

Assessing the impacts of natural flood management on downstream flood risk: a case study of the River Aire

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Intellectual Property and Publication Statements

The candidate confirms that the work submitted is their own, except where work which has formed part of jointly authored publications has been included. My contribution and the other authors to this work has been explicitly indicated below. I confirm that appropriate credit has been given within the thesis where reference has been made to the work of others.

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QZ led the manuscript writing, with feedback from all other authors who approved the final version.

Chapter 4 is the following manuscript, prepared for submission:

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Contributions: QZ led the study design and planning with support from all authors. QZ developed the coupled model approach with guidance from supervisors. Model calibration, validation, scenario runs, and analysis were led by QZ. TW provided additional knowledge of the model. QZ led the writing of the manuscript, and the supervisors critically assessed drafts.

The research questions for the project were investigated using a range of approaches, which made the presentation of the data chapters as three individual manuscripts appropriate. One of the manuscripts has now been published, one is under review, and the final one is prepared for submission to a journal. The main body of the thesis therefore consists of the published, submitted, and prepared manuscripts. This is preceded by an introduction, which provides background information, reviews relevant literature, and outlines the aims and objectives of the work. A synthesis chapter, bringing together the findings of the three research papers and discussing them in the context of the research questions, concludes the thesis.

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Abstract

Natural flood management (NFM) offers a potentially sustainable solution to mitigating flood risks, yet its effectiveness at larger catchment scales and under varying rainfall intensities remains uncertain. This thesis combined a quantitative meta-analysis of 454 NFM studies with hydrological (SD-TOPMODEL) and coupled hydrological-hydrodynamic (SD-TOPMODEL to Flood Modeller 2D) modelling in the River Aire Catchment (81.4 km²), to address research gaps. The meta-analysis revealed a shift in focus over time from localized flood mitigation to catchment-wide strategies, accompanied by increasing emphasis on ecosystem services. Contrary to previous findings, the effectiveness of NFM interventions were not found to diminish with increased catchment size nor rainfall intensity. Using SD-TOPMODEL, this research simulated diverse NFM interventions and their combinations at a high resolution (5m), including woodland planting, soil aeration, and hedgerow planting, achieving 4.2-16.0% flood peak reductions. NFM interventions were found to be most effective during single-peaked storm events and dry antecedent conditions. Combined interventions demonstrated greater resilience and effectiveness than single interventions in the catchment, emphasising the importance of integrated flood management strategies. A coupling of SD-TOPMODEL with Flood Modeller 2D was used to investigate downstream impacts of NFM scenarios (combining leaky dams, riparian buffer strips and other interventions mentioned above) and the maximum catchment woodland scenario, revealing changes in inundation extent and depth. An unintended inundation increases for a large village occurred under a widespread woodland creation scenario highlighting the importance of integrated and targeted NFM planning at the catchment scale. This thesis concludes that storm characteristics and pre-event conditions play a more significant role in determining NFM efficacy than catchment size or rainfall intensity. The findings emphasise the need for strategically designed, catchment-scale intervention networks and advocates for modelling approaches as essential tools for optimizing NFM planning and ensuring its effectiveness in wider flood risk management.

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Chapter 1. Introduction

Flooding has become the most frequent and widely experienced type of natural disaster globally and affected more than 2 billion people and cost more than US\$ 656 billion in the period 1998 to 2017 (CRED and UNISDR, 2018). Flood risks are likely to increase under the context of climate change globally (Kundzewicz et al., 2013). Annual flood losses in the European Union are projected to be € 23.5 billion by 2050, increased from € 4.9 billion between 2000 and 2012 (Jongman et al., 2014). Climate change projections suggest that increases in the frequency and intensity of heavy rainfall will contribute to increases in soil saturation and surface flows at catchment and regional scales (Innocenti et al., 2019; Martel et al., 2020). As climate change impacts accelerate, the probability of river flooding may increase four-fold by 2080 compared to 2000 (Thorne, 2014), and flood risks will become one of the top five risks in terms of likelihood over the coming decade (WEF, 2020). Thus, a sustainable and effective flood mitigation strategy is critical.

Nature-based solutions (NBS) management frameworks is an international topic and encompass a variety of nature-based measures designed for diverse purposes. These measures tackle flooding by working with nature through restoration, emulation and promotion of natural processes that contributed to flood mitigation. Compared to traditional hard engineering flood defence measures, nature-based approaches often achieve greater cost-effectiveness and can be considered either as a separate component or as part of a twin track approach with traditional measures. As a subset of NBS, Natural Flood Management (NFM) using nature-based measures focuses primarily on flood mitigation more than other nature hazards or broader environmental objectives, which is being widely implemented in the UK and Europe, although the evidence base for its effectiveness is limited (Dadson et al., 2017; Wingfield et al., 2019; Kumar et al., 2021). The effectiveness of NFM faces challenges under scenarios of increased rainfall intensity, particularly in the context of climate change (Kay et al., 2019).

This introductory chapter provides the background to the research topics of the thesis and the research objectives and provides an overview of the research methodology. The focus is on the influence of potential factors, identified in previous NFM research, on NFM effectiveness, including catchment scale, research methodology, type of

intervention, rainfall characteristics and confidence evaluation. Different hydrological and hydrodynamic models were reviewed to present the rationale for the choice of modelling approach adopted in the thesis.

Chapters 2-4 include three manuscripts investigating the effectiveness of NFM in flood mitigation. Chapter 2 reviews the dynamic trends and hotspots in NFM research over the last 30 years and investigates the correlation between catchment size and rainfall intensity and the effectiveness of flood mitigation. Chapter Three used a hydrological model (SD-TOPMODEL) to investigate the response characteristics of different types and combinations of soil and land management NFM interventions in a case study catchment under rainfall events with different return periods, and the impacts on peak discharge and timing. In Chapter Four, a hydrodynamic model (Flood Modeller) is coupled to SD-TOPMODEL to simulate surface structure NFM interventions in the catchment and to output spatially distributed flood extent and water depth results in addition to runoff time series.

1.1 Natural flood management

NFM is broadly engaged as a flood risk management strategy by working with natural processes in catchments, taking measures such as river and floodplain restoration, installation of leaky barriers, creation of offline storage areas, and encouraging land use and land management practices to reduce flood risk (SEPA, 2016; Burgess-Gamble et al., 2017; Short et al., 2019). NFM seeks to mitigate the frequency and severity of flooding while delivering other environmental, social, and economic benefits within catchments (Dadson et al., 2017). Co-benefits include improving water quality and enhancing ecological services (Morris et al., 2016; DEFRA, 2013). Despite these advantages, the effectiveness of NFM techniques at larger catchment scales and under increased rainfall intensities remains uncertain due to limited evidence on their impacts and the influence of spatial configuration and scale (Black et al., 2021; Dadson et al., 2017; Kay et al., 2019; Wingfield et al., 2021).

1.1.1 River and floodplain restoration

River and floodplain restoration in context to NFM aims to slow and store flood flows by restoring natural hydrological processes (SEPA, 2016). Restoration often involves modifying the morphology of river channels, such as re-naturalising flow and sediment supply regimes through the removal of artificial structures, reshaping river channels, and adding wood or sediment (Addy et al., 2016). While restoration has been shown to reduce water velocities and flood peaks at localised scales, its effectiveness at the catchment scale is less clear (Parry et al., 2014; Wohl et al., 2015; Shuttleworth et al., 2019; Goudarzi et al., 2021; Goudarzi et al., 2024). Changes within a tributary may influence flood attenuation and could lead to runoff synchronisation across tributaries, thereby increasing flood peaks in the main channel (Sholtes and Doyle, 2011; Keesstra et al., 2012; Pattison et al., 2014; Dixon et al., 2016; Rogger et al., 2017). The effectiveness of river and floodplain restoration may be limited by scale, and there is a lack of evidence to prove the effect on reducing flood risk at different catchment scales.

1.1.2 Offline and online storage areas

Offline storage areas, such as small and medium-sized impoundments, store water temporarily during flood events. Floodplain storage, particularly in washlands with high surface water storage capacity, has proven effective for managing fluvial flood risk (Burgess-Gamble et al., 2017; Gunnell et al., 2019). Model experiments have demonstrated the potential of these storage areas to reduce peak flows (Nicholson et al., 2012; Quinn et al., 2013; Ghimire et al., 2014). However, these studies did not consider the influence of storage area location and configuration on their effectiveness. A more comprehensive storage network that optimally integrates the location, number, and size of storage areas is necessary to enhance flood peak attenuation across catchments (Wilkinson et al., 2019). Further research is required to evaluate the performance of offline storage areas in larger catchments and their potential effects on runoff synchronisation.

Leaky dams, also referred to as (large) woody dams, are commonly used as online (in-channel) storage techniques in NFM, as they are integral to naturally functioning rivers and floodplains in forested catchments (Wohl, 2017). These structures consist of multiple successive leaky barriers made of wood or woody debris, strategically placed in

small streams to allow low flow passage while impeding higher flows (Kitts, 2010; Thomas and Nisbet, 2012; Burgess-Gamble et al., 2017). Leaky dams increase hydraulic roughness and resistance, leading to reduced flow velocities and creating temporary storage space in the floodplain, which can influence downstream flood risk (Kitts, 2010; Keys et al., 2018; Addy and Wilkinson, 2019). Most studies investigating their effectiveness in flood mitigation, using physical experiments or modelling approaches, are local in scale (Addy and Wilkinson, 2019; Chapter 2). Current evidence is insufficient to establish the downstream impacts of upstream implementation of leaky dams at larger catchment scales, and their effectiveness appears to be constrained by factors such as rainfall intensity (Thomas and Nisbet, 2012; Hankin et al., 2020; Black et al., 2021; Norbury et al., 2021; Senior et al., 2022; van Leeuwen et al., 2024).

1.1.3 Soil and land management

Land management practices, including woodland and grassland management, headwater drainage interventions, and soil management, are among the most widely adopted NFM interventions by area (Figure 1.1). These practices aim to intercept overland flow by increasing surface roughness and physically slowing the rate at which water is delivered to river channels through increased hydraulic roughness, encourage infiltration and soil water storage (Roni et al., 2015; Burgess-Gamble et al., 2017; Murphy et al., 2020). Modelling and experimental studies have shown that planting trees can affect flood generation processes (Thomas and Nisbet, 2007; Birkinshaw et al., 2014; Wells and Labadz, 2016), but these studies were implemented locally on a small scale. The spatial distribution of woodlands in catchments and the catchment geometry can influence runoff synchronisation and may increase flood risk (Dixon et al., 2016). Additional factors, such as tree species and seasonal variations can impact soil hydrophobicity and the development of macro-porous soil structures (Solloway, 2012; Palmer and Smith, 2013; Dixon et al., 2016; Alaoui et al., 2018; Monger et al., 2022a). Furthermore, tree planting also interacts with leaky barriers by providing woody material that contributes to flow attenuation (Collins et al., 2012; Wohl et al., 2015; Grabowski et al., 2019). However, the effectiveness of woodland management at larger catchment scales requires further investigation.

Compared to afforestation, tillage and grazed grassland management have been shown to generate higher overland flow and reduce saturated hydraulic conductivity during rainfall events in experimental sites such as Pontbren in the River Severn catchment, UK (Marshall et al., 2009). However, the relationship between soil permeability and land cover change is variable and the evidence from other sites remains limited. For instance, saturated hydraulic conductivity has been found to vary significantly with grassland type (Bond et al., 2020), as well as surface roughness and overland flow velocity (Monger et al., 2022b), highlighting its critical importance for the management of upstream grassland habitats and their spatial distribution.

Soil aeration and subsoiling are commonly used in arable and grassland systems to alleviate soil compaction, yet their effectiveness as flood risk mitigation measures is uncertain due to limited data. Several studies demonstrated that soil aeration can significantly enhance soil water storage capacity and delay runoff peaks by improving infiltration in compacted fields (Franklin et al., 2007; Alaoui et al. 2018; Wallace and Chappell, 2020). Conversely, Curran Cournane et al. (2011) reported no significant differences in surface water volume between aerated soils and untreated control plots. Furthermore, the structural changes induced by soil aeration are often temporary and can revert to their original state through natural hydrological processes. Consequently, the long-term impact of soil aeration on surface runoff may be minimal. The benefits of soil aeration and subsoiling are likely to be context-dependent, varying with soil type and the degree of loosening.

Overall, well-drained and well-structured soils, particularly those with vegetative cover such as grasses and trees in headwater areas, can reduce overland flow velocity and mitigate soil erosion (Holden et al., 2008; Archer et al., 2013; Bond et al., 2020; Bond et al., 2022). Upland peatland management measures, such as ditch blocking and gully blocking, have also resulted in significant effects on increasing lag times and reducing peak flows at small scales (Holden et al., 2017; Shuttleworth et al., 2019; Goudarzi et al., 2021; Goudarzi et al., 2024). However, these outcomes can vary between storm events and depend on the spatial arrangement of ditches and gullies in relation to local topography and the broader stream network (Holden, 2005; Lane and Milledge, 2013). Agricultural features, such as hedges and buffer strips, may contribute to intercepting

overland flow by increasing surface roughness and enhancing soil hydraulic conductivity (Hansen et al., 1999; Zheng et al., 2012; Holden et al., 2019). Nevertheless, there remains a lack of qualitative or quantitative studies that explicitly link land management changes to catchment-wide reductions in flood risk.

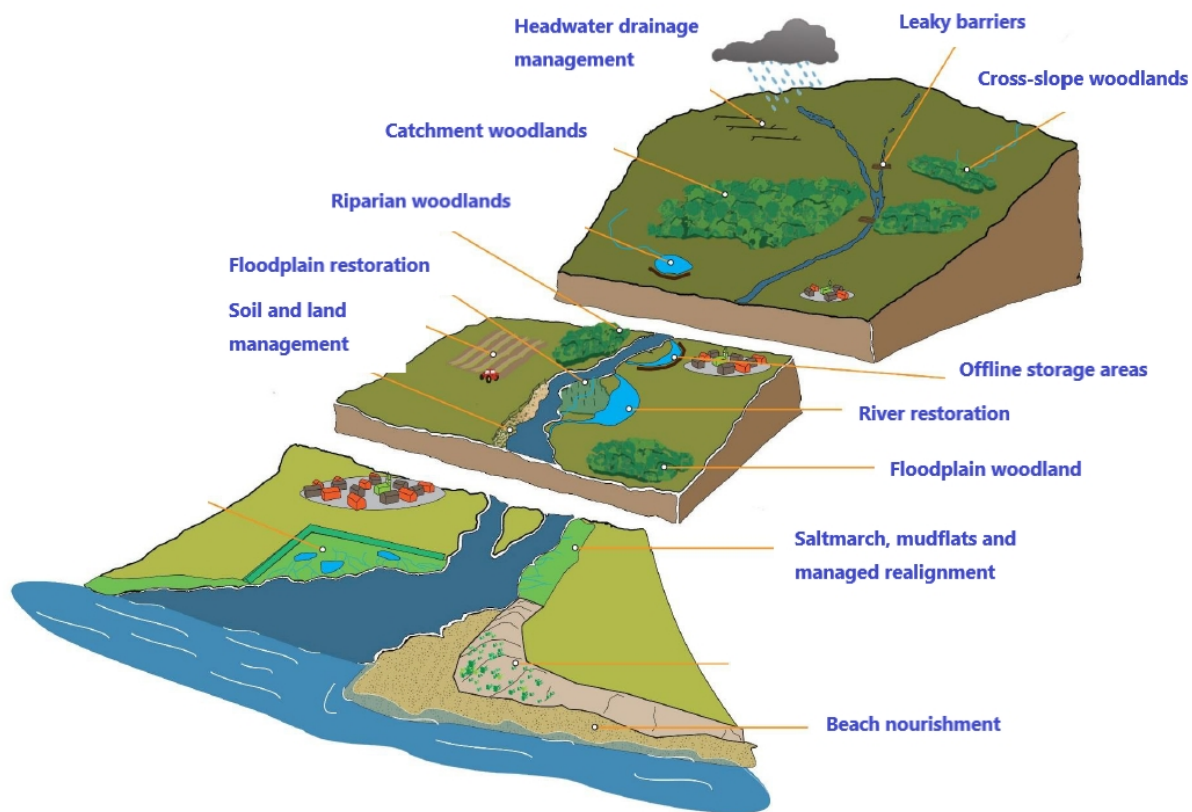


Figure 1.1. Examples of Natural Flood Management measures-from source to sea (Burgess-Gamble et al., 2017)

1.2 Modelling in NFM

A key challenge in evidencing the effectiveness of NFM interventions lies in understanding their impact at the larger catchment scale. Specifically, it is critical to evaluate whether the investment in NFM measures can yield sufficient benefits, such as flood discharge reduction, while also considering potential disadvantages at the catchment scale, such as tributary synchronisation (Beven, 2019; Pattison et al., 2014). As described in section 1.1, NFM techniques encompass interventions across the entire catchment, from headwaters to the river estuary. To evaluate their effectiveness

comprehensively, it is essential to categorize techniques based on their influence on the rainfall-runoff and inundation process. These techniques can be broadly classified into four groups according to their main purposes: slow catchment flow generation and rainfall-runoff processes (off-channel); increase surface and subsurface water storage in offline/online areas; reduce water velocity in channel; integrated catchment management (Table 1.1, details in Chapter 2).

Table 1.1. Four groups of NFM techniques classified by their main purposes

	<i>Groups by purposes</i>	<i>NFM measures</i>
<i>Group A</i>	Slow catchment flow generation and rainfall-runoff processes (off-channel)	Cross slope reforestation Floodplain/riparian reforestation Soil and land management (soil aeration, sub-soiling, peatland, woodland, grassland, hedges) Peatland restoration (including gully blocking) Floodplain restoration/reconnection
<i>Group B</i>	Increase surface and subsurface water storage in offline/online areas	Offline storage areas (water retention/detention ponds) Online storage areas (grip blocking, drainage/ditch blocking, buffer strips, beaver dams) Land cover changes (floodplain/riparian reforestation, floodplain restoration/reconnection, grassland, hedges)
<i>Group C</i>	Reduce water velocity in channel	Leaky barriers Woody logjams
<i>Group D</i>	Integrated catchment management	Multiple NFM interventions

Numerous modelling and fieldwork studies have investigated the effectiveness of NFM interventions by simulating soil property changes, land cover/land use changes and surface elevation changes under varying rainfall events (Table 1.2 and 1.3). The tables

showed a selection of the most representative examples within each group of NFM techniques. A comparison of these tables highlights that modelling studies can account for the spatial distribution of measures and represent the influence of spatial variability on NFM interventions. For instance, in larger catchments, the synchronisation of flood peaks may pose a significant challenge, where slowing the flow in tributaries could exacerbate flood peaks in the main channel (Pattison et al., 2014; Dixon et al., 2016). To address these issues, spatially distributed models, which can accurately reflect the location of interventions, are more suitable for simulating dispersive NFM measures at a catchment scale (Wingfield et al., 2019; Hill et al., 2023).

Table 1.2. Examples from each group of NFM techniques (Table 1.1) demonstrating key parameters in modelling studies, which can inform NFM modelling of flood risk impacts

Group	Reference	Key parameters	Model type	Implications of flood risk	Spatial resolution	Rainfall resolution	Catchment descriptions
Slow catchment flow generation and rainfall-runoff processes (off-channel)	Gao et al., 2016	Soil storage depth, soil hydraulic conductivity, surface roughness.	Spatially distributed TOPMODEL (SD-TOPMODEL), hydrological model.	Land management scenarios reduce flood peak by 10.1%, 1.8% and 13.4% respectively in three sub-catchments.	Grid size (20m * 20m) for 3 sub-catchments.	20 mm/h event.	Three upland peat basins in the southwest England: Trout Beck catchment (11.4 km ²); Wye catchment (10.6 km ²); East Dart catchment (21.5 km ²).
	Gao et al., 2018	Soil storage depth, soil hydraulic conductivity, surface roughness.	SD-TOPMODEL.	Land cover change on sensitive areas in upland peat catchments have greater reduction (maximum 11.74%) on peak flows for different rainfall pattern.	Grid cell (20m * 20m).	Different rainfall patterns (rainfall that was uniform, rainfall with an early peak intensity during the storm, middle peak, and late peak), and variety among locations.	Trout Beck catchment (11.4 km ²), southwest England.
	Dixon et al., 2019	Live/dead tree dynamics Bank erosion rates.	Northeastern Coarse Woody Debris (NE-CWD) model, conceptual model.	Reforestation increase flood travel time and reduce peak flow, which is more significant with time of stand establishment.	Run yearly, output per 5 years.	Annual	No specific study sites.

	Buechel et al., 2022	Canopy height, leaf area index, soil infiltration factor and root depth.	Joint UK Land Environment Simulator (JULES), physically based land-surface model.	Afforestation can reduce high flow; the location of afforestation in a small catchment affects the highest streamflow extremes.	Grid size (1 km * 1 km), output yearly.	Annual	Twelve UK catchments (500-10000 km ²).
<i>Increase surface and subsurface water storage in offline/online areas</i>	Thomas and Nisbet, 2007	Channel and floodplain surface roughness.	1D Hydraulic Engineering Centre-river Analysis System (HEC-RAS); River2D hydraulic model.	Decrease river velocity, increase water level by up to 270 mm, increase flood storage by 15% and 71%; flood peak travel time was increased by 30 and 140 min.	50 ha woodland on a 2.2 km reach on the River Cary.	1 in 100 years flood event.	A sub-catchment of River Parrett catchment (82.4 km ²) in southwest England.
	Ghimire et al., 2014	DEM Channel roughness or bed resistance values.	Coupled 1D (for storage modelling) and 2D (flow routing and flood inundation) hydraulic models.	The storage attenuates the flow significantly with a reduction of the peak flow by ~9%.	Grid size (5m * 5m).	1 in 2 years flood event.	Tarland Burn (74 km ²), a sub-catchment of the River Dee catchment (2105 km ²)
<i>Reduce water velocity in channel</i>	Dixon et al., 2016	Channel hydraulic resistance values.	OVERFLOW model.	Engineered logjam insertion changes flood peak magnitude in ±6%.	Grid size (20m * 20m).	A rainfall and subsequent moderate flood event of 3% exceedance, 30–31 March 2006.	Lymington River catchment (98 km ²) in Southern UK.
	Thomas and Nisbet, 2012	Manning's n-value.	1D hydraulic model: Infoworks RS river modelling software package.	Large wood debris dams increase upstream water levels, reduce 2.1 m/s at peak flow, and delay flood	15 cross-sections with 50 m intervals.	A flood event of 1% exceedance.	The River Fenni catchment (9.2 km ²), a tributary of the River Usk.

				peak for the 1% AEP by 15 min.			
<i>Integrated catchment management</i>	Ferguson and Fenner, 2021	Lateral saturated transmissivity, form of exponential decline in conductivity, initial root zone storage, maximum root zone storage, unsaturated zone time delay, overland flow routing velocity.	Dynamic TOPMODEL coupled with HEC-RAS 2D, integrated with Yorkshire Water's Infoworks integrated catchment modelling (ICM) drainage model.	A slight delay in rural response can significantly improve drainage performance and reduce instances of nuisance flooding. The upstream NFM is greatest in the most adverse storm directions – reducing flood magnitudes by approximately 10% during the northwest 50-year event.	Hydrological response units (HRUs) Grid size (1 km *1 km)-coupled model.	5 designed events with 8 storm direction each in the upper Calder River catchment, Yorkshire, UK.	Upper Calder River catchment (18 km ²), Yorkshire.
	Kingsbury-Smith et al., 2023	Soil storage depth, soil hydraulic conductivity, surface roughness.	SD-TOPMODEL.	Improved soil infiltration caused 7% reduction in peak runoff and 8% increase in lag time. Catchment wide woodland planting reduced peak flow by 11% during the 100-year event but was not effective during the 10-year event. Multiple NFM interventions did not offer additive or more effective outcomes.	Grid cell (5m * 5m).	10-year and 100-year occurrence events.	Bishopdale catchment (38 km ²), Yorkshire.

Table 1.3. An example from each group of NFM techniques (Table 1.1) demonstrating key parameters in fieldwork studies, which can inform NFM modelling of flood risk impacts

<i>Measure Group</i>	<i>Paper</i>	<i>Methods</i>	<i>Implications of flood risk</i>	<i>Key variables</i>	<i>Hydrological/soil properties of the study site</i>
Increase overland flow storage areas in offline areas	Mason-Mclean, 2020	A 5m long concrete V-flume, designed using the Modified Rational Method for a 100-year flood event.	Riparian buffer strips can increase interception and storage of runoff and reduce flood risk but limited by the location and microtopography.	Surface runoff; slope; land use change; soil infiltration rates; soil moisture; water table height; and stream water level.	A riparian 13-year-old and 9m wide fenced buffer strip in Easttown Farm, Scotland, located on a hillslope with surrounding agricultural land and well-estimated vegetation.
Slow upland flow generation and rainfall-runoff processes	Bond et al., 2020	Hillslope flume for measuring vegetative roughness to overland flow.	Headwater grassland vegetation increase roughness, rough buffer strips are important in slowing the flow.	Darcy–Weisbach roughness; slope angle.	Swindale catchment, Lake District, UK, comprises a 2.66 km ² U-shaped valley.
Reduce water velocity in channel	Muhawenimana et al., 2021	An open channel recirculating flume located in the main channel and floodplain.	Leaky barriers have backwater effects and distributing logs to maximize channel obstruction will improve flood attenuation.	Cross-sectional blockage ratio; hydraulic drag coefficients.	No specific study sites.

Spatially distributed hydrological models are particularly advantageous for modelling soil and land management techniques (see also the review in section 1.3.1). As indicated in Table 1.2, hydrodynamic models are frequently employed for simulating interventions in Groups B and C, whereas interventions in Group A are better simulated using distributed hydrological or conceptual models. To capture the combined effects of multiple NFM interventions (Group D), direct coupled hydrological-hydrodynamic models are the preferred approach.

The impact of NFM interventions is subject to uncertainties across spatial and temporal scales, raising key questions regarding their optimal placement within large catchments and their responses to future flood events under varying rainfall intensities (Dixon et al., 2016; Dadson et al., 2017). A recent empirical study has demonstrated that both single and multiple NFM interventions can effectively increase the lag time of flood peaks (Black et al., 2021), exceeding the 20 km² scale limit for evidence available to Dadson et al. (2017) when they reviewed UK-based studies. Current evidence suggests that NFM can be implemented either independently or in combination with other flood risk management strategies, forming part of an integrated catchment flood management approach. However, most modelling studies have focused primarily on assessing the impacts of NFM interventions on locations directly downstream of the intervention sites, rather than evaluating their effects across entire catchments (Wilkinson et al., 2019; Wingfield et al., 2019; Hill et al., 2023). Considering the potential synchronisation of runoff peaks at the catchment scale, comprehensive assessments of NFM impacts on flood risk should encompass both immediate surroundings and downstream areas, as well as hydrological functions and hydrodynamic impacts.

Upscaling small-scale NFM interventions to evaluate their performance in downstream catchments introduces additional challenges, including uncertainties mentioned above and related to synchronisation effects in larger catchments. A minimum grid size of 5 m is often required for spatially distributed and 2D modelling to meet the resolution demands of certain NFM interventions, such as leaky dams, which require fine-scale implementation (Addy and Wilkinson, 2019). However, conducting high-resolution modelling at large catchment scales is constrained by computational capacity and model applicability (Hill et al., 2023). Decision-makers and stakeholders have expressed a strong

need to identify the optimal location and scale of future NFM features to maximize flood risk reduction benefits (Wells et al., 2020; Black et al., 2021). Consequently, for large catchments, addressing uncertainties in the modelling process and resolving epistemic uncertainties associated with adjusting model configurations and parameters to explore the potential scope of NFM interventions are crucial areas for further research. Additionally, there is limited evidence evaluating reductions in inundation extent and depth as measures of NFM effectiveness (Lane, 2017; Addy and Wilkinson, 2019; Kay et al., 2019; Chapter 2). These aspects need to be incorporated into model outputs to enhance NFM planning and provide stakeholders and decision-makers with a clearer understanding of its effectiveness (Kumar et al. 2021).

1.3 Hydrological, hydrodynamic and coupled modelling approach

Flood process simulations typically employ hydrological models, hydrodynamic models, or coupled hydrological-hydrodynamic models. This section provides a critical review of the principles, characteristics, strengths, limitations, and application contexts of each model type, with the objective of identifying the most appropriate modelling approach for evaluating the effectiveness of NFM interventions.

1.3.1 Hydrological modelling

Compared to empirical and conceptual models, physically based models mathematically represent hydrological processes, typically including subsurface flow in saturated and unsaturated zones, overland flow, infiltration, and evapotranspiration (Pechlivanidis et al., 2011). These models often require extensive parameterization of the physical characteristics of the catchment but are less reliant on large datasets of hydrological and meteorological observation (Abbott et al., 1986a, b). However, they generally employ average variables and parameters at grid or element scales that are larger than the scale at which hydrological processes occur. This limitation often leads to scaling issues, where model parameters fail to accurately capture the heterogeneity within a catchment (Pechlivanidis et al., 2011).

Distributed models address these challenges by incorporating spatial variations of physical processes as predictions, enabling simulations of spatially heterogeneous

scenarios (Huisman et al., 2009; Smith, 2012). The spatial resolution of distributed models can be tailored to the requirements of specific scenarios, such as using finer resolutions in urban areas compared to rural regions (Salvadore et al., 2015). Distributed models also provide insights into multiple internal state variables, such as water table levels, soil moisture, and channel flows across the river network. However, the representation of these state variables with improved spatial resolution may result in problems of overparameterization and equifinality (Beven, 1993; Das et al., 2008; Andréassian et al., 2012). More complex model structure and spatial resolution means there are higher parameter calibration requirements, which creates difficulties for model calibration and uncertainty assessment. In contrast, lumped models avoid these issues by using predefined and rigid parameter sets, albeit at the expense of flexibility and detailed spatial representation (Arsenault et al., 2014; Willems et al., 2014).

Semi-distributed models offer a compromise by incorporating spatially distributed catchment characteristics while representing hydrological processes in a lumped manner at the Hydrological Response Unit (HRU) scale (Beven, 2011). These models are derived from lumped conceptual frameworks but introduce a spatial dimension based on hydrological similarities within the catchment. By aggregating grid elements with similar hydrological responses, semi-distributed models simplify distributed models, reducing computational demand and easing implementation.

Distributed models can be further classified based on their structural approach, including those using storage, grid, or hillslope elements. For instance, the Probability Distributed Moisture (PDM) model simulates rainfall and inter-storm dynamics using multiple storage elements (Moore and Clarke, 1981). Grid-to-Grid (G2G) models extend PDM by employing a grid-based routing method to explore spatial distribution (Bell et al., 2007, 2009). Alternatively, models like TOPMODEL emphasize the role of catchment topography and soil properties in hydrological responses to precipitation, employing a hillslope-based approach (Beven et al., 1995). The spatially distributed version of TOPMODEL (SD-TOPMODEL) extends the original TOPMODEL framework by incorporating a grid-based routing method and a dynamic overland flow module (Gao et al., 2015). This enhancement enables the use of grid-based inputs and outputs with

explicit physical interpretations. Table 1.4 presents a comparative overview of various hydrological models, highlighting their advantages and disadvantages.

Conceptual models are limited in their ability to represent spatial heterogeneity, while distributed models often lack a framework grounded in hydrological theory. Semi-distributed models, which integrate spatially continuous simulations with theoretical hydrological processes, address this gap and have become widely used for catchment-scale rainfall-runoff predictions (Beven, 2011). Given the focus of this thesis, the semi-distributed conceptual hydrological model emerges as the most appropriate choice for investigating NFM effectiveness on flood mitigation. This approach is particularly advantageous for analysing interventions in upstream hillslope areas, where SD-TOPMODEL excels in capturing the hydrological dynamics and spatial variability critical to effective NFM assessment.

Table 1.4. Comparison of different example hydrological models, including model features, application, and advantages and disadvantages

Model	Model type	Data requirements	Key parameters	Application scenarios	Advantages	Disadvantages	Key references
MIKE SHE	Distributed physically based	Time-series of meteorological inputs. Time-series of output variables for testing the model. Property data for characterizing the basin (soil, vegetation, topographic and sediment characteristics).	Saturated hydraulic conductivity. Function relationship between unsaturated hydraulic conductivity and soil moisture deficit.	Land use and land cover change; climate change; soil, sediment, and dissolved substance transport.	Complete integration of surface and subsurface water. Independence on long-term data gauge. Clear physical meanings.	Require numerous specific hydraulic properties. Over-refined physically based modules with complex algorithms of hydrological processes.	Refsgaard et al., 2010 Ma et al., 2016
SHETRAN	Distributed physically based		Strickler resistance coefficient. Ratio of actual evapotranspiration to potential evapotranspiration at field capacity.		Good coupling of surface and subsurface water system with strictly physical basis.	Overparameterization in site-based model application. Require numerous measured data to calibrate model parameters.	Bathurst et al., 2006 Op de Hipt et al., 2019
Hydro-GeoSphere	Distributed physically based	Precipitation. Digital elevation. Soil property data. Land use data.	Leaf Area Index (LAI). Root and evaporation distribution function. Canopy storage.	Land cover and vegetation change; headwater and storage dynamics.	Complete integration of surface and subsurface flow systems. Graphical user interface.	Require long-term meteorological and hydrological data for model calibration and validation.	Cornelissen et al., 2016
TOPMODEL	Lumped/ semi-	Time-series of precipitation and	Soil-topographic index. Soil storage deficit.	Hillslope rainfall-runoff process; distributed	Represent dynamics of the saturated and unsaturated zone.	Based on assumptions without strictly physical basis.	Beven and Kirkby, 1979

	distributed conceptual	potential evapotranspiration. Digital elevation.	Channel routing wave velocity.	catchment-scale forecasting.	Wide applications by numerous extensions and coupled with DEM.		
<i>SD-TOPMODEL</i>	Distributed conceptual	Time-series of precipitation and potential evapotranspiration. Digital elevation. Land cover types.	Water depth parameter. Soil conductivity parameter. Surface roughness parameter.	Hillslope rainfall-runoff process; land cover and vegetation change; rainfall patterns.	Fully distributed with flexible cell scale. Each cell characteristic is associated with slope, water depth and surface roughness.	Parameters used for each land cover type lack physical evidence.	Gao et al., 2015
<i>SWAT</i>	Semi-distributed conceptual	Digital elevation. Time-series of meteorological inputs. Soil property data. Land use and land cover data.	(Depend on the model application purposes)	Climate change; contaminant transport; soil erosion and sediment transport.	Numerous variable input parameters. Wide application fields. Combined with DEM and GIS techniques.	Require numerous measured data to calibrate and validate model parameters. Sensitive analysis and uncertainty analysis for numerous parameters are necessary.	Arnold et al., 2012
<i>HBV</i>	Lumped conceptual	Time-series of areal precipitation, temperature, and potential evaporation.	Recession coefficient. Soil storage. Threshold for reduction of evaporation.	Ungauged catchments; climate change.	Independence on spatial-distributed measurements. Require relatively less data and run fast.	Not clear physical meanings. Lack of representation of spatial heterogeneity. No integration between surface and subsurface flow systems.	Seibert, 2000

1.3.2 Hydrodynamic modelling

Hydrodynamic models simulate fluid movement based on data derived from physical experiments or mathematical formulations. Commonly applied to flood modelling are 1D and 2D models. The 1D hydraulic model simplifies the water channels into a series of cross sections and then simulates flow rate, discharge, water depth and velocity using the Saint-Venant equations. These equations consist of a continuity equation to calculate input, storage, and output within the channel, and a momentum equation to represent flow dynamics in relation to pressure, effectively simulating backwater effects (De Saint-Venant, 1871, cited in Saleh et al., 2013; Liggett, 1975; Bathurst, 1988; Becker and Serban, 1990).

Compared to the simplicity of 1D models, 2D models incorporate a wider range of parameters, including roughness, topography, infiltration, permeability, and surface obstructions. These models simulate hydraulic movement across both channels and floodplains. Most commonly, 2D hydrodynamic models are based on the 2D shallow water equations, which are widely used in flood inundation modelling. Variants of 2D shallow water models, featuring different levels of complexity, have demonstrated high accuracy in simulating transient flow phenomena (Dee et al., 1986; Luigi and Eleuterio, 1995; Jia et al., 2002).

Table 1.5 provides examples of 2D hydrodynamic models, each employing distinct numerical solvers such as the Finite Difference Method (FDM), Finite Element Method (FEM) and Finite Volume Method (FVM). Tools like MIKE 21, TUFLOW, and Flood Modeller 2D utilize the Alternating Direction Implicit (ADI) solver (Table 1.5), originally developed from the DIVAST numerical engine in the 1980s (Lin et al., 2006). In addition to the ADI solver, Flood Modeller incorporates MacCormack-Total Variation Diminishing (TVD) and FAST solvers for specific scenarios. TELEMAC 2D uses both FEM and FVM to solve the 2D shallow water equations, while JFLOW employs the FDM (Table 1.5). Among these, the FVM is particularly advantageous for its theoretically perfect mass and momentum conservation and geometric flexibility, offering an optimal balance between computational efficiency and simplicity compared to the FDM and FEM (Caleffi et al., 2003; Néelz and Pender, 2009). The FDM is valued for its simplicity, computational efficiency, and ease of implementation, particularly when dealing with regular grid

structures. These features make FDM-based, 2D SWE models like JFLOW effective for simulating NFM interventions such as leaky dams and offline storages, where fine-scale details of flow dynamics are critical (Hankin et al., 2019). Similarly, Flood Modeller's range of solvers, combined with its ability to integrate 1D structures, allows for accurate and flexible representation of flow routing and energy dissipation around leaky dams and riparian buffer strips, which are essential for capturing the hydrodynamic impacts of these NFM measures (Jacob, 2022a, 2022b; Néelz and Pender, 2009).

Table 1.5. Examples of 2D hydrodynamic models, updated from Néelz and Pender (2009, Table 2.2)

Name	Physics	Further information on numerical method	Developer	Status	Remarks
Finite Difference Method					
TUFLOW	SWE *	ADI **	BMT-WBM	Commercial	Own 1D river and pipes solver
DIVAST	SWE	ADI	Cardiff University	Research	As part of ISIS 2D
Flood Modeller (ISIS 2D)	SWE	ADI TVD ** FAST **	Jacobs	Commercial	Own 1D river solver
MIKE 21	SWE	ADI	DHI	Commercial	As part of MIKE FLOOD
JFLOW	SWE	Explicit	JBA	Commercial	
Finite Element Method					
TELEMAC 2D	SWE		EDF	Commercial	
Finite Volume Method					
TELEMAC 2D	SWE	Harten Lax Leer-Contact & Weighted Averaged Flux	EDF	Commercial	
Others					
LISFLOOD-FP	Normal flow in x and y direction.	Explicit	University of Bristol	Research	A coupled 1D/2D hydraulic model based on a raster grid. 1D kinematic wave and vertical link.

* SWE: Shallow Water Equations

** ADI: Alternating Direction Implicit solver; TVD: Total Variation Diminishing solver;
FAST: Simplified and fast solver

1.3.3 Coupled model approach

Compared to 2D hydrodynamic models, which require substantial computational resources and time to achieve high-resolution simulations, coupled modelling effectively reduces computational demands and data requirements (Simons et al., 2014). Catchment-scale flow generation and propagation is inherently complex and using a single hydrological or hydrodynamic model may introduce limitations by excluding or simplifying certain physical processes (Table 1.4). Coupled hydrological-hydrodynamic modelling is widely employed to capture rainfall-runoff processes, overland flows, flooding dynamics, and in-channel flow interactions at the catchment scale, addressing more complex flood modelling challenges (Felder et al., 2017). It can more effectively visualize the inundation process during floods, capturing the spatial and temporal dynamics of flow velocity, discharge, and water depth, which are crucial for effective flood risk management (Liu et al., 2019).

Numerous studies on flood simulation using coupled hydrological-hydrodynamic models have demonstrated their ability to improve the physical plausibility of flood modelling while achieving a good fit with observed data (Felder et al., 2017; Liu et al., 2019; Thompson et al., 2004; Xu et al., 2022). However, challenges remain in applying coupled models. One issue is the variety of known models, which can introduce uncertainties in the construction process regarding the coupling framework and approach (Parker et al., 2013). Another challenge is the increased data requirements for parameterization due to the larger number of parameters in coupled models (Li et al., 2023). These challenges make it more difficult to apply coupled models in flood modelling. Enhancing the applicability of coupled models can be achieved by developing coupling methods that are better suited to the specific characteristics of the targeted models (Shen et al., 2024).

Mainstream coupling methods include full coupling, internal coupling, and external coupling (Morita and Yen, 2002). External coupling, the most common approach for hydrological and hydrodynamic model integration, involves running models separately and using the outputs from one or multiple models as inputs for another (Lian et al., 2007; Mejia and Reed, 2011; Nguyen et al., 2016; Nandi and Reddy, 2022). This "loose" or indirect coupling method relies on boundary conditions for integration (McMillan &

Brasington, 2007; Yu & Lane, 2011). By incorporating simulations of rainfall-runoff processes, 1D river discharge, and 2D inundation dynamics, this approach maintains satisfactory numerical accuracy while significantly reducing computational time and resource requirements compared to full-region 2D hydrodynamic models. The stepwise nature of the indirect coupling mechanism can introduce bias in the representation of flood propagation, while direct coupling between hydrological and 2D hydrodynamic models offers a more realistic simulation of flood processes (Brewer et al., 2018). Recent advancements have introduced a direct, bidirectional coupling approach, where the governing equations of hydrological and 2D hydrodynamic models are solved synchronously through a time-dependent coupling interface (Jiang et al., 2021; Shen et al., 2024).

In NFM studies, cascading modelling approaches have been used for further model integration (Hill et al., 2023). Combining semi-distributed or distributed hydrological models with 1D or 2D hydrodynamic models provides enhanced representation of in-channel flow dynamics and catchment-scale hydrology (Rodríguez-Rincón et al., 2015; Hankin et al., 2019). This approach has proven effective in realistically simulating soil and land management interventions (e.g., tree planting, hedgerows, soil aeration) alongside in-channel and off-channel interventions (e.g., leaky dams, large wood debris, runoff attenuation features) within the same model setup (Hankin et al., 2019; Hill et al., 2023). Therefore, to achieve a more realistic simulation of overland flow and inundation processes influenced by NFM interventions, the direct coupling of distributed hydrological models with 2D hydrodynamic models represents the most effective approach.

1.4 Research gaps and questions

From the reviewed literature on NFM and modelling approaches, three key research gaps have been identified:

1. Research gaps and variations in NFM effectiveness at larger catchment scales and higher rainfall intensities.

The first gap pertains to limits regarding the effectiveness of NFM in reducing flood peaks and delaying peak timing at larger catchment scales and under higher rainfall intensities (Blanc et al., 2012; Lane, 2017; Dadson et al., 2017; Kay et al., 2019; Black et al., 2021; Hill et al., 2023). For this research, larger catchments are defined as systems exceeding 50 km², and rainfall intensity is considered up to a 200-year return period. There is a pressing need to quantitatively summarise and evaluate the influencing factors and flood mitigation effects reported in existing NFM studies.

2. Uncertainties in the effectiveness of single or multiple NFM interventions under different storm characteristics and catchment conditions.

The second gap addresses the uncertainties arising from the designed combination of multiple NFM interventions, as well as the variability in storm characteristics and antecedent catchment conditions on flood mitigation performance (Lane, 2017; Kay et al., 2019). This issue is critical for assessing the sustainability and long-term benefits of NFM interventions under storm events with various rainfall intensities, shapes and moving directions. More evidence, particularly from modelling, is needed to support large-scale implementation of NFM within catchments and its integration with other flood risk management strategies.

3. Lack of evidence regarding the effectiveness of NFM in mitigating floods through inundation processes.

The third gap highlights the lack of scientific studies examining the overland flow processes in the flood mitigation effects of NFM, particularly in terms of inundation extent and depth (Hankin et al., 2019; Ferguson and Fenner, 2021). Such information is crucial for stakeholders and landowners to understand the impacts of interventions on flood risk. Current modelling efforts predominantly focus on verifying the hydrological impacts of interventions (e.g. infiltration, interception, and flow peaks). However, this narrow focus restricts the scale and applicability of NFM studies (Wilkinson et al., 2019; Hill et al., 2023). Coupled modelling approaches, capable of simulating the impacts of multiple interventions on inundation processes at larger spatial scales, present a promising solution to these limitations.

Based on these research gaps, the following research questions (RQs) are proposed:

RQ1: What insights can a quantitative meta-analysis of NFM studies provide regarding the effectiveness of NFM interventions from a global and national perspective?

RQ2: How does the combination or spatial configuration of multiple NFM interventions alter overland flow responses to different rainfall events under varying catchment antecedent conditions at larger scales, as assessed using modelling approaches?

RQ3: How can coupled modelling approaches be applied to simulate NFM structural surface interventions and evaluate the changes in inundation within downstream urban areas resulting from multiple NFM interventions at larger catchment scales?

1.5 Overview of methodology

This section outlines the methodology employed for the quantitative review (RQ1), hydrological modelling (RQ2), and coupled hydrological-hydrodynamic modelling (RQ2&3) to address the three RQs. The selection of the study site and modelling approaches are justified, and the specific methods are described. Detailed methodologies are presented in the respective chapters where they are applied. Finally, the overall structure of the thesis is summarized at the end of this chapter.

1.5.1 Quantitative review approach

A quantitative review was conducted to address RQ1, extracting data from published studies. Studies related to NFM and NBS published between 1991 and 2022 were identified using ISI Web of Science and Google Scholar. The search included journal articles, books and theses containing relevant topics and keywords. An initial screening process excluded studies not directly related to flood impacts and NFM/NBS, ensuring the further categorisation focus on pertinent literature. The identified studies were categorized into three main groups: NFM Basis, NFM Global, NFM Europe. Word frequency analysis of titles and abstracts of articles within each category was presented to examine the spatial and temporal distribution of NFM/NBS studies and to identify global trends. A meta-analysis was conducted by extracting valid information and data

from the literature to investigate the impact of the underlying variables in the study on the effectiveness of NFM.

1.5.2 Modelling approach

As discussed in section 1.2, a conceptual hydrological model with spatially distributed parameters is more suitable for simulating the effectiveness of NFM interventions on flood mitigation. Additionally, a 2D hydrodynamic model was selected for inundation modelling due to its capability to represent surface structural changes and simulate the dynamic processes of surface flow.

The Upper Aire catchment to Gargrave (~81.4 km²), an upland catchment in northern England, was chosen as the study site for modelling. This area was selected because it hosts extensive NFM implementation. The choice of study catchment was also constrained by availability of reliable river gauging data, which is critical for robust model calibration and validation. In this thesis, SD-TOPMODEL is used as the hydrological model, Flood Modeller 2D as the hydrodynamic model, and a direct coupling approach to integrate the two models effectively was employed.

a) SD-TOPMODEL

SD-TOPMODEL is a fully distributed version of the original TOPMODEL, a rainfall-runoff model (Gao et al., 2015). It scales grid cells based on the original TOPMODEL and used the Darcy-Weisbach equation to calculate the surface water flow velocities for each grid cell according to slope, water depth and surface roughness (Gao et al., 2016). The grid-based algorithm provides the model with spatially distributed characteristics, allowing parameters to vary in each grid cell across the catchment. Key parameters include the scaling soil depth parameter m for subsurface flow, the soil conductivity parameter K_s and surface roughness parameter K_v . These spatially flexible parameters enable the model to account for variations in land cover and soil saturation conditions, giving it spatio-physical significance. Consequently, compared to other hydrological models, SD-TOPMODEL is an optimal choice for understanding how soil and land cover/land use changes influence rainfall-runoff processes during flood events (Table 1.4).

b) Flood Modeller 2D

Flood Modeller 2D (formerly ISIS 2D) is a commercial modelling software with an intuitive user interface. The 2D hydrodynamic model is ideal for studying flood inundation processes, striking a balance between computational efficiency and the ability to represent complex surface structures. Unlike 3D hydrodynamic models, which require high computational power, or 1D models, which oversimplify inundation processes, Flood Modeller 2D provides detailed simulations of surface structures, including flood walls, leaky dams, and water storage areas (Jacob, 2022a). Compared to other 2D inundation models, such as JFLOW (Bradbrook, 2006), TUFLOW (Syme, 2001) and LISFLOOD-FP (Bates and De Roo, 2000), Flood Modeller 2D offers several advantages:

- Solver options: It includes three Finite Difference Methods (FDM) - Alternating Direction Implicit (ADI) solver, Total Variation Diminishing (TVD) solver and FAST solver – to accommodate different catchment scales and computational needs.
- Shape file integration: The use of manual add-in 1D structures to the model allows for precise representation of surface structures such as leaky dams, bridges, storage areas, embankments, and weirs.
- Structured mesh: Flood Modeller 2D uses a structured mesh for discretisation, making it compatible with spatially distributed hydrological models through runoff discharge linking.

c) Coupled model

To model NFM interventions in the Upper Aire catchment to Gargrave, SD-TOPMODEL and Flood Modeller 2D are used in a complementary manner. SD-TOPMODEL simulated soil and land cover/land use changes in the upstream areas of the Upper Aire catchment, capturing interventions such as hedgerow planting, woodland planting, and soil aeration. Flood Modeller 2D has two functions: one is for modelling leaky dams and storage areas in the upstream catchment, and another is for simulating flood inundation in the downstream areas (Gargrave town). Each model addresses specific limitations of the other: SD-TOPMODEL lacks the ability to accurately represent engineered structures and artificial geomorphology, while Flood Modeller 2D does not effectively model subsurface water movement, infiltration, and saturated-excess overflow processes. By coupling these two models, it becomes possible to model all types of NFM interventions in the Upper Aire catchment, providing a comprehensive representation of NFM effectiveness on flood mitigation.

1.5.3 Coupling approach

The coupling of SD-TOPMODEL and Flood Modeller 2D is achieved through the integration of their runoff at the same timestep. The runoff outputs from SD-TOPMODEL are used as inputs for overland flow in Flood Modeller 2D. Within Flood Modeller 2D, the shallow water equation calculates the impacts of elevation changes, incorporating human-made constructions and corresponding surface roughness modifications. However, it excludes rainfall-runoff and infiltration processes, as these are fully simulated within SD-TOPMODEL. This constitutes a one-way coupling approach, particularly suitable for upland catchments with steep topography, where surface runoff from precipitation flows downstream following the slope direction, consistent with the conceptual basis of TOPMODEL. Most rainfall-runoff and infiltration processes occur within the sub-catchments and are predominantly driven by surface runoff after convergence to the main channel. Consequently, the flow entering the main channel is assumed to be the sum of subsurface and surface runoff from these sub-catchments. The key advantage of this coupling approach is improved computational efficiency, as it simplifies the integration process. It also enables the 2D hydrodynamic model to simulate larger catchment scales effectively. However, a limitation of this approach is its inability to capture potential backwater effects that may arise following overbank flow at confluences between tributaries and the main river channel, as no feedback is incorporated from Flood Modeller 2D to SD-TOPMODEL.

1.5.4 Generic methods for parameterisation and calibration

To determine the values of three key parameters for representing different land cover types and NFM interventions, empirical data were collected from research publications. For example, Bond et al. (2020) provided data on saturated hydraulic conductivity parameters for various grazing land covers. In this work, model results applied with different parameter sources from publications, were tested and compared. For Flood Modeller 2D, surface roughness values were parameterised using Manning's n values (Chow, 1959). These values provided a basis for representing the influence of surface characteristics on flow resistance.

To address modelling uncertainty, the Generalised Likelihood Uncertainty Estimation (GLUE) method was used for parameter calibration. GLUE, introduced by Beven and

Binley (1992, 2014), is a statistical technique widely used in hydrology to quantify the uncertainty of model predictions. It identifies the most likely parameter sets by repeatedly resampling parameters in the empirical ranges and evaluating their performance. The performance of GLUE is assessed using dot plots. The key advantage of GLUE lies in its consideration of parameter interactions, rather than focusing on individual parameters in isolation. This approach mitigates uncertainty arising from equifinality—the phenomenon where multiple parameter combinations yield equally plausible outcomes (Beven and Freer, 2001; Beven, 2006). Differences in parameterisation and calibration methods between SD-TOPMODEL and Flood Modeller 2D are addressed within the respective research chapters, where detailed methodologies are provided.

1.5.5 Model characteristics, parameters, and setup

SD-TOPMODEL:

- Model preparation:

SD-TOPMODEL was configured for the research catchment to simulate various rainfall events, real land cover types and existing soil and land cover/land use NFM interventions. High-resolution (5 m) DTM data were prepared using ArcGIS by clipping the DTM to catchment boundaries and converting it into ASCII files with data processing tools. Rainfall and river discharge data were collected and prepared as input files. Specific model configurations were established by setting up the .par file and params.txt for simulations.

- Model processing and production:

Model 0 (baseline model) was developed using the three key parameters: m , K_s and K_v . These parameters were assigned specific values within empirical ranges across grid cells to represent different land cover types in the catchment, based on UKCEH Land Cover Map 2015. The GLUE approach was used to analyse the influence of model parameters on outputs by comparing model results with observed discharge data. Model performance was evaluated using the Nash–Sutcliffe model efficiency coefficient (NSE), flood peak fits and correlation analysis as metrics, which provided insight into the sensitivities and uncertainties of model parameters. After calibrating the parameters for the land cover model, simulation results for various rainfall events were validated against

observed data. Existing NFM interventions were subsequently imported into the model, employing the same parameter calibration process. Additional NFM intervention combinations, consisting of various groups and spatial configurations of intervention types detailed in Table 1.1, were tested under seven real rainfall events with varying return periods to address RQ2.

- Model outputs:

The outputs included hydrographs from Model 0, the land cover model and various NFM scenario models. These hydrographs illustrated total runoff, overland flow, and subsurface flow volumes at 15-minute timesteps.

Coupled SD-TOPMODEL and Flood Modeller 2D:

- Model preparation:

A 5 m resolution DTM was prepared to represent the topography of the catchment and the geomorphology of river channels. Modelled total runoff outputs from SD-TOPMODEL were configured as inputs for Flood Modeller 2D, maintaining consistent scale and resolution. Manning's n values were applied as surface roughness parameters in Flood Modeller 2D to represent the roughness variations among river channel, floodplains, riparian buffer strips and leaky dams. Surface roughness parameters were calibrated based on GLUE method for the study catchment.

- Model processing and production:

Elevation changes and artificial infrastructure, such as leaky dams, riparian buffer strips, and water storage areas, were manually incorporated into the model. These structures were added as 2D items through shapefiles containing height and width attributes. The coupled SD-TOPMODEL and Flood Modeller 2D simulations were run for all NFM scenarios, assessing their flood mitigation impacts under real rainfall events with varying return periods, addressing RQ3.

- Model outputs:

Outputs included hydrographs, inundation maps showing extents and water depths, animations illustrating overland flow dynamics, and comparative analyses of scenarios, particularly emphasizing differences between cases with and without NFM interventions.

1.6 Summary of the thesis

Using the methodology described above, the RQs identified in Section 1.4 are explored and answered in subsequent chapters. An overview of the thesis is given below.

Chapter 2: A quantitative review of natural flood management research. This chapter examines 454 NFM-related articles over 30 years, identifying shifts in research focus from localized mitigation to catchment-wide strategies and from wood-related studies to broader ecosystem services. Content analysis highlighted the dominance of modelling approaches for large-scale catchment research. Contrary to earlier reviews suggesting reduced NFM efficacy at larger scales and higher rainfall intensities, no strong empirical evidence supported these claims, though studies at large scales remain underrepresented. Highlighting the need for integrated, catchment wide NFM networks, this chapter emphasizes the potential for scalable interventions.

Chapter 3: Use of Spatially Distributed TOPMODEL to assess the effectiveness of diverse natural flood management techniques in a UK catchment. Using Spatially Distributed TOPMODEL (SD-TOPMODEL), this chapter modelled instream and terrestrial NFM interventions, including woodland planting, soil aeration, floodplain restoration, and hedgerow planting. Enhanced grid-based modelling allowed simulations for a 200-year return period flood across an 81.4 km² catchment at 5 m resolution. Model calibration achieved a NSE up to 0.93 for flood peak simulations. Results indicated NFM interventions were particularly effective during single-peaked storms and dry pre-event conditions. Combined interventions proved more effective and resilient than single ones, reducing flood peaks by 4.2% to 16.0%. These findings highlight the value of integrated NFM strategies for enhancing flood resilience.

Chapter 4: A coupled hydrological-hydrodynamic modelling approach for assessing the impacts of various natural flood management interventions on downstream flood hazards. This chapter assessed high-flow impacts using a coupled model integrating SD-TOPMODEL with a 2D hydrodynamic model (Flood Modeller 2D). Synchronising model outputs at river junctions ensured accurate representation of flood dynamics. Results

revealed leaky dams delayed flood peaks more effectively than reducing discharge, with impacts shaped by tributary characteristics such as channel gradient. NFM scenarios demonstrated consistent flood mitigation benefits, including reduced peak discharge and inundation extent. However, maximum woodland scenarios increased inundation due to unintended synchronisation of flood wave arrivals. This chapter underscores the value of coupled models for evaluating NFM strategies and calls for further validation at larger catchment scales. By exploring interactions between interventions and catchment dynamics, it informs optimized flood risk management and policy development.

Chapter 5: Synthesis and conclusions. This chapter discusses the outcomes of Chapters Two, Three and Four, relating key conclusions back to the overarching RQs and discussing future research recommendations and limitations of this research.

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Chapter 2. A quantitative review of natural flood management research

2.1 Abstract

Natural flood management (NFM), a subset of nature-based solutions (NBS) in catchment management, attempts to utilise and mimic natural processes in the landscape to reduce flood hazards, and it has been widely applied across Europe and other regions. Despite the wide use of NFM techniques, there is a lack of quantitative evidence for the effectiveness of NFM interventions in flood reduction. This paper examined 454 NFM relevant articles over the past 30 years, and the data they contain. Word frequency and cluster analyses showed changing trends and associations among nature-based flood mitigation research topics, including shifts from localised flood mitigation to catchment-wide flood management strategies, and from wood-related studies to a broader assessment of ecosystem services. Content analysis was conducted on literature directly related to NFM and NBS, revealing that research in large-scale catchments continues to be dominated by modelling approaches. While past reviews have suggested that increased catchment scale and rainfall intensity may diminish the effectiveness of NFM, we did not find strong empirical evidence (field monitoring and modelling) for this in our systematic review, although research at large catchment scale is still lacking. By assessing the confidence in NFM studies, the paper concludes that integrated understanding of a network of combined NFM interventions at a large catchment scale is necessary for future nature-based flood mitigation strategies.

2.2 Introduction

Hard engineering solutions to flooding are often difficult to justify and resource across large parts of river basins and flood management is shifting from defence to ecosystem-based adaptation (Iacob et al., 2017). Natural flood management (NFM), a subset of nature-based solutions (NBS), attempts to utilise and mimic natural processes in the landscape to reduce flood hazards (Cooper et al., 2021; Dadson et al., 2017). NFM interventions are considered to provide additional co-benefits including enhancing ecosystem services and improved cost effectiveness of engineered flood management measures (Bark et al., 2021; Dadson et al., 2017). Enhancing temporary and permanent

catchment water storage capacity by reforestation, offline storage areas, online (instream) storage via leaky dams, blocking ditches or gullies, changing land cover and soil management, seeks to delay flood peak time and reduce discharge during a rainfall event (Bond et al., 2022; Gao et al., 2016; Ghimire et al., 2014; Goudarzi et al., 2020; Grayson et al., 2010; Gunnell et al., 2019; Marshall et al., 2009; Nicholson et al., 2012; Nicholson et al., 2020; Quinn et al., 2013; Shuttleworth et al., 2019; Wilkinson et al., 2019). Land cover changes and soil aeration techniques adopted as part of NFM aim to increase soil porosity and encourage infiltration to slow water travel times to main channels (Alaoui et al., 2018; Dixon et al., 2016; Franklin et al., 2007; Marshall et al., 2014; Murphy et al., 2020; Palmer & Smith, 2013; Wahren et al., 2012). Some land cover changes seek to increase surface roughness to reduce overland flow velocity and increase peak flow lag times (Archer et al., 2013; Bond et al., 2019; Holden et al., 2008; Roni et al., 2015).

The impact of NFM interventions on flooding at different scales is unclear (Black et al., 2021; Fennell et al., 2022; Goudarzi et al., 2021; Hankin et al., 2020; Lane, 2017). Small catchments, in particular, have greater spatial and temporal heterogeneity in response to rainfall events (Merot, 2003). NFM benefits to flood reduction observed at smaller scales may also not translate to larger scales (Dixon et al., 2016; Hankin et al., 2021; Wilkinson et al., 2019). For example, simulation of different NFM land cover scenarios in the Rhine basin showed that scenarios that have a significant impact in a sub-catchment do not necessarily have an impact in a larger catchment (Hurkmans et al., 2009), and some studies have concluded that there is no evidence to support the idea that land-cover changes and river restoration measures have the same flood mitigation effects from the plot to hillslope and catchment scales (O'Connell et al., 2007; Rogger et al., 2017; Rowinski et al., 2018).

Despite the wide use of NFM techniques, the effectiveness of NFM interventions in flood reduction lacks quantitative evidence (Dadson et al., 2017; Lane, 2017; Wilkinson et al., 2019; Wingfield et al., 2019). To enhance confidence in implementing NFM interventions for flood mitigation, it is imperative that a quantitative synthesis of NFM research literature be used to assess NFM impacts on flood characteristics, including flood peaks and duration. The aim of this paper is to categorise NFM-related studies and determine

the nature of the evidence for NFM in impacting flow peaks and lag times. We screened and categorised research outputs according to specific interventions, the rationale of the interventions, and study regions. We quantitatively analysed word frequencies in the literature to identify research trends on NFM-related topics. We also undertook content analysis and quantitative analysis of numerical results to determine what has been reported in modelling and fieldwork studies at different scales in terms of flood peak reduction and lag time changes. Thus, our paper generated a confidence evaluation for distinctions between study methods, type of interventions, catchment size and rainfall intensity to help determine impact and effectiveness of NFM on flood mitigation.

2.3 Data and methods

2.3.1 Literature search

We constructed a dataset of NFM-related techniques and research. To capture journal articles containing potentially related topics, we searched ISI Web of Science (WoS) from 1 January 1900 to 14 November 2022, search terms as shown:

TS= ("flood" AND ("river*" OR "catchment*" OR "river basin*" OR "watershed*") AND ("natural flood management" OR "work* with natur*" OR "nature based solution*" OR "nature-based" OR "build* with nature" OR "slow the flow" OR "leaky dam*" OR "logjam*" OR "woody dam*" OR "in-stream wood*" OR "leaky barrier*" OR "woody debris*" OR "offline storage area*" OR "re-meander*" OR "embankment remov*" OR "reconnect*" OR "soil and land management" OR "soil aeration" OR "sub-soil*" OR "woodland management" OR "floodplain woodland*" OR "riparian woodland*" OR "afforest*" OR "reforest*" OR "grassland management" OR "unimproved grassland*" OR "peatland* restoration" OR "hedge*" OR "headwater drainage" OR "runoff attenuation feature*" OR "grip block*" OR "gully block*" OR "ditch block*" OR "buffer strip*"))*

This yielded 1561 papers from 1991 to 2023 (one paper available in November 2022 was formally published in a journal issue in 2023) which included peer reviewed manuscript articles, conference papers and book sections. We also identified 132 relevant references that were not found on WoS via Google Scholar, including articles, books, and theses.

Studies focused on biology, zoology, water quality, carbon, and wildfire, which did not cover flood impacts were excluded, resulting in a total of 1335 references remaining in the dataset for further screening and categorisation (Figure 2.1).

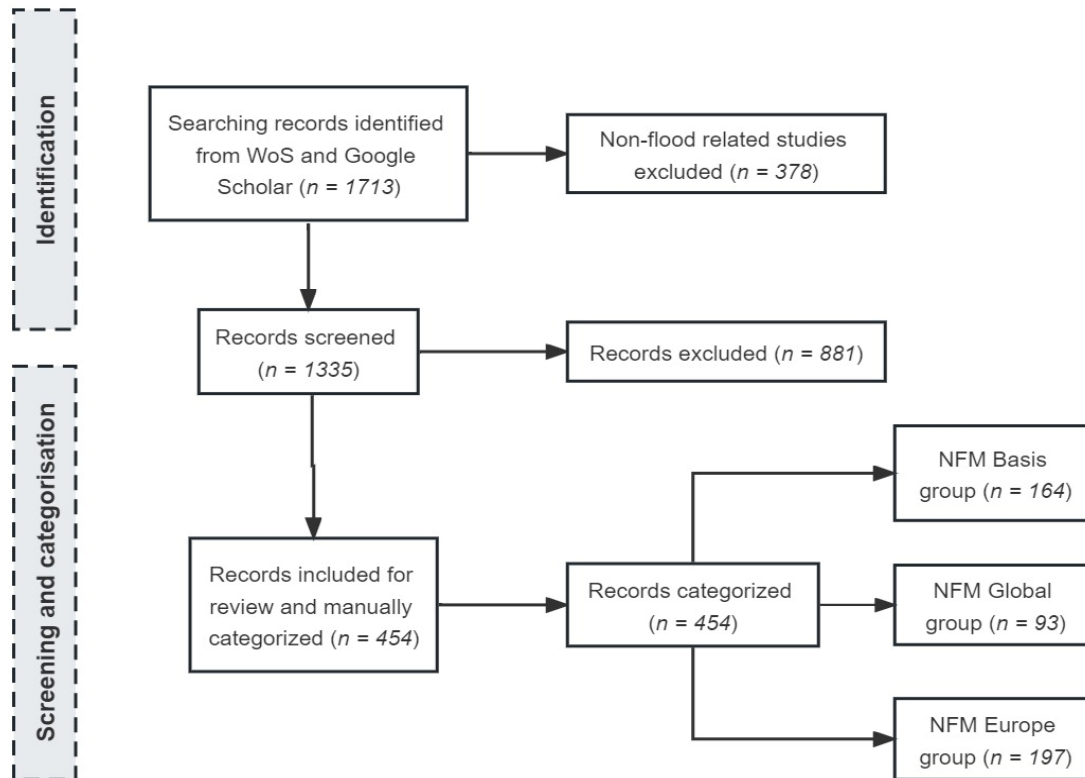


Figure 2.1. Flow diagram of the literature search, screening protocol and categorisation

2.3.2 Literature classification

After excluding 881 non-NFM related articles, each article was screened and manually categorized into one of three main categories (Figure 2.1): 1) 'NFM Basis' group (164 articles), which represents references focussed on the basic principles of NFM or NBS techniques, but which did not specifically use the terms NFM or NBS. These sources typically included related research on the role of soil characteristics, vegetation, geomorphology, and landscape restoration in affecting runoff generation processes in river catchments during rainfall events; 2) 'NFM Global' group (93 articles). This group represents journal articles and conference papers working at sites outside of Europe referring directly to or mentioning NFM or NBS for flood protection, catchment runoff management or ecosystem services benefits; 3) 'NFM Europe' group (197 articles). These sources were European specific research (including UK) that directly mentioned

or utilized NFM & NBS concepts and techniques, including modelling and field research. The dataset of 454 literature was also classified into regions based on the research locations of the studies for spatial analysis, which included: Europe (excluding UK), United States, United Kingdom, Canada, Oceania, China, Asia (excluding China), Africa, South America, and global scale studies.

2.3.3 Quantitative analysis

Analysis of words in titles and abstracts was undertaken to assess the main NFM study topics among the three literature groups - NFM Basis, NFM Global and NFM Europe - during the period 1991–2022 using word frequency and hierarchical clustering analysis. A quantitative analysis of reported information including catchment size, rainfall intensity and flood mitigation effects reported in 197 articles within the NFM Europe group was undertaken. The NFM Europe group shared similar nature-based techniques and measures for flood mitigation, and contained similar implementation, modelling and experimental data and results of these techniques and measures, making articles within the NFM Europe group comparable so that confidence could be assessed to the same degree.

2.3.3.1 Word frequency and cluster analysis

Word frequency and hierarchical clustering analysis of word content in titles and abstracts were performed using the 'quanteda' and 'rainette' packages in R (Barnier, 2023; Benoit et al., 2018). Wordclouds were constructed using the 'quanteda.textplots' package in R based on the word frequency of each literature group (Benoit et al., 2018). The 'rainette' method used in this study was developed from the 'Reinert' method (Barnier, 2023; Reinert, 1983). Hierarchical clustering groups data samples by building a hierarchy of clusters. The simple clustering method by 'rainette' is a divisive (top-down) hierarchical clustering applied to a document-term matrix. After removing symbols, English stop words (e.g., an, or, the), and other distractions in the content, such as publisher information, we identified four main clusters via the Rainette method (Barnier, 2023), based on words that occurred at least 15 times. We computed χ^2 values of the grouped matrix and kept the grouping which corresponds to the highest χ^2 values, as χ^2 values are an indicator of the estimated 'distance' between two clusters regarding their

term distributions: the higher the value, the more different the two clusters are from each other and vice versa (Barnier, 2023). Each segment was paired and a χ^2 value was calculated between them and retained in the cluster whose χ^2 values are at a similar level. This process was repeated in the grouped array until there was no reassignment to make the χ^2 higher. Next, we applied hierarchical clustering analysis for NFM Europe to determine any change of topics between two different periods (2006-2018 and 2021-2022). These periods were chosen so that there was an equal number of articles (76 articles) in each group, which means there is a similar chance of words and topics occurring.

2.3.3.2 *Quantitative content analysis*

To understand the confidence in the effectiveness of the different NFM or NBS techniques, NFM Europe papers were investigated through the full text and then were categorised according to their purpose. The categorisation was based mainly on the location of the measures (offline and online), and the two different impacts on surface flow during a rainfall event: increasing water storage capacity and reducing water velocity. Then, articles in NFM Europe were separated using intervention types, resulting in eight separate groupings by NFM techniques plus subgrouping by UK or European study location (Table 2.1).

We constructed four indicators (flood reduction and delay, the exact value of reduction, researching multiple catchment sizes, and researching multiple rainfall intensities) to understand the confidence level of each subgroup. Among the eight subgroups for the UK and Europe separately, the number of papers investigating or reporting any of these four indicators was counted in each subgroup. The number of papers was calculated as a percentage of the total number of papers in each subgroup. Weight of confidence was evaluated as low (33rd percentile), medium (33rd–66th percentile), and high (66th percentile) according to the percentage within each subgroup. Further details are provided in Appendix A2.

For content analysis, papers which recorded exact flood reduction or delay values were classified by their research methods: modelling, fieldwork, hybrid modelling and fieldwork, and perceptual/conceptual analysis. Modelling refers to sources using

physically based or statistical modelling, while perceptual/conceptual sources focused on using perception and concept-based evidence to summarise or predict NFM benefits. Next, we extracted reported values of flood discharge reduction and peak discharge delay time, catchment sizes and rainfall intensities from the NFM Europe group. This was the only group with comparable nature-based flood mitigation interventions.

2.4 Spatial and temporal analysis of nature-based flood mitigation research

2.4.1 Spatial and temporal distribution of research topics

The total number of relevant articles per year progressively increased from 1991 onwards, but NFM Global and NFM Europe articles did not appear until 2003 and 2011, respectively (Figure 2.2a). Meanwhile, the number of articles each year in NFM Basis (articles focussed on the basic principles of NFM or NBS techniques, but which did not specifically use the terms NFM or NBS) tended to even out and decreased substantially since 2017. The spatial distribution of NFM Basis was found to be consistent with the overall distribution of three literature groups, with a notable emphasis on relevant studies in Europe, particularly in the United Kingdom (Figure 2.2b).

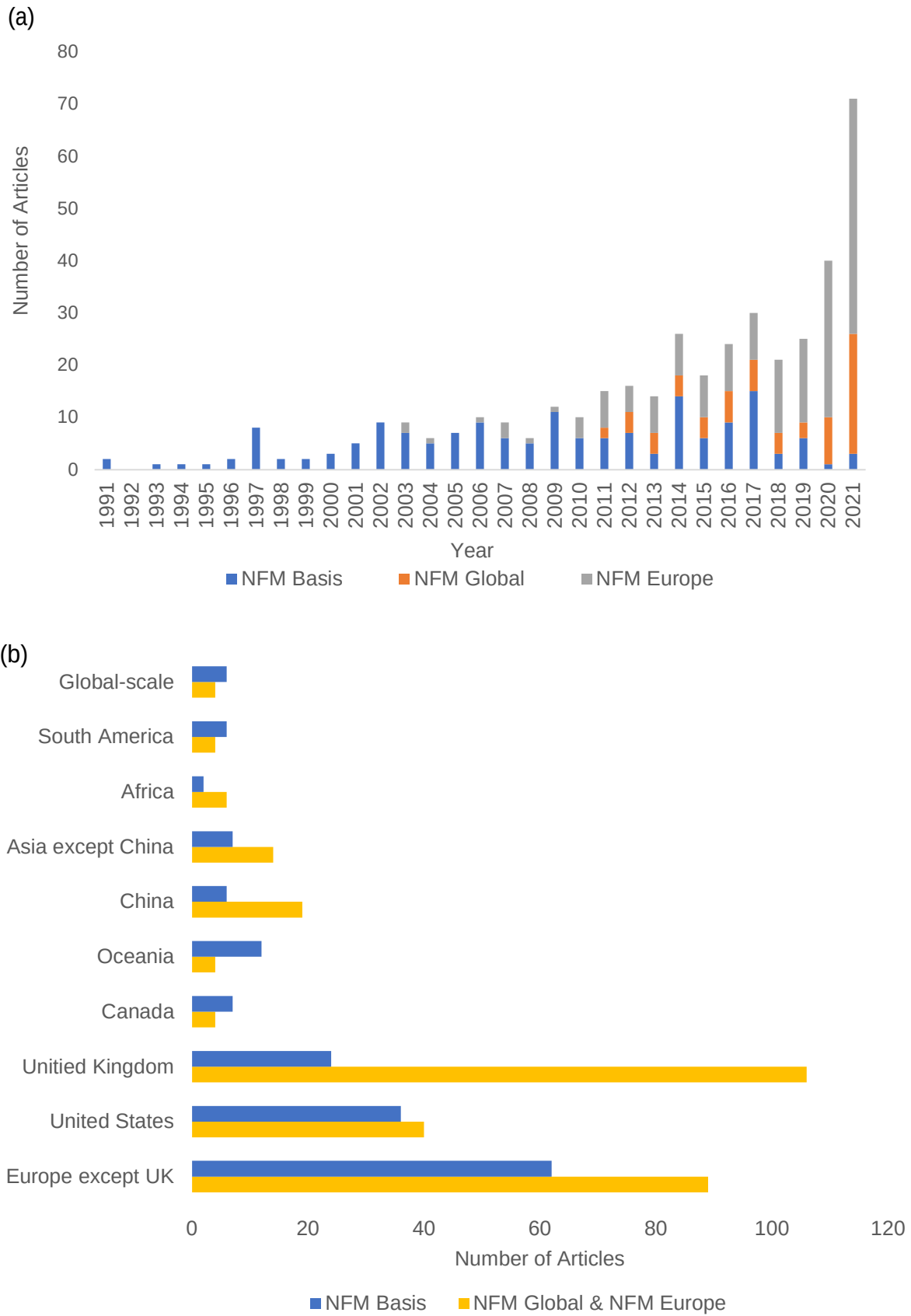


Figure 2.2. The number of published articles in NFM Basis, NFM Global and NFM Europe groups for (a) complete years in the timeseries; (b) the ten different regions.

Forest and wood-related studies were distributed evenly across time and were identified across all regions examined. Studies from 1991-2000 focused on understanding the impact of riparian woodland management and previous afforestation (Bren, 1993; Brown et al., 1997; Buttle, 1994; Decamps et al., 1998; Fahey & Jackson, 1997; Nelson et al., 2000; Piegay, 1997; Piegay & Bravard, 1997; Youngblood & Zasada, 1991). In several studies, woodland management was studied for flood mitigation purposes (Al-Weshah & El-Khoury, 1999; Bren, 1993; Fahey & Jackson, 1997), and some studies quantified the influence of forests on catchment hydrological conditions (Buttle, 1994; Cadier, 1996; Nagasaka & Nakamura, 1999; Nelson et al., 2000; Piegay, 1997; Piegay & Bravard, 1997). Studies in the US, Canada and Japan suggested that land clearing and tree harvesting as a result of agricultural and industrial practices beginning in the 1950s have significantly heightened flood risks in riparian and floodplain areas (Nelson et al., 2000; Slaymaker, 2000). For instance, a study in Japan found 22,500 ha deforestation increased flood peaks by 1.5 to 2.5-fold and shortened peak lag times by seven hours in ~300 km² catchment (Nagasaka & Nakamura, 1999). Riparian forest has been evidenced as providing flood buffering effects by enhancing hydraulic roughness during channel overflows to the floodplain and slowing flows during extreme flood events in France (Piegay & Bravard, 1997). However, the efficacy of such measures is dependent upon the location, tree species and spatial distribution of the trees in the landscape (Buttle, 1994; Nelson et al., 2000).

The term NFM did not appear in the study period 2001-2010 but there were a wide range of studies determining the hydrological impacts of land-use changes. These studies included the impact of different land-use types, scales of land-use change, seasonal characteristics of land use and field measurement versus modelling studies (Archer et al., 2010; Bormann & Klaassen, 2008; Hurkmans et al., 2009; Lopez-Moreno et al., 2006; O'Connell et al., 2007; Petty & Douglas, 2010; Vásquez-Méndez et al., 2010). The most frequent keywords in article titles and abstracts were related to reforestation and restoration research in the catchment. However, more specific topics also emerge, such as the 'improvement' of soil properties and changes to hydraulic conductivity via tree roots (Emmanouloudis et al., 2002; Nakamura et al., 2002), the changes in floodplain surface roughness associated with hedges (Cobby et al., 2003), and the use of buffer

strips to mitigate flooding (Evrard et al., 2007). Large woody debris (LWD) received more attention during 2001-2010 than 1991-2000 period, with nine articles studying their dynamics and their interactions with river discharge, sediment movement and channel regime during rainfall events (Angradi et al., 2004; Faustini & Jones, 2003; Seo & Nakamura, 2009; Webb & Erskine, 2003; Wyzga & Zawiejska, 2005). Several forest-related studies demonstrated that afforestation reduced sediment transport and volume to the river channels (Hughes et al., 2001; Keesstra, 2002; Keesstra et al., 2005; Liebault & Piegay, 2002), as well as reducing both subsurface and surface runoff to reduce flood discharge (Anderson et al., 2006; Andreassian, 2004; Bahremand et al., 2006; Lambs & Muller, 2002; Ranzi et al., 2002; Verbunt et al., 2005; Yao et al., 2009). For example, a modelling study of a large catchment in Slovakia predicted that a 50% increase in forest areas can decrease the flood peak discharge by 12% (Bahremand et al., 2006), while a monitoring study in Japan showed that the presence of a 36-year old forest reduced mean annual runoff by 11% by decreasing the runoff/precipitation ratio and increasing the evapotranspiration/precipitation ratio (Yao et al., 2009).

Articles from the period 2011-2022 were not limited to the direct effects of individual land-cover types and utilised more developed techniques for monitoring and modelling hydrological changes. The proportion of studies focusing on woodland during this period declined in comparison to the previous two decades. Instead, researchers shifted their focus towards investigating how land-cover changes have impacted runoff by influencing soil properties and surface roughness (Humann et al., 2011; Palmer & Smith, 2013; Viola et al., 2014; Zheng et al., 2012). Remote sensing, aerial photography and GIS techniques have been used extensively to observe and map long-term changes in land cover, landscape and sediment movement (Diaz-Redondo et al., 2021; Dufour et al., 2015; Frazier et al., 2012; Hajdukiewicz & Wyzga, 2019; Hlozek, 2014; Kasai et al., 2019; Keeton et al., 2017; Martinez-Fernandez et al., 2017; Miklin & Cizek, 2014; Solin et al., 2011; Zhang et al., 2014). Hydraulic and hydrological models are commonly used for hydrological simulation at various scales (Gasser et al., 2019; Keesstra et al., 2014; Munoz-Mas et al., 2017; Pattison et al., 2014; Schilling et al., 2014), while fieldwork and experiments are used for long-term monitoring at small scales (Gao et al., 2016; Kochel et al., 2016; Palmer & Smith, 2013; Solin et al., 2011). A wide range of management-based research became a major study area during the 2011-2022 period, including

investigations into post-flood LWD and the associated problems of debris blockages, which have the potential to increase flood risks (Gasser et al., 2018; MacVicar & Piegay, 2012; Ruiz-Villanueva et al., 2014; Ruiz-Villanueva et al., 2014; Ruiz-Villanueva et al., 2017; Schmocker et al., 2013; Schmocker et al., 2014). Investigations into the development of new flood mitigation strategies such as channel-floodplain reconnection and restoration (Dawson et al., 2017; Eekhout et al., 2015; Hester et al., 2016; Wohl et al., 2015) were also dominant at this time.

2.4.2 Global NFM studies

From 1991 to 2022, there was a shift in research focus in the NFM Global group from examining the impacts of floods on ecosystems, geomorphology, and hydrology to investigating the effects of land cover and landscape changes on flood characteristics. The representation and emphasis of nature-based flood risk management strategies vary across different regions of the world. Except for extensive research on upstream water conservation and restoration of wetland and forests (Fan et al., 2022; Kabeja et al., 2020; Li et al., 2022; Shih & Chen, 2021; Wu et al., 2020; Yu et al., 2015), Chinese studies have recently focused on nature-based urban flood management (Chia et al., 2020; Shen et al., 2019), such as the Sponge Cities Program, which uses urban green infrastructure and underground drainage systems to manage surface water floods (Peng et al., 2022; Qi et al., 2021; Zhai et al., 2021). Studies conducted in other regions of Asia, such as Thailand, have modelled the impact of different land-use types and combined implementation of conservation practices on catchment flood management (Jamrussri & Toda, 2017; Kheereemangkla et al., 2016; Trisurat et al., 2016). The rationale behind these measures is 'more space for water', both in the upstream and downstream areas, as well as in cities. Studies in Asia have shown that these nature-based measures provide better flood mitigation than traditional structural flood controls (Lo et al., 2021a, 2021b; San Liew et al., 2021; Sonu et al., 2022; Zheng et al., 2022). These studies highlight the variability and effectiveness of nature-based, non-structural flood measures under urban planning and climate change.

US based studies also focus on specific measures including upstream, riparian and river channel restoration for flood attenuation, via reforestation, floodplain rehabilitation, river channel re-meandering, channel-floodplain reconnection and wetland restoration

(Boughton & Pike, 2013; Federman et al., 2022; Kurki-Fox et al., 2022; Kurki-Fox et al., 2022; Lau & Franklin, 2013; Maxwell et al., 2021; Sholtes & Doyle, 2011; Worley et al., 2022). These studies support the storm water mitigation and flood resilience benefits of nature-based restoration measures and have indicated positive evaluation results both in the terms of long-term planning and cost effectiveness. A new concept called ‘Distributed Flood Attenuation’ integrating all flood management measures in the catchment, beyond those mentioned above, also covers structural and non-structural distributed water storage (Antolini & Tate, 2021; Wohl, 2021). Instream wood and logjams are commonly discussed in the US and Canadian literature. There has been a shift in research from how to avoid logjam hazards in flood events to using and replacing logjams to mitigate flooding and reduce channel erosion (Kramer et al., 2017; Wohl et al., 2016; Wohl & Scamardo, 2021).

In the period 1991 – 2022, the US had a similar number of NFM Basis and NFM Global studies, while Europe had the highest number of NFM Basis studies (Figure 2.2b). However, the number of studies focused on NFM & NBS studies was greater in the UK compared to other regions. Canada and Oceania have produced NFM Basis papers on the topic but have not produced any papers directly using NFM & NBS measures, at least as far as is reported in the literature, and possess only a limited number of relevant studies discussing the potential of ecosystem-based adaptation to flooding (Biron et al., 2018; Daigneault et al., 2016; Westbrook et al., 2020). In Africa and Asia, research hotspots on land management and NBS for flood risk reduction exist, indicating a significant potential for sustainable solutions compared to the traditional flood risk management strategies that have been employed in these regions. Furthermore, these regions exhibit significant market and research potential for sustainable solutions in the future.

2.5 Analysis of recent trends and dynamics among main study topics

2.5.1 Trends of keywords and main topics

Although the different literature groups share similar theoretical premises for solving flooding problems, the focus of studies varies. The most frequent keyword in NFM Basis was ‘vegetation’, with a concentration in locations such as ‘riparian’ or ‘mountain’ areas,

river 'channel' or 'reach' (Figure 2.3). This indicates the focus in relevant foundation studies on the hydrological impact of riparian and hillslope vegetation in the catchment (Anderson et al., 2006; Dufour et al., 2019; Keeton et al., 2017; Mosner et al., 2011; Rowinski et al., 2018). Studies in NFM Global started to focus on 'restoration', 'infrastructure' and 'wetlands' within 'river' and 'basin' in response to climate and ecosystem resilience since 2011 (Boughton & Pike, 2013; Daigneault et al., 2016; Hobbie & Grimm, 2020; Lo et al., 2021a, 2021b; Muldavin et al., 2017; Opperman & Galloway, 2022; Wu et al., 2020).

High frequency keywords indicate that studies in NFM Europe focused on the impacts of flood risk reduction measures including 'decrease', 'reduced', 'resilience', 'mitigation', 'retention' and 'protection' (Figure 2.3a). 'Model' was the most common research method used in NFM Europe and respectively appears in three wordcloud levels developed on word frequency with much higher frequency than other research methods (red, green, and blue in Figure 2.3b). 'Restoration' and 'forest' were the two most frequently mentioned interventions, with a higher frequency of the former. The high frequency term 'flow', 'hydrological' and 'runoff' reflect that these studies sought to understand the effects on hydrological conditions. These studies seek evidence for 'hydrological' and 'hydraulic' effects (including 'overland' flow, 'infiltration' and flood 'peaks') of NFM & NBS measures through modelling or monitoring methods (Barnsley et al., 2021; Birkinshaw et al., 2014; Black et al., 2021; Hankin et al., 2021; Lane & Milledge, 2013; Lockwood et al., 2022; P. Metcalfe et al., 2017), while exploring their 'potential' in other fields (Auster et al., 2022; Barber & Quinn, 2012; Kowalska et al., 2021; Wilkinson et al., 2014).

2.5.2 Cluster analysis for topic association

In the hierarchical clustering results, vertical ordering within a cluster is by word frequency from highest to lowest; the contribution of each word to the association χ^2 of that cluster is indicated by the length of the bar, where blue is a positive correlation and red is a negative correlation. Whereas in the horizontal axis, the presence of a link connecting two clusters indicates that they are associated, and the length of longitudinal link reflects the magnitude of their association χ^2 ; clusters that are not connected by a line segment are mutually exclusive. For example, clusters shown in Figure 2.4 vertically reflect the change in the frequency of keywords, and horizontally represent the association and mutual repulsion that exists between the different research topics. Words cluster 1 includes perspectives and components of NFM and NBS with management strategy perspectives (e.g., solutions, approaches, knowledge, review) and characterization based on sustainability or other ecological and biological parameters (e.g., restoration, ecosystem, ecological services, habitats, biodiversity). Words cluster 2 focuses on relationships between distributed land use and land change features in the catchment (basin) and hydrological impacts (e.g., flood mitigation, runoff, rainfall-runoff, detention), which are mainly based on modelling research. Words cluster 3 encompasses geomorphic impacts (e.g., recruitment, logjams, length) of wood and LWD in variable river sections (e.g., channel, reach, stream, bank, floodplain, bed, riparian). Words cluster 4 consists of functioning and dynamics of hydrological conditions (e.g., peak, rainfall, runoff, flows, similar, compared, maximum, yield, decreased, increased) related to vegetation (e.g., planted, bog, restoration) over different temporal scales (e.g., annual, daily, period, total).

Words cluster 1 'Management perspectives' and 2 'Land use & hydrological impacts' are highly connected, where the words with higher percentage (blue bars in Figure 2.4) have a stronger correlation to the other clusters. However, there are some terms that might be considered related but are negatively correlated with each other. The strength of negative association (red bars in Figure 2.4) refers to the probability of these irrelevant words that do not appear in the same word segment when high frequency keywords appear within it. For example, some terms of flood mitigation (e.g., peak, runoff) are incompatible with 'management' in cluster 1; several keywords on ecological benefits

(e.g., species, restoration) and geomorphology (e.g., sediment, floodplain, channel, wood) contradict the focus of cluster 2. This also exists between words clusters 3 'Geomorphic impacts of wood' and 4 'Hydrological conditions', where the term 'runoff' related to the hydrological topic was negatively associated with wood-related topics in cluster 3. This is consistent with the patterns observed in cluster 1. The keyword 'management' from cluster 1 shows an inverse relationship with the hydrological keywords in cluster 4.

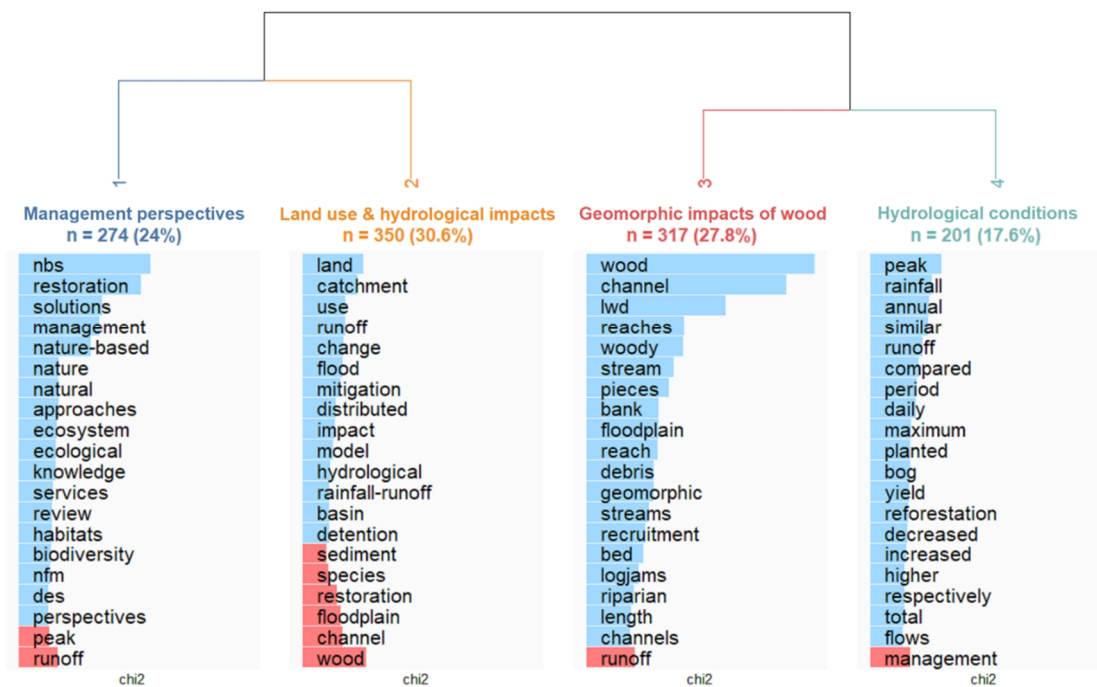


Figure 2.4. Divisive hierarchical clustering for the combined three literature groups (NFM Basis, NFM Global and NFM Europe). *N* is the number of word segments in each cluster. The length of blue and red bars under a word is proportional to the frequency that the word appears in the titles and abstracts in its home cluster (blue represents positive relationship, red represents negative relationship). The length of the longitudinal link between the two clusters represents the sum of the Association χ^2 values between them.



Figure 2.5. Divisive hierarchical clustering for the 'NFM Europe' literature group. *N* is the number of word segments in each cluster. The length of blue and red bars under a word is proportional to the frequency that the word appears in the titles and abstracts under its home cluster (blue represents positive relationship; red represents negative relationship). The length of the longitudinal link between the two clusters represents the sum of the Association χ^2 values between them.

The divisive hierarchical clustering results of NFM Europe (Figure 2.5) also showed similar grouping content to Figure 2.4. However, because the terms 'land use' and 'land change' were replaced by 'land management' and their impacts were not emphasised in NFM Europe, when words cluster 2 'Land use & hydrological impacts' in Figure 2.4 compared to cluster 1 'Hydrological impacts' in Figure 2.5, this research focus was missing. Instead, the terms of NFM & NBS in words cluster 1 'Management perspectives' were further divided into two separate clusters for the management and the ecological services aspects (words clusters 3 'Ecological impacts' & 4 'Management perspectives' in Figure 2.5).

The cluster of studies on catchment hydrology (words cluster 1 'Hydrological impacts' in Figure 2.5) represented the highest proportion of articles (38.3%) in NFM Europe. These studies are highly associated with the research of 'wood' and 'woody debris' manually

installed within the catchment which provide a flood mitigation and storage role (Black et al., 2021; Dixon et al., 2016; Ferguson & Fenner, 2020; Ferguson & Fenner, 2020; Lo et al., 2021a, 2022; Metcalfe et al., 2018; Norbury et al., 2021; Thomas & Nisbet, 2012). Not all NBS studies refer to flooding issues and the hydrological impacts of their measures. The NBS studies often focussed more on the integrated benefits of the implementation of these interventions, where ecological and environmental functions are more intensively mentioned (Albert et al., 2021; Eekhout et al., 2020; Ellis et al., 2021b; Guerrero et al., 2018, 2022; Pugliese et al., 2022; Rey, 2021; Schmidt et al., 2022; Turkelboom et al., 2021). Although the correlation indicated by the Association χ^2 values between clusters 3 and 4 are weaker than that between hydrology and instream wood studies, the overlap between NBS & NFM studies and ecological services & environmental protection studies is higher than with catchment hydrology, and most of these studies do not tackle hydrology-related topics (Andrikopoulou et al., 2021; Keesstra et al., 2018; Spray et al., 2022; Tsaryk et al., 2020; Turconi et al., 2020; Turkelboom et al., 2021).

For NFM Europe, there are differences between periods of 2006-2018 and 2021-2022. In terms of clusters, cluster 2 'Land use & hydrological impacts' (46.6%) in 2006-2018 (Figure 2.6a) corresponds to cluster 1 'Management perspectives' (44.5%) in 2021-2022 (Figure 2.6b). The proportion of wood-related research decreased from 39.3% to 19.3% over time and became more associated with ecological service topics ('ecosystem', 'species' and 'biodiversity'), while the proportion of hydrology-focused research ('overland' 'flow', 'peak' and 'discharge') increased from 14.1% to 36.2%. The term 'NFM' disappeared from words cluster 1 'Management perspectives' in 2021-2022 (Figure 2.6b), which means the contribution of 'NFM' to the relevance of topics declined significantly, and its position was replaced by 'NBS' in 2021-2022. However, the change in the frequency of 'NBS' and 'NFM' did not affect the trend towards hydrology-related studies, which implies both NFM & NBS studies are focusing on the hydrological effects as their potential benefits (Dadson et al., 2017; Dixon et al., 2016; Kumar et al., 2021; Raska et al., 2022; Standen et al., 2020; Tafel et al., 2022; Wilkinson et al., 2019). In this context, the association between hydrological studies and NFM & NBS and wood-related studies became stronger respectively. The composition of the hydrology cluster also changed, from focusing on flood peaks and rainfall to addressing overland flow, storms,

and flood events. This indicates that research in NBS & NFM is increasingly focusing on the hydrological effects during the entire flood process and the interaction between subsurface and surface water (Bond et al., 2020; Costa et al., 2021; Edokpa et al., 2022; Ellis et al., 2021a; Ferguson & Fenner, 2020; Monger et al., 2022; Monger et al., 2022; Revell et al., 2021; Revell et al., 2022; Shuttleworth et al., 2019; Wallace et al., 2021; Westbrook et al., 2020).

(a) 2006-2018

(b) 2021-2022

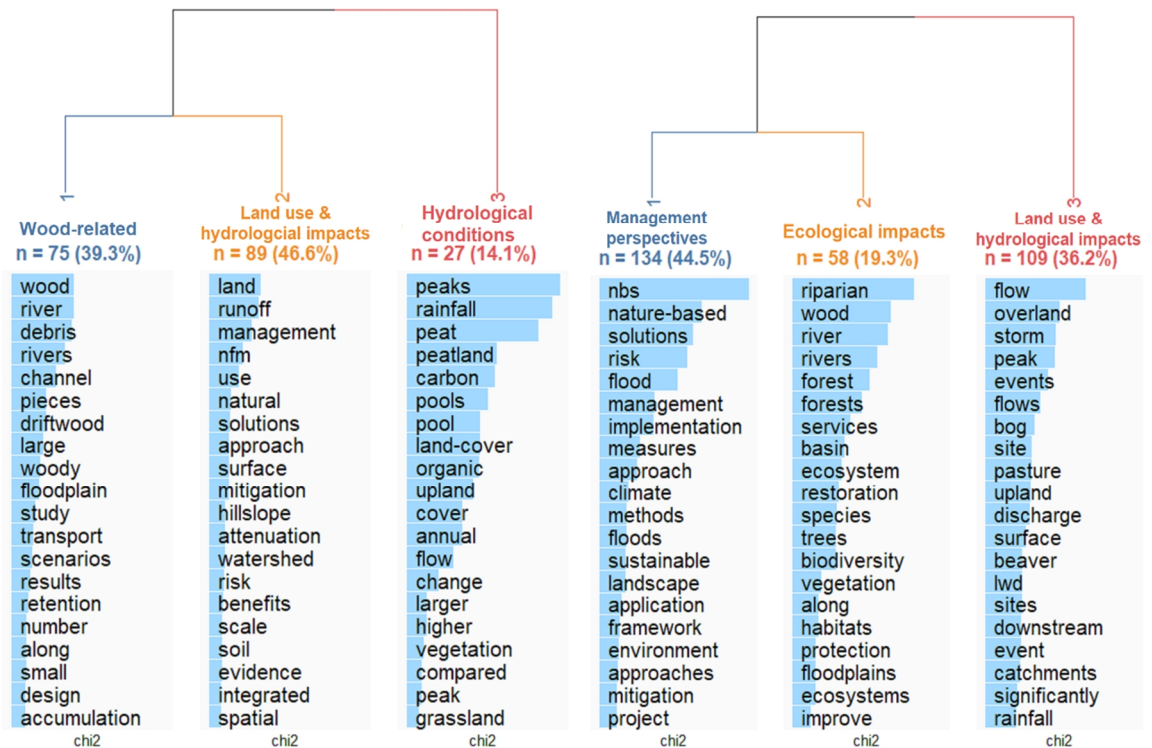


Figure 2.6. Changes in research topics and keywords by cluster analysis (Divisive hierarchical clustering, Rainette method, excluding words frequency < 10 times) of title and abstract contents for the periods 2006-2018 and 2021-2022. These periods were chosen as they contain the same number of articles (76 articles for each). N is the number of word segments in each cluster. The length of blue bars under a word is proportional to the frequency that the word appears in the titles and abstracts under its home cluster. The length of the longitudinal link between the two clusters represents the sum of the Association χ^2 values between them.

2.6 NFM techniques by target benefits

2.6.1 *Understanding confidence in NFM & NBS techniques*

To understand the confidence level of each NFM technique and measure, we categorized intervention type into four groups (Group A-D) by purpose and eight subgroups by NFM techniques and study regions of UK and Europe excluding UK (EU). Confidence levels were evaluated by four indicators for eight subgroups for the UK and EU separately (the evaluation process and data are provided in Appendix A2).

Table 2.1. Number of articles for NFM techniques and measures grouped by purpose, with the confidence of their effectiveness and references based on Europe and UK research (the 'EU' in the table refers to Europe excluding UK) (confidence level details and key references in Appendix A1)

	Purpose of intervention	NFM technique	Number of articles (n)	Confidence in the effectiveness on downstream flood risk reduction
Group A	Slow catchment flow generation and rainfall-runoff processes (off-channel)	Cross slope reforestation	n = 19 (UK)	UK: Low to Medium confidence
		Floodplain/riparian reforestation	n = 17 (EU)	EU: Medium confidence
				<i>Balanced proportion of research methods with several flood reduction conclusions reported; reduced effectiveness highly depends on rainfall intensity and initial soil conditions.</i>
		Soil and land management (soil aeration, sub-soiling, peatland, woodland, grassland, hedges)	n = 17 (UK) n = 11 (EU)	UK: Medium to high confidence EU: Medium to high confidence
				<i>Effectiveness results at multiple catchment scales with balanced proportion of research methods reported; lack of empirical evidence at larger scales.</i>
		Peatland restoration (including gully blocking) Floodplain restoration/reconnection	n = 9 (UK) n = 17 (EU)	UK: Low to high confidence EU: Low confidence
				<i>Studies in the UK and the EU are dominated by modelling approaches; moderate flood reduction results reported but without empirical evidence for larger scale effects.</i>
Group B	Increase surface and subsurface water storage in	Offline storage areas (water retention/detention ponds)	n = 10 (UK) n = 2 (EU)	UK: Low to high confidence EU: Low to high confidence
				<i>Relatively even proportion of research methods; lack of large catchment scale studies.</i>

	offline/online areas	Online storage areas (grip blocking, drainage/ditch blocking, buffer strips, beaver dams)	n = 6 (UK) n = 2 (EU)	UK: Low to high confidence EU: Low confidence <i>Studies are dominated by evidence from field measurements; lack of upscaling studies.</i>
		Land cover changes (floodplain/riparian reforestation, floodplain restoration/reconnection, grassland, hedges)	n = 11 (UK) n = 5 (EU)	UK: Medium to high confidence EU: Low to high confidence <i>Relatively even proportion of research methods; moderate flood reduction results of increasing water table depth and soil water storage reported but limited by catchment scales and rainfall intensities.</i>
Group C	Reduce water velocity in channel	Leaky barriers Woody logjams	n = 15 (UK) n = 7 (EU)	UK: Low confidence EU: Low confidence <i>Studies are dominated by evidence from field measurements and indoor physical experiments; lack of upscaling studies; effectiveness highly depends on the catchment scale.</i>
Group D	Integrated catchment management	Multiple NFM interventions	n = 29 (UK) n = 35 (EU)	UK: Medium to high confidence EU: Medium to high confidence <i>Studies are dominated by research methods of perceptual/conceptual analysis and modelling; effectiveness reported at multiple catchment scales; flood reduction strongly dependent on the location and extension of interventions and limited by rainfall intensity.</i>

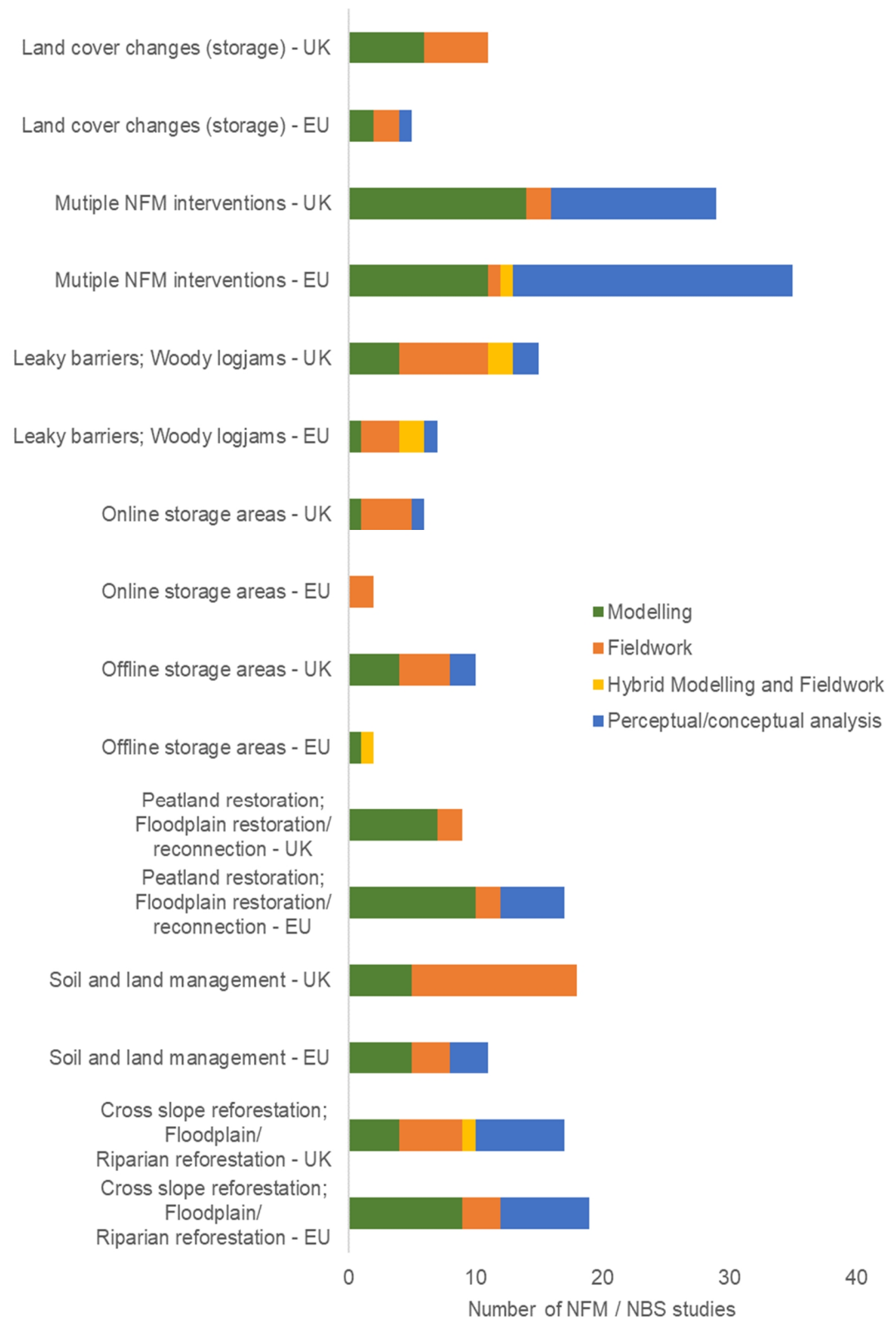


Figure 2.7. Number of NFM/NBS studies in the UK and other EU regions using research methods of modelling, fieldwork, hybrid modelling and fieldwork, and perceptual/conceptual analysis, grouped by purpose (the same as groups shown in Table 2.1)

Reviewing the literature within Group A, which focused on studies which slow catchment flow generation and rainfall-runoff processes (off-channel) (Table 2.1), the highest confidence aligns with soil and land management and reforestation which had the largest number of studies. The share of fieldwork, modelling, and perceptual/conceptual evaluation studies among reforestation effects on flooding is relatively balanced (Figure 2.7). The contribution of reforestation to flood mitigation effectiveness also comes from a variety of aspects, including reducing overland flow associated with decreased soil saturation, slowing rainfall-runoff processes by increasing soil hydraulic conductivity and soil water storage, as well as increasing surface roughness to attenuate surface runoff (Buechel et al., 2022; Chandler et al., 2018; Mihalcea, 2017; Mongil-Manso et al., 2021; Murphy et al., 2021; Revell et al., 2021; Revell et al., 2022; Thomas & Nisbet, 2007). The effectiveness of reducing flood flow is more dependent on the number of measures employed within the catchment and the original soil conditions than on the area of the intervention and its proportion of the catchment area (Page et al., 2020; Peskett et al., 2021). In contrast to the other two intervention types (soil and land management & catchment restoration) in Group A, there is no literature indicating that the effect of reforestation on flood risk reduction within catchments changes significantly with catchment scale.

Maintaining the same criteria of evaluation, Group B (increase surface and subsurface water storage in offline/online areas) has a greater range of confidence levels than Group A. Combining the three intervention types, the number of fieldwork and modelling studies is almost equal (Figure 2.7). The reduction of peak discharge by online and offline storage areas is effective and notable in both fieldwork and modelling results (Appendix A1). However, the location of offline storage features is the most important factor, which depends on soil type, number and spatial distribution of these features in the catchment (Bezak et al., 2021; Fennell et al., 2022; Graham et al., 2022; Metcalfe et al., 2017; Metcalfe et al., 2018; Nicholson et al., 2020). In contrast, impacts due to land-cover changes have more uncertainty. Modelling and fieldwork studies have an equal proportion in total, but the majority of modelling studies are from large-scale studies of reforestation and restoration which lack the before-after observed data for comparison, while grassland and hedges studies are dominated by fieldwork with less evidence for downstream reduction (Richet et al., 2017). There was variability in the results of

restoration studies, where the intervention did not significantly increase water storage or overland flow in the floodplain in a fieldwork-based study (Shuttleworth et al., 2019), while the modelling results showed a 6-fold increase in overland flow storage volume and additional catchment surface storage (Addy & Wilkinson, 2021; Clilverd et al., 2016; Goudarzi et al., 2021).

Modelling and experimental studies for leaky dams and woody logjams in Group C have a similar number of studies and both demonstrated significant flood mitigation and peak travel time delay effects at the local scale where the interventions were implemented, independent of rainfall intensity (Kitts, 2010; Norbury et al., 2021; Thomas & Nisbet, 2012). However, the effectiveness of leaky dams and woody logjams is limited by the catchment scale and mostly only have localised effects in the implemented tributaries or areas. There is still uncertainty about the impact of intensive implementation of leaky dams and woody logjams in small tributaries, where increasing their number does improve the peak reduction, but their location within the tributary and the contribution of the tributary to the entire catchment are important limiting factors (Follett et al., 2021; Hankin et al., 2020; Leahey et al., 2020).

Studies in Group D have two main purposes: to establish a GIS-based database to support spatial targeting and planning of future NFM & NBS measures; and to assess the effectiveness and cost-benefit of integrated catchment flood management strategies based on existing or designed scenarios. Their findings imply differences in the effectiveness of combining different interventions in the same catchment and implementing individual interventions. A recent empirical study has demonstrated that both single and combinations of several types of NFM measures can effectively increase the lag time of flood peaks (Black et al., 2021), beyond Dadson et al.'s (2017) and Barnsley et al.'s (2021) proposed 20 km² scale limit. Importantly, this indicates that NFM can be considered in isolation or combination with other forms of flood risk management at larger catchment scales, as an integrated catchment flood management strategy.

2.6.2 Quantitative analysis: catchment size and rainfall intensity impact on NFM effectiveness

A total of 88 papers clearly showed that NFM/NBS can be effective in reducing flood peaks, and 41 of them gave specific values of peak discharge reduction or delay. The studies from Europe (excluding UK) had a lower proportion of literature concluding that flood peak discharge is reduced or delayed compared to the UK studies. 34.3% of multiple intervention studies and 25.9% of individual intervention studies reported a reduction, with only 11.4% and 6.9%, respectively, mentioning exact reduction values. Because NBS interventions in the Europe group were more biased in examining the combined benefits delivered, such as ecosystem services and recreational benefits, the proportion of papers that specifically evidenced flood reduction was relatively low. Studies of multiple interventions in Europe had a higher rate of peak reduction results than studies of single interventions, or for the UK. This is because European studies were more often using multiple interventions of NBS as an integrated catchment strategy than in the UK.

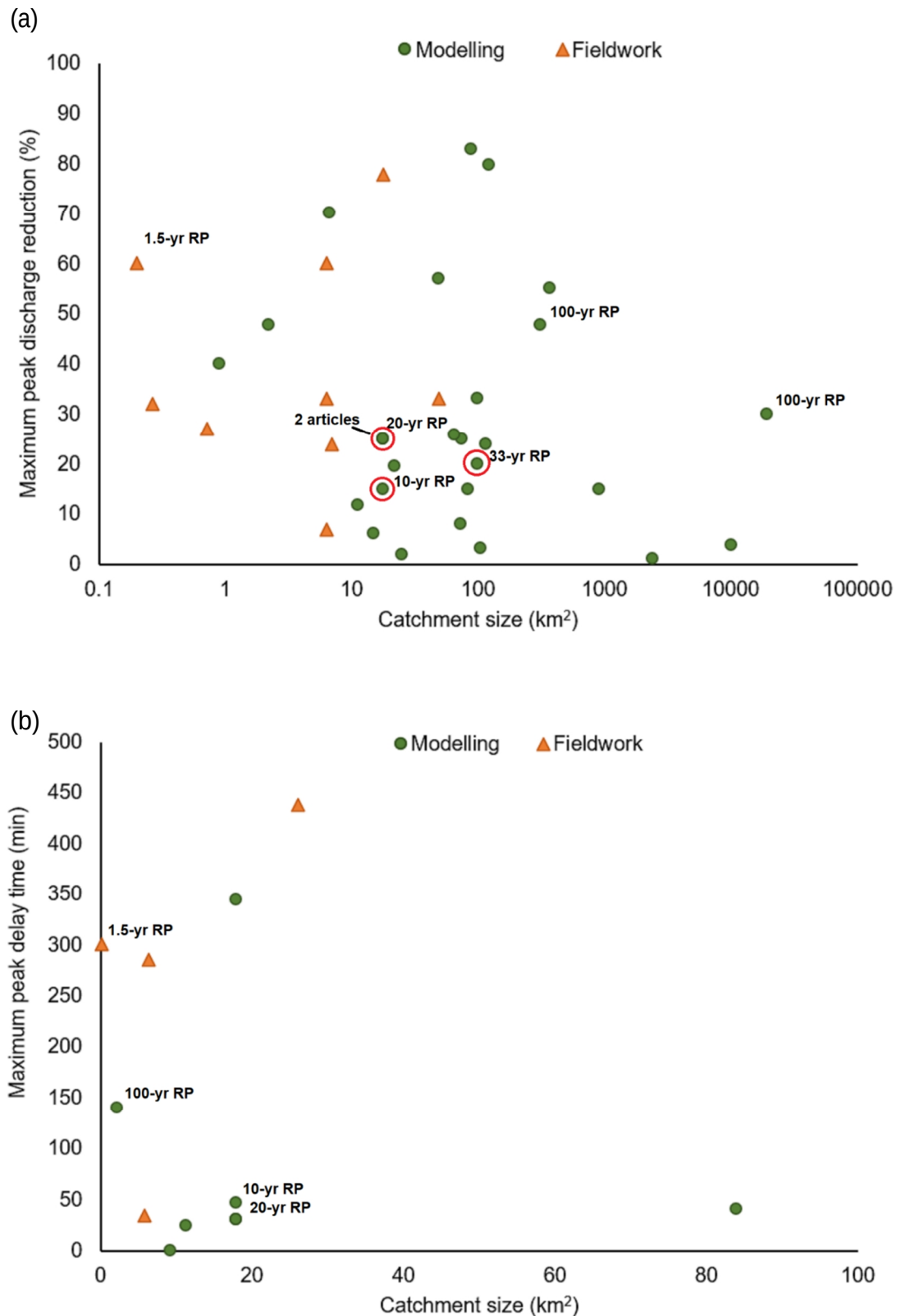


Figure 2.8. Peak discharge reduction (a) and delay time (b) values from literature in the NFM/NBS studies grouped against catchment size. Corresponding return period labels have been added where available.

The proportion of articles with flood reduction results drawn from the different study methods also varied considerably. We classified study methods into modelling, fieldwork, hybrid modelling and fieldwork, and perceptual/conceptual analysis. Overall, the highest proportion of flood peak reduction results was from modelling studies in the NFM/NBS literature dataset, followed by fieldwork, hybrid modelling and fieldwork, and perceptual/conceptual analysis. Results from modelling approaches are the most targeted to flood issues (Figure 2.8), with 65.8% of studies concluding flood reduction effects, whereas this rate is reduced to 43.1% and 42.9% in studies by fieldwork and hybrid modelling and fieldwork methods respectively. The same is true for studies using only fieldwork methods, with 21.6% giving specific reduction or delay values while none of perceptual/conceptual analysis studies give a reduction or delay value. The studies that do not give specific values all demonstrate observations that are mostly indirect evidence of reduced water velocity, increased soil infiltration rates or water storage, but are limited by the spatial distribution of the concentrated sampling sites, which makes it more difficult to provide direct evidence of attenuated flood peaks in the channels.

For the content analysis, there was no significant correlation between the maximum flood peak discharge reduction and catchment size or rainfall intensity ($p = 0.440$; $p = 0.306$) (Figure 2.8); an important and novel finding contrasted with previous studies, which have suggested that the attenuation effect on flood peaks is likely to decrease with increasing catchment scale and rainfall intensity, or that effects would only be local (Barnsley et al., 2021; Bezak et al., 2021; Costa et al., 2021; Dadson et al., 2017; Dixon et al., 2016; Ellis et al., 2021a; Kay et al., 2019; Lane, 2017, Fig.3; Leakey et al., 2020; Norbury et al., 2021; Page et al., 2020; Pattison, 2010; Thomas & Nisbet, 2012; Wahren et al., 2012; Wilkinson et al., 2019).

There is also a large body of literature in our dataset which utilises modelling or field data and which demonstrates that the effectiveness of interventions does not change with increasing catchment size or magnitude of rainfall events, which can support our findings of no significant correlation between them. These studies suggest that the effectiveness of flood attenuation can be amplified by combining and placing multiple measures over a larger catchment scale than a single measure in a local area (Black et al., 2021; Ferreira et al., 2020; Gao et al., 2017; Goudarzi et al., 2021; Graham et al., 2022;

Metcalf et al., 2017; Nicholson et al., 2020; Puttock et al., 2021; Ramsbottom et al., 2019). Although there is heterogeneity among different catchments, the results from one field-based study showed a maximum delay time of 7.3 hours measured in a 26 km² headwater catchment by implementing a combination of multiple measures (207 ha woodland planting, 116 large log structures, 31 flow attenuation ponds and 2.9 km of previously straightened river channel re-meandered, with embankment removed) within a 69 km² catchment (Black et al., 2021). The maximum peak discharge reduction rates of 80% and 83% highlighted in Figure 2.8 were modelled from catchments of 122 km² and 88 km² (Gabriels et al., 2022; Mihalcea, 2017). The largest catchment scale study was carried out by modelling, which predicted a 30% reduction of peak discharge for a catchment of 19,224 km² (Terencio et al., 2020). There is no strong empirical evidence from the combined set of field, modelling and hybrid studies showing that the effectiveness of NFM & NBS interventions on peak discharge reduction and peak delay decreases with increasing catchment size (Figure 2.8). While there are some smaller peak discharge reduction values using modelling methods for catchments of 1000 km² or above, the number of cases is too small for any effect to be confirmed (Figure 2.8a). Nevertheless, there are more small-scale studies than large ones and so further large-scale studies are required to help understand where to locate NFM measures within a catchment and how these measures will respond to future flood events.

There was no significant correlation between flood reduction effects of interventions and rainfall intensity ($p = 0.306$). The comparison of different rainfall intensity impacts used in studies can be categorised into two types: precipitation totals (mm; 7 articles) and event return period (years; 14 articles). Our finding, contrary to earlier literature which suggested that effectiveness could be limited by increasing rainfall intensity (Archer et al., 2010), opens up the possibility for large-scale, long-term implementation of NFM/NBS at the catchment scale. Some field evidence from northern England showed that the percentage of peak discharge reduction during high magnitude storm events was lower than for low magnitude storm events (Dadson et al., 2017; Ferguson & Fenner, 2020; Nicholson et al., 2020). However, at the larger catchment scale, the decrease of peak discharge responds more significantly to higher magnitude events due to the possibility of using expandable field storage (Hankin et al., 2021; Kay et al., 2019). Two studies conducted at large catchment scales (315 km² and 19,234 km²) for extreme

rainfall events (100-year return period) yielded peak discharge reductions of 48% and 30%, respectively (Reinhardt et al., 2009; Terencio et al., 2020). This indicates further evidence is required to develop understanding of the effectiveness of NFM for higher magnitude events. However, the evidence for understanding the impacts of rainfall intensity on NFM effectiveness is limited, as only 8 out of 41 articles with relevant data have reported the peak reduction or delay values with the return period of rainfall events (Figure 2.8). A key problem is that, depending on the characteristics of rainfall patterns and catchment antecedent conditions, the effect of NFM features on peak discharge reduction in different storm events may vary. The timings of discharge from NFM features might contribute to the timings of peak discharge and flow concentration, which is a potential issue for further research. Considering catchment scales of NFM may be related to the synchronisation of runoff peaks, NFM impact assessment on flood risk should be upscaled to immediate sub-catchments and downstream catchment areas.

2.7 Conclusions

This review identified several key findings in NFM and related studies. Over the last decade, the number of NFM & NBS related studies has rapidly increased globally with the greatest concentration in the European region. Between 1991 and 2022, the research focus has shifted from examining the impacts of floods on ecosystems, geomorphology, and hydrology to investigating how land cover and landscape changes affect flood characteristics. A shift in keyword frequency indicates a broader evolution in NFM & NBS studies: from flood mitigation to flood management strategies, from localised hydrological impacts to catchment-wide flood processes, and from wood-related studies to broader ecosystem services assessments. There has been a notable transition in research focus from single to multiple interventions for flood mitigation, with a high proportion of studies using modelling methods.

This review, after integrating data and results from NFM and related studies during the past 30 years, concludes that the existing evidence suggests that NFM interventions maintain their flood mitigation effects regardless of catchment size or the magnitude of rainfall intensity. Modelling studies dominate this field and generally predict that NFM and NBS measures are effective for flood mitigation. Importantly, flood mitigation

effectiveness of interventions did not appear to diminish with increasing catchment size and rainfall intensity. While numerous large-scale studies, mainly modelling-based, have reported significant flood attenuation and peak flow delays, confidence in NFM & NBS interventions remains limited by variables such as their location and extent, rainfall intensity, catchment antecedent conditions, and catchment scale. Literature evidence suggests that implementing multiple interventions enhances the effectiveness of NFM & NBS. However, more experimental evidence, such as modelling the construction of a network of NFM interventions with physically-based models in large-scale catchments, monitoring the downstream impacts of different NFM intervention types in large-scale catchments, and monitoring of the combined effects of different NFM interventions, is needed to provide a more comprehensive understanding of the effectiveness of NFM. Thus, it is critical to design intervention networks at the catchment scale to support spatial models that can aid decision-making.

2.8 References

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Chapter 3. Use of spatially distributed TOPMODEL to assess the effectiveness of diverse natural flood management techniques in a UK catchment

3.1 Abstract

While natural flood management (NFM) is becoming more widely used, there remains a lack of empirical evidence regarding its effectiveness. The primary uncertainties arise from two key aspects: first, the determination of NFM effectiveness is constrained by the relatively small catchment scales studied to date; second, the combination of multiple NFM interventions within a catchment may lead to flood peak synchronisation. In this study, both instream and terrestrial NFM interventions were modelled using a spatially distributed hydrological model, Spatially Distributed TOPMODEL (SD-TOPMODEL). To demonstrate how the scale and type of interventions interact to influence flood peaks, we integrated various NFM interventions and land cover changes, including woodland planting, soil aeration, floodplain restoration, and hedgerow planting. In comparison to previous versions of SD-TOPMODEL, we improved simulation efficiency to enable grid-based modelling of up to a 200-year return period flood event for an 81.4 km² catchment with 5 m resolution. Following extensive parameter calibration and validation, the model demonstrated stability and provided a reliable fit for flood peaks, achieving a Nash-Sutcliffe Efficiency coefficient of up to 0.93 between modelled and observed discharge. The results highlighted the effectiveness of NFM interventions in reducing flood peaks at the scale studied, particularly during single-peaked storm events and under dry pre-event catchment conditions. Moreover, the combined use of multiple interventions was more effective and resilient than single interventions, with flood peak reductions ranging from 4.2% to 16.0% in the study catchment.

3.2 Introduction

Natural flood management (NFM) is a flood mitigation strategy which aims to work with natural processes to restore and enhance catchment hydrological functions which limit flood risk and impact (Dadson et al. 2017; Cooper et al. 2021). In particular, NFM seeks to reduce and delay flood peaks by optimising the natural water retention function of the catchment and to mitigate the potential hazards of flood peaks (Lane 2017; Kay et al.

2019; Black et al. 2021; Ellis et al. 2021; Kumar et al. 2021; Lashford et al. 2022). For example, altering the physical properties of soil that influence water movement and storage, such as porosity and permeability, can enhance subsoil water storage capacity and encourage infiltration to delay flood peak time and/or reduce peak discharge during a storm event. Soil properties might be altered directly through aeration and other soil management interventions or indirectly by implementing afforestation, reducing grazing intensity or delivering other ecological restoration practices (Grayson et al. 2010; Wahren et al. 2012; Palmer and Smith 2013; Marshall et al. 2014; Dixon et al. 2016; Gao et al. 2016; Alaoui et al. 2018; Gunnell et al. 2019; Wilkinson et al. 2019; Bond et al. 2022; Monger et al., 2024).

Evidence has shown that interventions such as those described above can potentially reduce and slow overland flow by locally increasing soil saturated hydraulic conductivity, the depth of soil water table and surface roughness. For example, results of experimental studies at the hillslope scale have shown that replacing grazed grassland with broadleaf woodland on hillslopes significantly increases saturated hydraulic conductivity and provides the soil with increased capacity to store rainfall by reducing soil compaction and bulk density and increasing depths of soil water table (Marshall et al. 2009; Archer et al. 2013; Murphy et al. 2020), thus achieving a reduction in overland flows (Marshall et al. 2014; Bond et al. 2022). Modelling studies by Gao et al. (2016) and Goudarzi et al. (2021) highlighted that upland peat restoration, including both revegetation and gully blocking interventions, are effective in increasing static and kinematic storage of rainfall in the implementation area to reduce and delay flood peaks, and such evidence has been supported in a field experimental study (Shuttleworth et al. 2019). Critically, the reduction of overland flow velocities by increasing surface roughness can yield reduced discharge peaks (Holden et al. 2008; Roni et al. 2015; Bond et al. 2020; Bond et al. 2022). Soil aeration, which is the process of mechanically piercing the soil to enhance porosity, has also been shown to be effective in enhancing infiltration to reduce overland flow by increasing topsoil saturated hydraulic conductivity (Franklin et al., 2007; Alaoui et al. 2018; Wallace and Chappell, 2019).

While a few NFM studies have been based on field experimental data these have been at the plot or small catchment scale (Kay et al. 2019; Kumar et al. 2021; Chapter 2). The

majority of studies of NFM effectiveness have been conducted using modelling and have focused on a specific NFM intervention. Most information from modelling studies is limited by the lack of understanding of the upscaling impacts from the local scales of intervention implementation to catchment-scale, and the modelling approaches vary in accuracy and complexity (Kumar et al. 2021; Hill et al. 2023). From previous modelling studies of multiple NFM interventions, conflicting conclusions have been obtained for different modelling approaches, resolution, and catchment scale. For example, in a study of the 98 km² Lymington River catchment in southern England, the simplified spatially distributed OVERFLOW model (20 m resolution) showed up to a 20% peak reduction by increasing mature floodplain forest to 20-35% of the area, with greater effects from additional reforestation and sub-catchment desynchronisation (Dixon et al. 2016). Metcalfe et al. (2018) used the semi-distributed Dynamic TOPMODEL with NFM interventions which enhanced hillslope storage lumped in several hydrological response units (HRUs) for a 223 km² catchment, reducing peak flow by a median of 5.8% and a maximum of 17.3% during one storm. The same model was coupled with the floodplain hydrodynamic model, JFlow (2 m resolution) to assess land management and peatland restoration interventions, including a runoff attenuation feature (RAF) in a 15 km² catchment, showing a 4% $\pm$ 2% flow reduction (Hankin et al. 2019). Dynamic TOPMODEL coupled with HEC-RAS 2D (5 m resolution) showed up to 25% surface flow reduction from a combination of afforestation and in-channel barriers in an 18 km² catchment (Ferguson and Fenner 2020). The Generalized Multistep Dynamic TOPMODEL (2 m resolution) was employed to model peatland restoration scenarios in a 25 km² catchment, showing a high likelihood of > 5% peak discharge reduction (Goudarzi et al., 2024). Although these modelling results all demonstrate effective flood mitigation by NFM, the differences in implementation of interventions in each catchment, such as intervention types, locations and area, and the differences in the complexity, spatial resolution and modelling scale of each model make it difficult to compare NFM benefits under the same criteria.

Using modelling to understand the impacts of types, location and size of interventions, and the combination of interventions, is important for NFM research (Bond et al. 2022; Hill et al. 2023; Kingsbury-Smith et al. 2023; Peskett et al. 2023; Monger et al. 2024). Modelling could be used to support investment decisions, especially via the assessment

of NFM from an integrated catchment perspective with single and mixed types of interventions. The number of UK NFM studies that have investigated multiple interventions and achieved valid flood mitigation results (10 articles) is less than those that have only investigated a single intervention (24 articles) (Chapter 2). Implementation of single or a combination of interventions can be effective at larger catchment scales than the evidenced 20 km² limit proposed by Dadson et al. (2017) and increases the resilience of NFM by combining it with other forms of flood management interventions (e.g. leaky dams and runoff attenuation features) (Black et al. 2021). All NFM interventions have the potential to influence the synchronisation of flood peaks across tributaries in the catchment (Thomas and Nisbet, 2007; Pattison et al., 2014). During large storms, multiple interventions yielded less peak reduction and no peak timing impacts compared to a single intervention due to the increased likelihood of peak synchronisation (Dadson et al. 2017; Kingsbury-Smith et al. 2023; Metcalfe et al. 2018). However, empirical evidence addressing positive or negative effects of the type of combined interventions, location, and area on NFM effectiveness at a large catchment scale remains very scarce.

Ideally, a modelling study for NFM effectiveness requires a model with sufficient spatial resolution to simulate all land and soil management interventions yet which is simplified enough to efficiently simulate storms with different characteristics at larger catchment scales. The Spatially Distributed TOPMODEL (SD-TOPMODEL) used in this study meets these requirements (Gao et al., 2015). SD-TOPMODEL has been used to demonstrate flood peak reductions varied across catchments for different types NFM interventions. Peatland revegetation scenarios tested (20 m resolution) in an 84 km² upland catchment with peatland headwaters showed a 4 – 15% reduction in flood peaks (Gao et al. 2017). Hillslope grassland management scenarios achieved up to 42% reduction in overland flow peaks in a predominantly grassland-covered upland catchment (21 km²), where afforestation intervention was most effective (Bond et al. 2022). Woodland planting scenarios demonstrated up to 15.3% reduction in flood peaks in a 2.62 km² steep upland catchment predominantly covered by unimproved grassland and semi-natural woodland (Monger et al. 2024). Kingsbury-Smith et al. (2023) used the model in a 38 km² predominantly rural upland catchment for several single intervention scenarios, such as woodland and hedgerow planting, riparian buffer strips, and soil aeration, and a

combination of all these interventions. SD-TOPMODEL has been validated to effectively simulate rainfall-runoff processes in steep upland catchments with land and soil management measures (Gao et al. 2018; Bond et al. 2022), and the resolution has been improved from 20 m to 5 m to enable representation of a wider variety of NFM interventions (Bond et al. 2022; Kingsbury-Smith et al. 2023). However, further testing of different combinations of NFM interventions, storm characteristics and catchment antecedent conditions by using SD-TOPMODEL at larger catchment scales is still required, as SD-TOPMODEL has not been applied to catchment scales $> 50 \text{ km}^2$ at a fine resolution of 5 m.

Although no significant correlation between rainfall intensity and NFM effectiveness was identified in both our review and previous modelling studies, the response of different NFM intervention types to varying rainfall intensities remains variable (Gao et al. 2018; Ferreira et al. 2020; Kingsbury-Smith et al. 2023; Chapter 2). Notably, there is a research gap regarding the potential impacts of different rainfall event characteristics, such as single- versus multi-peaked events, in addition to rainfall intensity (Hankin et al. 2020). Furthermore, catchment antecedent conditions may influence NFM effectiveness (Wallace and Chappell, 2019; Bond et al. 2020). The influence of these factors on NFM effectiveness have been investigated in this modelling study.

Following the work of Chapter 2, this study is designed to investigate the effects of the first two groups (slow catchment flow generation and rainfall-runoff processes (off-channel); increase surface and subsurface water storage in offline/online areas) on flood mitigation, where the main interventions were: afforestation (woodland planting) and soil and land management (soil aeration and hedgerow planting) via their impacts on soil infiltration rates, soil storage capacities and surface roughness. SD-TOPMODEL is used to simulate NFM interventions impacting soil hydrological functions and surface roughness at a catchment scale. The aim is to calibrate and validate the model with parameter choices supported by evidence from previous empirical studies and improve model performance to gain a full understanding of NFM effectiveness. The land cover and NFM scenarios were applied to compare different combinations of NFM interventions and how they interacted with seven observed storms with different characteristics at a catchment scale.

3.3 Data and methods

3.3.1 *Study site*

The Upper Aire catchment is a 370.8 km² upland catchment in northern England (Figure 3.1). Following extensive flooding in 2015, which exceeded a 200-year return period at the Armley gauging station (location in the city of Leeds, Figure 3.1b), multiple NFM interventions (woodland planting, hedgerow planting and soil aeration) have been implemented to slow runoff response to rainfall and increase surface and subsurface water storage in off-channel areas across the catchment (Figure 3.1c) (Leeds City Council, 2024; Upper Aire Project, 2024). The Upper Aire Catchment to Gargrave (~81.4 km²) was chosen as the study site, as it encompasses a significant proportion of these interventions which also have well-documented records about their locations and nature (Yorkshire Wildlife Trust, 2022). The catchment also benefits from reliable river gauging data at Gargrave. The Gargrave station is located on the main channel of the River Aire and its catchment area is dominated by a rural hilly landscape with a maximum elevation difference of 467 m.

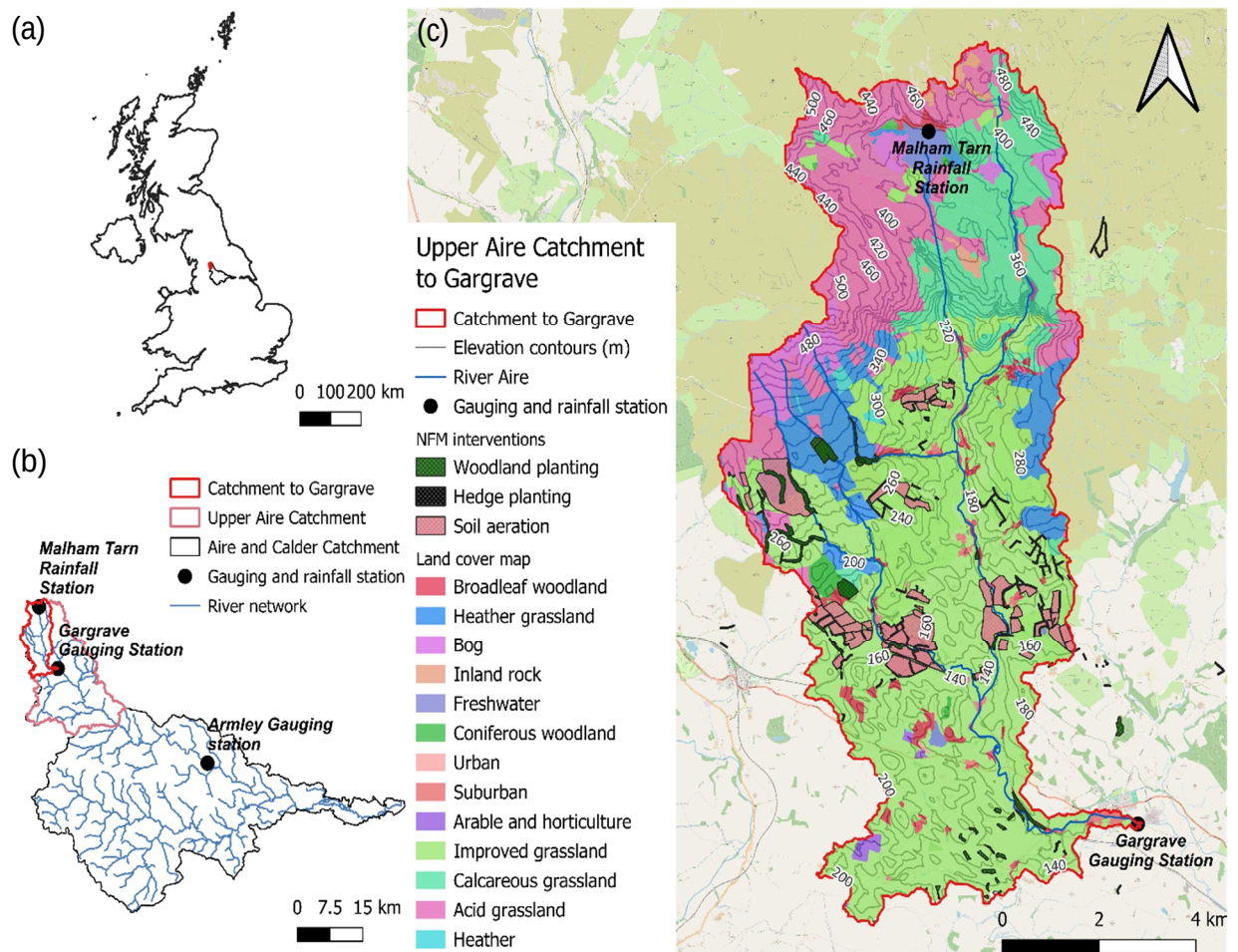


Figure 3.1. Study site: (a) location of study catchment in the UK; (b) Aire and Calder catchment; (c) study area upstream of Gargrave gauging station including land cover data from the UK 2015 landcover map, and locations of NFM interventions.

The catchment is dominated by improved grassland (49.7%), followed by calcareous grassland (18.7%), acid grassland (12.1%) and heather grassland (10.4%), bog (3.7%), broadleaf woodland (1.9%) and coniferous woodland (1.0%) (CEH, 2015). Soils are mainly fine or coarse loamy, slowly permeable loamy and clayey, very shallow loamy, or well drained silty soils over limestone (NATMAP, 2016), resulting in high spatial variability in soil depth. The underlying geology is dominated by carboniferous limestone, along with sandstone, mudstone, and shale (NATMAP, 2016). The area experiences a mean of 220 days of rain, with 1510 mm of mean precipitation annually (Upper Aire Project, 2024).

The River Aire catchment faces a high flood risk during extreme rainfall. The Boxing Day Flood (26-27 December 2015) caused £500 million losses in Yorkshire, with 89.6 mm of rain in 34 hours (West Yorkshire Combined Authority, 2016). During this event, the return

period for the River Aire at the Armley gauging station (in the city of Leeds) was > 200 years of the calculated range (Figure 3.2), with a discharge peak of 344.4 m³/s, the highest value recorded since the record started in 1961 (Marsh et al., 2016).

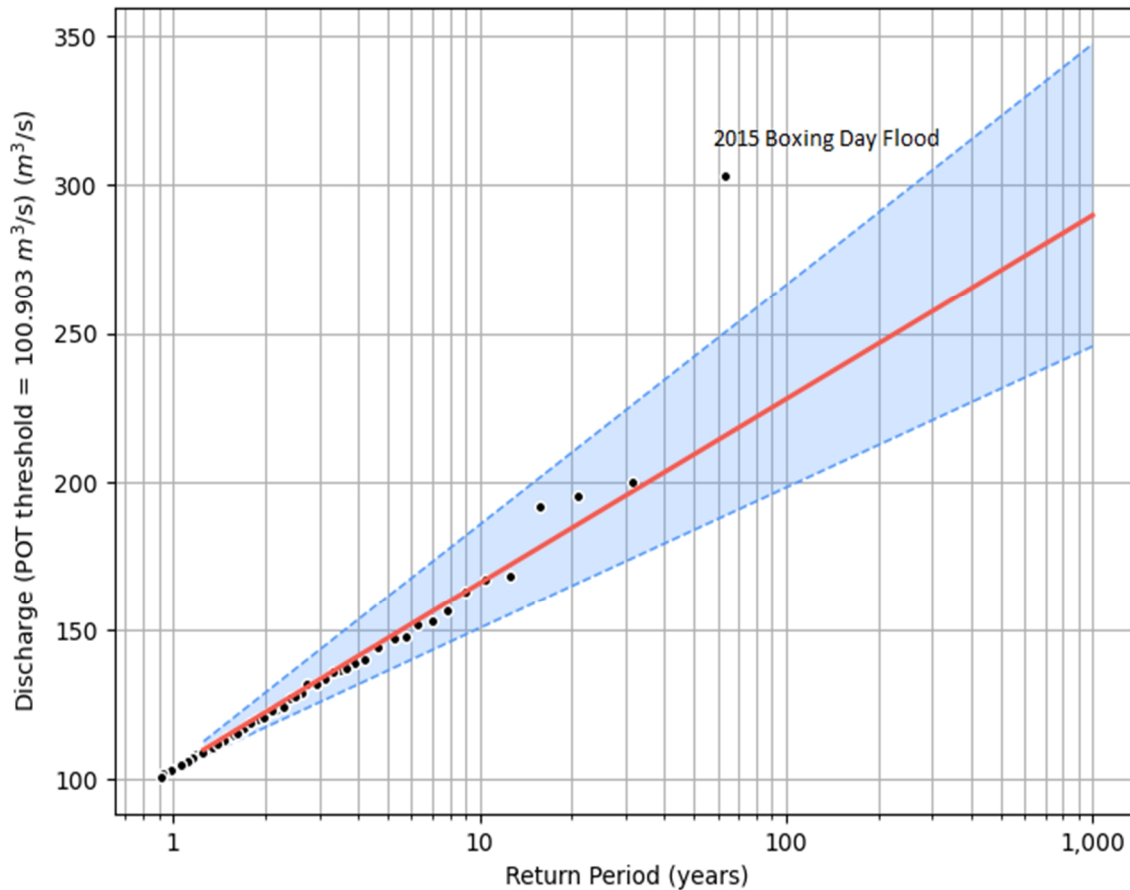


Figure 3.2. Return period for Armley Gauging Station calculated from its measured daily discharge (m³/s) filtered by Peaks over Threshold (POT) method from 1961 to 2022 with trendlines at the 95% confidence level.

3.3.2 Spatially distributed rainfall-runoff model: SD-TOPMODEL

To investigate the influence of land cover changes and NFM interventions on flood response at the catchment scale, SD-TOPMODEL was employed, using the same governing equations and parameters as described in Gao et al. (2015). SD-TOPMODEL is a spatially distributed version of the original lumped or semi-distributed TOPMODEL (Beven and Kirkby 1979). Gao et al. (2015) developed the model by downscaling the original TOPMODEL equations from the catchment scale to grid cell equations. It has the advantage of allowing each grid cell to be saturated at different times based on the local wetness by using precipitation, slope, and soil water depth in each cell. The overland

flow module uses the multiple-direction flow theory of Quinn et al. (2006) with a dynamic velocity parameter related to surface roughness to conduct overland flow directions and rates in each grid cell. Furthermore, the simplification of model parameters from six to three increases the efficiency of model parameterisation, enabling a more targeted simulation of land cover and land use impacts on rainfall-runoff processes. This facilitates the representation of hydrological variability across the land surface and shallow subsurface conditions by adjusting parameters within each grid cell. This high-resolution capability enables the inclusion of spatially specific NFM interventions. The model is also well suited to simulate extreme rainfall events in catchments with steep topography and shallow soils (Gao et al. 2015; Gao et al. 2016; Bond et al. 2022; Kingsbury-Smith et al. 2023; Monger et al. 2024), thus, is ideal for use in the Upper Aire catchment for the NFM effectiveness study.

SD-TOPMODEL can deliver three catchment outlet outputs at each timestep: overland flow, shallow subsurface flow, and the total of overland and subsurface flow outputs. Three key parameters are employed in SD-TOPMODEL to represent the catchment physical properties: overland flow velocity, K_v equals $1/n$ where n is the surface roughness, soil hydraulic conductivity K_s , and scaling soil active depth for subsurface flow m (Gao et al., 2015). The remaining three model parameters were set to default values: maximum capacity of the root zone (S_{rmax}) = 0.5; initial storage in root zone at the start of a run (S_{ro}) = 0; and time delay for recharge to the saturated zone (T_d) = 0.1. To increase the efficiency of SD-TOPMODEL for simulating extreme rainfall events, the model is written in C++ language and was batch run on the Advanced Research Computing High-Performance Computer (HPC) platform at the University of Leeds.

3.3.2.1 Data Sources

An Ordnance Survey 5 m digital terrain model (DTM) was used for the Upper Aire catchment (Ordnance Survey, 2022). The 2015 England Land Cover Map (CEH, 2015) and the National Soil Map (NATMAP) were provided as vector datasets at the same resolution (5 m) to represent land cover, vegetation, and soil types. The resolution used was the highest possible as determined by data availability and limitations of model run time (maximum 48 hrs of HPC platform runtime).

For rainfall data, 15-min measured precipitation (mm) from the Malham Tarn station (Figure 3.1) from January 2012 to January 2022 was used (Environment Agency, 2022). 15-minute observed river flow (m^3/s) was obtained from the Gargrave gauge and Armley gauge over the same period (Environment Agency, 2022). Within the ten-year dataset from January 2012 to January 2022, storm events were selected using the POT method in Extreme Value Analysis (EVA) (Leadbetter, 1991), identifying high-flow events, and including multiple occurrences within a year. The Python package 'pyextremes' (<https://georgebv.github.io/pyextremes/>) was utilized as a selection tool for this analysis, while return periods were calculated at the Armley station. Threshold exceedances were defined as $40 \text{ m}^3/\text{s}$ using a functional generalisation of the generalised Pareto distribution and generalized extreme value distribution (de Fondeville and Davison, 2022). 15 discrete flood events were initially identified, each exceeding the discharge threshold and having a time interval of more than seven days since the preceding rainfall event. We selected seven of these flood events that occurred in different months with varying rainfall intensities, durations, and return periods for observations at the Armley gauging station (which was used due to its urban fluvial flood risk location), which covered very common, common, uncommon, and rare flood events in the catchment (Table 3.1). Every event was initialised with a base flow derived from discharge data, which served as the overland flow input into the model. A 5-hour warmup runtime was required for each grid cell to reach water balance within the catchment. To represent base flows under different antecedent conditions, the warmup period incorporated either 0 mm per timestep (for dry conditions) or 0.2 mm per timestep (for wet conditions). Dry and wet antecedent conditions were defined from soil moisture reports (COSMOS-UK, 2020) and the Hydrological Summary for the UK (CEH, 2012-2020). This helped to categorise and understand the differences in flood mitigation effectiveness of different NFM intervention types for flood events with different antecedent characteristics.

3.3.2.2 Model 0 and calibration

To establish a Model 0 (baseline model to start calibration) with optimal and spatially uniform parameter settings for the catchment, model calibration was conducted for each of the seven observed storm events. Each model run had a 5-hour spin up before the rainfall event and finished after discharge observations returned to base flow levels, with

a timestep of 15 min and a cell size of 5 m * 5 m. To enhance efficiency by reducing the number of calibration runs and computing time, parameter spaces were selected based on prior experience with SD-TOPMODEL testing and calibration, as outlined in Table 3.1a (Gao et al., 2015; Gao et al., 2016; Kingsbury-Smith et al., 2023). For calibration, 150 simulations were conducted for each event, totalling 1050 simulations across seven events, using varying parameters with the intervals specified in Table 3.1. In previous studies which have applied SD-TOPMODEL, the Nash-Sutcliffe efficiency coefficient (NSE) was used as a criterion for evaluating and selecting the best performing model (Bond et al. 2022; Gao et al. 2017; Kingsbury-Smith et al. 2023; Monger et al. 2024). The best simulation and parameter setting for Model 0 were determined for each event based on the highest NSE value and minimal differences in flood peak discharge and timing compared to observations (Table 3.1b). Following this, despite some discrepancies in the best-fit parameters for Events 2, 6 and 7, the parameters can be constrained to the following ranges: m (0.006-0.01); K_s (100-200); K_v (25-30). A generic parameter setting that can be used to represent the entire catchment was derived through 100 Monte Carlo tests run for each of the seven events using the narrowed range. The model was considered credible when NSE values exceeded 0.5 (Moriassi et al. 2007). However, NSE has been shown to be potentially insensitive to low and peak flows in assessing model errors (Althoff and Rodrigues, 2021), thus, the absolute peak error and peak error percentage were also considered. This generic parameter setting serves as Model 0 which does not account for the spatial distribution of land cover or variations between event years resulting from NFM implementation and land cover changes. Model 0, with uniform parameters, achieved NSE values exceeding 0.6 for all events, with peak discharge errors limited to no more than 32% of observed values. The best-fit model during baseline calibration attained an NSE of 0.92, aligning with the performance reported in previous studies (Bond et al. 2022; Gao et al. 2017; Kingsbury-Smith et al. 2023; Monger et al. 2024). Once the parameter setting was determined, all subsequent model runs used this set of baseline parameter values.

Table 3.1. Calibration parameters and results: a) parameters spaces used for narrow ranges for calibration; b) calibration results of Model 0 for seven observed storm events (the date is when the storm started)

(a)	Parameter	Lower limit	Upper limit	Intervals	Model 0		
	<i>Kv (-)</i>	20	40	5	30		
	<i>m (m)</i>	0.002	0.018	0.004	0.009		
	<i>Ks (m/h)</i>	100	600	50	100		
(b)		Event 1	Event 2	Event 3	Event 4	Event 5	Event 6
		(12 Dec	(3 Jan	(25 Dec	(8 Feb	(10 Oct	(16 Mar
		2015)	2012)	2015)	2020)	2019)	(15 Feb
							2020)
	<i>Return Period in</i>	50	10	> 200	100	1	20
	<i>Armley Station</i>						
	<i>(~years) (Figure 3.2)</i>						
	<i>Storm duration (h)</i>	16	60	34	50	25	18
		(single-	(multi-	(multi-	(single-	(multi-	(single-
		peaked)	peaked)	peaked)	peaked)	peaked)	peaked)
	<i>Total rainfall (mm)</i>	22.4	64.0	89.6	70.2	37.0	44.6
							49.2
	<i>Rainfall intensity</i>	1.400	1.067	2.635	1.404	1.480	2.478
	<i>(mm/h)</i>						2.319
	<i>Maximum rainfall</i>	6.4	4.2	5.6	7.6	5.6	4.2
	<i>intensity (mm/h)</i>						5.2
	<i>Simulation duration</i>	45	90.5	65	55	41.25	35
	<i>(h)</i>	(Wet)	(Dry)	(Wet)	(Dry)	(Dry)	(Dry)
							(Wet)
	<i>Kv (-)</i>	25	35	25	25	30	25
							40
	<i>m (m)</i>	0.006	0.006	0.006	0.01	0.01	0.014
							0.01
	<i>Ks (m/h)</i>	200	400	200	200	100	200
							200
	<i>NSE of best fit</i>	0.93	0.80	0.87	0.84	0.83	0.96
							0.86

3.3.2.3 Data for determining parameter values

The model was applied for different NFM interventions. This study attempts to calibrate three parameters of SD-TOPMODEL to larger catchment scales and more complex combinations of existing NFM interventions. There are two formats to input parameters in SD-TOPMODEL used in this study: (1) a parameter file which displays baseline values of each parameter conducted by Model 0 calibration (see section 3.3.2.2); (2) a spatially distributed map for all three parameters based on land cover and NFM interventions to apply upon the baseline values.

To represent the spatially distributed parameters, each parameter was individually spatially distributed on the base map to assign the parameter to each grid cell at the same resolution as the elevation data and the entire model. During the model run, the values within each grid cell of each parameter distribution map were calculated as multipliers on the baseline values (as the improved grassland land cover, due to its dominance in the catchment) (Bond et al., 2022; Kingsbury-Smith et al., 2023; Monger et al., 2024). The calibration ranges for these values were determined with reference to previous empirical studies (Table 3.2). The upper and lower limits specified by the measured ratios allow the model to be more realistic, but also constrained by the physical meaning of them.

Table 3.2. Parameter multipliers used for land cover types and existing NFM interventions in the catchment and the ratio of them compared with improved grassland with references (from previous field measurements and experimental results), and the proportional area of land cover types in 2015 and 2020, as well as the proportional area of implemented NFM interventions.

Class name	Modelled parameter ranges (multipliers)			Ratio of land cover type compared with improved grassland from literature			Percentage of area (2015, 25m raster)	Percentage of area (2020, 25m raster)**
	<i>m</i> (m)	<i>Ks</i> (m/h)	<i>Kv</i>	<i>M</i>	<i>Ks</i>	<i>Kv</i>		
Broadleaf woodland	0.0135 – 0.018 (1.5 – 2)	200 – 1000 (2 – 10)	12 – 22.5 (0.4 - 0.75*)	1.5 - 2 (Archer et al., 2013)	1.8 (Murphy et al. 2020) 2.4 (Marshall et al. 2009) 12 (Gonzalez-Sosa et al. 2010) 11 - 20 (Monger et al. 2022a)	1.3 (Monger et al., 2022b) 2.4 (Manning's <i>n</i> values, Chow, 1959)	2.09%	1.87%
Coniferous woodland	0.0135 – 0.018 (1.5 – 2)	150 - 500 (1.5 – 5)	12 – 22.5 (0.4 - 0.75*)		1.2 – 5.6 (Archer et al. 2013) 2.1 (Gonzalez-Sosa et al. 2010) 3.9 (Kingsbury-Smith et al. 2023) ≤38 (Chandler et al. 2018)		0.71%	1.04%

<i>Arable and horticulture</i>	0.009 (1)	50 (0.5)	22.5 (0.75)	The same as Baseline (NATMAP)	0.5 (Holden et al. 2019)	The same as Heather	0.34%	0.11%
<i>Improved grassland (baseline)</i>	0.009 (1)	100 (1)	30 (1)	Baseline			58.78%	48.71%
<i>Calcareous grassland</i>	0.009 (1)	200 - 500 (2 – 5)	15 - 24 (0.5 - 0.8)	The same as baseline (NATMAP)	4.6 (Gonzalez-Sosa et al. 2010)	1.4 (Monger et al., 2022b)	12.07%	18.66%
<i>Acid grassland</i>	0.009 (1)	200 - 500 (2 – 5)	15 - 24 (0.5 - 0.8)		≤ 4.9 (Kingsbury-Smith et al. 2023)	1.2 – 2.8 (Bond et al., 2020)	17.54%	12.11%
					≤ 10 (Monger et al. 2022b)	1.4 – 4 (Manning's <i>n</i> values, Chow, 1959)		
					Significantly greater (Bond et al. 2021)			
<i>Heather</i>	0.009 (1)	100 (1)	22.5 (0.75)	The same as baseline (NATMAP)	The same as baseline	0.75 (Manning's <i>n</i> values, Chow, 1959)	0.32%	0.00%
<i>Heather grassland</i>	0.009 (1)	100 (1)	22.5 (0.75)				7.73%	10.41%
<i>Bog</i>	0.009 (1)	350 (3.5)	15 (0.5)	The same as baseline (NATMAP)	3.3 – 4.2 (Holden et al. 2007)	1.9 – 2.3 (Holden et al., 2008)	3.53%	3.66%
<i>Inland rock</i>	0.0045 (0.5)	100 (1)	22.5 (0.75)	0.5 (NATMAP)	The same as baseline (Medici et al. 2019)	1.3 (Manning's <i>n</i> values, Chow, 1959)	0.74%	0.66%
<i>Freshwater</i>	0.0009 (0.01)	500 (5)	0.3 (0.01)	-	-	-	0.96%	0.89%

<i>Urban</i>	0.0009	1 (0.01)	150 (5)	-	-	Set as the highest	0.03%	0.07%
<i>Suburban</i>	(0.01)					value	0.71%	0.86%
<i>NFM interventions</i>	<i>Parameter multipliers</i>			<i>Ratio of NFM interventions compared with improved grassland with references</i>			<i>Percentage of area</i>	
	<i>m (m)</i>	<i>Ks (m/h)</i>	<i>Kv</i>	<i>M</i>	<i>Ks</i>	<i>Kv</i>		
<i>Hedgerow</i>	0.009 (1)	200 – 1000 (2 – 10*)	15 (0.5)	The same as baseline	2 (Kingsbury-Smith et al. 2023) 2 – 6 (Holden et al. 2019) 22.5 – 27.7 (Wallace et al. 2021)	1.6 – 2.3 (Manning's <i>n</i> values, Chow, 1959)	1.30%	
<i>Woodland (new planted)</i>	0.0135- 0.018 (1.5 - 2)	150 – 250 (1.5 - 2.5)	12 – 22.5 (0.4 - 0.75)	The same as woodland land cover	1.2 (45-yr-old woodland, (Archer et al. 2013)) 2.3 (18-month-old saplings, (Mawdsley et al. 2017)) 2.4 (7-yr-old broadleaf woodland, (Marshall et al. 2009))	The same as woodland land cover	0.61%	
<i>Soil aeration</i>	0.009 – 0.0135 (1 - 1.5)	100 – 500 (1 – 5)	30 (1)	1 – 1.5 (Willis and Klaar, 2021; Kingsbury-Smith et al., 2023)	2.5 – 3 (Chehaibi et al. 2010) 1 – 15 (Wallace and Chappell 2019)	The same as baseline	6.40%	

*Bold numbers are the ranges for parameter sensitivity tests.

**The classification of subgroups in woodlands and grasslands in CEH Land Cover Map partially changed from 2015 to 2020. Confusion and misclassification within grassland classes will also occur (CEH, 2020)

3.3.2.4 Calibration for land cover, NFM interventions and model validation

This section describes the process of incorporating land cover and NFM interventions into the hydrological model through the spatial distribution of parameter multipliers, which were calibrated using an observed event (Event 1) based on Model 0. Land cover (based on CEH land cover map 2015) included broadleaf woodland, coniferous woodland, calcareous grassland, and acid grassland, and NFM scenarios consisted of three implemented interventions in the research catchment: hedgerow planting, woodland planting, and soil aeration. Spatially distributed multipliers of each parameter (Table 3.2) were applied to Model 0 (uniform parameters) to represent these scenarios.

The multipliers summarised in Table 3.2 showed high variability in woodland and grassland land cover types. The range of parameter choices were informed by the results of the previous empirical studies while also considering the baseline values for the study catchment and the limit of parameter settings in the model. Event 1 from 2015 was used for parameter testing, as the shape of hydrograph for this event is characterized by concentrated rainfall and a single flood peak and is particularly relevant for parameter testing since the model's land cover map also corresponds to 2015, making it the most representative event. Sensitivity tests using Event 1 were conducted within the valid parameter test ranges detailed in Table 3.2. For land cover types, the aim was to identify the most accurate set of parameter multipliers for each type, while for NFM interventions, it was to identify the most sensitive parameter set.

Sensitivity tests were conducted using fixed intervals where parameters were selected and paired within the multiplier test range for five sets of tests (Table 3.2): (1) in land cover tests, K_s values were tested at intervals of 2, which paired with K_v values by intervals of 0.1 and 0.15 for woodlands, with m tested at values of 1 and 1.5; (2) in grassland scenarios, K_s was tested by intervals of 1 and K_v at intervals of 0.1; (3) in NFM scenarios, K_s values were tested at intervals of 2 to represent hedgerow planting; (4) for woodland planting, K_s was tested at intervals of 0.5 and K_v at intervals of 0.1 and 0.15, while m was tested at values between 1 and 1.5; (5) soil aeration scenarios involved testing m at intervals of 0.25 and K_s at intervals of 1. The land cover tests identified parameter multipliers that optimised model accuracy for each grassland and woodland type by assessing the correlation with NSE values. After calibrating the multipliers for the

2015 land cover map to achieve the best NSE values for Event 1 (closest to 1), all calibrated values were integrated into the land cover model. For the NFM intervention tests, calibration prioritised maximum flood peak reduction with minimal NSE decrease to ensure intervention effectiveness and maintain the rainfall-runoff relationship established in Model 0, thereby preserving model reliability. Optimal multipliers were applied to represent single and combined NFM scenarios, calibrated to achieve maximum flood mitigation without compromising model accuracy. Final parameter settings are shown in Table 3.3. Pearson correlation analysis, conducted in SPSS after confirming the normal distribution of the dataset, was used to assess the relationship between NSE and parameter values in land cover tests, and between peak reductions and parameter values in NFM intervention tests. Correlation strength was evaluated using Cohen's guidelines ($r > 0.5$ = notable effect) (Cohen, 1988). Correlation analysis was employed to assess the model's sensitivity to the parameters and to explore the pattern of SD-TOPMODEL's response to parameter multiplication for adding spatially distributed land cover and NFM interventions to the spatially uniform Model 0. This analysis identified parameter sensitivity patterns, reduced model uncertainty, and prevented multiple parameter choices from yielding similar model performance.

Table 3.3. Final parameter multiplier settings after sensitivity testing

<i>Land cover class</i>	<i>Model parameter values (multipliers)</i>		
	<i>m</i>	<i>Kv</i>	<i>Ks</i>
Broadleaf woodland	0.0135 (1.5)	22.5 (0.75)	800 (8)
Coniferous woodland	0.0135 (1.5)	22.5 (0.75)	400 (4)
Improved grassland (baseline)	0.009 (1)	30 (1)	100 (1)
Calcareous grassland	0.009 (1)	24 (0.8)	300 (3)
Acid grassland	0.009 (1)	24 (0.8)	300 (3)
NFM interventions			
Hedgerow	0.009 (1)	15 (0.5)	1000 (10)
Woodland (new planted)	0.0135 (1.5)	18 (0.6)	250 (2.5)
Soil aeration	0.0135 (1.5)	30 (1)	400 (4)

For model validation, discharge results after land cover was applied to the spatially uniform Model 0 were compared with observed flow rates from the Gargrave gauging station for the seven events used for calibration and three additional events (two with wet conditions and one with a dry condition) from the 15 discrete flood events identified above. Validation involved calculating NSE values (Table 3.4) and assessing the fit of flood peak discharge and arrival times. Following validation, NFM scenarios were applied to the land cover model, and flood peak reduction effectiveness was assessed by comparing results with the land cover model. A radar plot quantified the area and flood mitigation effects of each scenario using quantile comparisons. Results were grouped by event characteristics (single/multi-peaked and dry/wet catchment conditions) and scenario characteristics (single/multiple interventions) to evaluate their impacts on flood mitigation effectiveness.

Table 3.4. NSE values and peak fits between model outputs and observations for the seven storm events used in the model calibration and three additional events used for model validation (SD = standard deviation)

Scenarios	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6	Event 7	Mean	SD	Validation 1 (31 Dec 2012, wet)	Validation 2 (2 Jan 2015, dry)	Validation 3 (14 Oct 2017, wet)
NSE (Model 0)	0.92	0.86	0.90	0.63	0.73	0.60	0.78	0.78	0.13	0.64	0.96	0.95
NSE (Land cover model)	0.93	0.77	0.82	0.68	0.66	0.59	0.70	0.74	0.12	0.61	0.97	0.91
Percentage of peak differences* of Model 0 (%)	9%	-4 %	12%	24%	5%	32%	10 %	13%	12%	-14%	-5%	-7%
Peak time difference of Model 0 (h)	0.25	-0.25	1	-0.25	-0.75	-2.25	-0.5	-0.39	1.00	-1	-0.5	-0.25
Percentage of peak differences* of land cover model (%)	-2%	-5%	-8%	15%	5%	26 %	2%	5%	12%	-21%	-8%	-10%
Peak time difference of land cover model (h)	0.25	0	1.25	0	-3	-3	-0.5	-0.71	1.65	-1	-0.5	-0.25
Overland flow peak arrival time different of land cover model (h)	0.25	0.25	1.25	0	-0.5	-2	-0.25	-0.14	0.99	-0.5	-0.25	-0.25

*Peak discharge here is the sum of subsurface and overland flow. Percentages are the differences between the modelling peaks compared to the observed peaks as a percentage of observed peaks.

3.4 Results

3.4.1 Sensitivity tests

3.4.1.1 Correlation analysis for model calibration – land cover and NFM interventions

The sensitivity of different land cover types to the three parameters' multipliers varied, and a significant correlation existed between K_s , K_v and model performance. As shown in Figure 3.3 (a), surface roughness K_v was significantly positively correlated with NSE values ($r = 0.918$, $p < 0.001$) as the NSE values increased with the increasing K_v values, but not with soil hydraulic conductivity K_s ($r = 0.303$, $p = 0.195$). NSE values increased until K_s multiplier reached 6 after which they were no longer affected by K_s . This indicates that for woodland land cover types, including broadleaf woodland and coniferous woodland, the model fit improved with a marginal increase in surface roughness. Thus, the best fit of the model (the maximum NSE values) for woodland land cover types was achieved when K_v decreased by 0.75 times and K_s increased by 8 times (as highlighted in Figure 3.3a). Multiplier values of 1.5 or 2 for soil active water storage depth m did not affect the correlation patterns between K_s , K_v and model fit. Choosing the multiplier of 1.5 reduced the impact of model performance caused by parameter changes, while a multiplier of 2 increased the standard deviation of NSE results in general.

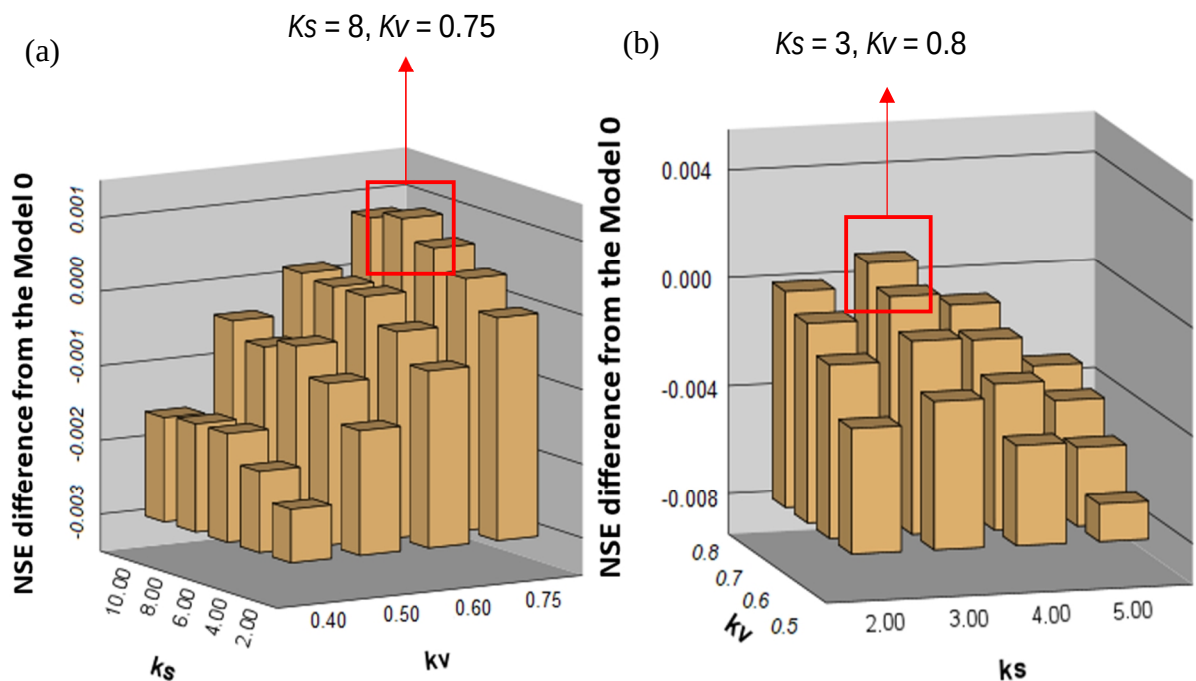


Figure 3.3. The model parameter multipliers: surface roughness K_v and soil hydraulic conductivity K_s , plotted with NSE difference from Model 0: (a) woodland, (b) grassland. Note the differences in axes limits between figures.

As highlighted in Figure 3.3 (b) for grassland land cover types (calcareous grassland and acid grassland), K_s ($r = -0.650$, $p < 0.01$) was more strongly correlated to NSE values than K_v to NSE ($r = 0.625$, $p = 0.01$). The correlation between K_s and NSE tended to arc and had a relative peak when K_s multiplier was 3. The relationship between K_v and NSE values were consistent with the above results of woodland tests, i.e., increases in surface roughness led to better model fit. Thus, model fit of grassland land cover types were significantly correlated with both K_v and K_s . The best model fit was achieved when K_s increased to 3 times that of Model 0 and K_v increased marginally from Model 0. Similar to the woodland results, m had no significant correlation to the model fit of grassland scenarios. Overall, the parameter multipliers for woodland and grassland scenarios were chosen using the highest NSE values achieved in the sensitivity tests.

For the NFM interventions, the same sensitivity tests were used to find the most effective combination of parameter multipliers to represent three NFM interventions. All NFM scenarios were applied upon the land cover, and their test results were compared with the Model 0 results. As shown in Figure 3.4, none of these parameter tests caused a significant decrease in the NSE values from Model 0, indicating that the test did not affect model performance. Thus, correlation analysis for NFM scenarios was focused on comparing the effects on flood peaks.

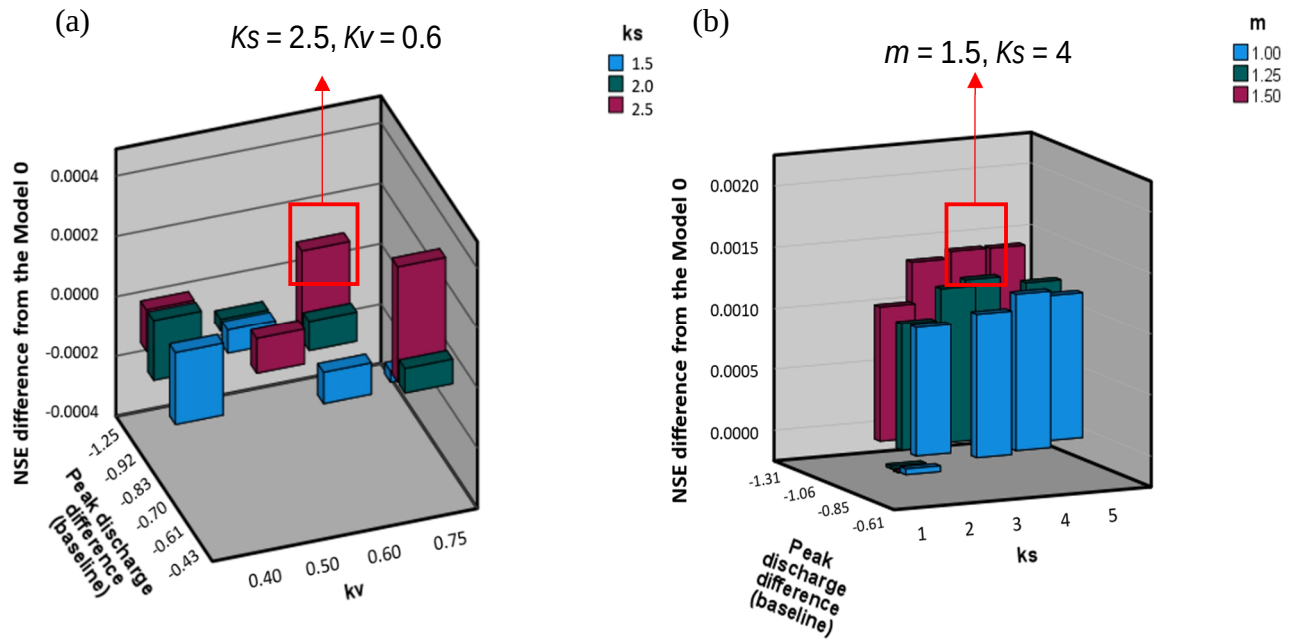


Figure 3.4. The model parameters: surface roughness K_v and soil hydraulic conductivity K_s plotted with NSE difference and peak discharge difference from Model 0: (a) woodland planting, (b) soil aeration. Note the differences in axes limits between figures.

Among the three NFM interventions, there was no significant pattern among K_s , NSE values, peak discharge differences and peak arrival time differences for hedgerow planting. The greatest flood peak reduction occurred when K_s reached 10 times the baseline value, suggesting this as the most effective multiplier for hedgerows. For woodland planting, test results were first compared between m multiplier of 1.5 and 2. While the multiplier of 2 reduced mean flood peak discharge by 0.58 m³/s and delayed mean peak arrival time by 0.02 h, it increased variability as the standard deviation increased. To maintain consistency with the land cover tests described above, the multiplier was chosen as 1.5 to represent newly planted woodlands. K_v in woodland planting was strongly correlated with peak discharge reduction ($r = 0.900$, $p < 0.001$), which indicates that the increase in surface roughness significantly reduced peak discharge, while K_s changes had no significant impacts on peak reductions ($r = -0.119$, $p = 0.712$). When the multiplier of K_s was taken as 2.5, using a K_v multiplier of 0.5, 0.6 and 0.7 all increased the NSE values, with the multiplier of 0.6 resulting in the greatest reduction in peak discharge. For woodland planting, changes in K_v and K_s had no significant impact on peak arrival delay. For soil aeration, all parameter pairs increased the NSE value. The most effective flood reduction test results were chosen (Figure 3.4b). An increase in m significantly reduced peak discharge ($r = -0.619$, $p = 0.014$), and an

increase in K_s slightly reduced peaks ($r = -0.646$, $p < 0.01$) (Figure 3.4b). Finally, a parameter pair that maximized flood reduction and maximized the NSE value was chosen for soil aeration. Final parameter multipliers for land cover and NFM interventions are shown in Table 3.3.

3.4.1.2 Sensitivity of peak changes – land cover and NFM interventions

For peak discharge reduction and arrival time delay in land cover tests, K_v was significantly correlated with peak discharge reduction for woodland ($r = 0.959$, $p < 0.001$) and grassland land cover types ($r = 0.750$, $p < 0.001$), but not with peak arrival time. K_s and m showed no correlation with peak changes. This indicates that surface roughness increases via woodland and grassland land cover significantly reduced peak discharge. For Event 1, woodland land cover attenuated mean peak discharge by 1.35% (SD = 0.84%) and delayed arrival by 0.3 h (SD = 0.1 h). Grassland land cover reduced mean peak discharge by 3.6% (SD = 1.6%) but had no peak delay (0 h; SD = 0.17 h). Therefore, woodland was more effective at delaying peaks, while grassland had a greater effect on peak discharge reduction.

Parameter test results for all three NFM interventions (section 3.4.1.1) revealed sensitivity in reducing peak discharge compared to the Model 0 results for Event 1. Woodland planting and soil aeration decreased flood peaks by a mean value of 0.731 m³/s (1.15%) and 0.883 m³/s (1.40%) respectively, showing greater sensitivity than hedgerows. However, none of the three NFM interventions had a significant impact on flood peak delay.

3.4.2 Model performance: robustness and accuracy

To calibrate and validate the model, NSE values and peak fit results were evaluated for the baseline and land cover models (Table 3.4). While NSE values for some events in the land cover model were lower than in Model 0 with spatially uniform parameters, this did not indicate that land cover reduced model accuracy. Since the study focuses on flood peaks, the accuracy of peak fits was deemed more important. Hydrographs for Event 1 (Figure 3.5a) showed that the land cover model increased low flows at the start of the event and reduced peak flows, providing a better fit than Model 0.

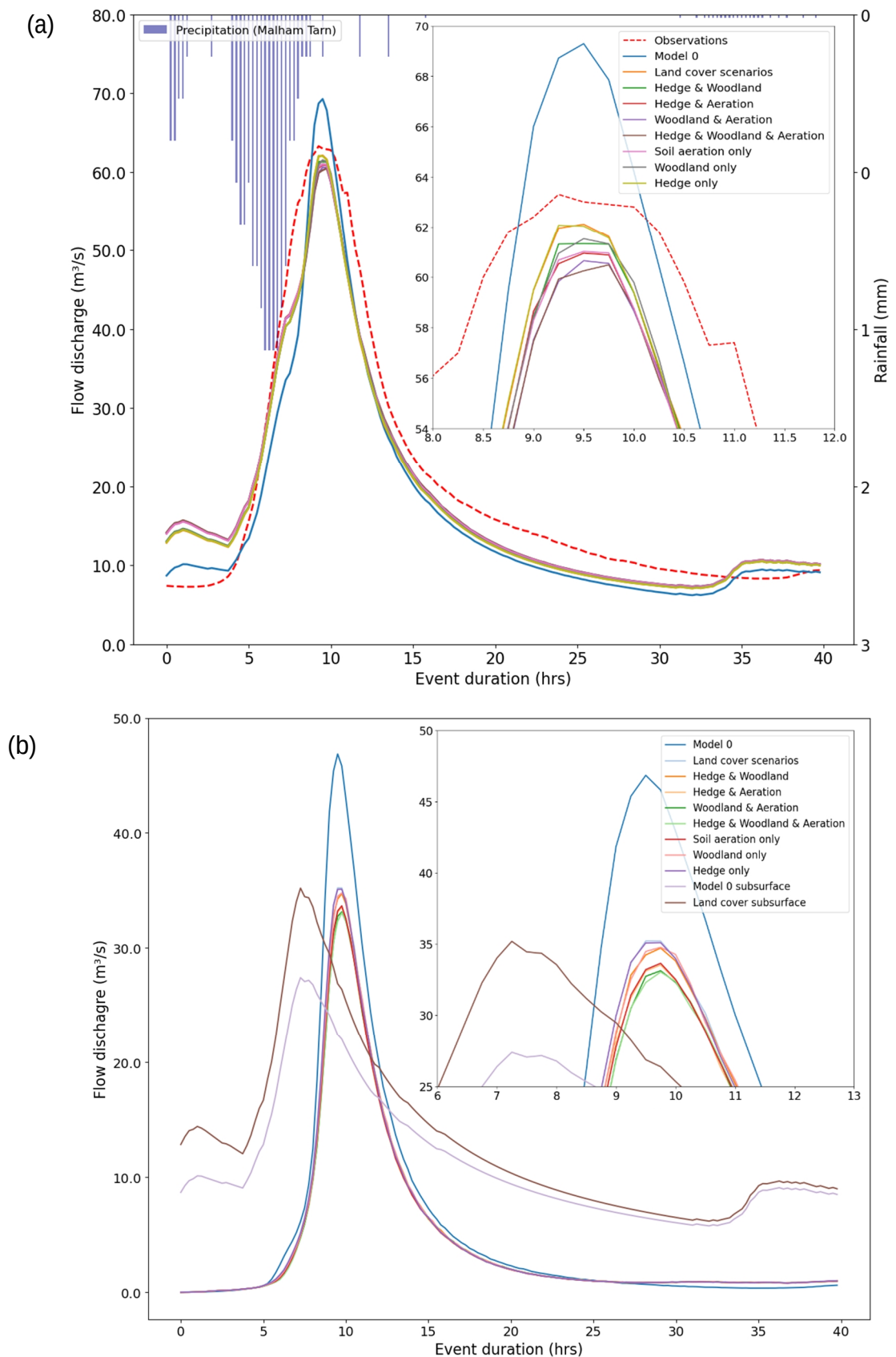


Figure 3.5. Hydrographs comparing observations, Model 0, land cover model and NFM scenarios for Event 1 (16-h storm event on 11/12/2015, 45 hr simulation duration without showing the first 5 h of precondition preparation) with inset showing close-up details of flood peaks; (a) total runoff, (b) overland flow and subsurface flow discharge.

Peak fits were assessed by comparing maximum flood peaks and arrival times to observations for Model 0 and the land cover model, respectively (Table 3.4). The land cover model had a better fit for peak discharge but not for arrival times. When comparing the total runoff and overland flow time series data in the model results, there was a difference in peak arrival times as illustrated in Figure 3.5. These biases were from 0 to 2.5 h in several events. It is likely the bias may be due to model characteristics and does not represent an error in the model results. Moreover, it was verified that the difference between the peak arrival times of overland flow time series in the land cover model and observations were negligibly small (Table 3.4) and did not affect subsequent NFM scenario results. This is the reason why only overland flow discharge data were used for the analysis of the NFM scenario results.

3.4.3 NFM scenarios

After obtaining all parameter expressions as shown in Table 3.3 through sensitivity testing, all land cover and NFM scenarios were put into the model and run for all seven storm events. For NFM scenarios, the best possible impacts identified through modelling in this study have been demonstrated. There was variability in the effectiveness of the different NFM interventions for each storm event and the impact of the different events by NFM scenarios. The details of overland flow results for NFM scenarios were compared to overland flow results for the land cover model as detailed below.

3.4.3.1 Impacts of single intervention scenarios

The soil aeration intervention was implemented across the largest proportion of the study catchment (6.40%), which is much higher than the area of the other two interventions: woodland planting (0.61%) and hedgerow planting (1.30%) (Figure 3.1). The axes of the radar plot (Figure 3.6) represent the quartiles of peak discharge reduction and area proportion. Notably, Event 4 showed the highest flood peak reduction percentage compared to other events (Figure 3.6a). The overland flow peak reduction effect of the single intervention scenarios varied. Discharge reduction by soil aeration was largely proportional to the increase in area of implementation. The results showed that the discharge reductions achieved by soil aeration interventions were consistently above the 50th quantile for peak reduction in Figure 3.6b. Woodland planting represented the smallest area yet achieved effective flood peak reduction in all events.

This contrasts with the results for hedgerow planting. Although hedgerow planting increased K_s ten-fold and doubled the K_v of baseline values, neither resulted in a significant reduction in flood peaks, with a maximum reduction of only 1.3% across all seven events (Table 3.5).

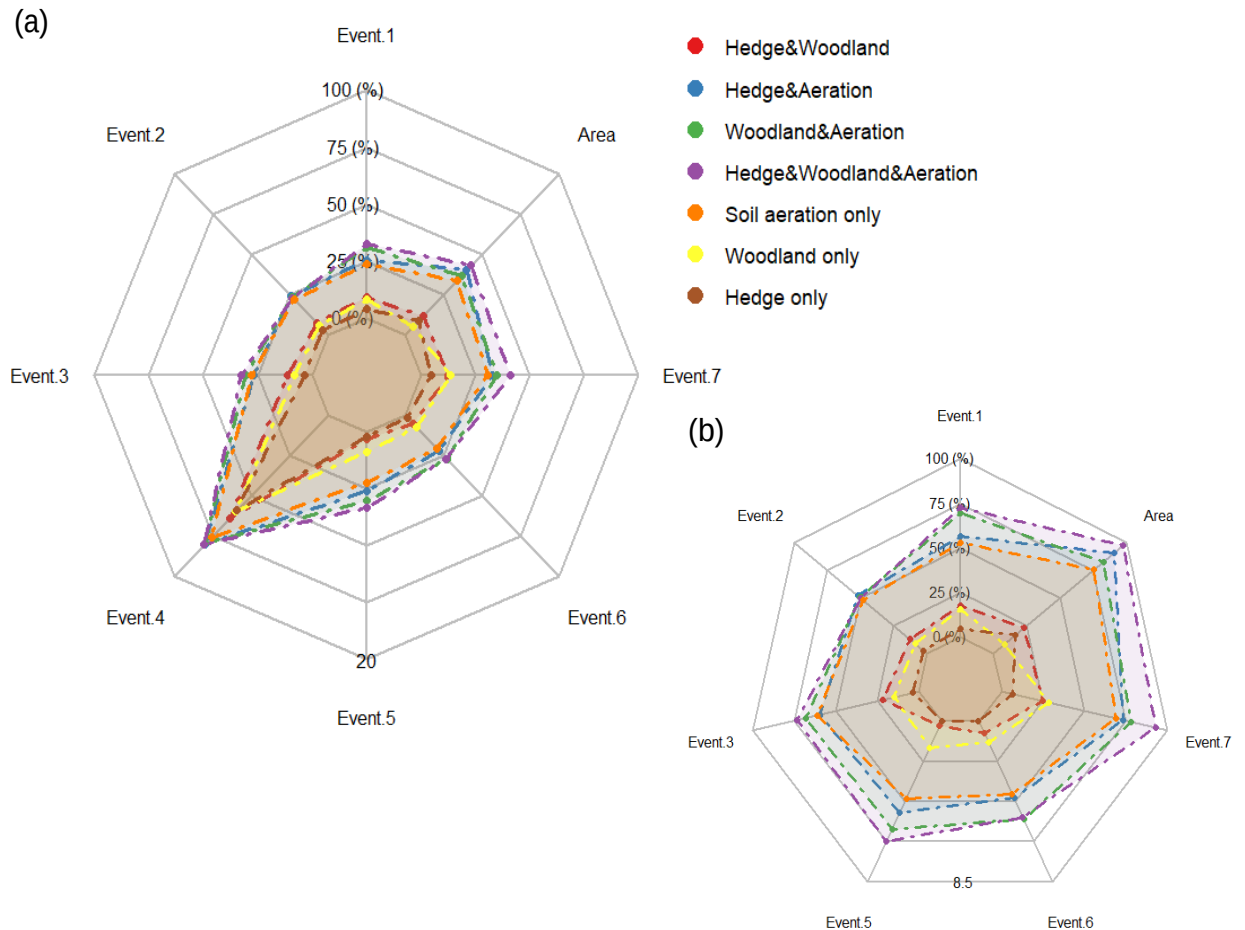


Figure 3.6. Radar plot of overland flow peak reductions for single and combined NFM intervention applications among seven storm events (the axis labels are in percentage and axes were divided into quartiles); (b) excluded Event 4 from (a).

Consistent with the results of the previous parameter sensitivity tests of NFM scenarios for Event 1 (Figure 3.4), soil aeration was more sensitive in reducing peaks than woodland planting, but both had a greater effect than hedgerow planting (Figure 3.6). This was reflected in the mean values of overland flood peak reductions calculated for seven events in Table 3.5. While the standard deviations of peak reductions across the seven events were relatively similar, hedgerows led to slightly higher peak flow variability compared to the other two interventions. The high standard deviation values indicated

that the characteristics of the events may have contributed to the increased heterogeneity in the results of NFM scenarios. To better interpret the validity of different NFM scenarios, the results were analysed by grouping according to event characteristics: the shape of hydrographs (single or multi-peaked), the wet or dry preconditions of the catchment and their combinations (Figure 3.7). The grouped results showed that the same NFM interventions were less effective in reducing overland flow peaks in multi-peaked flood events compared to single-peaked events. The peak reduction driven by NFM interventions in dry conditions was approximately twice as effective as in wet conditions. NFM interventions can therefore have greater effectiveness under certain conditions, such as dry antecedence in soil during a single-peaked flood event.

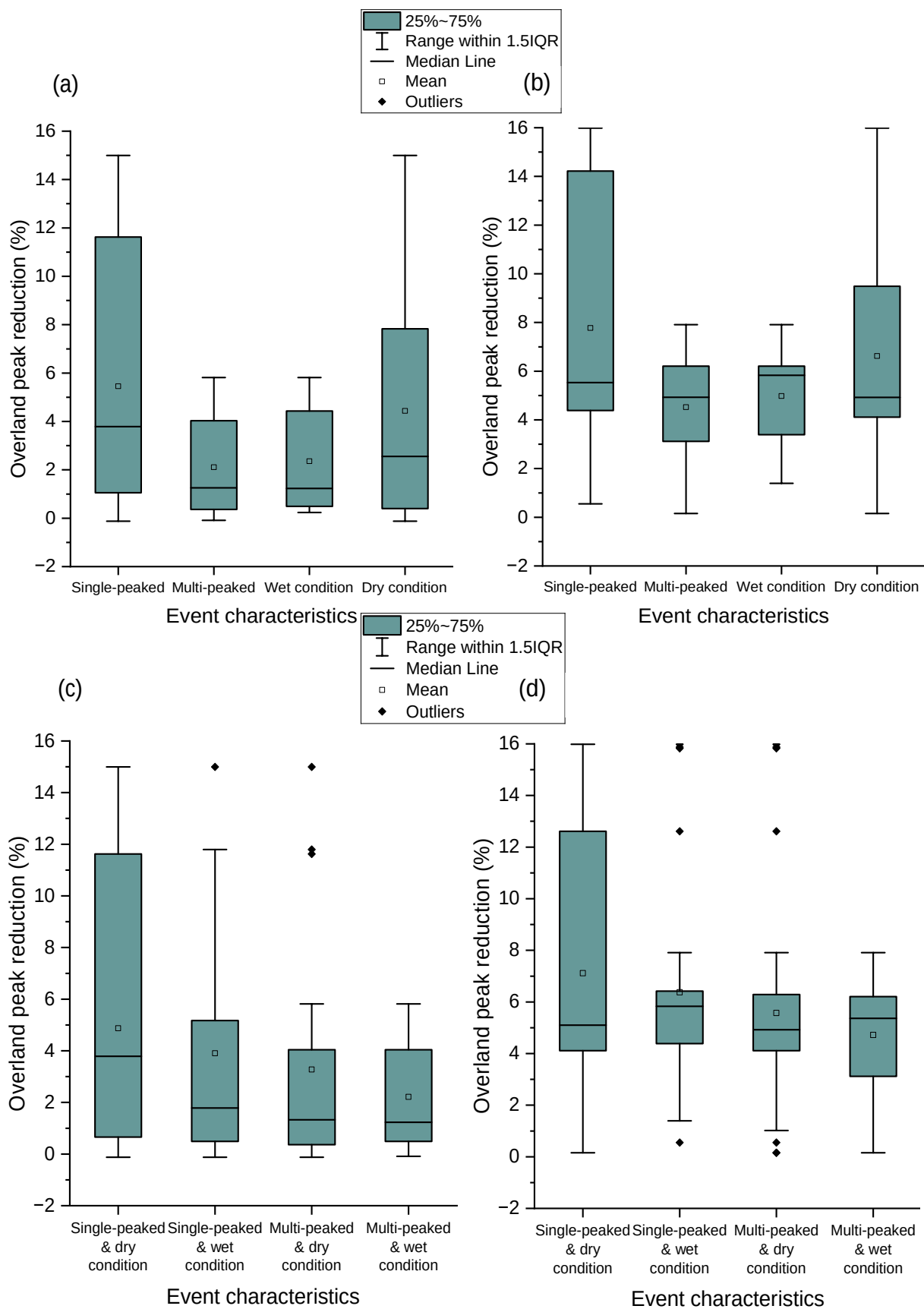


Figure 3.7. Overland flow peak reduction (%) grouped by characteristics of flood events.

(a) & (c) single intervention, (b) & (d) multiple interventions.

Table 3.5. Percentage reduction in overland flow peak discharge across seven storm events for NFM scenarios, and proportion of catchment area for each scenario (SD = standard deviation, SEM = standard error of mean)

NFM Scenarios	Overland flow peak reduction (%)							Overland flow peak delay (h)			Area (%)		
	Event 1 (wet)	Event 2 (dry)	Event 3 (wet)	Event 4 (dry)	Event 5 (dry)	Event 6 (dry)	Event 7 (wet)	Mean	SD	SEM	Mean	SD	SEM
Soil aeration only	4.43	4.02	5.17	15.00	4.04	3.79	5.82	6.04	3.72	1.41	0.11	0.23	0.09
Woodland only	1.23	0.66	1.18	11.79	1.33	1.05	2.34	2.80	3.70	1.40	0.11	0.18	0.07
Hedgerow only	0.31	0.14	0.23	11.62	-0.09	-0.12	0.49	1.80	4.02	1.52	0.00	0.19	0.07
Hedgerow & Woodland	1.39	1.02	1.75	12.61	0.15	0.55	2.03	2.79	4.06	1.53	0.07	0.11	0.04
Hedgerow & Soil Aeration	4.75	4.39	5.04	15.87	4.81	4.02	6.20	6.44	3.90	1.47	0.04	0.16	0.06
Woodland & Soil Aeration	5.90	4.24	5.76	15.83	5.68	5.16	6.62	7.03	3.65	1.38	0.14	0.12	0.05
Hedgerow & Woodland & Soil Aeration	6.17	4.20	6.21	15.99	6.36	5.04	7.91	7.41	3.66	1.38	0.18	0.17	0.07
Mean	3.45	2.67	3.62	14.10	3.19	2.78	4.49						
SD	2.24	1.80	2.29	1.86	2.48	2.06	2.61						
SEM	0.85	0.68	0.86	0.70	0.94	0.78	0.99						

3.4.3.2 Impacts of combinations of scenarios

Results from the single NFM intervention scenarios were combined into pairs or with all three and tested for seven storm events. The overland flow peak reductions varied among different combinations of NFM interventions (Table 3.5). Comparing the mean of reductions shows that the flood mitigation effectiveness of the combined intervention scenarios is not simply equivalent to the sum of the effects of single intervention scenarios, where different combinations may have enhanced or reduced effects on the flood mitigation. For example, the mean overland flow reductions for the hedgerow & woodland planting combination and for the single woodland planting intervention were almost identical. However, for the hedgerow & soil aeration intervention combined, the mean discharge reduction increased by 0.4% compared to the single soil aeration intervention. These increases by combining hedgerow planting with another intervention are all less than the mean discharge reduction of 1.8% that can result from the hedgerow planting intervention alone. The standard deviations in Table 3.5 are all between 3.5 – 4%, which is relatively high compared to the mean indicating that the impact of the interventions vary widely between events.

Although there is a clear flood mitigation effect in each combination, not all events have a stronger peak reduction by combining NFM interventions. Figure 3.6 shows that the effectiveness of overland flow peak reduction varies among events. For example, the hedgerow & woodland combination (red line) achieved an overland flow peak reduction effect comparable to the proportion of area implemented for all events except Event 5. This differed from the results for the woodland only scenario, where the inclusion of the hedgerow intervention significantly increased peak mitigation in Event 4 but had the opposite effect in Event 5. The soil aeration intervention had the greatest overland flow peak reduction as it had been applied to the largest proportion of the catchment and had positive interaction effects when woodland or hedgerow planting were combined with it among all seven events. The combination of woodland and soil aeration had a more effective overland flood peak reduction effect than the combination of hedgerow and soil aeration in five events. The combination of three interventions resulted in the maximum peak reduction, except in Event 2 where the effect was slightly lower than that of hedgerow & soil aeration and woodland & soil aeration combinations and in Event 6 where the effect was slightly lower than that of the woodland & soil aeration

combination. Thus, even though the addition of woodland planting and soil aeration interventions to the combinations were effective in peak reduction, there were still differences in response to different storm events. Comparing Figure 3.7 (a) and (b) for event groups, the increase in the median under all four groups shows that multiple interventions enhanced the overland flow peak reduction effect overall. A similar finding is shown in Figure 3.7 (c) and (d), where multiple interventions were effective at enhancing NFM performance under unfavourable conditions, such as multi-peaked events and wet soil conditions. Thus, the weakening of NFM effectiveness due to multi-peaked flooding and wet conditions were less pronounced under multiple interventions compared to a single intervention.

In scenario tests, overland flow peaks were delayed in arrival by up to 0.5 h. Several scenarios had overland flow peaks that were advanced by one timestep (0.25 h) in some events. Hedgerow & woodland, woodland & soil aeration and all three interventions scenarios resulted in no advance in overland flood peak arrival time among the events. Overall, the mean delay for each scenario across the seven events ranged between 0 and 0.18 h. The mean delays for soil aeration and woodland planting were the same but woodland planting had a smaller standard deviation suggesting less individual variation among events. The hedgerow planting scenario had no effective peak delay compared to the other scenarios. The mean delays for various combinations of scenarios generally followed the pattern of the overland flow peak reductions: adding soil aeration and woodland planting on any interventions increased the delay slightly, while the combination of three interventions resulted in the greatest delay.

3.5 Discussion

This study used SD-TOPMODEL to investigate the impacts of different land cover types and NFM interventions at an 81.4 km² catchment. These effects include impacts on model accuracy and performance, flood peak reduction and arrival time delays, and impacts on the interaction of subsurface and overland flows. In general, it was found that SD-TOPMODEL can efficiently and accurately simulate different types of NFM interventions at this catchment scale, validated against multiple storm events, while allowing high resolution (5 m) spatial distribution. The modelling results indicated that

multiple interventions were not always the most effective. Event characteristics and antecedent conditions played a significant role in determining the level of flood mitigation.

3.5.1 Evaluating model parameters and model performance

In the parameter calibration and validation of the model, the evaluating criteria are dynamic, including model fit metrics (e.g., NSE values) and flood peak reduction, which are adapted based on the objectives of each calibration scenario. Multi-objective optimization has been justified to improve compromised solutions and enhance the hydrological consistency of parameter settings (Dung et al., 2011; Wöhling et al. 2013; Shafii and Tolson, 2015; Althoff and Rodrigues, 2021). A multi-objective calibration approach is needed for the accuracy of the simulation as indicated by the NSE values and the effectiveness against flood mitigation in this study, which depend on the purpose of the test (Efstratiadis and Koutsoyiannis, 2010). For example, during the calibration of parameters for land cover types, results indicated that increasing surface roughness was the most effective factor in reducing peak discharge, but the multipliers with least amount of change within the range were chosen. This is because the best model accuracy (NSE values closer to 1) was achieved when the roughness parameter was increased by the least amount. The land cover model aims to determine the best fit to the actual land cover distribution by comparing to observations, thus, NSE values were more critical criteria for the land cover model. On the contrary, in the NFM scenarios, while the NSE values were used as criteria for model stability, the determination of the parameter values depended on the best flood peak reduction that could be achieved with similar NSE values. This dual-objective approach aligns with the methods used in recent studies that emphasize balancing model stability with functional performance (e.g., flood peak reduction) (Shafii and Tolson, 2015; Althoff and Rodrigues, 2021). Future research could build on this strategy by exploring how different catchment characteristics influence the trade-off between stability and effectiveness, potentially leading to the development of adaptive calibration frameworks tailored to specific hydrological contexts.

3.5.2 Impacts of land cover type and NFM interventions on flood peak reduction and timing

Results from this study suggest that NFM interventions achieve maximum potential effectiveness during single-peaked storms, particularly under dry antecedence. In previous modelling studies of NFM on flood peak reduction, it has been shown that the reductions vary between events, and that this is mainly related to event characteristics (Gao et al. 2016; Gao et al. 2018; Ferreira et al. 2020), particularly pre-event soil moisture (Wahren et al. 2012). Some studies also considered seasonal rainfall, which could be adjusted by model parameters (Gabriels et al. 2022). The seven events used in this study occurred in winter months from October to March and were grouped based on event characteristics and catchment antecedent conditions allowing them to be compared by their impact on overland flow peak reduction (Figure 3.7).

Overland flow peak reductions delivered by NFM scenarios were not significantly different for high or low rainfall intensity events when rainfall was concentrated. The most prominent of these was Event 4, which resulted in a greater peak reduction than the other events in each of the single intervention scenarios. This may be because Event 4 was a rapid flow event that occurred under dry antecedent conditions and had a much higher flood peak discharge than the other events. Overall, the results suggest that greater overland flow peak reduction occurs under dry antecedence compared to wet antecedence (Figure 3.7), which aligns with findings from other monitoring and modelling studies on land cover and land use (Bond et al., 2020; Breuer et al., 2009; Wallace and Chappell, 2019). However, the sample size of events in this study is small and further testing for rainfall varieties is needed in the future.

The overland flow peak reduction obtained in this study for the three combined NFM interventions was in the range of 4.20% - 15.99%. We found modelling the effects of upland interventions on downstream runoff at a larger catchment scale (81.4 km²) did not yield significantly different results to other local scale modelling studies (Bond et al., 2022; Hankin et al. 2019; Kingsbury-Smith et al. 2023; Monger et al., 2024). No significant correlation was observed between the peak reduction and rainfall intensity, consistent with findings from the data synthesis by Chapter 2. The study with the closest results to ours also employed SD-TOPMODEL though at a lower resolution (20 m) and

concluded that upland land management scenarios covering most of the catchment (84 km²) resulted in 3.9% to 15% flood reduction with various rainfall intensities (Gao et al. 2017). In contrast, our study used a higher resolution and covered all realistically existing land cover types, which is closer to the reality.

The closest catchment used for a published NFM simulation to that of the Upper Aire was for Bishopdale in northern England, a study which utilised SD-TOPMODEL and yielded flood peak reductions up to 11% (Kingsbury-Smith et al. 2023). Their study concluded that the scenario combining all types of NFM interventions across a large percentage of the 38 km² catchment achieved the smallest peak reduction for a 100-year rainfall event and suggested that such an effect may be caused by increased synchronisation between small tributaries. This is contrary to the findings of our study in our larger catchment (81.4 km²), which showed that a combination of existing interventions (covering 8.31% of the catchment) produced greater reductions in peak flow than any single intervention, including soil aeration (6.40% of the catchment), the largest and most effective individual intervention. The larger catchment scale of our study offers greater potential for a strategic distribution of multiple NFM interventions leading to desynchronisation of peak flows and achieving solid peak reductions with a lower percentage of intervention areas. However, the differences in NFM modelling results between catchments and scenarios highlight the importance of modelling potential responses on a case-by-case basis for each individual catchment (Chapter 2). This is essential for the effective planning and implementation of a portfolio of catchment based NFM interventions both within the UK and internationally. Additionally, we tested observed rainfall events ranging from 1-year to over 200-year return periods, and calibrated and validated the model using observed data, enhancing the model's credibility and realism. Another study conducted in Swindale in northern England used the Dynamic TOPMODEL combined with a 2D hydraulic model to find flow reductions of 2 – 6% by NFM (Hankin et al. 2019). This suggests that even though the study is for a combination of NFM interventions and excludes differences in catchment size and rainfall intensity, the area and location of the interventions, the characteristic or precondition of the catchment, and the model used, as well as its resolution and parameter choices, all have an impact on the simulation results.

We also found that the flood reduction from different NFM combinations is not directly proportional to the sum of the areas where interventions were implemented. The hydrological response of NFM interventions is primarily attributed to the attenuation of the main flood wave traveling through the intervention area (Dixon et al. 2016). When upscaling the study area, the peak flow reduction effects from different sub-catchments did not simply accumulate at the whole catchment scale (Pattison and Lane, 2012). As a result, potential synchronisation between sub-catchments means that the NFM effect on peak discharge does not increase in direct proportion to the area and number of interventions implemented. These subtle differences in peak discharge make it challenging to isolate model uncertainty.

3.5.3 Implications for SD-TOPMODEL and NFM

There was a bias in the flood peaks in the three outputs of the model (total runoff, subsurface flow, overland flow), which is dictated by model characteristics. A lag time exists between the peak of total runoff and the peak of overland flow (Figure 3.5). The arithmetic mechanism of the model is to prioritise subsurface runoff and to start generating saturation-excess overland flow when the soil is saturated, and these flows are calculated separately in each grid and each timestep (Gao et al. 2015), which allows the model to fully represent the rainfall-runoff process within the topsoil. This procedure allows the model to output the amount of runoff from the subsurface and surface at each timestep and each grid. Thus, the model produces total runoff and overland flow rising and falling limbs at different times, and their delay lengths also vary between events (Figure 3.5).

The scenarios in this study significantly reduced total runoff compared to the spatially uniform Model 0, while overland flow decreased, and subsurface flow increased (Figure 3.5b). Similarly, Monger et al. (2024) found that woodland scenarios critically affected the interactions of subsurface and overland flows in SD-TOPMODEL results and reduced total runoff. Increasing the woodland cover improved soil permeability, which increased subsurface flow and reduced its conversion to overland flow (Monger et al. 2022a; Monger et al. 2022b; Monger et al. 2024). Grasslands were found to have higher surface roughness and lower soil permeability than woodlands (Bond et al. 2020; Monger et al. 2022b), which may influence overland flow more than subsurface flow in SD-TOPMODEL

(Bond et al. 2022). When land cover and NFM scenarios were applied, the subsurface flow increased at the beginning of storm events, which delayed the time before the onset saturated-excess overland flow. This is because all simulated scenarios increase soil hydraulic conductivity and surface roughness in general. Higher infiltration rates and longer infiltration times allow more water to be stored in shallow soils. Moreover, the land cover and NFM scenarios increase the efficiency of the soil saturation process while increasing the active area of subsurface runoff in the catchment. Therefore, overland flow peaks are reduced by these scenarios. The simulation results of SD-TOPMODEL efficiently and accurately demonstrate the effectiveness of NFM.

3.6 Conclusions

Our study demonstrates the first successful application of SD-TOPMODEL in a catchment (81.4 km²) at a 5 m resolution, achieving a strong fit to observed data, with NSE values reaching up to 0.93 and minimal peak flow errors. In the modelling of land cover types in the study catchment, woodland was found to be more effective in delaying peaks, whereas grassland was more effective in reducing peak discharge. Among the existing NFM interventions, soil aeration emerged as the most effective individual measure, achieving greater peak discharge reduction results than woodland planting and hedgerow planting. However, the effectiveness of NFM interventions was influenced by flood and rainfall characteristics, as well as pre-event catchment conditions (wet or dry). Notably, greater flood peak reductions were observed during single-peaked events and in dry pre-event conditions. Furthermore, multiple interventions proved more effective and resilient than single interventions in attenuating floods at the catchment scale we examined. The results also revealed that the area and number of interventions were not decisive in flood mitigation. This finding presents an opportunity to strategically plan multiple NFM interventions at the catchment scale, enabling a trade-off between intervention area and cost-effectiveness. Therefore, we recommend that high-resolution, spatially distributed modelling of more catchments be undertaken to investigate the impact of catchment characteristics on the effectiveness of NFM. This would support the optimisation of spatial planning and enhance the integration of NFM with other flood risk management measures during the planning stage.

3.7 References

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Chapter 4. A coupled hydrological-hydrodynamic modelling approach for assessing the impacts of multiple natural flood management interventions on downstream flooding

4.1 Abstract

While natural flood management (NFM) as a flood mitigation strategy is becoming widely used, there remains a lack of scientific evidence regarding the effectiveness of different NFM scenarios under various high flow events within a catchment. To demonstrate how catchment scale and NFM interventions interact to determine flood peaks, combined scenarios of existing NFM interventions in the Upper Aire and an ideal maximum woodland scenario were modelled by a coupled model, integrating Spatially Distributed TOPMODEL (SD-TOPMODEL) with a 2D hydrodynamic model (Flood Modeller 2D) at the same catchment scale. The output of SD-TOPMODEL and the input of Flood Modeller at river junctions can be synchronised at each time step, making it possible for the coupled model to be fully synchronised. Results showed that the coupled model exhibited a strong fit with observed data, effectively capturing flood peaks and peak shapes. Leaky dams were found to be more effective at delaying flood peaks than reducing peak discharge, though these effects were inversely proportional and influenced by tributary characteristics such as channel gradient. Simulations of NFM scenarios consistently demonstrated positive flood mitigation impacts, including reduced peak discharge, inundation extent, and depth, while the maximum woodland scenario increased inundation extent and depth due to unintended synchronisation of flood wave arrivals. The study demonstrated the utility of the coupled model for evaluating NFM strategies while emphasizing the need for further validation and exploration of systematic interventions at larger catchment scales. By providing insights into the interactions between NFM interventions and catchment characteristics, this research contributes to the optimization of flood risk management strategies and informs future policy development.

4.2 Introduction

The number of nature-based solutions (NBS)-related studies has grown rapidly over the last decade worldwide but especially in Europe, including a large number of natural flood management (NFM)-related studies (Thaler et al., 2023; Chapter 2). NFM as a subset of NBS attempts to work with natural processes to reduce flood hazards (Iacob et al., 2014; Dadson et al., 2017), and currently requires a shift from pursuing localised flood mitigation effects to catchment-wide flood management strategies (Lane, 2017; Wilkinson et al., 2019; Bark et al., 2021; Black et al., 2021; Carter et al., 2024; Lalonde et al., 2024; Chapter 2). Leaky dams, riparian buffer strips, and land and soil management are often utilized as NFM interventions to achieve flood mitigation. Leaky dams reduce flow velocity in the channels and increase upstream channel overflow to the floodplain (Kitts, 2010; Thomas and Nisbet, 2012; Addy and Wilkinson, 2019; Grabowski et al., 2019; Hankin et al., 2020; Norbury et al., 2021; Follett and Hankin, 2022; van Leeuwen et al., 2024). Expandable field storage alongside riparian buffer strips increases surface and subsurface storage capacity with greater surface roughness in the floodplain and offline storage (Keys et al., 2018; Metcalfe et al., 2018; Hankin et al., 2019; Beven et al., 2022; Lockwood et al., 2022). NFM interventions based on land and soil management can slow the rainfall-runoff response process in the catchment by increasing infiltration rates and soil water storage capacity (Marshall et al., 2014; Dixon et al., 2016; Gao et al., 2016; Bond, Stephanie et al., 2022; Monger et al., 2024; Chapter 3). Research suggests that the implementation of multiple NFM interventions in a catchment has the potential to enhance flood mitigation effectiveness, however, the interactions and impacts of different types of interventions remains uncertain (Ramsbottom et al., 2019; Ferreira et al., 2020; Nicholson et al., 2020; Black et al., 2021; Carter et al., 2024; Chapter 2; Chapter 3). The effectiveness of flood mitigation has not been consistently improved by the deployment of multiple interventions across all study catchments, suggesting that factors such as catchment scale, the spatial extent, and the location of interventions play a significant role (Dixon et al., 2016; Kay et al., 2019; Barnsley et al., 2021; Black et al., 2021; Kingsbury-Smith et al., 2023). These findings highlight a critical need to better understand the impacts of a network of multiple NFM interventions on flood hazards at the catchment scale.

As described in Chapter 3, NFM interventions designed to mitigate flood hazards and peak flows by altering soil and surface roughness properties have been successfully modelled in SD-TOPMODEL. The subsequent step entails expanding this modelling framework to include surface structures introduced by NFM interventions within river channels and floodplains, particularly leaky dams, which are currently underrepresented in the hydrological model (Addy and Wilkinson, 2019). The integration of a coupled hydrological and hydrodynamic model offers a robust approach for encompassing all types of NFM interventions (Hankin et al., 2019; Ferguson and Fenner, 2020). This coupled approach also presents potential benefits for scaling up to larger catchments and enhancing flood-related outputs, including inundation extents and depths (Hill et al., 2023).

Leaky dams have been widely recognized for their flood mitigation benefits and their ability to delay peak travel time at local scales, independent of rainfall intensity (Kitts, 2010; Thomas and Nisbet, 2012; Addy and Wilkinson, 2019; Norbury et al., 2021; Chapter 2). However, their effectiveness diminishes at the catchment scale, where their impact remains largely localized to the specific tributaries or areas of implementation (Thomas and Nisbet, 2012; Addy and Wilkinson, 2019; Hankin et al., 2020; Black et al., 2021). Both physical experiments and modelling studies have demonstrated that increasing the number of these interventions within small tributaries can enhance peak flow reduction (Thomas and Nisbet, 2012; Hankin et al., 2020; Follett et al., 2021; Follett and Hankin, 2022; Follett et al., 2024), but their efficacy is constrained by factors such as the location and physical properties of the leaky dams, as well as the characteristics of the tributary and its contribution to the overall catchment hydrology (Hankin et al., 2020; Black et al., 2021; Norbury et al., 2021; Follett and Hankin, 2022; van Leeuwen et al., 2024). There are also uncertainties in the effectiveness of leaky dams under various conditions, necessitating further investigation. Recent modelling studies of leaky dams have found that incorporating geometric adjustments (e.g., barrier walls, gates, or orifices) alongside roughness adjustments in 1D and 2D hydrodynamic models can accurately represent leaky dams within stream networks (Addy and Wilkinson, 2019; Leahey et al., 2020; Follett and Hankin, 2022; Senior et al., 2022). A notable gap in existing research is the lack of evidence regarding the performance of leaky dams under

conditions exceeding their bankfull capacity, during which overtopping may occur, potentially altering their effectiveness (Addy and Wilkinson, 2019).

This study addresses these research gaps by employing a coupled modelling approach that integrates SD-TOPMODEL (hydrological model) with Flood Modeller 2D (hydrodynamic model). Leaky dams are represented as orifices with increased roughness to evaluate their performance under various high flow events, including those exceeding bankfull conditions. This coupled modelling approach enables the simultaneous and independent representation of various NFM intervention types within a catchment, facilitating the simulation of different intervention combinations and idealized scenarios. The findings of this study offer novel insights into the variability of NFM intervention effectiveness across tributaries and under different flood event characteristics, as well as the implications for scaling these interventions from tributary to catchment levels. Furthermore, the study explores the interplay between flood peak delay, peak discharge reduction, and inundation extent, highlighting limitations at broader scales and emphasizing the need for further research to design effective catchment-scale NFM schemes.

4.3 Data and sources

4.3.1 Study sites

The Upper Aire catchment draining to Gargrave covers 81.4 km² with elevation ranging from 572 to 105 m (Figure 4.1). The mean annual precipitation at Malham Tarn station (54°06'00"N, 02°09'49"W) for 1991-2020 was 1587 mm, with monthly mean totals ranging from 90.9 – 181.3 mm, with typically less rainfall in spring and summer and more in autumn and winter (Met Office, 2024). The headwaters are formed of many small and dendritic streams. The dominant soils are characterised by either fine or coarse loamy soils, slowly permeable loamy and clayey soils, very shallow loamy soils, or well drained silty soils over limestone (LandIS, 2016). The predominant land cover in the catchment is improved grassland, followed by calcareous grassland, acid grassland, heather grassland, and woodland (Table 3.2 in Chapter 3). The woodland consists of broadleaf woodland and coniferous woodland, which contributes to large wood inputs and the source of materials for artificial woody dams in the catchment (Grabowski et al., 2019; Hankin et al., 2020). Several streams within the catchment are documented to have leaky

dam installations (Yorkshire Wildlife Trust, 2022). For modelling purposes, four sub-catchments were delineated based on the locations of these leaky dams (Figure 4.1). The sub-catchments extend from headwaters to the 7th or 8th stream order (Strahler, 1957) at their confluences. Each sub-catchment joins the main channel of the River Aire, providing a logical framework for coupling steps in the modelling process. To understand the impacts of leaky dams on overland flow, the coupled model was individually simulated on the four sub-catchments. In addition to leaky dams and the three NFM interventions (woodland planting, hedge planting and soil aeration) modelled in Chapter 3, multiple riparian fencing and buffer strips have been applied around the main river channel (Yorkshire Wildlife Trust, 2022).

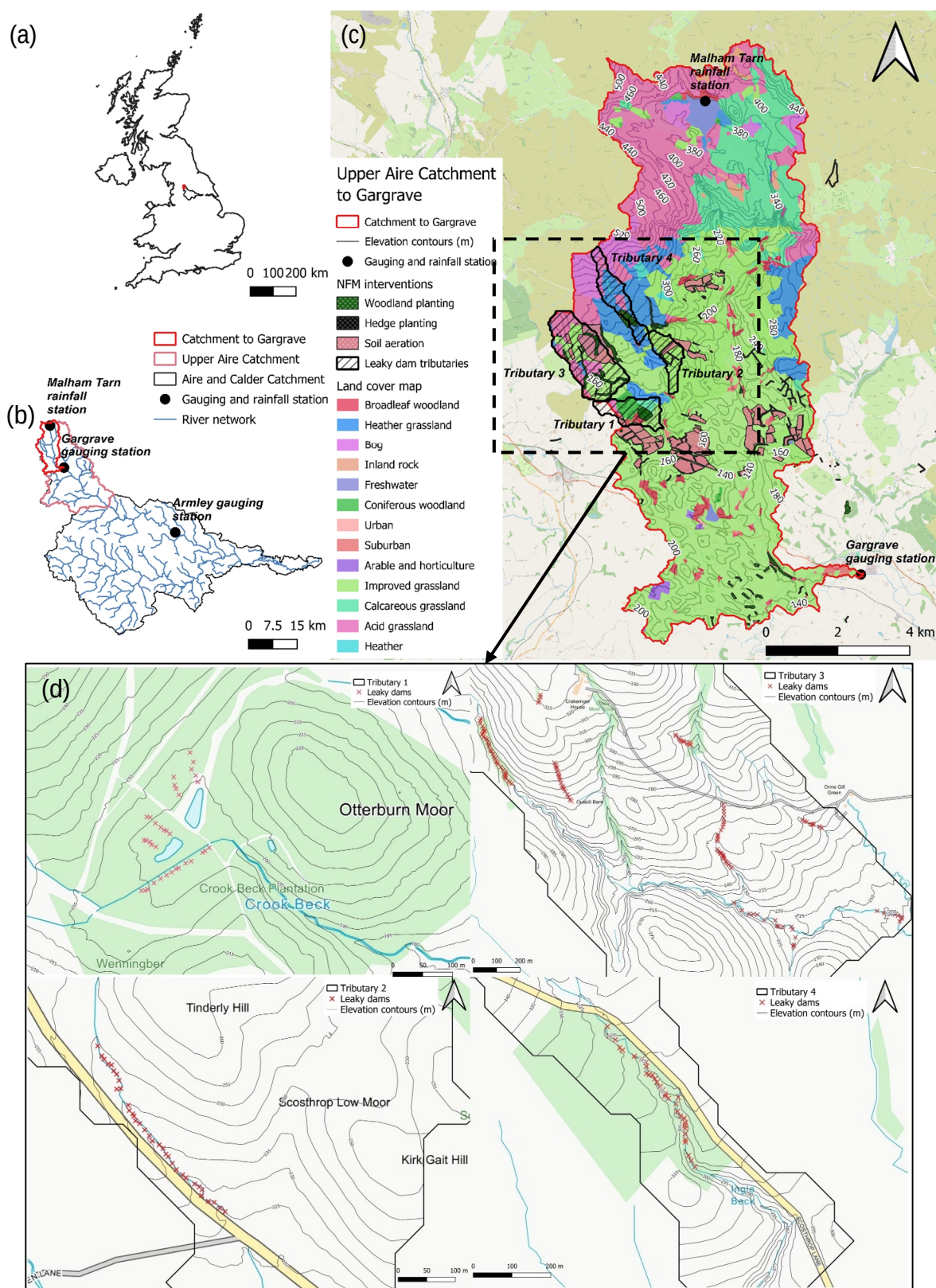


Figure 4.1. Study site: (a) location of study catchment in the UK; (b) Aire and Calder catchment; (c) study area upstream of Gargrave gauging station, Upper Aire Catchment, North Yorkshire, UK. Location of NFM interventions in the study area, and the Environment Agency operated rainfall station and gauging stations. The inset (d) shows the location of four modelled streams with leaky dams in the research catchment.

4.3.2 Data sources

Elevation data for the catchments were obtained from the Ordnance Survey Terrain 5 m digital terrain model (DTM) (Ordnance Survey, 2022). The stream catchment area (Table 4.1) and boundaries were obtained from the Flood Estimation Handbook (FEH). The number and locations of leaky dams applied in each tributary catchment were provided by Yorkshire Wildlife Trust. For rainfall data, the study used 15-min measured precipitation (mm) from the Malham Tarn station which is situated near a natural lake at the headwaters of River Aire (station number 73422; Figure 4.1) (Environment Agency, 2022). The 15-minute observed river flow data (m³/s) was used for model calibration and validation from the Gargrave station (53°58'54"N, 02°05'49"W, station number F1508) during 2012-2022 (Figure 4.1) (Environment Agency, 2022). Gargrave gauging station is located on the main channel of the River Aire with a stage datum of 104.8 mAOD.

Table 4.1. Leaky dam tributary catchment characteristics

<i>Tributary</i>	<i>Highest elevations (m)</i>	<i>Lowest elevations (m)</i>	<i>Catchment area (km²)</i>	<i>Average channel gradients (m/m)</i>	<i>Number of leaky dams applied</i>	<i>Number of points used for coupling</i>	<i>Final stream order</i>
1	274	159	1.13	0.037	35	4	8
2	302	181	0.79	0.024	35	2	7
3	379	201	2.89	0.034	125	4	7
4	513	247	1.16	0.023	33	1	7

In this chapter, land cover inputs derived from the 2015 CEH land cover map (CEH, 2015), consistent with those used for SD-TOPMODEL (Chapter 3), served as the baseline layer for all coupled model simulations. Based on the land cover map, multiple NFM interventions known to be applied in the study catchment were selected, including woodland planting, hedge planting, soil aeration, leaky dams, and riparian buffer strips (Figure 4.1). To investigate the impacts that potential NFM opportunities and expanded NFM implementation within the catchment may have on flood mitigation, the study generated a potential woodland map by incorporating the Environment Agency's Working with Natural Processes (WWNP) dataset (Environment Agency, 2024a). It provided all potential locations within the catchment where 66.86% of the catchment

area could be covered by woodland except for existing human-made structures and land constraints (Figure 4.1).

4.3.3 High flow events

To model the potential impacts of NFM interventions during different characteristic flood events, a range of high flow periods were determined from rainfall and discharge data. These high flow periods were selected to represent flood events for modelling before and after NFM implementation or other scenarios. High flow events were permitted to be single or multi-peaked for diversity. Discrete events were identified from observed river flow and precipitation time series using a similar rules-based methodology to Deasy et al. (2009) and van Leeuwen et al. (2024). Peak Over Threshold (POT) and Annual Maximum (AMAX) series of discharge data (National River Flow Archive, 2024) from an Environment Agency maintained flow gauging station at Armley gauging station (in the city of Leeds; Figure 4.1) on the River Aire, which is downstream of Gargrave, were utilized to identify when high flow events occurred of urban interest. The same method as described in section 3.2.2.1, was used to select discrete high flow events. Seven storm events from 2012-2022 were chosen with rainfall durations of 16-60 h with between 1 and >200-year return periods for the coupled modelling (Table 4.2).

The high flow events were categorised according to event characteristics for two attributes: wet or dry antecedent conditions, and single or multi-peaked. The wet and dry conditions in the catchment prior to the event were determined by the precipitation time series from Malham Tarn station and from soil moisture reports (COSMOS-UK, 2020) and the Hydrological Summary for the UK (CEH, 2012-2022). The observed flow rates from the Gargrave gauge were used to determine whether the event was single or multi-peaked.

Table 4.2. Characteristics of seven selected high flow events (the date is when the storm started)

	<i>Event 1</i> <i>(12 Dec 2015)</i>	<i>Event 2</i> <i>(3 Jan 2012)</i>	<i>Event 3</i> <i>(25 Dec 2015)</i>	<i>Event 4</i> <i>(8 Feb 2020)</i>	<i>Event 5</i> <i>(10 Oct 2019)</i>	<i>Event 6</i> <i>(16 Mar 2019)</i>	<i>Event 7</i> <i>(15 Feb 2020)</i>
<i>Return Period in Armley Station (~years)</i>	50	10	> 200	100	1	20	20
<i>Storm duration (h)</i>	16 (single-peaked)	60 (multi-peaked)	34 (multi-peaked)	50 (single-peaked)	25 (multi-peaked)	18 (single-peaked)	23 (multi-peaked)
<i>Total rainfall (mm)</i>	22.4	64.0	89.6	70.2	37.0	44.6	49.2
<i>Rainfall intensity (mm/h)</i>	1.400	1.067	2.635	1.404	1.480	2.478	2.319
<i>Maximum rainfall intensity (mm/h)</i>	6.4	4.2	5.6	7.6	5.6	4.2	5.2
<i>Simulation duration (h)</i>	45 (Wet)	90.5 (Dry)	65 (Wet)	55 (Dry)	41.25 (Dry)	35 (Dry)	37.5 (Wet)

4.4 Coupling models

4.4.1 SD-TOPMODEL

As described in Chapter 3, spatially distributed TOPMODEL (SD-TOPMODEL) as a hydrological model (Gao et al., 2015) was used to represent and simulate land cover types and existing NFM interventions impacting soil hydrological functions and surface roughness at a catchment scale. The outputs from SD-TOPMODEL, generated by simulating land cover data and three NFM intervention scenarios (woodland planting, hedgerow planting, and soil aeration) (Chapter 3), were utilized as inputs for the coupled model in this chapter. Both parameter inputs and model outputs were grid-based and

maintained a consistent resolution of 5 m, aligning with the spatially distributed framework of SD-TOPMODEL.

4.4.2 Coupling processes

After SD-TOPMODEL has completed the entire catchment scale simulation (Chapter 3), the sum of subsurface and surface runoff for each timestep in each 5 m grid can be obtained. Most rainfall-runoff and infiltration processes occur within the sub-catchments and are predominately driven by surface runoff after convergence to the main channel. Consequently, the flow entering the main channel is assumed to be the sum of subsurface and surface runoff from these sub-catchments. This total runoff is then used as input to Flood Modeller. This process gives the opportunity to externally one-way couple SD-TOPMODEL and the hydrodynamic model (Flood Modeller) at the same catchment scale. Then, the coupled model is used to simulate surface flows in the leaky dam sub-catchments and the main river channel (stream order from 7 up to 10 in the catchment) with its floodplain.

4.4.3 Flood Modeller and coupled model

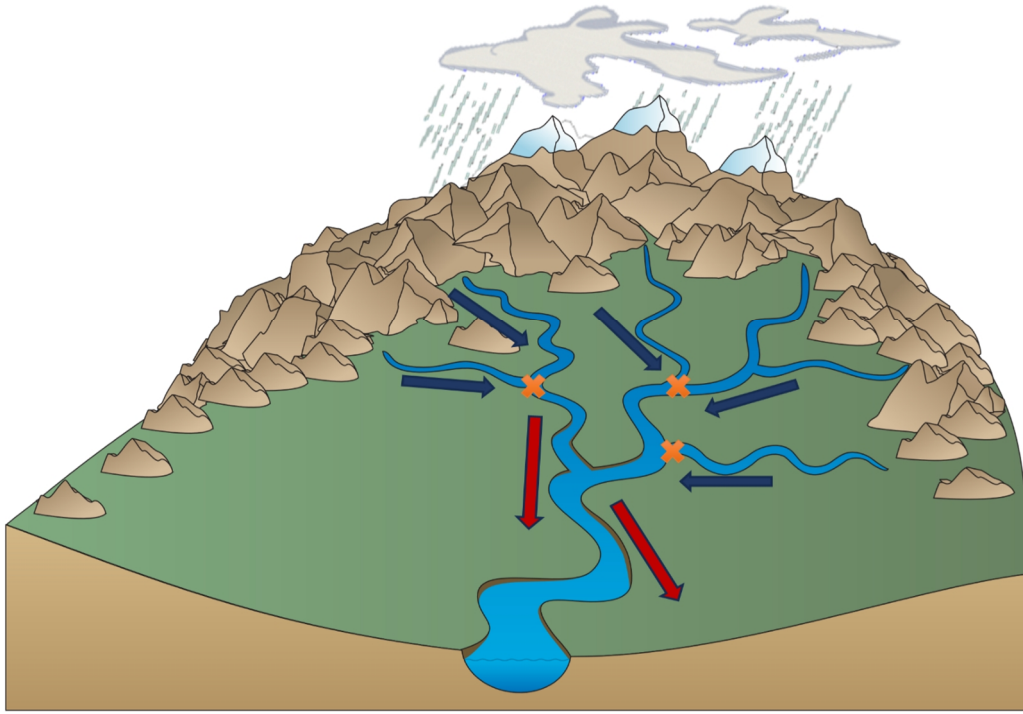
The hydrodynamic model used in this study is Flood Modeller (version 7.0, Jacobs). All model runs used the Alternating Direction Implicit (ADI) solver for 2D modelling, which computes flow depths and discharges using a method based on the two-dimensional Saint-Venant equations (Jacobs, 2022a). The ADI solver has more efficient computation of backwater effects and better accuracy for mixed flow regimes, such as adding new 1D hydraulic structures (Jacobs, 2022b). The model was run with 1 s timesteps and 5 m grid size with the same DTM elevation data as used in SD-TOPMODEL. The model parameters were set to default values except for the surface roughness parameter. The leaky dams were added into the 2D model by creating fully integrated simulations linking 2D components with embedded 1D orifice structures (Jacobs, 2022c). After these model setups, the coupling process was implemented in Flood Modeller.

The leaky dam sub-catchments are shown in Figure 4.1d. The extent of the active area for the coupled model, including the main channel and its floodplain, was defined using elevation data from the DTM. This area spans from the lowest elevation of the river channel to an elevation increase of 15 – 20 m on both sides of the channel. The same

coupling method was used in the leaky dam sub-catchments and the main channel catchment (Figure 4.2, Appendix B).

As described in Chapter 3, the same SD-TOPMODEL framework was utilized for the coupling process. The rainfall-runoff process was conducted using the spatial distribution of soil properties and hydrological functions based on land cover within SD-TOPMODEL. This produced spatially distributed, grid-based runoff maps (5 m grid size) for each 15-minute timestep. To ensure the validity of these runoff maps, a set of points was strategically selected at river junctions across the catchment. By systematically assessing the outputs from these selected grids, a representative grid for each junction was identified for subsequent point-to-point coupling procedures. The methodology for this selection process is depicted schematically in Figure 4.2a. In this schematic representation of the river catchment, blue arrows indicate tributary flows modelled within SD-TOPMODEL, while red arrows denote the surface flows of the main channel, and its floodplain area simulated by Flood Modeller. The coupling boundaries between the two models were established at the river junctions, specifically where tributaries converge with the main channel, as denoted by the orange crosses in Figure 4.2a. The actual coupled model domain (covered 90.4% of the study catchment) with linked locations were illustrated in Appendix B. At these junction points, the coupling section was executed (Figure 4.2b), wherein the time series runoff was extracted from the corresponding grids in the runoff maps. These time series data were subsequently used as input flow for Flood Modeller. The inflows, along with elevation data, were incorporated into the coupled model, and after the addition of surface roughness parameters (as shown in Table 4.3), the final configuration of the coupled model in Flood Modeller was completed.

(a)



(b)

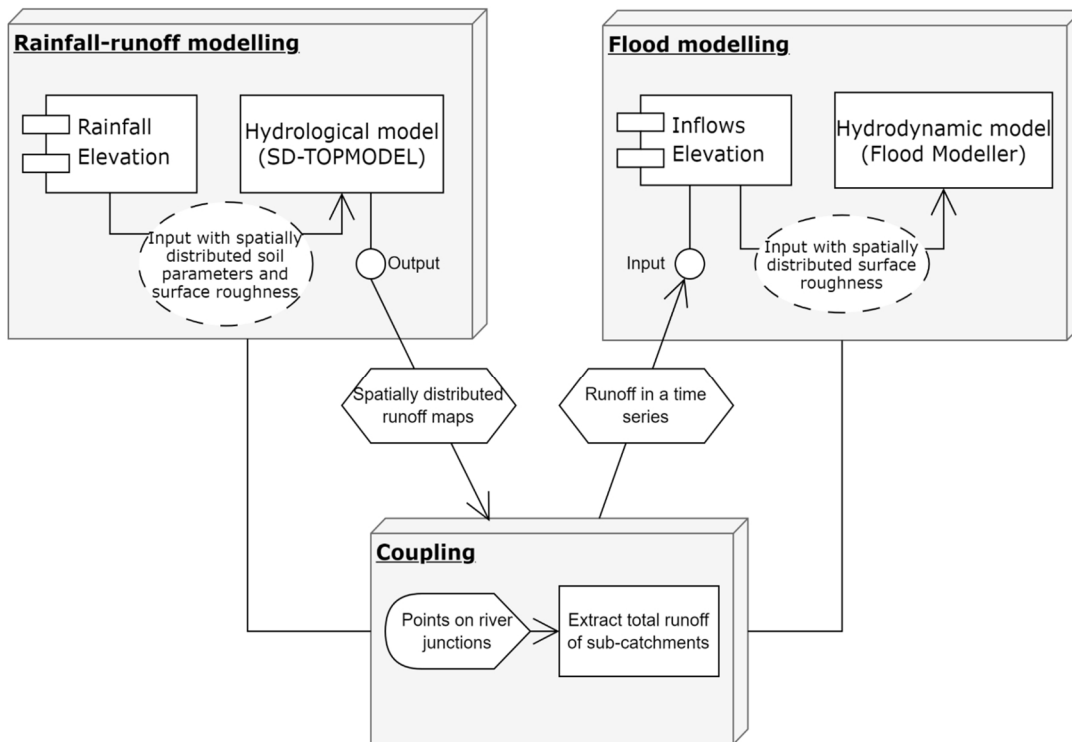


Figure 4.2. (a) Schematic view of coupling SD-TOPMODEL to Flood Modeller 2D in the catchment (blue arrows represents hydrological flow, red arrows stand for hydrodynamic flow, and the orange crosses are the schematic coupling points) and (b) coupled model structure: the smaller rectangles indicate two required inputs in each model, dashed ellipses depict model parameters, and hexagons represent data used for coupling. All components are interconnected through the coupling module.

Table 4.3. Manning's *n* roughness values used in modelling scenarios (applied in the Flood Modeller 2D)

Scenario	Description	Manning's <i>n</i> roughness coefficients in the coupled model (Chow, 1959)
No NFM	The catchment with land cover	0.05 (default as improved grassland) 0.03 (river channel)
NFM – leaky dams and riparian buffer strips	The catchment with land cover, a total of 228 leaky dams and riparian buffer strips applied	0.05 (default as improved grassland) 0.03 (river channel) 1.00 (area of leaky dams) 0.15 (riparian buffer strips)
NFM combination	The catchment with land cover and all NFM interventions (NFM interventions include woodland planting, hedgerow planting, soil aeration, riparian buffer strips and leaky dams)	0.05 (default as improved grassland) 0.03 (river channel) 1.00 (area of leaky dams) 0.15 (riparian buffer strips)
Wider catchment woodland	The catchment with land cover and wider catchment woodland scenario (woodland covered 66.9% area of the catchment), (Environment Agency, 2024a)	0.1 (default as improved grassland) 0.03 (river channel) 0.15 (riparian woodland)

4.4.4 Model calibration and validation

4.4.4.1 Calibration of Manning's *n* roughness coefficients

The coupled model calibration utilized the surface roughness parameter range (Manning's *n* roughness coefficient) as defined by Chow (1959). The calibration range for the active areas (0.035 – 0.060) corresponded to the classification of floodplains with "light brush and trees in winter" as the entire area was covered by improved grassland. For the river channel, the calibration range (0.030 – 0.040) reflected "full stage, no rifts or deep pools, with stones and weeds" channel conditions. The baseline model (No NFM scenario) of the coupled model only reflects the land cover maps, which includes these two settings in Manning's *n* values. Among seven tested events, Events 1-3 occurred in 2012 and 2015, prior to the implementation of NFM interventions, while Events 4-7 occurred in 2019 and 2020, after the implementation of these NFM interventions as shown in Figure 4.1. The baseline model was calibrated based on the 2015 Land Cover Map, which may not fully reflect the actual conditions in 2012 and 2019-2020. This

discrepancy may introduce some degree of uncertainty in the model's performance for these time periods.

The goodness-of-fit metrics were computed from the coupled model results of No NFM scenario and observed data across seven events and used to evaluate model calibration within these specified ranges. The metrics include RMSE (Willmott and Matsuura, 2005), PBIAS (Yapo et al., 1996), NSE (Nash and Sutcliffe, 1970), wNSE (Hundecha and Bardossy, 2004), d (Willmott, 1981), r (Pearson, 1920), R^2 (Box, 1966), VE (Criss and Winston, 2008) and KGE (Gupta et al., 2009), all of which are defined, including ranges and optimal values defining a good fit in Table 4.4. The final calibrated Manning's n values that achieve the best metrics for all seven events are shown in Table 4.3.

Table 4.4. Goodness-of-fit and their associated attributes used for model calibration

Goodness-of-fit metrics	Description	Range	Value indicates better fit	Reference
RMSE (Root Mean Square Error)	Measuring the average magnitude of prediction errors	0 to ∞	0	(Willmott and Matsuura, 2005)
PBIAS % (Percent Bias)	Quantifying the average tendency of the simulated values to observations	$-\infty$ to ∞	0	(Yapo et al., 1996)
NSE (Nash-Sutcliffe Efficiency)	Assessing the predictive skill relative to the mean of observations	$-\infty$ to 1	1	(Nash and Sutcliffe, 1970)
wNSE (Weighted Nash-Sutcliffe Efficiency)	Increasing the weight of peaks based on NSE	$-\infty$ to 1	1	(Hundecha and Bardossy, 2004)
d (Index of Agreement)	A standardized measure of model predictive accuracy emphasizing both magnitude and pattern errors	0 to 1	1	(Willmott, 1981)
r (Pearson correlation coefficient)	Quantifying the linear relationship between observed and simulated data	-1 to 1	1	(Pearson, 1920)
R² (Coefficient of determination)	Representing the proportion of variance explained by the model	0 to 1	1	(Box, 1966)
VE (Volumetric efficiency)	Evaluating the accuracy of total flow volume estimation	0 to 1	1	(Criss and Winston, 2008)
KGE (Kling-Gupta efficiency)	Combining correlation, bias, and variability into a single performance metric	$-\infty$ to 1	1	(Gupta et al., 2009)

4.4.4.2 Using Manning's n roughness coefficients to represent NFM interventions

Among NFM scenarios presented in Table 4.3, improved grassland and riparian buffer strips represented by changes in Manning's n values were incorporated into the baseline model. For the riparian buffer strips and riparian woodland, the calibration range (0.10 – 0.16) was applied, corresponding to the 'heavy stand of timber, a few down trees, litter undergrowth, with flood stage reaching branches' floodplain conditions. In the leaky dam sub-catchments, the predominant land cover is a mixture of grassland and woodland. For simplicity in the coupled model, a lumped roughness parameter was applied as a default value for the sub-catchments. The Manning's n roughness coefficient was set at an intermediate value of 0.10 between the calibrated values of the improved grassland (0.05) and the riparian woodland (0.15).

The friction conditions in the leaky dam implementation area can vary. Studies have shown that the Manning's n roughness coefficient of the leaky dam area is influenced by factors such as the density of leaky dam placement, the material and positioning of the leaky dam, streambed morphology and flow conditions (Wilcox and Wohl, 2006; Shields and Alonso, 2012; Turcotte et al., 2015; Addy and Wilkinson, 2019). Given that the natural conditions of the four leaky dam tributaries were very similar (Table 4.1), and the leaky dams were implemented by the Yorkshire Wildlife Trust according to a uniform standard, factors other than flow conditions were assumed to have negligible differences in these tributary catchments. During high flow events, the flow conditions at leaky dams rapidly transition from the rising limb of unsteady flow to steady overflow (Leakey et al., 2020). Resistance during water level rise was found to be 2-3 times higher than that after inundation, leading to afflux, adjacent floodplain connections and backwater rise during the rise phase (Shields and Alonso, 2012; Keys et al., 2018; Follett et al., 2021). Consequently, Manning's n values during this process must increase significantly to account for the added water resistance and drag forces induced by the leaky dams. The range of Manning's n values was informed by field measurements conducted by Kitts (2010) in the New Forest, England, and Curran and Wohl (2003) in Washington State, USA. For similar coarse gravel bed conditions, the mean Manning's n values were 0.60 for step-pool and steep streams (representative of Washington streams), and 1.42 for meandering and gentle streams (New Forest, UK) under overflow. Based on these findings, the calibration range for the model was set between 0.60 and 1.50, with

parameter values selected at intervals of 0.10. For simplicity, only one decimal place was retained after the decimal point. Ultimately, the model was calibrated to a final value of 1.0.

4.4.4.3 Model validation

The validation of the model was conducted by comparing its output to historic flood records as well as observed hydrographs. Historic flood records were sourced from the Environment Agency’s post-flood emergency oblique aerial photography (Environment Agency, 2024b) and historic flood outlines (Environment Agency, 2024c), which were only available for Event 3 (beginning on 25 Dec 2015) and Event 7 (beginning on 15 Feb 2020). Traces of inundation were shown in the aerial photographs, and the area of inundation was determined based on geographic location and reference objects (roads, bridges, and buildings). The flood inundation extents from these records were extracted and compared with the modelled inundation extents (Figure 4.3). The modelled inundation extents within the active area of the coupled model covered all historic records, indicating that the model performance is viable and accurate.

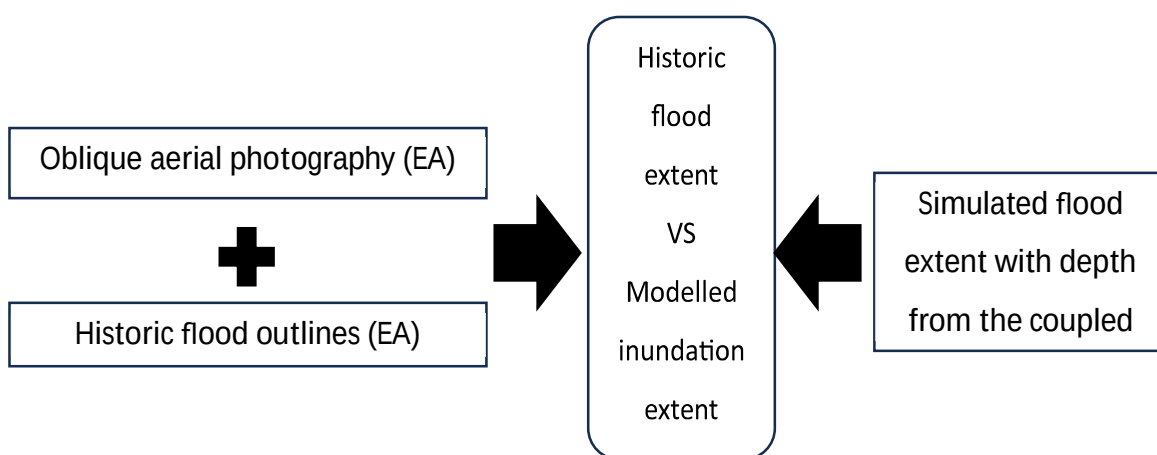


Figure 4.3. Model validation with historic flood records

4.4.5 Modelling scenarios

A total of four scenarios were tested in the coupled model (Table 4.3). All scenarios required parameter adjustments within the coupled model to simulate these nature-based interventions. These adjustments involved modifications to both the parameters and settings in Flood Modeller. Additionally, some scenarios incorporated land cover changes and three soil and land-use interventions, which required corresponding

parameter modifications in SD-TOPMODEL. These parameters in SD-TOPMODEL were calibrated as described in Section 3.3.2.4, while parameterisation in Flood Modeller was described in Section 4.4.4.

4.4.5.1 Leaky dams and riparian buffer strips scenarios

A total of 228 leaky dams and riparian buffer strips were implemented in the catchment. This scenario was applied upon the land cover maps, requiring adjustments to Manning's n roughness coefficients in the coupled model to represent these interventions. Given that the cumulative flow mitigation effects of a large number of leaky dams were modelled at the catchment scale, minor differences between individual leaky dams were disregarded, and a uniform representation was used in the coupled model, as illustrated in the schematic (Figure 4.4). A review suggested that modelling leaky dams using the hydraulic structure method allows for a more detailed investigation (Addy and Wilkinson, 2019). To better reflect real-world conditions (photo in Figure 4.4), the embedded 1D orifice structures, along with adjustments to the Manning's n roughness coefficients, were used to represent leaky dams and were integrated into the 2D hydrodynamic model in Flood Modeller (Jacobs, 2022b). As shown in the structure schematic (Figure 4.4), partial channel blockages were placed at each leaky dam cross section, leaving a gap (0.1 - 0.3m depending on elevation differences in the DTM before and after the dam) under the blockage to allow low flows to pass through. With a grid size of 5 m, the model set the width of all leaky dams to 5 m, and the top height of each leaky dam matched the height of the channel sides. Height data for each leaky dam were individually assigned. The characteristics of the tributary catchments and the number of leaky dams is detailed in Table 4.1, with the average channel gradients of the four tributaries being similar, allowing for consistent height and roughness settings for all leaky dams.

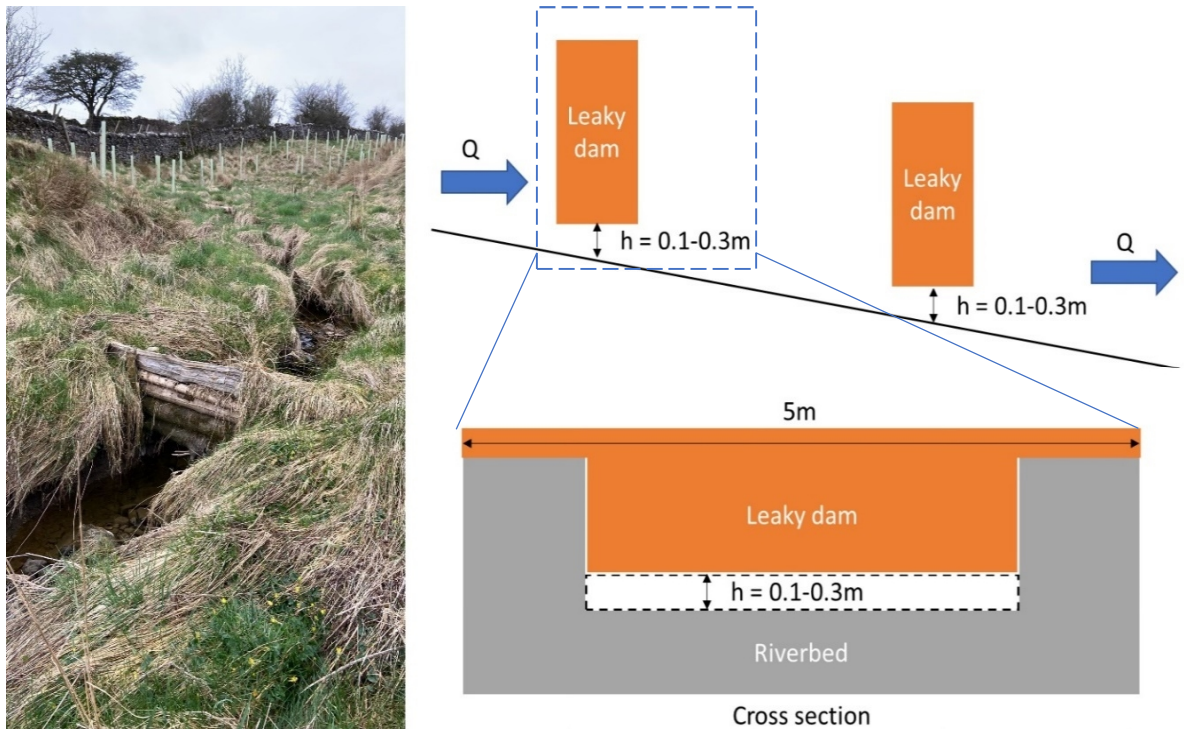


Figure 4.4. The leaky dams and riparian buffer strips implemented in Tributary 4 (photo on 29 March 2022), schematic stream channel and cross-section of a 1D structure in the hydrodynamic model

4.4.5.2 Land cover, NFM interventions and potential woodland scenarios

Scenarios requiring parameter adjustments in each model include No NFM, NFM combination and wider catchment woodland scenarios (Table 4.3). The No NFM scenario consisted solely of land cover maps within the catchment, with parameters representing topsoil properties and surface roughness applied only in SD-TOPMODEL (see Table 3.3 in Chapter 3 for details). The calibrated surface roughness parameters for the active areas in Flood Modeller were set as default as this area was all recognised as improved grassland in the land cover maps. In this case, the default Manning's n roughness coefficient was used for the area and a reduced value was set as the river channel (Table 4.3).

The NFM combination scenario incorporated leaky dams and riparian buffer strips in addition to the No NFM scenario, along with other NFM interventions in the catchment such as woodland planting, hedgerow planting, and soil aeration modelled in SD-TOPMODEL. The setup for leaky dams and riparian buffer strips followed Section 4.3.4.1, while other interventions were consistent with all NFM scenarios described being used

within SD-TOPMODEL in Chapter 3. The wider catchment woodland scenarios were based on the Catchment Woodland Potential map from Environment Agency, which used the same parameter settings as the NFM intervention woodland planting (new woodland) in SD-TOPMODEL. In Flood Modeller, the potential woodland in the active area applied the same Manning's n roughness coefficient as riparian buffer strips. Thus, all scenarios were fully implemented in the coupled model.

4.5 Results

4.5.1 Coupled model performance for various high flow events

The model performance of the calibrated coupled model was evaluated by goodness-of-fit metrics calculated between the No NFM scenario results and observed data (Table 4.5). The model demonstrates a good overall fit for all events except Event 2. For example, NSE, R^2 , VE, and KGE were all greater than 0.6. Optimal values for each metric were achieved in Event 3, where RMSE and PBIAS were both close to 0, while other metrics approached 1. In contrast, Event 2 (occurring in 2012) showed a poor fit for some metrics (e.g. NSE of -0.02 and R^2 of -0.02), though wNSE, VE and KGE values improved (ranging between 0.4 and 0.5) due to their focus on flood peaks, even when the overall fit remains suboptimal. Events 4-7 (occurring between 2019 and 2020) also showed a lower fit compared to Event 1 and 3 occurring in 2015. This may be attributed to the baseline model's use of the 2015 land cover map, which may differ slightly from land cover in other years. Some NFM interventions had been implemented in the catchment by 2019-2020, which are not included in the baseline model (No NFM scenario) for simulation of Events 4-7.

Model performance is also affected by the characteristics of high flow events. When catchment preconditions are dry, the lack of an infiltration simulation module in the coupled model results in less water losses in the simulation, especially compared to wet conditions. Events 2, 5, 6, and 7 are small to medium-sized flood events with return periods from 1 to 20 years with lower peak discharge than more extreme events (return periods from 50 to > 200 years). The receding limbs of these small peaks are more affected by infiltration processes. This effect is more pronounced in Event 2, which has lower flow and multiple flood peaks. While the discharge and timing of flood peaks are

well-matched in the hydrographs of model results (Figure 4.7), the peak recession process diverges from observed data. This discrepancy is also evident in goodness-of-fit metrics but does not compromise the accuracy of the model in simulating peak times and other high flow peaks. Therefore, the characteristics of the coupled model allow it to accomplish a good fit for extreme flood events with return periods greater than 50 years, and to ensure the modelling accuracy of flood peak discharge and timing for small to medium flood events (1-20 years of return period).

Table 4.5. Goodness-of-fit metrics for coupled model results (No NFM) with calibrated Manning's n values applied across seven events

	<i>Event 1</i>	<i>Event 2</i>	<i>Event 3</i>	<i>Event 4</i>	<i>Event 5</i>	<i>Event 6</i>	<i>Event 7</i>
<i>RMSE</i>	6.95	8.56	4.74	9.53	7.9	9.54	9.78
<i>PBIAS %</i>	18.10	57.30	-0.30	-10.70	37.30	30.20	31.20
<i>NSE</i>	0.81	-0.02	0.95	0.83	0.61	0.68	0.67
<i>wNSE</i>	0.89	0.49	0.94	0.81	0.69	0.59	0.75
<i>d</i>	0.94	0.79	0.99	0.95	0.92	0.94	0.92
<i>r</i>	0.94	0.9	0.98	0.94	0.96	0.99	0.97
<i>R²</i>	0.81	-0.02	0.95	0.83	0.61	0.68	0.67
<i>VE</i>	0.69	0.41	0.91	0.81	0.62	0.70	0.69
<i>KGE</i>	0.71	0.42	0.97	0.74	0.6	0.65	0.68

4.5.2 Flood mitigation impacts of NFM scenarios

4.5.2.1 Leaky dams' impact on tributaries

The simulation of leaky dams was conducted by applying the coupled model across each of four sub-catchments for seven events. This process involved SD-TOPMODEL simulating the land cover map, followed by extracting runoff inputs into the leaky dam-implemented stream segments by the same point-to-point coupling method. Scenario results were then compared between the coupled model utilizing only the land cover map and the model with leaky dams layered on top of the land cover map, assessing the effects of leaky dams for seven events in each of the four tributaries (Figure 4.5).

Because the four sub-catchments are all upland, they share similar soil and landscape characteristics, though other characteristics differ as shown in Table 4.1. However, integrating the simulation results for the seven events revealed notable differences among the tributaries. The effects on peak delay and peak discharge reduction were inversely proportional among the four tributaries; in one tributary, a higher delay time was often coupled with a smaller peak discharge reduction (Figure 4.5). For example, in Tributary 2, results showed effective peak delays ranging from 30 to 75 minutes across seven events, alongside increased peak discharge for all but one event. Similar inverse effects appeared in the other three tributaries, although not as markedly as in Tributary 2. In contrast, differences between events within the same tributary were minimal, shown as outliers in Figure 4.5 with only five outliers present overall. In general, leaky dams resulted in peak delays in all four tributaries, with mean values ranging from 8.6 to 60 minutes; except for Tributary 1, which had a greater reduction in peak discharge (mean 1.84%), and the other three tributaries, which had subtle reductions (mean values ranging from 0.53 to 0.63%). Therefore, the peak delay effect of leaky dams is greater than the effect on flood peak reduction.

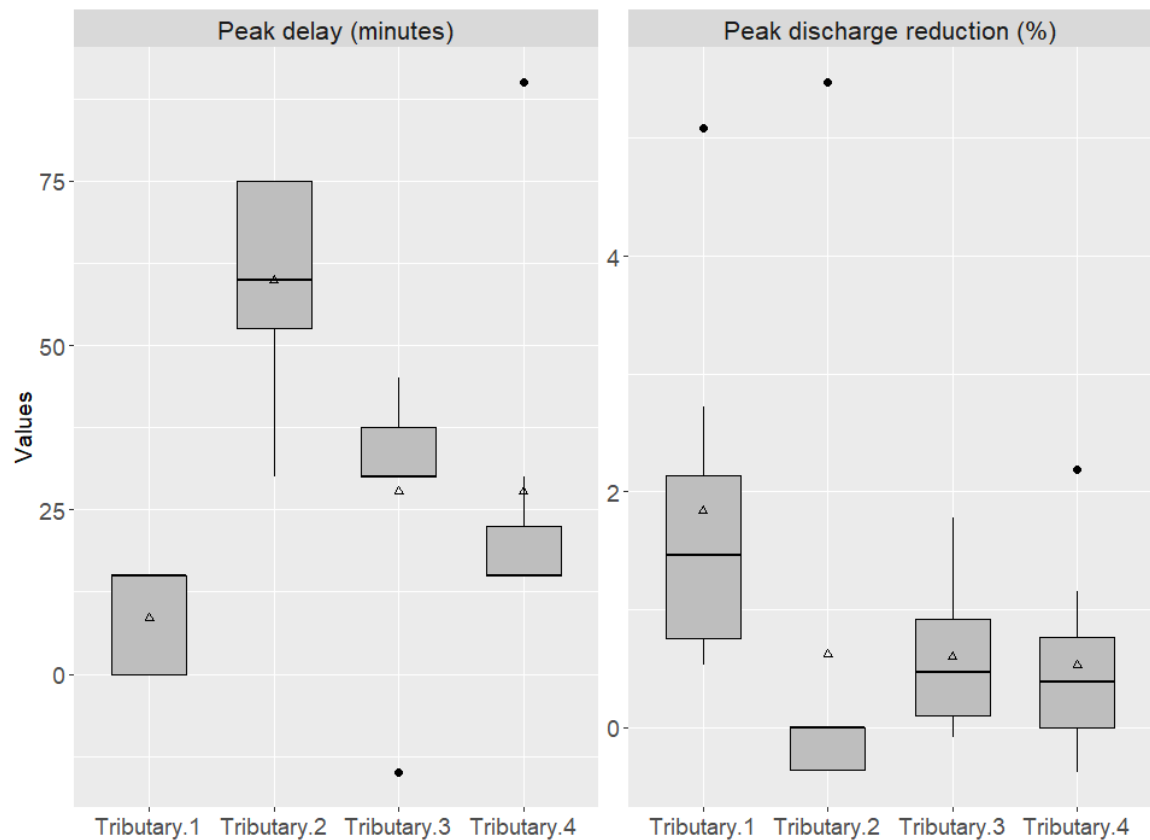


Figure 4.5. Impacts of leaky dam implementation on peak delay (minutes) and peak discharge reduction (%) in seven events grouped by four leaky dam tributaries (the triangle represents the mean value; the line is the median value)

4.5.2.2 Catchment-scale NFM scenario impacts on flood peaks

The flood mitigation effects across three NFM scenarios were evaluated by comparing the percentage of peak discharge reduction and the value of peak delay relative to the No NFM scenario (Figure 4.6). All scenarios demonstrated positive flood mitigation impacts, yet differences were observed across various high flow events and NFM scenarios.

Among the events, Event 1 exhibited the highest peak reduction percentages across all scenarios, while Events 2 and 5 showed small flood reductions ($> 1\%$), and Events 3, 4, 6 and 7 experienced only minimal peak reductions ($< 0.5\%$). Notably, peak delay impacts did not always correspond to peak reductions in certain events. For example, Events 4 and 6 displayed flood delays of up to 15 mins despite minimal peak reductions, while Events 1 and 5 achieved greater peak reductions with comparable or smaller peak delays in NFM (leaky dams and riparian buffer strips) and NFM combination scenarios. These

variations in flood peak behaviour are also depicted in the hydrographs (Figure 4.7). These differences between events are likely influenced by specific event characteristics. For instance, two of the seven high flow events, extreme Events 3 (with a return period exceeding 200 years) and 4 (with a return period of 100 years) both showed flood reduction effects of less than a 0.5%. However, this pattern did not hold for Event 6 and 7, both with 20-year return periods, which experienced high average rainfall intensities that may have diminished flood mitigation effects in the modelling results. This feature was similarly reflected in the peak delay results: Events 3, 5 and 7 showed no delays for NFM (leaky dams and riparian buffer strips) and NFM combination scenarios.

While the pattern of differences between events remained consistent across scenarios, there were subtle variations in event responses between scenarios. The hydrographs indicated that the runoff results for the NFM (leaky dams and riparian buffer strips) scenario and NFM combination scenario were very similar, with only minor non-overlapping peaks. This was consistent, as shown in Figure 4.6, where the percentage of peak reduction increased in the NFM combination scenario except for Events 1 and 2, with only Event 2 showing an increase in peak delay time.

In contrast, the wider catchment woodland scenario caused more marked changes across all seven events, as shown in Figure 4.6 and in the hydrographs in Figure 4.7. Peak reduction percentages and delay times increased compared to the other two scenarios, especially in Events 4, 6 and 7, which had only minor reductions in the other two scenarios. Increases were smaller for extreme Events 3, with only a minimal rise (from 0.03% to 0.14%). The impact of the wider catchment woodland scenario on peak delays was also significant: all events showed notable increases in peak delay time of 30 – 60 minutes. This effect is clearly visible in the hydrographs for each event, where all rising limbs are flattened and slowed, resulting in delays for both single and multiple flood peaks. The increases in delay times did not vary greatly across events, suggesting minimal influence from event characteristics, except flood magnitude (return period). Overall, the NFM combination scenarios offer slightly improved flood mitigation than the NFM (leaky dams and riparian buffer strips) scenario, while the wider catchment woodland scenario significantly enhanced flood mitigation compared to the other two

scenarios. This indicates adding more intervention types in the catchment is not beneficial for all events.

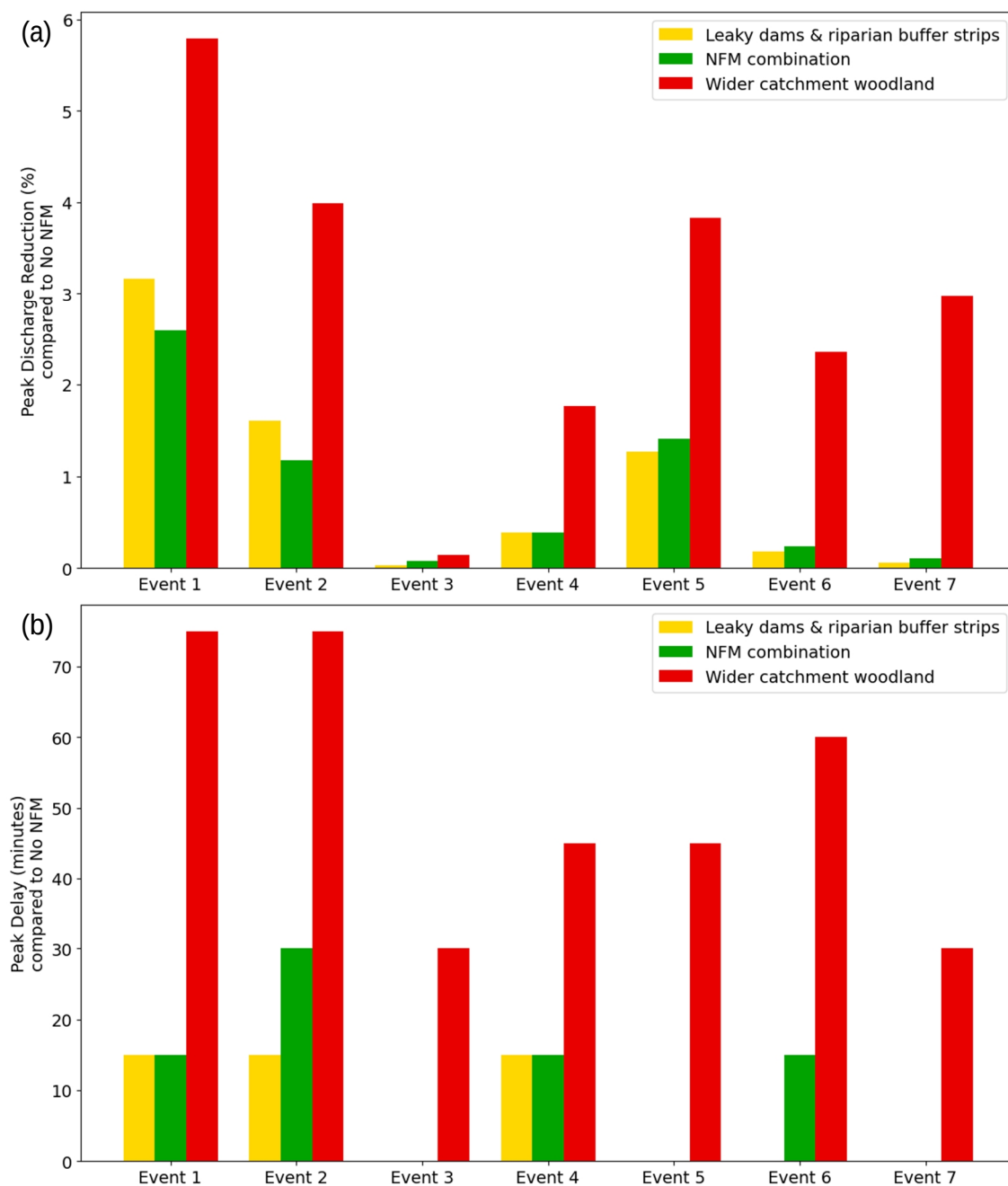


Figure 4.6. Flood mitigation results from the coupled model by comparing NFM scenarios with No NFM scenario. (a) Peak discharge reduction; (b) Peak delay.

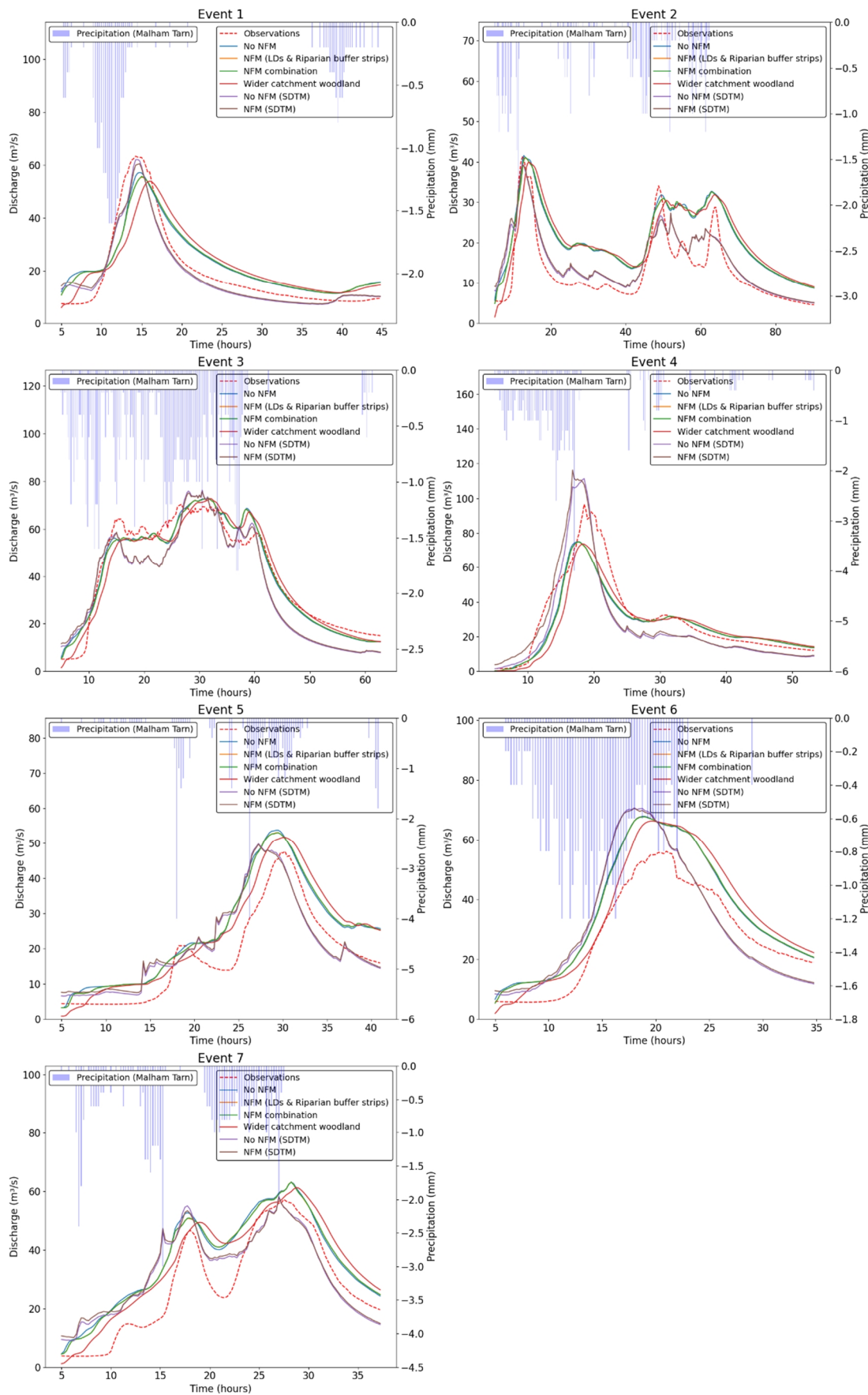


Figure 4.7. Hydrographs for seven events produced by the coupled model (No NFM, NFM – leaky dams and riparian buffer strips, NFM combination, wider catchment woodland scenarios) and SD-TOPMODEL (No NFM and NFM scenarios)

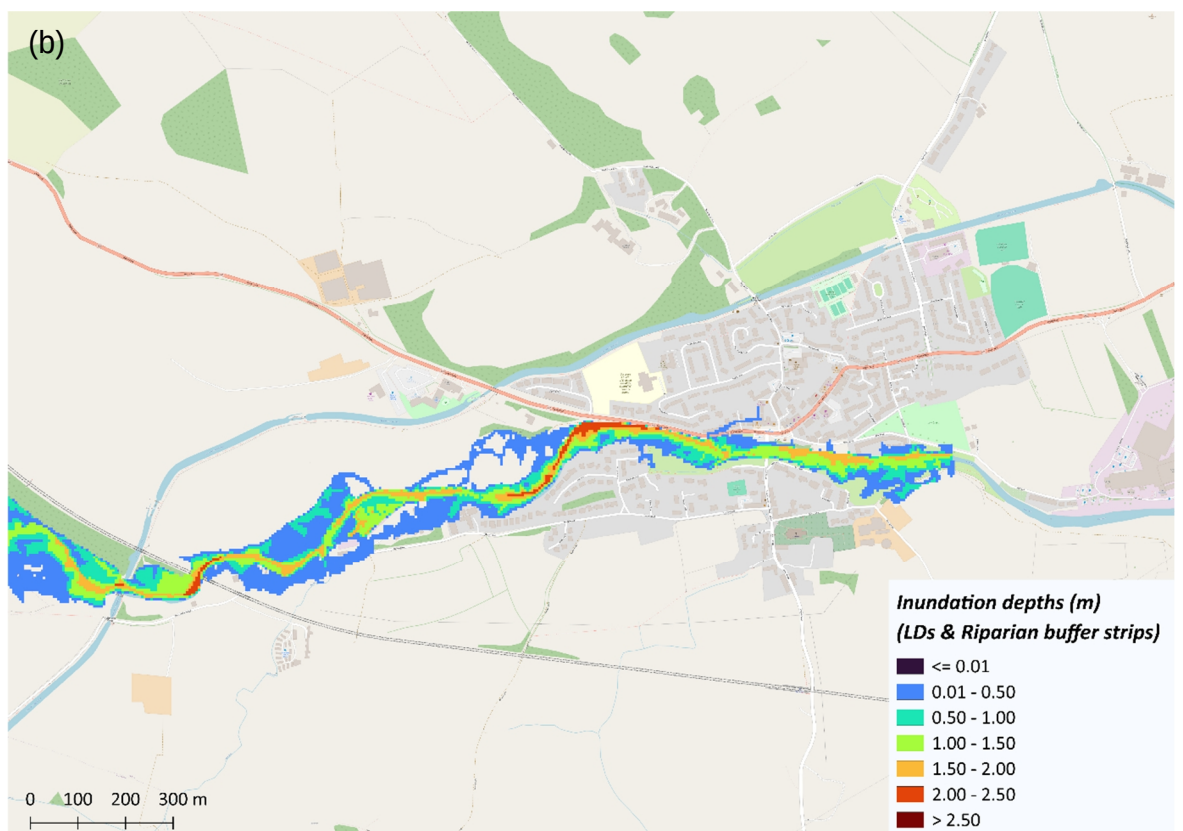
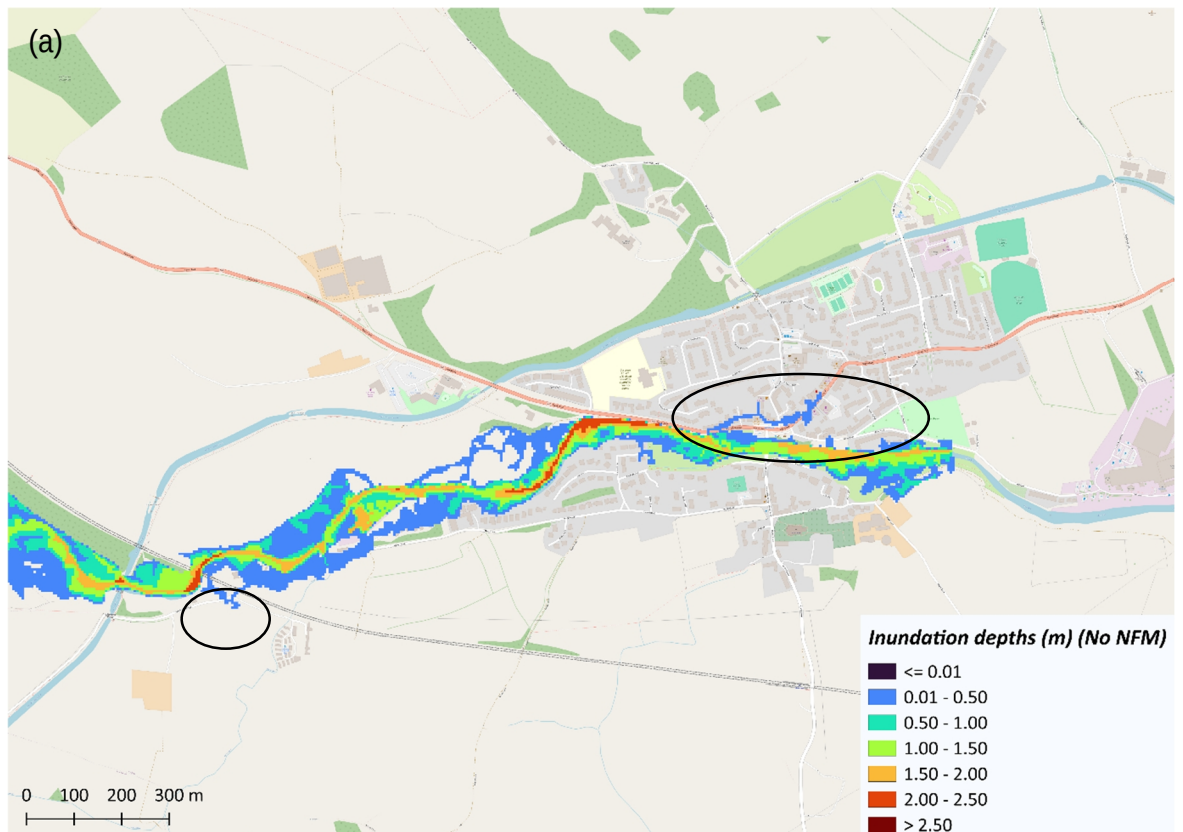
4.5.2.3 Impacts on flood inundation extent and depths

In addition to evaluating peak discharge reduction and peak delay times, the coupled model also produced inundation extent and depth results for each high flow event. The maximum extent of inundation under the No NFM scenario was used for model validation by comparing it with historical flood records, while the maximum inundation depth across different scenarios served as an additional indicator of the effectiveness of downstream flood mitigation effects by NFM interventions. Taking Event 1 as an example, Figure 4.8 illustrates the maximum extent and depth of inundation near the downstream end of the study catchment (around Gargrave town) for this event under different NFM scenarios, which varied noticeably between scenarios.

Firstly, there are variations in the flood inundation extent. The NFM (leaky dams and riparian buffer strips) scenario exhibited the smallest inundation area under the same rainfall conditions, closely followed by the NFM combination scenario. Compared to the No NFM scenario, these two scenarios resulted in reduced inundation at critical points, such as on roads on the edge of the reach (notably Skipton Road and High Street in Gargrave town centre) and overflow around the railway and Priest Holme Bridge, both of which are highlighted in Figure 4.8a. These reductions in inundation extent are significant improvements. However, the wider catchment woodland scenario notably increased the maximum extent of inundation, which was reflected across all the demonstration areas in Figure 4.8. This expansion of the inundation was particularly pronounced in Gargrave town, including roads, green spaces, and some residential areas. This outcome contradicts the findings that the wider catchment woodland scenario achieved greater peak discharge reduction and peak delay. The apparent contradiction arises because extensive tree planting in this scenario increases surface roughness in the catchment thus slowing down the flow. As a result, the prolonged runoff process led to a higher number of wet cells in the catchment compared to other three scenarios, as indicated by the model results. This suggests greater overland flow within the catchment, including overflow onto floodplains and channel perimeter, resulting in a larger inundation extent.

When comparing the maximum inundation depths, the results for the two NFM implementation scenarios and the No NFM scenario are generally similar, with

differences of less than 0.5 m in most areas. This aligns with previous findings for peak discharge, where reductions due to NFM interventions were not substantial. However, in the wider catchment woodland scenario, significant increases in maximum inundation depth were observed across inundated areas. Distinct colour changes in Figure 4.8 highlight regions where inundation depth increased. This suggests that the NFM (leaky dams and riparian buffer strips) scenario and the NFM combination scenario effectively reduce critical inundation extents, but their impact on inundation depth is minimal. Conversely, the wider catchment woodland scenario may exacerbate potential flood risk due to increases in both maximum inundation extent and depth.



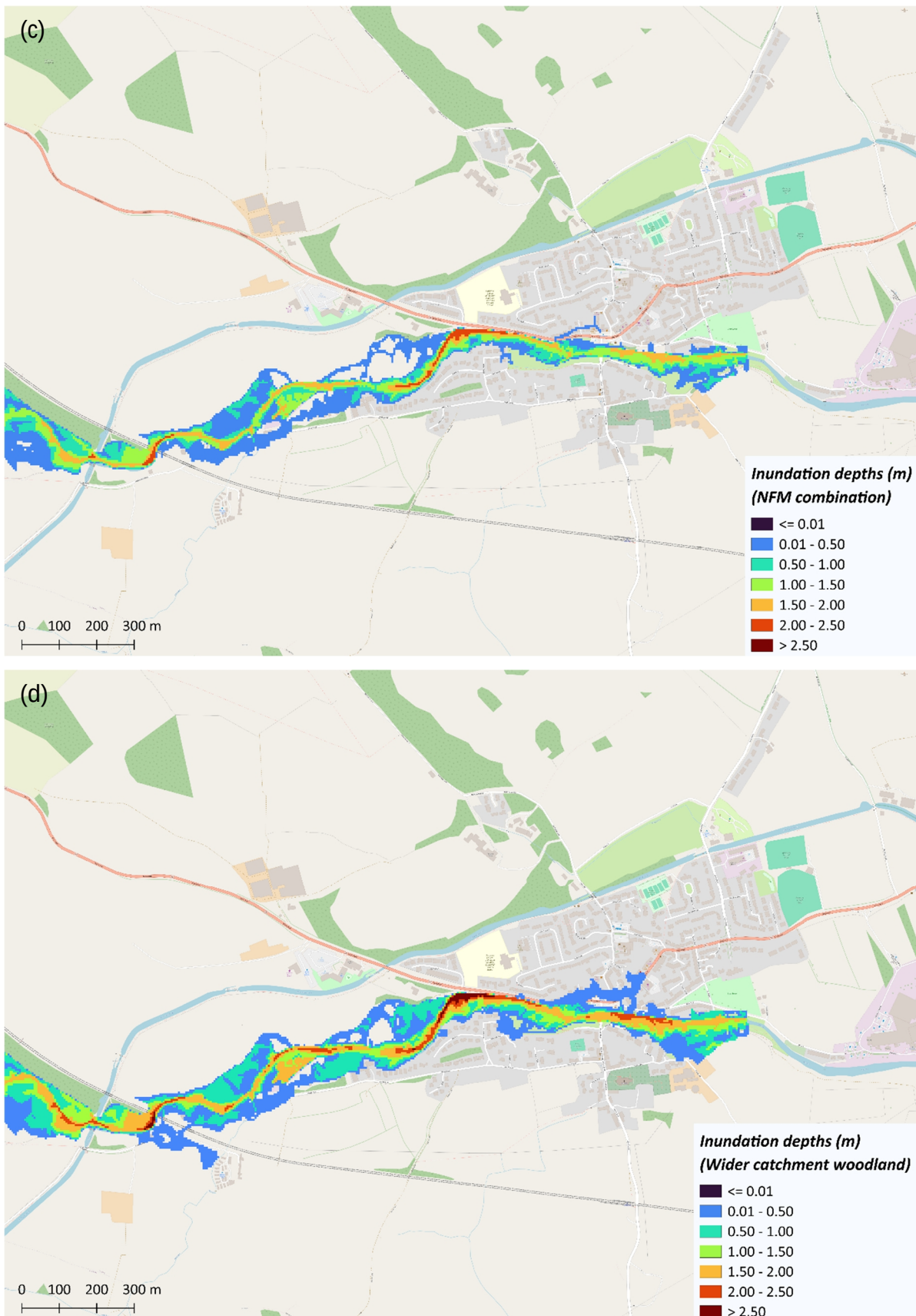


Figure 4.8. Coupled model outputs of maximum inundation extents and depths (m) among different scenarios (Event 1) for the large village of Gargrave. (a) No NFM scenario; (b) Leaky dams and riparian buffer strips scenario; (c) NFM combination scenario; (d) Wider catchment woodland scenario.

4.5.3 Assessing model performance of the coupled model in comparison to SD-TOPMODEL

The hydrographs also included the results of the SD-TOPMODEL simulations from Chapter 3 (only the scenarios with land cover and all NFM interventions were shown as No NFM and with NFM in Figure 4.7), to compare the performance of the coupled model with SD-TOPMODEL. The hydrographs indicated that SD-TOPMODEL generally provided a better fit between simulated runoff and observed data for most events (e.g. Events 1, 2, 3, 5, and 7), while overestimation of peak discharge occurred in Events 4 and 6. Notably, these overestimations were mitigated in the coupled model results. This pattern was consistent across all events but did not always result in a decrease; in some cases, the coupled model showed increased peak discharge. A distinguishing feature of the coupled model compared to SD-TOPMODEL was its ability to flatten flood peaks and reduce hydrograph fluctuations. For multi-peaked events, the second or subsequent peaks were often elevated. This behaviour is likely due to the coupled model's lack of an infiltration module in its computing mechanism. Focusing on the localisation of the flood peaks, the coupled model provided a better fit for peak shapes and discharge compared to SD-TOPMODEL. This was especially evident in the arrival time of peaks, where the coupled model results showed strong consistency with observed data.

In addition to the visual inspection of the hydrographs, goodness-of-fit metrics were employed as statistical criteria to assess the baseline models of both the coupled model and SD-TOPMODEL for model accuracy. The box plot (Figure 4.9) illustrates the comparison between the coupled model and SD-TOPMODEL across nine goodness-of-fit metrics, calculated from seven events under the No NFM scenario (land cover map applied only) and the observed data.

First, the model performance indices (d , KGE, r , VE, NSE, R^2 , wNSE) are compared: the results for d , NSE, R^2 , and wNSE are similar between the two models, with the coupled model having slightly better NSE and R^2 values than SD-TOPMODEL. For the Pearson correlation coefficient (r), the coupled model shows better performance. Conversely, SD-TOPMODEL slightly outperforms the coupled model in KGE and VE, though outliers representing over- and under-performance are observed in the coupled model results.

Metrics such as NSE, R^2 and d are lumped criteria, insensitive to the variability in the results, while KGE and VE are normalized by the average observation, leading to an underestimation of peak discharge (Althoff and Rodrigues, 2021). The wNSE metric increases the weighting of the peak discharge to address the limitation of NSE (Hundecha and Bardossy, 2004). Pearson's r reflected the correlation between the modelled results and observed data, indicating that the trends are closely aligned. For error measures, the coupled model provides worse results than SD-TOPMODEL in PBIAS, a metric normalized by the average of observed values. However, as RMSE assigns greater weight to larger errors and outliers, the coupled model achieves a lower RMSE value, indicating smaller absolute errors compare to SD-TOPMODEL.

Overall, these assessment metrics demonstrate that the coupled model and SD-TOPMODEL exhibit comparable accuracy, with the coupled model outperforming SD-TOPMODEL in capturing flood peaks and peak rates. The coupled model does not simulate the receding limb as effectively as SD-TOPMODEL, which is reflected in several metrics normalized by means. The coupled model provides better performance in metrics emphasizing peaks and outliers.

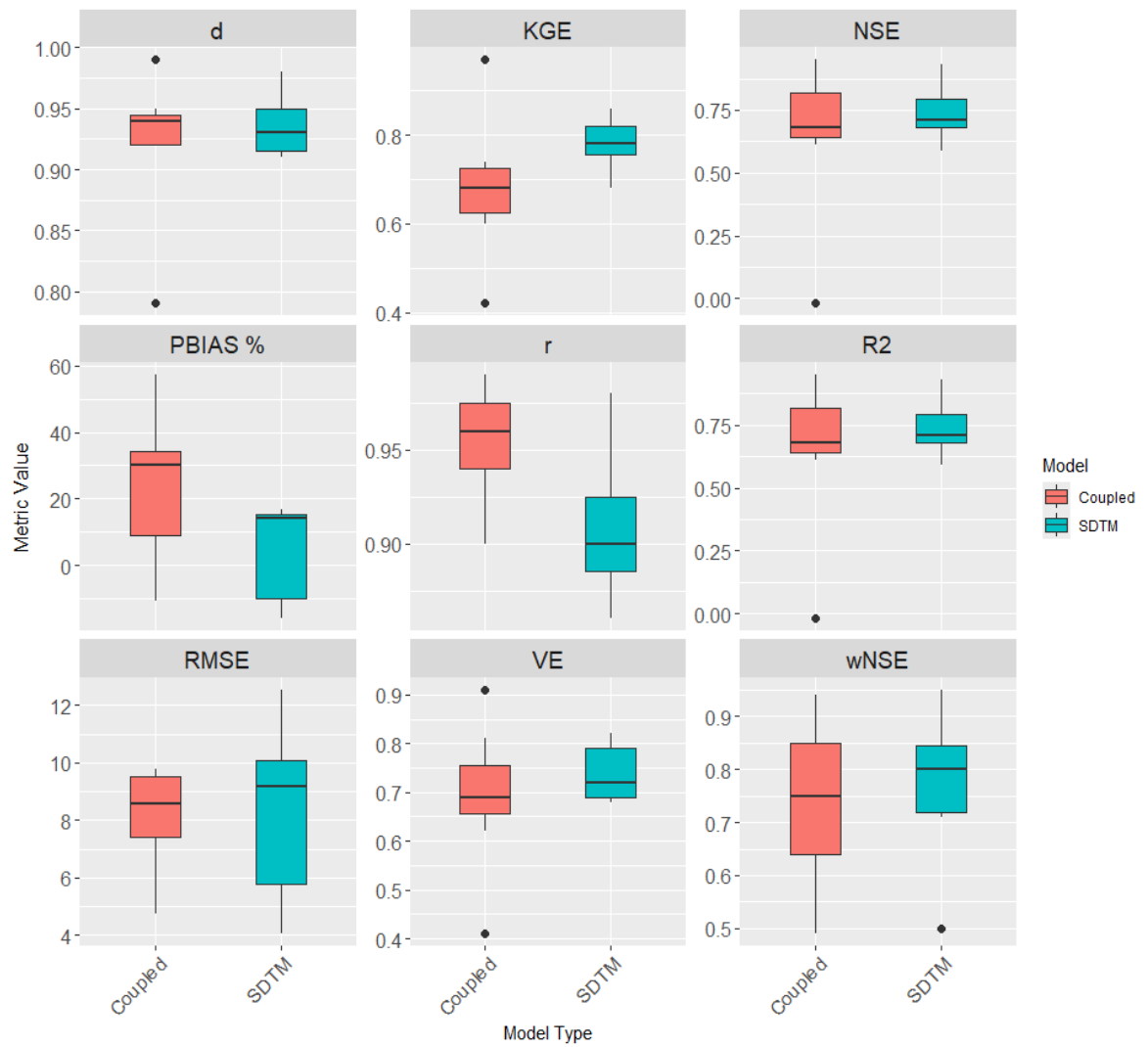


Figure 4.9. Comparison of goodness-of-fit metrics calculated for seven events (No NFM scenario) between SD-TOPMODEL (SD-TM) and the coupled model

4.5.4 Variations between the coupled model and SD-TOPMODEL in responses to NFM

In Chapter 3, SD-TOPMODEL was employed to simulate a realistic combination scenario of all NFM interventions, which aligns with the NFM combination scenario tested using the coupled model in this chapter, except for the additions of leaky dams and riparian buffer strips. As described in Section 4.5.2.1, the implementation of leaky dams was effective in delaying flood peak arrivals in tributaries and had no significant impact on peak discharge reduction. Similarly, Section 4.5.2.2 demonstrated minimal differences in peak analysis results between the NFM (leaky dams and riparian buffer strips) scenario and NFM combination scenario tested using coupled model. Consequently, the differences attributable to leaky dams can be excluded when comparing the two models'

responses to the No NFM scenario (land cover map applied only) and the NFM combination scenario.

The differences in discharge over time generated by the two models simulating the catchment with or without NFM interventions for each of the seven events are illustrated in Figure 4.10. These comparisons highlight how the coupled model maintains robustness in simulating NFM effectiveness while exhibiting distinct model characteristics. Additionally, they illustrate the models' performance under different high-flow event characteristics. A consistent feature across all events was that the SD-TOPMODEL simulation under NFM scenarios increased total runoff during the period of the rising limb following rainfall onset compared with the No NFM scenario, whereas the coupled model generally showed a decrease. This difference arises because SD-TOPMODEL represents NFM interventions as increasing soil infiltration and water storage, resulting in a rapid increase in subsurface runoff after rainfall onset along with a rapid increase in total runoff in the final output of the model. This is a process that is not fully delivered in the coupled model. In contrast, the Flood Modeller part accounts for NFM interventions by increasing surface roughness, which could reduce runoff after rainfall onset. An exception occurred in Event 3, where intense and concentrated rainfall rendered increased surface roughness insufficient to reduce runoff effectively.

During the flood peak period, the timing and discharge of peak differences were broadly consistent between the two models, with similar reductions observed. However, some deviations were evident in specific events, likely influenced by event characteristics. For example, in Events 3 and 4, which were characterized by high intensity continuous rainfall, the models exhibited asynchronous responses to NFM interventions. In the hydrograph for Event 3 (Figure 4.7), prolonged high flow resulted in unsynchronised hydrograph shapes and NFM-induced variations between the models, driven by reduced fluctuations in the coupled model. Event 4, occurring under dry antecedent catchment conditions, revealed SD-TOPMODEL's heightened sensitivity to high-intensity rainfall with the addition of NFM, producing substantial increases in total runoff. Conversely, the coupled model reduced runoff due to increased surface roughness. In other high flow events, the NFM simulations by the two models were unaffected by multi-peaked floods or varying catchment conditions (wet or dry).

Thus, the coupled model demonstrated some divergence from SD-TOPMODEL under high-intensity rainfall events but retained robustness and reliability in simulating NFM scenarios. It also provided robust insights into the impacts of NFM interventions on peak discharge and timing, affirming its suitability for NFM intervention modelling.

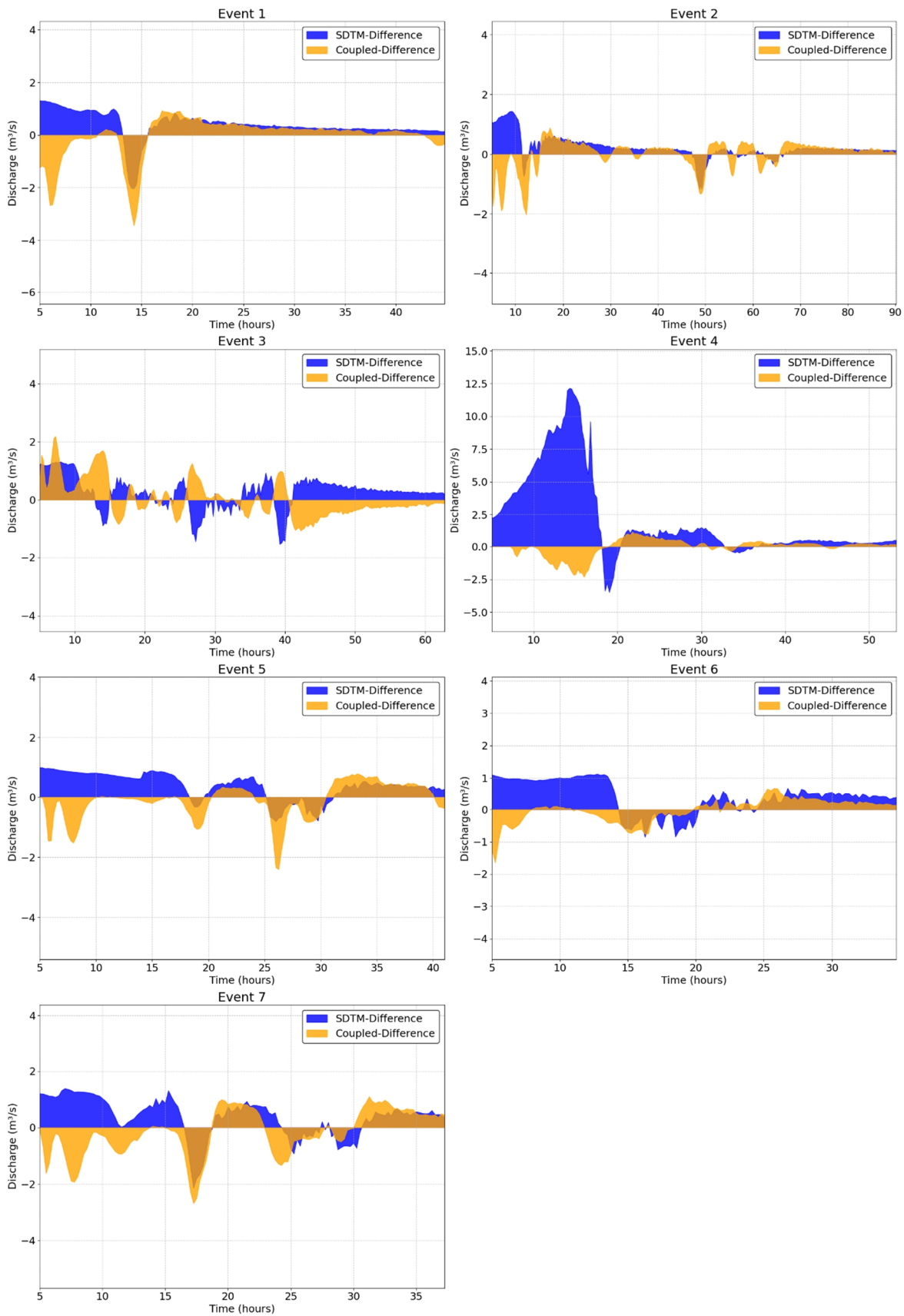


Figure 4.10. The discharge differences between No NFM and with NFM in SD-TOPMODEL (SDTM) and the Coupled model (positive values represent increases in discharge by using NFM discharge minus No NFM discharge, and vice versa). Full details of the event hydrographs can be found in Figure 4.7.

4.6 Discussion

Using the coupled model, all NFM interventions in the study catchment were integrated into the catchment-scale modelling framework, including detailed representations of leaky dams and other surface structural measures. This approach provides opportunities to evaluate the effectiveness of NFM interventions and assess their potential impacts on tributary synchronisation under various rainfall events and NFM scenarios at larger catchment scales.

4.6.1 The effectiveness of leaky dams by scale

In this Chapter, experimental comparisons were conducted using the coupled model to evaluate the effects of leaky dams in four tributaries before and after their implementation. A review study highlighted a lack of results under bankfull conditions in both field experiment and modelling studies (Addy and Wilkinson, 2019). To address this gap, all high flow events simulated in this study exceeded the bankfull capacity of the channel, resulting in overtopping of leaky dams across all tributaries and events. Previous studies suggested that leaky dams were most effective for events with a return period less than 1.5 years, with diminishing peak reduction effectiveness as the return period increases (Senior et al., 2022; van Leeuwen et al., 2024). However, no reduction in effectiveness with increasing return periods of events (from 1 to > 200 years) was observed in this study. While no significant differences in effectiveness were found across event characteristics, results varied between tributaries. These variations showed no correlation with tributary catchment area or the number of leaky dam implementations, supporting findings from other modelling studies (Hankin et al., 2020; Black et al., 2021). Some studies suggested that these variations can be attributed to differences in dam physical properties, location and spacing distances, and differences in geology and surface cover (Black et al., 2021; Follett and Hankin, 2022). However, these factors were treated as uniform in this modelling study. Thus, the differences were most likely influenced by varying average channel gradients among the tributaries, as identical leaky dams in steeper channel gradients generate greater upstream depth and backwater volume but lower backwater length, resulting in reduced effectiveness in delaying and reducing flood peaks (Hankin et al., 2020; Follett and Hankin, 2022; Follett et al., 2024).

Leaky dams were more effective at delaying flood peaks than reducing peak discharge, though these two effects were not synchronised and inversely influenced each other. A previous modelling study observed that lag time increased with rising flood magnitudes until reaching bankfull discharge, beyond which the lag time either plateaued or decreased (Black et al., 2021). Although leaky dams facilitate the availability of floodplain connectivity and expandable field storage during high flow events, the small storage capacity of these features may impede their downstream flood mitigation impacts at the (sub-) catchment scale (Thomas and Nisbet, 2012; Kay et al., 2019; Hankin et al., 2020; Beven et al., 2022; van Leeuwen et al., 2024). The findings of this study also support this, showing that both peak delay and peak reduction were less effective at the catchment scale compared to the tributary scale. All evidence points to the limited ability of leaky dams to delay and reduce flood peaks at catchment scales, but there is a lack of research on the flood mitigation potential of overflows on both sides of the overtopped dam. Further modelling is required to explore the potential for utilizing expandable field storage within tributaries to better understand the relationship between peak delay and peak reduction caused by leaky dams.

4.6.2 NFM impacts on peak discharge and flood inundation

Most NFM modelling studies have concentrated on their impacts on peak discharge and timing within the flood hydrograph, with only limited attention given to the extent and depth of flood inundation (Lane, 2017; Addy and Wilkinson, 2019; Kay et al., 2019; Chapter 2). The coupled model utilized in this chapter offers detailed spatial-scale information, complementing hydrograph analyses, and thus provides robust scientific evidence for understanding the inundation impacts of NFM during high flow events.

As described in the previous results, some differences were observed between the outputs of SD-TOPMODEL and the coupled model. These differences were not evident when comparing the peak mitigation effects of NFM interventions, as both models achieved similar reductions in peak discharge and peak delays. However, discrepancies became apparent in the hydrographs (Figure 4.10), suggesting that the coupled model may have introduced additional uncertainty due to the increased complexity of the coupling process. Despite this, the coupled model offers valuable outputs of flood inundation depths and extents, which the hydrological model alone cannot provide. This

distinction informs the targeted use of each model in NFM modelling. In upland catchments, where rainfall-runoff processes dominate, SD-TOPMODEL offers a more efficient modelling approach. Conversely, in scenarios involving surface structures, runoff convergence, and floodplain inundation, the coupled model is more appropriate due to its ability to simulate flood inundation dynamics.

This study reveals that under NFM scenarios, both inundation extent and depth decrease as peak discharge decreases. However, large-scale tree planting across the catchment, despite reducing peak discharge, increases inundation extent and depth. The effects of increased woodland on flood peaks remain debated, with evidence suggesting reduced effectiveness for larger flood events and in larger catchments (Xiao et al., 2022). This observation aligns with the results in Figure 4.6, where the reduction in flood peaks is smaller for extreme events such as Events 3 and 4, which have return periods ≥ 100 years. Additionally, previous studies have concluded that woodland effectiveness is highly related to their desynchronisation of flood waves through the catchment (Dixon et al., 2016; Dadson et al., 2017; Lane, 2017; Metcalfe et al., 2018; Kingsbury-Smith et al., 2023).

The coupled model accounts for two critical effects caused by woodland: slowing the process of saturation-excess overland flow (Murphy et al., 2020) and increasing surface roughness during the conveyance of overland flow across the catchment (Bond et al., 2020; Monger et al., 2022; Monger et al., 2024). A plausible explanation for the model results is that these effects may inadvertently synchronise flood wave arrivals downstream under the ideal maximum woodland scenario. While upstream woodland reduces total runoff (as seen in hydrograph runoff reductions), delayed streamflow and overland flow may arrive simultaneously downstream, leading to a greater inundation extent and depth, particularly in Gargrave town. This finding underscores the need to understand interactions between NFM interventions, as poorly coordinated designs within sub-catchments could result in unintended synchronisations (Blanc et al., 2012; Dixon et al., 2016). Thus, it is strongly recommended that modelling is undertaken for all catchments where NFM interventions are proposed to ensure effective planning mitigates such synchronicity risks and optimizes spatial designs.

4.6.3 Benefits and future implications of the coupled model

Even though SD-TOPMODEL has enabled spatially distributed simulations at high resolutions (Gao et al., 2015; Gao et al., 2017; Kingsbury-Smith et al., 2023), its outputs remain constrained by the TOPMODEL algorithm, which produces spatial-scaled, cumulative and conceptual results. These outputs are primarily valid at river channels and their confluences, and catchment outflow boundaries, in alignment with hydrological principles. However, the model's outputs in accumulation areas, such as hillslopes, are stochastic and do not provide detailed hydrological insights. The coupling of SD-TOPMODEL and Flood Modeller 2D enhances their capabilities by enabling the input of precise surface structural changes, such as leaky dams, into the model, and by producing fully spatially distributed outputs.

The direct coupling of a hydrological and 2D hydrodynamic model at the same scale, as implemented in this study, is computationally more efficient than using a 2D hydrodynamic model alone to simulate surface runoff across the whole region (Shen et al., 2024). In the rainfall process, runoff flows through both the hydrological model and the 2D hydrodynamic model regions simultaneously. Using this direct coupling method synchronises the rainfall-runoff and surface convergence processes, allowing the model to represent flooding dynamics more accurately (Brewer et al., 2018). Furthermore, goodness-of-fit metrics used to evaluate model performance demonstrate that the coupled model achieves high accuracy and performs particularly well in simulating flood events with high return periods. This improved performance can be attributed to the computational mechanisms and default parameters inherent in Flood Modeller 2D (Pinos and Timbe, 2019). Thus, the coupled model effectively incorporates SD-TOPMODEL's operational mechanisms for soil property changes and rainfall-runoff processes, maintaining both accuracy and performance while providing enhanced spatiotemporal outputs.

However, the coupled model faced certain limitations. One significant limitation was the representation of leaky dams, which was constrained by the model's 5 m resolution. This constraint required all leaky dams to be represented with a uniform width of 5 m, potentially overestimating, or underestimating their real-world physical characteristics. Additionally, a common challenge in NFM modelling is the limited availability of post-

implementation monitoring data for model validation (Hill et al., 2023). In this study, the inundation validation of the coupled model, which relied on historical flood records, demonstrated limited accuracy, thereby introducing potential uncertainties into the model outputs.

The coupling method employed in this study was developed specifically for SD-TOPMODEL and requires further validation for its application across other hydrological and hydrodynamic models. Currently, the approach involves manually identifying coupling points and extracting runoff data, which limits its scalability and efficiency. Future advancements could focus on developing automated processes through coding, incorporating necessary parameters to streamline the coupling workflow. Additionally, the next stage of research should aim to model systematic NFM interventions at a catchment scale, enabling simulations at larger scales and across diverse catchments with varying characteristics. Such advancements will provide robust, numerical evidence to support NFM planning and inform future policy development.

4.7 Conclusions

This study demonstrated the effectiveness of a coupled hydrological-hydrodynamic model in evaluating NFM interventions, particularly leaky dams, and their influence on flood peak delay, discharge reduction and inundation extents across different tributaries and high flow events. The coupled modelling approach developed for SD-TOPMODEL provides a good fit and reliable performance for peak discharge and timing. However, its performance on the receding limb was comparatively less effective than SD-TOPMODEL. Despite these limitations, the coupled model proved robust, offering enhanced spatiotemporal inundation outputs and a valuable tool for modelling the impacts of NFM interventions on flood hazards in downstream towns and cities.

Notably, tributary characteristics such as the channel gradient played a critical role, with steeper gradients reducing the effectiveness of leaky dams. The study also revealed that while leaky dams are more effective in delaying flood peaks than reducing peak discharge, these effects were inversely proportional and not synchronised. While NFM scenarios consistently showed positive flood mitigation impacts with reductions in peak

discharge, inundation extent, and depth, the maximum woodland scenario across the catchment unexpectedly increased inundation extent and depth due to the potential synchronisation of flood wave arrivals downstream. These results highlight the critical need for coordinated NFM planning to avoid unintended synchronisation and optimize intervention effectiveness. While practitioners may be keen to simply go ahead and apply NFM and land cover interventions based on anticipated 'typical' flood outcomes, catchment by catchment modelling is necessary to reduce the possibility of inadvertent impacts being realised. Such modelling has a cost implication for catchment planners, but ultimately this consists of a very small component of the overall cost of implementing an NFM scheme at scale and is trivial compared to the scale of costs associated with flood damage to properties and infrastructure. The coupling of SD-TOPMODEL with Flood Modeller 2D enabled the precise incorporation of structural changes such as leaky dams while providing fully spatially distributed outputs, demonstrating its utility for integrated catchment-scale NFM modelling.

4.8 References

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Chapter 5 Synthesis and conclusions

5.1 Section outline

The overall aim of this research was to understand and quantify the effectiveness of a range of NFM interventions in flood mitigation and to investigate how their effectiveness varies with catchment and rainfall characteristics. A quantitative review of existing NFM studies was undertaken, and the insights gained informed the development of modelling approaches for a case study of the Upper Aire catchment. Hydrological and coupled hydrological-hydrodynamic models were used to investigate and evaluate the impacts of implementation scenarios for single types or combined multi types of NFM interventions within the catchment under different historical flood events and catchment antecedent conditions. Additionally, the implications of NFM interventions for flood inundation hazards in downstream areas were also assessed.

This chapter aims to bring together key findings from the thesis and discuss how the work presented in the preceding three chapters has contributed to addressing the three overarching research questions (RQs) outlined in Section 1.4. The following sections provide a summary of the key findings drawn from each of the three data chapters. The benefits and limitations of this work are discussed, along with broader implications for future research directions.

The original RQs were as follows:

RQ1: What insights can the quantitative meta-analysis of NFM studies provide regarding the effectiveness of NFM interventions from a global and national perspective?

RQ2: How does the combination or spatial configuration of multiple NFM interventions alter overland flow responses to different rainfall events under varying catchment antecedent conditions at larger scales, as assessed using modelling approaches?

RQ3: How can coupled modelling approaches be applied to simulate NFM structural surface interventions and evaluate the changes in inundation within downstream urban areas resulting from multiple NFM interventions at larger catchment scales?

5.2 Summary of key findings

The quantitative review of natural flood management research in Chapter 2 highlighted a significant global growth in NFM and NBS-related studies, particularly in Europe, over the past three decades. Research focus has shifted from assessing flood impacts on ecosystems and hydrology to understanding how land cover and landscape changes influence flood dynamics. This evolution is marked by an emphasis on catchment-wide strategies, integration of ecosystem services, and the transition from single to multiple NFM interventions. Modelling studies dominate this field, consistently demonstrating the effectiveness of NFM interventions for flood mitigation across various scales and conditions. Importantly, evidence suggests that NFM interventions remain effective regardless of catchment size or rainfall intensity, with combined interventions leading to greater effectiveness than single interventions. However, confidence in these findings is limited by the variability in storm and catchment characteristics, and the spatial distribution of interventions. The research underscores the need for further empirical evidence through large-scale, physically based models and the strategic design of catchment-wide intervention networks to enhance decision making and flood risk management.

The third chapter represents the first application of SD-TOPMODEL at a high spatial resolution (5 m) for a moderately sized (81.4 km²) catchment, achieving reliable model performance with observed data (NSE ranging from 0.59 to 0.93). The effectiveness of interventions is influenced by storm characteristics and pre-event conditions, with greater flood peak reductions during single-peaked storms and dry antecedent conditions, while no correlation was found between rainfall intensity and peak reductions. Combined interventions out-performed single interventions, emphasizing the potential of strategic planning to optimise cost-effectiveness and implementation locations. High-resolution spatially distributed modelling is recommended to better understand the interplay between specific storm/catchment characteristics and spatial configuration of interventions. To support the integration of NFM into broader flood risk management strategies, further integration of hydrological and hydrodynamic models is required to cover all NFM interventions at the catchment scale, especially surface structural interventions such as leaky dams.

The coupled SD-TOPMODEL and Flood Modeller 2D approach outlined in Chapter 4 proved effective in evaluating the spatiotemporal impacts of NFM interventions, particularly surface structural interventions, on downstream flood hazards. The coupled model demonstrated reliable performance in capturing peak discharge and timing. Modelling showed that tributary characteristics, such as channel gradient, significantly influenced intervention outcomes, with steeper gradients reducing the effectiveness of leaky dams. Flood wave synchronization among tributaries could lead to unintended consequences, such as increased inundation in an urban area downstream (Gargrave) in maximum woodland scenarios. These findings highlight the importance of coordinated, catchment-specific planning to avoid adverse effects. Despite higher initial costs, detailed modelling offers long-term savings by ensuring interventions are spatially designed for best flood outcomes and reducing flood damage risks. The study demonstrates the utility of coupled models for integrating structural NFM interventions and generating spatially distributed outputs, advancing flood risk management practices at the catchment scale.

5.3 Implications for NFM planning: a case study of the River Aire

In this thesis, the Upper Aire catchment was used as the study site for both hydrological modelling and coupled hydrological-hydrodynamic modelling. Over the past decade, this catchment has had a range of NFM interventions implemented within it (UAP, 2024), developed through landowner engagement. These interventions include woodland and hedgerow planting, soil aeration, leaky dams, and riparian buffer strips. However, there is a lack of published scientific evidence examining the flood mitigation effects of these interventions in the catchment. The modelling results presented in this thesis begin to address this gap by providing insights into the effectiveness of single and multiple interventions, their spatial extent, and the scale of study (modelling) in the Upper Aire catchment.

5.3.1 Size and location of interventions within various catchment and study scales

Some studies have argued that NFM interventions must exceed a minimum size to be effective in flood mitigation (Bathurst et al., 2011b; Blanc et al., 2012). For example, the flood mitigation capacity of floodplain wetlands depends significantly on their size and

location (Acreman & Holden, 2013; Acreman et al., 2003). It has also been suggested that changes in forest cover need to exceed 20–30% to induce noticeable reductions in peak discharge, with diminishing effects as rainfall event size increases (Bathurst et al., 2011a; Bathurst et al., 2011b). Modelling approaches dominate research on the impact of intervention size and location on flood mitigation (Hill et al., 2023; Chapter 2), with their reliability validated in published results (Bond et al., 2022; Kingsbury-Smith et al., 2023; Monger et al., 2024; Peskett et al., 2023).

The modelling outputs presented in this thesis demonstrated that the effectiveness of individual interventions in the Upper Aire is not determined by their size but varies according to the type of intervention (Chapter 3). For instance, simulations of an ideal maximum woodland scenario (66.9% of the catchment covered by woodland) indicated a stronger effect on flood peak delay than on peak discharge reduction, with no significant improvements in inundation maps (Chapter 4). All NFM interventions have the potential to influence the synchronisation of flood peaks across tributaries in the catchment (Pattison et al., 2014; Thomas & Nisbet, 2007), which provided opportunities to improve NFM resilience by integrating different NFM interventions and combining them with other forms of flood management measures at the catchment scale (Black et al., 2021). The greatest flood mitigation benefits were achieved by combining all types of existing interventions at the catchment scale (Chapter 3). This suggests that implementing multiple interventions across the catchment is more effective than single interventions applied over large areas. However, this thesis does not include scenario modelling or discussions on the specific locations of NFM interventions due to data and research scope limitations. Previous studies have clarified suitable topographic and hydrological conditions for specific types of interventions and land cover changes (Addy & Wilkinson, 2019; Archer et al., 2013; Bond et al., 2022; Gabriels et al., 2022; Peskett et al., 2023; Reaney, 2022; Roberts et al., 2024; Shuttleworth et al., 2019; Table 2.1), however, the spatial configurations and trade-offs of multiple interventions require further exploration through modelling (Chapter 2).

Previous studies have suggested that implementing a single type of NFM intervention can only mitigate floods at a localised scale where the interventions are implemented (Barnsley et al., 2021; Bezak et al., 2021; Costa et al., 2021; Dadson et al., 2017; Ellis et

al., 2021; Kay et al., 2019; Lane, 2017; Norbury et al., 2021; Page et al., 2020; Thomas & Nisbet, 2012; Wahren et al., 2012; Wilkinson et al., 2019). There is currently no conclusive evidence demonstrating their effectiveness in mitigating floods at the catchment scale (Blanc et al., 2012; Dadson et al., 2017; Peskett et al., 2023). However, catchment-scale understanding is critical and has become a key focus in NFM research (Carter et al., 2024; Hill et al., 2023; Chapter 2).

The quantitative review of past NFM studies (Section 2.5) found no evidence that flood mitigation effectiveness decreases when scaling from local to large catchments (up to 19,234 km²; Chapter 2). This contradicts the predictions of most small-scale studies, which suggest that effectiveness diminishes at larger scales (Black et al., 2021; Kay et al., 2019; Lane, 2017). Both model-based research chapters (Chapter 3 and 4) in this thesis were undertaken for the Upper Aire catchment scale (81.4 km²) and produced results consistent with those of smaller-scale studies in terms of flood peak reduction and inundation mitigation (Bond et al., 2022; Ferguson & Fenner, 2020; Hankin et al., 2019; Kingsbury-Smith et al., 2023; Monger et al., 2024). This suggests that combinations of NFM interventions in upland areas maintain effectiveness at larger catchment scales, particularly for downstream urban areas.

In the Upper Aire catchment, a greater emphasis on strategically integrated NFM interventions is required. For instance, woodland planting was identified as the most effective intervention in Chapter 3 but accounts for only 0.61% of the catchment area. Soil aeration resulted in more significant mean peak flow reductions but had a lower effectiveness: area ratio (0.9:1) compared to woodland planting (4.6:1) and hedgerow planting (1.4:1). While these differences diminish when combining interventions, the cumulative effect of multiple interventions does not equate to the simple summation of their individual effects. Moreover, the combined impacts vary depending on rainfall characteristics and antecedent catchment conditions. These findings align with results from other modelling studies (Hankin et al., 2021b; Kingsbury-Smith et al., 2023; Willis & Klaar, 2021). This thesis utilises the use of historical rainfall and soil moisture data to determine the extent to which NFM combinations within the Upper Aire catchment respond to rainfall and antecedent conditions associated with flood events. If the effects of climate change scenarios on these factors are considered, these findings can be used

to predict the response of NFM to future events. In future studies, using the predicted distribution of rainfall and antecedent conditions within a catchment to design integrated NFM interventions is beneficial to increase effectiveness at large scales.

Expanding the implementation of more effective NFM interventions, such as woodland planting, should be paired with carefully planned combinations of other interventions. In the Upper Aire catchment, the overlap between woodland planting and soil aeration interventions highlighted the importance of realistic parameter adjustments in the model, which was expressed as the largest parameter change in the model for consistency with reality. Despite this overlap, increased implementation did not translate into enhanced flood mitigation benefits. Therefore, planning combined interventions requires active collaboration between decision-makers and practitioners to develop an optimised implementation timeline and spatial distribution strategy for all intervention types at a local scale. Numerical modelling, spanning from local to wider catchment scales, should be employed as a critical tool to provide robust evidence for this planning process.

5.3.2 Recommendations for upscaling NFM impacts

The exploration of flood responses further downstream within the River Aire catchment, including urban areas such as Skipton, Keighley, and Leeds, was constrained by model computational capacity. The Upper Aire catchment, which represents 29% of the total River Aire catchment area (904.8 km²), hosts the majority of NFM interventions, particularly in the upland areas that account for 9.6% of the River Aire catchment. While the model outputs demonstrated notable flood mitigation effects within this 9.6% upland area, the implications for flood mitigation across the entire catchment remain uncertain. Assuming a 15% peak discharge reduction in the upland region, the downstream flow reduction would be approximately 1.44% based on an area-proportional calculation. However, uncertainties persist regarding whether the upland peak flow could synchronise with other tributary flows to result in an observable downstream peak reduction (Dixon et al., 2016; Hankin et al., 2021a; Lavers et al., 2022). Additionally, factors such as topography, land cover, and surface structures that influence surface flow velocity could further complicate flow propagation dynamics (Metcalf et al., 2017; Thomas & Nisbet, 2007). To address these uncertainties and improve the

understanding of NFM effectiveness, a more computationally robust hydrological and coupled conceptual model is required. Such a model should incorporate detailed spatial characteristics and enable multi-scale, multi-scenario simulations. This capability is essential not only for advancing NFM research but also for broader investigations into NBS (Hill et al., 2023; Kumar et al., 2021).

5.4 Challenges and recommendations in modelling NFM

Numerous limitations and challenges persist in the modelling of NFM, including issues related to data availability and resolution (e.g. rainfall, land cover and elevation), computational capacity, and model applicability to real-world scenarios. This section critically examines these challenges and offers recommendations for future research, informed by the review of previous NFM modelling studies (Chapter 2) and findings from the spatial modelling applied within the Upper Aire catchment (Chapters 3 and 4).

The review in Chapter 2 identified 31 studies employing modelling as a research approach, all of which provided numerical results for flood reduction. Of these, 18 studies were conducted at a smaller spatial scale than the catchment size modelled in this research (81.4 km²; Figure 2.8). However, as the scale of the modelled catchment increased, the spatial resolution of the models typically decreased. For instance, when SD-TOPMODEL was previously applied to a catchment of 84 km², it was constrained by computational requirements and limited to a spatial resolution of 20 m (Gao et al., 2017). Similarly, other models (e.g. Dynamic TOPMODEL) frequently utilized hydrological response units (HRUs) to enable simulations at larger catchment scales (Hankin et al., 2019; Metcalfe et al., 2017). While sacrificing resolution enhances computational efficiency, it also reduces the fidelity with which certain NFM interventions, such as hedgerows and leaky dams—typically narrower than 5 m in width—are represented. Goudarzi et al. (2021) developed a General Multistep Dynamic (GMD) TOPMODEL with adaptive timesteps and arbitrary topographic index discretisation to enhance efficiency based on the Dynamic TOPMODEL framework. The adaptive time-stepping mechanism enables high accuracy during flood peak simulations, while longer timesteps during pre- and post-peak periods reduce computational demands. However, this approach remains constrained by the resolution of rainfall data, with a minimum timestep of 15 minutes.

In this work, the use of high-performance computing (HPC) significantly reduced the time required for high-resolution model runs and facilitated efficient batch calibration of the model. To address the varying resolution demands of different NFM interventions, future models should incorporate algorithms capable of converting resolutions dynamically. Such approaches can be operationalized through boundary condition equations and integrated into model coupling frameworks. The representation of catchment spatial characteristics, such as land cover, through topographic index discretization serves as a promising example for the future development of dynamically adjustable spatial resolutions within TOPMODEL (Goudarzi et al., 2024).

Theoretically, an increase in catchment size does not inherently diminish the effectiveness of NFM (Lane, 2017; Chapter 2). Implementing comprehensive NFM strategies at broader catchment scales, beyond the immediate areas of intervention, is both logical and practical. However, in addition to challenges related to computational capacity and spatial resolution, models must retain sufficient flexibility to accommodate diverse scenarios, especially when catchment-scale simulations incorporating multiple NFM interventions are required to inform decision-making. Decision-makers require robust and valid information to guide cost-effective and strategic decisions. This includes understanding the combinations and trade-offs of intervention types, locations, and implementation areas that deliver the most effective flood mitigation outcomes, rather than pursuing widespread implementation without strategic planning. For example, large-scale implementation, such as the wider catchment woodland scenario modelled in Chapter 4, may not always yield significant flood hazard reduction. Multi-scenario modelling offers an approach to investigate targeted and effective solutions. In this study, as well as in previous research where multiple interventions were modelled, the flexibility and reliability of models were often constrained by data availability and model applicability.

In terms of rainfall inputs, this study relied on measured data from gauging stations. However, as only one station was available within the Upper Aire catchment, the spatial dynamics of rainfall were not represented in the simulations. Standardized rainfall data derived from the FEH method introduced further uncertainty by disregarding catchment-specific rainfall variability (Kingsbury-Smith et al., 2023). Second, there remains a

potential discrepancy between the modelled effectiveness of NFM and observed outcomes. Model validation was impeded by the absence of empirical data on the localized or catchment-wide flood mitigation effects of NFM interventions. Such data would ideally include comparative measurements taken before and after the implementation of NFM interventions, accounting for other natural and anthropogenic changes in the catchment. The Before-After-Control-Impact (BACI) approach, widely utilized in monitoring studies, has been demonstrated to provide critical evidence for evaluating NFM interventions (Black et al., 2021; Goudarzi et al., 2024; Lo et al., 2022; van Leeuwen et al., 2024; Wallace & Chappell, 2019). Finally, there is a need to enhance the applicability of modelling to real-world scenarios. In this study, all simulations were based on observed events to align model outputs with real-world conditions. However, explaining the variability in model responses to different rainfall events proved challenging. Although model results were grouped and analysed based on event characteristics and catchment antecedent conditions, a degree of variability remained unaccounted for. This uncertainty may be attributed to model assumptions. The NFM interventions incorporated into the model were pre-calibrated using generalized equations, which may not fully account for specific events, scenarios, or catchment conditions (Hill et al., 2023). Addressing these limitations is essential for advancing the utility of NFM modelling in large-scale flood risk management.

5.5 Insights between modelling and decision-making

A clear and effective workflow for modelling NFM is essential to address the limitations of existing models, alongside advancements in multi-scale and multi-scenario spatial modelling with enhanced computational efficiency. A suggested workflow is presented here, following the research framework and logic of this thesis (Figure 5.1). Thaler et al. (2023) identified key opportunities for successful NFM implementation, encompassing environmental, social, institutional, and financial aspects that can reduce costs and facilitate the transmission of stakeholder knowledge. This section provides recommendations for decision-making focused on addressing environmental opportunities and challenges, specifically from the perspective of stakeholders and practitioners. Two survey and interview studies of NFM stakeholders and practitioners showed that most participants were supportive of NFM implementation and future

prospects but still face the challenge of balancing the realities of cost-effectiveness, multiple benefits, and uncertainties to achieve changes (Bark et al., 2021; Wells et al., 2020). This included a lack of evidence demonstrating the effectiveness of NFM leading to an inability to calculate cost-benefit ratios, as well as a lack of funding due to a lack of public understanding of NFM and confidence in its long-term maintenance. These challenges should all be factored into the initial NFM decision-making and implementation, and modelling approaches are the targeted tools to address these issues.

Even though a UK NFM manual (CIRIA, 2022) has outlined the technical and manual guidance for NFM in practice, there is still a lack of confidence in NFM implementation. To clearly demonstrate what evidence was missing on NFM effectiveness, Chapter 2 summarised information from the literature, including the purpose, techniques, and confidence levels regarding the downstream flood risk reduction efficacy of various interventions are outlined in Table 2.1. The findings indicate that it is essential to use modelling approaches to investigate the impact of intervention size and location, and catchment scale on NFM effectiveness and that in doing so we can show how to maximise flood benefits without wasting resources (Figure 5.1).

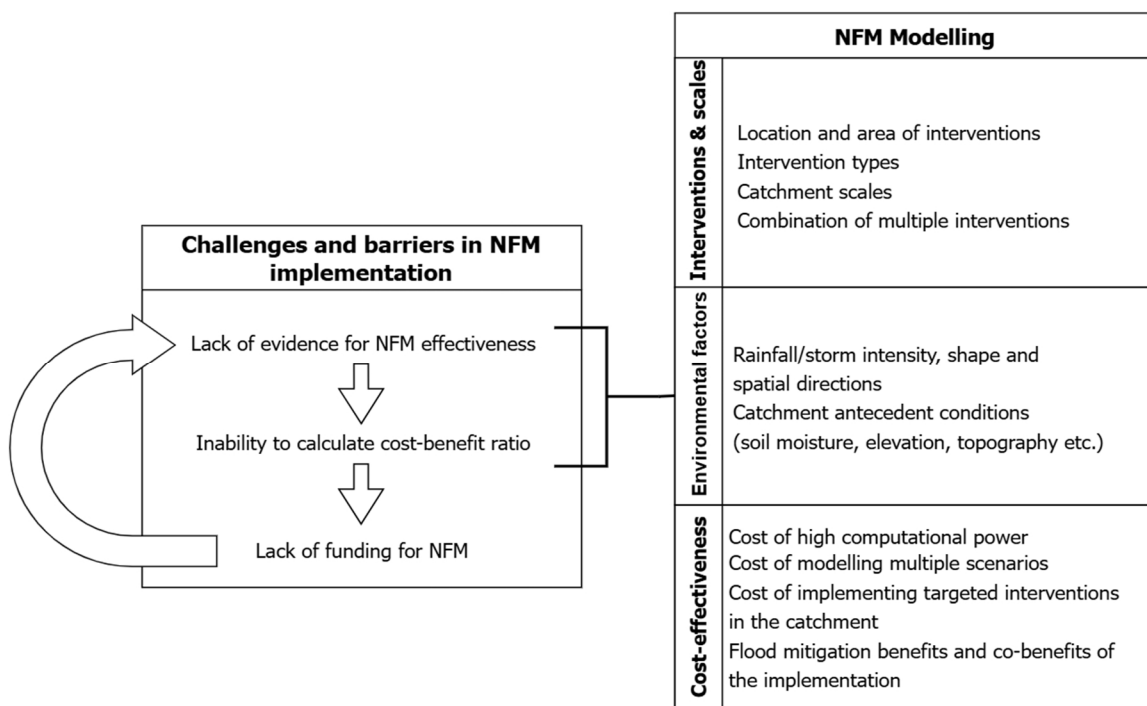


Figure 5.1. The framework of using modelling approaches to evaluate the effectiveness and cost-benefit of NFM as solutions to address identified challenges and barriers in NFM implementation (source: adapted from Wells et al., 2020, Figure 2).

Planning decisions should be informed by modelling approaches, as models based on known data can yield the most accurate representation of real-world outcomes in the shortest time and at the lowest cost (Kumar et al., 2021; Hill et al., 2023). Moreover, priority should be given to modelling approaches that can investigate the most effective combinations and spatial configurations of interventions, particularly when considering downstream impacts at catchment scales. The modelling outcomes in this thesis demonstrate that strategic configurations are more effective than merely increasing the number and size of interventions, offering valuable guidance for future NFM investments. When the objective is well-defined—for example, assessing the impact of tree planting on soil infiltration—a targeted model equipped with rainfall and infiltration modules should be selected for NFM modelling. Preference should be given to models that are flexible and capable of adapting to diverse conditions. Models should effectively account for catchment-specific attributes, such as the environmental factors illustrated in Figure 5.1. There is no intrinsic hierarchy between these modelling options, and the selection should be adjusted based on the specific goals and user needs. Another advantage of the modelling approach is its cost-effectiveness. With relatively low costs for high computational power and the ability to model multiple scenarios, it can efficiently support decisions (and hence costings) around implementing NFM interventions, before they are undertaken, through predicting the downstream discharge and inundation outcomes of the different intervention scenarios. In this thesis, SD-TOPMODEL and its coupling with Flood Modeller 2D can address all three groups of indicators outlined in Figure 5.1, ultimately identifying adaptive combinations of interventions tailored to rainfall patterns and catchment characteristics. However, it is crucial to acknowledge that different catchments possess unique features and requirements. Future research should therefore explore a broader range of scenarios and conduct additional modelling tests to enhance adaptability and applicability.

For local or catchment-wide pilot practice, monitoring or experimental approaches should be prioritized. For instance, if physical experiments confirm the local flood mitigation effects of a specific intervention, catchment-scale modelling can extrapolate its potential downstream impacts. Conversely, if monitoring validates the effectiveness of interventions at the catchment scale, validated models can simulate spatial

configurations and intervention combinations more efficiently. Such models can leverage reliable data from monitoring to enhance their accuracy and reliability.

A comprehensive and effective NFM implementation programme for a given catchment can be achieved through integrating targeted and flexible modelling approaches with robust monitoring strategies. This integration will enable decision-makers and practitioners to optimize the planning and implementation of NFM interventions, cost-effectively addressing flood risk.

5.6 Conclusions

This thesis has demonstrated the effectiveness of NFM both in previous studies and through a case study (81.4 km²) of the River Aire, utilizing hydrological and coupled hydrological-hydrodynamic modelling approaches. A quantitative review revealed no significant correlation between increasing catchment size or rainfall intensity and the flood mitigation effectiveness of NFM. This finding is further corroborated by the results of the two modelling chapters presented in this thesis.

The case study highlighted that storm and rainfall characteristics exerted a greater influence on NFM effectiveness than return period magnitude. Additionally, pre-event catchment conditions (e.g., wet, or dry) were found to have a more substantial impact on NFM performance than catchment size, with superior flood mitigation observed under single-peaked rainfall events and dry antecedent conditions. The coupled modelling approach highlighted the utility of integrating structural NFM interventions and generating spatially distributed outputs. It also identified potential unintended consequences arising from the asynchronous or synchronous effects of interventions, further emphasizing the need for careful spatial and temporal planning. These findings underscore the practical importance of coordinated and strategically planned catchment-scale NFM implementation in future flood risk management strategies. In conclusion, the modelling approach is pivotal to informing the successful deployment of catchment-scale NFM, serving as a highly efficient and cost-effective tool for NFM planning and effectiveness verification. It ought to be adopted in most catchment based NFM projects when designing options for interventions.

5.7 References

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Appendix A. Supporting information for Chapter 2

A.1 Detailed information for NFM techniques and measures grouped by purpose (Table 2.1)

Table A1.1. Number of articles for NFM techniques and measures grouped by purpose, with the confidence of their effectiveness and references based on Europe and UK research (the 'EU' in the table refers to Europe excluding UK)

	Purpose of intervention	NFM technique	Number of articles (n)	Confidence in the effectiveness on downstream flood risk reduction	Key references
Group A	Slow catchment flow generation and rainfall-runoff processes (off-channel)	Cross slope reforestation	n = 19 (UK)	UK: Low to Medium confidence	Bathurst et al., 2018; Birkinshaw et al., 2014; Buechel et al., 2022; Chandler et al., 2018; Monger et al., 2022; Monger et al., 2022; Mongil-Manso et al., 2021; Murphy et al., 2021; Page et al., 2020; Pattison, 2010; Peskett et al., 2021; Revell et al., 2021; Revell et al., 2022; Thomas & Nisbet, 2007; Wahren et al., 2012
		Floodplain/riparian reforestation	n = 17 (EU)	EU: Medium confidence The relatively balanced proportion of the three research methods improves confidence. There are several studies showing that afforestation consistently decreases median and low streamflow and water velocity by increasing soil saturated hydraulic conductivity, water-table depths, and surface roughness. But its role in reducing flood peaks depends on the size and location of afforestation, rainfall intensity and soil saturation conditions. The studies cover small, medium and large scales without significant scale issues. Effectiveness on flood attenuation can be limited by the rainfall intensity and initial soil conditions. Hillslope reforestation may be limited by the fact that these areas already have deeper subsurface flow.	

Soil and land management (soil aeration, sub-soiling, peatland, woodland, grassland, hedges)	n = 17 (UK) n = 11 (EU)	UK: Medium to high confidence EU: Medium to high confidence The UK studies were conducted as field experiments, all showing at small study scales (0.2 - 11.74 km ²) that restoring natural grassland and planting hedges reduced flood generation and surface flow rates. Studies at larger scales (21.5 – 2400 km ²) are dominated by modelling, with evidence of a mitigation effect of woodland compared to other land-use types, but are limited by catchment characteristics, locations and sizes of woodlands. There is a lack of empirical evidence at larger scales.	Ahlen et al., 2022; Bond et al., 2020; Caubel et al., 2003; Deasy et al., 2014; Edokpa et al., 2022; Ellis et al., 2021; Gabriels et al., 2022; Gao et al., 2016; Gao et al., 2017; Gao et al., 2018; Holden et al., 2019; Holden et al., 2018; Howson et al., 2021; Iacob et al., 2017; Kovar et al., 2011; Lane & Milledge, 2013; Marshall et al., 2014; Monger et al., 2022; Monger et al., 2022; Pulley & Collins, 2021; Richet et al., 2017; Shuttleworth et al., 2019; Terencio et al., 2019; Wallace & Chappell, 2020; Wallace et al., 2021
Peatland restoration (including gully blocking) Floodplain restoration/reconnection	n = 9 (UK) n = 17 (EU)	UK: Low to high confidence EU: Low confidence Studies of upland peatlands and of floodplain restoration in the UK and the EU are dominated by modelling approaches. Two field studies, at small scale, show that peatland vegetation restoration increases surface roughness slowing flow. Artificial and natural peatland pools also help with some additional temporary storage during storms. Modelling studies also suggest that peatland revegetation and gully blocking reduced peak discharge and increased lag times by increasing surface water storage but without empirical evidence for larger scale effects. Modelling studies also showed that floodplain restoration and reconnection are	Acreman et al., 2003; Addy & Wilkinson, 2021; Ballard, 2011; Capobianco et al., 2021; Clilverd et al., 2016; Edokpa et al., 2022; Fischer & Cyffka, 2014; Goudarzi et al., 2021; Holden et al., 2018; Holubova et al., 2016; Lane & Milledge, 2013; Leyer et al., 2012; Mongil-Manso et al., 2021; Shuttleworth et al., 2019

				effective for reducing flood risk, but the combined impact of their spatial distribution needs to be considered.	
<i>Group B</i>	Increase surface and subsurface water storage in offline areas	Offline storage areas (water retention/detention ponds)	n = 10 (UK) n = 2 (EU)	UK: Low to high confidence EU: Low to high confidence The proportion of different study methods is relatively even, but most of the UK studies for runoff attenuation features (RAFs) are at two small-scale study sites (~6 km²). Both modelling and experimental results indicated that offline and online surface storage can effectively attenuate flood peak discharge and increase the travel time of peaks, and the attenuation is independent of the intensity of the storm event and is less affected by the scale of catchment. The drainage characteristics of the storage is the only factor that limits their storage capacity.	Barber & Quinn, 2012; Bezak et al., 2021; Lindermuth et al., 2018; Lockwood et al., 2022; Metcalfe et al., 2018; Nicholson et al., 2020; Wilkinson et al., 2010
		Online storage areas (grip blocking, drainage/ditch blocking, buffer strips, beaver dams)	n = 6 (UK) n = 2 (EU)	UK: Low to high confidence EU: Low confidence This type of intervention is dominated by evidence from field measurements, particularly for beaver dams. The studies of four site (~6 km²) where beavers have been reintroduced in England, with abundant monitoring data in Before-After Control-Impact (BACI) experiments demonstrated beaver dams attenuated peak flows and delayed peak times significantly, even with increasing rainfall magnitude. There is a lack of	Graham et al., 2022; McLean et al., 2015; Misiukiewicz et al., 2018; Puttock et al., 2021; Puttock et al., 2017; Wilson et al., 2011

			upscaling studies, e.g., modelling and monitoring evidence at larger catchment scales.		
Land cover changes (floodplain/riparian reforestation, floodplain restoration/reconnection, grassland, hedges)			n = 11 (UK) n = 5 (EU)	UK: Medium to high confidence EU: Low to high confidence For reforestation and vegetation restoration, which are studied at relatively large scales, modelling methods are predominant, but field measurements are more frequently used for the effects of grassland and hedges on soil properties. Reforestation can decrease the flood peak by increasing water table depth and soil water storage. Floodplain restoration expands the effective area of inundation extent on floodplains, thereby increasing water storage and reducing peak discharge. Grassland and hedge soils have shown that they can store more water than arable land and woodland by field measurements, because they have a high rate of soil drying and active soil water level and are less likely to become saturated during wet periods.	Acreman et al., 2003; Addy & Wilkinson, 2021; Bathurst et al., 2018; Brunke, 2019; Buechel et al., 2022; Caubel et al., 2003; Clilverd et al., 2016; Goudarzi et al., 2021; Holden et al., 2019; Kovar et al., 2011; Mihalcea, 2017; Monger et al., 2022; Richet et al., 2017; Shuttleworth et al., 2019; Thomas & Nisbet, 2007; Wallace & Chappell, 2020
Group C	Reduce water velocity in channel	Leaky barriers Woody logjams	n = 15 (UK) n = 7 (EU)	UK: Low confidence EU: Low confidence As these interventions are implemented on a small scale and small tributaries, the studies are based on field measurements and indoor physical experimental simulations, also applying measured parameters to hydrodynamic modelling.	Addy & Wilkinson, 2016; Addy & Wilkinson, 2019; Follett et al., 2020, 2021; Hankin et al., 2020; Kitts, 2010; Leakey et al., 2020, 2021; Lo et al., 2022; Norbury et al., 2021; Schmocker & Hager, 2013; Schmocker & Weitbrecht, 2013; Thomas & Nisbet, 2012

The studies showed that these interventions are more applicable for implementation in small tributaries. The effects of flood peak attenuation and peak travel time delay are not limited by the magnitude of storms, and all have a significant water velocity reduction effect in the implemented channels. The amount and location of barriers is important in the effectiveness of flood peak reduction at the catchment scale. However, the backwater rise and sediment retention beneath the barrier or jam may increase the risk of geomorphological and environmental alteration.

<i>Group D</i>	Integrated catchment management	Multiple NFM interventions	n = 29 (UK) n = 35 (EU)	UK: Medium to high confidence EU: Medium to high confidence Most of the studies of integrated catchment management measures are large-scale studies, and part of them provide comparisons between local areas and entire catchment effects. Thus, this group is dominated by research methods of integrated analysis and modelling. Several studies have indicated that online or offline water detention ponds is the most effective single measure to reduce the flood peak when they are multiply distributed in the catchment scale. The results of these studies have emphasized the effectiveness of interventions limited by scale and other factors. The effectiveness of the individual NFM/NBS scenarios, depended strongly on the location and extension of the interventions, as well as on storm intensity, increase with increasing proportion	Barnsley et al., 2021; Bellu et al., 2016; Black et al., 2021; Costa et al., 2021; Dadson et al., 2017; Dixon et al., 2016; Ferguson & Fenner, 2020a; Ferguson & Fenner, 2021; Ferguson & Fenner, 2020b; Ferreira et al., 2020; Ghimire et al., 2014; Habersack et al., 2015; Hankin et al., 2019; Hankin et al., 2021; Kay et al., 2019; Lavers & Charlesworth, 2018; Metcalfe et al., 2017; Mrozik & Przybyla, 2013; Ramsbottom et al., 2019; Reinhardt et al., 2009; Reinhardt et al., 2011; Rieger & Disse, 2013; Spyrou et al., 2021; Terencio et al., 2020; Tseng et al., 2021; Wilkinson et al., 2019
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or areas of the interventions, and decrease with increasing storm intensity and return periods.

Despite these limitations, the consistent conclusion of the studies (mainly modelling) is that a spatial distribution of NFM/NBS network within the upper and middle of catchments, combining multiple interventions with the sub-catchment desynchronization can maximize flood mitigation effects at larger catchment scale.

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A.2 Detailed records of 197 articles with grouping information (Table 2.1) within the NFM Europe group, followed by statistical analysis and confidence assessments.

Detailed records of all articles classified under the eight NFM technique subgroups listed in Table 2.1 and Table A1.1 are available in the supporting information (Data S2) of the published paper at <https://wires.onlinelibrary.wiley.com/doi/full/10.1002/wat2.1765>.

Subsequent statistical analyses and assessments are based on these 197 records in this appendix, examining whether peak reductions were reported, details of articles providing specific reduction values, percentage statistics, and confidence assessments. All statistics were reclassified and analysed according to the eight NFM subgroups, intervention type (multiple or individual), research approach (modelling, fieldwork, combined modelling and fieldwork, perceptual), and geographic region (UK or EU, excluding the UK).

Table A2.1. Number of papers reporting flood reduction conclusions and exact reduction values in investigated NFM studies

<i>Subgroup number</i>	<i>NFM technique subgroups</i>	<i>No. paper with reduction</i>	<i>No. paper with exact reduction values</i>	<i>Total</i>
1a	Cross slope reforestation; Floodplain/ Riparian reforestation - EU	6	2	19
1b	Cross slope reforestation; Floodplain/ Riparian reforestation - UK	9	3	17
2a	Soil and land management - EU	5	2	11
2b	Soil and land management - UK	13	9	18
3a	Peatland restoration; Floodplain restoration/ reconnection - EU	2	0	17
3b	Peatland restoration; Floodplain restoration/ reconnection - UK	8	4	9
4a	Offline storage areas - EU	2	0	2

4b	Offline storage areas - UK	6	3	10
5a	Online storage areas - EU	0	0	2
5b	Online storage areas - UK	3	2	6
6a	Leaky barriers; Woody logjams - EU	0	0	7
6b	Leaky barriers; Woody logjams - UK	4	3	15
7a	Land cover changes (storage) - EU	3	1	5
7b	Land cover changes (storage) - UK	9	6	11
8a	Multiple NFM interventions - EU	12	4	35
8b	Multiple NFM interventions - UK	18	9	29

Table A2.2. Number of papers reporting flood reduction conclusions and the exact reduction values from investigated NFM studies, categorized by multiple or individual interventions examined in each paper.

	No. paper with reduction	No. paper with exact reduction values	Total
Multiple interventions-UK	18	10	29
Individual interventions-UK	43	24	75
Multiple interventions-EU	12	4	35
Individual interventions-EU	15	4	58

Table A2.3. Number of papers reporting flood reduction conclusions and the exact reduction values from investigated NFM studies, categorized by research approaches (modelling, fieldwork, modelling & fieldwork, perceptual) used in each paper.

	No. paper with reduction	No. paper with exact reduction values	Total
Modelling	50	29	76
Hybrid Modelling and Fieldwork	3	2	7
Fieldwork	22	11	51
Perceptual/conceptual analysis	13	0	63

Table A2.4. Statistical results of data obtained from meta-analyses based on subgroups of NFM techniques.

Subgroup number (same as Table A2.1)	Percentage of papers with reduction/delay	Percentage of papers with exact reduction/delay values	Percentage of papers showed reduction/delay without values	Percentage of papers did not show any reduction/delay	Percentage of papers containing multiple catchment sizes	Percentage of papers containing multiple rainfall intensities
1a	31.6%	10.5%	21.1%	68.4%	5.3%	21.1%
1b	52.9%	17.6%	35.3%	47.1%	29.4%	29.4%
2a	45.5%	18.2%	27.3%	54.5%	9.1%	27.3%
2b	72.2%	50.0%	22.2%	27.8%	27.8%	27.8%
3a	11.8%	0.0%	11.8%	88.2%	0.0%	0.0%
3b	88.9%	44.4%	44.4%	11.1%	44.4%	0.0%
4a	100.0%	0.0%	100.0%	0.0%	0.0%	0.0%
4b	60.0%	30.0%	30.0%	40.0%	10.0%	50.0%
5a	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%
5b	50.0%	33.3%	16.7%	50.0%	33.3%	33.3%
6a	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%
6b	26.7%	20.0%	6.7%	73.3%	20.0%	0.0%
7a	60.0%	20.0%	40.0%	40.0%	0.0%	40.0%
7b	81.8%	54.5%	27.3%	18.2%	36.4%	27.3%
8a	34.3%	11.4%	22.9%	65.7%	8.6%	11.4%
8b	62.1%	34.5%	27.6%	37.9%	20.7%	34.5%

Table A2.5. Assessment results of confidence obtained from regrouping EU and UK studies based on NFM technical subgroups. See Chapter 2 for methodology details, which were evaluated using percentiles in Table A2.6.

	Percentage of papers with reduction/delay-EU (EU1)		Percentage of papers with reduction/delay-UK (UK1)		Percentage of papers with exact reduction/delay values-EU (EU2)		Percentage of papers with exact reduction/delay values-UK (UK2)		Percentage of papers containing multiple catchment sizes-EU (EU3)		Percentage of papers containing multiple catchment sizes-UK (UK3)		Percentage of papers containing multiple rainfall intensities-EU (EU4)		Percentage of papers containing multiple rainfall intensities-UK (UK4)	
1	31.58%	Medium	52.94%	Medium	10.53%	Medium	17.65%	Low	5.26%	Medium	29.41%	Medium	21.05%	Medium	29.41%	Medium
2	45.45%	Medium	72.22%	High	18.18%	High	50.00%	High	9.09%	High	27.78%	Medium	27.27%	High	27.78%	Medium
3	11.76%	Low	88.89%	High	0.00%	Low	44.44%	High	0.00%	Low	44.44%	High	0.00%	Low	0.00%	Low
4	100.00%	High	60.00%	Medium	0.00%	Low	30.00%	Medium	0.00%	Low	10.00%	Low	0.00%	Low	50.00%	High
5	0.00%	Low	50.00%	Low	0.00%	Low	33.33%	Medium	0.00%	Low	33.33%	High	0.00%	Low	33.33%	High
6	60.00%	High	81.82%	High	20.00%	High	54.55%	High	0.00%	Low	36.36%	High	40.00%	High	27.27%	Medium
7	0.00%	Low	26.67%	Low	0.00%	Low	20.00%	Low	0.00%	Low	20.00%	Low	0.00%	Low	0.00%	Low
8	34.29%	Medium	58.62%	Medium	11.43%	Medium	31.03%	Medium	8.57%	High	20.69%	Medium	11.43%	Medium	34.48%	High

Table A2.6. Statistics and percentiles in each column (EU1-4; UK1-4).

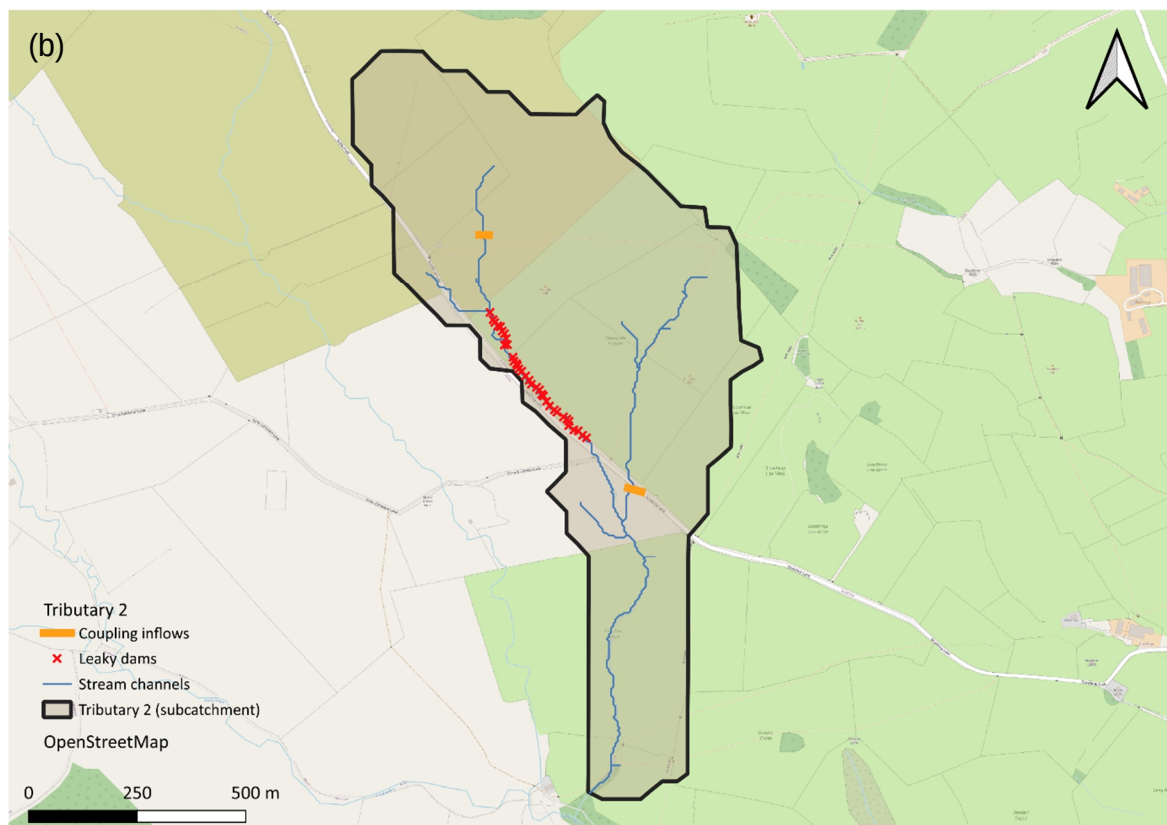
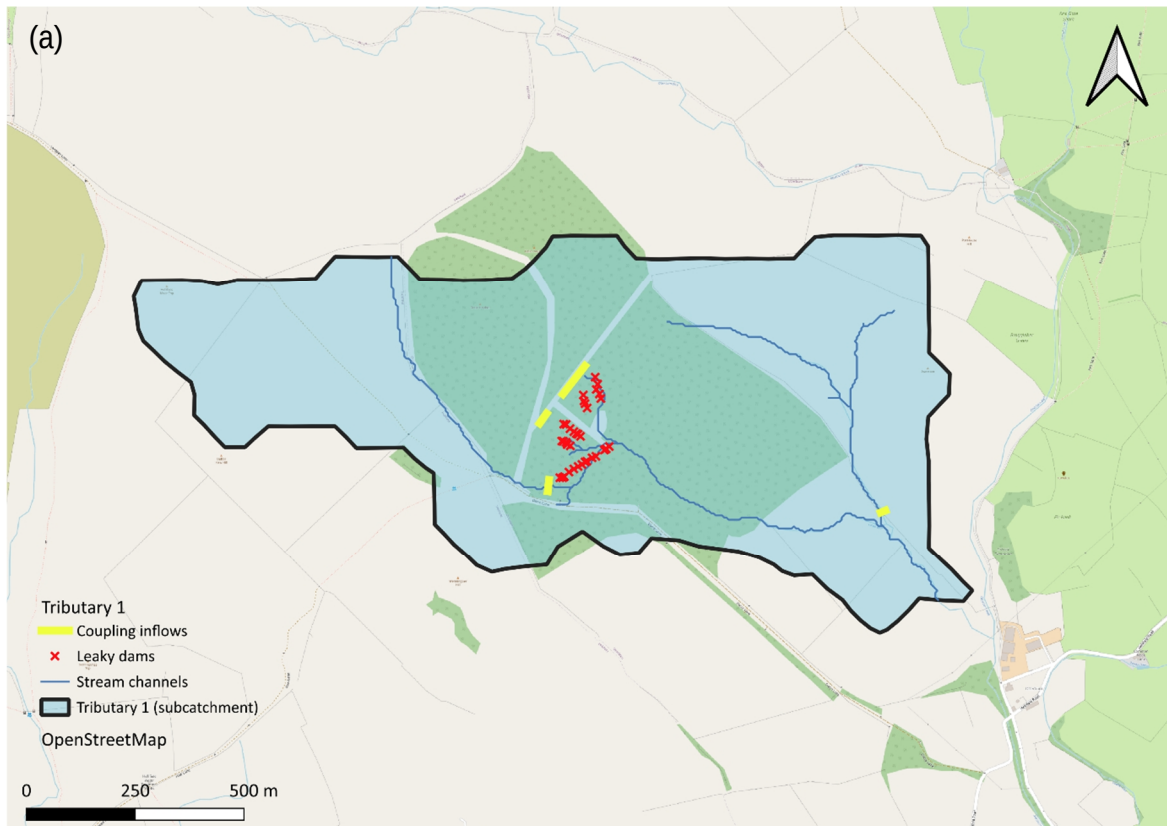
		Statistics							
		EU1	UK1	EU2	UK2	EU3	UK3	EU4	UK4
N	Valid	8	8	8	8	8	8	8	8
	Missing	0	0	0	0	0	0	0	0
Mean		35.4000%	61.3875%	7.5125%	35.1000%	2.8750%	27.7500%	12.4750%	25.2875%
Std. Error of Mean		11.92181%	6.95027%	3.04710%	4.75316%	1.45611%	3.80413%	5.46981%	6.07390%
Median		32.9500%	59.3000%	5.2500%	32.1500%	0.0000%	28.6000%	5.7000%	28.6000%
Std. Deviation		33.71998%	19.65833%	8.61849%	13.44396%	4.11851%	10.75971%	15.47096%	17.17959%
Variance		1137.037	386.450	74.278	180.740	16.962	115.771	239.351	295.138
Range		100.00%	62.20%	20.00%	36.90%	9.10%	34.40%	40.00%	50.00%
Minimum		0.00%	26.70%	0.00%	17.60%	0.00%	10.00%	0.00%	0.00%
Maximum		100.00%	88.90%	20.00%	54.50%	9.10%	44.40%	40.00%	50.00%
Percentiles	25	2.9500%	50.7250%	0.0000%	22.5000%	0.0000%	20.1750%	0.0000%	6.8250%
	33.33	11.7965%	52.8991%	0.0000%	29.9970%	0.0000%	20.6998%	0.0000%	27.2918%
	33.33333333	11.8000%	52.9000%	0.0000%	30.0000%	0.0000%	20.7000%	0.0000%	27.3000%
	50	32.9500%	59.3000%	5.2500%	32.1500%	0.0000%	28.6000%	5.7000%	28.6000%
	66.66666667	45.5000%	72.2000%	11.4000%	44.4000%	5.3000%	33.3000%	21.1000%	33.3000%
	66.67	45.5044%	72.2029%	11.4020%	44.4017%	5.3010%	33.3009%	21.1019%	33.3004%
	75	56.3750%	79.4000%	16.5000%	48.6000%	7.7750%	35.6250%	25.7500%	34.2000%
	100	100.0000%	88.9000%	20.0000%	54.5000%	9.1000%	44.4000%	40.0000%	50.0000%

Appendix B. Supporting Information for Chapter 4

B.1. Figures to demonstrate the point-to-point coupling method

The following figures illustrated how SD-TOPMODEL and Flood Modeller Pro were coupled using point-to point methods within the four sub-catchments where leaky dams were implemented, as well as the broader research catchment (Upper Aire Catchment to Gargrave). All coupling inflows/points represented the locations/grids selected to use SD-TOPMODEL outputs as the Inputs of Flood Modeller 2D.

The coupled model was initially run for the four leaky dam sub-catchments before being extended to the larger catchment (up to Gargrave), incorporating six additional coupling points exported from SD-TOPMODEL along with the simulation results from the four sub-catchments. See Chapter 4 for further details.



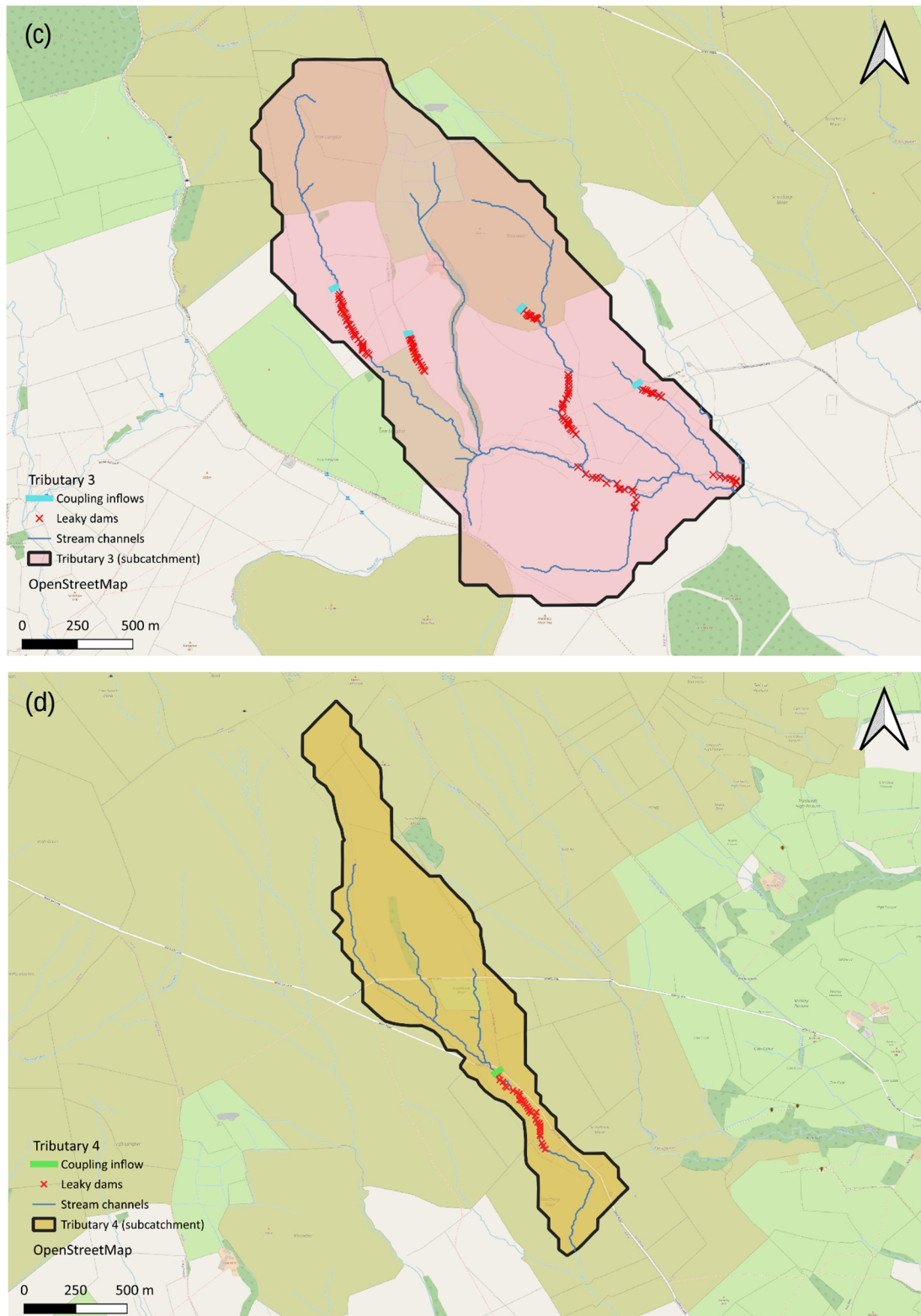


Figure B.1. The four sub-catchments with implemented leaky dams used in the coupled model. The coupling inflows in each figure indicated the locations of coupling points, where outputs from SD-TOPMODEL were utilized as inputs for Flood Modeller 2D. The coupled modelling areas encompassed all leaky dams within each sub-catchment. (a)–(d) correspond to Tributaries 1–4, as referenced in Chapter 4.

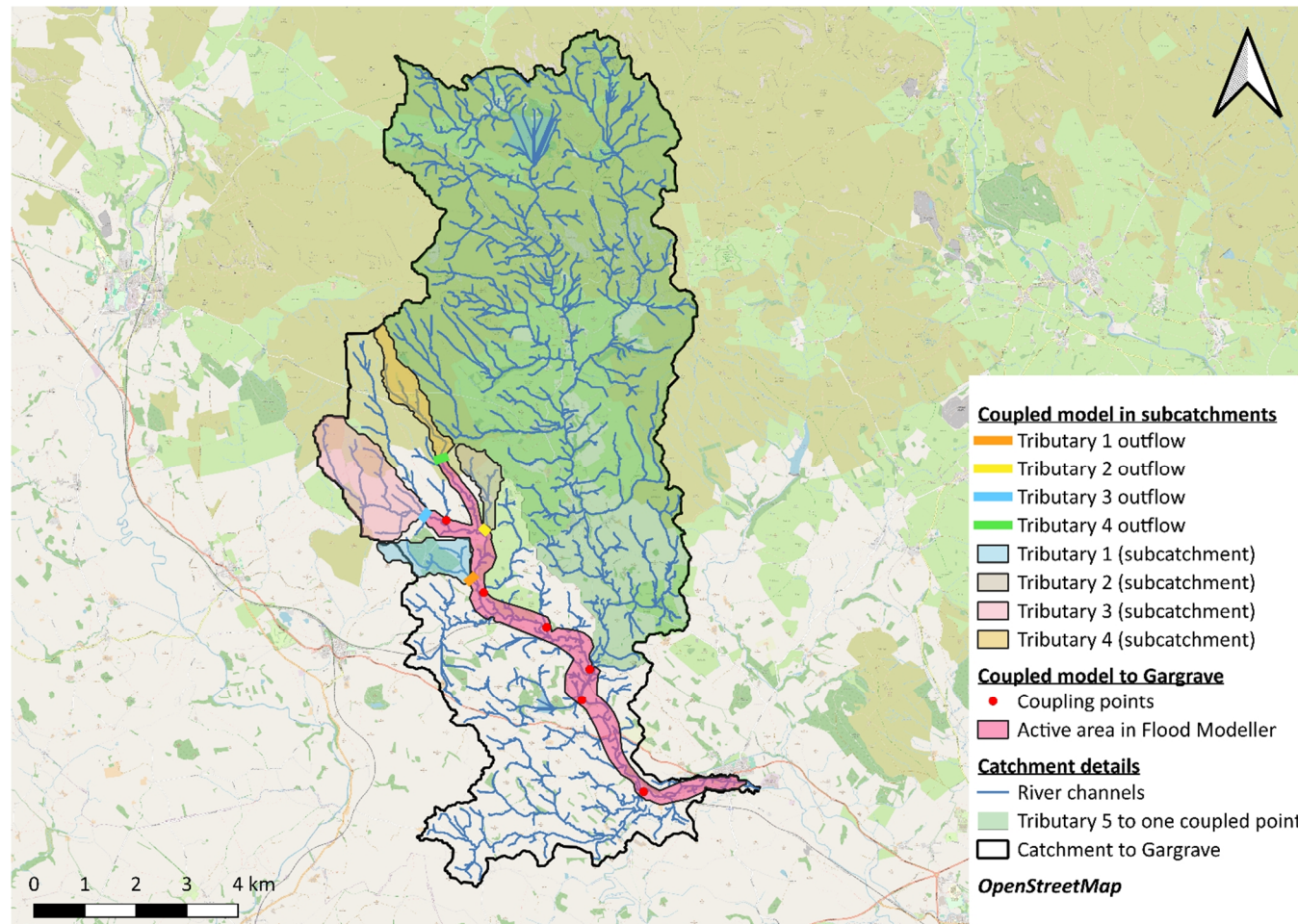


Figure B.2. The area and points used for the coupled model in the research catchment to Gargrave. The inputs for the Flood Modeller 2D component of the coupled model include six coupling points for generating SD-TOPMODEL outputs and four sub-catchment outflows. The coupled model was applied exclusively to the active area (executed in Flood Modeller) depicted in the figure.