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# The Performance of Natural Flood Management at the Large Catchment-Scale: A Case Study in the Warwickshire Stour Valley

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**Abstract:** The limited understanding of Natural Flood Management (NFM) performance, especially at large hydrological scales, is considered a critical barrier for the further funding and implementation of these nature-based solutions to the increasing international problem of flooding. The publications of the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report and Environment Agency's National Flood and Coastal Erosion Risk Management Strategy (NFCERMS) for England have shown that extreme weather, including increased likelihood of high magnitude flood events, will occur and will require more novel management methods. This study focused on the ability of co-designed NFM measures to ameliorate downstream fluvial flooding by attenuating catchment response through a highly spatially distributed network of attenuating and roughening measures. Performance was characterised by the ability of NFM to attenuate flood peaks at different spatial scales across a large (187 km$^2$) dendritic catchment, including the lowering of flood peaks and delaying the time-to-peak. Using a coupled modelling methodology and applying it to the upper Stour Valley, Warwickshire-Avon, UK, a rural response to the application of a set of NFM interventions was developed using the hydrodynamic model Flood Modeller Pro and XPSWMM ©. The method demonstrated a means of incorporating local knowledge in a realistic set of NFM schemes, tested to multiple flood risk scenarios (including climate change). Under frequent, smaller design storm events (e.g., Index Flood (QMED) and 3.3% AEP), flood peaks were lowered across all hydrological scales tested (5.8 km$^2$ to 187 km$^2$). As the design flood event severity increases, impact from upstream NFM attenuation on downstream peak response diminished significantly, especially at the largest hydrological scales. However, even at the largest hydrological scale, delays in time-to-peak were noted, increasing the ability of downstream communities to respond and enact flood preparation activities, thus increasing resilience to potential flooding events. While the benefits were limited to large flood events, the modelling indicated that NFM has the potential to reduce downstream flood risk. However, greater integration of observed data to improve model confidence and reduce uncertainty in modelled events is needed, especially the uncertainty associated with using single peaked design storm events from the Flood Estimation Handbook (FEH). This paper proposes a future Before–After Control–Impact (BACI) monitoring programme that could be integrated with models and applied across non-tidally influenced catchments seeking to empirically test the hydrological performance of in-situ NFM.

**Keywords:** Natural Flood Management; computational modelling; peak attenuation

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## 1. Introduction

The management of flood risk has undergone a paradigm shift in recent years, acknowledging the need to adapt to the growing pressures from climate change and urban creep to work with the natural processes that regulate catchments [1,2]. By working with natural processes, relevant authorities and agencies who manage water resources, flood risk and coastal erosion can provide a more sustainable and low-cost approach to reducing flood risk. Examples of national and international policies and strategies that advocate such an approach include the Water Framework Directive (2000/60/EC), Floods Directive (2007/60/EC), Flood and Water Management Act [3] and Defra's 25-Year Environment Plan [4]. Techniques that aim to work with natural processes are referred to hereinafter as NFM, defined by Burgess-Gamble et al. [5] as "measures that help to protect, restore and emulate the natural functions of catchments, floodplains, rivers and the coast".

However, systematic reviews of NFM case studies (e.g., [5–7]) have found a lack of evidence, notably a lack of studies empirically testing the flood risk performance of NFM, especially to large storm events at large hydrological scales. Factors such as antecedent conditions, spasmodic rainfall, and duration of storm events can alter the response of a catchment to a rainfall event [8,9]. Given the complex and diffuse nature of storm events and catchment characteristics, the modelling and design of such systems rarely consider these aspects. Furthermore, land managers are often not consulted during these modelled studies, and therefore follow-up engagement (and further refined modelling) is required to understand the performance of such schemes—if modelled at all [10,11]. Uniquely, this study engaged landowners prior to modelling, to test the realistic co-designed NFM scenario, presented in Lavers and Charlesworth [11], in order to encourage a greater likelihood of uptake.

Several UK and international studies have already tested the performance of NFM using various modelling methods and software. Hankin et al. [12] used Dynamic Topmodel with JFlow to simulate the effects of woodland planting, attenuation features and leaky barriers across Swindale Valley, Calderdale, UK, at a 15 km$^2$ 2D domain. The maximum reduction noted in the peak was 1.8 m$^3$ s$^{-1}$ $\pm$ 1.4 m$^3$ s$^{-1}$. Chen et al. [13] identified a similar effect during a modelled 50-year event in the Stockbridge area, UK.

NFM can be key in the philosophy of catchment flood management by making use of nature-based solutions to address high flows causing downstream flood risk. This often deliberately redistributes flood flows from the rising to the receding limb of the hydrograph. This is achieved in three ways: by encouraging infiltration of excess water into the ground; by reducing overland flow; and by the creation of extra storage in the catchment [6]. Examples of NFM measures to address these strategies include planting trees, installing leaky barriers, designing runoff attenuation features, re-meandering the course of the river, and reconnecting the floodplain. However, whilst there are many studies which investigate the reduction of peak flows using NFM (e.g., [14–16]), the evidence base remains inconclusive for catchment extents larger than 10 km$^2$ [17,18].

The objective of the study was to use a case study site (the Warwickshire-Stour valley) to model the potential of co-designed NFM across a large hydrological scale to attenuate downstream flood peaks in multiple flood risk scenarios. The rural response from the upper Warwickshire-Stour Valley, in Warwickshire, UK was characterised using Flood Modeller and XPSWMM ©. It included several fluvial and surface drainage networks which provided flow downstream to Shipston-on-Stour (Figure 1).

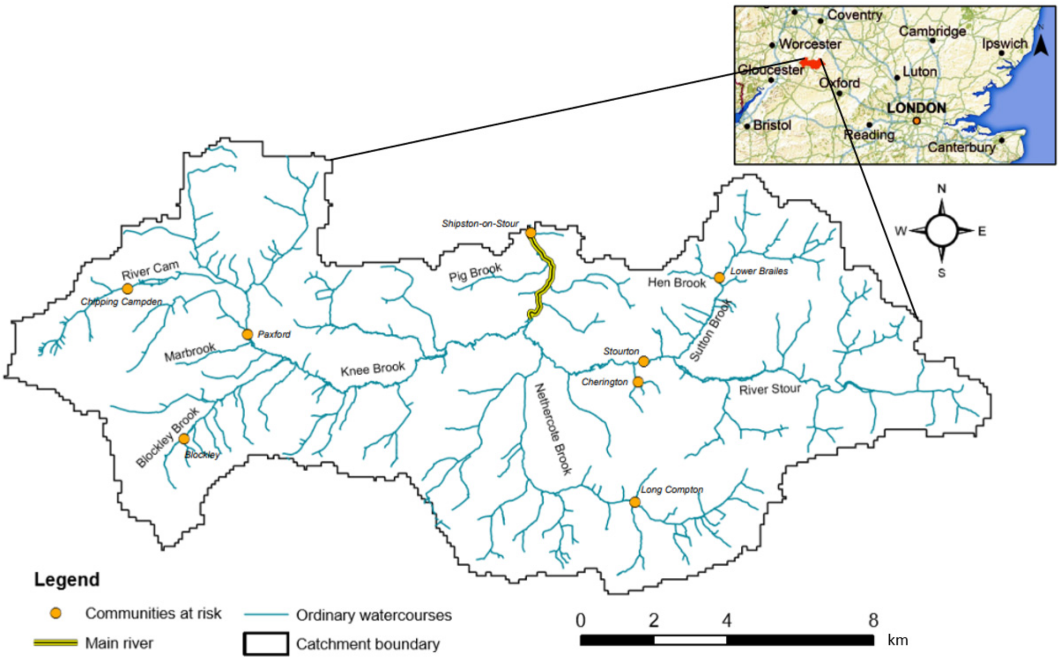


Figure 1. Catchment area (Data Source: [19,20]).

## 2. Method

### 2.1. Study Site

Shipston-on-Stour (with a population of approximately 4500) is located in the headwaters of the Warwickshire-Avon (Rural) Operational Catchment Boundary, downstream of a large-dendritic basin (187 km$^2$) comprised of three main sub-catchments: Knee Brook, Nethercote Brook and River Stour (Figure 1). Shipston-on-Stour was inundated by flooding in 2007, and subsequently every year since, with the most recent internal flooding of properties occurring in March 2016 [21]. Capita Symonds [22] found after the 2007 floods that a 'do nothing' scenario was the only financially feasible option for Shipston-on-Stour (the furthest downstream community at risk in the study site). This was based on reductionist analysis of the event's storm flow, in which in excess of 166,790 m$^3$ from the 24 h event was required to be removed from the hydrograph, and therefore was considered unfeasible based on flood defence grant-in-aid (FDGiA) economic appraisals. Whilst this sort of analysis applies to conventional flood storage areas (FSAs), it does not apply to the hydrological principles of catchment based NFM that seeks to distribute the storm flow across the hydrograph, increasing the time-to-peak (Tp) to ultimately lower the flood peak (Qp) and rate of recession.

Whilst most properties in fluvial flood zones are located downstream, there are also properties at risk in the headwaters, detailed in Figure 1, including Chipping Campden, Blockley, Paxford Lower Brailes, Long Compton, Stourton and Cherington, making this NFM approach spatially complex. This requires the NFM scheme to reduce risk downstream whilst not enhancing risk to upstream communities via backwater effects or peak synchronisation. Furthermore, this scheme explored the role of cumulative benefits when hydrological up-scaling is used to counter dilution effects. The high number of contributing delineations across the whole catchment represent different runoff generation patterns and levels of contribution that were analysed in more detail, prioritising NFM with the use of spatially targeted measures.

### 2.2. Available Data

Topographical LiDAR Digital Terrain Model (DTM) data were obtained from the Environment Agency at 2 m resolution; repercussions of this coarser DTM compared with the 1 m, 0.5 m and 0.25 m publicly available for other areas are discussed in Section 4.1.

Using the developed DTM enabled the contributing area above the National River Flow Archive (NRFA) gauging station (Station No. 54,106 in Figure 2) to be defined.

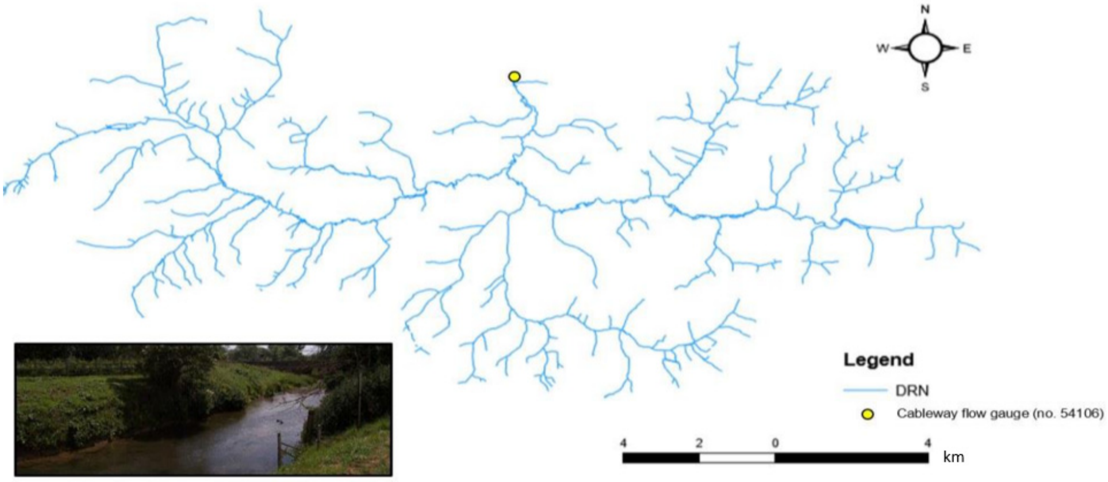


**Figure 2.** Station Gauge in Shipston-on-Stour (no. 54,106).

This extent of the catchment was used to extract data layers using various sources, which included the 2012 CEH Hydrology of Soil Type (HOST) data for infiltration coefficients, the 2015 CEH Land Cover Map for floodplain roughness coefficients, and the OS MasterMap Water Network. The spatial data were then rasterised onto the underlying DTM data. There is one rainfall gauge in the watershed, located in Shipston-on-Stour. However, this private gauge is only available as daily totals and not in a format suitable for time-series modelling, furthermore, there are no rain gauges for the upstream catchment extent. Therefore, FEH design storms were used as inputs for the flood models on sub-catchments < 10 km$^2$. The river flow gauge sited in Shipston-on-Stour was primarily for flood warning services provided in stage, but high flow records in July 2007 exceeded the gauge upper threshold and prohibited the ability to reliably measure the highest recorded flows. However, the flow data were still considered robust enough to test the sensitivity of the model to changes in parameters to smaller events than the July 2007 flood (0.1% Annual Exceedance Probability (AEP)) according to the Environment Agency [23].

### *2.3. Model Build and Sensitivity Analysis*

Flood Modeller Pro 4.0 (Jacobs, London, UK) and XPSWMM 2.0 © (Innovyze, Newbury, UK) were both used to build and simulate the hydrodynamic computational routing models of the catchment at varying spatial scales, from small (<10 km$^2$) to large (>100 km$^2$). Flood Modeller Pro evolved from the former ISIS model, a long-established integrated 1D–2D software for representing both floodplain and in-channel processes and used in various NFM modelling studies [24,25]. XPSWMM © operates in a similar manner, using the same Saint-Venant equations for 1D (in-channel) and 2D (floodplain) calculations. The integration of both industry standard software tools, using XPSWMM © to build the DTM, building channel cross-sections and defining catchment and tributary extents, and Flood Modeller Pro was used to represent NFM features, linking sub-catchment domains and simulating FEH design events, has enabled some coupled modelling for enhanced confidence in outputs and increased modelling efficiency. The integration of 1D and 2D environments in the model is common practice when representing whole catchment processes. For example, a coupled modelling approach consisting of Dynamic TOPMODEL, HEC-RAS, and Infoworks Integrated Catchment Modeller (ICM) models was used to characterise the response from a small (<10 km$^2$) catchment by Ferguson and Fenner [26].

The overall approach adopted in this study used individual 1D–2D hydraulic models defined in XPSWMM ©, linked by a routing model in areas where there were no NFM opportunities so efficiencies in simulation area and time within Flood Modeller Pro could be undertaken. NFM options were grouped based on their spatial proximity, resulting in a total of 36 models (sub-catchments), the build of which is outlined in Figure 3. These options enabled simulation of different sized design-storms from FEH (QMED, 3.3% AEP, 1% AEP and 1% AEP + Climate Change Allowance for Higher Central 2080s epoch based on the 70th percentile of peak river flow forecasts (+35% in peak river flow) [27]. In accordance with the Risk Assessment for Spatial Planning (RASP) framework [28], the build was guided by Flood Impact Modelling (FIM) principles [29]. This enabled the identification of areas of synchronisation and de-synchronisation through multi-scaled level analysis of the fluvial network. Furthermore, the model build was developed to be appropriate to the catchment it was simulating, with critical characteristics of changing land cover (roughness) and infiltration (soil type) represented to reflect the study site. This also enables the model build data sources and processes to be suitable for other large rural, dendritic basins.

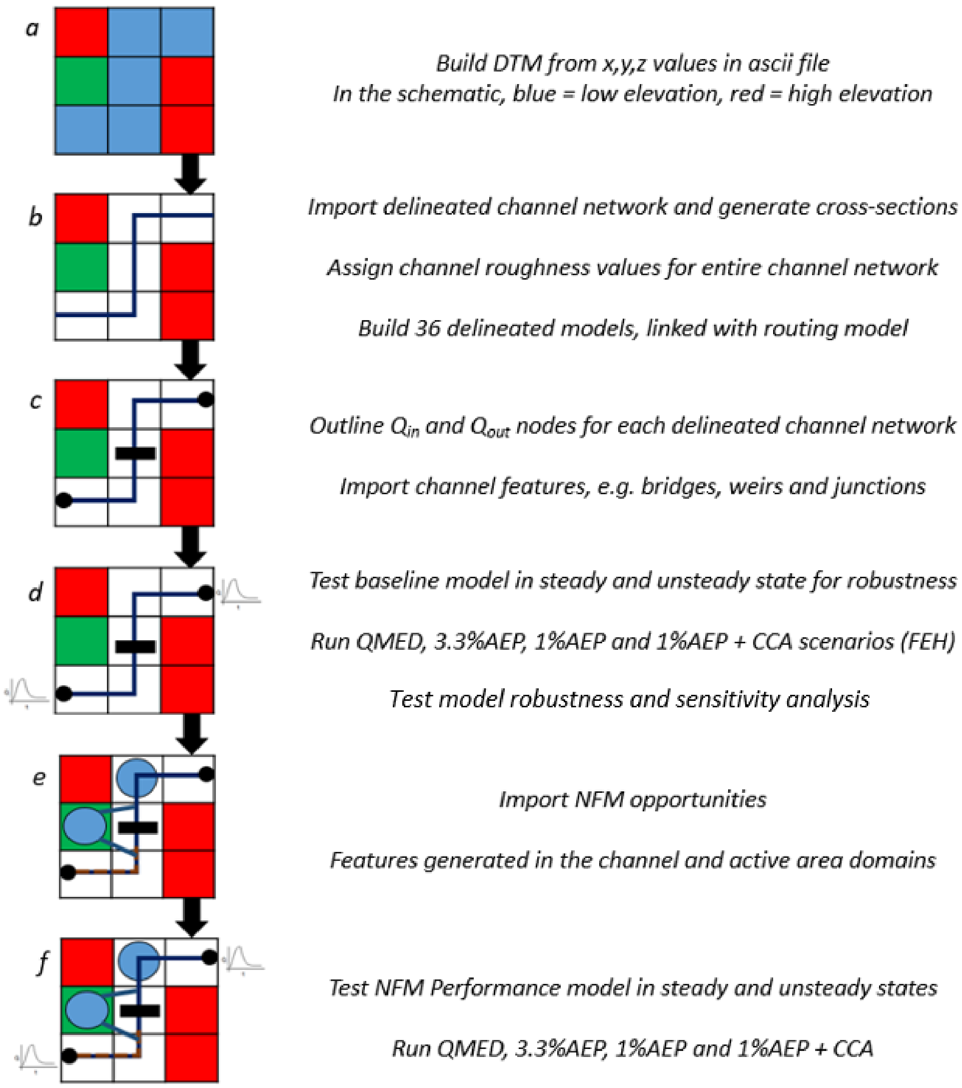


**Figure 3.** Model build schematic example for one of the sub-catchment models. Coloured squares represent elevation, blue (low)—green (middle)—red (high). Blue circles conceptually represent NFM features, and the black line across the channel is an in-channel feature (e.g., bridge).

Using the UK-based FEH rainfall-runoff methodology of inflows of defined events enabled design storm hydrographs to be generated for the study site to estimate complete hydrographs and flood volumes. A number of events were run at different return intervals (1% AEP + Climate Change Allowance, 1% AEP, 3.3% AEP and QMED) for a 12 h storm duration as per recommendations in Hankin et al. [12] to reflect the total duration of the design event, total depths and time to peak in a realistic storm in the UK across a large catchment, see Table 1. Each event has been modelled to a 12 h storm duration.

**Table 1.** Characteristics of flood estimation handbook (FEH) rainfall-runoff hydrographs for 12 h storm duration events.

| | **Design Storms—Annual Exceedance Probabilities (AEPs)** | | | |
|---|---|---|---|---|
| | **1% + 35% *** | **1%** | **3.3%** | **QMED ** (50%)** |
| Total rainfall (mm) | 137.30 | 101.73 | 63.42 | 29.54 |

Notes: * Climate change allowance for peak river flow Higher Central 2080s epoch. ** Index flood.

The modelling simulated the observed flood event of the March 2016 event with an FEH design event (1% AEP, 12 h storm duration), with a total rainfall depth of 101.73 mm. This rainfall depth was almost the same as the observed rainfall at the gauge in Shipston-on-Stour (100.66 m) for this event. No GIS layers were available for this period, but the limited temporal difference (<3 years) between the catchment characteristics and this storm event is a common limitation when conducting model simulations [30].

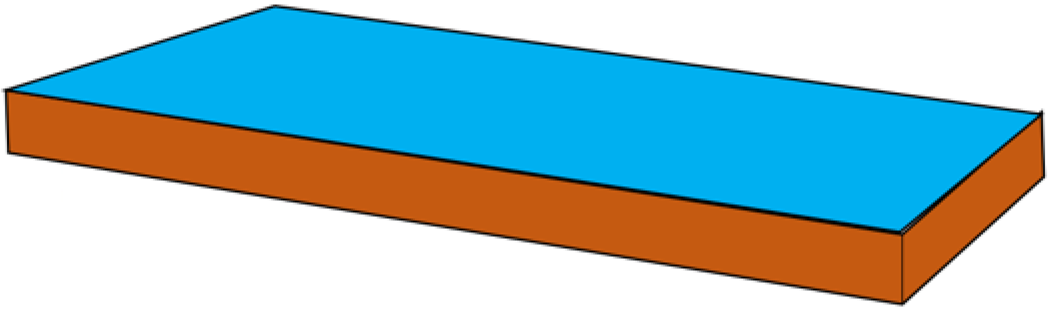
Testing the sensitivity of the model by altering the Manning's $n$ value for surface and channel roughness (values provided in [31]) recognised significant variability in outputs. It has been identified that the model's flows were very sensitive to changes in these values, controlling the resistance of in-channel and overland flows in relation to downstream river flows, by increasing Manning's $n$ and thus reducing network conveyance [32]. It was identified that localised Manning's $n$ changes in stream value and bank crest profile could significantly alter the hydrograph response to the FEH input storm. For example, Capita Symonds [22] identified a number of fences along the bank crest, increasing Manning's $n$ in comparison to natural stream roughness values by 0.035, from a channel with stones and weeds (0.035), to then simulating a lined channel with heavy bank growth (0.070). Increasing the peak stage at Shipston-on-Stour to more accurately represent the observed data was attempted by increasing the Manning's $n$ value in upstream communities. Results from this exercise are presented in Section 3.1.

This study also developed and tested a novel method of representing NFM. Lavers and Charlesworth [11] detailed the Participatory GIS (PGIS) approach to co-designing NFM opportunities with land managers. Table 2 and Figure 4 detail how these NFM opportunities were represented across 1D and 2D domains within the model, altering in and out of channel processes.

**Table 2.** Modeled representation of co-designed NFM opportunities.

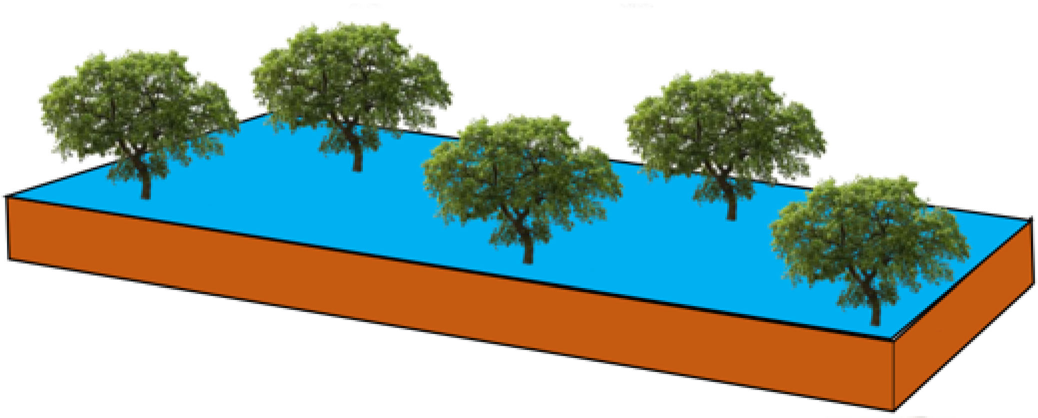
| **NFM Feature** | **Modelled Representation** |
|---|---|
| Woodlands (including hedgerows) ** | Increased floodplain roughness—0.15 $n$ value |
| Online storage | Online storage unit * |
| Offline storage | Reservoir unit * |
| Leaky barriers | Increased channel roughness—0.15 $n$ value |
| River and floodplain restoration | Reservoir unit *, alter digital terrain model (DTM) + channel network |
| Track drainage alteration ** | Junction function in the 1D network to divert |
| Buffer strips | Increased floodplain roughness—0.075 $n$ value |
| Soil aeration, winter crops and zero tillage | Increased floodplain roughness—0.050 $n$ value |
| Swales, ponds, bunds and sediment traps ** | Edit DTM for runoff attenuation features (RAF) |

Notes: * Built—in features in the software can be amended to represent area and volume. ** Only opportunities within the active 2D area (floodplain) are represented and tested.



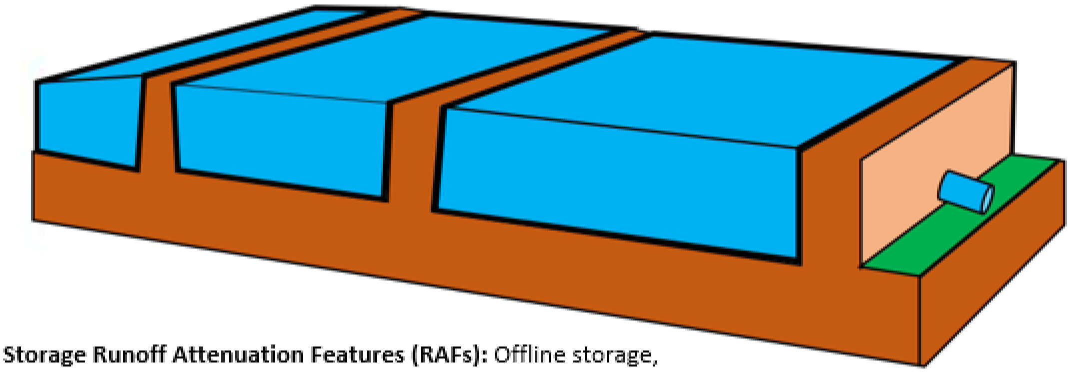
**Floodplain:** Buffer strips, soil aeration, winter crops and conservation tillage

- No storage, shallow depth
- Medium Manning's *n* value for surface roughness: 0.050-0.075



**Floodplain:** Woodlands (all types) and hedgerows

- No storage, medium depth
- High Manning's *n* value for surface roughness: 0.015



**Storage Runoff Attenuation Features (RAFs):** Offline storage, swales, ponds, sediment traps and bunds

- High storage, high depth
- Altered DTM values based on NFM opportunities

**Figure 4.** Schematic effects of NFM opportunities on flood flows in the model 2D domain.

Figure 4 represents different NFM opportunities in the 2D active area of the model domain across the assortment of opportunities. This includes changing roughness values and altering the DTM to represent storage units within the floodplain. The model was used in the evaluation of the impact of NFM measures both during the event of sensitivity analysis (1% AEP) and during other design events from the FEH inputs (QMED, 3.3 AEP and 1% AEP + CCA). This study modelled all co-designed NFM measures as fully matured interventions (e.g., fully established trees) applied across the whole catchment. Practically, this design required significant changes in terms of land management in the rural uplands of the catchment. However, the design could be used hypothetically as a reference to enable evaluation of the potential of the agreed, and thus feasible, co-designed opportunities (see [11]). Two critical components of change in hydrograph response (pre and post NFM) were also further analysed, the change in time-to-peak (ΔTp) and change in flood peak (ΔQp). Figure 5 represents the different modelled sub-catchments to understand the spatial variability of NFM performance across the catchment.

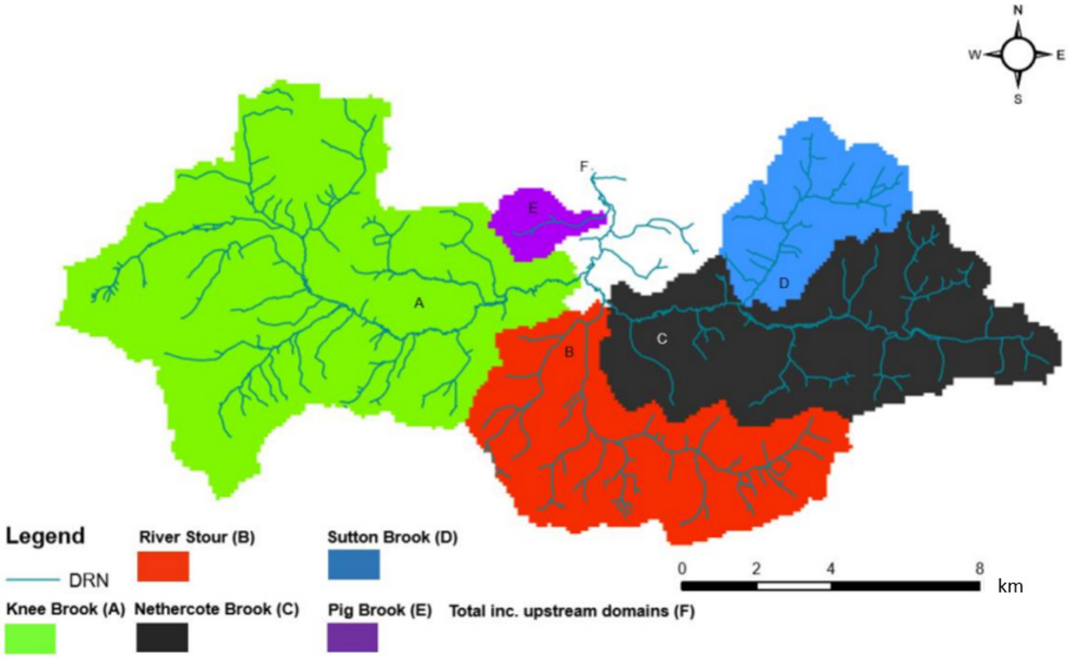


**Figure 5.** Modelled domains across the Stour Valley.

## 3. Results

This section presents the findings from the model sensitivity analysis exercise in Section 3.1, and the NFM performance results in Section 3.2 that correspond to the modelled domains presented in Figure 5.

### *3.1. Model Sensitivity Analysis Findings*

This section presents the findings from the model sensitivity analysis methods detailed in Section 2.2. The differences of Qp magnitude between observed and simulated events was −0.91% (−0.294 m) in the model, presented in Figure 6. In relation to discharge, based on the rating curve (converting stage to discharge) peak errors were $-54.44\ \mathrm{m}^3\ \mathrm{s}^{-1}$ (−12.45%). In relation to the timing of flood peak, Tp, the prediction was more accurate with an error +0.12 h (+0.36%). Therefore, the Nash–Sutcliffe coefficient for the March 2016 (1% AEP) model was 0.84 with a root mean square error (RMSE) of ±0.026, which, according to recommendations by [33], are within acceptable values in hydrological and hydraulic flood models of >0.65.

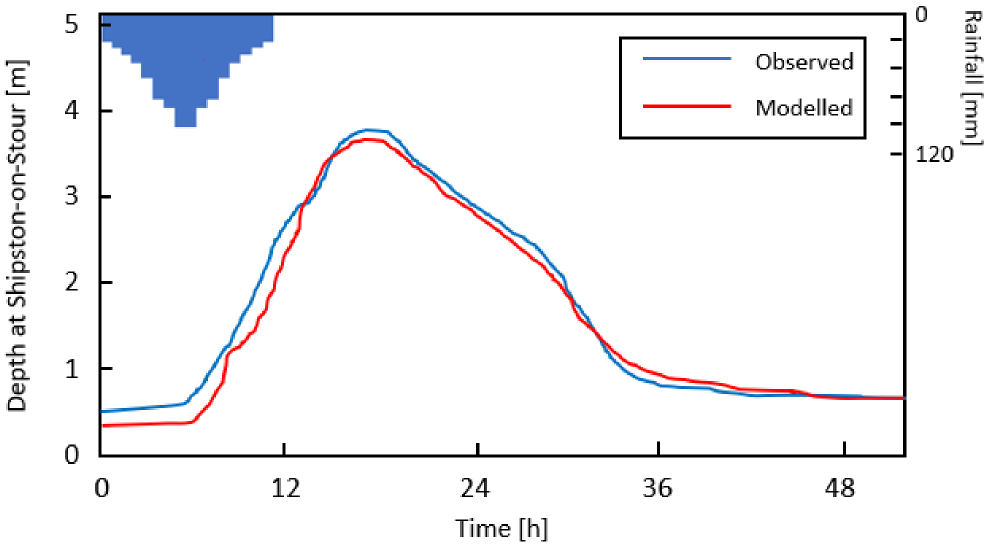


**Figure 6.** Model sensitivity of whole catchment to Shipston-on-Stour outlet.

With regards to sensitivity analysis of model parameters, increasing the peak stage at Shipston-on-Stour to represent the observed data more accurately was attempted by increasing the Manning's *n* value in upstream communities identified as having the same riparian land use and conveyance-reducing effects on high flows as identified in Shipston-on-Stour. However, when roughness was raised by 0.035 in the upstream channels through Chipping Campden, Blockley, Lower Brailes, Cherington and Long Compton (labelled on Figure 1), the modelled hydrograph varied significantly to the observed March 2016 event. Figure 7 outlines the hydrograph response in Shipston-on-Stour as a result of these raised Manning's *n* values in the streams upstream of the downstream main river Stour. In the raised roughness value at Cherington, the Qp was more representative of the observed storm event, but the Nash–Sutcliffe coefficient was lower and the RMSE higher than the roughness increase only in the reach of the Shipston-on-Stour simulation. Table 3 outlines the Nash–Sutcliffe comparisons of different scenarios of the observed event.

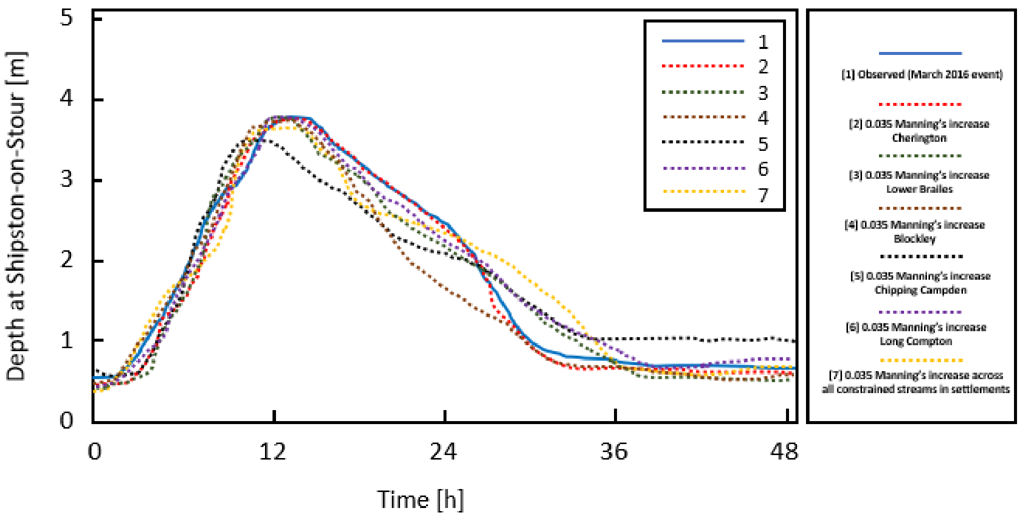


**Figure 7.** Sensitivity analysis of difference channel roughness scenarios.

**Table 3.** Sensitivity analysis of models. Nash–Sutcliffe and root mean square error (RMSE) values.

| | Cherington | Brailes | Blockley | Campden | Compton | All | Shipston |
|---|---|---|---|---|---|---|---|
| Nash–Sutcliffe | 0.72 | 0.78 | 0.69 | 0.54 | 0.70 | 0.65 | 0.84 |
| RMSE (±) | 0.041 | 0.039 | 0.089 | 0.108 | 0.068 | 0.092 | 0.026 |

### *3.2. NFM Performance Summary: Lag-Times and Peak Attenutation*

This section presents the deconstructed hydrograph components, synthesising hydrograph response results, comparing NFM and do-nothing scenarios to multiple storm events. This section synthesises the hydrograph responses as a result of the co-designed NFM opportunities based on percentage change in Qp and difference in lag-times (Tp), critical factors when assessing the performance of NFM at the catchment scale [5,34].

The performance of NFM was highly variable across the catchment's hydrological scales and different storm events for the schemes tested. Figure 8 identifies a general pattern that flood peaks were less altered by larger magnitude storm events (1% AEP and 1% AEP + CCA) in comparison to more frequent, smaller storm events (QMED and 3.3% AEP). Exceptions to this pattern were identified in the 1% AEP and 1% AEP + CCA design events in the Sutton Brook (modelled domain D), in which both hydrographs indicated a larger Qp. The 1% AEP and 1% AEP + CCA NFM scenarios demonstrated a + 0.24 m and + 0.32 m increase in Qp respectively. This gain in the downstream peak was attributed to the relative sub-catchment timings of converging peaks across the Sutton Brook headwater tributaries. Figure 8 provides an overview of these tributary peak timings, suggesting the larger designed storms led to peak convergence across the Sutton Brook modelled domain because of the NFM measures adversely slowing tributaries to synchronise Qps.

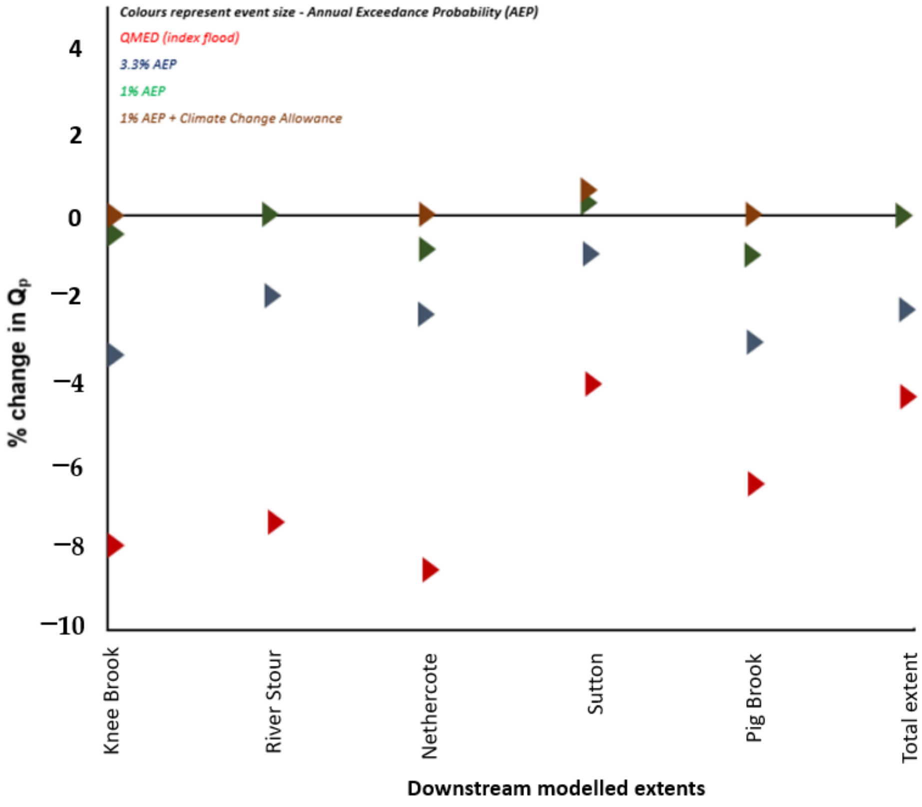


**Figure 8.** Downstream change (Δ) in peak discharge (Qp) across modelled domains to different sized events.

Regarding the smaller flood events (QMED and 3.3% AEP), NFM reduced the flood peak at all hydrological scales (localised and large) and across multiple tributaries. The greatest change in Qp as a result of NFM was identified across Nethercote Brook, with an −8.9% reduction in Qp as a result of the co-designed NFM opportunities to the index flood. This effect significantly reduced with increasing storm size, to only a −2.1% change as a result of the NFM opportunities at the 3.3% AEP storm, the next smallest event tested. Figure 9 represents the change in Tp, where the greatest modification in Tp because of NFM opportunities was across Nethercote Brook.

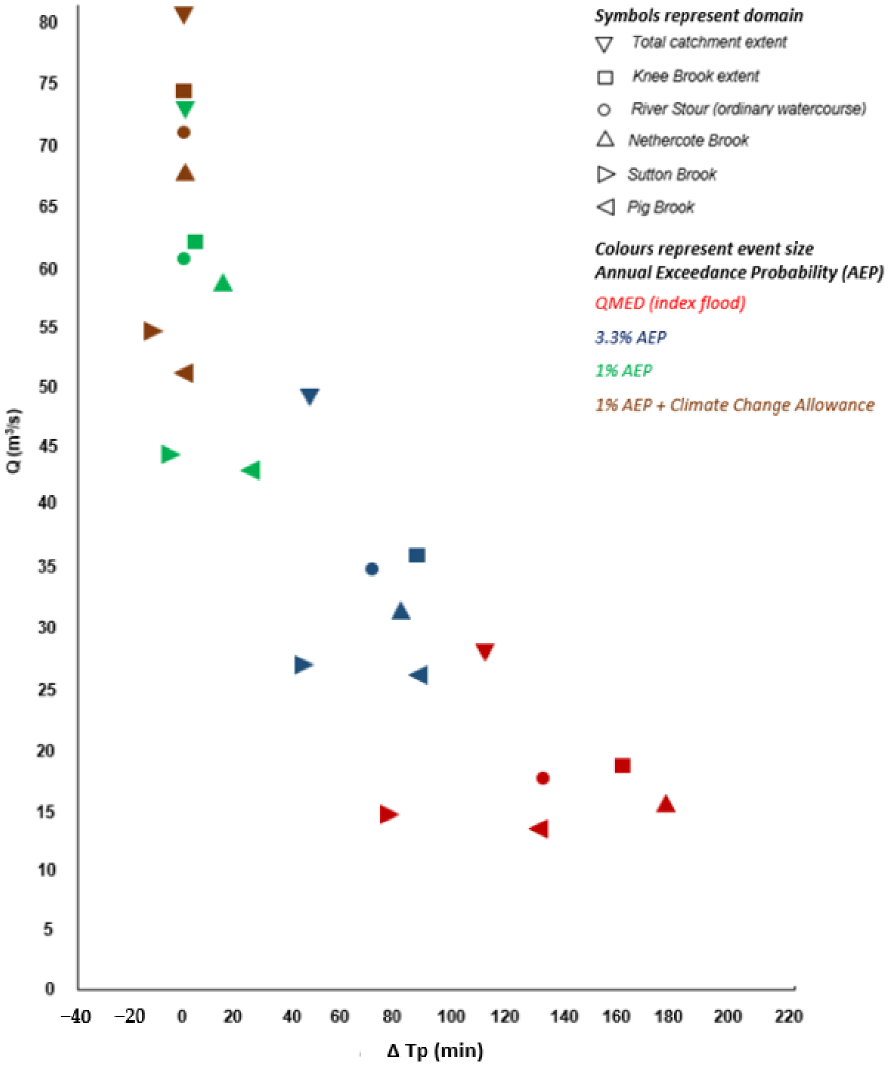


**Figure 9.** Change (Δ) in time-to-peak (Tp) across modelled domains at varying hydrological scales, where Q = discharge.

A general pattern across the catchment was that the larger the catchment scale, the greater the hydrological dilution effects. Figures 8 and 9 demonstrate the total catchment area at Shipston-on-Stour as having the most negligible change in Qp as a result of the NFM scenario: −4% at the QMED design event, 0% at the 1% AEP and 1% AEP + CCA.

Systematic reviews of NFM case-studies conducted by [5,6] also identified negligible effects of NFM when applied at large (>100 km$^2$) catchment scales. Meire et al. [35] refer to this hydrological dilution as the phenomenon in which other contributing hydrological regimes (including areas without NFM) dilute the effects of any upstream interventions altering the Qp.

## 4. Discussion

### *4.1. Relative Sub-Catchment Timings of Peaks*

The modelling of the catchment delineations that applied flood impact modelling (FIM) principles [36] highlighted the significance of assessing how the catchment's component delineations respond to varied storm events. Extensive modelled studies have shown targeting NFM at different delineations have had varied impacts at the furthest downstream extent, even at large hydrological scales [10,37–39]. The overall concept of storm flow propagation across large catchments allows for an infinite number of scenarios to be considered, across a variety of NFM techniques and return periods. This research refined the scenarios tested by undertaking a co-design PGIS process to identify a realistic scope of NFM opportunities.

Questions about peak synchronisation, and the degree of assessment required to identify and avoid such an outcome, are disputed in literature and practice. Hankin et al. [12] adopted a full-modelled scope, prior to engagement, in order to identify converging peaks across the Eden, Derwent and Kent, UK. An intense hydrological monitoring network of both the rainfall and river flow network supplemented this. However, ungauged and particularly large (>100 km$^2$) catchments often lack the level of baseline data to inform such detailed hydrological assessments of the catchment's flow characteristics. Such projects, including the Stroud Rural SuDS scheme, relied on obtaining more anecdotal detail from considerable local engagement in order to facilitate an NFM scheme based on local knowledge [40]. However, the scoping methods often negate any assessment of the relative sub-catchment timings of peaks due to the lack of observed data to assist in building a reliable catchment model. The method used in this study devised a novel hybrid scope that used available observed data to model the catchment.

The modelling results highlighted that the catchment-scale effects of NFM are more diluted the larger the hydrological extent in which they are tested. The impact of mitigation was most identified at the small to medium catchment scales, in the sub-catchment extents (most notably Nethercote and Knee Brooks). The tributaries in the relative sub-catchment's peak timings were not assessed as part of this study, and therefore any de-synchronisation effects cannot be ascertained. However, synchronisation of tributary feeds in Sutton Brook was identified as a dis-benefit of the NFM scenario to the 1% AEP and 1% AEP + Climate Change Allowance, resulting in a greater downstream Qp in Lower Brailes, Warwickshire. Mass balance checks identified the same volume of water in the hydrograph; however, the converging peaks led to a shorter time-to-peak with a reduced lag-time in the river response as a result of the NFM scenario.

In terms of prioritisation at the catchment-scale, Knee Brook was identified as the delineating sub catchment with the greatest travel distance, hydrological contribution and flashiest time-to-peak across all return periods tested. Other modelled studies identified risks in slowing proximal sub-catchments to the outlet, with an increased likelihood of convergence [41]; however, even with a large number of NFM opportunities co-designed across Pig Brook (the closest sub-catchment to Shipston-on-Stour), convergence of peaks was not identified.

A key caveat with the assessments of the relative sub-catchment timings of peaks in this study is the limited gauged spasmodic rainfall and delineated baseline flow data available to disaggregate the upstream flow regimes in the model. The FEH design storms have limitations in homogenising complex localised flows and require rainfall and gauges to be within 10 km$^2$ to more representatively replicate the possible river responses [42].

### *4.2. Peak Attenutation and Flood Mitigation*

The investigation identified key upstream contributions across the multiple return periods, but also upscaled the performance of highly dispersed NFM opportunities to the large catchment scale at Shipston-on-Stour. The ability to identify the large catchment-scale performance of NFM is a critical evidence gap for FRM authorities seeking to explore the role of working with natural processes (WwNP) in agricultural uplands [5,7,39,43–45].

NFM was shown to effectively attenuate downstream flood peaks, delaying the time-to-peak and lowering river stage during return periods across most hydrological scales. Nonetheless, the change in Qp was highly variable across the catchment area; the greatest reduction in Qp as a consequence of the NFM opportunities in the Knee Brook (−8.1%), Nethercote Brook (−8.9%) and the River Stour (−7.6%) to the index (QMED) flood. In comparison to other modelled NFM case studies, the results from the Stour Valley indicated a smaller effect on the flood hydrograph than those tested in other rural headwaters. Many of these projects were tested using an 'ideal' scenario, with no local engagement. Similar performance was shown in the Holnicote Estate (−10%) [46] and Lustrum Beck (−12%) [47] schemes, both larger catchments that tested spatially diffuse NFM opportunities to small flood events. The NFM opportunities assessed in this study proved less effective, and in most catchment locations largely negligible, to larger events (1% AEP and 1% AEP + Climate Change Allowance) that cause internal flooding to downstream properties and businesses. Only three of the six modelled domains showed a reduction in flood peak to the 1% AEP: Knee Brook (−0.6%) Nethercote Brook (−0.9%) and Pig Brook (−1%) sub-catchments, with the greatest reduction identified for the smallest sub-catchment, Pig Brook (6.8 $\text{km}^2$). This pattern of diminished performance with increasing storm size is common across other projects and flood risk management schemes more generally [43,48].

However, two NFM studies (both at smaller catchment scales) have identified more considerable reductions in downstream flood peaks. The Runoff Attenuation Features (RAFs) modelled and monitored in Belford, Northumberland, UK, provided a 30% reduction in Qp to the 1% AEP [29,42] across a 6.8 $\text{km}^2$ catchment. The Water Friendly Farming project, designed as a long-term demonstration scheme to test the performance of catchment-wide agri-environment measures, identified an average of 21% reduction in downstream flood peaks to the 1% AEP across the River Thame, UK in a 12.5 $\text{km}^2$ catchment [49]. However, these are exceptions compared to other NFM schemes, which have yet to be tested (particularly through monitoring networks) for such events and therefore have not identified any peak attenuation and flood risk reduction to larger events.

Regarding other limited co-designed/farmer led NFM schemes, the Pontbren, Wales, scheme also provided a reduction in flood peaks (50% and 38% respectively) to smaller events (3.3% AEP). These other farmer engagement schemes, which have also had performance testing, identified a much greater reduction in flood peak compared to the co-designed Stour Valley NFM opportunities based on comparable return periods. Furthermore, at the furthest downstream extent at Shipston-on-Stour the NFM scenario did not reduce the threshold of flooding below 3.4 m at the 1% AEP and 1% AEP + Climate Change Allowance. Therefore, the NFM scheme did not provide significant flood risk reductions, defined by the Environment Agency under Flood Defence Grant-in-Aid criteria as transitioning properties and businesses to a lower risk banding (1% AEP to a 2% AEP) [50]. The large hydrological scale of the study could be a probable reason for the lesser flood peak reduction (particularly $\geq$ 1% AEP) in the Stour Valley. At 187 $\text{km}^2$, it was identified that the highly spatially dispersed NFM measures were not able to provide an up-scaled aggregation of marginal gains to considerably reduce flood peaks below the threshold required to move properties and businesses out of flood risk. Greater flood peak reduction was identified across the smaller and medium hydrological scales, which agrees with findings across multiple NFM evidence reviews [5,6,51].

Furthermore, ecohydrology is an international concept that supports the NFM approach assessed in this study: using the understanding of relationships between hydrological and biological processes at different scales to reduce hazards from flooding to droughts, whilst enhancing biodiversity and further opportunities for sustainable development, maximising greater harmony within catchment processes [52]. The complexities of biological and hydrological interactions (especially at larger hydrological scales) and their influence on hydrological response is a critical area for further research to better optimise NFM and nature-based solutions.

## 5. Conclusions

The hydrodynamic modelling of NFM performance using XPSWMM © and Flood Modeller Pro © enabled the assessment of NFM performance at variable hydrological scales and return periods. Analysis of catchment response pre and post NFM enabled the following hydrological responses to be considered: the lag time of the catchment (Tp); assessing the propagation of flood waves through the catchment; and overall flood peak (Qp) attenuation across multiple hydrological scales from small upstream delineations, to the total catchment extent at Shipston-on-Stour where the model's sensitivity was tested. The NFM opportunities had diminishing effects on the downstream hydrograph response to the larger flood events; this was especially the case for the 1% AEP + climate change allowance. However, across all hydrological scales the co-designed NFM scheme was able to alter the downstream hydrograph response to smaller events (QMED and 3.3% AEP), with greater influence from hydrological dilution at the larger scale of assessment. This adheres to wider literature findings of NFM performance across fluvial (non-tidally influenced) basins, which have also identified diminishing effects at larger hydrological scales. The relative sub-catchment timings of peaks were also considered a risk for NFM application to the Sutton Brook headwaters delineation, with a reduction in time-to-peak and heighted hydrograph response due to converging tributary responses. Studying local time series of flow data in this method provided an insight into a more targeted approach if risk management authorities were to pursue an approach to delivery and in-situ monitoring.

Furthermore, it is important to sustain local engagement and relationships (obtained in an earlier phase of the research, see [11] with land managers able to continue the active engagement around modelled results, to 'locally calibrate' and refine catchment understanding further when there is a lack of observed. Hence open access and telemetered hydrological data to support wider understanding are fundamental to NFM delivery. This aims to reduce model uncertainty and improve confidence with a greater resolution of catchment rainfall and runoff response at a more detailed and delineated scale, advocated by many hydrological studies in catchment scale NFM and altered land use management methods (e.g., [5–7]). The modelling method had issues with homogenisation of catchment response using the FEH design storms as inputs. The lack of localised rainfall and runoff data required FEH data to be used as design event inputs and for model sensitivity testing using the furthest downstream extent of the study site (the National River Flow Archive Gauge, in Shipston-on-Stour), which was a key limitation for assessing varied antecedent conditions during an event and the effects on catchment saturation. Current evidence indicates there is diminishing effectiveness of interventions the more saturated the catchment becomes; the modelled analysis was unable to deconstruct the hydrograph and assess this influence due to the lack of observed antecedent data including infiltration rates and evapotranspiration losses.

The study also recommends further investigation into appraising the costs and multiple benefits of the modelled and co-designed NFM scheme. The monetary appraisal of NFM is a critical evidence gap limiting uptake, particularly in relation to whole life costs (when accounting for maintenance) and whole life multiple benefits, particularly as many NFM measures are purported to increase in effectiveness as they establish (e.g., tree planting, river restoration). Therefore, more observed data on whole life performance enabled through monitoring would provide a more robust basis to understand costs and benefits.

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