductions in the South and East, where baseline conditions are drier and rainfall intensities lower than in the wetter West and North. Under warming, winter precipitation increases are smaller here, summer rainfall declines more sharply, and higher temperatures drive greater evapotranspiration and soil moisture deficits, reducing runoff generation. Consequently, these catchments become more sensitive to antecedent moisture and less likely to produce high flows. Lower extreme rainfall and the influence of NFM on runoff coefficients make NFM measures relatively more effective in these regions under climate change. Figure 10 also shows that SHETRAN produces larger reductions in flow than HBV. These changes (and those assessed for all return periods through to 1in100 years) are carried forward to the assessment of risk below.

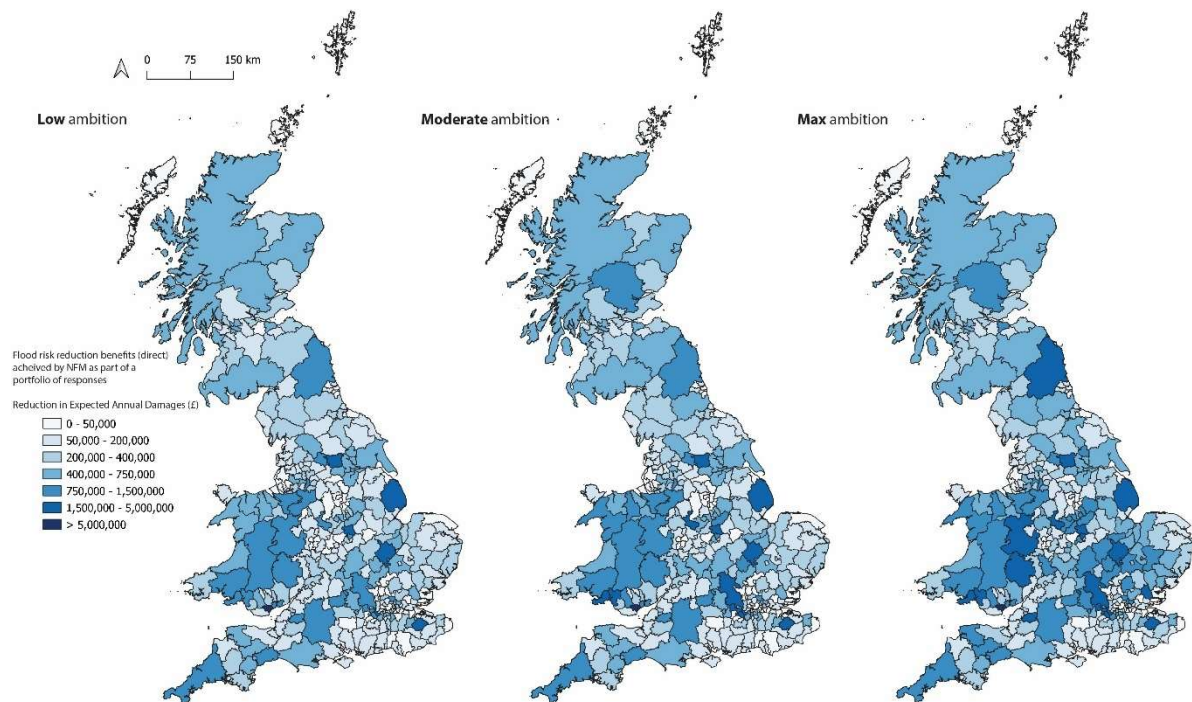


Top: Based on results from HBV-TYN. **Bottom:** Based on results from SHETRAN. This provides a spatial comparison between the hydrological model outputs. The legend is based on the percentage reduction in the peak flow assessed at each downstream point of a catchment.

Figure 10 Natural Flood Management – Spatial variation in the reduction in the 1in10 year return period flow

Ability of NFM to reduce flood risk

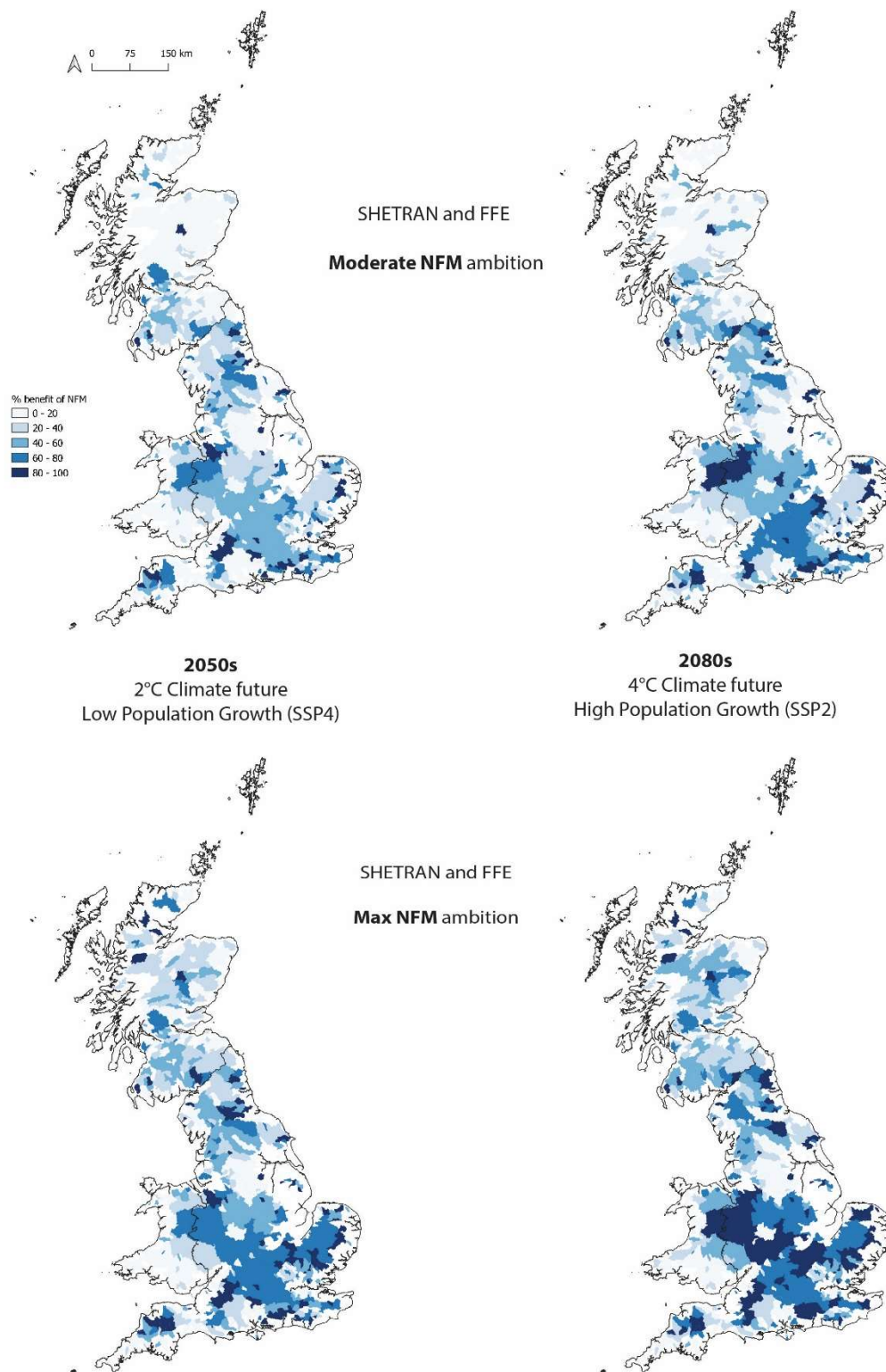
Figure 11 shows the reduction in fluvial EAD achieved for each level of NFM ambition when implemented as part of a portfolio of measures (with all other measures reflecting a continuation of current levels of adaptation as defined by Sayers *et al.*, 2020). The reduction in EAD is shown to vary both spatially and with increasing policy ambition. In some catchments, 'Low ambition' policies are shown to yield large annual returns (>£1.5million), whereas elsewhere, higher policy ambitions are needed to reduce EAD. The influence of NFM on fluvial flows within the CAMELS-GB catchment are assumed to persist to the coast with not further reductions. This enables the full benefit of the NFM measures within these catchments, to be captured through to river mouth.



Maps presented here show the benefit of the NFM measures implemented within the CAMEL-GB catchments summed to each Local Authority (2019). The results shown are based on the HBV-TYN and FFE. Similar analysis has been undertaken with SHERTRAN (Moderate and Max NFM scenarios only) and the FFE but is not presented here. The analysis includes fluvial risks only and excludes coastal and tidal influences.

Figure 11 Reduction in Expected Annual Damage achieved by different levels of NFM ambition in the 2050s under a 2°C climate future and low population growth (SSP4) future.

The results indicate that NFM has the potential to contribute significantly to flood risk reduction in many catchments. By the 2050s in some more rural catchments, with limited existing flood defence infrastructure, NFM is projected to provide ~80% of the benefits achieved by the portfolio (assuming a continuation of current levels of adaptation in all other measures). In most catchments, it is much less than this but remains significant (**Figure 12**).

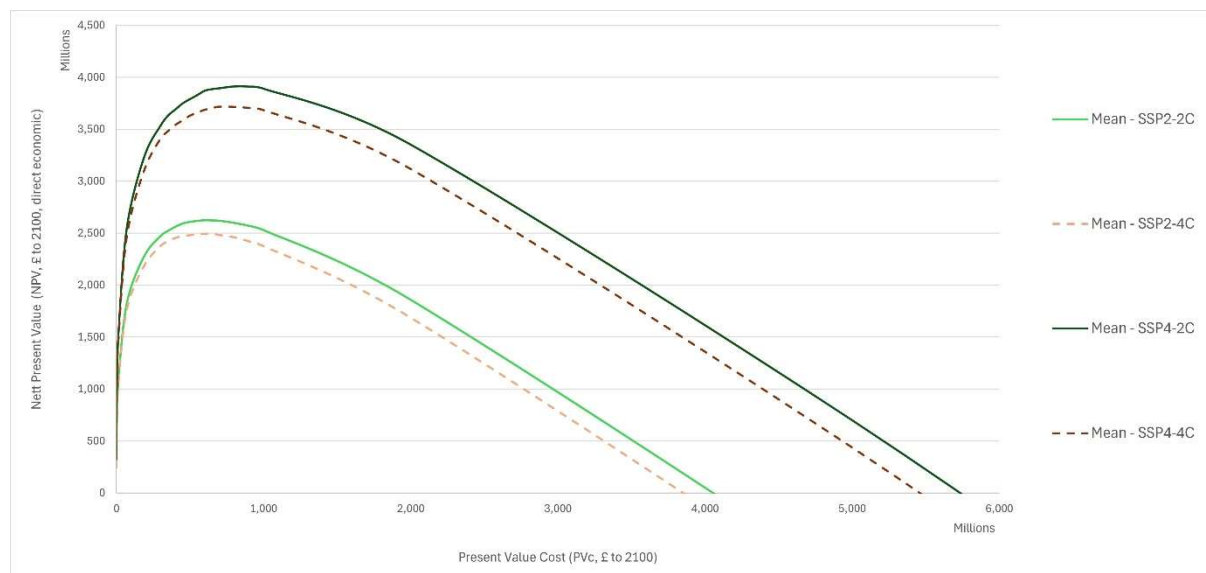


Top left: Moderate NFM ambition, 2°C, low population growth future (SSP4). **Top right:** Moderate NFM ambition, 4°C, high population growth future (SSP4). **Bottom left:** 'Max' NFM ambition, 2°C, low population growth future (SSP4). **Bottom right:** 'Max' NFM ambition, 4°C, high population growth future (SSP4). The results are based on SHETRAN and the FFE.

Figure 12 Spatial variation in the contribution of 'moderate' and 'maximum' ambition NFM approaches to the reduction in Expected Annual Damages achieved by the portfolio of risk management responses by the 2050s and 2080s given a SSP4/2°C rise and SSP2/4°C rise in GMST from pre-industrial times.

National optimal investment in NFM

The return on a single unit of investment tends to reduce as more is invested (the law of diminishing returns). Investment in NFM measures (and flood risk management more generally) is shown to reflect this principle, with the marginal return on investment in NFM measures reducing as more is spent (**Figure 13**). The economic optimum level of investment in NFM measures is represented by the combination of NFM actions that return the maximum NPV across Great Britain. The results suggest higher optimal returns are accrued under a 2°C when compared to a 4°C future, with greater benefits accrued in both cases under higher population growth population projections. This may be a function of the increased exposure given higher population and the greater ability for NFM to accommodate (and moderate) the increase in flow under 2°C future compared to a 4°C climate future. Disaggregating these drivers however remains an issue of continued exploration. The positive case of investment in NFM measures is however robust in both futures tested. In both significant investment of between £550-775m (Value) is justified, achieving a Benefit to Cost Ratio (BCR) of ~5 (**Table 5**). This is based solely on benefits accrued through the reduction in direct property damage. Inclusion of the wider benefits NFM provides would significantly increase this estimate.



The chart presents the relationship between Present Value Cost (to 2100) and the Net Present Value achieved (the difference between Present Value Benefits and Costs). The results shown represent the mean of the values achieved based on the two hydrological models (SHETRAN and HBV-TYN). The figure illustrates both the economic optimum investment (the investment that achieves the maximum NPV) and the law of diminishing returns as the NPV achieved reduces as the Present Value investment increases. The results shown are for 2°C rise in GMST by 2100 and low population growth (SSP4), and 4°C rise in GMST by 2100 and high population growth (SSP2) are shown.

Figure 13 The relationship between investment and risk reduction achieved by NFM measures at the scale of Great Britain

Table 5 Economic optimal benefits of NFM across Great Britain

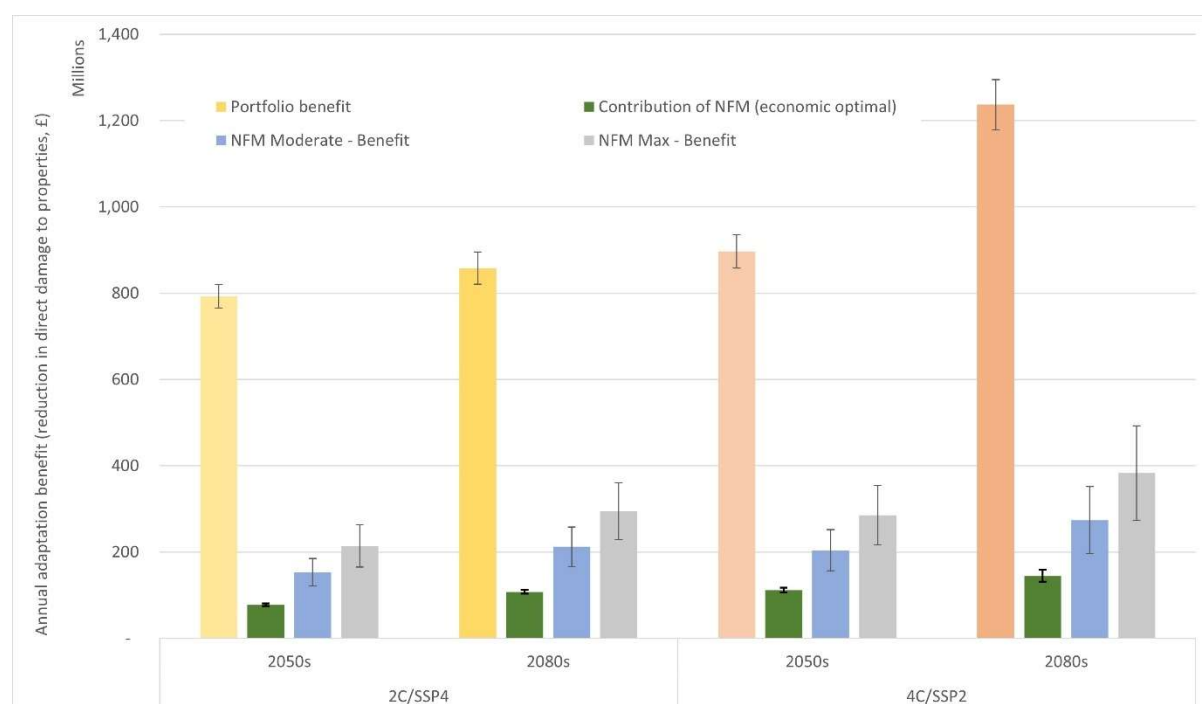
Climate change (rise in GMST by 2100 from pre-industry)	2°C		4°C	
Development future	SSP2	SSP4	SSP2	SSP4
Single criteria optimised Present Value investment (£)				
Central	600,000,000	550,000,000	775,000,000	750,000,000
HBV	550,000,000	450,000,000	650,000,000	700,000,000
SHETRAN	650,000,000	650,000,000	900,000,000	800,000,000
Single criteria optimised Present Value benefit (£, reduction in Expected Annual Damage, residential direct)				
Central	2,032,619,515	1,947,674,108	3,140,543,455	2,972,344,307
HBV	1,562,084,314	1,543,595,403	2,363,812,235	2,147,626,489
SHETRAN	2,503,154,715	2,351,752,812	3,917,274,675	3,797,062,125
Whole life Benefit Cost Ratio (residential flood risk reduction benefits only)				
Central	3.3	3.5	4.0	3.9
HBV	2.8	3.4	3.6	3.1
SHETRAN	3.9	3.6	4.4	4.7

Based on a contribution to Flood Risk Management assuming a continuation of Current Levels of Adaptation for all other aspects of the portfolio as defined in Sayers et al., 2020)

Contribution of NFM to the portfolio of FRM measures

Assuming the hierarchy of adaptation choice that prioritises natural flood management measures ahead of investment in built flood defences and the other non-structural flood risk management measures (such as property level protection and flood forecasting and warning) the results suggest NFM measures have the potential to contribute significantly to the reduction in EAD (**Error!**

Reference source not found.Figure 14).



The 'economic optimal' contribution is determined by the optimisation process described earlier and is shown as the average optimal contribution determined using HBV-TYN/FEE and SHETRAN/FEE results. The error bars reflect the model uncertainty associated with the use of the HBV-TYN and SHETRAN results. All other aspects of the modelling chain and data used are common. HBV-TYN/FEE runs have been undertaken to determine the contribution associated with the Low, Moderate, High and Max ambition. SHETRAN/FEE runs are only available for the Moderate and Max NFM ambition scenarios and hence only the optimum, Max, and Moderate ambitions scenarios are shown.

Figure 14 NFM contribution to flood risk reduction as part a wider portfolio of measures – Single criteria optimised, *NFM Max* and *Moderate* ambitions.

Discussion

The analysis presented highlights that there is a strong economic case to investment in NFM based on fluvial flood risk reduction benefits alone, without recourse to arguments based on wider benefits NFM provides. As with all national scale analysis, and in the context of the emerging understanding of the performance of NFM measures. These issues, including important caveats, are discussed below.

A strong case for increasing investment and wider take up of NFM

NFM measures are shown to offer a significant contribution to flood risk reduction when implemented as part of a portfolio of measures. The benefits achieved are shown to be robust to climate change, suggesting NFM is likely to provide a 'good' choice regardless of the climate future. Well-targeted investments in NFM (based on optimising the location and ambition of the NFM measures taken) can play a significant role in managing risk, with the analysis suggesting that by the 2050s, an optimal approach to NFM would reduce the EAD (associated with direct property damage only) by ~£75m (~£70m based on HBV-TYN and £80m based on SHETRAN, respectively) given a 2°C and low population growth (SSP4) future. This increases under 4°C and a high population growth (SSP2) future to ~£105-120m, representing between ~9-13% of the risk reduction achieved by the portfolio of flood risk management measures (within NFM applied within a broader portfolio that assumes all other adaptation measures continue based on current levels of activity). By the 2080s the contribution increases further to ~£110m in a 2°C and low population growth (SSP4) future and ~£145m under 4°C and high population growth (SSP2) future. The relative contribution as part of the portfolio remains similar (~11-13%). The similarity of the economic optimum investment based on both SHETRAN/FFE and HBV-TYN/FFE improves confidence that the results are robust. Most of these benefits are accrued through the modification of more frequent in-river water levels and the influence NFM has on flood hazards in undefended downstream areas and modifying the loads experienced by downstream defences (and hence of the chance of ultimate or serviceability limit state failure).

Local credibility of the analysis

The hydrological representation of the NFM measures here are necessarily approximations. No single measure is represented in detail. To do so remains an active area of research not only in terms of large-scale models (as here) but also in support of local analysis. The estimates of costs are broadscale and do not offer insights into any single NFM scheme. Nonetheless these caveats do not detract from the thrust of the analysis that brings together nationally calibrated hydrological models, the representation of NFM measures and their performance, the influence of climate change and development, and the assessment of risk in a meaningful way at a national scale.

The assumed portfolio of measures

It is assumed here that the varying levels of NFM ambition are implemented as part of a portfolio of measures, where all other measures continue to be adapted in line with the Current Level of Adaptation (CLA) scenario set out in CCRA3 (Sayers *et al.*, 2020). If significantly more investment was directed toward conventional flood defences the contribution of NFM would reduce, and would increase if investment in conventional defences reduced. Similar changing approaches to spatial planning (either increasing or reducing the percentage of new properties built in flood plain compared to the recent past) would influence the contribution of NFM. It is important so see the results presented here as the contribution of NFM within this context.

The impact on the risk profile

Flood risk is presented here in terms of an EAD. EAD represents an integration of probability and consequence across all possible events. The estimate of EAD is biased towards the consequences of frequently occurring events. Analysis of the hydrological response of the NFM measures suggests that their influence is greatest during frequent events and tends to zero with increasing return period of the fluvial flood flow. This performance signature is reflected in the significant reduction in EAD observed here. This does not however suggest the impact of NFM on more extreme events is significant. This reinforces the importance of '*designing for exceedance*' (Digman *et al.*, 2014) and ensuring FRM strategies are effective in managing residual risks will inevitably remain (Sayers *et al.*, 2002).

Long term performance

The performance of NFM measures changes autonomously over time. This change in performance exhibits significant hysteresis, with the preceding sequence of events (over days, months or even years) influencing run-off and storage potential. NFM 'assets' also mature over time (trees grow and soil structures change). The modelling chain presented here seeks to capture these issues in simplified ways, but nonetheless there remains a lack of theoretical and empirical understanding of these changes (*e.g.* Sayers *et al.*, 2014; Dadson *et al.*, 2017; Kay *et al.*, 2019). No consideration is given here, for example, to the viability of woodland planting under conditions of climate change (heat and water stress) or invasive species that may influence performance over the longer term. Addressing these knowledge gaps will be a pre-requisite in advancing the analysis presented here.

Aligned catchment planning and policy priorities

Developing a *whole system response* to managing flood risk, including NFM, requires an understanding of the interactions within, and beyond, FRM. The analysis here starts this narrative by considering the influence of development choices, food security (through the priority given to agricultural yield), and biodiversity (through the priority given to conservation and restoration). Exploration of types of afforestation and water storage that align with conservation and restoration would allow synergies with NFM to be explored and quantified. The approach is however a first pass and more nuanced and wider ranging catchment planning processes will be needed to make strategic progress towards more integrated landscape scale planning and management.

The National Flood and Coastal Erosion Risk Management (FCERM) Strategy (Environment Agency, 2021) identifies NFM as an important part of the resilience framework that it sets out. The third National Adaptation Programme (NAP3) published in 2023 also suggests wider action is needed to implement NFM in relation to highways (*i.e.* integrating NFM into National Highways' climate risk management plans) and land management (*i.e.* supporting NFM implementation through environmental land management schemes (ELMs)).

At the local level where these schemes are implemented, Russell *et al.* (2024) have shown only 10 of the 152 Local Flood Risk Management Strategies in England include more than passing references (or no references) to NFM (or similar). This limited progress highlights the significant work to be done at the national and local level (in England at least) to integrate NFM as a central component of flood risk management. To be successful, landowners will need be supported and encouraged to implement NFM on their land. This will continue to require co-design and financial support, but also reinforces the importance of the evidence gap this paper responds to.

NFM delivers more than flood risk reduction

Flood risk reduction benefits represent only one narrow focus and ignore the numerous wider benefits of NFM. These include carbon sequestration, amenity, biodiversity, water resources (including the potential to improve low flows) and many others. As introduced earlier, the analysis here deliberately excludes these, but their inclusion, on balance, would only add further to the positive case for NFM. There are also potential disbenefits in terms of opportunity losses (preventing alternative development or productive uses) and in some instances NFM may reduce low flows and negatively impact water resource (*e.g.*, Elliot and Giritharan, 2023; Sayers *et al.*, 2025).

Conclusion

Natural Flood Management (NFM) seeks to work with natural processes to restore the natural functions of rivers and aligns with this shift in emphasis. The multiple benefits of doing so are well known and intuitive, including biodiversity gains, amenity, carbon sequestration, but there is limited quantified understanding of the scale of the contribution NFM could make to reducing **fluvial** flood risk across Great Britain, and how this contribution may vary with climate change. This paper, for the first time, projects national scale NFM scenarios reflecting various policy ambitions and considering competing land use demands (urban development, agriculture and biodiversity demands) and presents an assessment of the contribution of NFM to fluvial flood risk reduction.

The results of the analysis confirm NFM as a legitimate supporting measure in fluvial flood risk management. The use of two national-scale hydrological models (SHETRAN and HBV-TYN) to assess changes in flood flows and the use of a flood risk system emulation to translate these changes into a change in risk (using the Future Flood Explorer, FFE) are shown to enable the benefits of NFM actions to be disaggregated from the wider set of measures that form the overall flood risk management portfolio.

The results show NFM robustly contributes to the flood risk management portfolio under conditions of climate and socio-economic change, suggesting that well-targeted investment in NFM measures have the potential to significantly reduce overall flood risk. The broad estimate of costs suggests implementing these well-targeted actions would cost approximately £550m-775m through to the 2080s, equivalent to an annual spend of around £20-30m.

The analysis presented is only a first step. There is potential for future analysis to provide integrated insights into catchment development (including interactions across the rural/urban interface) and the best mixture of flood risk management measures, delivering wider benefits for people and nature. Realising all these benefits, and the broader opportunities NFM provides (not quantified here), will require proactive strategic landscape-scale planning that looks beyond flood management alone to develop aligned investment incentives that support sustainable outcomes for people and nature.

Acknowledgements

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The underlying HBV and SHETRAN results are available on DAFNI for registered users. Further datasets continued to be added.

Statements and Declarations

None

Competing Interests

Authors have no financial or non-financial interests that are directly or indirectly related to the work submitted for publication.

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