

Multi-objective optimisation of natural flood management for community-level property damage reduction using a physically based distributed hydrological model

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Abstract

Natural flood management (NFM) at the catchment scale requires cost-effective spatial configurations that maximise flood risk reduction while minimising implementation cost. Existing studies often assess predefined scenarios at catchment outlets, limiting systematic portfolio evaluation and community-scale impact assessment. This study couples the fully distributed, physically based SHETRAN hydrological model with the NSGA-II multi-objective optimisation algorithm to minimise total NFM area and community-level property damage across the Upper Irwell catchment in the UK. Four NFM types, runoff attenuation features, floodplain reconnection, woodland, and soil improvement, were represented at the grid cell scale, with volume damage avoided curves developed for 47 communities. SHETRAN achieved a Nash-Sutcliffe Efficiency of 0.78 against observed daily discharge over 13 years. Individual NFM types reduced peak flow by up to 10.4%, while a combined scenario reduced it by 15.3%. Optimisation using a 10-day event identified 100 Pareto-optimal solutions, including one that achieved the same damage avoidance as maximum NFM implementation while requiring 39.6% less intervention area. Benefit-cost ratio filtering identified 30 high-performing solutions, with damage avoidance of up to £33 million when applied across the full 35-year simulation. Efficient sub-catchments were mainly concentrated upstream. The framework enables systematic identification of cost-effective NFM portfolios across large spatial solution spaces, supporting community-scale flood risk reduction beyond scenario-based or semi-distributed hydrological approaches.

Keywords: hydrological modelling, natural flood management, multi-objective optimisation, NSGA-II, property damage reduction

1 Introduction

River flooding is amongst the most widespread and damaging natural hazards globally, with projected increases in frequency and severity under climate change placing growing pressure on con-

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ventional flood risk management (Bagheri-Gavkosh et al., 2025; Carter et al., 2024). In England, 2.4 million properties are at risk of fluvial flooding (Environment Agency, 2025a), at an economic cost of £1.1 billion annually (Environment Agency, 2026). Natural Flood Management (NFM) works with natural landscape features and processes to attenuate flood peaks rather than relying solely on hard-engineered defences (Hill et al., 2023). Interventions such as floodplain reconnection, woodland creation, soil improvement, and runoff attenuation features (RAFs) enhance infiltration and evapotranspiration, increase temporary storage, and slow runoff pathways (Kingsbury-Smith et al., 2023; Nicholson et al., 2020; Quinn et al., 2013), while delivering co-benefits for biodiversity, carbon sequestration, and water quality (Metcalf et al., 2017).

NFM is nonetheless more complex to plan and appraise than conventional defences, since interventions are small in scale and their benefits depend on the collective effect of many features implemented in a coordinated, distributed manner (Beven et al., 2022; Environment Agency, 2023; Lavers et al., 2022). Performance is strongly scale-dependent, with local attenuation diminishing at larger spatial scales and remaining highly sensitive to storm characteristics and antecedent conditions (Carter et al., 2024; Zhu et al., 2025b). UK evidence remains predominantly confined to catchments below 10 km², with limited evidence at scales relevant to community-level flood protection (Bagheri-Gavkosh et al., 2025; Nicholson et al., 2020). Combined impacts are further complicated by non-linearity, since spatial configuration determines whether tributary flows are synchronised or desynchronised, either amplifying or reducing downstream peaks. Assessing interventions in isolation therefore rarely captures these catchment dynamics (Monger et al., 2024; Zhu et al., 2025a).

UK NFM appraisal has relied on tools that function largely independently: the NFM Opportunities Map identifies suitable implementation areas (Environment Agency, 2018; JBA, 2018); EA community property reports estimate properties at risk and weighted annual average damages; the NFM Storage Tool relates storage volume to hydrograph change; and the DEFRA Partnership Funding framework links risk reduction to funding allocation (Environment Agency, 2024). These have since been consolidated into a national NFM Benefits Method and Calculator, combining water storage potential with downstream damage data from the National Flood Risk Assessment (Environment Agency, 2025b). Both the earlier tools and the current method are explicitly designed as simplified, largely empirical representations of NFM processes, limiting their ability to capture the spatial dependencies and process interactions that govern catchment-scale response.

Physically based hydrological models offer a more rigorous alternative, representing NFM through its effects on infiltration, water storage, surface flow, subsurface flow, and channel routing. These range from simplified distributed approaches such as SD-TOPMODEL (Gao et al., 2015), which represents catchment processes in a topography-driven form derived from TOPMODEL (Beven and Kirkby, 1979), to fully distributed models such as SHETRAN (Ewen et al., 2000), which resolves surface and subsurface processes and their interactions in greater detail and captures exchanges that conceptual or semi-distributed approaches often struggle to reproduce (Badjana et al., 2023; Sayers et al., 2025). Distributed modelling studies of NFM have nonetheless mostly evaluated

a small number of manually defined scenarios (Barnes et al., 2023; Bathurst et al., 2018) rather than exploring the large combinatorial space of possible spatial designs. A further challenge is translating modelled hydrograph changes into quantifiable economic risk metrics at the community scale, reflecting a persistent disconnect between physical hydrology and the appraisal frameworks used to justify and fund NFM investment (Beven et al., 2022; Carter et al., 2024).

Building on these gaps, this study presents an integrated catchment-scale NFM optimisation framework coupling the fully distributed, physically based SHETRAN model with the Non-dominated Sorting Genetic Algorithm II (NSGA-II) to identify cost-effective spatial configurations of NFM interventions. While multi-objective optimisation has previously been coupled with a detailed hydrodynamic flood model for urban Blue-Green Infrastructure placement (Ur Rehman et al., 2024, 2025b,a), its application to rural NFM planning using a fully distributed, process-based hydrological model with community-scale damage-based risk metrics has not, to the authors’ knowledge, been reported previously. The framework is applied to the Upper Irwell catchment in Northwest England, an upland-to-urban system with a well-documented history of severe fluvial flooding, linking modelled hydrological responses to community-level property damage and enabling evaluation of benefit-cost trade-offs across thousands of alternative intervention portfolios. However, evaluating this many portfolios makes full-period simulation infeasible, requiring a representative event as a proxy for long-term damage. The resulting bias is quantified and attributed in this study. The specific objectives are:

1. To quantify the hydrological impacts of catchment-scale individual and combined NFM types on community-scale flows, using grid-cell-level representation within a fully distributed model.
2. To develop community-level volume-damage-avoided relationships linking modelled flow attenuation to property damage.
3. To optimise the spatial configuration and extent of NFM across sub-catchment units and evaluate the resulting portfolios against the individual benefit-cost performance of each sub-catchment.
4. Quantify and attribute bias in event-based damage estimates relative to full-period benchmarks and determine the pre-event simulation duration required to constrain it.

2 Materials and methods

2.1 Catchment description

The Upper Irwell catchment (Figure 1) is an upland-to-urban headwater sub-catchment of the River Irwell in Northwest England, draining approximately 155 km² from Pennine moorland southward to an outlet near Bury, with elevation ranging from approximately 40 m to 480 m. Land cover is dominated by pasture and grassland, with upland moorland and blanket bog on higher ground. Impermeable Carboniferous bedrock, peat, and glacial deposits limit infiltration capacity and produce

a rapid, flashy hydrological response, with times-to-peak of less than two hours due to the mentioned upper-catchment conditions (Nicholson et al., 2020). Settlement is concentrated on narrow valley floors, where 47 communities are exposed to fluvial flood risk. Storm Eva in December 2015 produced record river levels in the Ramsbottom to Bury corridor and widespread property damage (GMCA, 2016). This combination of flashy response and concentrated valley-floor risk makes the catchment an appropriate test case for catchment-scale NFM optimisation. Further detail on catchment geology, tributaries, and flood history is provided in Appendix A.1.

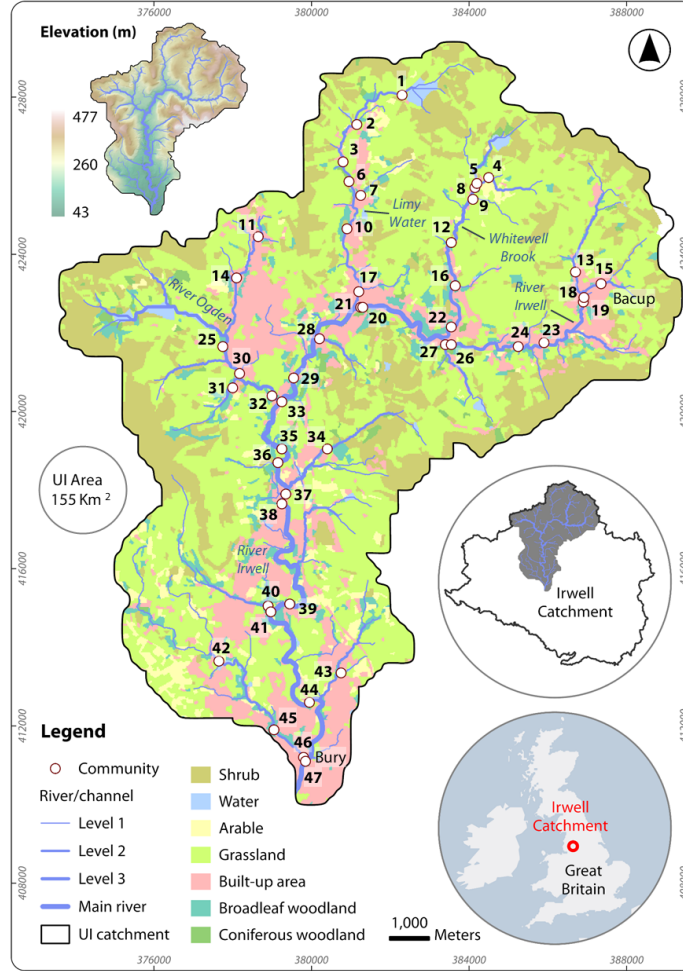


Figure 1: Land use map of the Upper Irwell catchment (155 km²), showing the river network and major tributaries, 47 community locations, with elevation inset illustrating the upland-to-urban topographic gradient. Communities are labelled by ID for brevity.

2.2 Hydrological model

This study uses the physically based, fully distributed SHETRAN model (Ewen et al., 2000), which simulates potential evapotranspiration, canopy interception, surface runoff, infiltration, soil moisture dynamics, groundwater flow, and snowmelt. SHETRAN is suited to this work because its distributed structure allows NFM features to be represented explicitly across the model domain, and

its process-based formulation simulates hydrological behaviour throughout the catchment rather than reproducing flows at the outlet alone. Model calibration is detailed in Appendix A.2.

2.2.1 Extraction and mapping of river flow to communities

SHETRAN delineates a river network from the supplied topography, with channels flowing along grid square edges, and simulates discharge along all channel segments, allowing flows to be extracted at any point. Most hydrological studies focus on catchment outlet flows, whereas this study evaluates NFM impacts on flood risk across spatially distributed communities along river reaches. Each at-risk community was therefore mapped to a specific river element based on its hydrological position relative to the channel. Community 36, for example, extends downstream of a confluence and is assigned to river link 207, the first link downstream of that confluence, rather than the geographically closer but hydrologically unrepresentative link 213 (Figure 2).

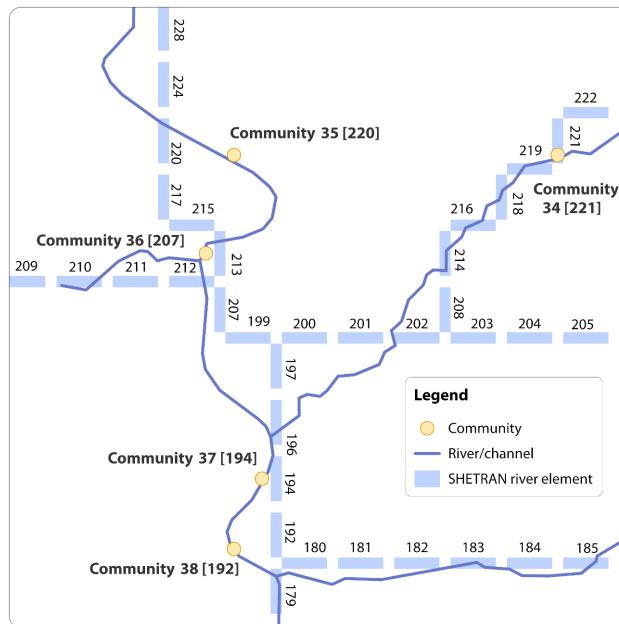


Figure 2: Example of linking communities to the simulated river network within SHETRAN. Community points represent the centroids of settlement extents.

2.3 NFM design and representation in SHETRAN

Four NFM types were selected for modelling based on their suitability for representation within SHETRAN and their feasibility confirmed through stakeholder engagement: Runoff Attenuation Features (RAFs), Floodplain Reconnection (FPR), Woodland for Water (WfW), and Improved Soil. Opportunity extents were taken from the Irwell Strategic NFM Targeting Maps (JBA Consulting, 2017), which refine the national Working with Natural Processes maps (Environment Agency, 2018) through field-level consultation, with the national layers used where refined data were unavailable (Figure 3).

RAFTs and FPRs were represented as temporary surface storage, allowing a defined volume of surface water to accumulate within designated grid cells to a maximum depth of 1 m, giving a capacity of 40,000 m³ per 200 m cell at full storage (Sayers et al., 2025; Smith et al., 2024). Once capacity is exceeded, surface runoff proceeds as under baseline conditions, with retained water released through runoff or infiltration. RAFTs cover 0.91 km² and FPRs 0.93 km², each corresponding to approximately 23 cells with a full 1 m depth (Figure 3a, Figure 3b).

Woodland was represented by increasing the intercepted evaporation rate in proportion to the woodland cover assigned to each grid cell, reflecting the effect of greater canopy height and surface roughness on turbulent airflow, across a total area of 10.7 km² (Figure 3c).

Improved soil was represented by replacing the existing soil parameters with peat-like characteristics from Lewis (2016) where an NFM polygon overlaps at least 50% of a grid cell, since SHETRAN cannot assign soil types fractionally. Key parameters are a saturated water content of 0.766 and a saturated conductivity of 8 m/day, approximately 3.5 times the medium-fine topsoil value, with the full parameter set given in Table 1. The sequential allocation algorithm, which carries residual areas forward between polygons to conserve total extent, is described in Appendix A.3. Improved soil covers 36.0 km² (Figure 3d).

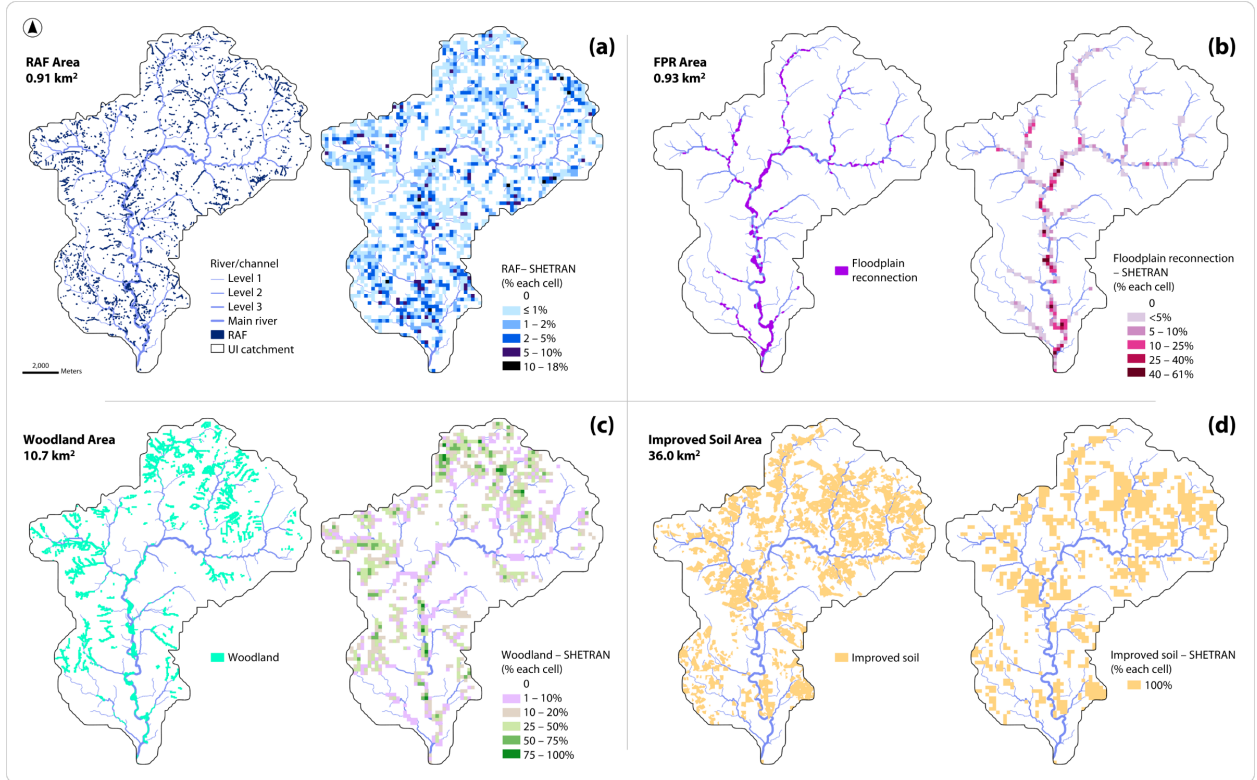


Figure 3: Input polygons (left) and corresponding SHETRAN grid-cell representations (right) for (a) RAFTs (0.91 km²), (b) floodplain reconnection (0.93 km²), (c) woodland (10.7 km²), and (d) improved soil (36.0 km²), illustrating the spatial distribution and discretisation of each NFM type within the 200 m model grid.

Table 1: Parameters used in SHETRAN for the unaltered soil map and the Improved Soil NFM.

Type	Saturated water content	Residual water content	Saturated conductivity (m/day)	Van Genuchten α (cm^{-1})	Van Genuchten n
Medium Topsoil (18% to 35% clay and <15% sand or <18% clay and 15% to 65% sand)	0.439	0.01	12.061	0.0314	1.1804
Medium-Fine Topsoil (<35% clay and <15% sand)	0.43	0.01	2.272	0.0083	1.2539
Improved Soil (Lewis, 2016)	0.766	0.01	8	0.013	1.2039

2.4 NFM evaluation across the communities

The impacts of implementing the maximum available extent of each NFM type are investigated to establish the upper bound of potential flow reductions. SHETRAN is run for five years (1 January 1980 to 31 December 1984) using daily meteorological inputs, a computationally efficient alternative to the full 35-year record that retains sufficient rainfall variability to characterise NFM effectiveness and identify a representative event for optimisation (Section 2.6.2). Simulation periods for all study components, including spin-up allowances, are summarised in Figure 4, and outlet-discharge sensitivity to intervention extent was additionally bounded by a hypothetical whole-catchment scenario for each NFM type (Appendix A.4). The maximum flow reduction, ΔQ_{Max} , and maximum percentage flow reduction, $\Delta Q_{Max}(\%)$, for each NFM type are calculated as:

$$\Delta Q_{Max} = \text{Max}(Q_{baseline} - Q_{NFM}) \quad (1)$$

$$\Delta Q_{Max}(\%) = \left(\frac{\Delta Q_{Max}}{Q_{baseline_max(t)}} \right) \times 100 \quad (2)$$

where $Q_{baseline}$ is the baseline flow time series, Q_{NFM} is the flow time series under the specified NFM scenario, and $Q_{baseline_max(t)}$ is the baseline flow at the timestep t at which ΔQ_{Max} is achieved.

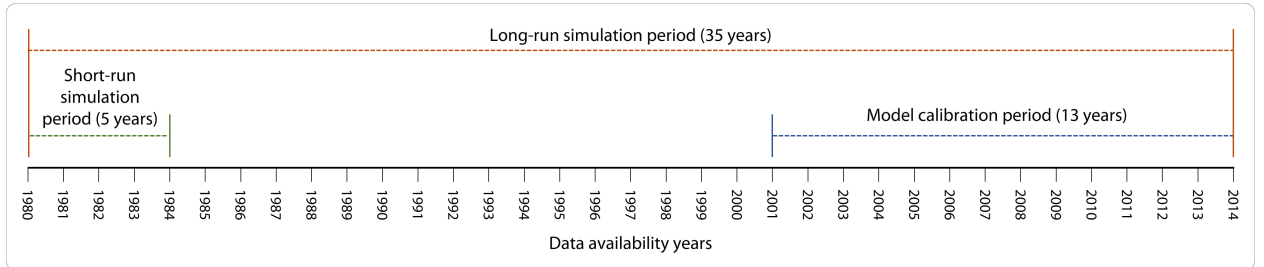


Figure 4: Simulation periods used in this study relative to the available rainfall record (1980–2014). The short-run simulation period (1980–1984) was used for preliminary NFM evaluation and for selecting representative events for optimisation. The long-run simulation period (1980–2014) was used for water balance analysis and damage estimation. Model calibration was performed over the period 2001–2014.

2.5 Water storage and retention under the maximum NFM scenario

Water balance variables were simulated for both the baseline and maximum NFM scenarios at the catchment scale over the full 35-year rainfall record, rather than the 5-year period used for hydro-graph comparison, since reliable estimation of long-term storage differences requires a sufficiently large sample of rainfall events across the full range of catchment conditions. Volumetric differences in each component were derived by subtracting scenario values from the baseline and multiplying by the total catchment area. The dominant storage processes differ by NFM type, as summarised in Appendix A.5.

2.6 NFM optimisation

2.6.1 Rationale and optimisation framework

The hydrological benefit of an NFM intervention depends not only on its type and extent but critically on its location within the catchment. Certain spatial combinations, or portfolios, produce favourable desynchronisation of flood peaks between tributaries, while others synchronise peaks or deliver only marginal benefit. As the number of spatial units increases, the number of possible combinations grows exponentially, making exhaustive evaluation computationally infeasible. This study therefore adopts the multi-objective optimisation framework of [Ur Rehman et al. \(2024\)](#), coupling SHETRAN with the Non-dominated Sorting Genetic Algorithm II (NSGA-II) ([Deb et al., 2002](#)). NSGA-II suits this problem because it handles non-linear, non-convex objective spaces, requires no gradient information, and produces a Pareto front of trade-off solutions in a single run. Integration and optimisation are implemented in Python, with code available as described in the Data availability statement.

2.6.2 Rainfall event selection

Each SHETRAN simulation of the full 35-year record requires approximately nine hours, so the tens of thousands of simulations required for optimisation make long-run evaluation impractical, and a representative short-duration event was adopted instead. The maximum combined NFM scenario was simulated over the five-year period (Section 2.4), the date of greatest absolute flow reduction at each community was identified, and the most frequently recurring date across communities was selected as the optimisation event. Given the short duration, daily precipitation was spatially averaged and applied uniformly across all grid cells to ensure consistent activation of NFM capacity. Baseline antecedent conditions were generated by running SHETRAN from the dataset start to the event onset, with the resulting states used as initial conditions for all event-based simulations. The hydrological uncertainty that an event can produce relative to long-run simulation is assessed in Section 2.8.

2.6.3 Decision variables

Ideally, each 200 m grid cell containing an NFM opportunity would be an individual decision variable, but with thousands of eligible cells this produces a 2^N search space that is computationally impractical. NFM cells within each sub-catchment are therefore treated as a single entity, included or excluded together. Sub-catchments were delineated hydrologically from the same 200 m DEM used in SHETRAN, yielding 60 units finer than the seven Water Framework Directive management units (UK Government, 2017) while remaining consistent with their boundaries (Figure 5a; Appendix A.6).

Improved soil accounts for approximately 77% of the 48.5 km² available NFM area, woodland 21%, and RAFs and FPRs together 2%. Given this imbalance, optimisation uses the combined NFM within each sub-catchment rather than treating types separately, preventing improved-soil configurations from dominating regardless of spatial merit. Spatial differentiation is preserved because the NFM types mix varies considerably across sub-catchments (Figure 5b, 5c) and is retained through the spatially explicit SHETRAN representation. Each sub-catchment thus acts as a binary decision variable (Figure 5d). Two fixed scenarios are always included, the baseline and the maximum with all 60 sub-catchments activated, with all other configurations evolved by NSGA-II from a randomly initialised population (Ur Rehman et al., 2024).

2.6.4 Objective functions

The optimisation involves two objective functions: total combined NFM area, minimised as a proxy for implementation cost, and total damages avoided across all communities, maximised as the measure of flood risk benefit. Using NFM area as a cost proxy assumes a linear relationship between area and cost. Although simplified, given variations in NFM type unit costs and its spatial distribution across sub-catchments, this provides a reasonable first-order approximation for strategic screening and was approved by EA experts.

2.6.5 Damage-avoided calculation

The damage-avoided calculation links modelled flow reductions at each community to property damage estimates, drawing on two data sources. The EA Property Report for each community gives the number of residential, non-residential, and undefined properties at risk within five predefined flood risk bands, from very significant (return period below 1 in 20 years) to low (above 1 in 200 years), together with a community deprivation weighting and the annual average damage (AAD) for each band (Penning-Rowsell et al., 2014). The EA NFM Storage Tool, developed by Jacobs Consulting for the Environment Agency (Jacobs, nd), applies the Flood Estimation Handbook methodology to relate upstream storage volumes to changes in design-flood hydrographs, return periods, and properties at risk.

The calculation estimates the attenuation volume produced by a given NFM sub-catchment combination, evaluates how this shifts properties between risk bands, and takes the resulting change

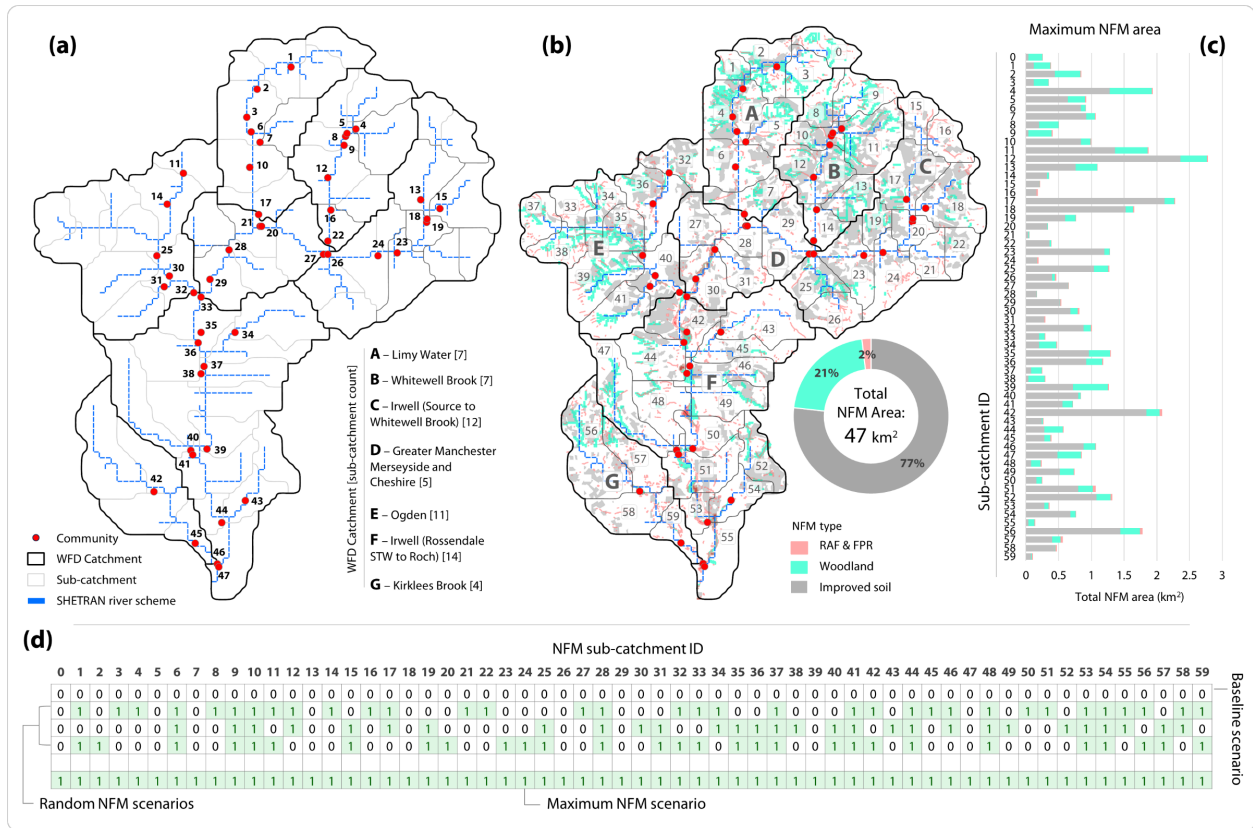


Figure 5: (a) Delineated small sub-catchments and WFD boundaries with community points, (b) NFM distribution in the catchment, (c) each NFM type area within each sub-catchment, and (d) sub-catchments representation in solutions as decision variables.

in AAD as the damage avoided (Figure 6). Because the original EA methodology changes damage only when properties cross a band boundary, producing discrete outputs, the optimisation cannot differentiate values in between (Ur Rehman et al., 2025b). Thus, AAD values are linearly interpolated to give continuous estimates (Figure 7). The full nine-step procedure, including the growth-curve fitting, event-based scaling, and reduction-factor derivation, is given in Appendix A.7 (Equations S1–S3).

2.6.6 Optimisation processes

The optimisation ran a population of 100 candidate configurations over 100 generations, yielding 10,000 solution evaluations, with each candidate’s NFM area and damages avoided estimated via SHETRAN and the flow-to-risk module (Section 2.6.5). Convergence was confirmed by the absence of further improvement in Pareto-front hypervolume. Standard NSGA-II operators were applied as detailed by Ur Rehman et al. (2024, 2025b).

2.7 Selection of high-performing optimal solutions

Although all Pareto-front solutions are optimal in the non-dominated sense, a further filtering step identifies those with the highest marginal efficiency. Following Ur Rehman et al. (2025a), the benefit-cost ratio (BCR) is total damages avoided (£ million) divided by total NFM area (km²), taking area as a proxy for cost. The marginal benefit-cost ratio (MBCR) is the incremental ratio of additional damages avoided to additional area between consecutive solutions on the sorted Pareto front, capturing diminishing returns as NFM area increases. Solutions are classified as high-performing where BCR exceeds 1, and MBCR exceeds 3. These are heuristic screening criteria rather than formal economic appraisal requirements. Economic appraisal of UK flood risk management schemes follows HM Treasury’s Green Book (HM Treasury, 2026) as applied through the Environment Agency’s FCERM appraisal guidance (Environment Agency, 2020), under which benefits are expressed relative to scheme costs. The BCR used here remains area-based rather than cost-based and therefore cannot be directly compared with these appraisal ratios. Translating NFM interventions into costs is beyond the scope of this work.

2.8 Uncertainty analysis and optimal event duration

To quantify the bias arising from the use of event-based simulations in the optimisation process, full 35-year long-run simulations were conducted for each of the 30 high-performing optimal solutions identified in Section 2.7, providing a benchmark against which event-based damage estimates were compared. Bias was attributed by applying both the growth-curve method and the event-based scaling method to the same long-run simulations, thereby isolating the bias attributable to the linear scaling procedure from that arising from the use of baseline antecedent conditions. Simulations were additionally conducted using pre-event durations of 10 days, 1 month, 3 months, and 6 months to identify the duration that minimises the discrepancy between event-based and long-run damage

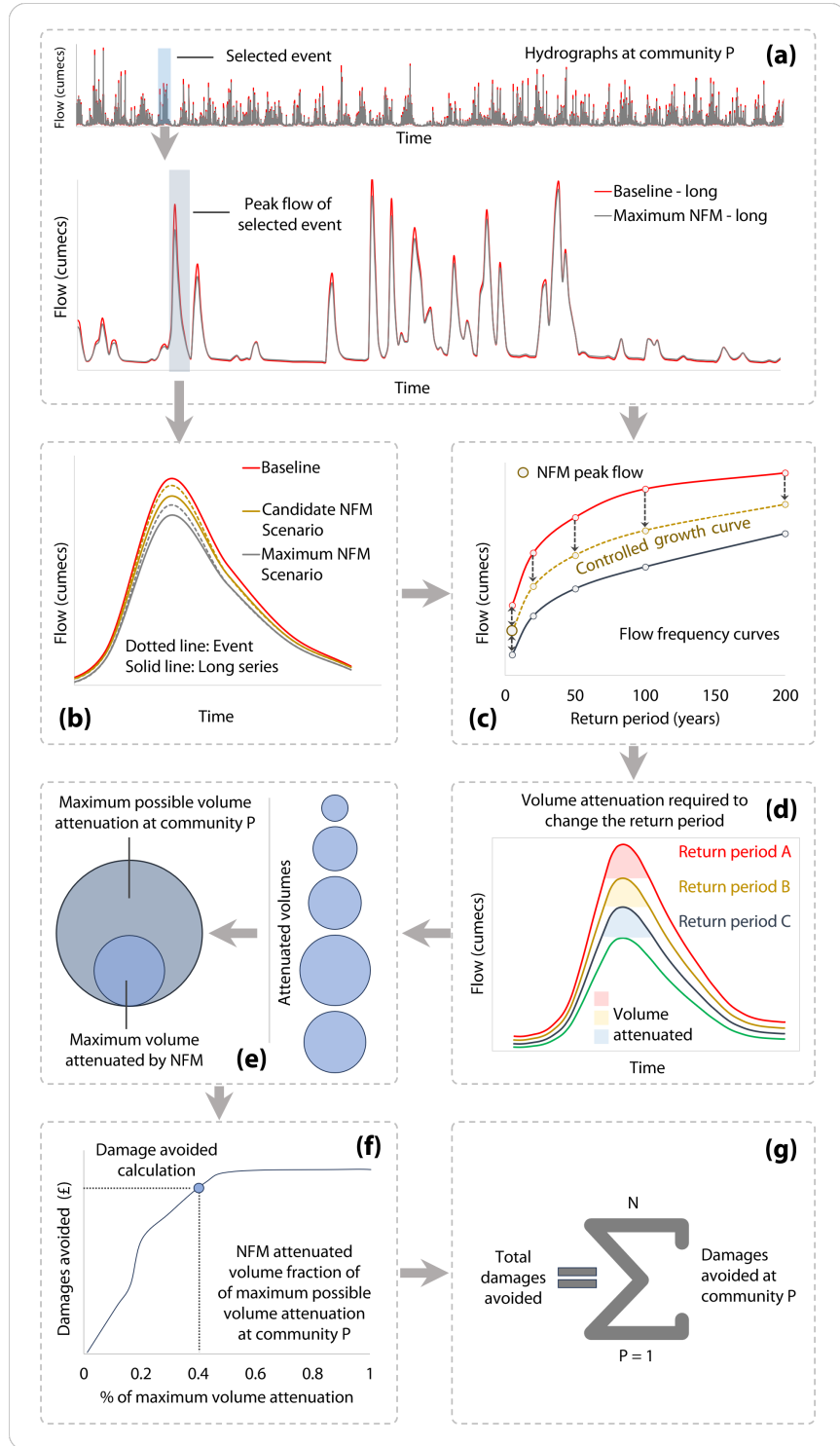


Figure 6: Schematic of the damage-avoided calculation framework, illustrating the sequential steps from long-run and event-based hydrograph simulation (a, b), through peak-flow derivation and NFM-controlled growth curve adjustment (c), volume attenuation estimation across return periods (d, e), to community-level damage-avoided curve application (f) and summation of total damages avoided across all communities (g).

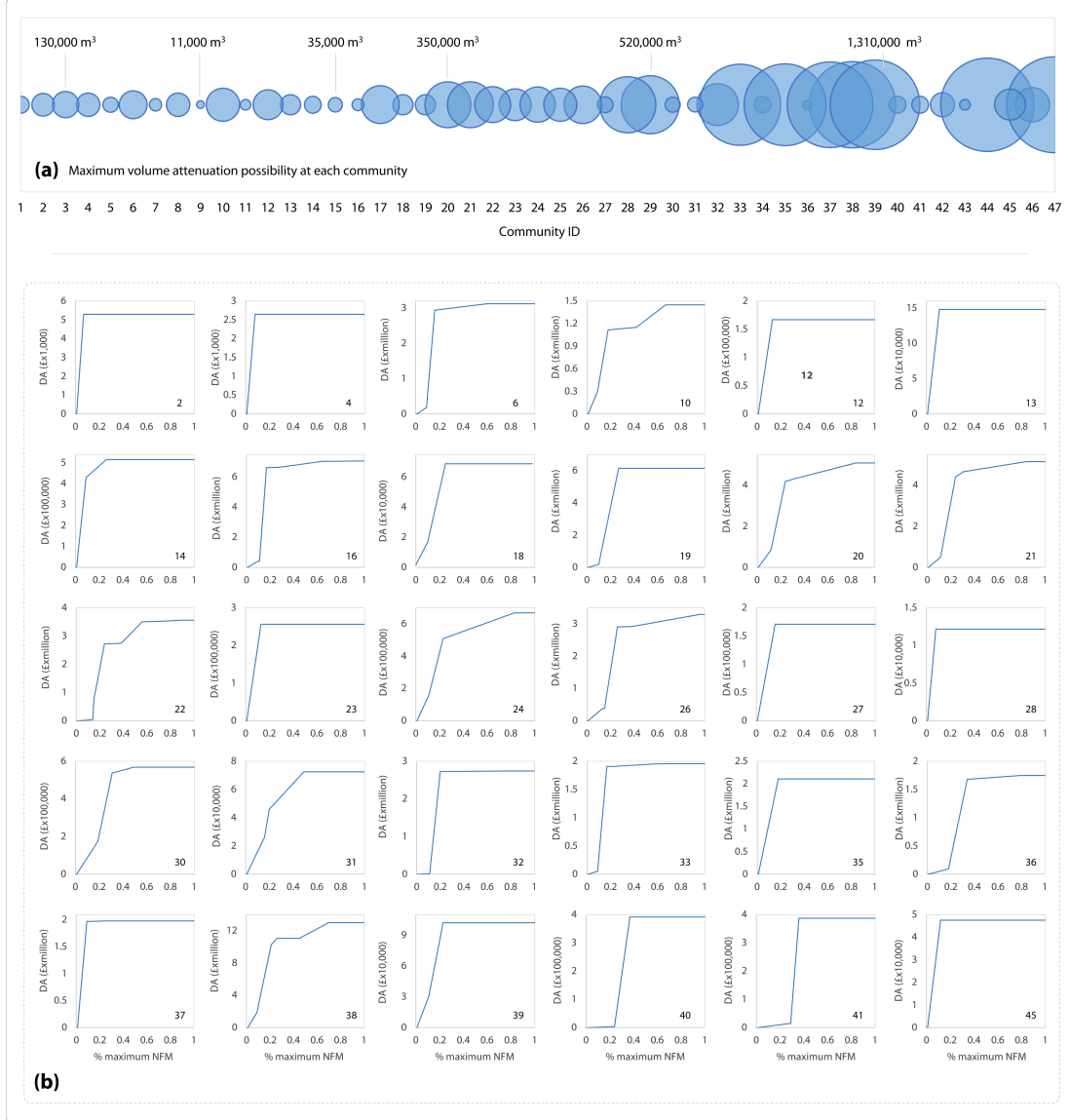


Figure 7: (a) Maximum volume attenuation capacity by NFM at each of the 47 communities shown as area-proportional circles, and (b) corresponding volume attenuation-damage-avoided curves, illustrating the non-linear relationship between NFM attenuation and property damage reduction across communities. Communities absent from panel (b) showed no damage reduction at any NFM fraction and are not displayed.

estimates.

3 Results

3.1 Model performance

The SHETRAN baseline model achieved an NSE of 0.78 against observed daily discharge at the Bury Ground gauge over the 2001 to 2014 calibration period, capturing both the timing and magnitude of peak flows across low-flow recession periods and high-flow flood events (Figure 8).

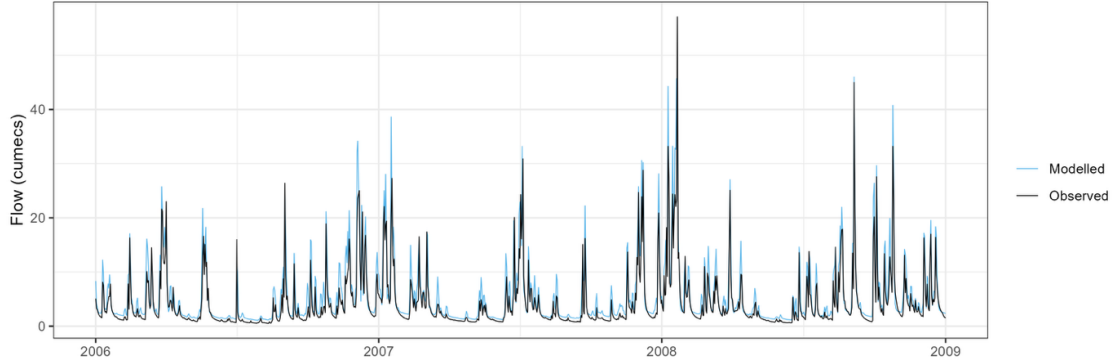


Figure 8: Simulated and observed daily discharge at the Bury Ground gauge (NRFA station 69044), shown for 2006 to 2009, a representative sub-period of the 2001 to 2014 calibration period. The model achieved an NSE of 0.78 over the full calibration period.

3.2 NFM impact on catchment hydrology

3.2.1 Catchment-scale flow reduction by NFM types

The hydrological effectiveness of each NFM type at its maximum available extent was assessed by comparing baseline and post-NFM flows at the catchment outlet over the five-year period (January 1980 to December 1984). Figure 9 presents the percentage change in daily flow at each timestep, alongside gridded frequency distributions across flow-magnitude bands, restricted to days on which baseline flow exceeded 5 cumecs ($n = 539$). Full hydrograph overlays are provided in Figure S1 (Appendix A.8).

RAFs and FPRs produced negligible changes across all flow magnitudes, with distributions confined almost entirely to the 0 to $\pm 5\%$ band and $\Delta Q_{Max}(\%)$ below 1.1% (Figure 9a, Figure 9b). Woodland reduced flows across all events, most frequently between 5 and 10 cumecs and decreasing progressively at higher flows, giving a $\Delta Q_{Max}(\%)$ of approximately 10% (Figure 9c). Improved soil showed the contrasting pattern, with reductions becoming more frequent as flow magnitude increased, although a subset of low-flow days showed marginal increases relative to baseline, giving a $\Delta Q_{Max}(\%)$ of 10.4% (Figure 9d). The combined scenario produced the broadest distribution of reductions across all flow magnitudes and the highest $\Delta Q_{Max}(\%)$, at 15.3% (Figure 9e).

Sensitivity analysis (Appendix A.9, Figure S2) indicates that increasing RAF storage beyond the maximum available extent yields modest additional reductions in medium-magnitude flows, and that hypothetical whole-catchment conversion to woodland or improved soil produces progressively greater peak reductions. The limited catchment-scale effect of these interventions therefore reflects the spatial extent of available opportunities rather than intrinsic ineffectiveness.

3.2.2 Water storage and retention by NFM type

Volumetric storage and retention contributions were quantified from water balance simulations over the full 35-year rainfall record (Appendix A.10, Figure S3) and are summarised in Table 2. Improved soil contributed the largest absolute volume reduction at 656,903 m³, consistent with its dominant spatial coverage, followed by woodland at 214,096 m³, with FPR and RAF contributing comparatively modest volumes. Normalising by intervention area reverses this ordering, with woodland yielding the highest reduction per unit area at 20,009 m³/km², ahead of FPR, improved soil, and RAF. The combined maximum NFM scenario yields 766,983 m³ (15,801 m³/km²), below the sum of the individual contributions.

Table 2: Maximum volume reduction per intervention.

Simulated intervention type	Spatial area (km ²)	Maximum volume reduction (m ³)	Maximum volume reduction per area of intervention (m ³ /km ²)
RAF	0.91	12,283	13,498
FPR	0.93	17,258	18,557
Woodland	10.7	214,096	20,009
Improved Soil	36.0	656,903	18,247
Combined NFMs	48.54	766,983	15,801

3.2.3 Community-wise maximum flow reduction by NFM

Maximum baseline flows at each of the 47 communities are shown in Figure S4 (Appendix A.11), and Figure 10 presents the corresponding maximum flow reductions from each individual intervention and the combined scenario. The combined scenario achieves the greatest reduction across all communities, followed by improved soil and woodland, with RAFs and FPRs contributing least. Both baseline flow magnitude and NFM-induced reduction vary along the network, with the spatial pattern of reductions tracking that of baseline flows.

3.3 NFM optimisation

3.3.1 Event selection

Figure 11 presents the date of maximum flow reduction under the combined NFM scenario at each community. The most frequent, 9 October 1983, is the maximum-reduction date for 26 communities (approximately 55%), indicating a widespread simultaneous benefit, and was selected

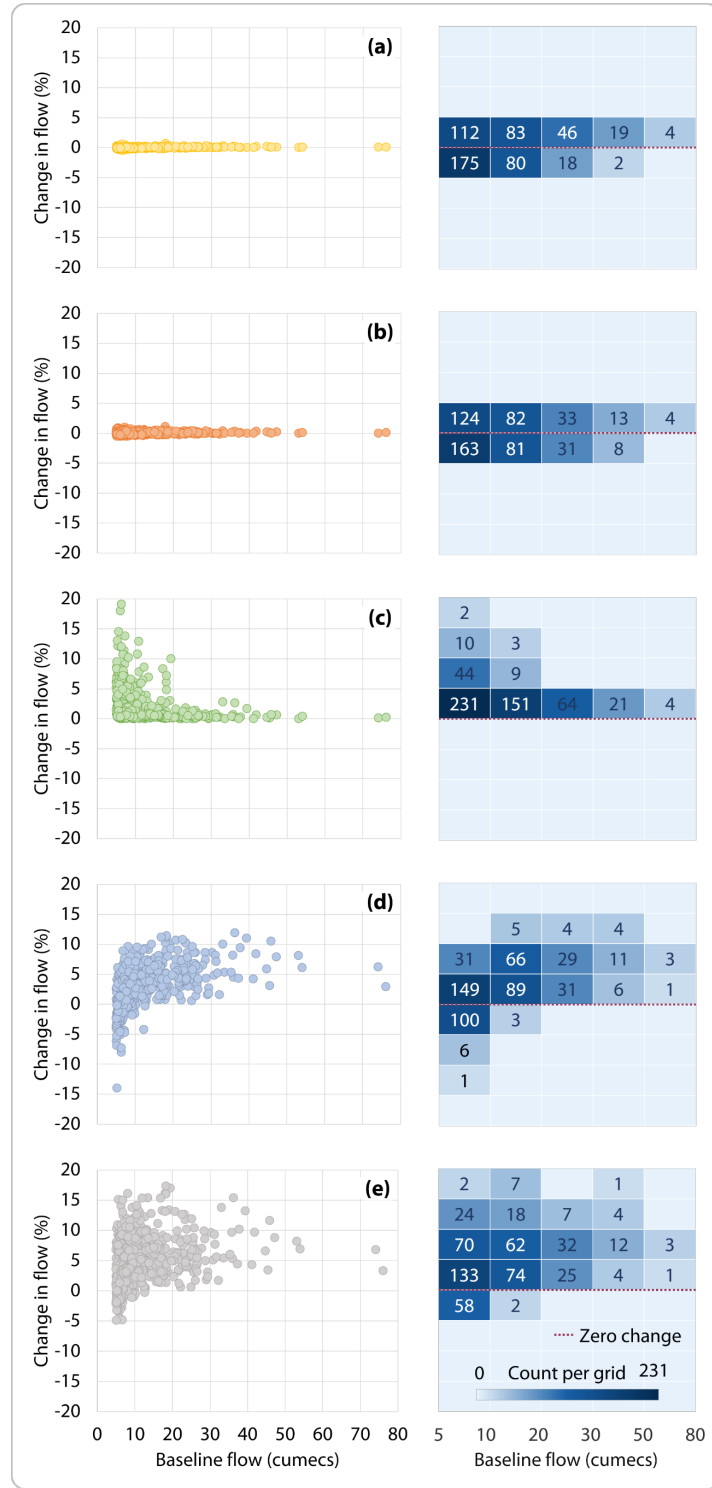


Figure 9: Percentage change in daily catchment outlet flow relative to baseline for each NFM type at maximum available extent (January 1980–December 1984): (a) RAFs, (b) FPRs, (c) Woodland, (d) Improved Soil, and (e) Combined NFM. Left panels show scatter plots against baseline flow magnitude; right panels show gridded frequency distributions ($n = 539$, baseline > 5 cumecs), with cell colour proportional to count on a standardised scale (maximum = 231). Dark red dashed line denotes zero change; values below indicate days where NFM marginally increased flow.



Figure 10: Maximum flow reduction (ΔQ_{Max}) achieved by each NFM type and the combined scenario across 47 communities, with bubble size indicating the percentage reduction relative to baseline peak flow, showing that improved soil and combined NFM deliver the greatest reductions, while RAFs/FPRs contribute negligibly across all communities.

as the optimisation event. Figure 12 shows the catchment outlet hydrograph for the selected 10-day window (3 to 12 October 1983), during which peak flow reduces from 36.3 to 30.7 cumecs. The window places most days before the peak-reduction date to capture the antecedent conditions influencing NFM performance.

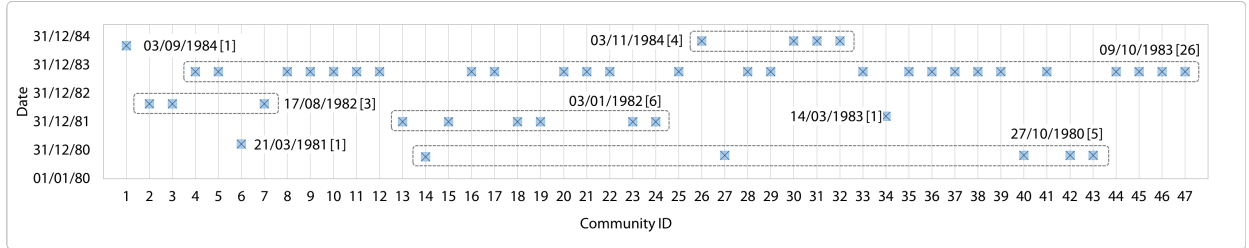


Figure 11: Date of maximum flow reduction by the combined NFM scenario at each of the 47 communities, with bracketed values indicating the number of communities sharing each date, showing 9 October 1983 as the most frequently occurring date across 26 communities.

3.3.2 Pareto front and sub-catchment contributions

The NSGA-II optimisation produced a Pareto front of non-dominated solutions across total NFM area and total damages avoided (Figure 13a; optimisation animation in Appendix B). At smaller NFM areas, incremental additions yield large gains in avoided damages, producing a steep initial gradient that flattens towards an upper bound of £51.3 million. Notably, solutions achieving damages avoided comparable to the maximum combined scenario are identified at 29.3 km² rather than the full 48.5 km², a 39.6% reduction in NFM area for near-equivalent benefit.

Figure 13b maps each sub-catchment by the percentage of Pareto-front solutions in which it is selected. High-contributing sub-catchments appear across a wide range of portfolios, indicating reliable benefit, whereas low-contributing ones appear only at the upper end of the front where

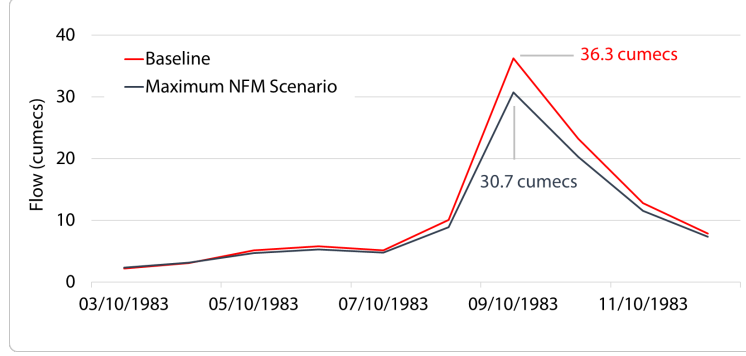


Figure 12: Baseline and maximum NFM scenario hydrographs at the catchment outlet for the selected 10-day optimisation event (3–12 October 1983), showing a reduction in peak flow from 36.3 to 30.7 cumecs. The event was extracted from a 5-year-long simulation (1980–1984).

larger areas are considered. The distribution is spatially non-uniform, reflecting the influence of sub-catchment location, drainage area, and proximity to at-risk communities on damage reduction.

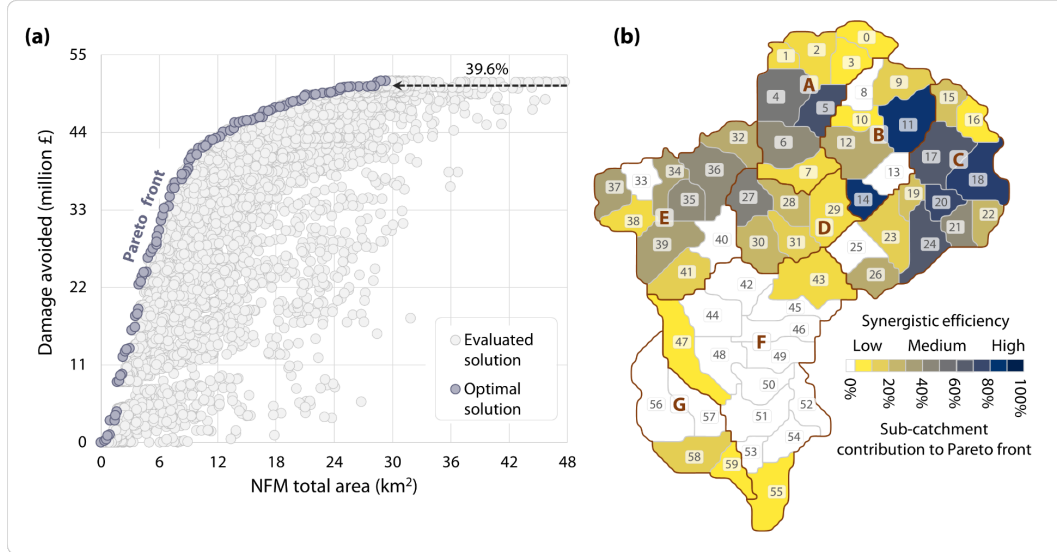


Figure 13: (a) Pareto front showing the trade-off between total NFM area and damages avoided across all evaluated and optimal solutions, with the 39.6% area reduction annotated, and (b) spatial map of sub-catchment synergistic efficiency, indicating the percentage contribution of each sub-catchment to Pareto front solutions across WFD management units A to G.

3.4 High-performing optimal solutions

The Pareto front comprises 100 non-dominated solutions spanning approximately 0.7 to 30 km² and £1 million to £47 million damage avoided (Figure 14a). Applying the $BCR \geq 1$ and $MBCR \geq 3$ thresholds (Figure 14b) identified 30 high-performing solutions occupying the steep upper-left portion of the front. Beyond approximately 21 km², both ratios fall below the threshold, indicating diminishing returns.

Across these 30 solutions, a small number of sub-catchments in WFD units B and C, in the

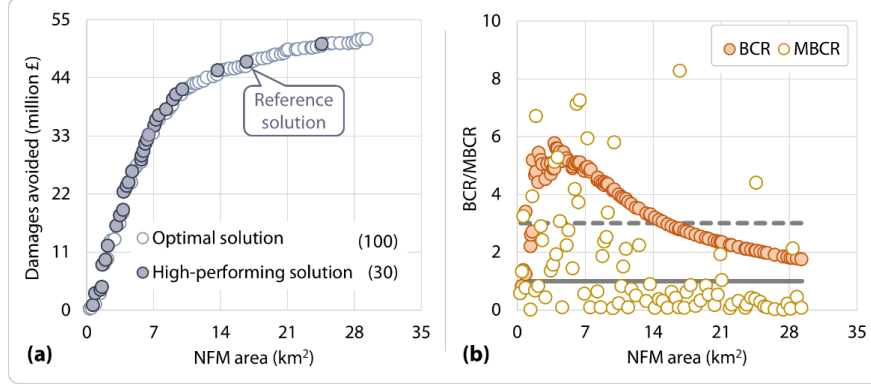


Figure 14: Pareto front of optimisation results showing (a) the trade-off between total NFM area and damages avoided for 100 optimal solutions and 30 high-performing solutions, and (b) BCR and MBCR values across all optimal solutions with threshold lines at BCR = 1 and MBCR = 3.

central and eastern catchment, show high synergistic efficiency and appear in most solutions, while those in the southern reaches (units F and G) contribute little (Figure 15a). The selection matrix (Figure 15c) confirms sub-catchments 14, 11, 18, 5, 20, and 17 as selected in up to 25 of the 30 solutions, establishing them as the most consistently beneficial locations.

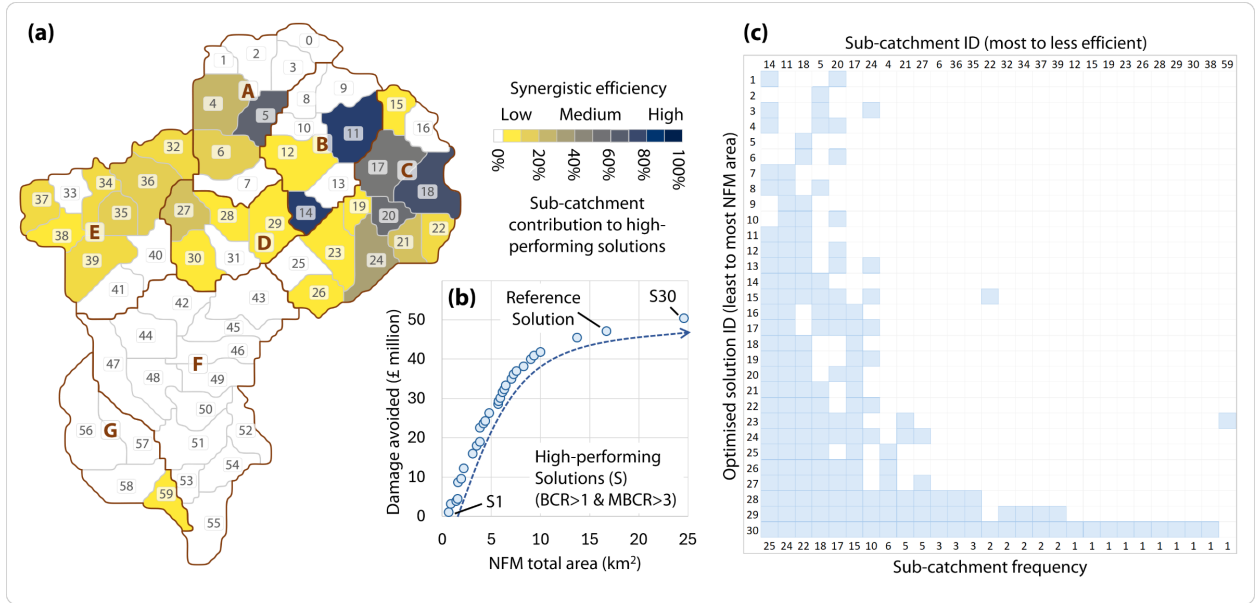


Figure 15: High-performing solutions showing (a) spatial map of sub-catchment synergistic efficiency (i.e. count of intervention usage) across the 30 high-performing solutions, (b) filtered Pareto front showing damages avoided against total NFM area for the 30 high-performing solutions, and (c) sub-catchment selection matrix for each high-performing solution ordered by total NFM area. The reference solution is considered in detail in Figure 16.

The reference solution (16.8 km²) is shown in Figure 16. Improved soil dominates the selected sub-catchments, with woodland secondary and RAF and FPR negligible (Figure 16b). Attenuated volumes and damages avoided concentrate along the main river and major tributary corridor through the mid-catchment (Figure 16a), giving approximately £48 million avoided across all 47

communities (Figure 16c). The progression across all 30 solutions is described in Appendix A.12 and animated in Appendix C.

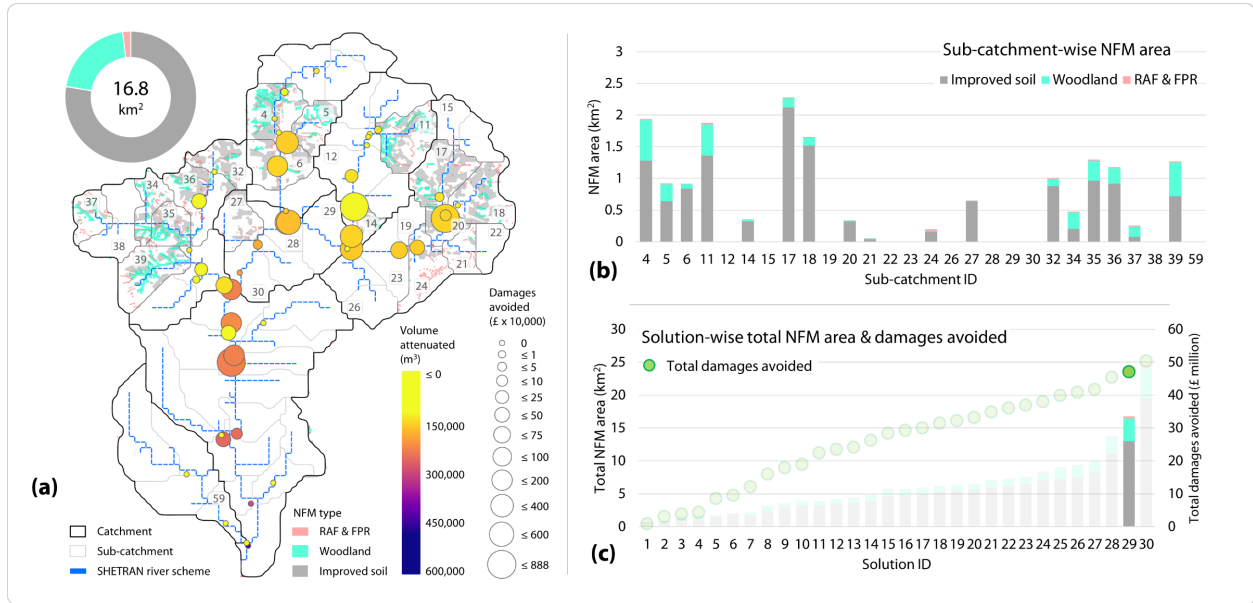


Figure 16: Spatial distribution of NFM types, volume attenuated, and damages avoided at each community for the reference solution (16.8 km²), showing (a) spatial map of NFM placement and community-level outcomes, (b) sub-catchment-wise NFM area composition by intervention type, and (c) total NFM area and damages avoided across all 30 high-performing solutions, with the reference solution being highlighted.

3.5 Individual NFM sub-catchment evaluation

Figure 17 distinguishes sub-catchments that perform well in isolation from those that contribute most to combination. The highest individual BCR values concentrate in WFD units B and C, with sub-catchments 11, 17, and 18 reaching up to 5.2 (Figure 17a). Unit A shows moderate values of 1.2 to 4.2, while lower-catchment sub-catchments (units D to G) return BCR below 1.0 or zero, yielding negligible damages avoided in isolation.

Synergistic efficiency broadly follows this pattern (Figure 17b), but several sub-catchments with only moderate individual BCR show high synergistic efficiency, indicating that their value lies in combination rather than standalone performance. Units F and G remain low on both measures, confirming their limited contribution either individually or combined.

3.6 Uncertainty in NFM evaluation and optimal event duration

Figure 18 summarises the terminology distinguishing simulation type (long-run versus short event-run) from damage-calculation method (growth-curve versus event-scaling). Figure 19 compares total damages avoided from the event-based simulations against the full 35-year benchmark for the 30 high-performing solutions. The event-based approach consistently overestimates damages avoided relative to the long-run benchmark, with the divergence widening as NFM area increases,

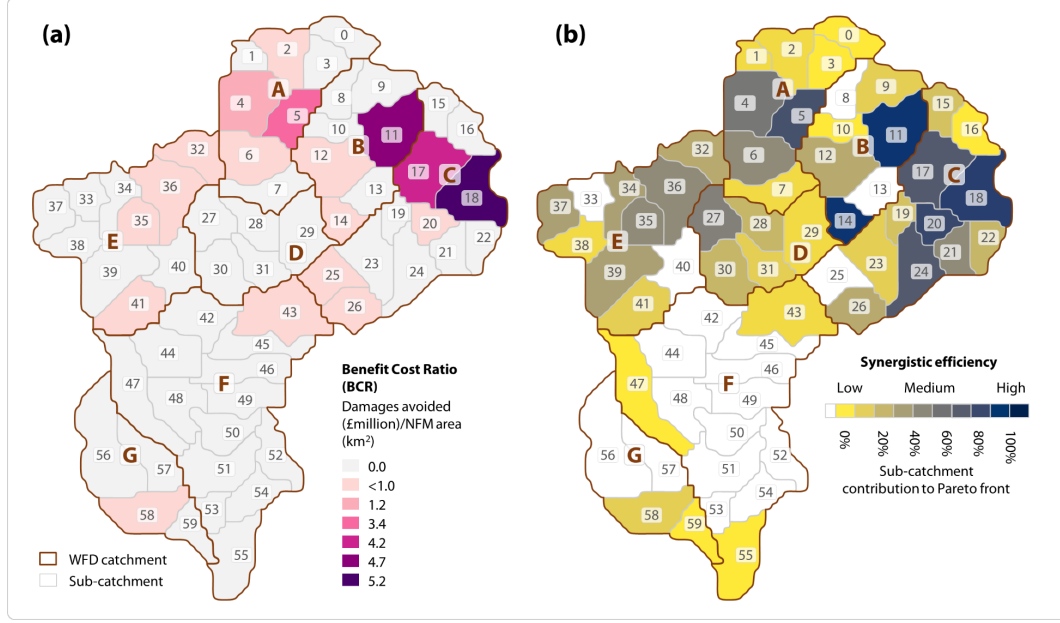


Figure 17: Sub-catchment-wise (a) individual benefit-cost ratio (BCR), calculated as damages avoided (£ million) per NFM area (km²), and (b) synergistic efficiency, representing the percentage contribution of each sub-catchment to the Pareto front solutions.

from under £2 million below 2 km² to approximately £14 million at 16.8 km². Event-based estimates range from approximately £3 million to £48 million, against £2 million to £33 million for the long-run benchmark. The relative ordering of solutions is nonetheless broadly preserved, confirming that event-based optimisation reliably identifies the same high-performing solutions and their ranking.

To attribute this bias, Figure 20 compares the benchmark growth-curve method against the event-scaling method applied to the same long-run simulations, isolating the error due to scaling from that due to baseline antecedent conditions. Although the 10-day event-based scaling method overestimates damages avoided (Figure 19), the same scaling applied to an event extracted from the long-run simulation underestimates them by up to approximately 20% (Figure 20b).

Extending the pre-event duration from 10 days to 6 months progressively reduces both the magnitude and variability of the bias (Figure 21), with the 3-month and 6-month durations closely approximating the long-run – Event method estimate (pre-duration hydrographs in Figure S6 (Appendix A.13) and bias statistics in Figure S7 (Appendix A.14)).

4 Discussion

4.1 Model performance

The SHETRAN baseline model achieved an NSE of 0.78 at the Bury Ground gauge over the 2001 to 2014 evaluation period, consistent with comparable physically based studies of UK NFM catchments, where NSE values of 0.78 to 0.84 indicate strong performance (Lavers et al., 2022; Zhu et al., 2025b). It is acknowledged that evaluation at a single gauge limits assessment of spatial variability

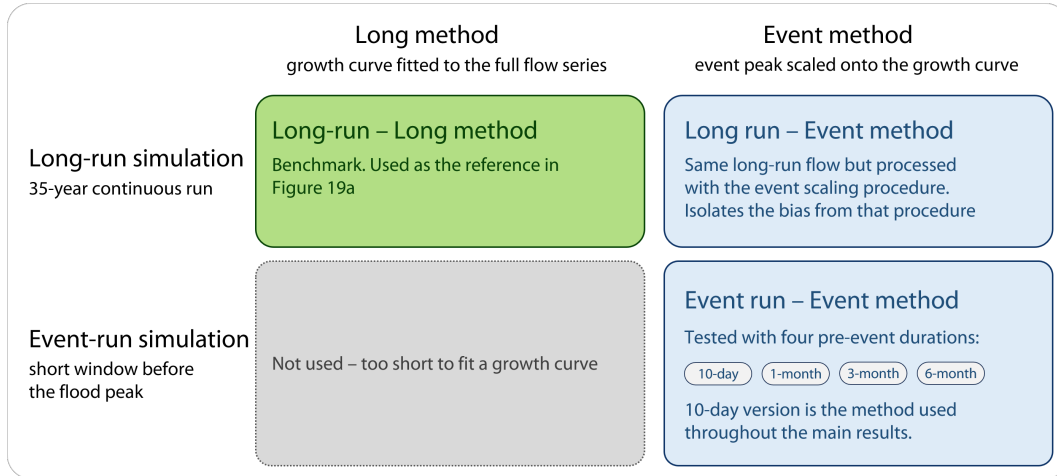


Figure 18: Terminology used for the damage-estimation methods, distinguishing the simulation type (long-run vs short event-run) from the damage-calculation method (Long method: growth curve fitted directly to the flow series; Event method: event peak scaled onto the growth curve), and indicating which method pairing is compared in Figure 19, Figure 20 and Figure 21.

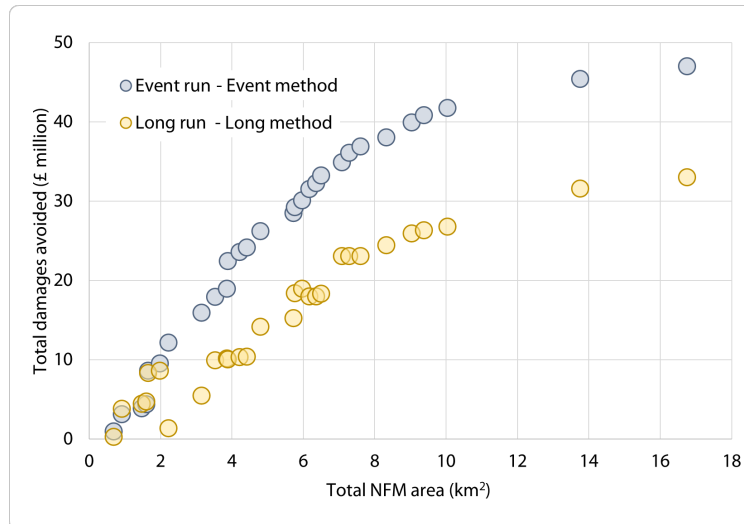


Figure 19: Comparison of total damages avoided, estimated from event-based and long-run SHETRAN simulations, for the 30 high-performing solutions, showing consistent overestimation by the event-based approach relative to the long-run benchmark across NFM areas.

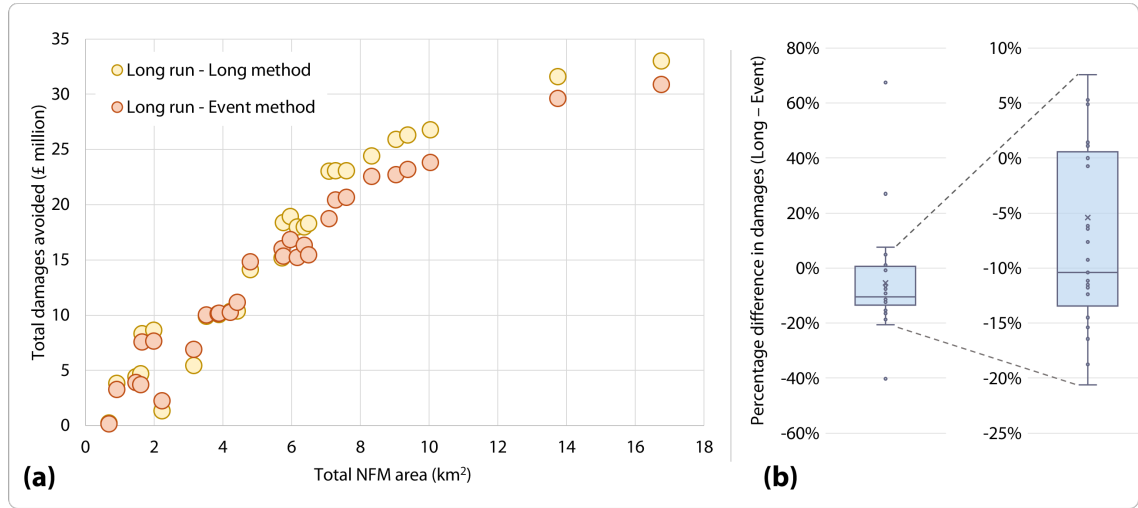


Figure 20: Comparison of damages avoided estimated by the long-run long method and long-run event method for the 30 high-performing solutions, showing (a) absolute values against total NFM area and (b) box plot of percentage difference between the two methods, indicating a systematic underestimation of up to 20% by the event-based scaling approach.

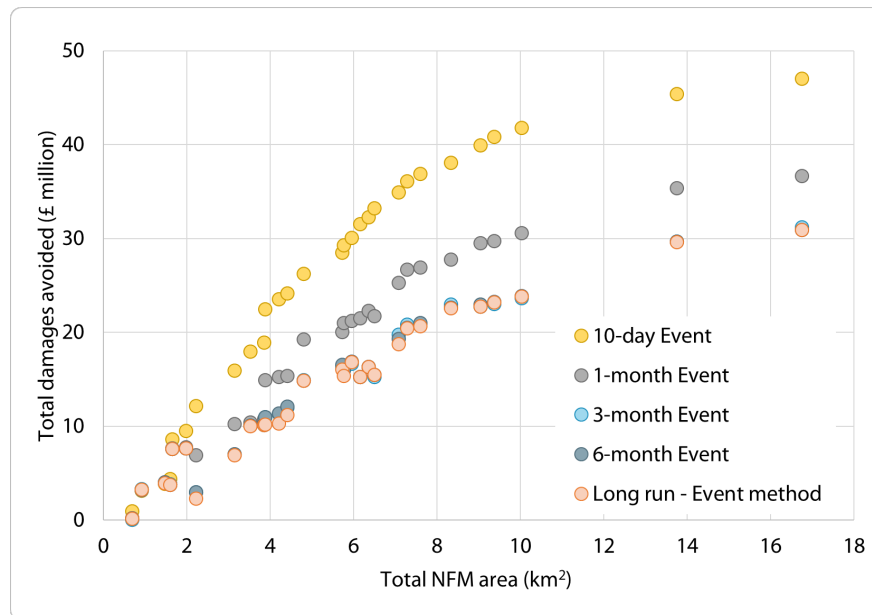


Figure 21: Total damages avoided against total NFM area for the 30 high-performing solutions across four pre-event simulation durations, showing progressive convergence towards the long-run estimate with increasing event duration.

in model performance across the catchment, and that the daily timestep may not fully capture the flashy sub-daily flow dynamics characteristic of the Upper Irwell. Nonetheless, the model’s ability to reproduce the timing and magnitude of peak flows across a range of conditions over the evaluation period supports its suitability for subsequent NFM scenario analysis and optimisation.

4.2 NFM hydrological effectiveness at the catchment scale

The maximum peak flow reductions by individual NFM types ranged from negligible for RAFs and FPRs to approximately 10% for woodland and 10.4% for improved soil, with the combined scenario reaching 15.3%. These are broadly consistent with comparable UK catchment-scale studies. [Ferguson and Fenner \(2020\)](#) reported reductions of 8.5% to 15.1% depending on event magnitude for a combined scenario in the Calder Valley, [Kingsbury-Smith et al. \(2023\)](#) found up to 10% for woodland during a 100-year event in a 38 km² North Yorkshire catchment, and [Zhu et al. \(2025b\)](#) reported overland flow peak reductions of 4.2% to 16.0% across storm events in a UK upland catchment, with woodland and soil interventions providing the most consistent reduction.

Improved soil produced the greatest individual peak reduction despite woodland’s higher volume reduction per unit area (Table 2), reflecting its dominant footprint (36.0 km² against 10.7 km²). At the catchment scale, aggregate extent can therefore outweigh unit-area efficiency in determining overall impact. The pattern of reductions across the 47 communities, tracking the distribution of baseline flows, indicates that effectiveness at each community is strongly conditioned by catchment position and upstream contributing area alongside the characteristics of the measures themselves.

The negligible reductions from RAFs reflect model representation rather than intrinsic ineffectiveness. In practice, RAFs and leaky barriers have a draw-off height above the channel bed, engaging storage only once flows exceed it and reserving capacity for peak attenuation ([Metcalf et al., 2017](#); [Nicholson et al., 2020](#)). SHETRAN instead represents them as static storage filling from rainfall onset, while the daily timestep averages out the sub-daily store-and-release cycle over which RAFs operate, so meaningful hourly peak reductions appear negligible in daily mean flow. Their contribution is therefore likely underestimated, warranting sub-daily modelling in future work. Notably, FPRs achieve higher volume reduction per unit area than RAFs (18,557 against 13,498 m³/km²) despite identical representation and near-identical extent (0.93 against 0.91 km²), attributable to their position adjacent to the channel (Figure 3b) and greater hydraulic connectivity during flood-generating events.

4.3 Sub-additive nature of combined NFM

The combined scenario achieved a maximum peak reduction of 15.3%, less than the arithmetic sum of the individual maxima. Figure S3 (Appendix A.10) shows that the volumetric reductions for each intervention type peak at different times across the 35-year record, confirming that their maxima are not temporally coincident, consistent with comparable catchment-scale studies ([Zhu et al., 2025b](#)). This has a direct implication for appraisal: estimating combined benefits by summing individual impacts systematically overestimates catchment-scale effectiveness, reinforcing the case

for integrated frameworks that simulate all interventions simultaneously rather than aggregating by type.

4.4 Importance of a fully distributed hydrological model and multi-objective optimisation

Most catchment-scale NFM studies, including distributed approaches such as SD-TOPMODEL, assess performance at the catchment outlet or a few sub-catchment outlets (Hill et al., 2023; Zhu et al., 2025b). This is inadequate for an optimisation framework evaluating damages avoided at dozens of distributed communities, each fed by a distinct upstream contributing area, where accuracy depends on extracting flows at the river link immediately upstream of each community rather than at an aggregated location conflating hydrologically unrelated contributions. SHETRAN generates discharge at every river link, allowing each community to be assigned to its hydrologically representative upstream location (Section 2.2.1), a coupling not achievable with lumped or semi-distributed approaches.

Existing studies also predominantly evaluate a limited number of manually defined configurations (Badjana et al., 2023; Kingsbury-Smith et al., 2023), which cannot systematically explore the vast design space arising when interventions may be placed across many locations, and may not yield cost-effective configurations (Ur Rehman et al., 2024). With 60 sub-catchments, the 2^{60} possible combinations are computationally infeasible to evaluate exhaustively. Coupling NSGA-II with SHETRAN navigates this space to identify the Pareto-optimal set. As shown in Section 3, the optimisation matched the maximum combined scenario’s damage avoidance using only 29.3 km², a 39.6% area reduction, confirming that spatial configuration, not total extent, is the primary determinant of community-scale flood damage reduction. This combination of a fully distributed model, multi-objective optimisation, and community-scale damage assessment is the key methodological advance of this study.

4.5 Difference in synergistic and individual efficiency of NFM sub-catchments

Figure 22 illustrates the mechanism distinguishing individual from synergistic efficiency. At Community 16, sub-catchment 14 alone attenuates only 565 m³ and yields £0.05M damage avoided, placing the community on the flat lower portion of its volume-damage curve, whereas sub-catchment 11 alone attenuates 3,696 m³ and delivers £4.5M damage avoided, near the steep portion of the curve. When the two are combined, the additional 565 m³ from sub-catchment 14 pushes total attenuation past the threshold at which the community’s maximum avoidable damage of £6.6M is reached, contributing a further £2.1M damage reduction. Sub-catchment 14 therefore has a low individual BCR but high synergistic value, because the non-linear volume-damage relationship amplifies its contribution when combined with sub-catchment 11. Selecting sub-catchments on individual BCR alone would systematically overlook those whose value is contingent on their role within a broader portfolio, reinforcing the necessity of the multi-objective optimisation approach.

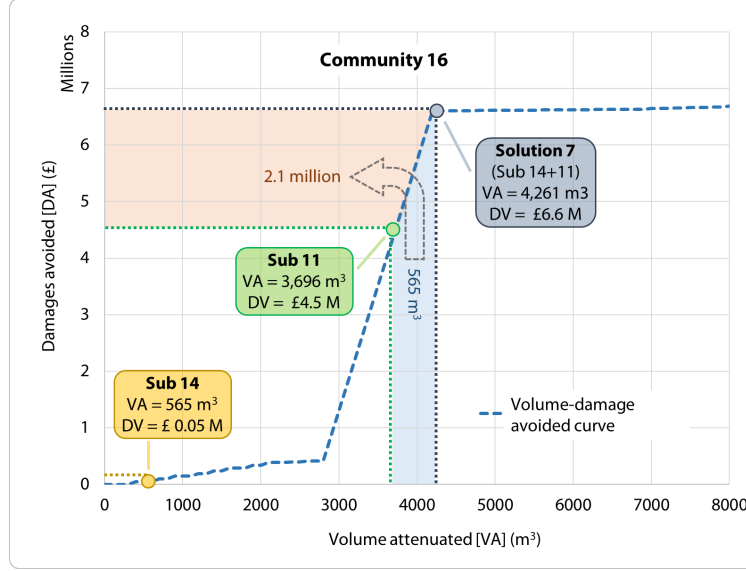


Figure 22: Volume-damage-avoided curve for Community 16, illustrating the individual contributions of sub-catchments 14 and 11 and their combined effect, which reaches the maximum avoidable damage at this community.

4.6 Value of strategic NFM placement

The cost-effective placement of NFM is spatially heterogeneous across the catchment (Figure 17b), governed by three interacting factors. First, the non-linear synergistic effect (Figure 22), whereby high-yielding sub-catchments in WFD units B and C, including 11, 14, 18, and 20, generate disproportionate avoided damage by positioning communities on the steep portion of their volume-damage curves. Second, the flood risk profile of the communities served (Figure S8, Appendix A.15): those in units F and G either have few at-risk properties or require very large attenuation volumes relative to their high baseline flows to shift flood risk category, making them inherently difficult to serve cost-effectively. Third, sub-catchments in the upper and mid-catchment exert cumulative influence on all downstream communities as their attenuation propagates through the channel network, whereas lower-catchment sub-catchments influence only the few communities immediately downstream, constraining their contribution to the Pareto front. This finding provides quantitative support for the principle that upper-catchment NFM delivers the broadest catchment-wide benefit, and that spatially explicit approaches are essential for identifying where investment yields the greatest flood risk reduction (Bagheri-Gavkosh et al., 2025; Ferguson and Fenner, 2020).

4.7 Uncertainty attribution and optimal event duration

The event-based optimisation consistently overestimates total damages avoided relative to the 35-year benchmark (Figure 19), and this bias originates in the antecedent conditions supplied to the short event runs (Appendix A.7, steps 2 and 3). Because all event simulations are initialised from baseline states, the maximum NFM scenario enters the event without the long-term storage evolution of an established NFM system and produces a smaller peak reduction than its long-

run counterpart. This compresses the normalising envelope ($Q_{baseline-event} - Q_{NFM-max-event}$) in Equation S1 (Appendix A.7), mapping candidate solutions disproportionately close to the maximum NFM growth curve in Equation S2 (Appendix A.7) and thereby inflating the reduction factor (Appendix A.7, Equation S3) and the damages avoided derived from it. The absolute bias grows with NFM area, since larger configurations depend more heavily on the antecedent storage state that the short run fails to represent.

A second, smaller bias is inherent to the scaling method itself (Appendix A.7, steps 6 and 7). Applied to the same long-run simulations, so that antecedent effects are excluded by construction, the uniform scalar adjustment underestimates damages avoided up to 20% (Figure 20), because NFM flow reduction varies non-linearly across return periods and cannot be captured by a single factor applied uniformly across the growth curve. The two biases therefore act in opposite directions, with the antecedent-condition component dominating at the 10-day duration.

The scaling bias is largely unavoidable, since growth curves cannot be fitted for candidate solutions during optimisation (Figure 18). The antecedent-condition component, however, can be minimised: as pre-event duration extends, NFM states approach their long-run equilibrium, and the 3-month and 6-month event runs converge on the long-run event-method estimate (Figure 21). Since a 6-month duration offers only marginal further tightening (Figure S7, Appendix A.14) at roughly double the computational cost, the 3-month duration is identified as optimal. The residual bias is then the scaling component alone, a modest and conservative underestimate. Since ordering is maintained across all durations, the framework is best applied as a strategic tool for identifying priority configurations rather than precise absolute damages. The optimal duration may differ in other catchments, and users are advised to repeat this uncertainty analysis when transferring the framework. Surrogate or physics-informed models could eventually remove the event-based constraint altogether, though representing NFM processes within them remains challenging.

A further contribution to scatter arises from the discretised structure of the volume-damage curves, built from property transitions across flood-risk bands (Figure S8, Appendix A.15). Although damages are interpolated within bands, sharp transitions persist in the curves (Figure 7). Near these transitions, even a small difference in volume attenuation between the event-based and long-run simulations produces a disproportionately large difference in damages avoided (Figure 23).

The uniform spatial rainfall assumption may introduce some uncertainty given the orographic gradients of Pennine catchments. However, because bias decreases consistently with pre-event duration and the 3-month spin-up closely approximates the benchmark, antecedent hydrological state rather than spatial rainfall distribution appears to be the dominant source of uncertainty, and the spatial averaging assumption has negligible influence on the relative ranking of solutions.

Finally, the EA NFM Storage Tool applies FEH-based relationships not specifically developed for process-based model outputs, and its assumptions on event shape and linear storage routing introduce some conceptual inconsistency when applied to SHETRAN attenuation volumes. This is acceptable for strategic screening, but future work should replace this step by linking river flows to a 2D hydraulic model (Green et al., 2025) to derive flood extent and depth at each community,

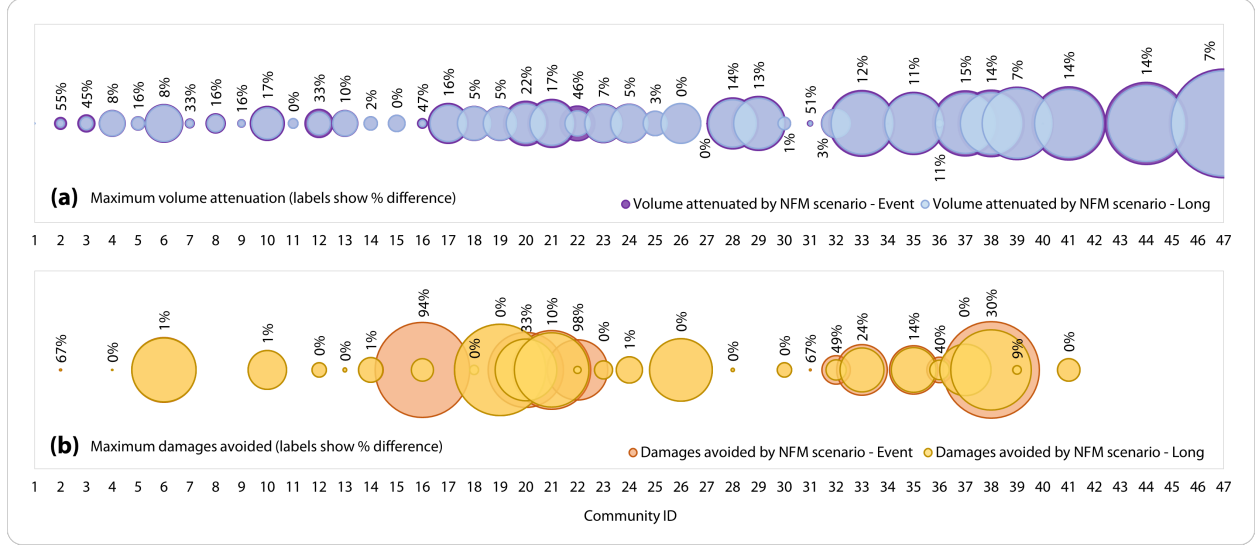


Figure 23: Community-wise comparison of maximum volume attenuation (a) and maximum damages avoided (b) between event-based and long-run SHETRAN simulations for the maximum NFM scenario, with percentage differences labelled at each community.

with damages from depth-damage curves (Penning-Rowsell et al., 2014). This would also allow climate change impacts to be represented, giving a fuller picture of how risk evolves beyond fixed risk-band categories.

4.8 Implications for NFM planning and policy

The framework directly addresses the disconnect between physically based modelling and economic appraisal identified as a key barrier to evidence-based NFM investment (Carter et al., 2024). By linking simulated hydrological responses to community-level property damage and producing Pareto-optimal solutions with associated BCR and MBCR metrics, it generates the structure of outputs required for UK appraisal under FCERM-AG and DEFRA Partnership Funding. Once NFM areas are translated into costs, this gives catchment managers and funders a transparent, reproducible basis for prioritising investment that scenario-based approaches cannot provide.

The sub-catchment results further show that individual BCR assessment alone cannot identify optimal portfolios, since low-performing sub-catchments may deliver substantial synergistic benefit when strategically combined (Bagheri-Gavkosh et al., 2025). That strategic placement in the current study achieves the same damage avoidance as full implementation with a 39.6% smaller intervention area is exactly the efficiency evidence the appraisal system needs to justify catchment-scale NFM funding, marking a shift from isolated intervention assessment to portfolio-level optimisation.

5 Conclusion

This study establishes that coupling a fully distributed, process-based hydrological model with multi-objective optimisation and community-scale damage assessment provides a physically cred-

ible and economically relevant framework for identifying cost-effective NFM configurations at the catchment scale. The distributed structure of SHETRAN is central, enabling spatially explicit representation of NFM features and accurate flow extraction at the river link upstream of each of the 47 communities, which in turn allows NFM locations to be formulated as sub-catchment decision variables and community risk as optimisation objectives, a capability not achievable with semi-distributed or lumped models.

NFM effectiveness at the catchment scale is governed by the spatial extent of available opportunities, the temporal non-coincidence of peak reductions across intervention types, and the non-linear interaction between sub-catchments and community-level flood risk. Combined benefits therefore cannot be estimated by summing individual impacts, and sub-catchments with low individual performance may deliver substantial synergistic benefit within a coordinated portfolio. The optimisation matches the damage avoidance of full implementation with 39.6% less intervention area, confirming that strategic spatial placement, rather than total extent, determines where NFM investment delivers greatest value.

Finally, the analysis shows that event-based optimisation reliably preserves the relative ranking of solutions, with a 3-month pre-event simulation sufficient to constrain the associated bias, offering a practical protocol for applying this framework in other catchments.

Acknowledgement

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Conflicts of interest

The authors declare no conflicts of interest.

Data availability statement

The Python optimisation framework developed for this study (RAINS: Resilient and Affordable Implementation of Natural flood management using SHETRAN) is openly available at <https://github.com/asidurrehman/rains>. Environment Agency Property Reports and NFM Storage Tool outputs were provided under licence and are available from the Environment Agency on reasonable request.

A Supplementary information

A.1 Catchment characteristics

The catchment drains through the Rossendale valley, with steep, confined valleys and a dense tributary network including Limy Water, Whitewell Brook, and the River Ogden. Beyond the dominant pasture, grassland, and upland moorland cover, patches of riparian and plantation woodland occur across the catchment. River corridors along the valley floors are frequently constrained by culverts, retaining walls, and weirs, reflecting a strong industrial legacy (Carter et al., 2024). The impermeable bedrock comprises Carboniferous Millstone Grit and Coal Measures, which together with peat and glacial deposits produce high surface-runoff connectivity (Environment Agency, 2009). Storm Eva was preceded earlier in December 2015 by Storm Desmond, which caused widespread flooding across Northwest England.

A.2 Model calibration

Model performance was assessed using the Nash-Sutcliffe Efficiency (NSE) against observed daily discharge at the Bury Ground gauge (NRFA station 69044) over 2001 to 2014, a period selected because of known data reliability concerns before 2001. Calibration was performed through 500 parallelised runs optimising the saturated hydraulic conductivity and saturated water content of the topsoil (medium texture) and the bedrock (moderately productive aquifer through pores or fractures), together with the potential evaporation and surface roughness coefficients for the principal land cover classes: grassland, shrubland, and built-up area. Remaining parameters were fixed from the national datasets described in Lewis (2016), limiting the number of free parameters and reducing the risk of overfitting. The calibrated set is applied from 1980 for NFM impact assessment and antecedent condition initialisation, since these parameters govern physical process representations that are not period dependent. Observed discharge data are available at <https://nrfa.ceh.ac.uk/data/station/info/69044>.

A.3 Improved soil allocation algorithm

Each NFM polygon is processed sequentially, and its overlap with the 200 m grid cells is calculated. Where a polygon is too small to justify a full cell conversion, its area is carried forward to the next adjacent polygon. For larger polygons, the number of cells to convert is estimated proportionally, with candidate cells selected based on the degree of overlap and the polygon’s spatial orientation. Where a residual area exceeds 50% of a cell, that cell is assigned the improved soil type, and any over-assignment is recorded as a negative balance for subtraction from the next polygon’s allocation.

A.4 NFM sensitivity analysis

The four NFM types vary considerably in their spatial extent across the catchment. To assess how sensitive the hydrological response at the catchment outlet is to intervention coverage, two

bounding conditions were examined: the maximum available extent, in which all grid cells occupied by the relevant NFM opportunity layer are implemented at full coverage, and a hypothetical whole-catchment scenario, in which the entire model domain is assigned the given NFM type (results in Figure S2, Appendix A.9).

A.5 Dominant storage processes by NFM type

For RAFs and FPRs, the key processes are surface storage through direct ponding and enhanced subsurface infiltration. For woodland, the principal processes are canopy and soil evaporation, plant transpiration, canopy storage, and subsurface storage promoted by root-zone infiltration. For improved soil, the dominant processes are subsurface storage, arising from the substantially increased moisture storage capacity of the peat-like soil parameters, which delays the onset of saturation and reduces surface runoff generation, and increased soil evaporation driven by higher moisture retention.

A.6 Sub-catchment delineation

Delineation was performed using ArcGIS Pro’s Spatial Analyst Hydrology toolbox (ESRI, 2026). Flow direction was computed using the D8 algorithm, followed by flow accumulation with a threshold of 15 cells, matching the criterion used by SHETRAN for river network generation. Confluence points were then used to extract individual sub-catchments, with post-processing merging very small sub-catchments and dividing excessively large ones to balance spatial resolution against computational tractability.

A.7 Damage-avoided calculation procedure

Following the framework summarised in Section 2.6.5 and Figure 6, the calculation proceeds through the following nine steps.

- (i) *Long-term baseline and maximum NFM simulations:* SHETRAN is run for 35 years under both the baseline and maximum NFM scenarios, producing long-term discharge series at each community ($Q_{baseline-long}$, $Q_{NFM-max-long}$).
- (ii) *Short event simulations:* Both the baseline ($Q_{baseline-event}$) and maximum NFM ($Q_{NFM-max-event}$) scenarios are simulated for the selected 10-day event using initial conditions extracted from the baseline long run at the event onset date.
- (iii) *Mapping flows to the event peak:* All four series are referenced to the peak flow of the 10-day event (Figure 6b). Because $Q_{NFM-max-event}$ receives baseline initial conditions rather than long-run NFM conditions, its peak flow reduction is expected to be smaller than that observed in $Q_{NFM-max-long}$.

- (iv) *Flow frequency analysis*: A Generalised Extreme Value (GEV) distribution is fitted to $Q_{baseline-long}$ and $Q_{NFM-max-long}$ to produce flow frequency growth curves ($GC_{baseline}$ and $GC_{NFM-max}$) at 5-, 20-, 50-, 100-, and 200-year return periods (Figure 6c).
- (v) *Candidate NFM scenario simulation*: An NFM sub-catchment combination ($Q_{NFM-cand-event}$), representative of solutions generated during optimisation, is simulated for the 10-day event using baseline initial conditions.
- (vi) *Event-based adjustment for the candidate NFM scenario*: $Q_{NFM-cand-event}$ is adjusted relative to $Q_{baseline-event}$ and $Q_{NFM-max-event}$ using:

$$Q_{NFM-cand-event-adj} = \left(\frac{Q_{NFM-cand-event} - Q_{NFM-max-event}}{Q_{baseline-event} - Q_{NFM-max-event}} \right) \quad (S1)$$

- (vii) *Reflecting the adjustment on the growth curves*: The adjusted event-based values are mapped onto the long-term growth curves.

$$GC_{NFM-cand} = ((GC_{baseline} - GC_{NFM-max}) \times Q_{NFM-cand-event-adj}) + GC_{NFM-max} \quad (S2)$$

where $Q_{NFM-cand-event-adj}$ is a scalar adjustment factor applied uniformly across all return periods of the growth curve.

- (viii) *Reduction factor calculation*: The reduction factor RF , representing the fractional reduction in baseline flows attributable to the candidate NFM combination, is given by:

$$RF = 1 - \left(\frac{GC_{NFM-candidate}}{GC_{baseline}} \right) \quad (S3)$$

RF is applied to the hydrograph storage volumes for each return period and community, taken from the EA NFM Storage Tool, to estimate the volume attenuation for that scenario. The maximum volume attenuation is then normalised by the maximum possible attenuation at each community to obtain an attenuation fraction (Figure 6e).

- (ix) *Damage avoided calculation*: The attenuation fraction at each community is used to estimate damages avoided using the EA Property Report and NFM Storage Tool methodology, with property damages linearly interpolated across the volume attenuation range to give continuous estimates (Figures 6f, 7) (Ur Rehman et al., 2025b). Total damages avoided is the sum of reductions across all communities.



Figure S1: Simulated baseline and maximum NFM hydrographs at the catchment outlet over the five-year period (1980–1984) for (a) RAFs, (b) floodplain reconnection, (c) woodland, (d) improved soil, and (e) all NFM combined, illustrating the peak flow attenuation achieved by each intervention type at its maximum available extent.



Figure S2: Sensitivity analysis comparing baseline, 100 percent grid-cells of maximum available, and hypothetical whole-catchment NFM hydrographs at the catchment outlet for (a) RAFs, (b) woodland, and (c) improved soil across representative short periods, and (d) whole-catchment comparison of all three NFM types.

A.8 Baseline and maximum NFM hydrographs by intervention type

A.9 Sensitivity analysis

A.10 Water storage and retention by NFM type

A.11 Community-wise maximum baseline flow

A.12 Progression of high-performing solutions

The progression of NFM configurations from least to most total area across the 30 high-performing solutions is illustrated in Figure S5, with an animation provided in Appendix C of the main document. Solutions 1 to 10 involve one to three sub-catchments concentrated in the central and upper-mid catchment, delivering targeted but modest damage avoidance, primarily along the main channel. From Solution 11 onwards, additional sub-catchments are progressively incorporated into upper tributaries and eastern parts of the catchment, with corresponding increases in both spatial coverage and total damages avoided. By Solution 30, NFM is distributed across a substantial proportion of the catchment, with the greatest community-level benefits remaining concentrated along the main Upper Irwell corridor and at key tributary confluences.

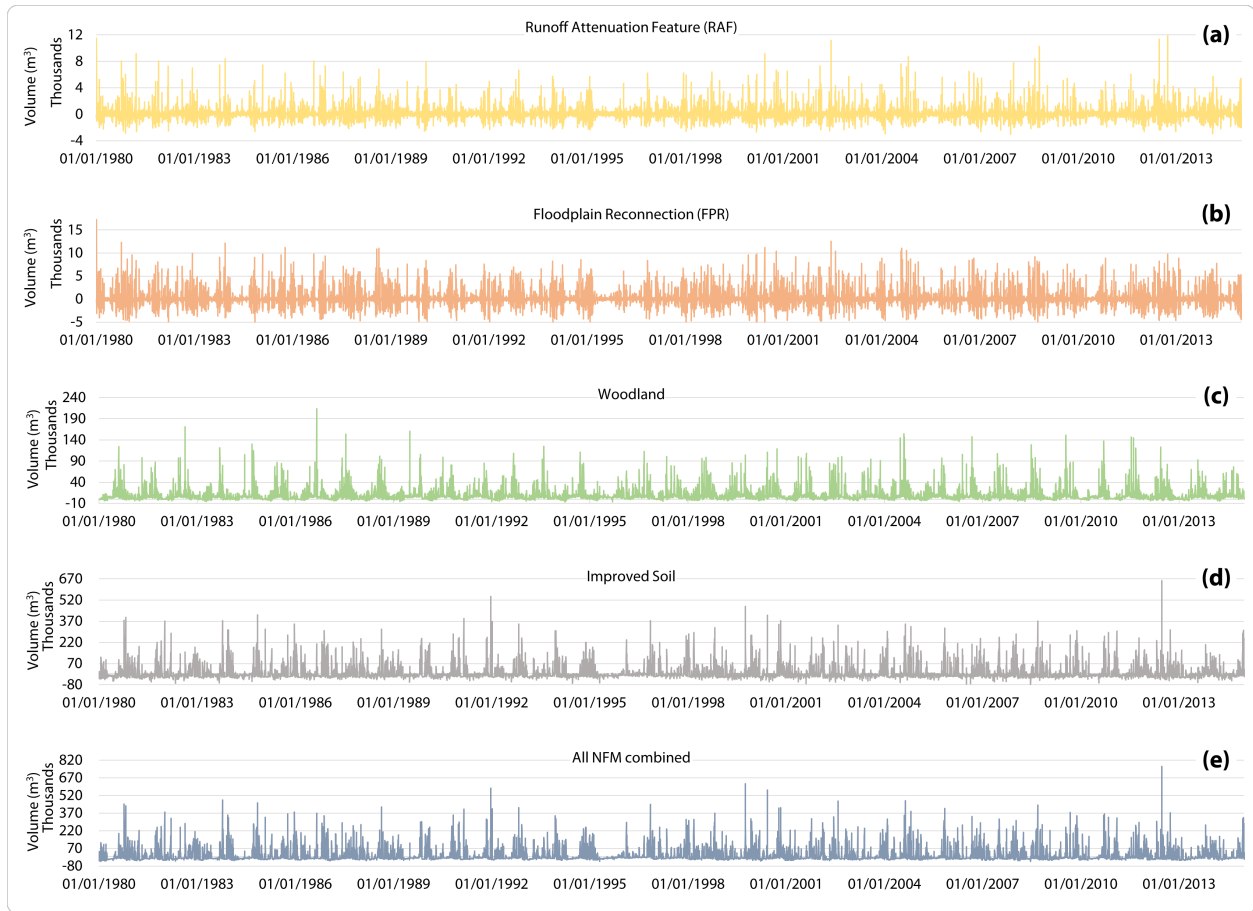


Figure S3: Daily volumetric difference between baseline and maximum NFM scenarios over the 35-year simulation period (1980–2014) for (a) RAFs, (b) floodplain reconnection, (c) woodland, (d) improved soil, and (e) all NFM combined, demonstrating the dominant storage contribution of improved soil and the temporal variability in volume retention across intervention types.

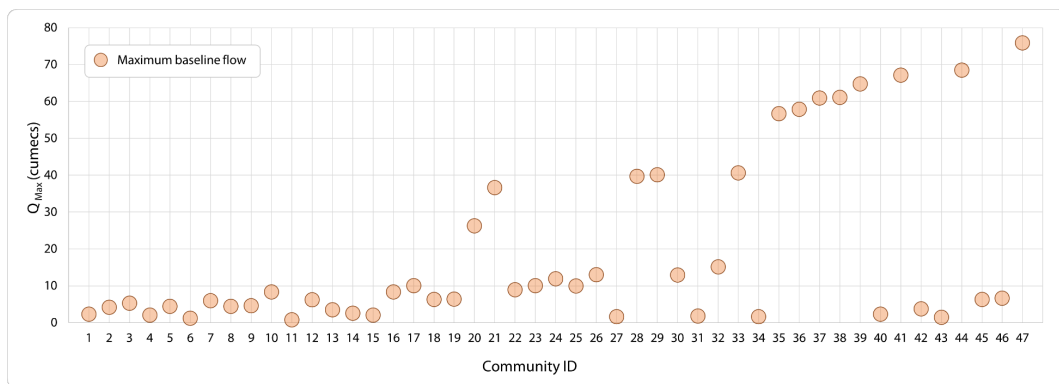


Figure S4: Maximum baseline peak flow at each of the 47 communities, showing substantial spatial variability ranging from below 5 cumecs at upper tributary communities to above 75 cumecs at the most downstream locations.

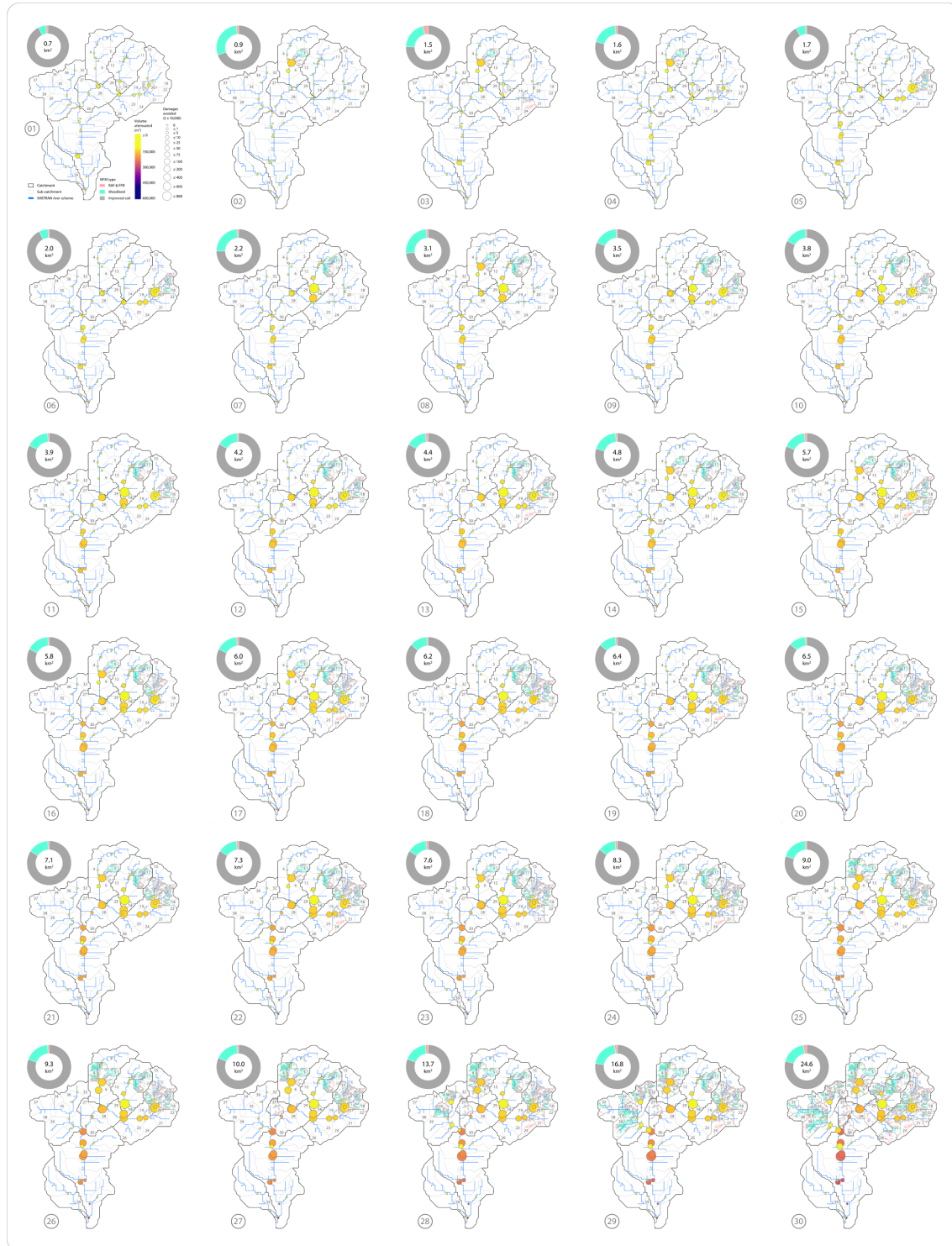


Figure S5: Spatial distribution of NFM placement and community-level damages avoided for each of the 30 high-performing solutions, ordered by increasing total NFM area (0.7 km² to 24.6 km²), illustrating the progressive expansion of selected sub-catchments and the corresponding growth in community-level damage avoidance along the main channel and tributaries.

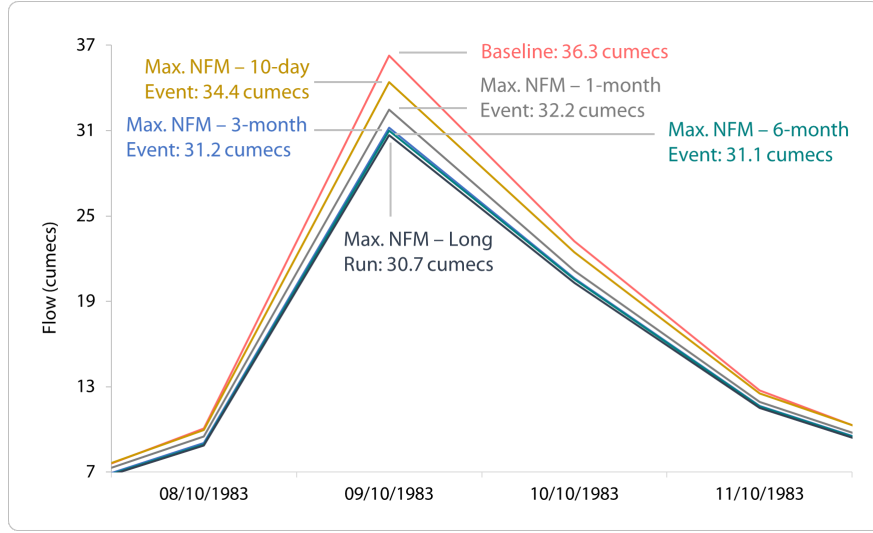


Figure S6: Catchment outlet hydrographs for the maximum NFM scenario simulated across five pre-event durations (10-day, 1-month, 3-month, 6-month, and long-run), showing convergence of peak flow towards the long-run result with increasing event duration.

A.13 Pre-duration hydrographs

A.14 Bias statistics

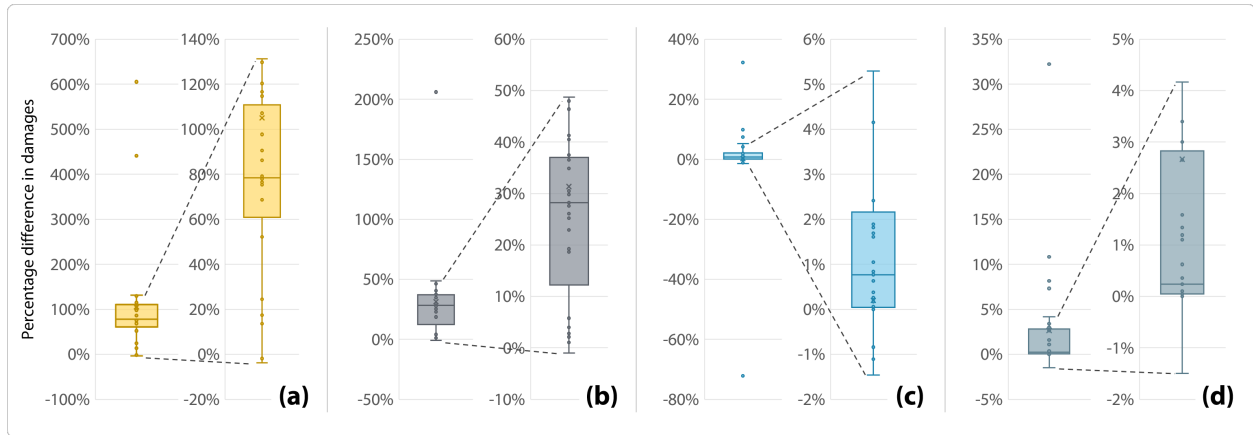


Figure S7: Box plots of percentage difference in damages avoided between event-based and long-run event-based estimates for the 30 high-performing solutions across four pre-event simulation durations: (a) 10-day, (b) 1-month, (c) 3-month, and (d) 6-month, showing progressive reduction in bias magnitude and variability with increasing pre-event duration.

A.15 Flood risk profile of the communities

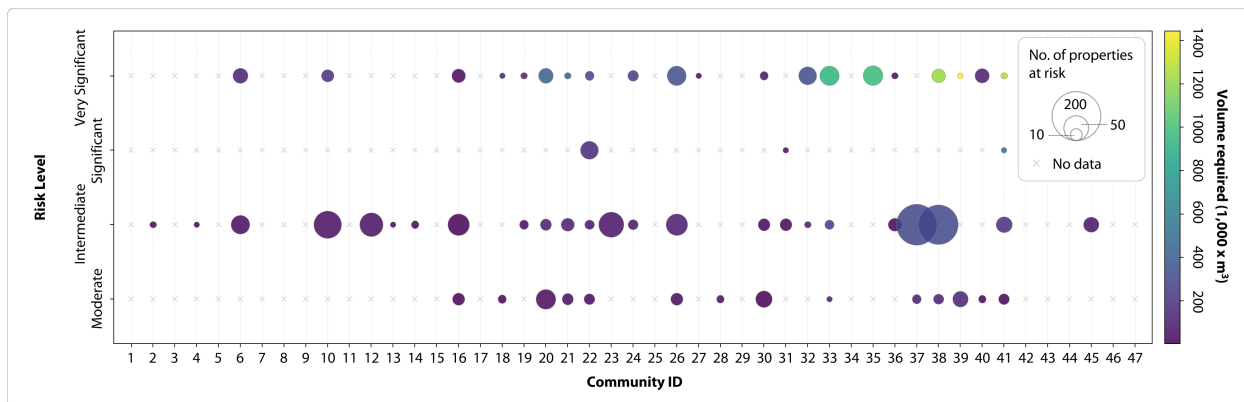


Figure S8: Communities at risk across the Upper Irwell catchment, showing flood risk level, number of at-risk properties (bubble size), and required storage volume for risk band transitions (bubble colour), illustrating the concentration of high-risk communities with large property counts in the mid- to lower catchment.

B Animation of NFM optimisation

Animated visualisation of the NSGA-II optimisation, showing the evolution of candidate NFM configurations and the Pareto front across successive generations. The animation is provided as a separate supplementary media file accompanying this manuscript.

C Animation of 30 high-performing solutions

Animated progression of the 30 high-performing solutions ordered by total NFM area, showing the spatial incorporation of sub-catchments and the corresponding increase in damages avoided. The animation is provided as a separate supplementary media file accompanying this manuscript.

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