Natural Environment Research Council

NATURAL FLOOD MANAGEMENT
RESEARCH PROGRAMME

Illustrating the value of presenting NERC NFM programme findings as effective volumes at flood peaks, flood damages avoided and learning on soil as an NFM tool

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Illustration of NFM effectiveness expressed as an *Effective Volume* at flood peaks

Flood risk management aims to maintain river-level below a critical threshold at locations where overtopping the banks would cause flooding. Traditional engineered techniques manage this risk by increasing the level at which the river must rise to overtop the banks (e.g. flood walls) or use large downstream storage reservoirs which activate near at very high flows. Natural Flood Management (NFM) by contrast uses more distributed, nature-based interventions to attenuate river hydrographs. For NFM to provide effective flood risk mitigation, flow must be attenuated around the time of peakflow of events that flood communities. The processes by which NFM reduce extreme peakflows vary with intervention type. Changing land cover (e.g. tree planting) may increase evaporation and soil infiltration capacity, or alternatively rougher ground vegetation or leaky bunds on hillslopes, leaky barriers in channels and floodplain bunds provide temporary in-storm storage of water. Whether NFM enhances the removal of water from the catchment by evaporation or surface storage during major floods, these changes to river hydrographs may be equated to an *effective volume* (m^3) around the flood peak

The new *effective volume approach* is illustrated using:

1. Modelled discharge effects of NFM interventions at the scale of 70-170 km^2

2. Observed discharge changes resulting from NFM interventions at scale of 0.01-1 km^2

Hydrological modelling can be used to simulate river-flow under different NFM scenarios. These models need to be able reproduce observed behaviour of individual NFM Interventions, ideally introduced within the same or nearby catchment. Where multiple models runs are undertaken to capture the uncertainty in the simulated results, measures of model acceptability need to be applied to constrain the uncertainty. Ranges in simulated behaviour (with averages and standard deviations) considered to be 'scientifically credible' may then presented. Each project in the NERC programme evaluated the behaviour and effectiveness of different types of NFM intervention.

Comparing the impacts of different NFM interventions can be difficult, owing to differences in units of the measured variables (e.g., evaporation rates, storage volumes, roughness of ground surface, or changes in streamflow). **All Interventions can be compared however, if all of the interventions are presented as *effective volumes* (m^3) around the flood peak (e.g., ±1 hr window) of a known return period**. Additionally, these values may be divided by catchment area to provide a volume per catchment area (m^3/km^2)

Community at risk 'catchment scale'

70-170 km² meso-scale catchments above a community at risk of flooding

To illustrate NFM effectiveness for a **1-In-5 year event for the 70 km² *River Kent at Bowston*** in Cumbria, Q-NFM's Dynamic TOPMODEL was used for the core modelling. The baseline (pre-Intervention) scenario for the Kent was undertaken using observed 15-min rainfall and river discharge data provided by the EA, with 67 'acceptable' (I.e., not rejected) simulations were identified from the original 10,000 (Beven *et al*., 2022).

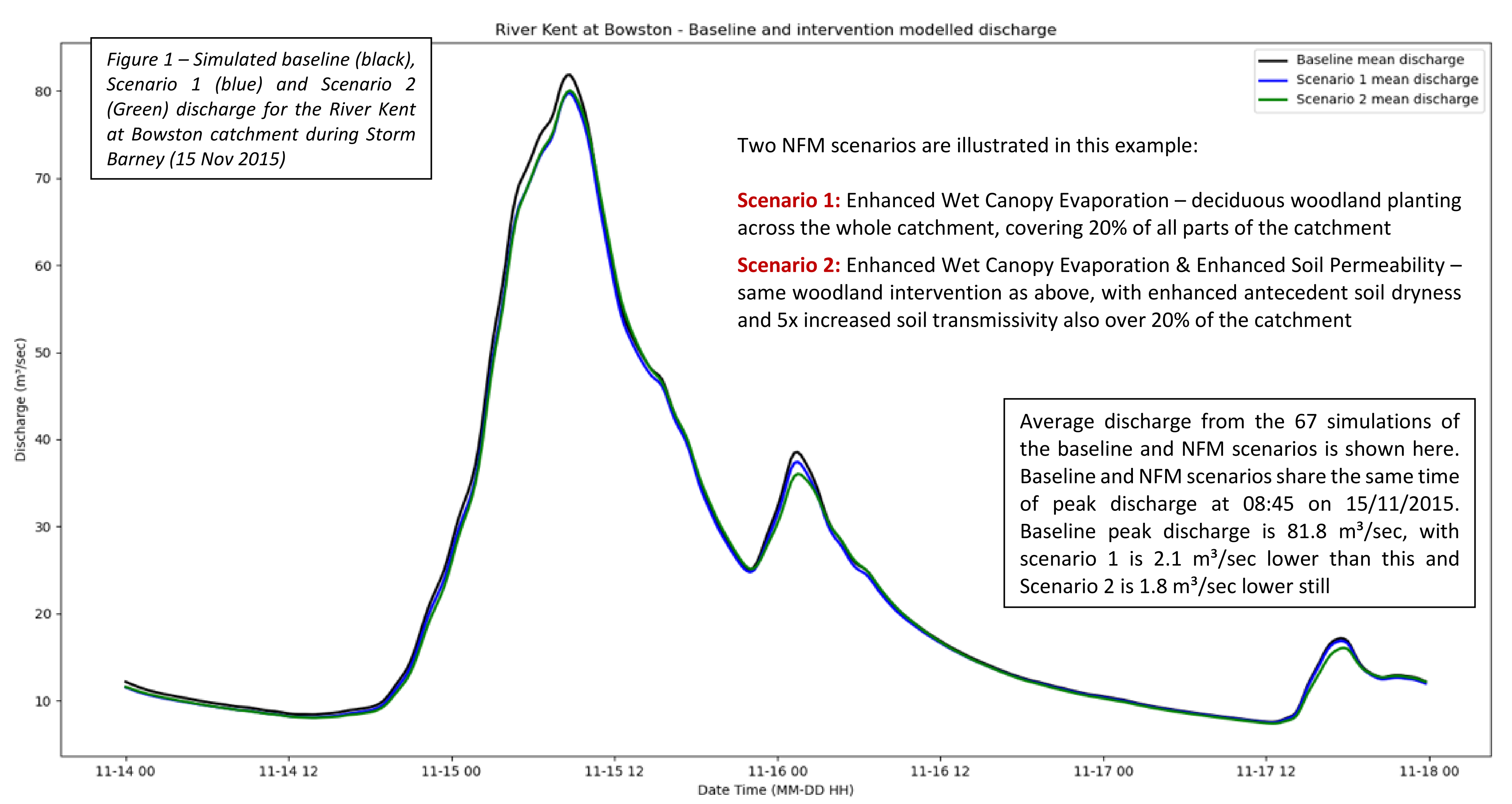


Figure 1 – Simulated baseline (black), Scenario 1 (blue) and Scenario 2 (Green) discharge for the River Kent at Bowston catchment during Storm Barney (15 Nov 2015)

Two NFM scenarios are illustrated in this example:

Scenario 1: Enhanced Wet Canopy Evaporation – deciduous woodland planting across the whole catchment, covering 20% of all parts of the catchment

Scenario 2: Enhanced Wet Canopy Evaporation & Enhanced Soil Permeability – same woodland intervention as above, with enhanced antecedent soil dryness and 5x increased soil transmissivity also over 20% of the catchment

Average discharge from the 67 simulations of the baseline and NFM scenarios is shown here. Baseline and NFM scenarios share the same time of peak discharge at 08:45 on 15/11/2015. Baseline peak discharge is 81.8 m³/sec, with scenario 1 is 2.1 m³/sec lower than this and Scenario 2 is 1.8 m³/sec lower still

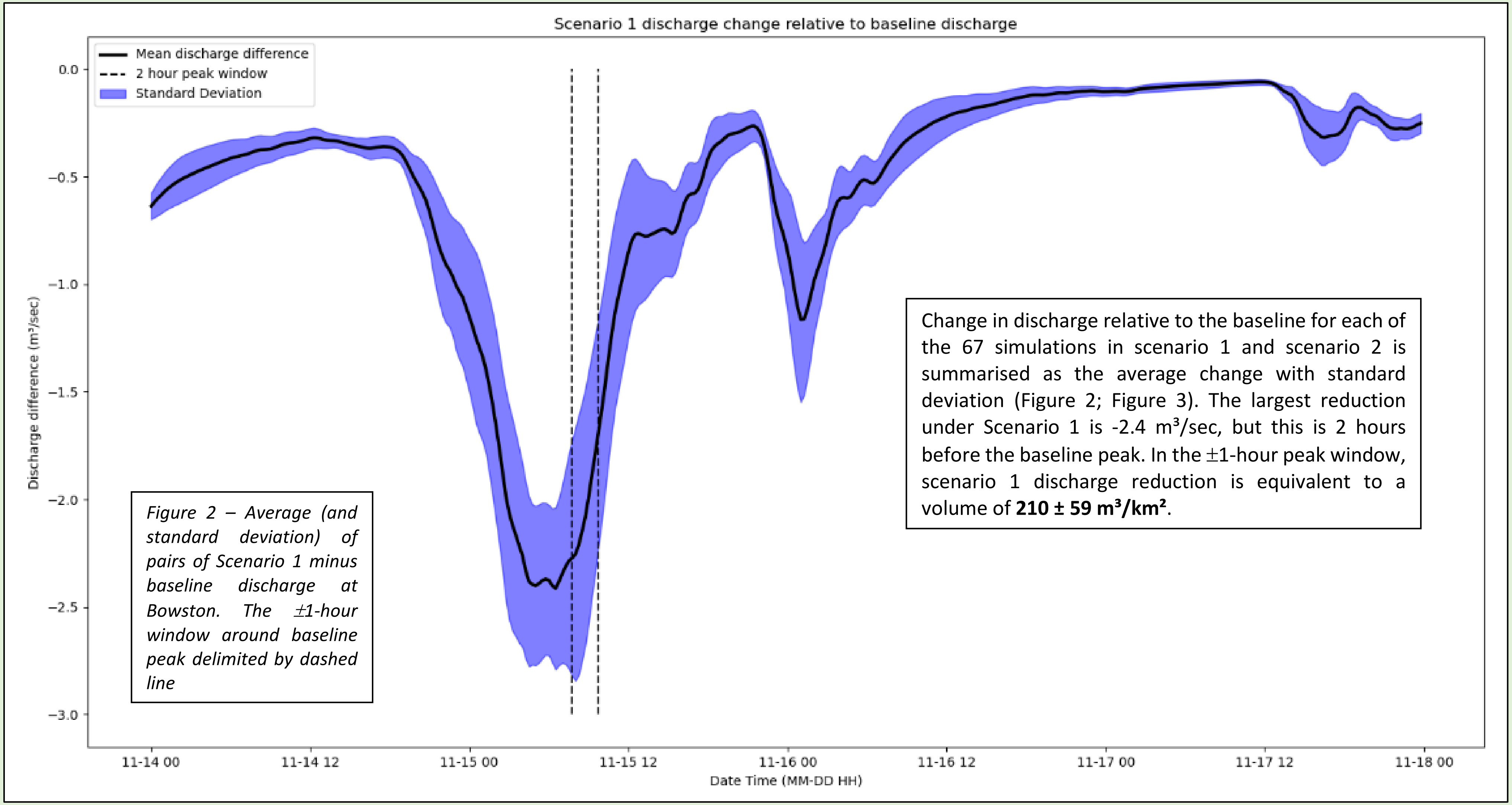


Figure 2 – Average (and standard deviation) of pairs of Scenario 1 minus baseline discharge at Bowston. The ±1-hour window around baseline peak delimited by dashed line

Change in discharge relative to the baseline for each of the 67 simulations in scenario 1 and scenario 2 is summarised as the average change with standard deviation (Figure 2; Figure 3). The largest reduction under Scenario 1 is -2.4 m^3/sec, but this is 2 hours before the baseline peak. In the ±1-hour peak window, scenario 1 discharge reduction is equivalent to a volume of **210 ± 59 m^3/km^2**.

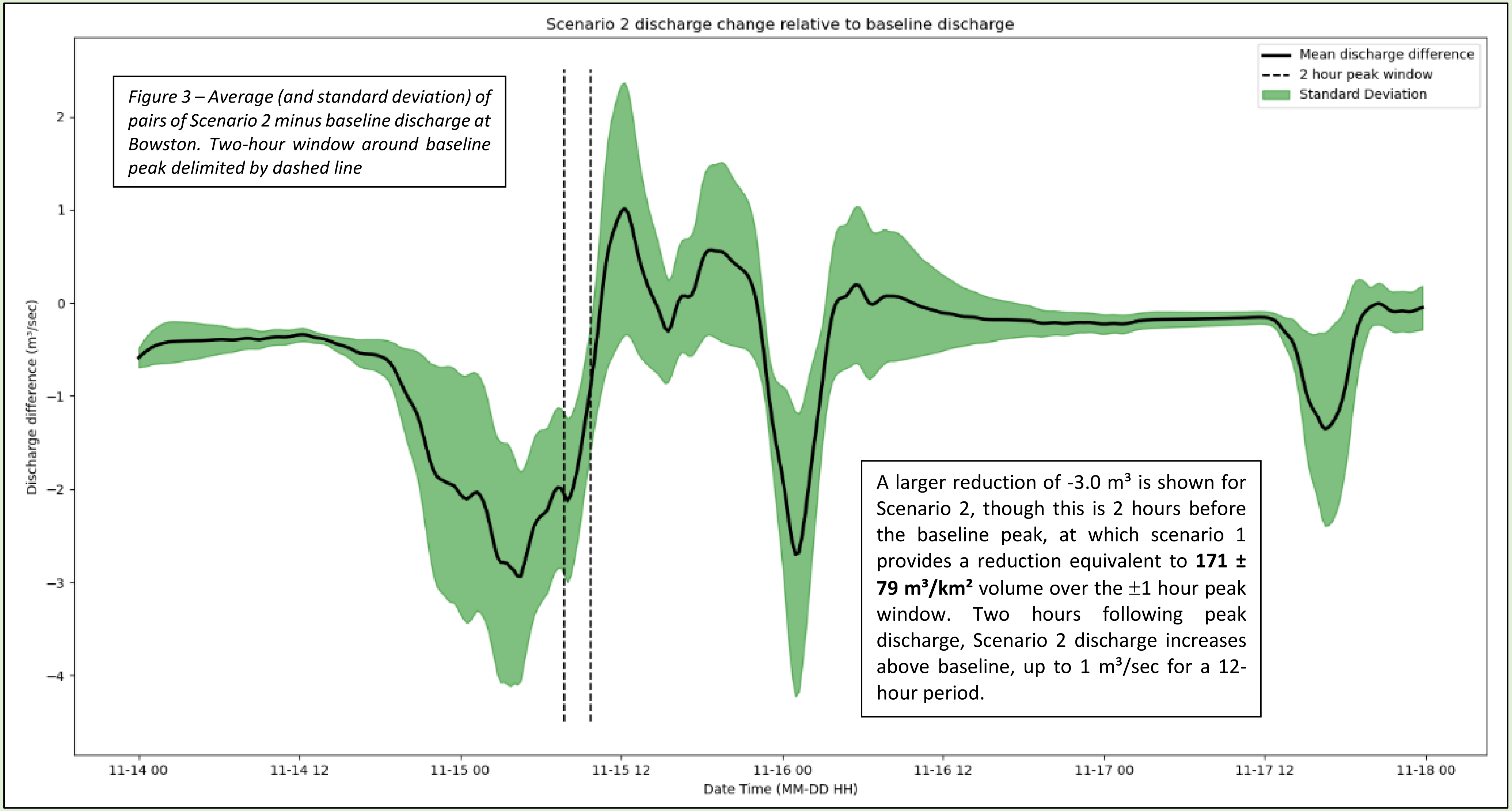
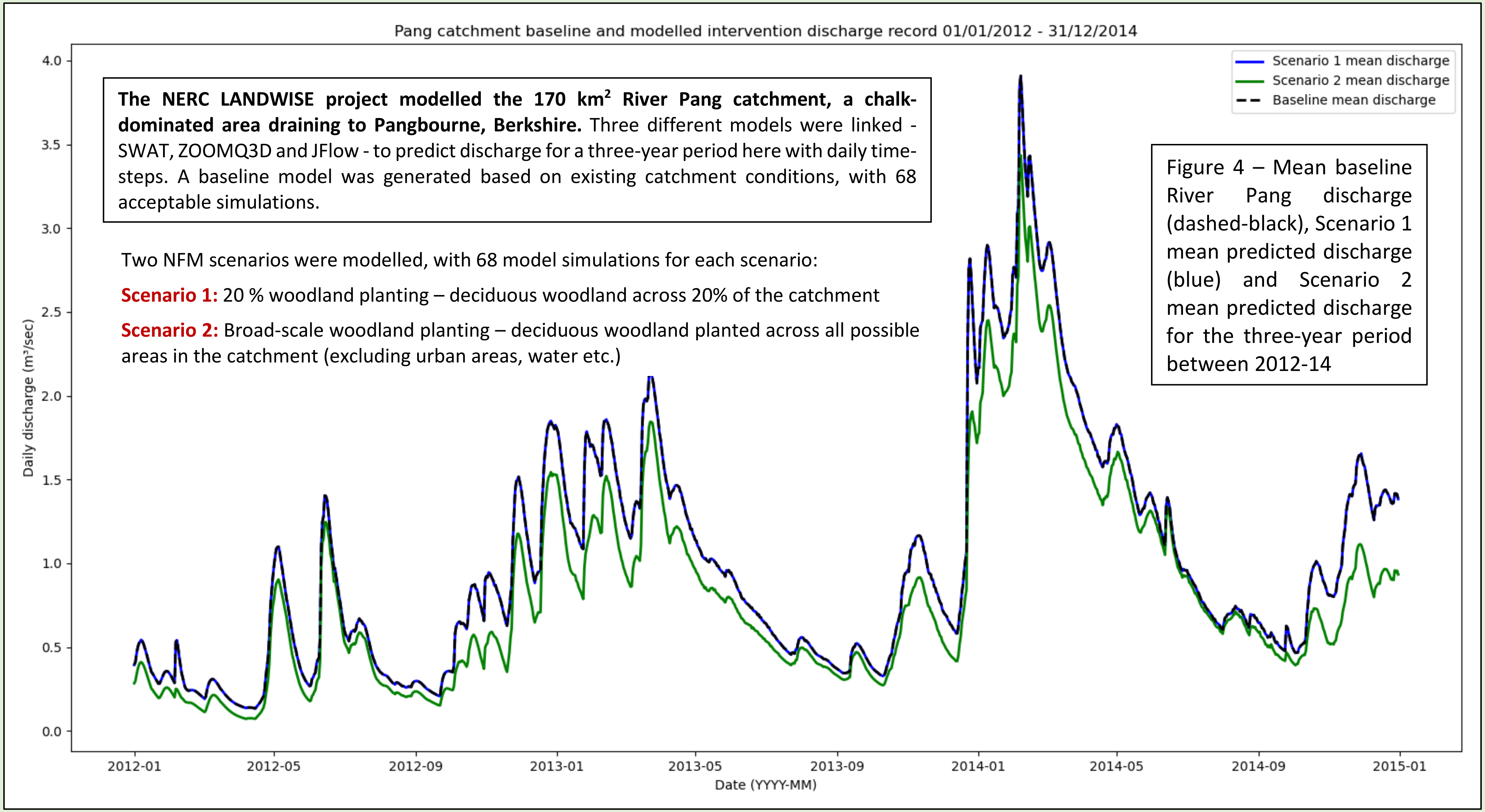


Figure 3 – Average (and standard deviation) of pairs of Scenario 2 minus baseline discharge at Bowston. Two-hour window around baseline peak delimited by dashed line

A larger reduction of -3.0 m^3 is shown for Scenario 2, though this is 2 hours before the baseline peak, at which scenario 1 provides a reduction equivalent to **171 ± 79 m^3/km^2** volume over the ±1 hour peak window. Two hours following peak discharge, Scenario 2 discharge increases above baseline, up to 1 m^3/sec for a 12-hour period.



The NERC LANDWISE project modelled the 170 km² River Pang catchment, a chalk-dominated area draining to Pangbourne, Berkshire. Three different models were linked - SWAT, ZOOMQ3D and JFlow - to predict discharge for a three-year period here with daily time-steps. A baseline model was generated based on existing catchment conditions, with 68 acceptable simulations.

Two NFM scenarios were modelled, with 68 model simulations for each scenario:

Scenario 1: 20 % woodland planting – deciduous woodland across 20% of the catchment

Scenario 2: Broad-scale woodland planting – deciduous woodland planted across all possible areas in the catchment (excluding urban areas, water etc.)

Figure 4 – Mean baseline River Pang discharge (dashed-black), Scenario 1 mean predicted discharge (blue) and Scenario 2 mean predicted discharge for the three-year period between 2012-14

The average discharge of the 68 simulations for each scenario are compared to mean baseline discharge in figure 4. Scenario 1 (20% woodland planting) produces discharge predictions almost identical to baseline predictions. Scenario 2 ('broad scale' woodland planting) predicts lower discharge than the baseline throughout the record. The difference between scenario 2 and baseline is generally smaller during low flows.

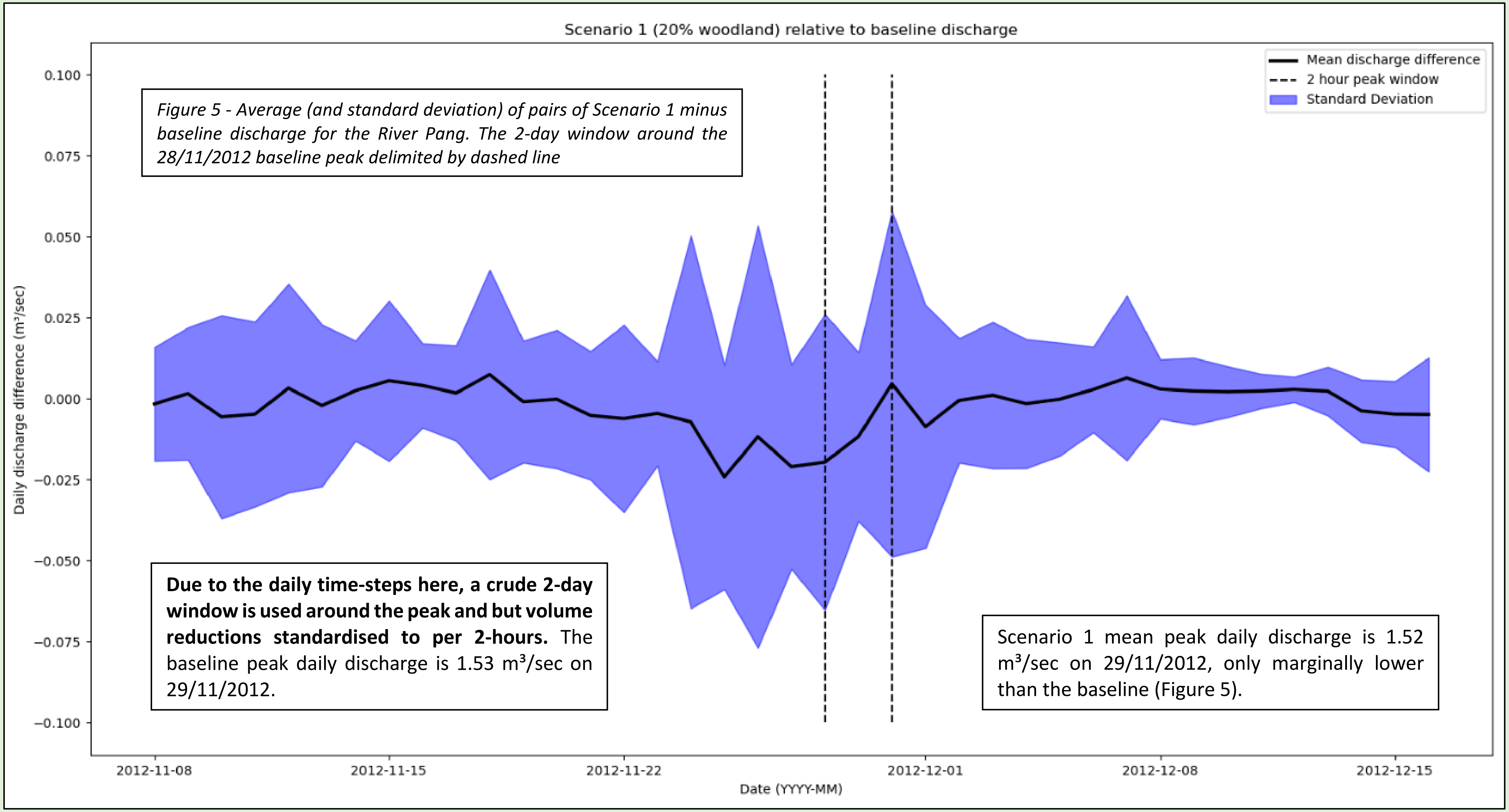


Figure 5 - Average (and standard deviation) of pairs of Scenario 1 minus baseline discharge for the River Pang. The 2-day window around the 28/11/2012 baseline peak delimited by dashed line

Due to the daily time-steps here, a crude 2-day window is used around the peak and but volume reductions standardised to per 2-hours. The baseline peak daily discharge is 1.53 m³/sec on 29/11/2012.

Scenario 1 mean peak daily discharge is 1.52 m³/sec on 29/11/2012, only marginally lower than the baseline (Figure 5).

In the 2 day window around the baseline peak discharge, the difference in Scenario 1 discharge from the higher baseline was equivalent to a volumetric reduction of **0.4 ± 0.4 m³/km²over a 2 hr period**. Scenario 2 mean peak discharge is lower at 1.18 m³/sec (Figure 6). Over the 2-day window the Scenario 2 reduction from baseline discharge is equivalent to **14.6 ± 6.4 m³/km² over a 2 hr period**

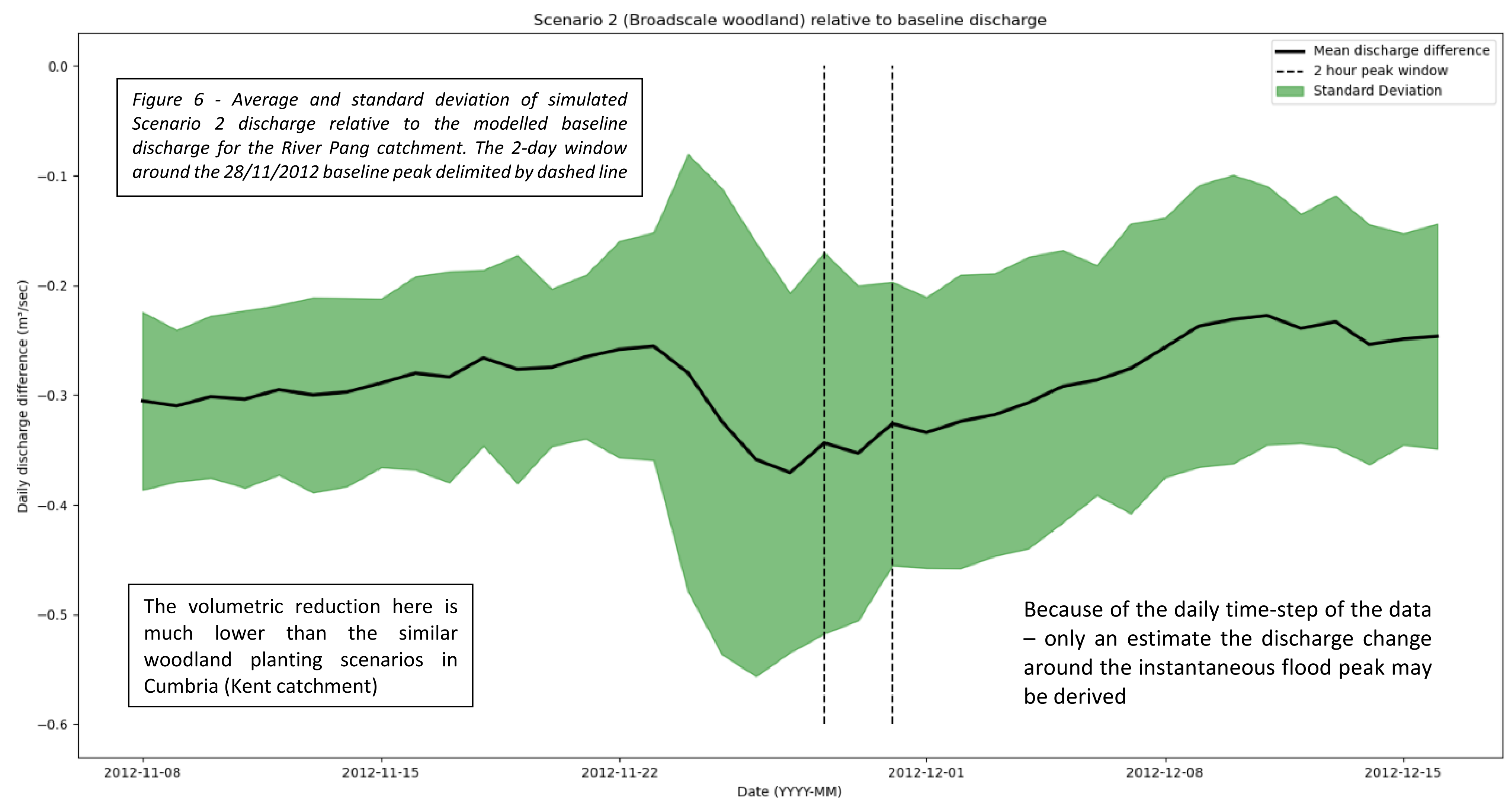


Figure 6 - Average and standard deviation of simulated Scenario 2 discharge relative to the modelled baseline discharge for the River Pang catchment. The 2-day window around the 28/11/2012 baseline peak delimited by dashed line

The volumetric reduction here is much lower than the similar woodland planting scenarios in Cumbria (Kent catchment)

Because of the daily time-step of the data – only an estimate the discharge change around the instantaneous flood peak may be derived

The impact of peatland restoration on flood flows was assessed by PROTECT using very small basins (e.g., 0.7 hectares or 0.007 km^2) on Kinder Scout in the Peak District National Park, Derbyshire (UK). An experimental intervention catchment which was degraded peatland was revegetated by gully blocking and sphagnum planting in 2010. Discharge out of the 'nano-basin' was monitored for 10 years and by 2020 the peat was revegetated with extensive sphagnum moss along gully floors (Figure 7). A control catchment, where no restoration was carried out, was also monitored to provide a comparison for discharge changes to be identified against. Two similar large storms are compared, one from pre-intervention (2010), the other post-NFM (2020) when the restoration is mature

Nano- and micro-basin scale

Directly observed evidence at a scale of approximately 0.01 km^2 (nano-basin or zero-order basin) or 1 km^2 (micro-basin drained by a perennial channel)

Figure 8a shows a storm hydrograph in 2010, before the intervention catchment has been restored. Discharge in the control basin was higher than the intervention basin. Peak discharge in the control was 11.2 m^3/5min. The intervention catchment peak was at the same time, but 56% smaller than the control at 5.0 m^3/5min. In the 2-hour window around the peak (I.e., $\pm$1 hr), there was 33 m^3 less channel-flow volume from the intervention catchment.

Figure 8b shows a hydrograph in 2020, 10 years following restoration in the intervention catchment. The storm is slightly smaller the 2010 example storm, with peak discharge in the control at 9.4 m^3/5min. The intervention catchment peak discharge was smaller relative to the control, 72% smaller than the control at 2.7 m^3/5min. The intervention catchment peak was also delayed from the control peak, with a 30-minute lag time. There was 38m^3 less runoff volume from the intervention catchment compared to the control over the 2-hour peak window. This was 5 m^3 less than the pre-intervention example, equivalent to **714 m^3/km^2** storage. Unlike in 2010, the intervention nano-catchment discharge exceeded control discharge after the peak, on the receding limb. This suggests that the reduced discharge around peak was temporarily stored and released gradually on the receding limb of the hydrograph.

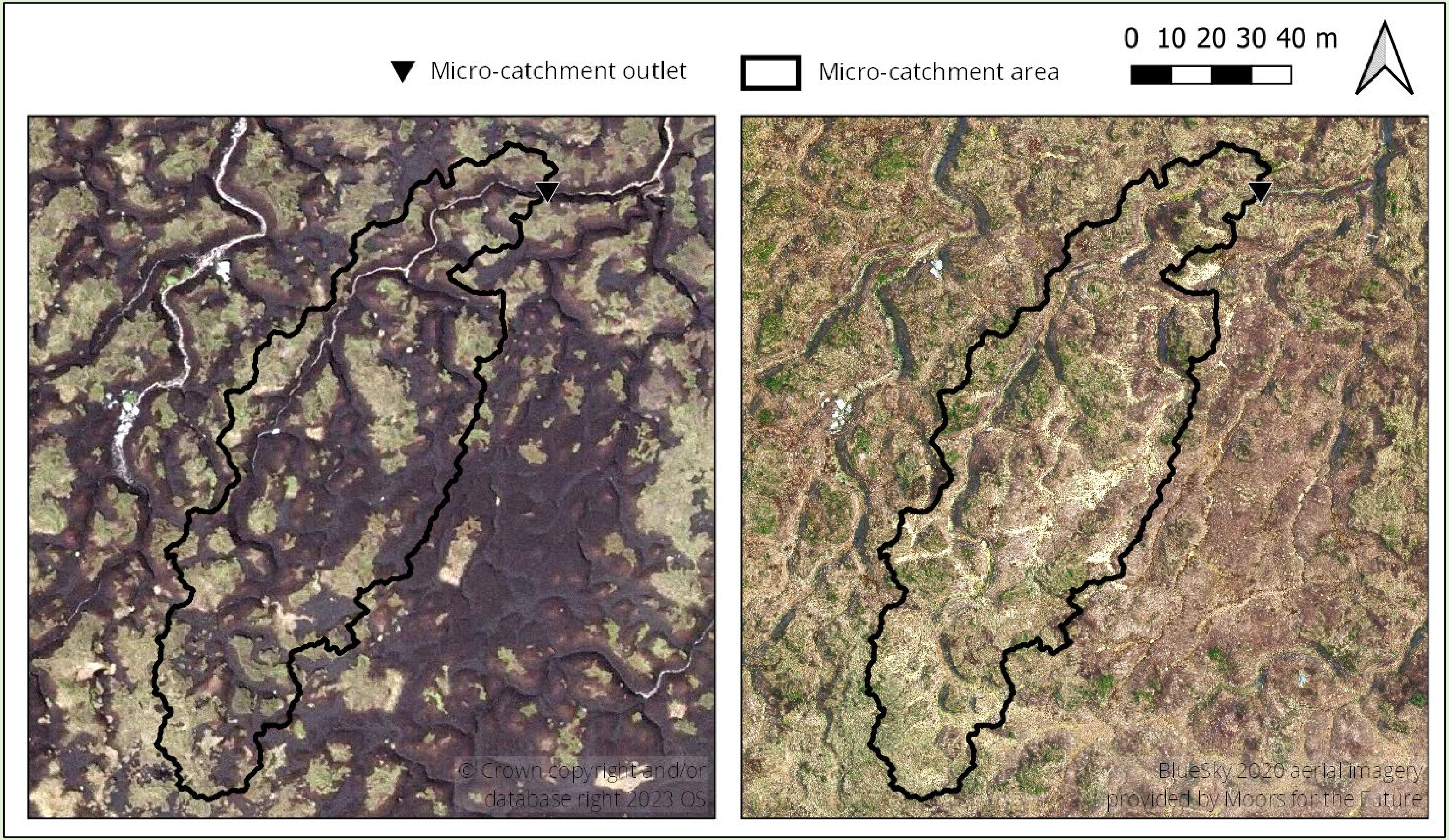
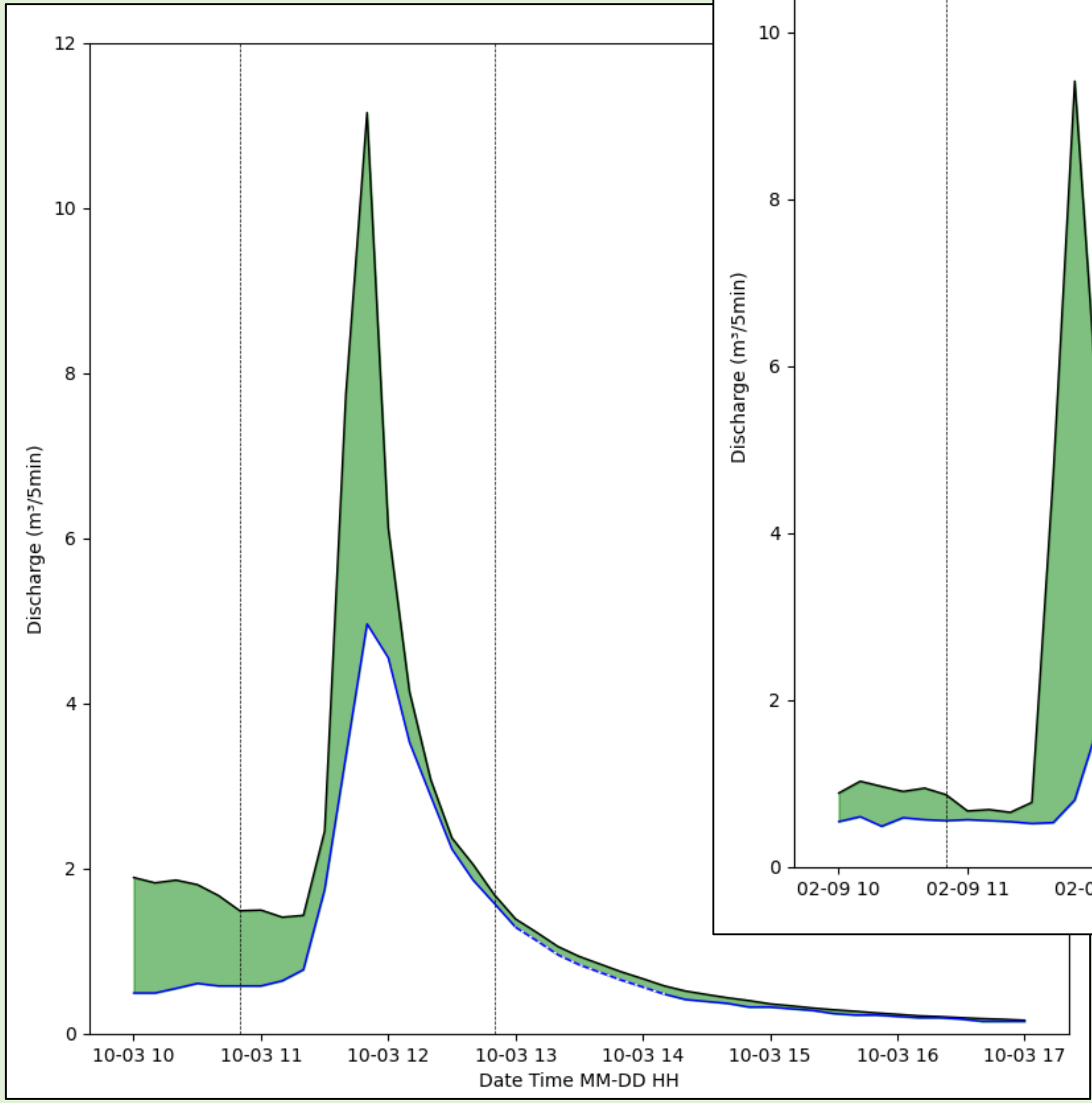
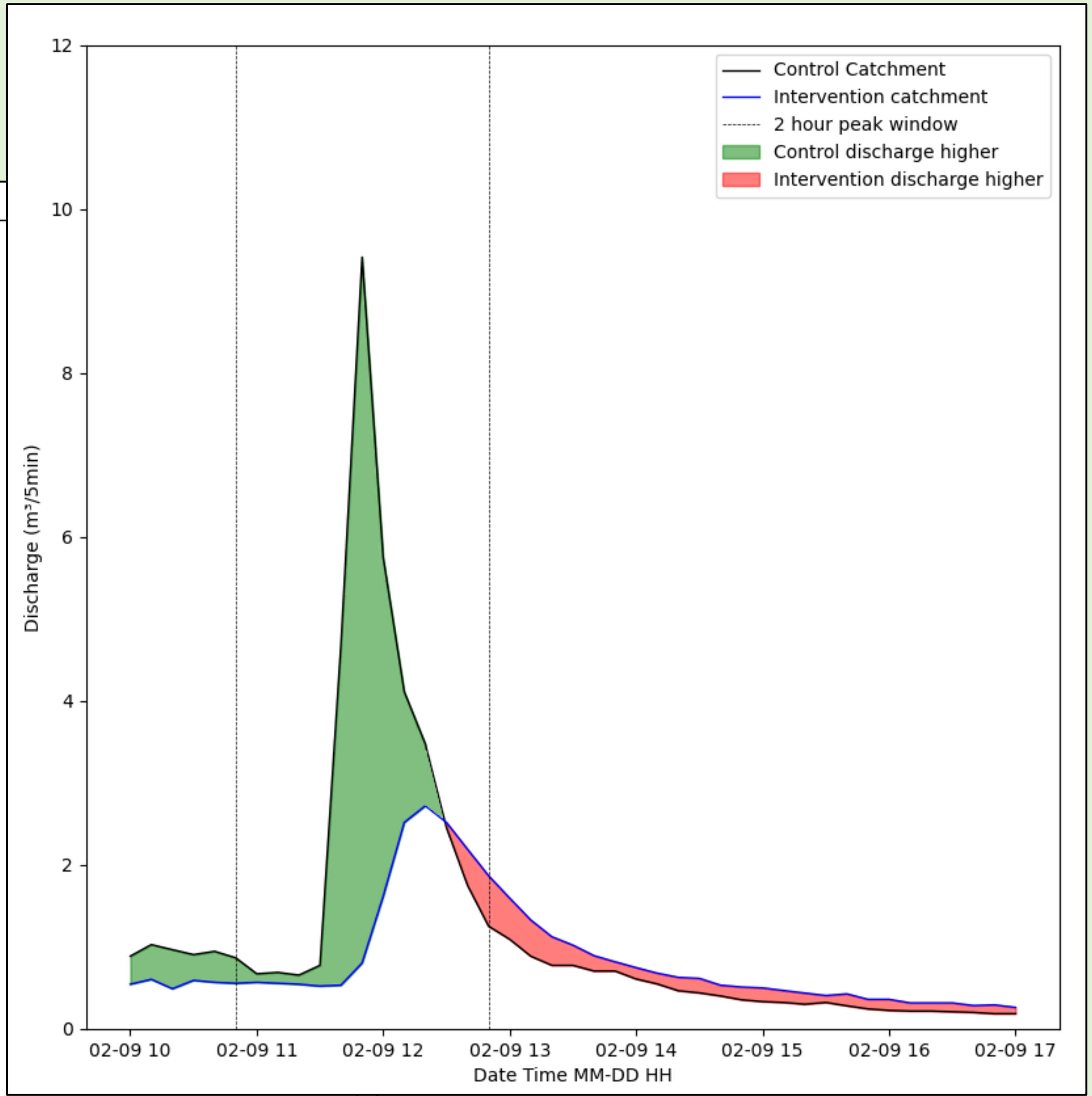


Figure 7 - (left) The intervention micro-catchment before restoration in 2010 with large areas of bare peat. (right) The intervention catchment in 2020, 10 years post-restoration, with extensive sphagnum moss cover.

Figure 8 - 8a (left) control and Intervention micro-catchment discharge for a storm in 2010, prior to intervention catchment restoration. 8b (right) Control and Intervention micro-catchment for a storm in 2020 after Intervention catchment restoration





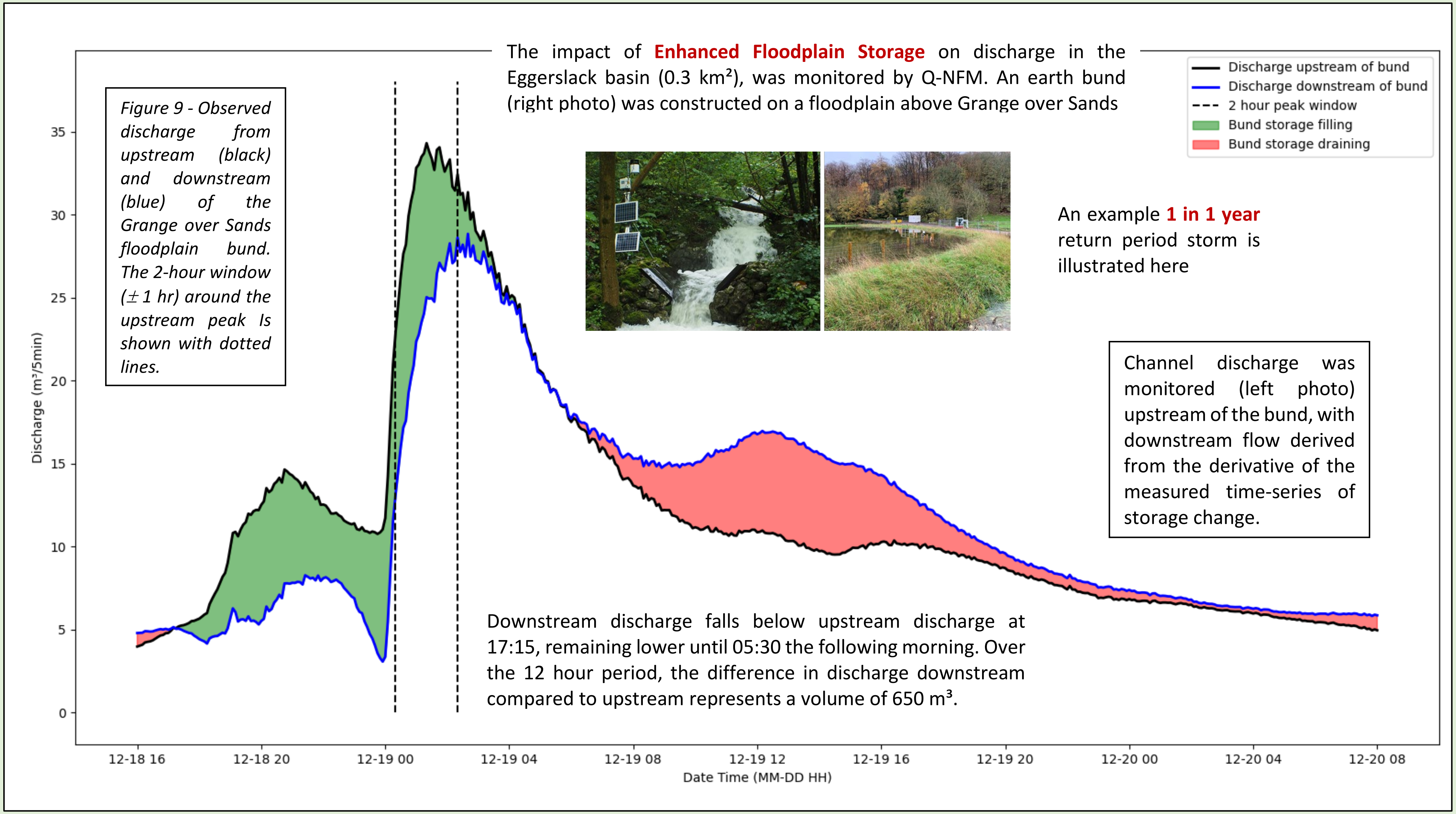
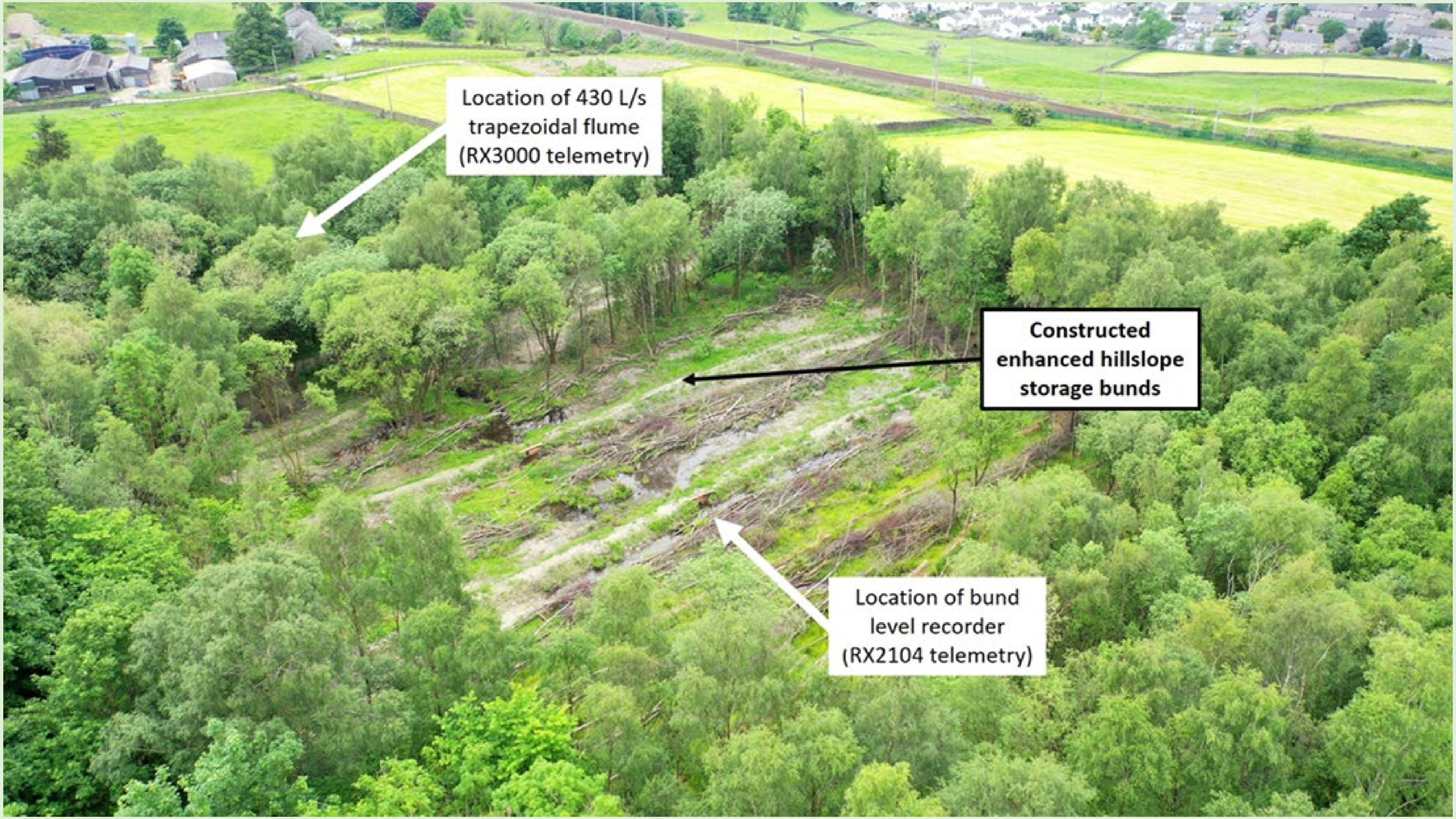


Figure 9 - Observed discharge from upstream (black) and downstream (blue) of the Grange over Sands floodplain bund. The 2-hour window (± 1 hr) around the upstream peak Is shown with dotted lines.

The upstream discharge reached a peak of 34.4 m³/5min at 20:00. In the 2-hour window around this peak, the discharge difference between downstream of the bund to upstream was equivalent to 205 m³ volume of runoff stored, or **682 m³/km²**. The downstream discharge peak was 6 hours after the upstream and 16% lower than the upstream peak. From 2 am, downstream discharge was higher than upstream of the bund for the remaining 26.5 hours, representing the release of water stored from the bund.

Illustration of flood damages avoided by NFM interventions



This report summarises the findings of a component project to illustrate the economic benefits of Natural Flood Management across NERC's research programme: *Understanding the effectiveness of natural flood management*. The programme was driven by the call to understand the effectiveness of Natural Flood Management (NFM) at larger scales and has comprised three NERC funded projects, LANDWISE, PROTECT and Q-NFM centred at the Universities of Reading, Manchester and Lancaster, respectively.

Each NERC team provided this component, illustrative investigation with predicted changes in hydrological response across a range of storm severities, resulting from hypothetical up-scaled NFM across small (15-44 km^2) catchments upstream of a community at risk. The changes were based on a wide range of empirical and modelling evidence that has been generated over the last five years of the programme. The research has also encompassed a cross-section of NFM measures, from soil permeability improvements to woodland planting, in-channel leaky barriers, peat restoration (including gully-blocking), enhanced hillslope storage on mineral soils and enhanced floodplain storage.

For each of the selected catchments, a consistent baseline flood model has been set up using high resolution (1-2m) digital terrain model based on the Environment Agency's National LiDAR Programme using the same 2d flood inundation model, JFlow. A range of design hydrographs have been generated using the Flood Estimation Handbook techniques providing a range of probability floods, such that the flood risk benefits of NFM can be appraised fully. These were used to drive the 2d inundation model, and the resulting maximum depth grids have been intersected with the Environment Agency's National Receptor Dataset and Ordnance Survey MasterMap building footprints to understand impacts in the communities at risk.

The vulnerability curves in the Multi-Coloured Manual from the Flood Hazard Research Centre have then been used to estimate direct damages and damages avoided, or long-term average annual benefits of NFM. Extended damages and environmental benefits were also estimated for the different NFM changes in the landscape.

The catchments investigated here represent a very small sample of those modelled by the three projects over the five years, with areas ranging from 15 km^2 - 44 km^2 across which to assess the economic benefits of up-scaled NFM in more detail. For the more extensive NFM footprints extending above 20% by area, the long-term average annual flood risk-reduction is relatively small of the order of £200k-£400k, although over a scheme lifetime of 50 years this equates to the order £5m-£10m. Added to that the indirect and intangible damages avoided, this could be increased by a factor of two. However, as indicated by the ranges, there is often uncertainty in these types of estimates, and there are cases where the relatively smaller NFM measures can have little impact, and some cases where the measures, without careful siting can make things worse. For example, modelling theoretical scenarios can lead to slowing the flow upstream of some communities, inevitably creating a backwater upstream, and if this impacts on an upstream community there can be negative economic benefits. This supports a call for model-led design to ensure such situations are avoided.

Environmental benefits have also been computed for up-scaled NFM measures across the projects, using the Partnership Funding Calculator Outcome Measure 4. Over a similar 50-year lifetime would equate to approximately £0.5b (unweighted), a large multiplier of the flood risk-reduction benefits, which has often found to be the case with NFM.

An analysis of the percentage reductions to the peak hydrograph response at the communities at risk, shows that the NFM can, under some circumstances, work for larger floods, where this may not be the case for traditional flood risk management measures such as embankments. Once the design level of an embankment or defence is reached, there is typically no additional storage, and flooding commences. Therefore, whilst the flood risk-reduction benefits of carefully designed NFM will require supplementing with other measures, they also provide a complimentary resilience where flows are expected to increase due to climate change. This requires an element of model-led design to avoid the situation of negative benefits, and the good news is that the three NERC projects have demonstrated ways of achieving this.

As part of an integrated flood risk management (IFRM) approach, and considering the environmental co-benefits, it is concluded that carefully designed, up-scaled NFM remains an important strategy for improving whole system resilience.

The NERC NFM programme of research comprised three projects, LANDWISE, PROTECT and Q-NFM centred at the Universities of Reading, Manchester and Lancaster respectively. The programme was developed in part to fill research gaps identified in the WwNP Evidence Directory[1] (Burgess-Gamble *et al.*, 2017), largely associated with forming a better understanding of the effectiveness of NFM at larger scales. All the NFM scenarios modelled in for the economic analysis include scaling-up the coverage of NFM measures from feature-scale measurements to catchments, but the analysis is hypothetical and does not imply feasibility or landownership agreement.

Where possible, the consistency in approach from choice of core datasets, 2d inundation modelling and economic appraisal assumptions have been kept the same across the studies. Similar sized catchments with areas 15-44 km^2 having a known impact on a named community at risk have been investigated, using a cross-section of the different types of NFM measures that were investigated in the NERC-funded programme.

For each study catchment the topography has been based on the EA national LiDAR programme 1 m or 2 m filtered digital terrain, and the JFlow® 2d inundation model has been used to route flood water over the terrain driven by the baseline and NFM 'change' scenarios from each of the projects.

The resulting maximum depth grids have been generated for a range of design events covering a range Annual Exceedance Probabilities, and the direct damages have been assessed for each using the Flood Hazard Research Centres (FHRC) Multi-Coloured Manual[2]. This permits a comparison of before-and-after appraisal of the long-term average annual damages within the communities at risk. The difference between baseline and NFM scenarios is reported to hep quantify the risk reduction, and this is summarised based on the extent of the up-scaled NFM.

[1] https://www.gov.uk/flood-and-coastal-erosion-risk-management-research-reports/working-with-natural-processes-to-reduce-flood-risk
[2] https://www.mcm-online.co.uk/

LANDWISE

The LANDWISE project has been focused on determining the effectiveness of land based NFM measures to reduce flooding risk caused by surface runoff, rivers and groundwater, using the Thames catchment as a case study. In particular, arable land management, such as crop choice, tillage and tree planting were studied. The ability of such measures to increase infiltration, evaporative losses and below-ground water storage, which in turn would reduce surface runoff and reduce peak levels in groundwater and rivers was explored. In a unique combination of models, the land-surface interactions, groundwater modelling and surface hydraulics have been considered across a wide range of geologies and soil types.

PROTECT

The PROTECT team for the last 11 years has been working with Moors for The Future Partnership to monitor restoration of peatland micro-catchments on Kinder Scout. The project has also set up restoration experiments on the moors above Stalybridge. Three main types of intervention have been deployed. The first is revegetation (grass seed spread onto bare upland peat alongside lime, fertiliser, and mulch). This stabilises the peat with a nurse crop providing a surface for native plant species, like Sphagnum moss, to re-establish. The second is gully blocking; over 6000 dams across the Kinder plateau have been deployed into channels formed in the peat due to erosion. The team also evaluated a range of different dam types at Stalybridge Moor, including stone dams, peat dams, and wooden dams. The third restoration method was reintroduction of Sphagnum moss through plug planting. *These results are not presented in this report, but will be presented in subsequent journal publications.*

Q-NFM

The primary aim of the Q-NFM project has been quantifying the effects of replicated NFM interventions over scales ranging from micro-basins (about 1 km^2) that flood certain housing developments to the basins of large rivers that flood cities. The focus has been three river basins in Cumbria (209 km^2 Kent, 667 km^2 Derwent and 2,287 km^2 Eden), though new observational evidence has been gained from a network of 1 km^2 micro-basins and plots located more widely across Cumbria, and through use of quality assured datasets collected within other temperate environments internationally. The micro-basin network received additional funding from the Environment Agency (Cumbria) as part of the Defra NFM programme; this support has strengthened considerably the evidence base for the Q-NFM project funded by UKRI-NERC.

Inundation and economic benefits modelling

Two key steps that have been required to assess the benefits of NFM at small to intermediate scales:

- Hydraulic modelling to understand the changes to inundation in communities at risk, driven by the change in hydrological response from up-scaled NFM, as computed by the NERC project teams.
- Economic modelling using the Multi-Coloured-Manual approach to estimate the benefits of the up-scaled NFM within the communities at risk.

Inundation modelling

For consistency of approach, all inundation modelling has been undertaken using JFlow®, which solves the two-dimensional Shallow Water Equations using GPU technology. JFlow® was designed to run in parallel on GPUs in order to run 2D models at very high spatial resolution across large areas that have been computationally prohibitive on traditional Central Processing Units (CPUs). It is implemented on a regular grid using the supplied DTM and does not require any secondary grid generation process, although requires edits to remove artificial barriers to the flow, such as bridges and culverts which can also be added back in as hydraulic units. JFlow® has been previously widely applied in undertaking numerous large-scale flood modelling assessments including the UK's Comprehensive Flood Map, the National Flood Risk Assessment for Wales and the Environment Agency Surface Water Flood Map amongst many others. It has been benchmarked using the test cases proposed by the EA in the Science Report SC080035/SR2, Benchmarking of 2D Hydraulic Modelling Packages, and the results have been submitted to the EA. Results from the full suite of benchmark tests are available on request. The software has also been subject to peer-review through numerous international journal papers and conference presentations (e.g. Lamb *et al.* 2009).

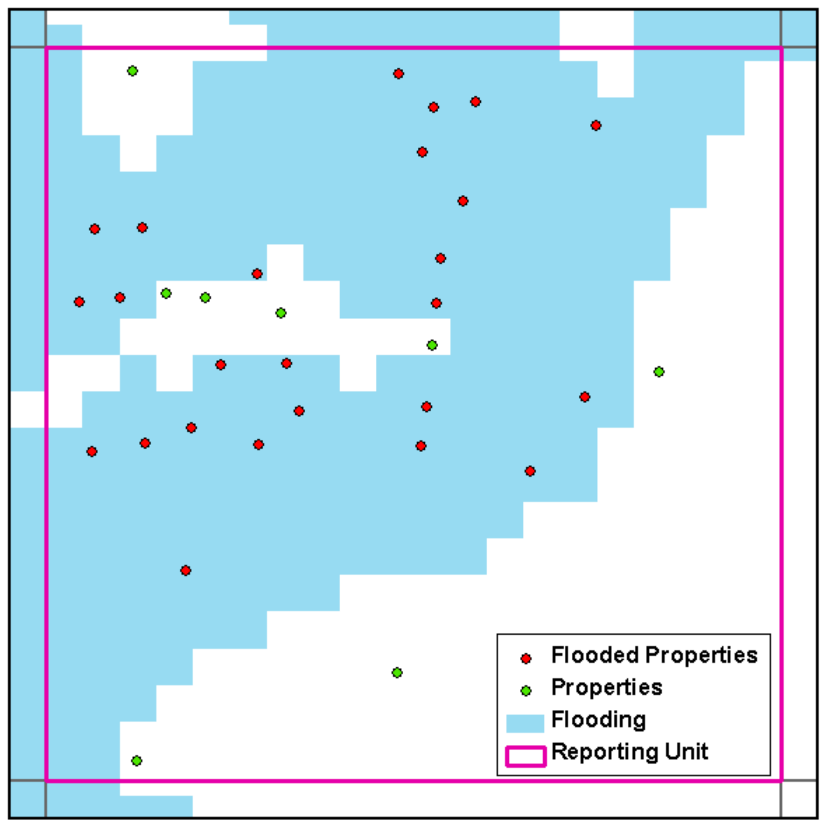
***Model Overview:* One of the two JFlow® models constructed within this study is fluvial (Q-NFM), whilst the other model (LANDWISE) is a pluvial model with a baseflow boundary based on groundwater emergence modelling. The key difference between these models is in the way inflows have been applied. As the pluvial model applies effective rainfall to every modelled cell, some additional post processing has been completed to remove shallow depths from the modelled outputs (≤5 cm). Additionally, by applying this threshold "wet islands" will form within the model outputs, island features with a flood depth >0.05 m and an area of ≤50 m^2 have therefore been excluded. These measures have been taken to ensure direct flooding to model cells identified as buildings were not artificially captured within the pluvial economic outputs.**

Economic analysis

Economic analysis of the hydraulic model results has been conducted using JBA's in-house risk analysis GIS software FRISM. This software provides a streamlined means to conduct spatial queries of property data against hydraulic model results, generating property count data and economic damages for a range of modelled events and scenarios. To assess the property damages and benefits across the NFM studies within the NERC programme the principles outlined in the Multi-Coloured Manual[3] (MCM) have been applied, combined with more recent supporting handbooks which are released annually to account for more recent research and inflation rates. The analysis has been kept simple and is based on the change to direct property damages, without estimating indirect and intangible losses although the implications of extended damages are discussed.

Property Identification: **Property information has been determined from two primary data sources, the recently published Environment Agency's National Receptor Dataset 2021 (NRD), and Ordnance Survey MasterMap (OSMM) data which is updated biannually. The NRD 2021 dataset is a spatial point database of assets across England. It contains information on property receptors such as their address, the floor level, floor area and how they link to the Flood Hazard Research Centre's Multi-Coloured Manual. For the purposes of the NRD, a receptor is considered to be any property, object or land area with an address, or any non-addressable property that has a building footprint greater than 25 square meters. In order to help refine the NRD data for flood risk analysis purposes, some standardised filters have been applied to remove addressable locations within the NRD dataset such as camping grounds and storage land. Details of these filters can be found within the Environment Agency guidance document LIT 59311 which was published alongside the NRD 2021 data in December 2022. The NRD data has been used in conjunction with the OSMM topography data which is a vector dataset of land parcels. From this building footprint information can be extracted allowing for a more detailed level of assessment required to calculate flood damages to receptors. This can be seen in the images below highlighting the benefits of conducting more detailed footprint analysis as opposed to point based queries.**

[3] Penning-Rowsell et al. (2013). Flood and Coastal Erosion Risk Management. A Manual for Economic Appraisal. Routledge.



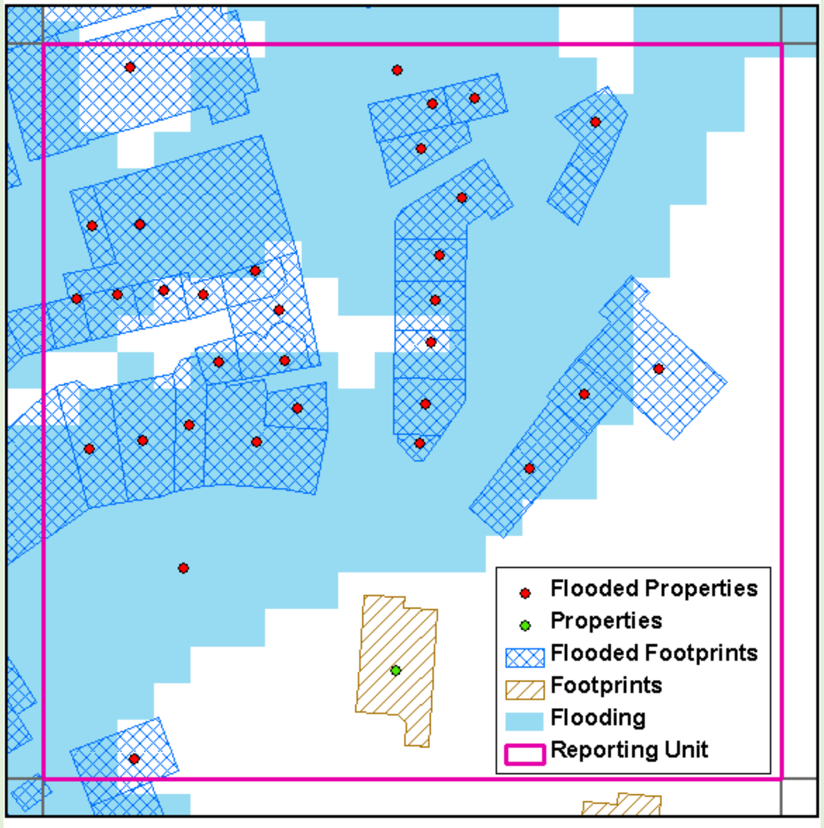


Figure 10: Two images showing the difference between utilising point data to quantify flood risk impacts comparatively with the use of building footprints. (Left: 25 flooded properties. Right: 32 flooded properties)

Upper floor properties have been included and reported as a separate 'class' for completeness here, due to the disruption and limited access and egress associated with flooding to these types of properties (however, damages to upper floor properties are excluded from this analysis). It should be noted that the base damage values calculated as described in section 0 do not double count receptors which share the same footprint and are listed as upper floor properties.

For these studies, modelled depth values have been ascertained based on both the statistical mean and maximum pixel values which fall within the property footprints obtained from the OSMM data. The mean depth value can sometimes reduce with increasing flooding due to increased extent of shallow water over a property at risk as represented in the terrain model. To counter this possibility, the maximum depth of flooding has also been reported and the two are used throughout to generate a range of economic damages to counter this discrepancy and reflect some of the calculation uncertainty.

Baseline Damages

Baseline damages have been calculated using the depth damage curves taken from the MCM Handbook and uplifted to present day values using the Consumer Price Index (CPI). The depth damage curve used across all three studies is representative of a fluvial, short storm duration curve without a flood warning being issued. This approach, adopting national scale averages, does not account for the intricacies that may occur in real time local scale events but does provide a means to derive a representative baseline on which to quantify impacts and benefits at a comparative level. Base damages are only accounted for in the calculation of ground floor and basement level properties.

Property Threshold

A flat 150 mm property threshold has been applied for all properties within the study area. This means that internal property flooding will only occur when flood depths exceed 150 mm. The value chosen is most representative of the majority of properties in the UK, equating to a rough calculation for one curb and one brick above ground level. This was deemed appropriate for this pan-programme appraisal, providing consistency between sites and is a standard unit used across economic appraisals where surveyed threshold information is not readily available.

Extended Damages

In an economic appraisal, a range of extended damages are often calculated. These include indirect damages (e.g. evacuation costs), emergency costs, vehicle damages, and intangible damages (e.g. long term stress and medication from flooding). Some of these extended damages may be applicable to upper flood properties albeit no flood incursion has occurred to the property itself. Detailed depth-based queries have not been undertaken within this study but for a high-level appraisal the following guidance taken from the MCM can be applied.

Indirect Damages

Indirect loss for residential properties can be evaluated based on the average evacuation costs per household over a 23-week period, this equates to a cost of £5,035 per household account for both temporary and alternative accommodation costs. For non-residential properties, indirect damage can be estimated at 3% of the total direct loss incurred.

Emergency Costs

Emergency costs can be estimated based on research from the floods in both 2000 and 2007 as somewhere in the range of 5.6 - 10.7% of the total incurred damage respectively. The lower end of this estimate is typically adopted in more urban environments due to the nature of the flooding that was appraised whilst the upper estimate is more likely to be applicable in a more rural setting.

Vehicle Damages

For residential properties this can be estimated as 42% of the total properties impacted multiplied by an average vehicle value of £5600. There is no means to reliably approximate vehicle damages to non-residential properties without conducting a detailed survey.

Intangible Damages

As stated in the MCM:

"…Research into the valuation of intangible health benefits concludes that the potential value of avoiding such impacts is, on average, £257 per household per year. In addition, this research concluded that the most important factor when calculating potential intangible impacts is the flood risk…" (Defra/Environment Agency, 2004).

Annual Average Damages

Annual Average Damages (AAD) have been calculated using the area under the damage-AEP curve with some basic assumptions on interpolation or extrapolation. which approximate the damage incurred in any given year assuming flood event probability and magnitude are evenly distributed year on year. This calculation functions best when a large number of events have been modelled, lack of high probability events may lead to an overestimation of AAD in relation to the considered onset of flooding (here a return period of 2 years was used, or QMED), whilst a lack of modelled low probability events can result in underestimated losses due to the application of linear scaling between known points.

AAD values have been linearly scaled up for extreme events the damages incurred at the largest magnitude modelled event (For both LANDWISE and Q-NFM this is the 0.1% AEP event).

The damages avoided or benefits will be expressed in terms of differences to AAD with and without the NFM measures. In order to estimate benefit-cost ratios (BCR), the Present Value Damages (PVD) over the estimated lifetime of the scheme must be estimated and compared with the whole-life costs. Scheme costs have not been estimated as part of this investigation.

Present Value Damages

Present Value Damages (PVD) have been calculated over a 50-year appraisal period for these studies. It has been assumed that there is no change in condition through time between each of the modelled scenarios. PVDs are calculated to take account of the future value of something at the present day. This is done by multiplying the calculated AAD values by a discount factor year on year and summing the product. Discount factors for this study have been applied at standard Social Time Preference Rate (STPR) as outlined in the HM Treasury Green Book[4].

Table 1: An extract from the Treasury Green Book listing the standard discount rate covering a period up to 125 years.

Year	0-30	31-75	76-125
STPR (Standard)	3.50%	3.00%	2.50%

To quickly calculate the PVD values assuming no change in conditions throughout the appraisal period the following formula can therefore be used:

$$PVD50 = AAD \times 24.495$$

Benefit Assessment

To quantify benefits the scenarios modelled for each of the three studies have simply been subtracted from the "baseline" case.

This method of quantifying benefits allows for individual model events to be assessed against one and other, and for the calculation of annual average benefit/present value benefits to be completed.

Environmental Benefits

These are incorporated *approximately* in the discussion based on approximate calculations on the NFM scenarios and using the OM4 measure in the Partnership Funding Calculator[5].

4 HM Treasury (2018). The Green Book. Central Government Guidance on Appraisal and Evaluation.

[5] https://www.gov.uk/government/publications/partnership-funding-calculator-2020-for-fcerm-grant-in-aid-gia

LANDWISE Analysis

As part of the wider LANDWISE research project, JBA Consulting's contribution to Work Package 4 (WP4) was to undertake a Natural Flood Management (NFM) hydraulic modelling study to: "…Integrate evidence through dynamic modelling to explore the efficacy and scalability of land management NFM to reduce risks from surface water (pluvial), fluvial and groundwater flooding, using different rainfall, land management/policy scenarios across sub-catchment to large river basin scales…".

Hydraulic modelling was undertaken across three catchments in the Thames Basin, these are focused on the Coln (Upper Thames), **Whitewater (Loddon)** and the Pang. These catchments are situated on complex geology with the majority of the area covered by Carbonated Limestone/Chalk. This is a highly permeable geology and therefore flood risk is likely to be driven by groundwater over a period of days/weeks of high groundwater.

As a result, WP4 has made use of three different hydraulic models to try and represent the surface flows (overland flow and channel flow) resulting from complex hydrological processes within the catchments. British Geology Survey (BGS) have simulated the complex groundwater processes across the greater extents of the groundwater catchments. University of Reading have simulated Land Surface Models (LSM) of the catchment to focus on the sub surface interactions. JBA used the JFlow® 2d surface water model to combine and route (over the best available DTM) overland flow across the catchments. These different models were cascaded to better represent the hydrological processes across the catchments including the River Loddon.

As a complementary piece of work within the NERC funded LANDWISE NFM research project JBA Consulting was asked to undertake additional baseline and NFM modelling on selected sub-catchments including Bow Brook[6]. These locations were selected due to their greater proportions of the catchment which are situated upon the Mudstone (London Clay) geology. This provides a layer of impermeable geology and therefore overland flow and shallow subsurface flow becomes the key flood risk mechanism as opposed to groundwater flooding.

Bow Brook is a tributary of the River Loddon. Contributory streams rise near Ramsdell and Sherborne St John, and after flowing through rural countryside, it joins the Loddon near Sherfield on Loddon, draining an area of **44 km^2**. The majority of the catchment is covered by the Mudstone (London Clay) geology, however some of the southern catchment is underlain by the highly permeable Grey Chalk geology.

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6 2021s1059 - Additional Landwise Modelling - JBA Consulting - October 2021.

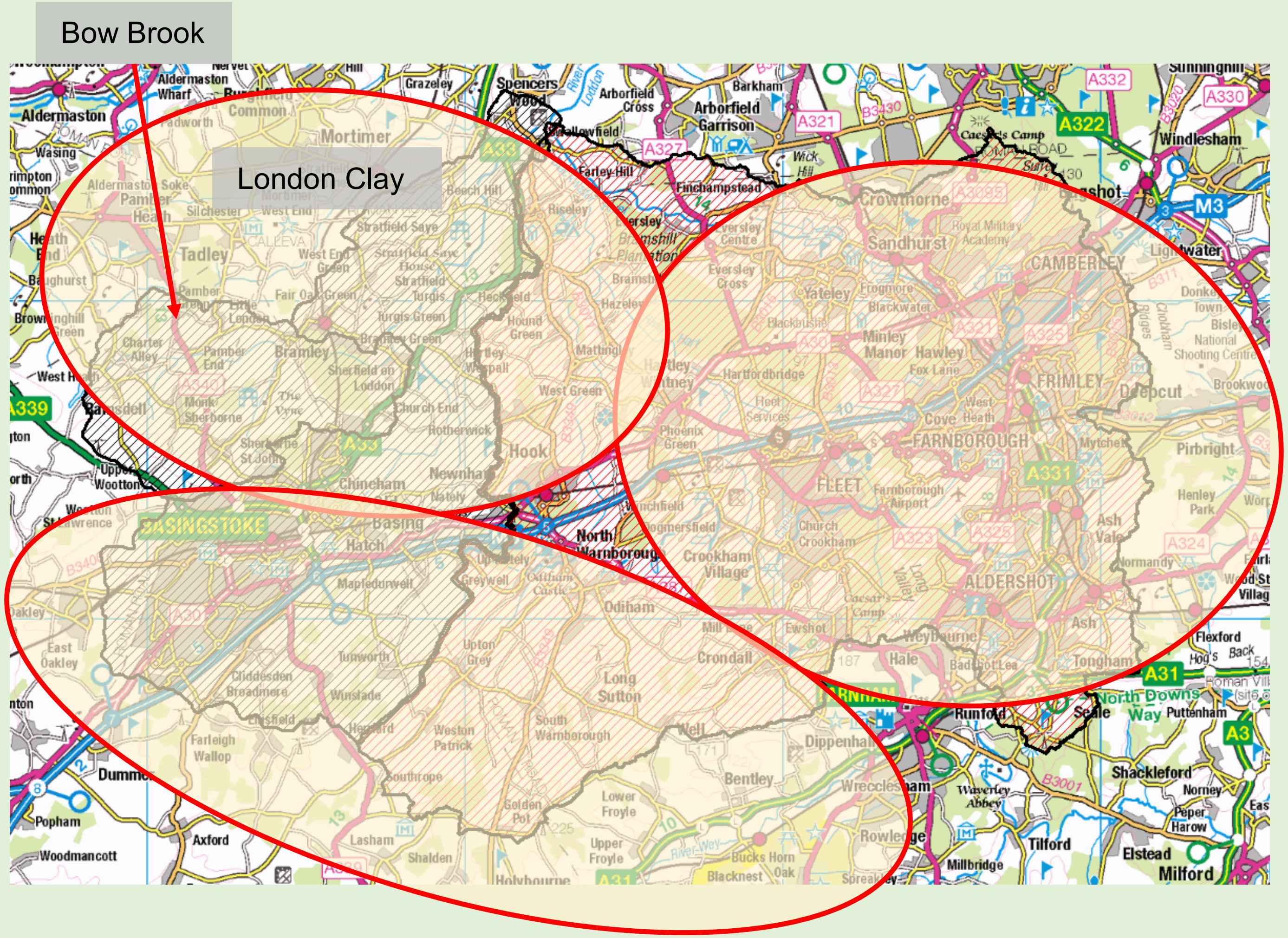

Figure 11: River Loddon geology overview with Bow Brook highlighted north of Basingstoke.

Hydraulic Modelling Set up

More information on the JFlow® Hydraulic Modelling Setup is in the modelling methodology technical note[7]. A key difference for the LANDWISE project over that for Q-NFM project has been that it was driven as a rainfall boundary using the ReFH design hyetographs from ReFH2 rather than a fluvial hydrograph boundary condition. In addition, the measures have been modelled directly by the hydraulic modelling team making assumptions about the parameter shifts, with some additional groundwater inputs incorporated from groundwater emergence provided by BGS.

7 Landwise JFlow® Modelling Methodology, internal JBA Report

Revitalised Flood Hydrograph method (ReFH) Hydrology

As a result of the impermeable Mudstone (London Clay) geology, this JFlow® 2D is derived from spatially varying gross rainfall, with representation of both rural soil infiltration, using the ReFH rainfall losses model and built-up area sewer loss rates. Rural ReFH losses are controlled by the maximum soil moisture storage capacity (Cmax) which is estimated using the catchment descriptors BFIHOST and PROPWET whilst any built-up area losses, if present, are based on estimated sewer capacity losses and percentage overland flow.

The ReFH2 model was used to generate design rainfall for input to the 2D model domain (JFlow®), which was used for modelling and testing NFM options. Groundwater emergence (modelled by BGS groundwater modellers) was supplied and scaled before applying as an additional boundary condition to the JFlow® 2d surface water model. This gives an improved representation of 'baseflow'/groundwater emergence form the Grey Chalk geology of the Bow Brook Catchment than possible using standard FEH approaches.

The hydrology was calculated for the entire upper catchment of the River Loddon as per the larger combined WP4 modelling[8]. In this way it was possible to calibrate against flow and level gauged data across the catchment to the Sheepbridge flow gauge (Figure 12).

Within the Bow Brook catchment, high resolution water quality and flow data was taken hourly from 00.00am GMT on 08/09/17 to 00.00am GMT on 09/09/18 as supporting information for PhD research (Hawkins *et al.*, 2019)[9]. Unfortunately, the flow measurement has not continued and therefore limited data is available for the hydrology. With the limited data available within the relatively impermeable Bow Brook catchment and the only flow/level river data that is available is in the "lower" catchment or upper "permeable". The verification for the critical duration is within the "lower" catchment. With a lack of data available for the upper catchment sub tributaries it is not possible to add confidence to the short intense storm duration likely to be critical in this location. It is recommended this flow data collection is continued in the future to provide local gauge adjustment to FEH estimates.

However, the data was used to sense check the baseline modelled flows, providing some confidence in the hydrograph shape from the JFlow® results when compared to the flow gauge data.

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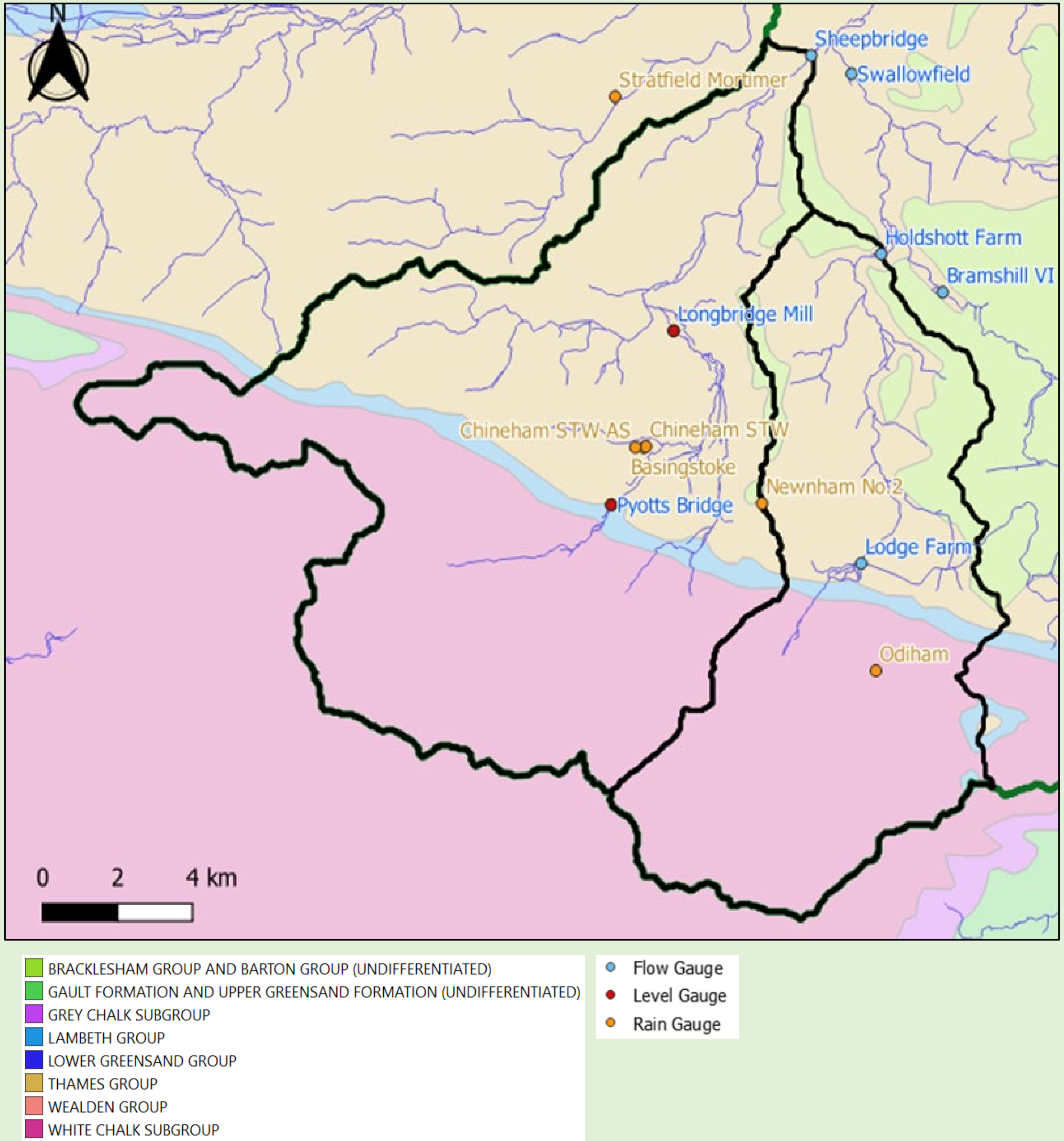
[8] JBA Consulting - Flood estimation report: Whitewater and Loddon - June 2021

[9] Hawkins, C.E; Kelly, T.J.; Loewenthal, M.; Smith, R.; Dudley, A.; Leggatt, A.; Dowman, S.; Oliver, R.G.; Collins, C.D.; Clark, J.M. (2019). High resolution water quality and flow monitoring data coupled with daily and storm samples from the Loddon catchment (Sept 2017-Sept 2018). NERC Environmental Information Data Centre. (Dataset).

Figure 12: River Loddon available hydrological data and geology overview



NFM Measures and Model Scenarios

NFM scenarios were created by Forestry Research for the Ock, Loddon, Cole and Whitewater sub-catchments. The NFM measures proposed were in-channel leaky barriers, catchment woodland and soil / land-use management as these were classed as the highest priority options within the catchment in stakeholder engagement workshops.

Two separate NFM scenarios were established, one based on the Working with Natural Processes (WwNP) maps[10] published with the Evidence Directory (Burgess-Gamble *et al.*, 2017), referred to as the "technical" scenario and one based on the stakeholder workshops, undertaken as part of the wider LANDWISE project.

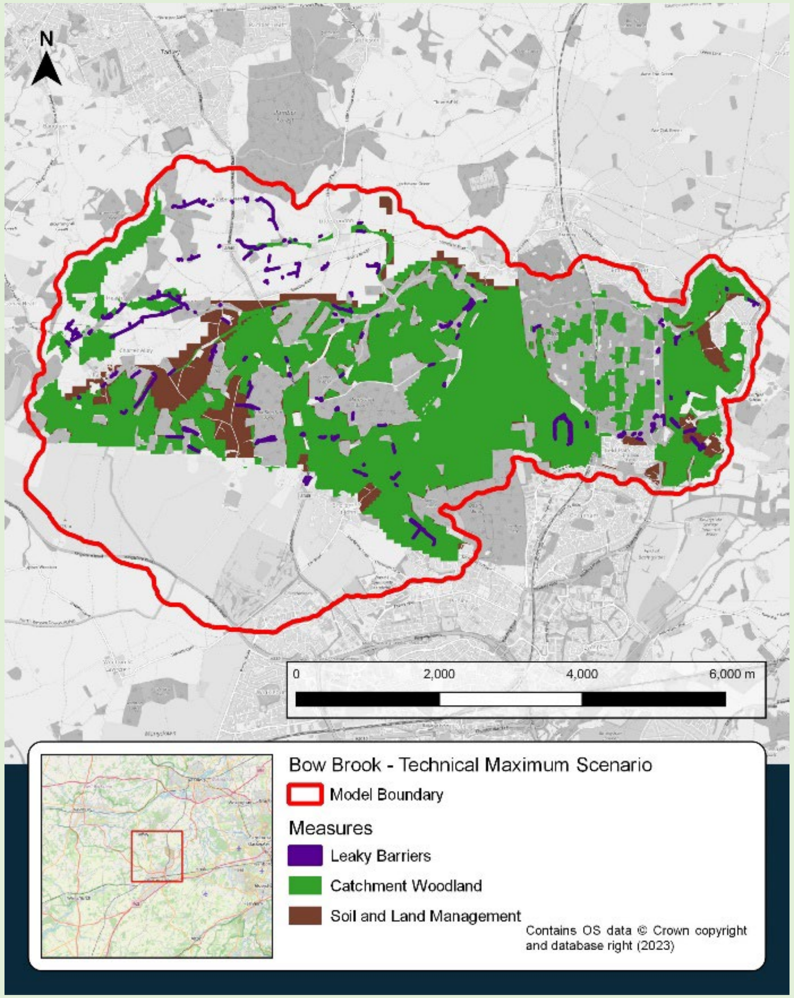
Technical Max/Refined (Scenarios 3/1 , respectively in Table 5)

The "Technical Max" scenario was based on the Working with Natural Processes potential maps which identifies areas for wider catchment woodland potential. The process targets areas where the soils are slowly permeable over a mudstone geology.

Within this scenario, this layer is used to target fields in Bow Brook for wider soil improvements. For the technical maximum, all grassland fields identified in this layer have been converted to mature woodland. Arable fields highlighted in this layer have been maintained as arable, but soil improvement measures have been applied within the scenario. This is due to productive arable land being unlikely to be converted to woodland. Within the technical and workshop scenarios, two different spatial distributions were tested, maximum extent and refined (20% catchment coverage) extent, the latter focusing measures, for example, on particular land-cover or within the riparian zone.

It should be noted that the *refined* scenarios do not always equate to 20% of the *maximum* measures, in that the refined 'technical refined' scenario comprises a larger amount of soil / land management improvements, and whilst there is a lot less catchment woodland, there is also a lot of additional riparian planting. More information is provided in the technical modelling note[7] for implementation of the scenarios within JFlow®.

[10] https://assets.publishing.service.gov.uk/media/6036c659d3bf7f0ab2f070c1/Working_with_natural_processes_mapping_technical_report.pdf



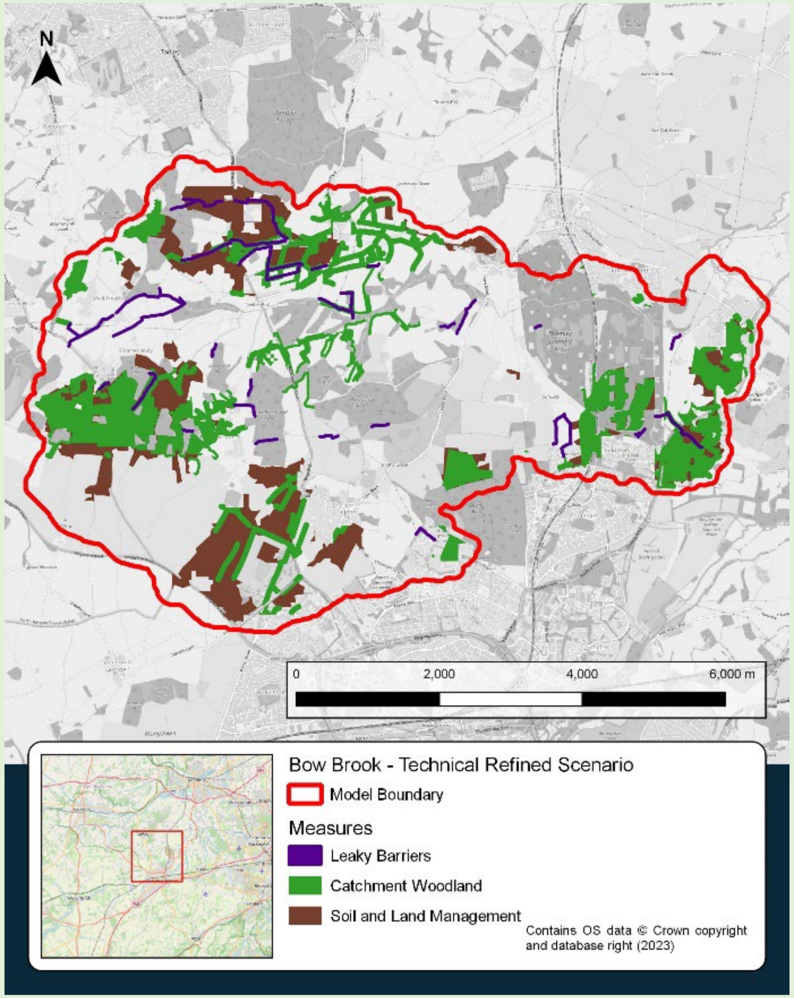
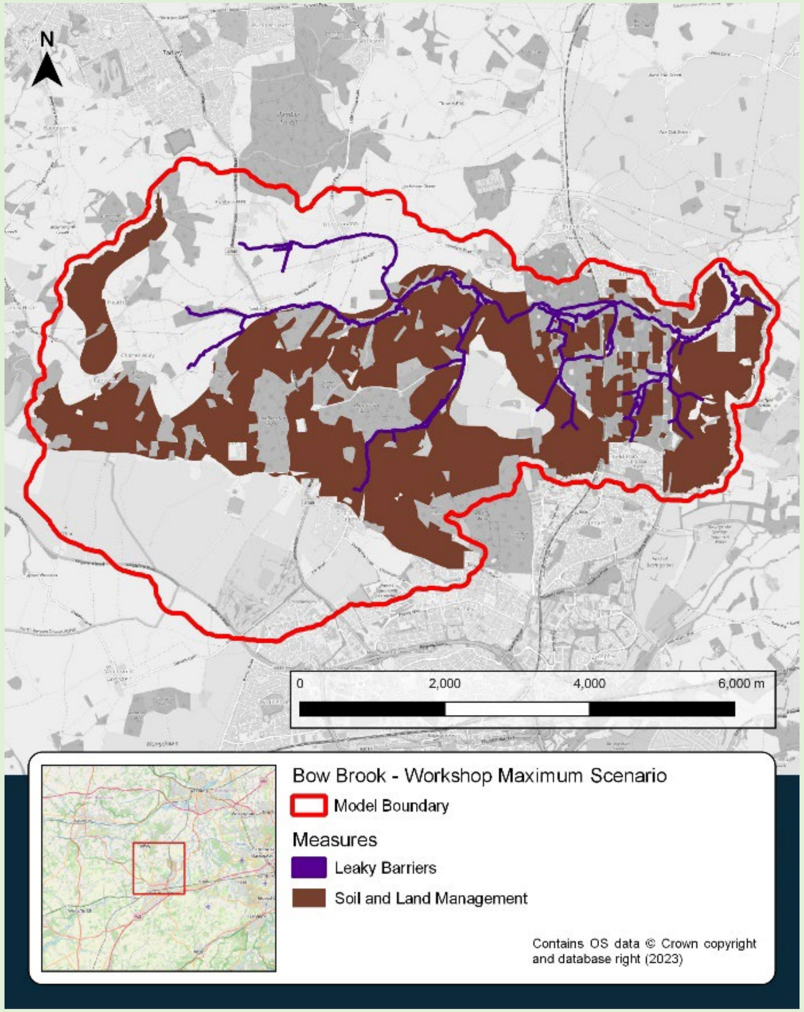


Figure 13: Bow Brook Technical Max (left) and Technical Refined (right) Scenario

Workshop Max/Refined (Scenarios 4/2, respectively in Table 5)

Within the workshop scenario all grassland and arable fields have been identified as potential locations for NFM.



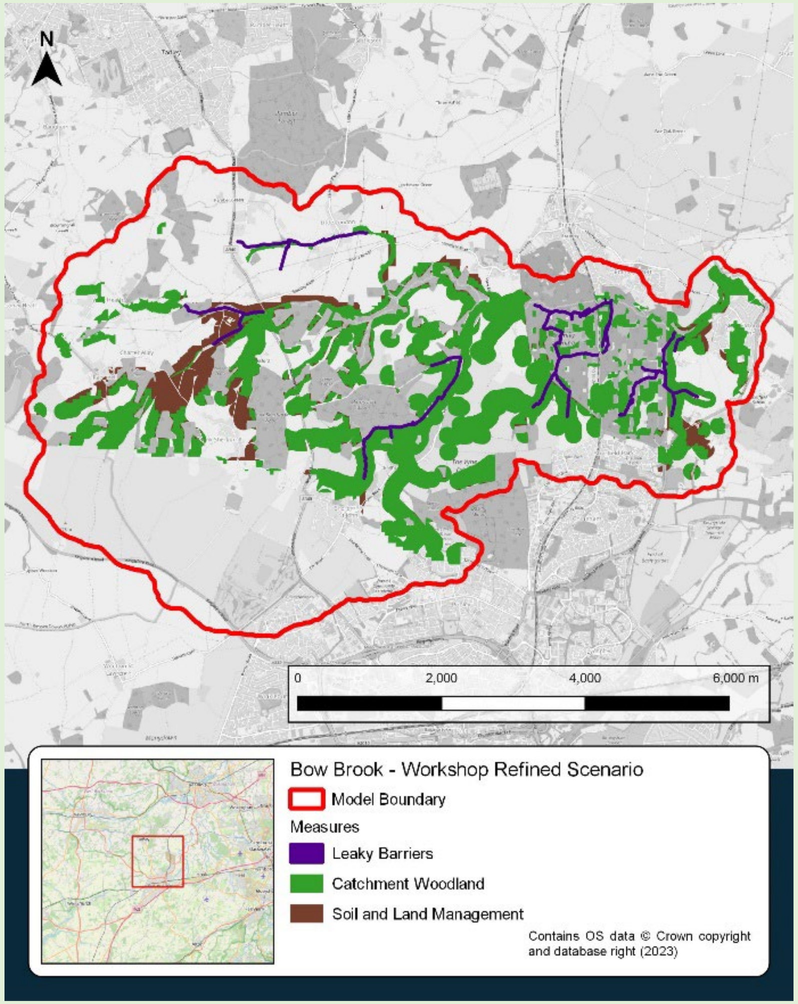


Figure 14: Bow Brook Workshop Max (left) and Workshop Refined (right) Scenario

However, within the workshop, large scale catchment woodland was not one of the highest 3 priorities for the Bow Brook landowners. Therefore, these identified fields have been prioritised for soil / land management improvements rather than woodland planting. For the refined scenario the NFM measures have been prioritised based of key flow pathways as per the Technical Refined scenario. In this case however, targeted riparian woodland has been used rather than larger scale soil improvement as this is likely to be more realistic across the catchment.

Communities at risk

The communities at risk in this lowland, low gradient catchment are small and scattered including Bramley, Charter Alley, Monk Sherbourne and Sherfield en Loddon. A key difference in this catchment from the other projects is that NFM the shallower gradients can mean more pronounced upstream as well as downstream changes in the hydraulics from NFM interventions.

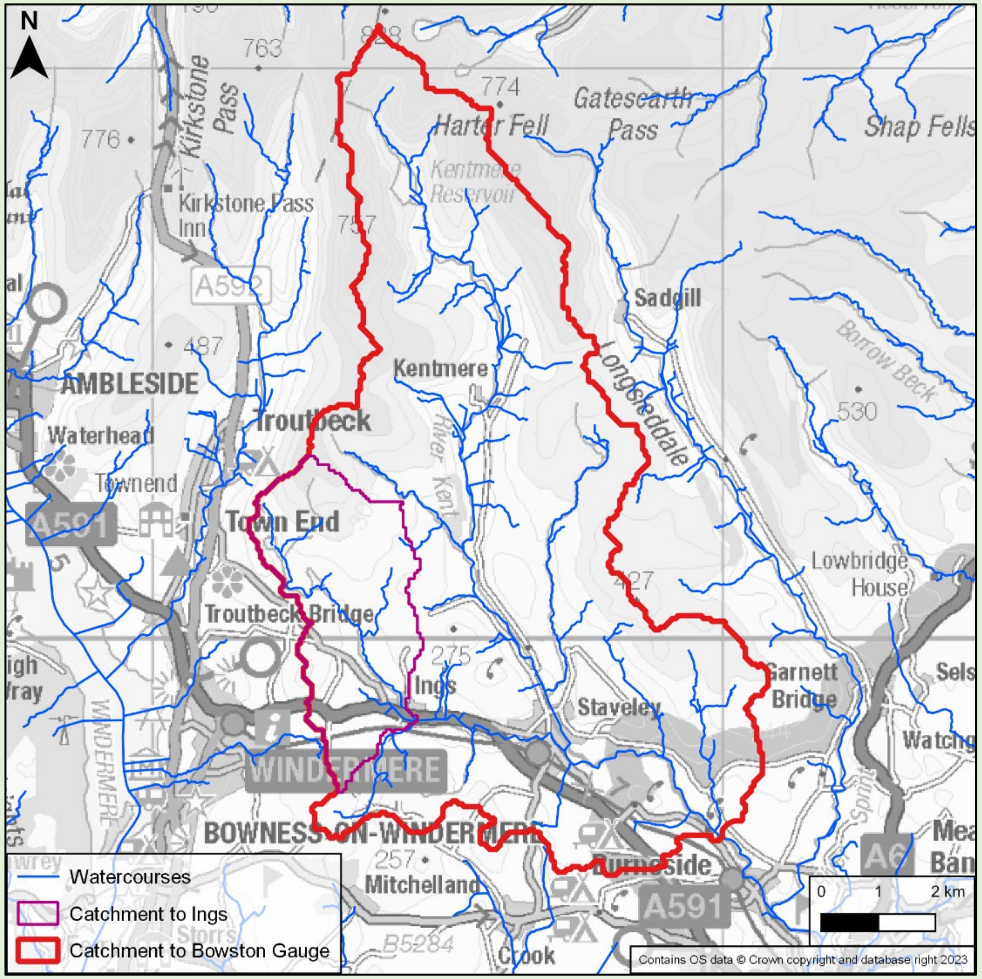
Inundation model

A high-resolution (1m) 2D model domain (JFlow®) was set up for Bow Brook, similar to the other two studies, with the exception of the boundary conditions. Here both rainfall and groundwater boundaries were used to drive the inundation. The effective rainfall design storm hyetographs produced by ReFH2 was the key forcing boundary condition, using the same flood estimation approach to the other two studies. Groundwater emergence (modelled by BGS groundwater models) was supplied directly to the JFlow® 2d surface water model using a broad inflow boundary to give a better representation of 'baseflow'/groundwater flooding within the Grey Chalk geology of the Bow Brook Catchment.

Summary for Bow Brook

Bow Brook was one of the smaller, less permeable catchments studied by the LANDWISE. For the economics modelling a range of NFM has been represented within a rainfall plus groundwater driven 2d inundation model to understand a range of measures represented in hydraulic model based on increases to friction, storage and changes to the infiltration reflecting processes researched in the project.

Q-NFM Analysis



The Q-NFM project has analysed the potential benefits of NFM within the Gowan catchment, a sub-catchment of the River Kent catchment in Cumbria. The catchment analysed includes key communities or receptors predicted at flood risk within Ings and Staveley.

The source of the River Gowan starts in the vicinity of Borrans Reservoir, flowing south east to the community of Ings, where the River Gowan drains a catchment area of **14.92 km^2** to Staveley (Figure 15)[11].

Figure 15: Catchment areas draining to Ings, Staveley and to the Environment Agency Bowston river gauge.

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[11] The catchment area is 6.6 km^2 to the northwest of Ings, this then very quickly becomes 9.9 km^2 with the southwest catchment addition, then 13.9 km^2 by the more downstream floodplain storage, then 14.9 km^2 in Staveley upstream from River Kent confluence, then 55 km^2 including the River Kent.

The River Gowan continues east to the community of Staveley where the catchment area increases to 14.92 km^2 from the River Gowan. The River Gowan and River Kent form a confluence within Staveley draining a combined catchment area of 55 km^2. The EA Bowston river gauge is situated downstream from Staveley on the River Kent, draining a catchment area of 70 km^2.

The test catchment and NFM measures represent a small proportion of the catchments modelled in Q-NFM, but provide a cross-section of the measures being more widely adopted from distributed hillslope storage to larger floodplain storage, plus woodland and soil improvements highlighted as important by partners.

Hydraulic Modelling Set-up

The upstream extent of the model domain is located upstream of Ings village, at coordinates 344155, 499193. The model domain follows the River Gowan and extends beyond the confluence with the River Kent at Staveley village. The downstream extent of the model is located at coordinates 348774, 498020, to the east of Staveley. A transmissive boundary type was applied within the model, representative of a normal-depth boundary where the efficiency of flows leaving the model is based on the slope and topography within the immediate vicinity.

To represent the 2D channel and floodplain ground topography, a DTM has been used. This has been based on the latest and highest resolution LIDAR which was flown between 2020 and 2021 at a 2 m resolution.

Roughness coefficients across the 2D model were defined to spatially vary with Ordnance Survey MasterMap land-cover. The Manning's 'n' roughness coefficients for each intended land-cover are outlined in Table 2. Buildings within the 2D model are represented with an increased roughness coefficient of 1.0 and no further additional topographic modification.

Table 2: Manning’s 'n' Roughness Coefficients

Land Use	Manning's 'n' Roughness Coefficient
Building	1.000
General Surface	0.050
Glasshouse	0.050
Inland Water	0.015
Landform - Manmade	0.040
Landform - Natural	0.050
Trees	0.080
Gardens	0.050
Fields (inc. agricultural land)	0.035
Rail Features	0.040
Roadside, Tracks & Paths	0.025
Structures	0.060
Unclassified Land	0.050

The 1D culvert units have been used exclusively for the enhanced floodplain storage scenario. Culvert invert levels have been based on the DTM channel at each face with their Manning's 'n' roughness coefficients set to 0.015. Three culverts have been applied to throttle flows through the raised bunds.

Structures within the DTM have been represented using DTM cuts, which have been used to enforce a rectangular incision into the raised ground to bring topographic levels down to adjacent channel levels. This enables the continued routing of floodwater downstream whilst providing some representation of the flow constriction provided by the raised infrastructure outside the channel. Width of DTM cuts were estimated based on Google StreetView and DTM channel-width dimensions. This approach was used at all structures within the model, and where poor DTM filtering was observed to cause blockages within the channel.

To derive hydrology estimates, catchment descriptors at five key locations along the River Gowan and River Kent were obtained from the Flood Estimation Handbook (FEH) Web Service. The catchment boundaries were compared to the DTM with catchment area and mean drainage path length (DPLBAR) descriptors updated where necessary. Peak flow estimates were derived for each catchment and return period using the Statistical Method. The ReFH method was used to generate baseline scenario design event hydrograph shapes. Catchment descriptors were imported into a ReFH boundary unit, fitting the peak of each design hydrograph to the Statistical Method peak flows.

The peak design flows were used to derive peak flow reductions factors based on Dynamic Topmodel (see the peak-matching process in Table 8 of Appendix A later in this report) for the enhanced wet-canopy evaporation and enhanced soil permeability, and enhanced hillslope storage scenarios. These results are presented in Table 3.

Hydrographs for each intervention scenario were derived by applying the percentage reduction in peak flow to the baseline design event hydrographs for modelled events having the same or very similar peak flow values for each design flow estimate. The exception to this was for the enhanced floodplain storage scenario, where the baseline design event hydrographs were applied, with modifications to the DTM to create additional storage areas as outlined earlier. In other words, this scenario was directly modelled.

Table 3: Peak flow reductions for each scenario compared to the baseline event

Return Period	Peak flow reduction compared to the baseline scenario (%)	
	Enhanced Wet Canopy Evaporation + Enhanced Soil Permeability	Enhanced Hillslope Storage only
2	15.5	4.2
5	13.2	3.6
10	13.6	7.0
20	6.4	4.0
50	5.8	1.1
100	5.1	0.7
200	3.2	0.8
1000	0.9	0.5

The adopted storm duration was 5.9 hours, with a time-step of 0.1 hours, which represents the recommended ReFH storm duration within the catchment at Staveley. The simulation for each return period and scenario was run for two times the length of the hydrograph and checked to ensure the flood peak had passed.

The application of design flow estimates involved a flow-time inflow at the upstream extent of the model, with additional inflows applied to represent both lateral area and tributary inflows such as the River Kent through to the downstream extent of the model.

NFM Measures and Model Scenarios

The project has analysed the following model scenarios which are discussed in more detail within subsequent sections:

- **Baseline event**
  - This comprises a catchment condition without any new NFM interventions.
- **1/ Enhanced floodplain storage**
  - This comprises significant additional fluvial flood storage as two distinct units within the floodplain between Ings and Staveley on the River Gowan. This scenario was developed using JFlow® as the primary model.
- **2/ Enhanced hillslope storage**
  - This comprises a network of small-scale distributed storage such as 'runoff attenuation features' or 'earth bunds' across the catchment hillslopes on the River Gowan and River Kent. These features were represented as units within Dynamic Topmodel.
- **3/ Enhanced wet-canopy evaporation and enhanced soil permeability**
  - This comprises land cover management changes designed to improve woodland cover and associated soil infiltration and drying across the catchment hillslopes on the River Gowan and River Kent. The enhanced soil permeability has been modelled based on increasing the downslope transmissivity of the upper soil layer in Dynamic Topmodel.

1/ Enhanced floodplain storage

This hypothetical scenario aims to simulate the potential benefits from including larger-scale floodplain enhancement along the River Gowan between Ings and Staveley. The storage locations have been identified at a high-level where the valley floor is not predicted to completely inundate until the most extreme events and where there may be potential to increase floodplain connectivity without adversely impacting properties. This is a purely hypothetical scenario and does not imply there are landowner permissions or a scheme being planned.

Two preliminary areas have been identified as illustrated in Figure 16. It is recognised that these areas would require landowner engagement and appropriate funding to support a change in land-use and promote environmental benefits. These areas combined cover an area of approximately 175,000 m^2 and would be predicted to **provide additional storage of approximately 145,000 m^3.**

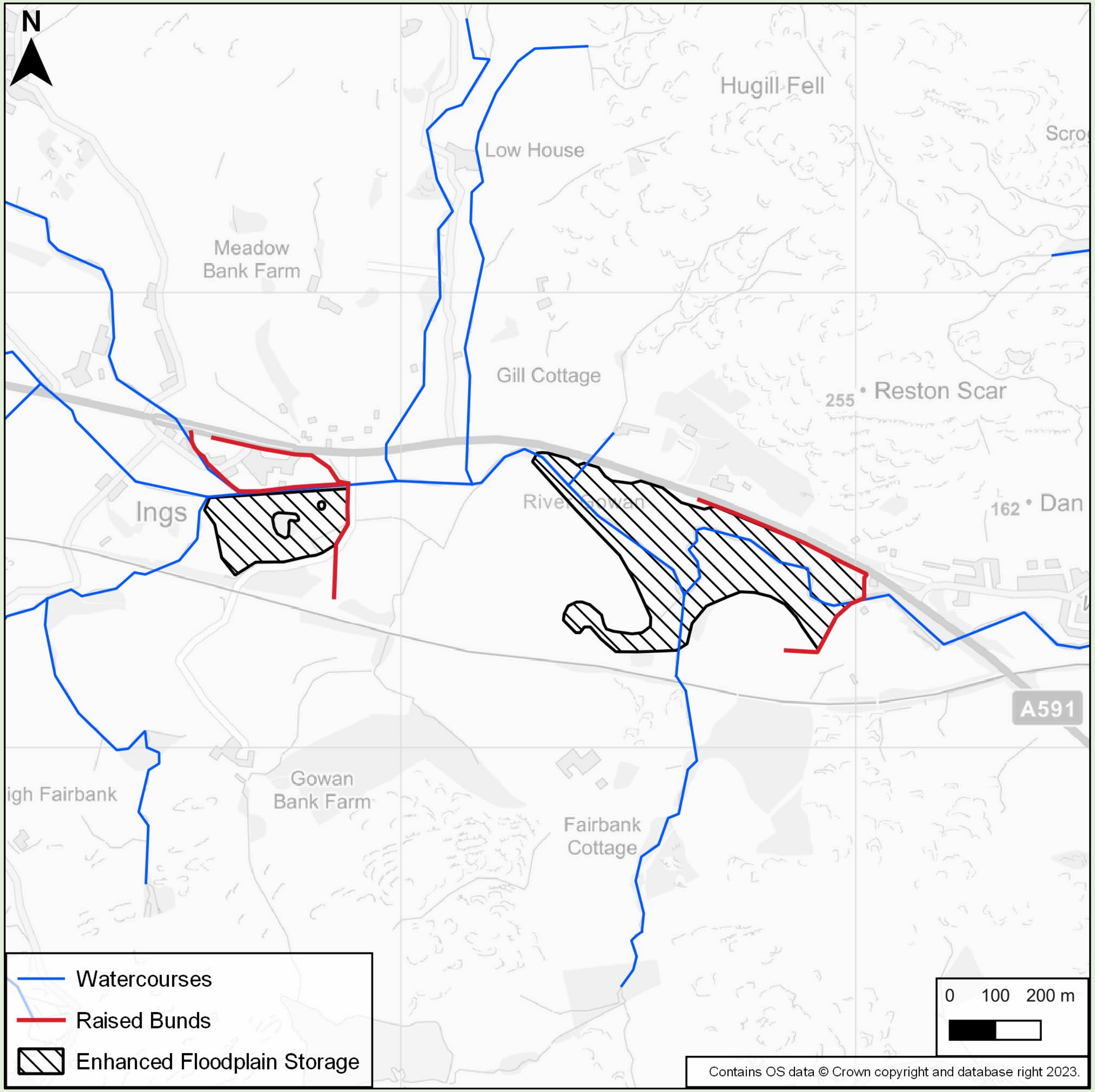

Figure 16: Hypothetical enhanced floodplain storage locations beside the River Gowan

To enhance the floodplain storage, the following interventions were necessary, although it is likely that a combination of man-made and more natural approaches may provide a similar flood risk benefit whilst further enhancing the environment. Detailed modelling, scoping and design would be required to inform specific combinations of interventions, site locations and sizes.

- **Raised bunds**
  - These were applied to areas shown in red in Figure 16 and either aim to reduce the onward conveyance of flows on the floodplain downstream or are providing localised flood risk management to property in Ings village or the A591 itself. The bund heights providing impoundment here are sized at up to 4m height although similar storage volumes may also be achievable with smaller heights in combination with re-profiling the floodplain topography within the reconnected areas.
- **Culvert capacity restrictions**
  - A series of low-flow culverts were applied where each raised bund intervention crosses the River Gowan. These culverts aimed to provide an increased throttle to flows permitted downstream whilst maintaining low-flows within the channel. The culverts promoted a backwater effect with elevated water levels predicted upstream from the raised bunds, encouraging the utilisation of additional floodplain storage and attenuating the flood hydrograph downstream.
- **Bank top management**
  - To maximise the benefit of floodplain storage it is important to consider when any enhanced storage activates and begins to be utilised. To enhance the floodplain storage considered here, localised bank top raising was applied alongside the storage locations. This aimed to manage the activation of additional storage until the flood event was further underway and prevent the storage filling too soon at the onset of the flood hydrograph.

2/ Enhanced hillslope storage

Enhanced Hillslope Storage comprises runoff attenuation features and these were represented in Dynamic Topmodel and reported in Beven *et a*l., 2022. This paper followed a similar strategy is followed to that used by Metcalfe *et al*. (2018) who showed that if they fill completely too quickly, then they will have little effect for larger events. If they drain too slowly, then there may be no remaining capacity for storage (freeboard) remaining as the next period of flood rainfall arrives. In total 1594 RAFs were represented across the whole Kent catchment, based on the EA potential Areas for Working with Natural Processes maps, and were designed to have a mean residence time for storage of 10 h.

3/ Enhanced wet-canopy evaporation and enhanced soil permeability

For this scenario, two factors were altered, controlling the increased losses associated with enhanced wet canopy evaporation (Page *et al.*, 2020) from woodland and enhanced permeability due to tree root growth. For this scenario the max transmissivity and associated m-parameters controlling the rate of the decline of the downslope transmissivity in the soil (topsoil and subsoil) were increased by 5x for 20% of the catchment hillslopes. Additionally, initial conditions for the modelling period were dried according to observed contrasts in topsoil moisture between grassland and woodland in Cumbria.

Community at risk

The Gowan catchment includes communities or key receptors predicted at flood risk at Ings and Staveley. Whilst Ings is predicted at flood risk from the River Gowan, Staveley is predicted at flood risk from both the River Gowan and River Kent. The predicted flood risk derived from the Environment Agency's Flood Map are shown in Figure 16. In addition, the A591 is a key transport route which runs parallel with the River Gowan at Ings linking the Lake District with the M6 motorway and Kendal.

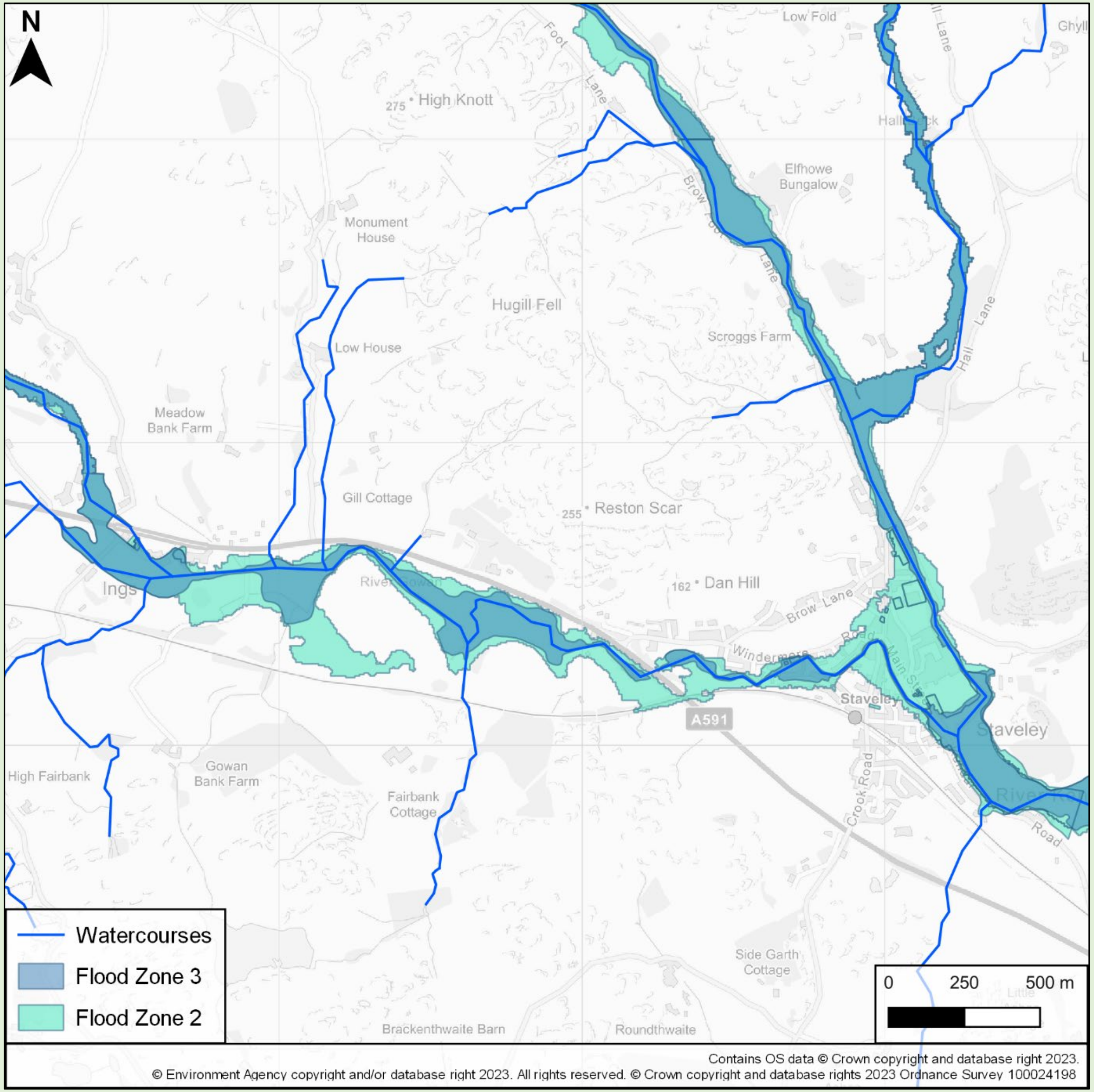

Figure 16: Environment Agency Flood Zones within Ings and Staveley

Inundation model

The extent of the JFlow® hydraulic model and predicted broad-scale 100-year (1% Annual Exceedance Probability) baseline flood depths are shown in Figure 17 together with the underlying topography. The broad-scale hydraulic model has been sized to focus on the predicted flood risk to Ings and Staveley, with flood risk outside this area not considered as part of this work.

The River Gowan flows across the model domain from west to east beside Ings, forming a confluence with the River Kent arriving from the north in Staveley.

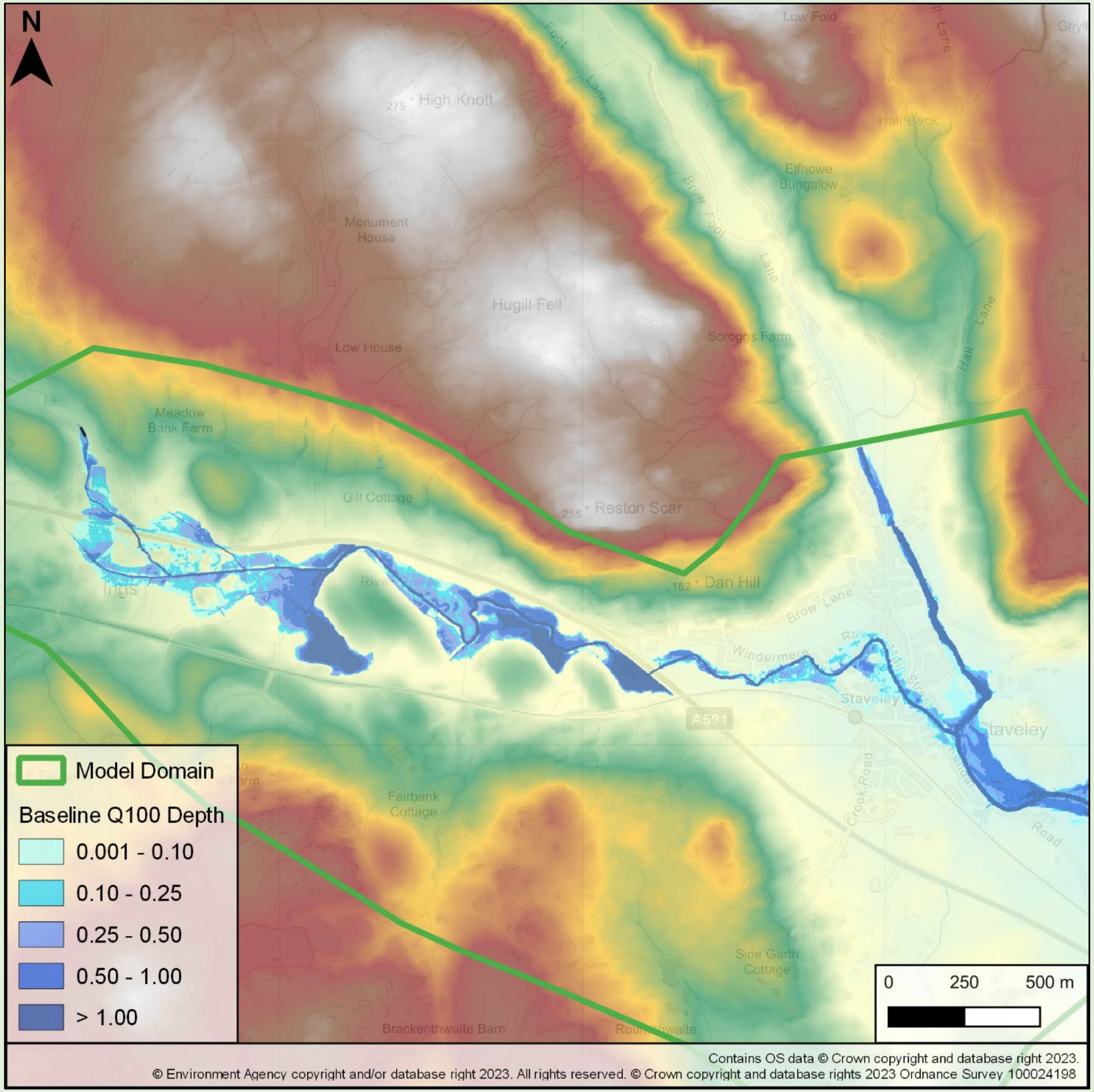

Figure 17: Predicted broad-scale baseline flood depths and ground topography through Ings and Staveley

The Q-NFM project has modelled a wide range of catchments using the rainfall-runoff model Dynamic Topmodel with continuous simulation of a series of storms having a range of magnitudes and durations, with and without a suite of up-scaled NFM scenarios. The Q-NFM modelled changes with storm severities yielding similar durations and peaks to the FEH / ReFH2 design hydrology were used to scale the design inflow boundaries in order to assign an AEP and permit quantitative economic analysis.

Results of LANDWISE and Q-NFM hydraulic modelling

The change to the hydrological response is summarised in brief to help understand how the effectiveness of NFM changes with increasing storm magnitude / severity. This also helps put in context the relative contributions to damage-reduction across the damage-probability curve and permits comparison with previous research or inter-comparison with other measures. The core results presented focus on the economic analysis, based on the modelling undertaken to route the hydrological responses and compute the impacts in the communities at risk. The resulting risk-reductions are summarised in terms of long-term average annual benefits of the NFM, and summarised based on the catchment scale and the extent of the up-scaled NFM within each illustrative catchment. The flood risk reduction benefits have also been scaled up assuming a scheme lifetime of 50 years using the recommended discounting rate, and yielding **Present-Value Damages** which can later be compared to whole life costs of the measures. This section provides summary tables based on average annual benefits, but the full tables of the economics are available in a separate Appendix B available at https://www.lancaster.ac.uk/lec/sites/qnfm/AppendixB.pdf).The wider environmental benefits of NFM are also reported based on the Outcome Measure 4 approach in the Partnership Funding Calculator.

Flood regulatory benefits of upscaling NFM

For each investigation the percentage peak flow reduction between NFM intervention and baseline are presented. Table 4 summarises these changes based on changes relative to the peak hydrograph for the modelled NFM upscaling scenarios for those models that were driven by fluvial hydrograph changes (Q-NFM) and a monitoring line at the outlet for the pluvial-driven LANDWISE model.

Table 4: Summary of changes to hydrological responses resulting from up-scaled NFM scenarios

	Return Period (years)		Enhanced Hillslope Storage only	Enhanced WCE + enhanced permeability	Floodplain reconnection with carefuly designed storage (175,000m²)	
Q-NFM 15km²	2	62.63	4.20%	15.50%	6.72%	
	5	80.37	3.56%	13.20%	9.21%	
	10	92.91	7.04%	13.60%	11.75%	
	20	106.14	3.99%	6.40%	12.78%	
	50	125.58	1.11%	5.80%	13.68%	
	100	142.22	0.74%	5.10%	13.84%	
	200	160.88	0.83%	3.20%	13.35%	
	1000	213.71	0.46%	0.90%	15.58%	
	Return Period (years)	**Baseline**	**Max Technical**	**Refined Technical**	**Max Workshop**	**Refined Workshop**
LANDWISE 44km²	2	1.54	20.14%	20.04%	28.93%	24.71%
	5	3.46	14.77%	13.16%	20.11%	15.89%
	10	4.62	14.94%	13.62%	18.29%	14.99%
	20	5.96	15.41%	12.83%	18.05%	15.16%
	50	8.12	15.28%	11.38%	17.33%	14.78%
	100	10.04	13.88%	10.00%	15.76%	13.27%
	200	13.22	18.15%	14.89%	16.52%	18.06%
	1000	26.38	14.40%	10.79%	13.49%	13.70%

It is worth revisiting the ‘Dadson Restatement’ (Dadson *et al*., 2017) that summarised NFM effectiveness based on a large evaluation of evidence at that point (Figure 18). Some of the findings in the schematic are borne-out here, with model-led design of enhanced floodplain storage in the Q-NFM project leading to some of the highest reductions, and enhanced hillslope storage (eg farm bunds) having a much greater impact at smaller storm-sizes. Whilst the effects of land-cover (notably the effects of tree planting) and soil management do tail off with increasing return period, the reduction in peak flow can still be significant at a 100 year Return Period (1% AEP) for the Cumbrian areas assessed in these scenarios.

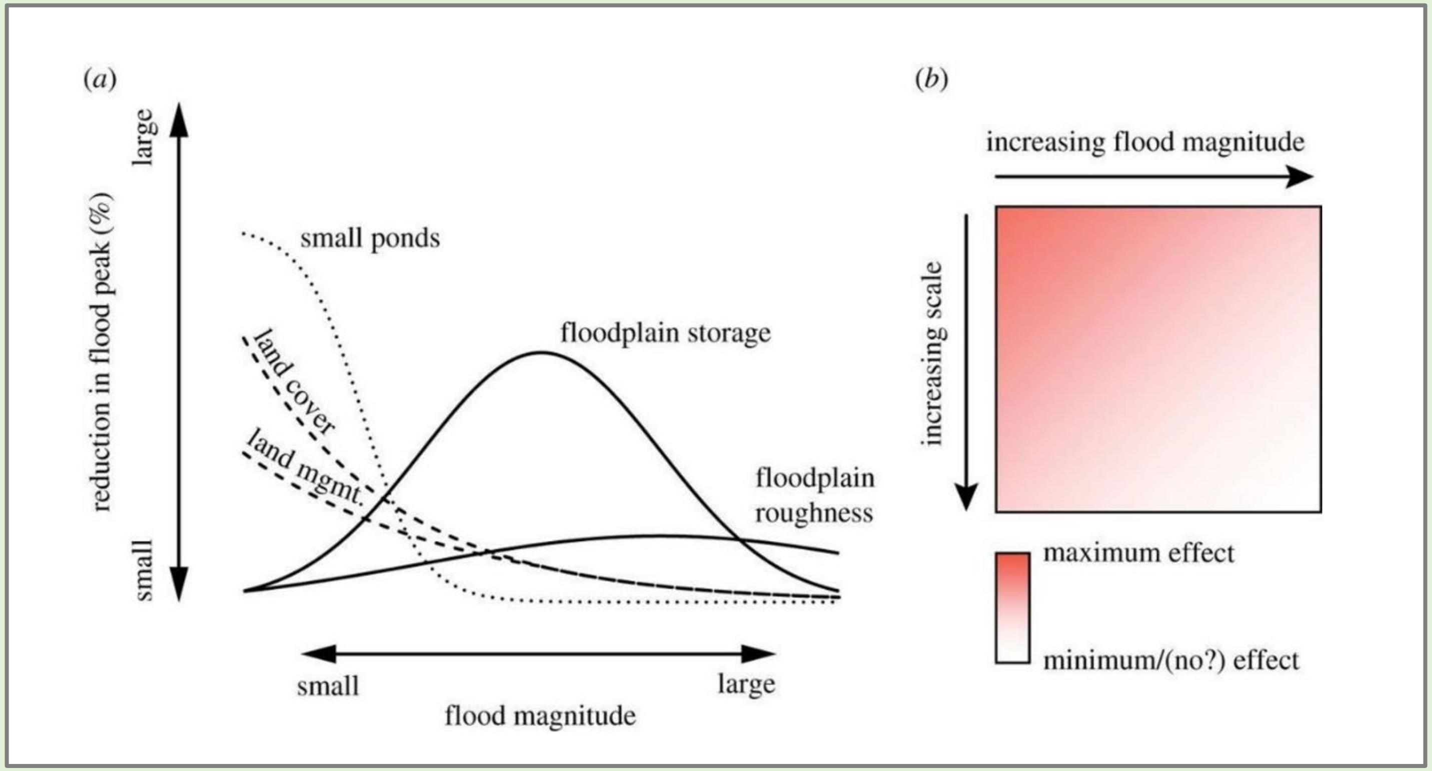

Figure 18: Summary schematic of NFM effectiveness after Dadson *et al*. (2017).

The right-hand side of the schematic (Figure 18) shows the relationship with increasing scale and flood magnitude, but it is perhaps more instructive to look at increasing proportion of catchment areas set aside for NFM (Figure 19).

Figure 19: Percentage peak flow reduction as a function of the severity of the flood event and proportion of NFM in the up-scaled catchment

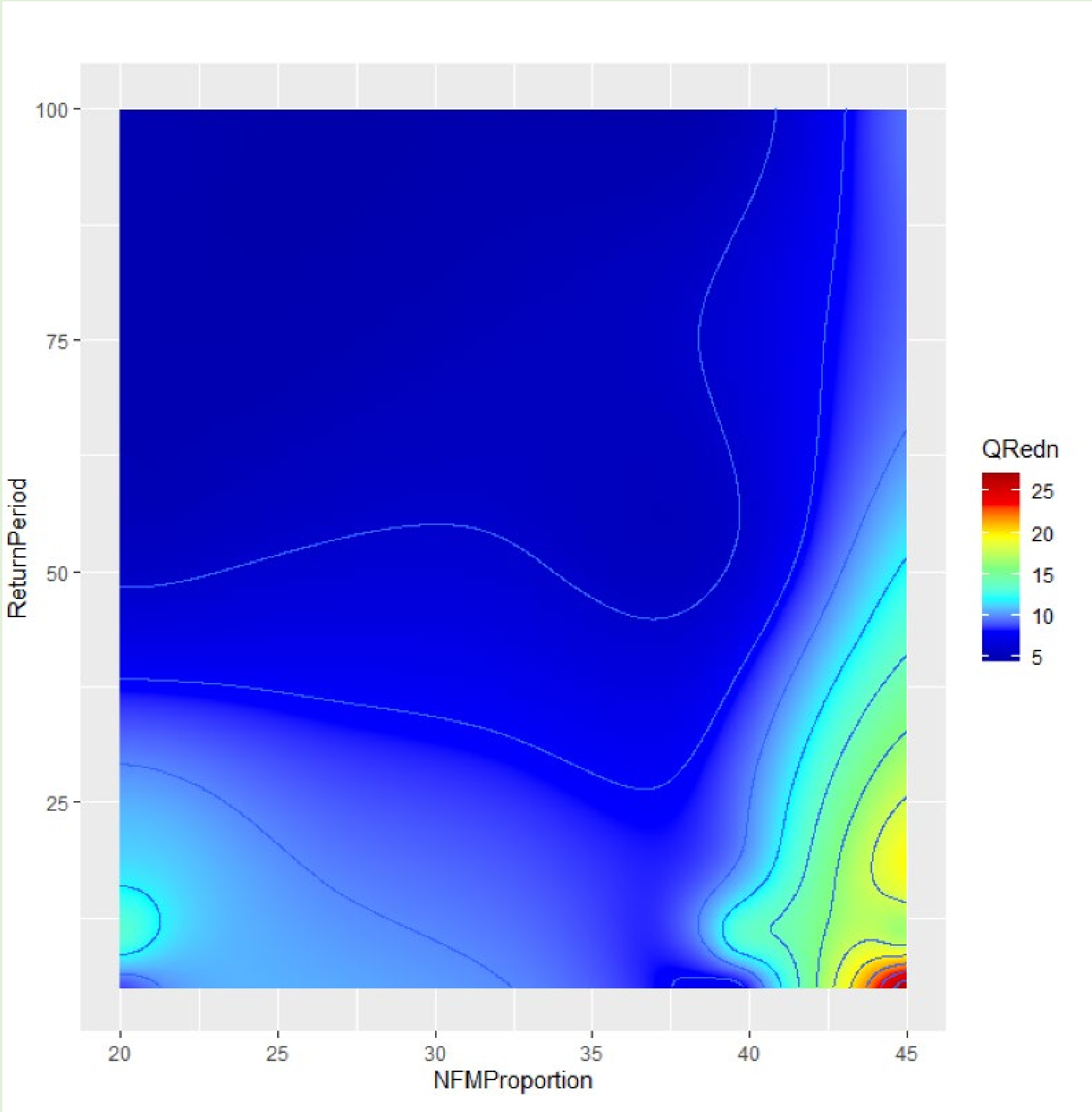

Figure 19 shows peak flow reduction as function of the storm severity (using measure of Return Period), but instead of plotting against catchment scale (Figure 18b), it uses the proportion of each modelled catchment incorporating NFM.

Whilst the results are similar to Figure 18b, in that NFM is more effective during smaller storms, this figure uses the proportion of the up-scaled catchment set aside for NFM, as opposed to the absolute scale of the catchment. Note here that there is always some peak flow reduction with a minimum of 4%, so the NFM is having some risk-reduction at high storm severities, but for the results presented there is always more than 20% of the catchment with a range of land management / land use improvements.

Economic benefits of upscaling NFM

Table 5 summarises the **Average Annual Damages (AAD)** for pre-NFM scenarios ('Baseline') and post-NFM scenarios (scenarios '1', '2' etc.), and the **resultant 'Benefit' by damages avoided**. For each illustrative catchment (**15 km^2 Gowan for Q-NFM**, and **44 km^2 Bow Beck for LANDWISE**) a range of economic damages are reported to reflect the uncertainty in the damage calculation depending on use of either the mean depth of flooding (see '**Mean**' in Table 5) or the max depth (see '**Max**' in Table 5). With further work, the uncertainty due to the model uncertainty could also be included in these ranges.

Table 5: Summary of Economic Benefits of up-scaled NFM

Q-NFM								
Scenario		**Total AAD**		**Benefit**		**Percentage Change**		**Benefits Range**
ID	**Name**	**Mean**	**Max**	**Mean**	**Max**	**Mean**	**Max**	
Basline	Baseline	£ 701,073	£ 1,440,173	£ -	£ -	0%	0%	0 - 0%
1	Hillslope Storage	£ 669,267	£ 1,376,700	£ 31,806	£ 63,473	5%	4%	4 - 5%
2	Canopy And Soil	£ 608,525	£ 1,262,162	£ 92,547	£ 178,011	13%	12%	12 - 13%
3	Floodplain Storage	£ 459,558	£ 955,936	£ 241,515	£ 484,237	34%	34%	34 - 34%
** Benefits calculated by subtracting scenarios against the baseline option*								

LANDWISE								
Scenario		**Total AAD**		**Benefit**		**Percentage Change**		**Benefits Range**
ID	**Name**	**Mean**	**Max**	**Mean**	**Max**	**Mean**	**Max**	
Basline	Baseline	£ 429,183	£ 867,326	£ -	£ -	0%	0%	0 - 0%
1	Refined Technical NFM	£ 405,574	£ 816,764	£ 23,609	£ 50,561	6%	6%	6 - 6%
2	Refined Workshop NFM	£ 429,001	£ 868,334	£ 182	-£ 1,008	0%	0%	0 - 0%
3	Max Technical NFM	£ 415,486	£ 844,160	£ 13,697	£ 23,165	3%	3%	3 - 3%
4	Max Workshop NFM	£ 422,323	£ 856,771	£ 6,860	£ 10,555	2%	1%	1 - 2%
** Benefits calculated by subtracting scenarios against the baseline option*								

It can be seen that, in general, the larger more ambitious interventions or NFM covering more of the catchment area deliver the greatest benefits, and a few smaller, refined scenarios deliver close to zero or even negative benefits. The enhanced floodplain storage scenario of Q-NFM is the closest measure to a more traditional flood-storage scheme, making use of hypothetical storage on fields just upstream of the community at risk, along with some model-led design to ensure it fills at the correct level. For the more extensive NFM scenarios, the long-term average annual flood risk reduction benefit is of the order of £200-400k, although this should be scaled up using the factor of 24.495 introduced above to understand the whole-life benefits.

These tables also require some careful interpretation and some of the titles can be slightly misleading for Bow Brook, since the 'refined' scenario name implies a proportion of the maximum scenario, whereas in actuality, the scenarios are quite different. The modelling of the refined workshop scenario includes hypothetical dense riparian tree-planting in the low-gradient Bow Brook catchment. This has led to slowing the flow upstream of some of the scattered communities, but also inevitably creating a backwater upstream. This impacted upstream communities leading to a very small net negative economic benefits. That is not to say such measures cannot work in practice if designed carefully to avoid such a situation.

It should be noted that the damages computed from the mean depth of inundation based on the MasterMap building footprints have some inconsistencies due to increased shallow flooding over footprints at higher return periods leading to lower mean depths of flooding. The use of mean and maximum depth of flooding intersecting the building footprints provides a range reflecting the uncertainty in the level of inundation.

Note: Uplifted Benefits of NFM with indirect damages

A range of indirect and intangible damages can be included in an economic damage assessment, but have been left out here for clarity, focusing on the change in direct damages only. Given the range of factors the damages and benefits could be scaled by a factor of approximately two.

Environmental Benefits of Up-scaled NFM

The Partnership Funding Calculator[12] uses the following table (Table 6) for computing the average annual environmental benefits of schemes that improve habitat or river restoration.

Table 6: Outcome Measure 4 Environmental Benefits per unit area (ha)

Outcome Measure 4 Payment tariffs			
Natural capital FCERM GiA tariff		20	p / £1
Assumptions for habitat improvements - annual benefit			
Habitat type	Poor	Moderate	Good
Intertidal habitat	£ 1,860	£ 6,410	£ 10,970
Woodland	£ 1,100	£ 3,440	£ 6,450
Wet woodland	£ 1,100	£ 3,440	£ 6,450
Wetlands/wet grassland	£ 670	£ 2,040	£ 3,410
Grassland	£ 60	£ 110	£ 490
Heathland	£ 90	£ 1,400	£ 2,720
Ponds/lakes	£ 670	£ 2,040	£ 3,410
Arable land	£ 30	£ 50	£ 60
Assumptions for river improvements - annual benefit			
Intervention types			**Benefit (£ /km/yr)**
Comprehensive restoration of physical modifications			£ 13,200
Partial restoration of physical modifications			£ 6,600
Improvements to fish passage (distance to next barrier)			£ 3,300

Some basic assumptions have been made as described in Table 6 for the NERC projects to estimate additional environmental benefits of the more extensive NFM scenarios.

Environmental benefits for NFM are typically greater than the flood risk reduction benefits, and here based on the maximum interventions, there is a factor of at least ten. Over a scheme lifetime of 50 years, the net present value of these average annual benefits should be multiplied by a similar factor used for the flood risk damages of 25.495, yielding whole life benefits of between £50m-£0.5b per catchment (for the most extensive NFM scenarios). It should be noted that the additional environmental benefits are typically weighted by 20% before using in a benefit cost calculation when attracting partnership funding.

12 https://www.gov.uk/government/publications/partnership-funding-calculator-2020-for-fcerm-grant-in-aid-gia

Project	NFM Scenario	Area of upscaled NFM (ha)	pre restoration (ha)	post restoration (ha)	Average Annual Environmental Benefit
			Poor Grassland	*Good Wetland*	
Q-NFM	(1) Wetland from floodplain reconnection	8	£ 60	£ 3,410	£ 26,800
			Poor Grassland	*Woodland*	
	(3) Tree-planting and permeability improvement	300	£ 60	£ 6,450	£ 1,917,000
			Grassland	*Woodland*	
LANDWISE	Technical max 20% 44km² = 850 ha	850	£ 60	£ 6,450	£ 5,431,500

Table 7: Estimate of Average Annual Environmental Benefits of up-scaled NFM (the land use change in the italics based on the closest approximate match in Table 6)

Environmental benefits for NFM are typically greater than the flood risk reduction benefits, and here based on the maximum interventions, there is a factor of at least ten. Over a scheme lifetime of 50 years, the net present value of these average annual benefits should be multiplied by a similar factor used for the flood risk damages of 25.495, yielding whole life benefits of between £50m-£0.5b per catchment (for the most extensive NFM scenarios). It should be noted that the additional environmental benefits are typically weighted by 20% before using in a benefit cost calculation when attracting partnership funding.

Conclusions of illustrative economic analysis

A series of illustrative examples of economic benefits of a diverse range of NFM measures investigated across the NERC NFM programme have informed NERC's overall objective of *Understanding the effectiveness of natural flood management*. The measures have encompassed a selection of NFM interventions, designed to help slow, store, evaporate, or infiltrate flood water and enhance catchment flood resilience through emulation of natural systems including soil permeability improvements; woodland planting; peat restoration (including gully-blocking); in-channel leaky barriers; enhanced hillslope storage on mineral soils and floodplain enhancement storage.

This investigation has only covered a sub-set of the research undertaken across the NERC projects forming the NFM programme, covering a cross-section of upland hillslope, lowland farming and moorland catchments. The two catchments with areas of 15 or 44 km^2 are a sample chosen in which to test the economic benefits in more detail across a range of design storms.

The NERC investigators have also assessed and modelled up-scaled NFM in larger catchments (eg Beven *at al*., 2022; Hankin *et al*., 2021ab, 2022, Goudarzi *et al*., 2021) that were also **modelled with other illustrative economic analysis of risk reduction for the very large Storm Desmond event in Beven *et al.* (2022).**

The two catchments and respective NFM types considered for the illustrative economic analysis were:

- **LANDWISE Bow Brook: area 44 km^2**
    - Soil and land management improvements
    - Wider woodland planting
    - Riparian planting
    - In-channel leaky barriers
- **Q-NFM River Gowan upstream of Staveley: area 15 km^2**
    - Enhanced soil permeability and enhanced wet canopy evaporation
    - Enhanced hillslope storage
    - Enhanced Floodplain storage

The approach taken used consistent, high resolution flood inundation modelling for the selected catchments and models the change in hydrological response for a set of design-events used to drive these models resulting from up-scaled NFM measures. The modelled maximum depths of inundation have been used to query the expected economic damages following standard practice for flood risk appraisal to estimate the long-term annual average direct damages in the communities at risk.

Across the more ambitious, up-scaled NFM deployments investigated here, long-term average annual flood risk-reduction can still be relatively small of the order of £200k-£400k, although over a scheme lifetime of 50 years, this equates to the order £5m-£10m. Add to that the indirect and intangible damages avoided this could increase by a factor of two.

However, as expressed by the interval of damages quoted, there is often uncertainty in these types of estimates, and there are cases where relatively smaller NFM measures can have little impact, and some cases where the measures, without careful siting, can make things worse. For example, modelling theoretical dense riparian tree-planting in the low-gradient Bow Brook catchment, led to slowing the flow upstream of some communities, inevitably creating a backwater upstream and this impacted an upstream community with some small negative economic benefits. That is not to say such measures cannot work in practice if designed carefully to avoid such a situation.

An analysis of the percentage reductions to the peak hydrograph response at the communities at risk also shows that some types of NFM can, under some circumstances, work for larger floods, whereas this is not typically the case for traditional flood risk management measures such as embankments. Once the design level of an embankment or defence is reached, there tends to be no additional storage. Therefore, whilst the flood risk-reduction benefits of carefully designed NFM require supplementing with other measures, they also provide a complimentary resilience to traditional measures which can especially help in larger catchments with increased rainfall from climate change.

The environmental benefits for up-scaled NFM measures were also estimated, using the Partnership Funding Calculator Outcome Measure 4. Over a similar 50-year lifetime would equate to approximately £0.5b (unweighted), a large multiplier of the flood risk-reduction benefits, which has often found to be the case with NFM.

Recommendations from the economic analysis

From this illustrative economic analysis, emulating Natural Flood Management requires some careful design and siting of measures within a catchment, and computational models can be used to help appraise the risk across the whole catchment system. Much like for traditional measures, it is recommended that there is an element of model-led design when NFM is up-scaled for small to intermediate catchments to ensure its effectiveness.

If carefully designed, NFM can add complimentary resilience to traditional measures to give a more integrated flood risk management (IFRM) approach. Whilst these flood risk reduction benefits are not hugely significant even for larger NFM deployments greater than 20% of a catchment area, there are significant environmental co-benefits, and it is concluded that carefully designed up-scaled NFM in larger catchments remains an important strategy. The more effective NFM investigated here were found to be the larger enhanced floodplain storage features, broad-scale soil improvement and tree planting measures across a larger proportion of land, and contingent on typology.

Up-scaled NFM requires careful targeting and modelling over a range of scales, but most types NFM can generally be represented in the kinds of hydraulic models used to appraise risk for traditional schemes, informed by the outputs of the three NERC projects. This is especially the case if the boundaries of those models extend upstream and include more of the upstream areas where there is space for NFM. It can also mean developing more integrated catchment models or hillslope models that include the functionality to represent a range of distributed hydrological processes.

The good news is that these types of models and integrated approaches, and how they can be adapted to represent NFM, have taken a step forward in the NERC projects and are now more widely available to use in practice.

Appendix A: Hydrograph matching analysis for Q-NFM

For Q-NFM the changes to the peak flows for the wider catchment enhancement scenarios were based on modelling of the whole Kent catchment, and the percentage changes at the first available river gauge (at Bowston) were used with modelled peaks that were similar in magnitude to the set of FEH design flows. These are provided in Table 8. The floodplain enhancement scenario did not require matching as the design hydrographs were modelled explicitly.

Table 8: Summary of peak flow reductions and matched hydrographs in Q-NFM (WCE = Wet Canopy Evaporation).

			Dynamic Topmodel scenario name	**nr_t0m_20_500_25_20XX_1**		**raf_100_10_20XX_0**		**nr_t0m_20_500_25_raf_100_10_20XX_1**	
RP Design storm	**FEH Design Qpeak m3/s**	**Matched Peak from DynaTop**	**Data and matched profile**	**Enhanced WCE + enhanced permeability**	**Enhanced WCE + enhanced permeability**	**Enhanced Hillslope Storage only**	**Enhanced Hillslope Storage only**	**EHS EWCE RAF**	**Everything**
2	62.54	64.34	15/11/2015 5%ile 63.16 m3/s	56.51	12.2%	61.64	4.20%	55.55	13.7%
5	80.22	75.56	24/11/2009 95%ile is 75m3/s	65.6	13.2%	72.87	3.56%	62.39	17.4%
10	92.68	88.63	10/01/2005 95% 88.63	77.45	12.6%	83.29	6.03%	73.45	17.1%
20	105.78	109.45	22/12/2015 109.5 m3/s 95%	102.42	6.4%	105.08	3.99%	97.14	11.2%
50	124.98	137.89	19/11/2009 137 m3/s 5%	129.88	5.8%	136.36	1.11%	129.23	6.3%
100	141.38	145.68	19/11/2009 peak median	139.37	4.3%	136.78	6.11%	138.8	4.7%
200	159.63	163.05	8/ 1 /2005 upper pecentile 160	160.09	1.8%	164.03	0.83%	159.14	3.8%
1000	211.13	197.14	Dec 2015 peak (~200m3/s)	195.44	0.9%	196.23	0.46%	190.08	3.6%

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Soil as a technique of natural flood management

The LANDWISE project has demonstrated that soil physical and chemical properties underpin natural flood management (NFM) measures in lowland catchments and are determined by land use, soil type and management

Evidence highlights the importance of Land Use and Soil Type in determining the near-surface hydrological properties of soils and their subsequent impact on supporting NFM measures. The effect of land use on these properties was greater than soil type, but both are significant. Land use and management can significantly enhance soil physical and hydrological/hydraulic properties and flood mitigation potential. Soil porosity is higher in soils under permanent pasture or woodland management. Under these land use types, water infiltration is higher and allows more water to penetrate the soil, slowing its flow.

In arable systems, the addition of grass or herbal leys into the rotation reduces soil bulk density and increases soil porosity compared to arable rotations without leys. Supporting rotations with these grass/herbal leys increase surface roughness and could help improve soil structural properties in subsequent parts of the rotation. In arable systems, trafficked areas, such as tractor tramlines, had significantly higher bulk densities and lower soil porosities compared to un-trafficked areas of the field and headlands. Using controlled traffic management of farm machinery localises compaction, maintaining higher average porosity across the field as a whole. Increasing soil organic matter improves soil structure and thus improves soil porosity. When soils have lower soil organic matter contents, small increases in soil organic matter can increase soil porosity significantly. NB. Not all soils can easily accumulate high amounts of soil organic matter, for example, sandy soils. Addition of organic matter, reduced tillage, and incorporation of grass or herbal leys into arable rotations increased soil organic matter and soil porosity. This supports increased infiltration of water and percolation through the soil, reducing surface runoff and associated flood risk. Soil bulk density and soil porosity measurements are useful measures of NFM potential of soils.

Farmers interacting with the LANDWISE project favoured soil-based NFM measures that support continued agricultural use, such as cover crops and minimal tillage, and were resistant to woodland creation incentives, preferring more support for soil and land management practices.

It should be noted that many co-benefits are associated with the changes in land management or use associated with NFM measures. These are likely to include reduced soil erosion, improved soil biodiversity and associated nutrient cycling to support crop growth, improved resources and habitats for wildlife associated with woodland creation and the use of cover crops.

Evidence Base

The physical and chemical properties of soils are inherently linked to their capacity to allow water to infiltrate and be stored within them. Consequently, soil is a critical resource for natural flood management schemes. Soil is a heterogeneous mixture of mineral (sand, silt and clay) particles, organic matter, water and air (in pore spaces) and living organisms. Interactions among soil composition inform its properties at a given time point or place. The assembly of mineral particles into aggregates and the pore spaces created between them inform the soil structure (Figure 20), which includes the density and porosity of the soil (especially pore size distribution and connectivity) and these soil properties regulate the flow of water, oxygen and nutrients through the system (Hartmann and Six, 2023). Improving soil properties, can help mitigate floods and also enhance soil productivities (Ellis *et* al., 2021).

Source: https://smallgrains.wsu.edu/soil-structure-critical-for-soil-stability-and-crop-production

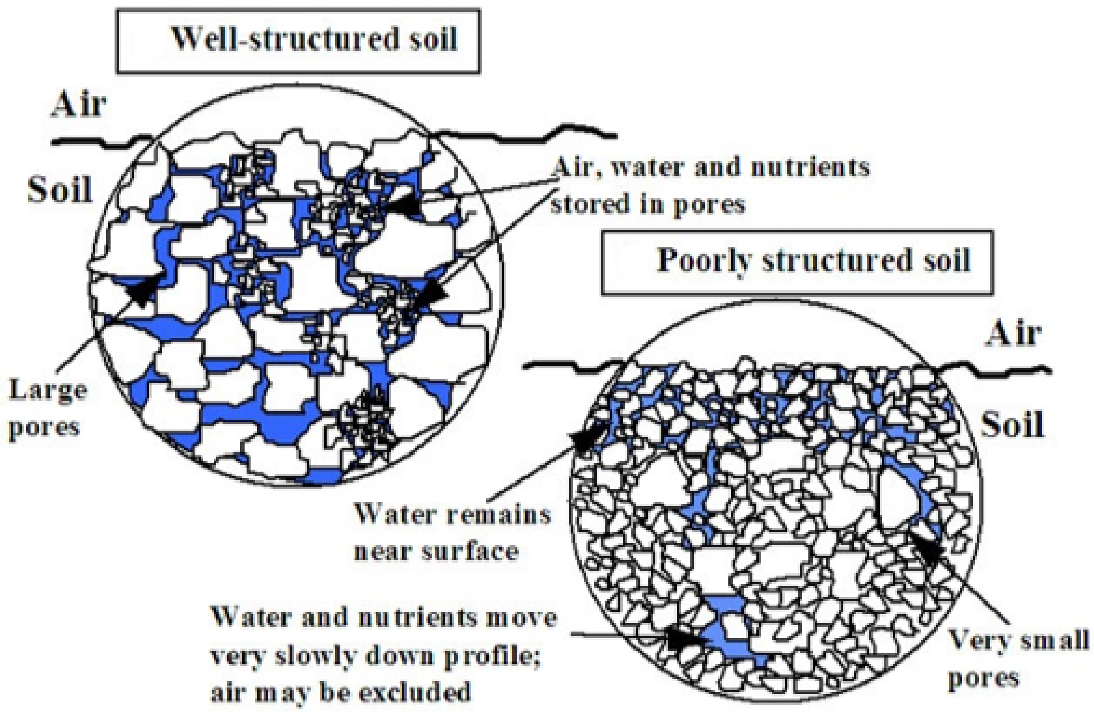

Figure 20: A sketch showing arrangement of soil aggregates and pore spaces between a well-structured soil and a poorly structured soil

Soils provide a number of ecosystem services, which include moderation and purification of water flows (FAO and ITPS, 2015). In this context, soils accept, store, transmit and clean the water and these roles are interrelated. Soils store water in pore spaces to support plant growth and soil biodiversity, thereby supporting food production and controlling soil erosion. Soils capacity to store water depends on its ability to accept incident water (e.g., rain) through its infiltration capacity (or topsoil permeability). Higher infiltration capacities help to reduce overland flow and erosion, so helping to reduce flood risk. The structural stability, porosity and permeability of soils determines the capacity of soil to store, accept and transmit water through the soil and this capacity can be enhanced through improved land use management.

Soil type, slope and land use and management can alter both the properties (including its hydrological properties) and functions of soils. For example, soil disturbance, through tillage can disrupt both the soil aggregates and influence soil porosity. Tillage activities might involve full inversion down to 30 cm (traditional ploughing) through to minimum or no tillage, where shallower depths of soil are disturbed (min-till) or the soil is left undisturbed (no-till). These activities can lead to formation of a reduced permeability sub-surface 'plough pan' and compaction of pore spaces by dispersed particles (Figures 21 and 23). These processes will in turn alter the flow of water through the system (Sander *et al*., 2008). Maintaining good soil aggregate stability is closely related to soil organic matter content and improving soil organic matter content is critical to soil aggregate formation and stability (Řezáčová *et al.*, 2021). When dry soil is rewetted, soil aggregates can be subjected to disruption through slaking, shrinkage or swelling, whereas, soil organic matter (SOM) stabilizes soil aggregates against these processes by increasing cohesion and decreasing the wetting rate (Bérard *et al.*, 2015). However, the relative importance of soil aggregate stability depends on key soil characteristics like pore size distribution and the intensity of previous wet-dry events. In addition, the type of land use, or changing land use and management could affect soil properties and function. For instance, land use management that frequently disturbs (e.g., increased frequency of cultivation) soil will increase the tendency for soil aggregate disruption (reduce aggregate stability), increase soil bulk density and reduce soil organic matter (or C) content (Six *et al*., 2000). These effects will then affect the ability of soil to infiltrate and store water and transmit it through the system. Monitoring of soil properties at field- and catchment-scales, by assessing impact of land use and management on soil properties relevant to infiltration and water storage, will be essential for the development and monitoring of NFM strategies.

Global changes in weather patterns, including increases in extreme weather events and changes in land use through urban development have resulted in flood events that are more likely to impact on properties and livelihoods. Nature-based solutions to mitigate flooding are being sought across Europe and UK by researchers and policy makers Use of off-line water storage, river restoration, leaky debris dams and land use management are examples of NFM approaches which are gaining increasing interest as effective methods of NFM (Monger *et al.*, 2022a). Soil and land use management can include different measures such as conservation tillage, reduced/sensitive vehicle trafficking, early sowing of crops, addition of organic amendments, altered stocking density in grasslands, planting of hedge rows and buffer strips, the use of cover crops in crop rotations etc. (e.g., Bond *et al*., 2022, Monger *et al.*, 2022a). These approaches may be able to reduce peak flows by slowing and storing overland flow and enhancing infiltration into the soil.

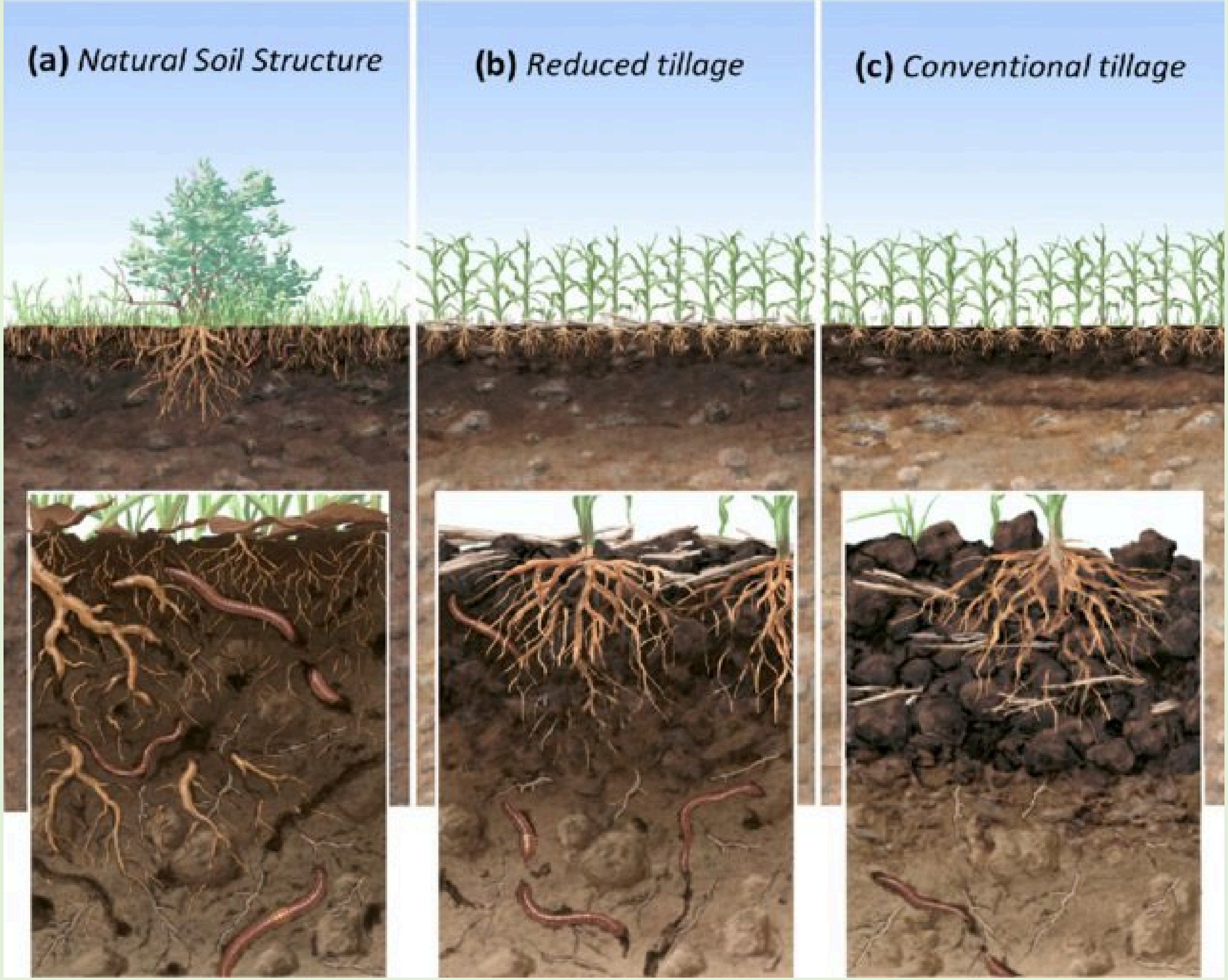

Figure 21: A sketch showing soil structural features under natural (a) reduced tillage (b) and conventional tillage (c). Both soil type, fauna and climate interact to shape natural soil structure. Reduced tillage management are characterized by higher biological activities, compared to conventional which is characterized by mechanical fragmentation of the top layer and consequent coalescence and consolidation of the loose structure.

Source: Or, D., Keller, T., and Schlesinger, W. H. 2021. Natural and managed soil structure: On the fragile scaffolding for soil functioning, Soil Tillage Res., 208, https://doi.org/10.1016/j.still.2020.104912

The potential of land use management as a NFM strategy depends on its ability to influence overland flow through hydrological processes such as infiltration into soil (Monger *et al.*, 2022b). Woodland planting or restoration can have significant impacts as a NFM strategy, with direct effects on infiltration (Chandler *et al*., 2018; Ellis *et al*., 2021). Comparing soil properties in pasture and mature semi-natural broadleaf woodlands showed increased permeability in the topsoil in woodlands compared to low-density grazing pastures (Monger *et al.*, 2022b). Yu *et al*. (2008) examined the functions of soil in regulating rainwater under three land uses – cultivated cropland, non-cultivated land and orchards inter-planted with cash crops using rainwater regulation ratio. Their results showed that orchards inter-planted with arable crops was more effective in regulating rainwater than the other two land uses.

The LANDWISE findings to quantify the impact of different land use and management strategies on key soil properties that affect infiltration and water storage across the main soils type in the West Thames catchment (Blake *et al*., 2022) and other available data within the NFM projects

LANDWISE or the "Land management in lowland catchments for Integrated Flood Risk Reduction" project is one of three NERC funded projects that formed the natural flood management research programme. We evaluated the effectiveness of realistic and scalable land-based NFM measures to reduce the risk from flooding from surface runoff, rivers and groundwater-fed lowland catchments. These measures were evaluated for their potentials to increase infiltration and below-ground water storage. The evidence from the LANDWISE project includes soil near-surface physical and hydrological properties, vegetation observations and land use and management information across the lowland Thames catchment (UK). It was collected during the **LANDWISE project's 'Broad-scale field survey' which sampled 1836 locations across 164 fields/land parcels** (Figure 22). The aim of the survey was to quantify the impact of land use and management on soil properties, with implications for NFM. The surveyed fields were selected to represent four broad land use and management classes (arable with grass/herbal leys in the rotation, arable without grass in rotation, permanent grassland, and broadleaf woodland) and five generalized soil/geology classes (Table 8).

Approximately eight fields were sampled for each of the twenty combinations of land use and soil/geology class. The sampled fields cover a range of traditional and innovative agricultural practices. Within each field/parcel, representative sampling locations were selected to cover the anticipated range of soil variability, including typical in-field areas, un-trafficked margins and trafficked headlands/tramlines. Sampling was undertaken once during the period 2018-2021. Samples were measured and analysed using a range of field and laboratory techniques. The **data (Blake *et al*., 2022) is archived in the Environmental Information Data Centre (EIDC)**, which is part of the Natural Environment Research Council's (NERC) Environmental Data Service and is hosted by the UK Centre for Ecology & Hydrology (UKCEH)**.** Further details about the broad scale survey of near surface soil properties can be found in the repository.

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Figure 22: Landwise Broad-scale field survey sites (yellow dots) overlain on a map of the Thames catchment (upstream of Maidenhead), also showing sub-catchments and Landwise target soil/geology classes. Typically, several fields/land parcels were sampled at each survey site.

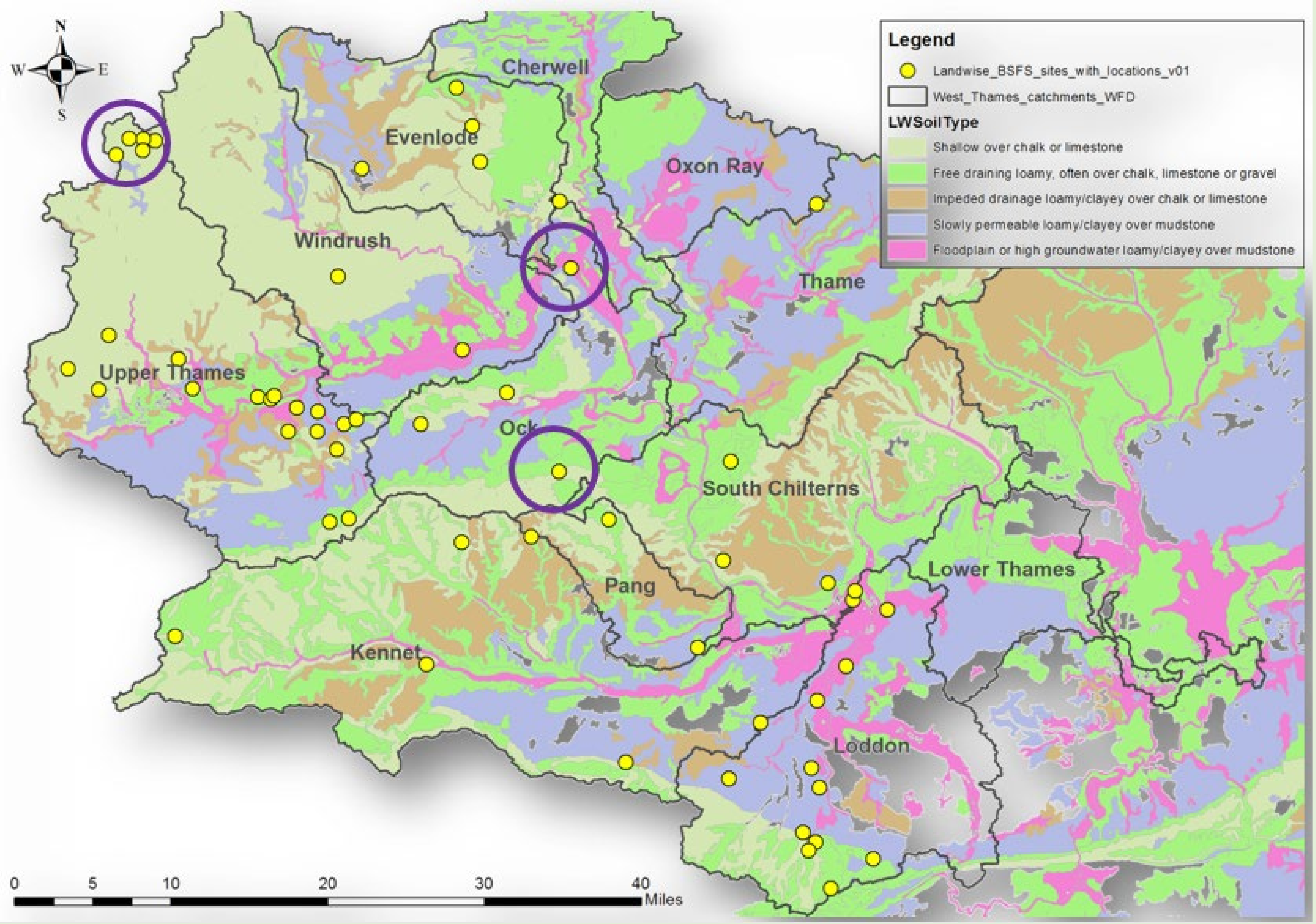

Table 8. Landwise broad-scale field survey sampling distribution across soil/geology and land use/management classes. Cells coloured blue indicate where the target of sampling 8 fields per cell was met, green - almost met, and amber - fewer sampled than anticipated.

Geology	**LANDWISE Soil Type**	**SSEW Higher Categories (Soil Type)**	**Land use and management**			
			Arable		Grassland (permanent, est. 5+ yr.)	Woodland (broadleaf, mature)
			Rotation with grass*	Rotation without grass		
Carbonate (Chalk, Limestone)	Shallow over chalk or limestone	Lithomorphic	8 + 6	9 + 1	8	8
	Free draining loamy [1]	Brown	9 + 1	8 + 1	8	8
	Impeded drainage loamy/clayey	Pelosol/Argilic brown earths	4	9	8	8
Mudstone	Slowly permeable loamy/clayey	Surfacewater Gley	8	8	8	8 + 1
	Floodplain or high groundwater loamy/clayey	Groundwater Gley	4	7	8	8

***** including grass-only rotation (e.g., dairy), not just grass as break crop

[1] sometimes also over gravel superficial deposits overlying mudstone.

Summary of LANDWISE findings on soil as an NFM tool

Soil Dry Bulk Density

Soil bulk density varies with land use and soil type and there was a significant interaction between these two factors. Soils from arable systems without grass/herbal leys in the rotation had higher soil bulk densities compared to soils from arable systems with grass/herbal leys in the rotation. Soils from permanent grasslands and woodlands had the lowest soil bulk densities. Soils from arable systems without grass in the rotation resulted into higher bulk densities under in all soil types, while grassland and woodland land uses had the lowest soil bulk density irrespective of the soil type. In arable fields, sampling location influenced the degree of soil compaction measured through bulk density. Trafficked tramlines/headlands had higher soil bulk density compared to the in-field areas, and the un-trafficked field margins had the lowest soil bulk density. Soils managed with no-till tillage management and from arable systems with grass/herbal leys in the rotation showed lower soil dry bulk density of infield areas compared to other combinations of tillage and land management methods.

Soil Porosity

Estimated soil porosity (accounting for variable soil organic matter content) varies with land use and soil type and there is a significant interaction between these two factors. Soils from woodlands and grasslands had higher porosities compared to soils of arable systems with grass/herbal leys in the rotation. Soils from arable systems without grass in the rotation had the lowest porosities, irrespective of soil type. However, arable with grass in rotation improved soil porosity especially in floodplain and shallow soils (Groundwater Gley and Lithomorphic soil) compared to soils from arable systems without grass in rotation on similar soils. In arable fields, sampling location influenced the soil porosity. Higher soil porosity was observed in un-trafficked field margins, followed by the in-field areas. The lowest soils porosities were observed in samples from trafficked headlands/tramlines. This risks the creation of preferential flow pathways for surface water to move through the landscape, particularly with tramlines-oriented downslope on steeper terrain. Soils managed with no-till tillage management and from arable systems with grass/herbal leys in the rotation improved soil porosity of in-field areas compared to other combinations of tillage and land management methods.

Soil Organic Matter

Soil organic matter content was affected by land use and soil type and there was a significant interaction between the two factors. Woodland and grassland soils were characterized by higher soil organic matter contents, which was generally more than double that of soils from arable systems without grass/herbal leys in the rotation. Soils from arable systems with grass/herbal leys in the rotation had higher soil organic matter compared to soils from arable systems without grass/herbal leys in the rotation. Grassland and woodland land uses had higher organic matter irrespective of soil type. In general, increasing soil organic matter content increased soil porosity. In arable fields, sampling location influenced the percentage soil organic matter content. Higher organic matter contents were found in soils from un-trafficked field margins compared to in-field areas and trafficked headlands/tramlines. Soils managed with no-till tillage management and from arable systems with grass/herbal leys in the rotation improved the soil organic matter content of in-field areas compared to mixed tillage management in arable systems with grass/herbal leys in the rotation or min-till and ploughed tillage practices in arable systems without grass/herbal leys in the rotation.

Soil Aggregate Stability (Slaking and dispersion)

Soil aggregate stability, measured using a slaking and dispersion test, was significantly greater in soils from grassland and woodland land use types compared to soils from arable systems. For arable systems, soils under crop rotations including grass/herbal leys were more likely to resist slaking compared to soils under rotations without grass/herbal leys. In general, relative to soils from arable systems without grass/herbal leys in the rotation, slaking is 4, 38 and 63 times less likely to occur in soils from arable systems with grass/herbal leys in the rotation, woodlands and grasslands respectively. Relative to soils from arable systems with grass/herbal leys in the rotation, slaking of aggregates is 10 and 17 times less likely to occur in woodland and grassland soils respectively.

Further discussion

Our findings revealed that the flood mitigation potential of various soil types found in the River Thames Catchment, a lowland catchment, can be improved using land use and land management methods. One of the properties of soil that determines how much water can be stored is its porosity. Using soil for grassland (e.g., permanent pasture) or woodland will significantly improve soil porosity compared to when used for arable farming. However, when arable soils are in rotation with grass or herbal leys, soil porosity is improved compared to arable rotations with grass or herbal leys. Improvement of soil porosity when used for grassland or woodland could be because there is little or no soil structural disturbance that would lead to clogging of soil pore spaces and the consequent reduction in soil bulk density under these land uses relative to arable systems. Furthermore, as outlined below, the increased soil organic matter generally found in woodland and grassland soil increases soil aggregate stability, which will promote improved soil structure, reduced bulk density and increased porosity. In arable systems, soils in trafficked headlands or tramlines had higher bulk density and lower soil porosity compared to un-trafficked margins, with porosity in infield areas between these two extremes. Soils managed with no-till tillage management and from arable systems with grass/herbal leys in the rotation, had lower soil bulk density and higher soil porosity. Wallace *et al.* (2021) compared hedge-margin overland flow, topsoil permeability (infiltration capacity) and found that, hedge-margins improved not only the soil properties and permeability but also produce less overland flow. They found significantly higher bulk density, higher organic matter, and lower soil porosity in topsoil within agriculturally improved pasture compared to hedge margins, which they attributed to the growth of tree roots. Their findings further support our observations that minimising traffic or compaction can improve soil hydrological properties and enhance their potential to mitigate floods. In terms of soil types, floodplain, and shallow soils (Groundwater Gley and Lithomorphic soils) inherently had higher soil porosity and lower soil bulk density compared to the other soil types measured. However, these soil properties were further improved when floodplain and lithomorphic soils were under woodland or grassland management. When heavier soils (eg Surfacewater Gleys), which had lower bulk density and higher porosity, were used for grassland or woodland they had higher soil porosity and lower soil bulk densities compared to when these soils were used for arable production. Improving soil organic matter is very important to enhancing infiltration capacity and soil water storage due to its direct and indirect effects of soil hydrological properties.

Increasing **soil organic matter** will enhance a soil's potential to mitigate flooding due to its direct effects on soil structural stability and indirect effect on porosity and permeability. For instance, increased organic matter and the subsequent increases in soil fauna activities will result into greater pore spaces which in turn will lead to a higher infiltration capacity (Alexandra and Benites, 2005).

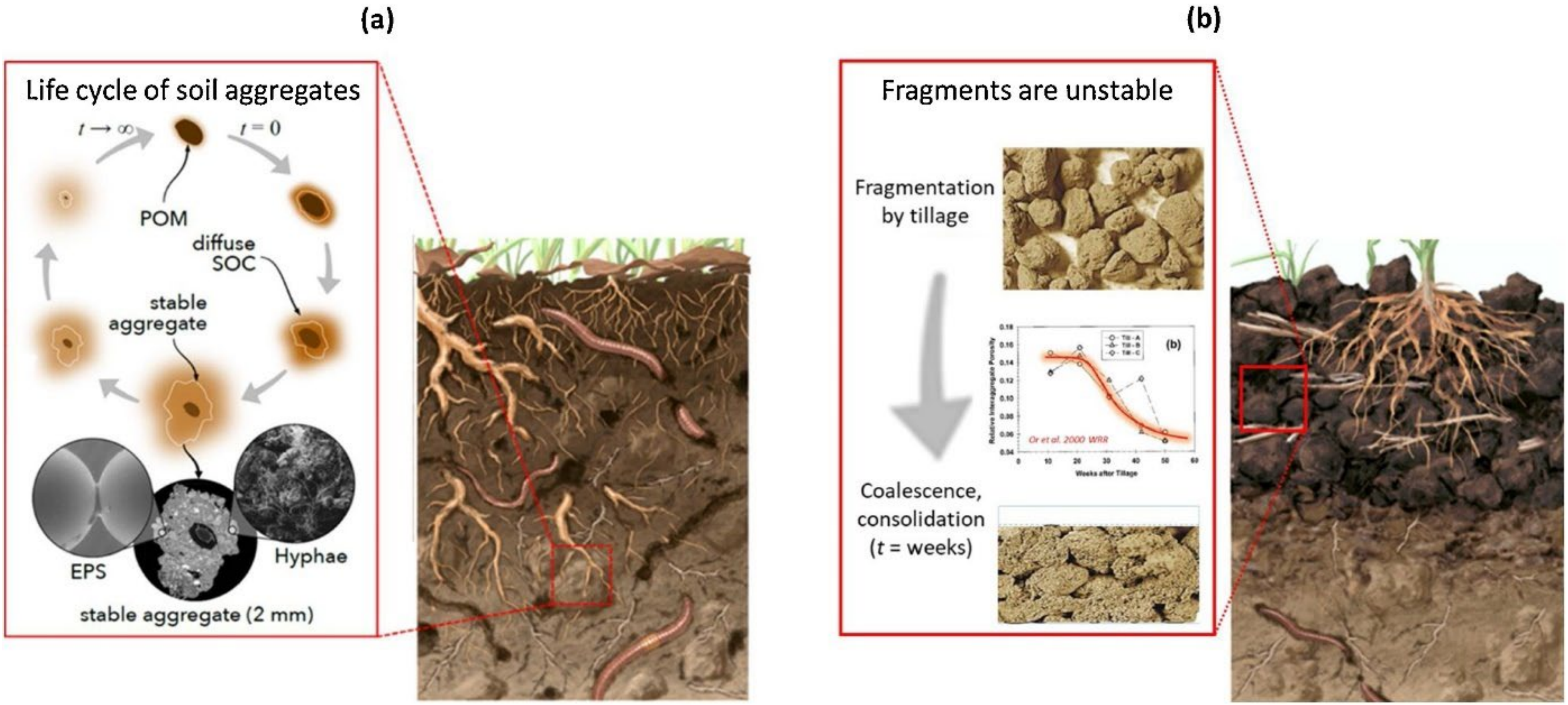

Figure 23: An image showing Stable aggregates (a) and fragmented soil structures (b). Stable aggregate is enhanced through products of biological activities where polymeric substances (e.g., particulate organic matter) and hyphae stabilizes and bind soil particles together. Also, soil fragmentation resulting from tillage operation tend to be weak and coalesce upon wetting disrupting macropores.

Source: Or *et al*. (2021)

Within the LANDWISE study, soil organic matter was 119% and 68% higher in soils from woodlands and 104% and 56% higher in soils from grasslands land compared to soils from arable systems without and arable systems with grass/herbal leys in the rotation respectively.

However, including grass in the rotation improved soil organic matter in arable systems. The higher soil organic matter contents of woodland and grassland soils coincide with higher soil porosity, and lower soil bulk density. In addition, improving soil organic matter by including grass in rotations in arable systems also resulted in higher soil porosity and reduced soil bulk density compared to when grass or herbal leys were not included in rotation. LANDWISE also found that grassland and woodland soils supported more structurally stable soil, by improving soil aggregate stability compared to soils from arable systems and that soils from arable rotations with grass or herbal leys in the rotation supported more stable soil structure compared to soils from arable systems without grass in the rotation. Effects of land use and management on soil structural stability could be a result of increased organic matter and products of organismal activities in binding aggregate and strengthening soil structure against disruptions (Or *et al.*, 2021; Figure 23).

Differences in ability of each soil type to accumulate soil organic matter follows a similar pattern as bulk density and soil porosity. Higher accumulation of soil organic matter in Groundwater Gley and Lithomorphic soils coincided with lower soil bulk density and higher soil porosity. Also, Surfacewater Gley and Brown of this study had the least soil organic matter, a higher bulk density and lower soil porosity. However, when Surfacewater Gley and Brown soils were covered by woodland and grassland, there was greater organic matter in the soil compared to these soils under arable land uses. LANDWISE also found that tillage and arable without grass rotations reduced the level of soil organic matter which in turn reduced porosity and increase soil bulk density.

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