Calderdale NFM Study

Final Report

Environment Agency

June 2022
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This document has 95 pages including the cover.

Document history

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Rev 3.0	Final Report	SM	CS	EG	EG	June 2022

Client

Client	Environment Agency
Project	Calderdale NFM Study

Contents

Abbreviations

Abbreviation	Description
1D/2D	1 dimensional / 2 dimensional
AAD	Average Annual Damage
AEP	Annual Exceedance Probability
AHP	Analytic Hierarchy Process
ALC	Agricultural Land Classification
B£ST	Benefits Estimation Tool
BAP	Benefits of Ecosystem Services
BD	Bulk density
BEIS	Department for Business, Energy and Industrial Strategy
BFIHOST	Base Flow Index based on Hydrology of Soil Types
BGS	British Geological Society
BL	Baseline
C	Carbon
COVID	Coronavirus disease
DEFRA	Department for Rural Affairs
DMMF	Daily Based Morgan–Morgan–Finney
DPLBAR	Mean of distances between each node on the IHDTM grid and the catchment outlet
EA	Environment Agency
ENCA	Enabling Natural Capital Approach
ET	Evapotranspiration
FARL	The Flood Attenuation by Reservoirs and Lakes
FAS	Flood Alleviation Scheme
FC	Field capacity
FCERM-AG	Flood and Coastal Erosion Risk Management – Appraisal Guidance
FEH	Flood Estimation Handbook
FSA	Flood Storage Area
GDP	Gross domestic product
GHG	Greenhouse Gasses
iCASP	Yorkshire Integrated Catchment Solutions Programme
ICM	Integrated Catchment Management
IF	Interflow
Ks	Hydraulic conductivity
LFA	Less Favoured Areas
LiDAR	Light Detection and Ranging
LNR	Local Nature Reserve
LR	Land Runoff
mAOD	Metres above ordnance datum
MCDA	Multi-criteria decision analysis
MCH	Multi-Coloured Handbook
MCM	Multi-Coloured Manual Handbook
MFFP	Moors For the Future Partnership
MFTF	Moors For the Future
NC	Natural Capital

NEA	National Ecosystem Assessment
NFM	Natural Flood Management
NRD	National Receptor Database
NUTS2	Nomenclature of territorial units for statistics
NWEBS	National Water Environment Benefits Survey
OG	Operational Group
OM2	Outcome Measure 2
OM4	Outcome Measure 4
ONS	Office of National Statistics
OPT1, OP2, OPT3	Option 1, Option 2, Option 3
OSMM	Ordnance Survey MasterMap
P	Phosphorus
PHI	Priority Habitat Inventory
PSO	Partnership and Strategic Overview
PV	Present Value
PVb	Present Value benefits
PVd	Present Value damages
Q	Superficial runoff
Q100	1 in 100 year flood
QMED	Mean annual maxima flood
R Eff	Effective rainfall
ReFH	Revitalised Flood Hydrograph Model
RoFSW	Risk of Flooding from Surface Water
SAAR	Standard Annual Average Rainfall
SAC	Special Area of Conservation
SD	Soil depth
SEPA	Scottish Environment Protection Agency
SoP	Standard of Protection
SPA	Special Protection Area
SPR	Standard Percentage Runoff
SPRHOST	Standard percentage runoff (%) associated with each HOST (Hydrology of Soil Types) soil class
SPZ	Source Protection Zone
SSSI	Site of Special Scientific Interest
SW	Soil water store
SW	Soil water
SWc	Soil water capacity
SWini	Soil Water Initial conditions
T2, T10, T20, T50, T100	1 in 2 year flood, 1 in 10 year flood, 1 in 20 year flood, 1 in 50 year flood, 1 in 100 year flood
TUFLOW	Flood, Urban Stormwater & Coastal Simulation
URBEXT2000	Index of urban and suburban land cover in 1990 / 2000 expressed as a fraction
WFD	Water Framework Directive
WWNP	Working With Natural Processes
θ ini	Initial soil conditions

Introduction

Welcome to the Natural Flood Management (NFM) report for the Calder Catchment within Calderdale that flows through Todmorden, Hebden Bridge, Mytholmroyd, Sowerby-Bridge and Brighouse.

This report has been commissioned by the Environment Agency and presents the results of a tool called NFM Studio that estimates the likely benefits that NFM (and associated natural capital benefits) might provide across the Calder Catchment within Calderdale.

The report also summarises the outputs of the modified hydraulic models to assess the economic benefit from a flood risk perspective. Costs for NFM implementation and a rate of delivery have also been estimated.

The project outputs will help NFM managers prioritise locations and measures and aid development of a long term NFM Strategy for the Calder Catchment within Calderdale.

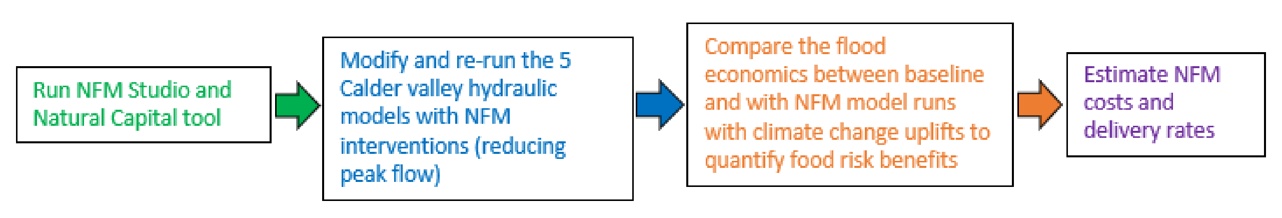
Executive Summary

Background

The Calder Catchment within Calderdale in Yorkshire has experienced a long history of flooding. Its steep sided valley with narrow floor promotes a flashy regime and impacts areas such as Todmorden, Hebden Bridge, Mytholmroyd, Sowerby Bridge and Brighouse. The devastating Boxing Day floods in 2015 provided the impetus for many of the Flood Alleviation Schemes and Flood Action Groups across the valley but also the motivation to consider alternatives. Natural Flood Management (NFM) measures are becoming a more mainstream option for reducing flood risk to communities by helping to dampen and slow the peak flows. Whilst NFM interventions such as gully blocking, woodland planting, leaky dams, storage ponds for example have been implemented in some areas within the Calder valley over the past 5 years or so, the benefits of such measures are not yet well known.

Aim and approach

The Environment Agency commissioned this study to help better understand the longer term catchment gains to flood risk and the wider environment to help steer the development of an NFM strategy for the Calder Catchment within Calderdale. Our project approach was as follows:



Results

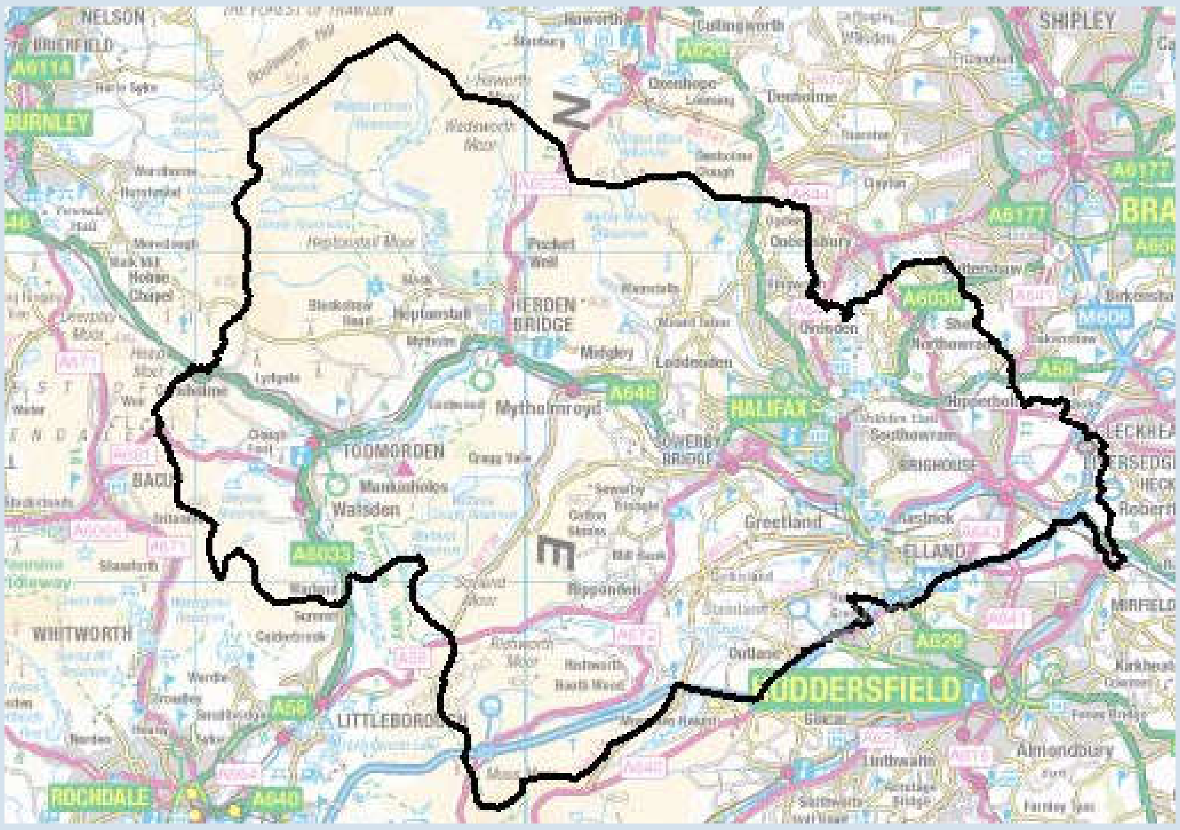
- The NFM Studio outputs show that between 1.8 million m^3 and 3.2 million m^3 of land runoff attenuation and storage can be achieved depending on the combination of NFM options utilised across the catchment for a 1 in 100 year (1% AEP) event. Using an average of the in-combination of NFM measures, a 10% reduction in peak flow is estimated. This rises to a 22% reduction for a 1 in 2 year event (50% AEP).
- Reducing land runoff through land use changes is the most effective type of NFM intervention in terms of attenuation. Flow pathway interventions through construction of bunds together with in-channel measures such as leaky dams are effective but only form between 7% and 15% of the total potential storage volume within the catchment (minimum (single) bund and maximum bunds respectively).
- The greatest natural capital benefits can be achieved from woodland planting and peat restoration (Option 2) with the majority of benefits being achieved through the carbon (>£90 million) and biodiversity (>£20 million) ecosystem services per year with a total of £111 million per year. Option 1 involving a mixture of improved and natural grasslands, woodland creation, moorland and peat restoration has a natural capital benefit total of £71 million per year but is approximately half the cost to implement compared to Option 2.
- The flood risk benefits have been calculated through a high level economic assessment. Overall, across the catchment, a 27% reduction in present value damages is achieved with NFM measures in place. This equates to a £91 million benefit over a 100 year appraisal period and this is likely to be an underestimate. No economic damages or benefits of the proposed NFM from surface water flood risk have been taken account of in this study due to the limitations of the models.
- Calculating the attenuation that the NFM measures installed over the last five years yield, the current rate of delivery achieves approximately 5% of the target storage. Therefore, at the present rate it will take approximately 100 years to achieve catchment wide NFM implementation. Indicative costs are £86 million but this will vary according to the type of intervention and is likely to be higher because of inflation.

The outputs from this study will prove very useful to justify funding further NFM across the Calder valley. The NFM Studio data will also be extremely valuable to help the Environment Agency and NFM Operational Group plan and prioritise NFM implementation in the Calder catchment in future years.

1. Project Background

Overview

The Calder Valley has experienced a long history of flooding. Its steep sided valley with a narrow floor promotes a flashy regime. Residential properties, industrial and retail units and infrastructure including a railway, main road and canal all share the valley with the River Calder. Flood Alleviation Schemes (FAS) have been designed and constructed in many of the flood hot spots. most recently in Mytholmroyd. Flood defences are also planned for Hebden Bridge and Brighouse amongst others and are in varying stages of development. The devastating Boxing Day floods in 2015 provided the impetus for Mytholmroyd FAS and there are now active Flood Groups across the valley that help alert residents to rising river levels and provide advice on flood preparedness. With current climate change predictions as they are, both flood frequency and flood magnitude are set to increase. Therefore there will still be a need, in places, to build engineered defences. However alongside traditional engineered solutions, Natural Flood Management (NFM) measures are becoming a more mainstream option for reducing flood risk to communities by helping to dampen the peak flows in the hot spot areas. Whilst NFM interventions such as gully blocking, woodland planting, leaky dams, storage ponds etc have been implemented in some areas of the Calder valley (e.g. Hardcastle Crags, Gorpley), the benefits of such measures are not yet known. Whilst some projects such as iCASP[1] have helped quantify the benefits of certain measures in specific locations, the potential flood risk (and wider environmental) benefits of NFM have not previously been evaluated on a catchment scale in Calderdale. This project helps to better understand the likely longer term catchment gains (and indicative costs) and will help steer the development of an NFM strategy for the Calder Valley.



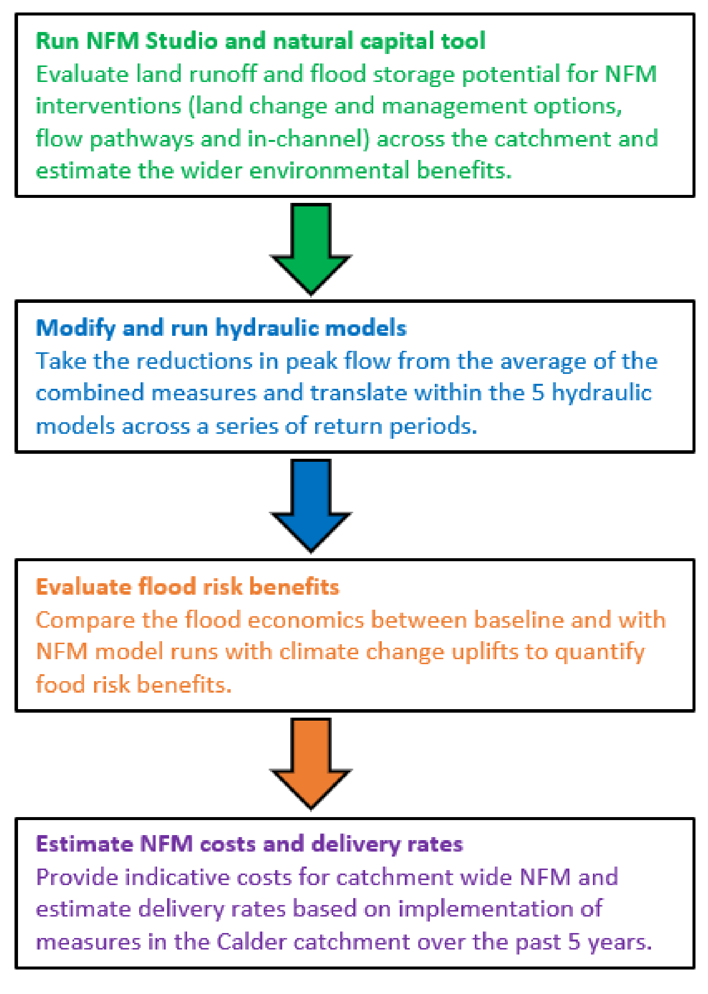
Aim and Objectives

The aim of the project is to provide a strategic, catchment-scale study of Natural Flood Management (NFM) techniques, evaluating the potential contribution and opportunity that NFM provides for flood risk reduction in the Calder Valley.

The project objectives include:

- Quantify catchment wide NFM potential (unconstrained in terms of what is physically possible within the landscape with no restrictions on land use, funding or policy).
- Evaluate NFM in terms of observed flood events and that required to maintain Standards of Protection given by current and planned flood alleviation schemes.
- Assess the scale, cost and timescale of NFM delivery required to provide climate resilience.
- Assess the benefit in terms of NFM delivered for flood risk reduction.

Approach



Run NFM Studio and natural capital tool
Evaluate land runoff and flood storage potential for NFM interventions (land change and management options, flow pathways and in-channel) across the catchment and estimate the wider environmental benefits.

Modify and run hydraulic models
Take the reductions in peak flow from the average of the combined measures and translate within the 5 hydraulic models across a series of return periods.

Evaluate flood risk benefits
Compare the flood economics between baseline and with NFM model runs with climate change uplifts to quantify food risk benefits.

Estimate NFM costs and delivery rates
Provide indicative costs for catchment wide NFM and estimate delivery rates based on implementation of measures in the Calder catchment over the past 5 years.

Interpreting Data and Outputs

This report presents a catchment scale assessment of volumetric storage, peak flow reductions and flood risk impacts across the Calder. NFM Studio is a strategic tool that quantifies NFM effectiveness relative to runoff reductions at the field scale. The tool is based on open source data, industry standards and methods. In applying these, the approach has necessarily made a series of assumptions to simplify what can sometimes be complex hydrological processes. The main assumptions made and the associated limitations are identified within the report and should be considered when interpreting the outputs.

The natural capital assessment is a high level but quantitative catchment assessment based on evidence and financial values provided in the literature. There is a varying level of confidence with the data (as with all current natural capital assessments) but is a useful method for evaluating wider benefits of NFM implementation.

In the case of the Calder, the outputs from NFM Studio have been interfaced and integrated within 5 separate hydraulic models that represent the main flood risk areas of the Calder catchment. Flood economics has then been undertaken to compare pre and post catchment wide NFM intervention to demonstrate the effectiveness on flood risk.

NFM costs have been estimated based on the cost of implementation in the valley per measure. Delivery rates have been approximated by quantifying the attenuation likely to have already been achieved compared to the catchment wide storage potential calculated using NFM Studio.

In adopting this approach, we ensure that a pragmatic, proportional and cost effective study has been undertaken to address the project objectives whilst delivering a catchment wide assessment of rural NFM benefits and costs.

The results presented in this report should be interpreted in the context of this overall catchment study objective and where possible should be confirmed by catchment specific field investigation.

The NFM Studio outputs will themselves provide a very powerful future resource to help the Environment Agency and Calderdale stakeholders to screen and prioritise NFM implementation and develop a long term NFM strategy for the catchment.

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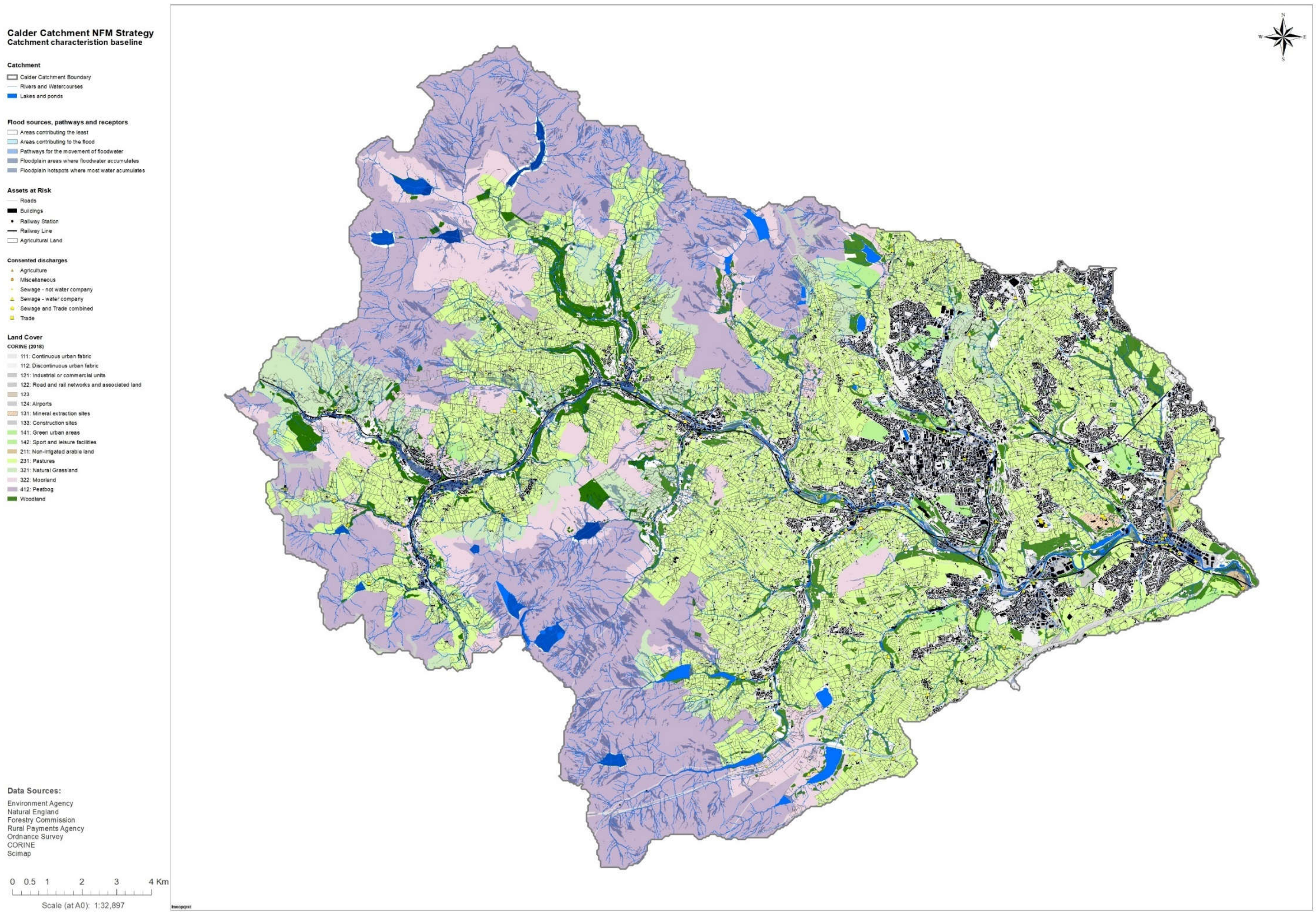
[1] Yorkshire Integrated Catchment Solutions Programme (iCASP) – Making Environmental Science Count

2. Catchment Characterisation

River Calder Catchment	
National Grid Reference	The approximate catchment centre point of the River Calder catchment is located at SE 00373 26538.
Catchment area	The estimated extent of the River Calder catchment down to Brighouse is 393 km^2.
Catchment	The catchment outline study extends to downstream of Brighouse (SE 17213 21222), although the overall Calder catchment outflows to Castleford, Leeds where it joins the River Aire. Therefore, reference to the Calder catchment in this report refers specifically to the area of the catchment which lies within Calderdale. The catchment extends northwards to Hardcastle Crags and Widdop and westwards to Todmorden. Calderdale sits across two WFD operational catchments, the Calder Upper and Calder Middle and comprises 20 river water bodies and 26 lake water bodies.
Land cover and usage	The catchment map below shows landcover across the Calder catchment. This indicates that most of the upper catchment is peat and moorland with the pastures being confined to the steeper valley sides and bottom. There are also several urban areas in the valley bottom which are under the protection of flood alleviation schemes, such as Todmorden and Mytholmroyd.
Geology	Groundwater is likely to be a limited source of floodwater in the Calder catchment. Most of the catchment is underlain by Mill Stone Grit, a coarse sandstone which is also present in the northern area of the Peak District and northeast Wales (see Appendix A.3).
Soils	The soils across the catchment vary in response to topography and geology. An open-source catchment soil map is provided in Appendix A.4. The majority of the lower Calder catchment is represented by soils variously described as being slowly permeable and freely draining. However, the upper catchment is dominated by the loamy upland soils and blanket bog peat. These peat soils are nationally important not just from a soil and water management perspective but also for carbon storage. The quality and status of these peat systems is relatively unrecorded and data on location of peatland restoration by the Moors for The Future group were used to indicate areas of good quality peatland systems.
Topography	The Calder catchment is a very steep catchment which slopes steeply from 47 mAOD (at Brighouse) to *ca.* 520 mAOD in the highest point in the catchment to the north (Boulsworth Hill) (Appendix A.1). The majority of the catchment is predominantly steep and lies within the 7-50 degree slope category, as evidenced by the general blue colour of the slope map shown in Appendix A.2.
Existing NFM measures	Across the Calder catchment a number of NFM measures have been proposed and implemented by project partners (see Rates of Delivery section). The measures include peatland restoration, runoff management (including in-field storage locations and flow pathway blocking) alongside in-channel slow-the-flow measures such as leaky barriers and tree planting.
Landownership	There are several large landowners in the Calder Valley, most notably Calderdale Council, Yorkshire Water and the National Trust. Whilst much of the previous NFM implementation in the valley has been focused on this land there has also been high levels of interest from private landowners.
Catchment map land cover (Corine)	



3. Flood Dynamics

Flood Hydrology

This section describes how much water passes though the River Calder catchment during a flood to put NFM in a catchment context and as a first step to understand the scale of NFM measures likely to be required. Flood flows and volumes for the River Calder have been assessed using the industry standard ReFH (Revitalised Flood Hydrograph Model) approach that provides a way of quantifying the magnitude of the catchment flood response, how flashy it is and how quickly the catchment responds to rainfall. These are all important metrics to distinguish between the types of catchment measures that may be more suitable to manage them, either those that reduce field runoff, store water along flow pathways or slow floodwaters once they reach watercourses.

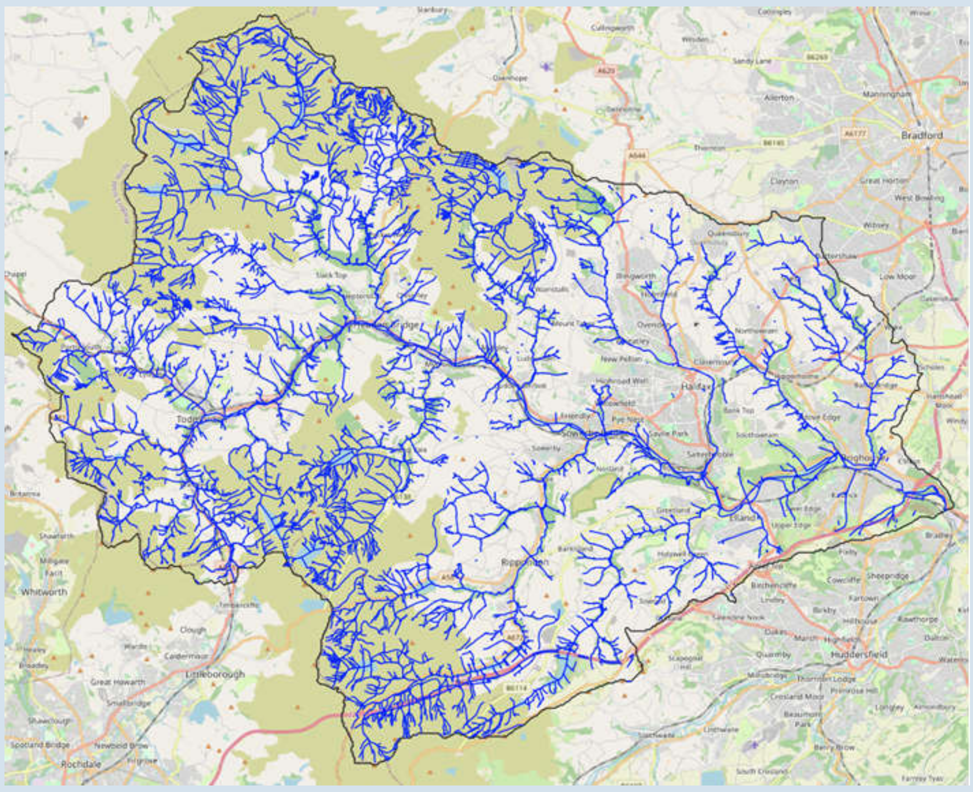
ReFH was applied to the River Calder using Flood Estimation Handbook (FEH) catchment descriptors for the location below:

FEH Catchment descriptors

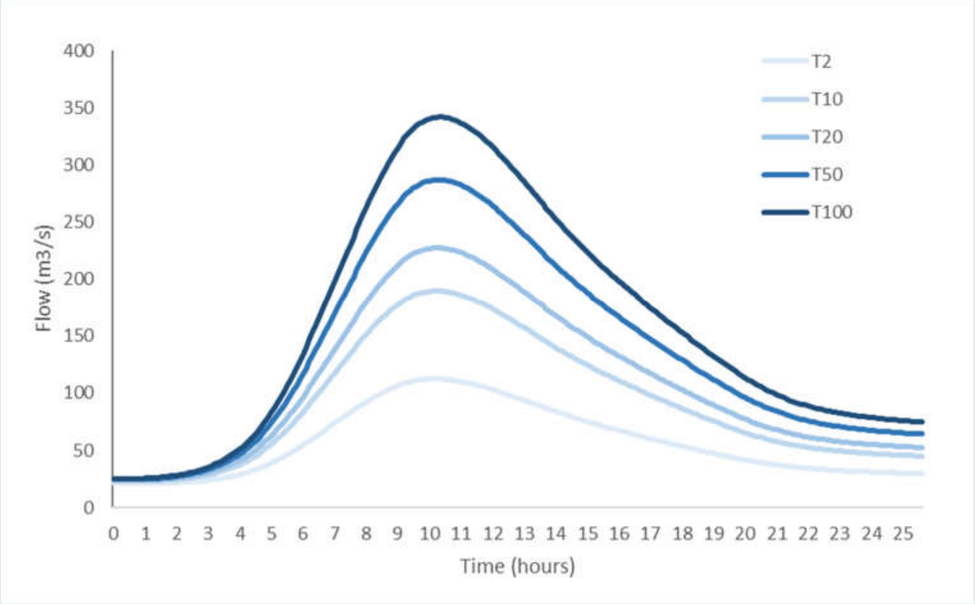
Catchment Characteristics[2]	
AREA (km²)	393
BFIHOST	0.479
DPLBAR	25.18
FARL	0.938
SPRHOST	1209
URBEXT2000	0.0423
Average Predicted Storm Duration (hrs)	26

The table above shows the FEH catchment descriptors used for the Calder catchment. The assessment point has been taken as the gauging station downstream at Brighouse at the downstream end of the catchment. The network of watercourses is also shown on the map.

Network of watercourses in the Calder Valley



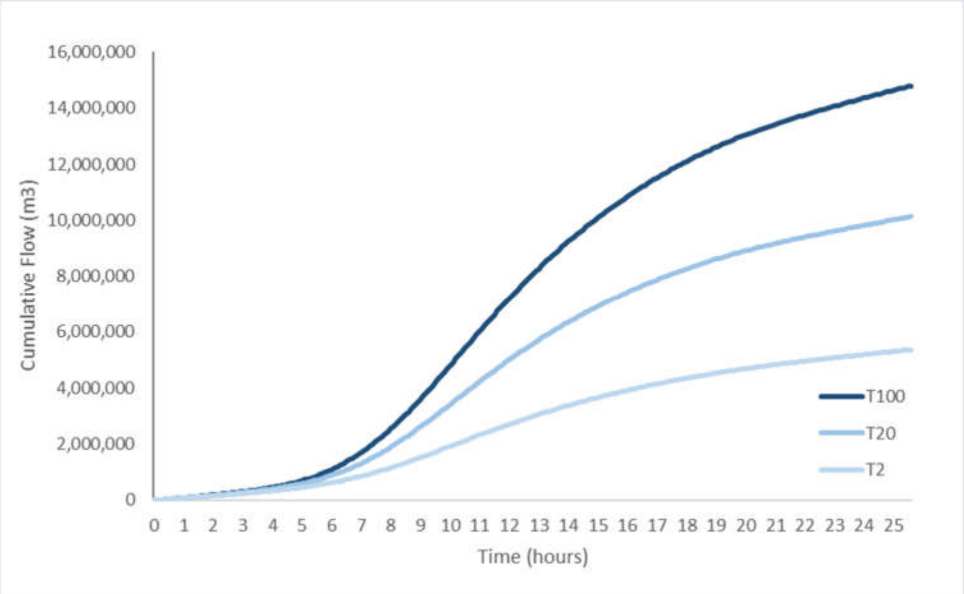
(a) Flood hydrograph



The graph above shows the hydrographs predicted for the Calder catchment for floods of a range of return periods or probabilities (T2 refers to a 1 in 2 year or 50% Annual Exceedance Probability (AEP) event).

The results show that flows in the River Calder peak around 10 hours after rainstorm events and the total average predicted storm duration for the catchment is close to 25 hours. These hydrographs have been generated using the catchment characteristic values in the ReFH methodology.

(b) Cumulative flood volume



The graph above shows the cumulative water volumes passing through the catchment downstream of Brighouse during the 50% (T2) ,5% (T20) and 1% (T100) AEP (return periods frequently used in NFM studies). Understanding cumulative volumes can help establish the scale of storage that might be needed to help protect communities from flooding.

For the 5% AEP event, the total estimated storm volume is just over **10,000,000 m³** of which around 5,000,000 m³ passed through in the first 12 hours during the peak of the flood.

For the 1% AEP event, the total estimated storm volume is just under **15,000,000 m³** of which around 7,000,000 m³ passes through in the first 12 hours during the peak of the flood.

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[2] FEH Catchment Descriptors | National River Flow Archive (ceh.ac.uk)

4. Natural Flood Management Studio

Summary of the Tool

NFM Studio is a decision support tool that helps catchment managers find the best places to implement NFM within the landscape. It is a strategic tool (see Appendix B for limitations), its purpose is to inform decisions on NFM at a catchment or landscape scale. To date, NFM Studio has been used at a number of locations for a number of organisations.

At the core of NFM Studio are three assessment streams:

- **Opportunity mapping:** to identify places in a catchment that are physically suited to NFM and where interventions might be easiest to implement from a practical and stakeholder perspective.
- **Hydrological assessment:** to estimate the volume of water stored by NFM interventions and how this attenuation changes the shape and the peak of the hydrograph at a catchment outlet.
- **Natural capital and multiple benefits:** to estimate the ecosystem service benefits generated by NFM. This provides a complete picture of the overall benefits of these nature-based solutions in the catchment.

The information generated by these three streams are integrated to produce a spatial NFM database of the catchment. Outputs from the hydrological and opportunity streams are combined to identify those parts of the catchment that are best for NFM i.e. those places that are particularly effective at storing flood water and most suited to implementing interventions. The natural capital assessment provides context by estimating the total benefits to ecosystem services generated by interventions – an essential consideration for catchment managers wanting to develop Integrated Catchment Management (ICM) solutions.

All assessments are carried out using open-source data. Open-source is a key ethos of NFM Studio. It enables the tool to be applied to any catchment or catchments in England without the need for data purchase. Outputs can then be readily shared without the need for data sharing licenses. To make the outputs more catchment specific additional data from Moors For the Future (MFTF) was also included to better represent areas of moorland restoration.

The spatial NFM database generated by the three assessment streams is presented in this report as a suite of maps. These show the best places to implement NFM and estimates of the flood risk benefits interventions are likely to deliver. A hydrology calculator allows the interactive manipulation of the catchment outlet hydrograph by changing assumptions on how NFM is implemented in the catchment. An additional set of maps consider the wider ecosystem service benefits NFM can provide such as water quality amelioration, carbon lock-up, biodiversity and recreation amongst others.

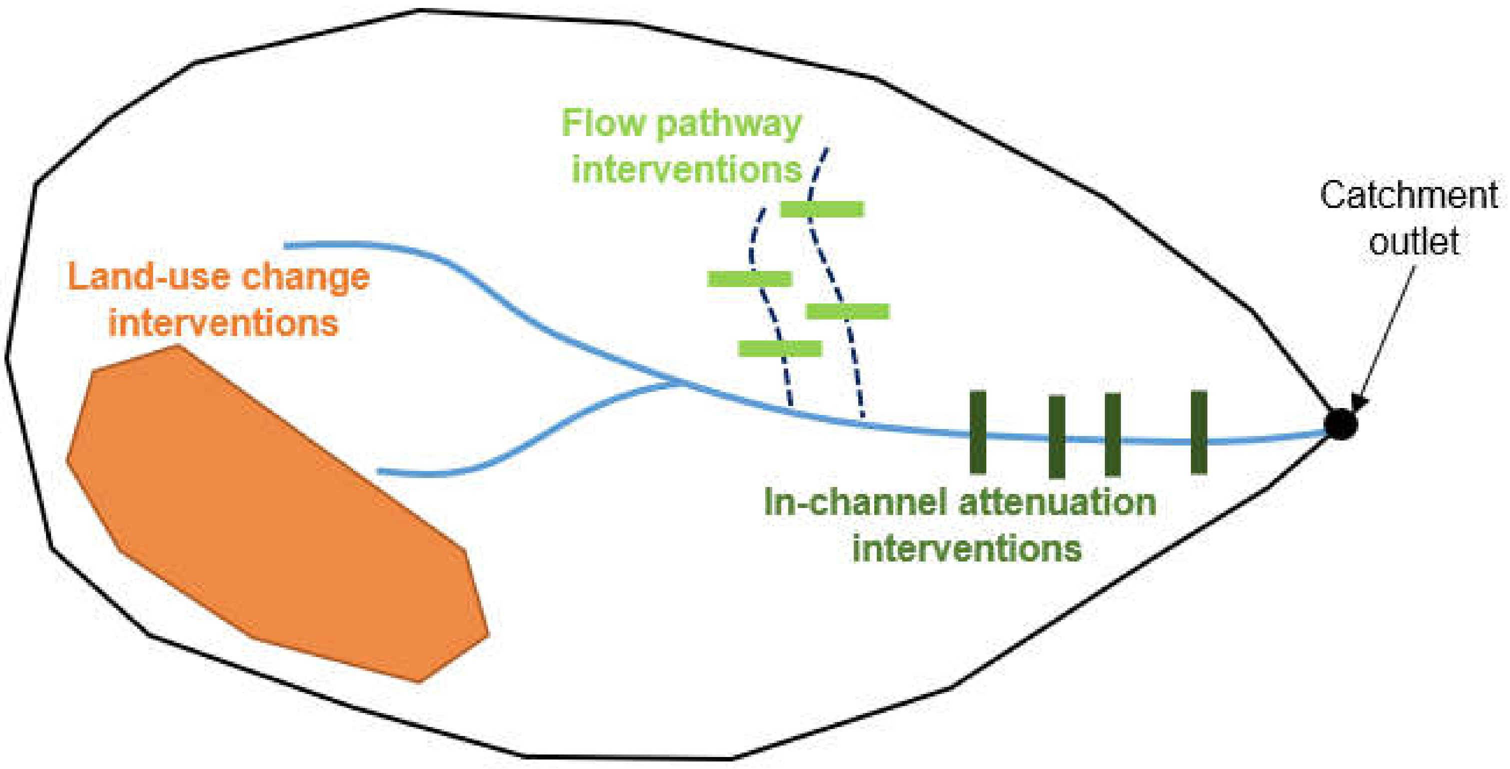
All outputs are generated at the field scale, based on field boundaries defined by Ordnance Survey MasterMap data. Whilst data are produced at this scale to allow flexibility in presentation and analysis, outputs are intended for interpretation at landscape or catchment scale.

Measures Considered by NFM Studio

The NFM intervention types considered and mapped by NFM Studio are grouped as shown in the figure below and include:

A. Land use (and management) change	Including measures such as: • Land use change along successional steps • Woodland planting and plantation management • Land use management improvements, for example, increasing soil health, reducing compaction and stocking densities • Peatland and moorland restoration including re-introduction of vegetation, gully blocking etc.
B. Flow pathway interventions	Including measures such as: • Hillslope bunds including leaky barrier, cross slope bund • Cross slope woodland and hedge planting • Track and overland flow path cross drains and grips • Gully blocking
C. In-channel attenuation and floodplain storage	Including measures such as: • In-channel woody structures • Headwater channel woody bundles • Floodplain reconnection measures

NFM interventions considered in NFM Studio



Tree planting

Flow pathway bund

In channel leaky barrier

5. NFM Opportunities

Opportunity Maps

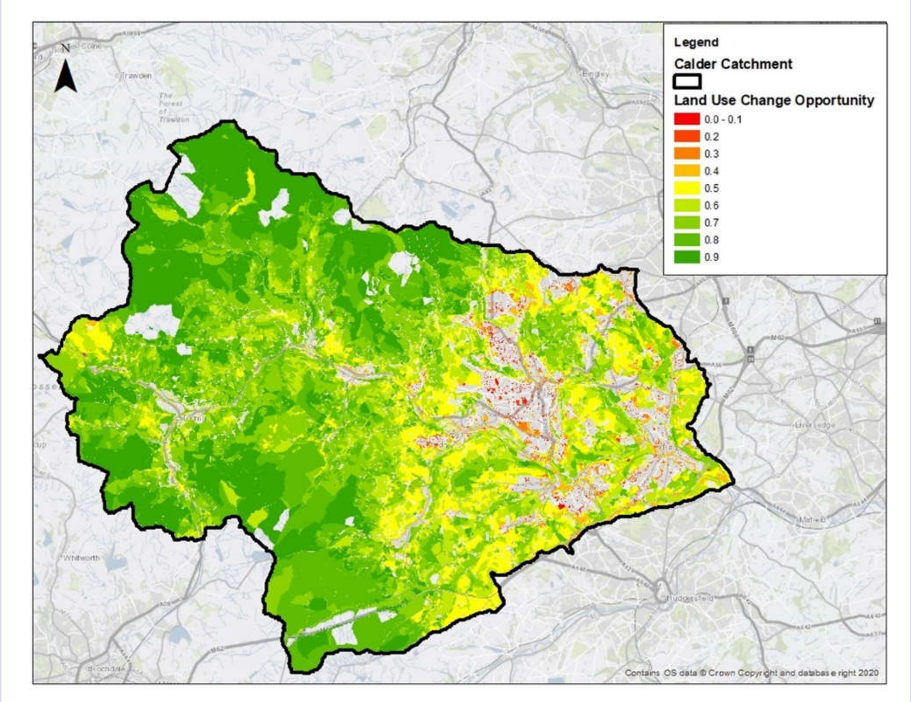
Opportunity-constraint metrics are used in NFM Studio to assess the opportunity for NFM at the field scale and are based on local knowledge. These opportunity maps are **separate** to the hydrological assessment (volumetric calculations) within NFM Studio but do provide the chance to create priority area maps which are the result of the opportunity maps and volumetric maps combined.

The opportunity-metrics are developed through one or a series of opportunity workshops that make the outputs catchment specific, but are based on a series of spatial data sets describing the landscape from which the suitability for implementing NFM is inferred (Appendix C). For the purposes of mapping, opportunity scores for each of the three NFM measure types are normalized and displayed in a numeric scale from 0 to 1, where a score of 0 is the least appropriate field and 1 the most appropriate field for the implementation of a given NFM measure.

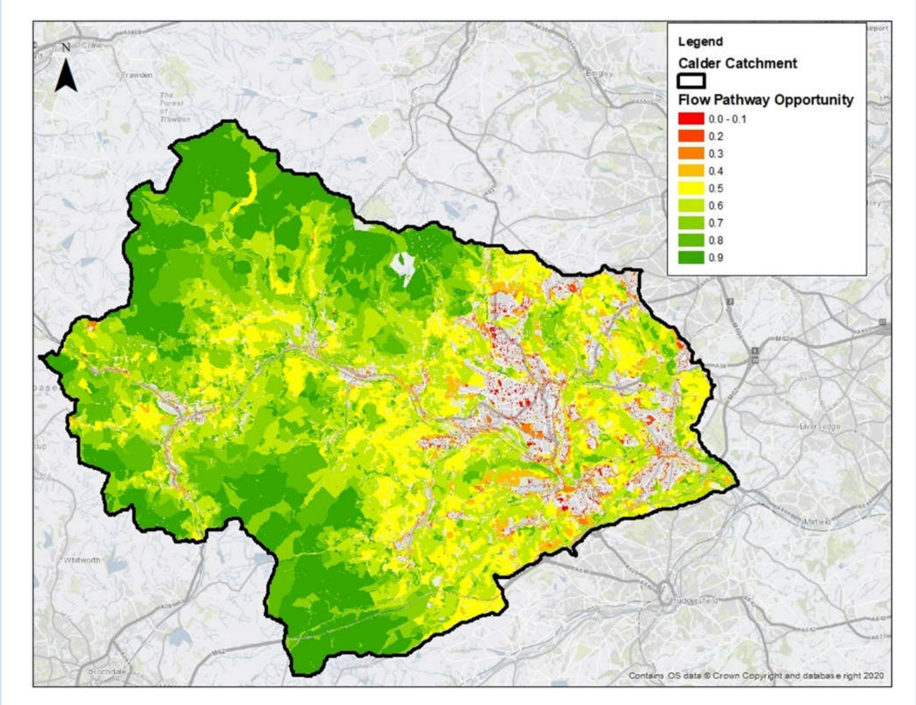
The opportunity assessment in NFM Studio considers the NFM potential of individual fields based on enablers and constraints identified by open-source datasets included in the NFM Studio tool (see Appendix C). The opportunity assessment is performed for each of the NFM intervention types summarised as follows:

- **Land use change measures** – All areas of the catchment are scored for suitability for land use change NFM, with the exclusion of urban areas.
- **Flow pathway measures** – All areas with risk of flooding from surface water are scored for suitably for catchment storage NFM, with the exclusion of urban areas.
- **In-channel and floodplain measures** – All areas bordering a river are scored for suitability for in-channel NFM, with the exclusion of urban areas.
- **In-combination** – A combination of all the above NFM intervention types.

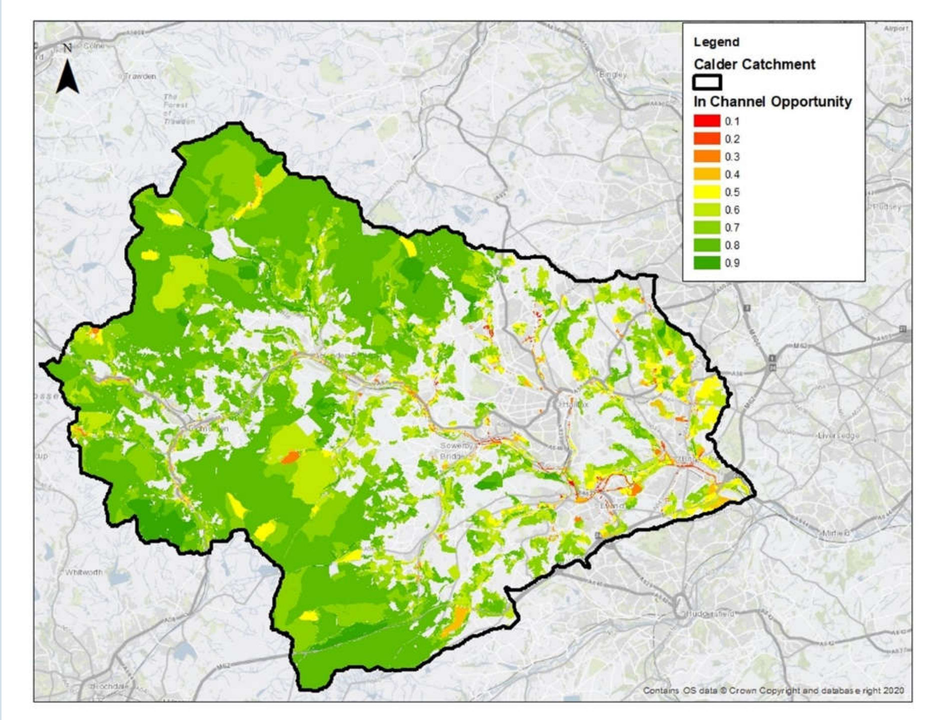
Land use change opportunity map



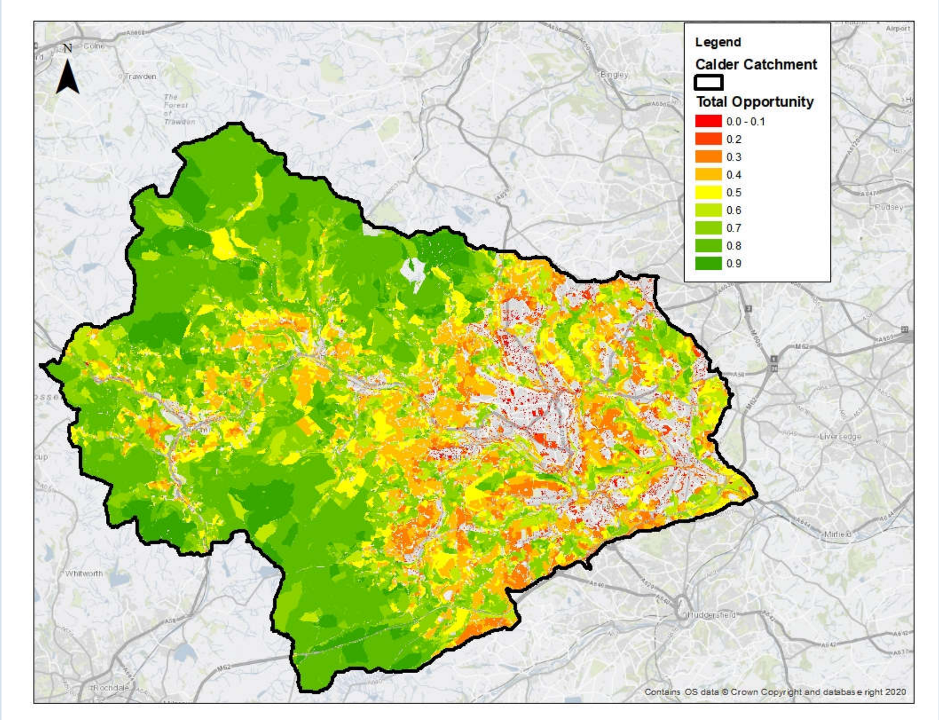
Flow pathway opportunity map



In channel opportunity map



In-combination opportunity map



Consultees

All the members of the NFM Operational Group were invited to contribute and included representatives from:

Environment Agency
Calderdale Council
Yorkshire Water
National Trust
Slow the Flow
Canal and River Trust
Calder and Colne Rivers Trust
Moors for the Future
Calder Future
Forestry Commission
Treesponsibility
Forus Tree

The opportunity maps for the Calder catchment are shown above and have benefitted from the input of a broad range of local specialists who have provided ideas, technical knowledge and practical advice to help develop the information presented. The opportunity mapping process has taken the form of regular meetings, an active workshop, and targeted one-to-one conversations.

All consultation has been undertaken digitally as the project has been delivered during the COVID pandemic when all organisational offices have been closed. We are extremely grateful to all those who have actively contributed.

The results of the stakeholder consultation, specifically the opportunity scoring agreed for different measures, is provided in Appendix D.

6. Hydrological Assessment

A. Land use change and management (land runoff measures)

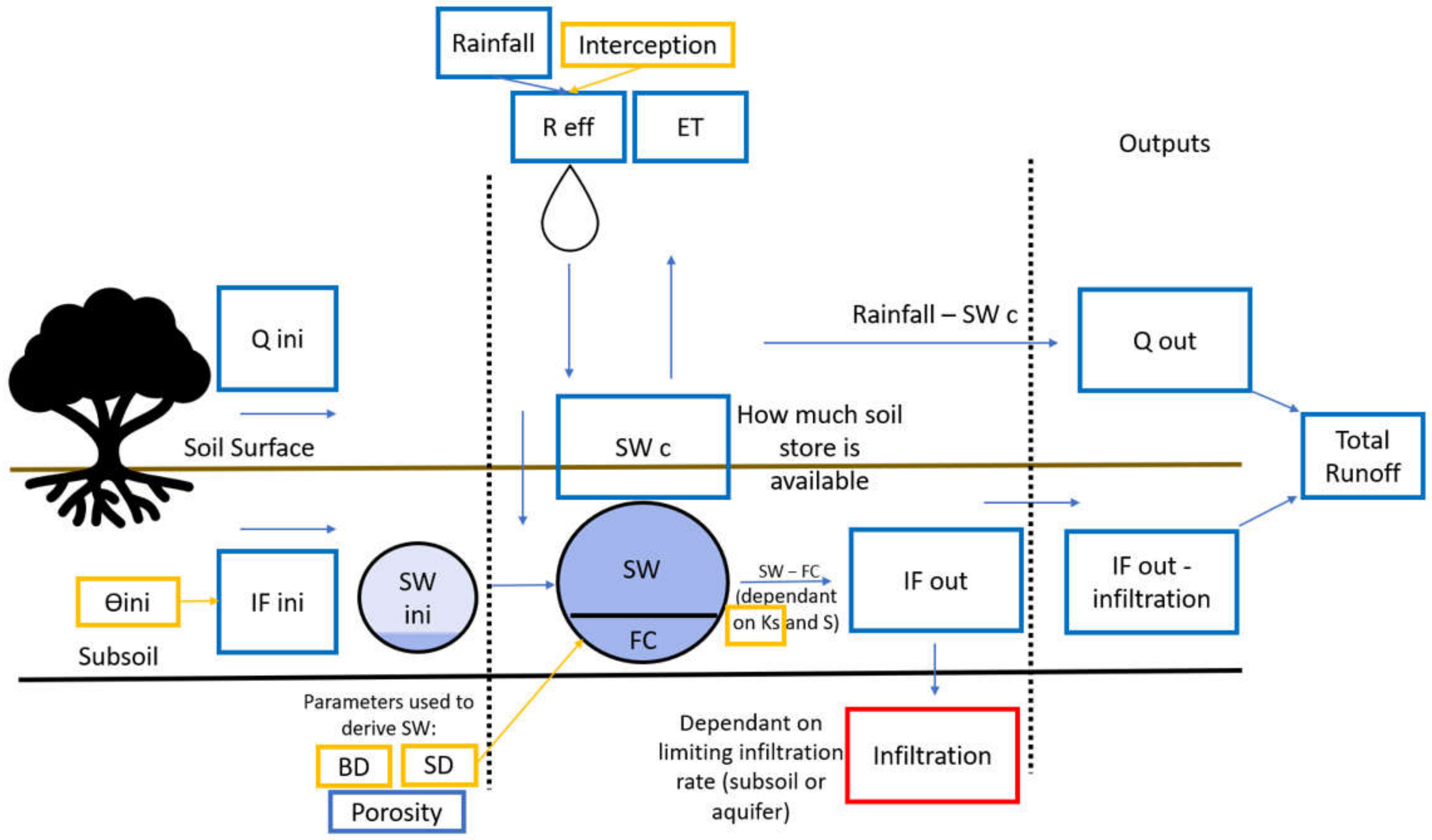
The methodology used to estimate changes in infiltration and runoff for different land use and management options in NFM Studio is the Daily Based Morgan–Morgan–Finney (DMMF) Model. The DMMF model outlined by Choi *et al.* (2017) is a widely used field scale surface water runoff and soil erosion model, which has been incorporated into NFM Studio to simulate runoff under different land-use, land management and rainfall scenarios. The figure below presents a schematic of the DMMF model in the NFM Studio tool, showing the different processes it considers and the range of parameters that can be adjusted. A number of model parameters control how each of these processes are calculated in each land use scenario and are highlighted in yellow. For example, the initial soil conditions ($\theta\ ini$) are used to derive the Soil Water Initial conditions (SW_{ini}), the bulk density (BD) and soil depth (SD) are used in the calculation of the soil water store (SW), the hydraulic conductivity is used in the calculation of the interflow (IF) and an interception coefficient is used to derive effective rainfall (R Eff).

Rainfall under different storm return periods is input to the model which considers catchment conditions such as baseline hydrology, soil characteristics, land cover and slope in calculating the volume of infiltration and run-off. The soil hydrological conductivity and infiltration rates of the soil and parent material are inferred from an open-source soil characteristics dataset developed as part of the tool, and the land-use determines the permanent interception factor. The DMMF model is run under baseline conditions and for four infiltration NFM intervention options detailed below.

Baseline: The DMMF runoff model is utilised to calculate superficial runoff in 50x50 m grids for a single timestep. Land, soil and catchment characteristics (i.e. land use, soil characteristics, sub-soil, slope, etc.) are processed from a number of physical, environmental and socio-economic spatial datasets. Initial conditions in the model are calibrated to match the total superficial runoff calculated from the Flood Estimation Handbook (FEH). The runoff generation calculated with the DMMF model is then assigned to the fields within the catchment and calibrated against ReFH[3] hydrographs.

Return periods assessed: For the Calder catchment, the DMMF model has been run for five return period events; the 1:2, 1:10, 1:20, 1:50 and 1:100 return period events.

Schematic of DMMF model. R eff is the effective rainfall, ET evapotranspiration, Q superficial runoff, IF interflow, SWc soil water capacity, FC field capacity, SW soil water, SD soil depth, BD bulk density, Ks hydraulic conductivity and ɵini the initial soil water content. Yellow boxes identify soil parameters that drive how different processes are calculated in the DMMF model



Land Use Options

NFM Studio considers the effects of land use and management on runoff from fields based on four standard options as follows:

- **Option 1 - Land use change and management:** This option assumes that arable land is transformed into pastures; pastures into natural grasslands; agro-forestry area, natural grasslands, moors and heathland (with no protected status) into woodland-shrub (see table below). Within NFM Studio, these changes are simulated by altering interception factors and bulk density values (shown in yellow in the above figure). Areas defined as 'Peat' or 'Moorland with Protected Status' were modelled in the same way, assuming these areas have been restored. Restoration has been simulated by adjusting the model parameters to physically simulate peatland restoration (refer to Peat restoration technical note[4] for more information). The model parameters adjusted were initial conditions, soil parameters and the interception factor.
- **Option 2 - Woodland creation:** This option assumes that all arable land, improved grasslands and natural grasslands and moorland (with no protected status) is transformed to woodland. As for option 1, this change was implemented in NFM studio by altering interception factors and bulk densities and the peat and protected moorland areas restored.
- **Option 3 - Soil recovery:** This option simulates the potential improvements in soil health that arise from soil recovery measures such as aeration. Within NFM Studio, this option is simulated by maintaining existing land use but altering bulk densities to simulate for example increased aeration or soil organic matter. This option varies from 'peatland restoration' which considers alteration to different soil properties other than just the bulk density. The soil recovery option was also not applied to the peat areas to provide a comparison with peatland restoration measures.
- **Option 4 – Unconstrained Woodland Creation:** This option was run additionally for interest only, as requested by the Environment Agency, to model the potential impact to runoff if woodland was to be planted across the whole catchment irrespective of land cover or protection status. The outputs for this option are included in Appendix E.

To assess the effects of different land use options, it is assumed that the calculated and calibrated baseline initial soil moisture/antecedent conditions are the same in the baseline condition (see map below) and each of the options. This assumes that the initial/antecedent conditions are the same regardless of the land intervention applied (Options 1, 2, 3). However, the initial conditions do change for the different return period events, this is based on how the initial conditions are calculated for each return period, see Appendix B for full explanation of this assumption. Another important point to note is that the inputs to the DMMF models represent average conditions over the year and therefore provide an annual average runoff. For example, the annual average interception rates inputted into the DMMF model for vegetation canopy growing above a soil surface contrasts with what actually occurs over the course of the year, especially for deciduous woodlands and crops.

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[3] The Revitalised Flood Hydrograph Model https://www.ceh.ac.uk/sites/default/files/FEH%20Supplementary%20Report%20hi-res.pdf

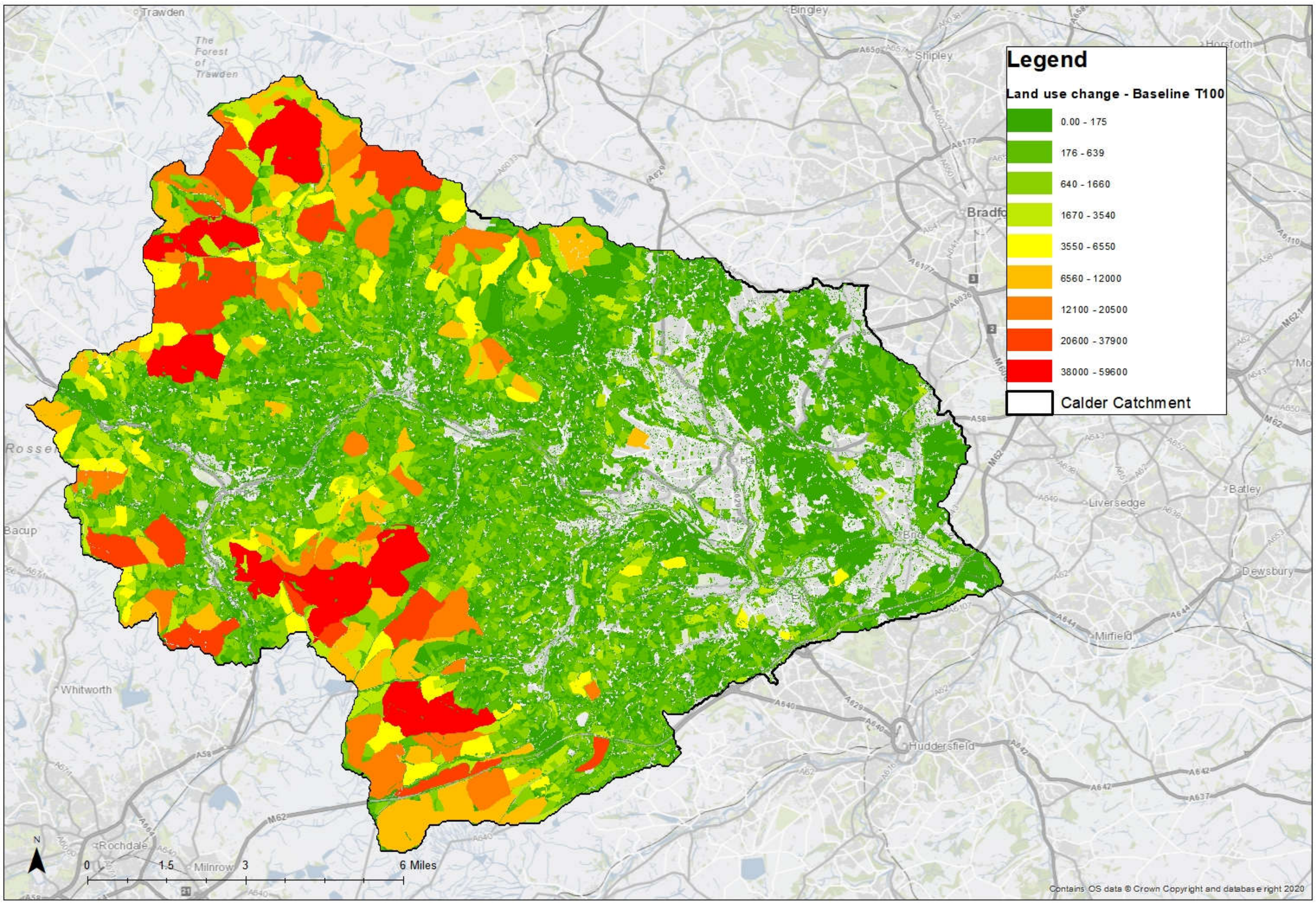
[4] 5206814 001 Peat tech note_2.0

Simulated land use changes for the different options

Current/baseline land cover	Option 1 – Land-use change and management	Option 2 – Woodland creation	Option 3 – Soil recovery	Option 4 – Unconstrained woodland creation
Peat	Restored peat	Restored peat	Peat	Woodland
Moorland	Transitional woodland-shrub	Woodland	Restored moorland	Woodland
Moorland with protected status	Restored moorland	Restored moorland	Restored moorland	Woodland
Arable	Improved grasslands	Woodland	Arable*	Woodland
Improved grasslands	Natural grasslands	Woodland	Improved grasslands*	Woodland
Natural grasslands	Woodland	Woodland	Natural grasslands*	Woodland
Woodland	Woodland	Woodland	Woodland *	Woodland

* With reduction in soil bulk densities

Estimated baseline runoff volumes for each field in the Calder catchment during the 1:100 year (T100) rainfall event (m^3)



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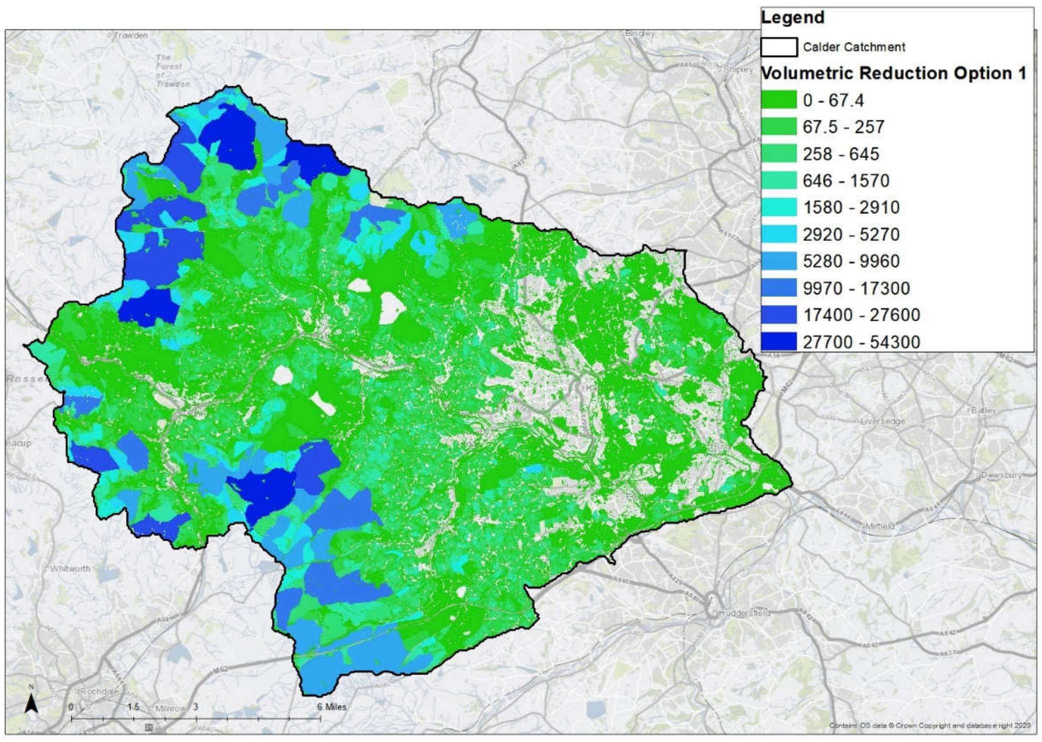
NFM Studio Results - Land Use Change and Management

The maps below show the volumetric reductions across the catchment under the three NFM options, for the 1 in 100 year return period (1% AEP). The volumes from the top 10% of fields have also been calculated and are available in Appendix F.

The spatial distribution of the land parcels which produce the greatest total runoff reduction remains largely the same across Option 1 and Option 2 with the upland areas showing the greatest total runoff reduction. Land parcel size does influence this total, but from a strategic perspective the bigger the field, the easier to initiate and implement and the greater the overall benefit. Standardised maps (mm runoff per area rather than total per field parcel) have also been provided for context in Appendix G and can be interrogated in detail according to the area of interest and similarly for all output datasets. Option 3, soil recovery shows a reduced overall benefit in runoff compared to Options 1 and 2 and further demonstrates the advantage of targeting the uplands (peat and moorland) to achieve the most productive land use change and management results.

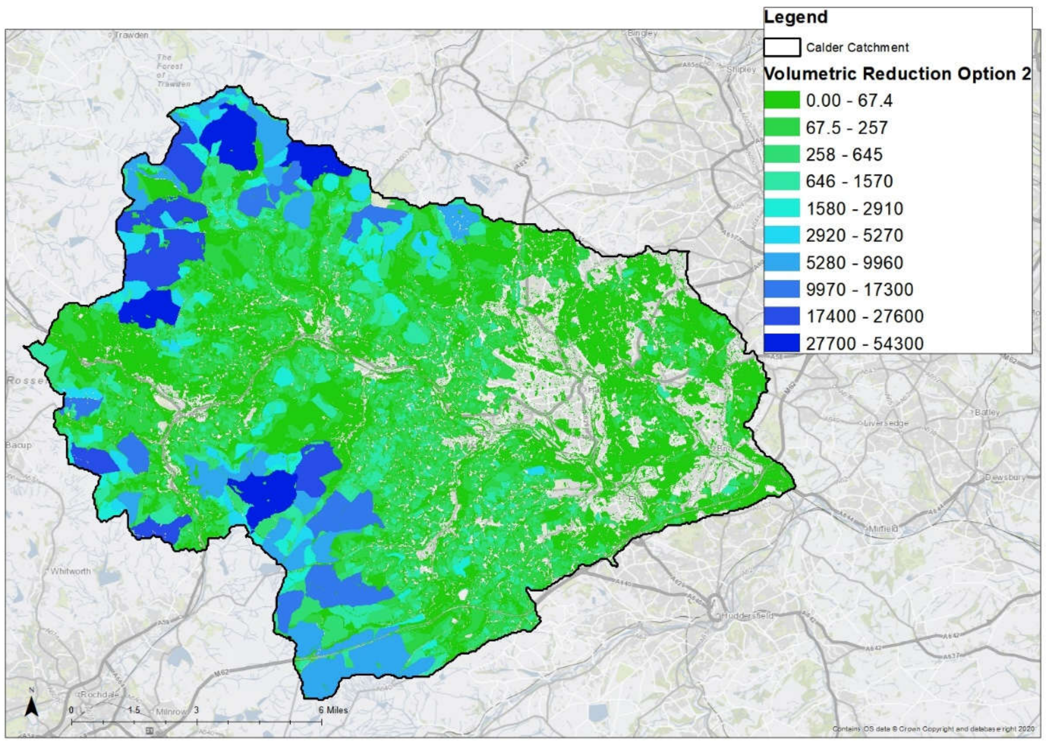


Option 1 – Land-use change and management

Total runoff reduction (m^3) = 2,500,524

This option assumes land use change/management in each field, see the table in the 'Land Use Options' section above for more details. The map on the left shows the best places in the Calder catchment for land use change measures, including likely volumes stored in each field. The fields in the dark blue are those in which there is most potential volumetric reduction in runoff (m^3), from land use change measures, whereas fields in green represent lower potential volumetric reduction in runoff (m^3) from land use change measures. Areas on the map to the left with no colour represent urban areas, thus no NFM measures take place in these areas.

NFM Studio estimates that if the land use change Option 1 was implemented across the Calder catchment, an estimated total runoff reduction of **2,500,524 m^3** is possible for a **1 in 100 year** event. This equates to a **36% reductio**n from the baseline runoff.



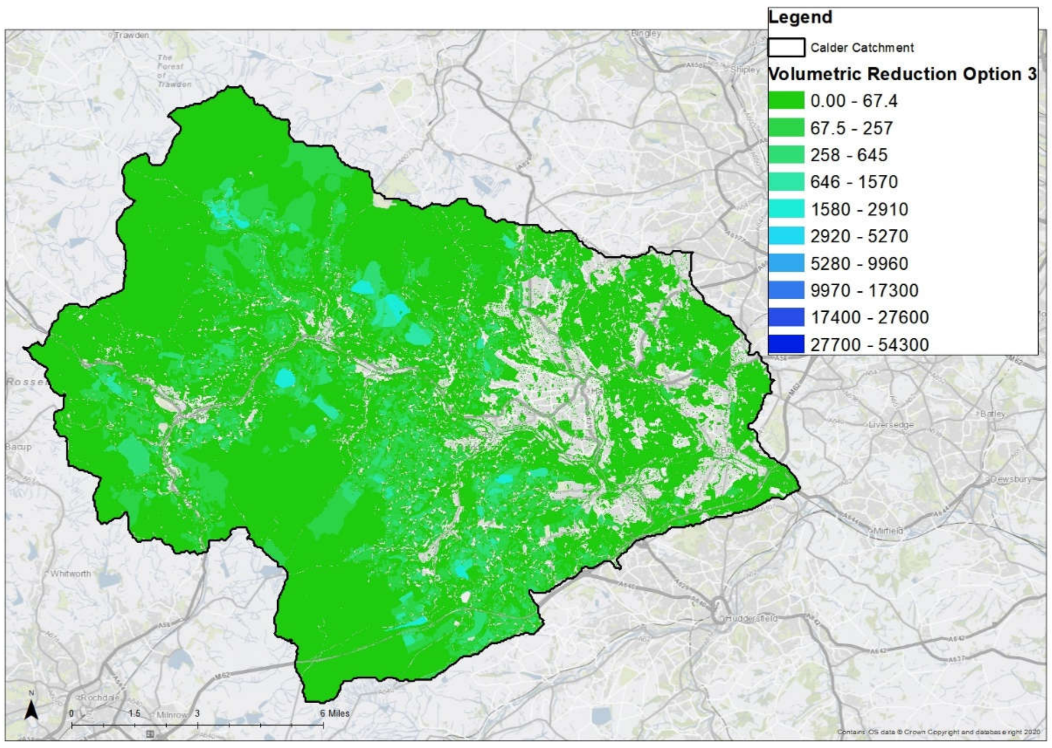
Option 2 – Woodland creation and peat and moorland restoration

Total runoff reduction (m^3) = 2,721,731

This option assumes **woodland creation** in each field other than peat and protected moorland, see the table in the 'Land Use Options' section above for more details. The map on the left shows the best places in the Calder catchment for woodland creation measures, including likely volumes stored in each field. The fields in the dark blue are those in which there is most potential volumetric reduction in runoff (m^3), from land use change measures, whereas fields in green represent lower potential volumetric reduction in runoff (m^3) from woodland creation. Areas on the map to the left with no colour represent urban areas, thus no NFM measures take place in these areas.

NFM Studio estimates that if this land use change option was implemented across the Calder catchment, an estimated total runoff reduction of **2,721,731 m^3** is possible for a **1 in 100 year** event, equivalent to a **40% reduction** from the baseline runoff.

This is the **largest reduction** in runoff of the three options, due to afforestation resulting in the largest interception values and soil characteristics alterations.



Option 3 – Soil Recovery

Total runoff reduction (m^3) = 1,666,718

This option assumes **soil recovery** in each field, see the table in the 'Land Use Options' section above for more details. The map on the left shows the best places in the Calder catchment for soil recovery measures, including likely volumes stored in each field. The fields in the blue are those in which there is most potential volumetric reduction in runoff (m^3), from land use change measures, whereas fields in green represent lower potential volumetric reduction in runoff (m^3) from soil recovery measures. Areas on the map to the left with no colour represent urban areas, thus no NFM measures take place in these areas.

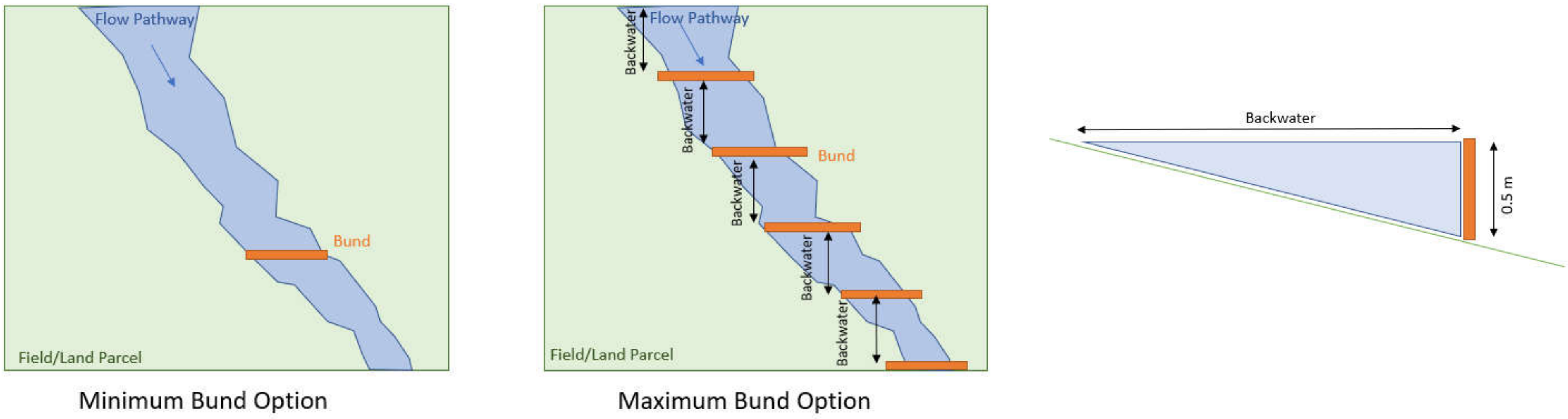
NFM Studio estimates that if this land use change scenario was implemented across the Calder catchment, an estimated total runoff reduction of **1,666,718 m^3** is possible for a **1 in 100 year** event. This is the lowest reduction in runoff of the three options and equates to a **24% reduction** from the baseline runoff.

B. Flow Pathway Interventions

The methodology used by NFM Studio to estimate the volumes of water that might be stored along flow pathway NFM measures uses the Environment Agency's Risk of Flooding from Surface Water (RoFSW) dataset. These data are first mapped for the catchment. Areas prone to fluvial flooding (within the Flood Zone 3 extents) are excluded and hence the flow pathways identified are the areas that convey flow within the catchment excluding watercourses and their floodplains. Small areas which are ponds and don't have a flow pathway attributed to them are also excluded. Once the location of the flow pathways in the catchment are identified, the volume of water stored behind a bund is calculated to assess the potential volumetric storage. The total volume stored in each field is then calculated as the sum of the water behind the bunds. The volumes from the top 10% of fields have also been calculated and are available in Appendix F.

The total volume store behind the bunds is calculated for two scenarios which reflect the minimum number likely to be applied in a field (a single bund) as well as the maximum number of bunds that could be applied along the flow pathway in any given field. In both cases, NFM Studio assumes that bunds are 0.5m high. The figure below presents a schematic of the flow pathway model in the NFM Studio tool.

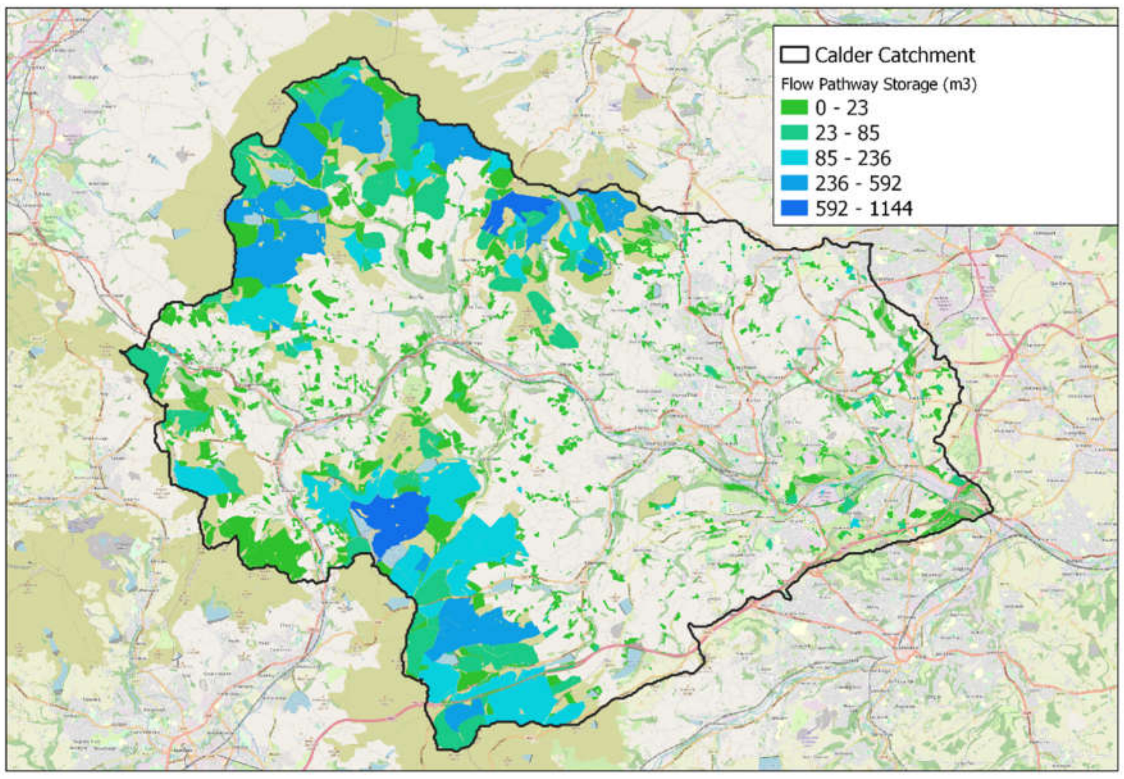
Method to calculate flow pathway storage



Minimum Bund Option

Maximum Bund Option

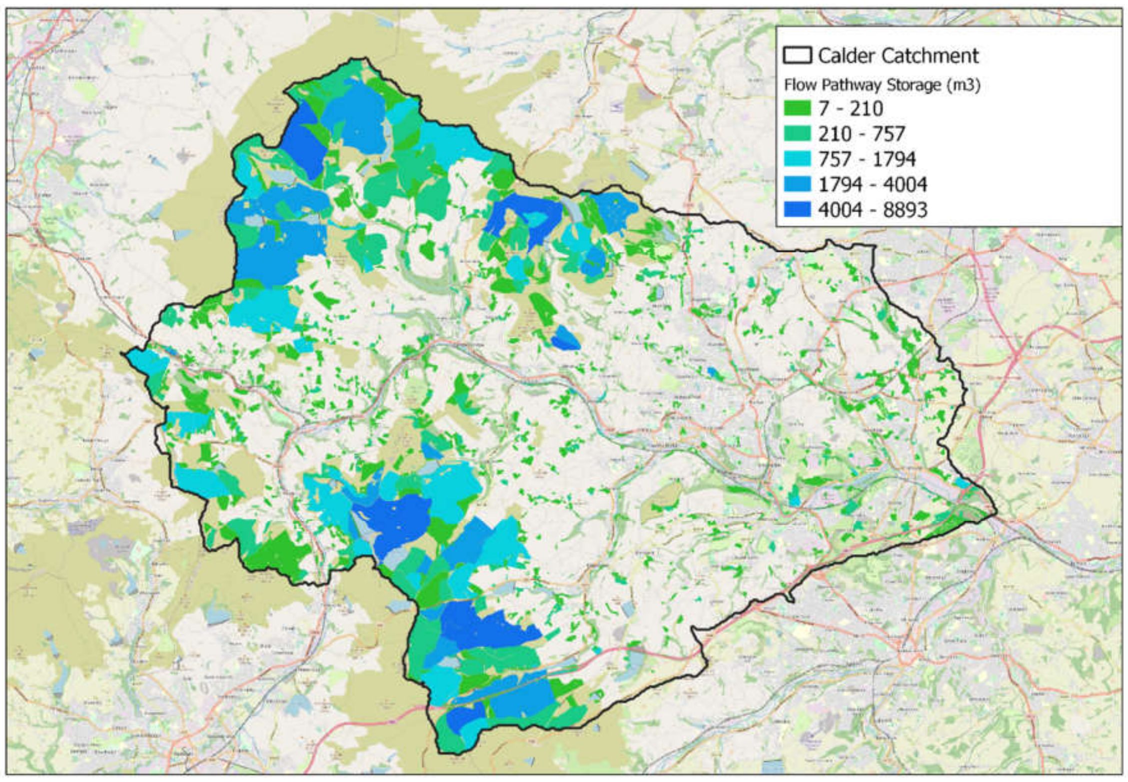
Minimum bunds map



This scenario assumes that a **single bund** is constructed along each flow pathway in each field. The map on the left shows the best places in the Calder catchment for flow pathway measures, including likely volumes stored. Active flow pathways are not present across the whole catchment and therefore the number of fields available to implement this measure are less than for land runoff measures.

NFM Studio estimates that if the minimum bund scenario was implemented across the Calder catchment, **a total volume of 42,839 m^3 could be stored.** This volume is indicative; as previously stated NFM Studio assumes that each bund is 0.5m high. A height of 0.5m was assumed as anything greater than 0.5m generally requires more detailed design rather than landowner/self build because of associated construction risk. Higher or lower bund heights may be relevant depending on local circumstances in different areas. The height of a bund will be determined in the detailed design stage of an NFM scheme and will vary on several factors including material chosen, site topography and volume of water requiring storage.

Maximum bunds map



This scenario assumes that a **sequence of bunds** are located along each flow pathway in each field. The number of bunds along each flow pathway in each field is automatically calculated with the backwater effect assuming that a bund is situated immediately upstream of where the backwater effect ends.

The map on the left shows the best places in the Calder catchment for flow pathway measures, including likely volumes stored. Active flow pathways are not present across the whole catchment and therefore the number of fields available to implement this measure are less than for land runoff measures.

NFM Studio estimates that if the maximum bund scenario was implemented across the Calder catchment, **a total volume of 406,150 m^3 could be stored.** This volume is indicative; as previously stated NFM Studio assumes that each bund is 0.5m high. Higher or lower bund heights may be relevant depending on local circumstances in different areas.

C. In-Channel Attenuation and Floodplain Storage

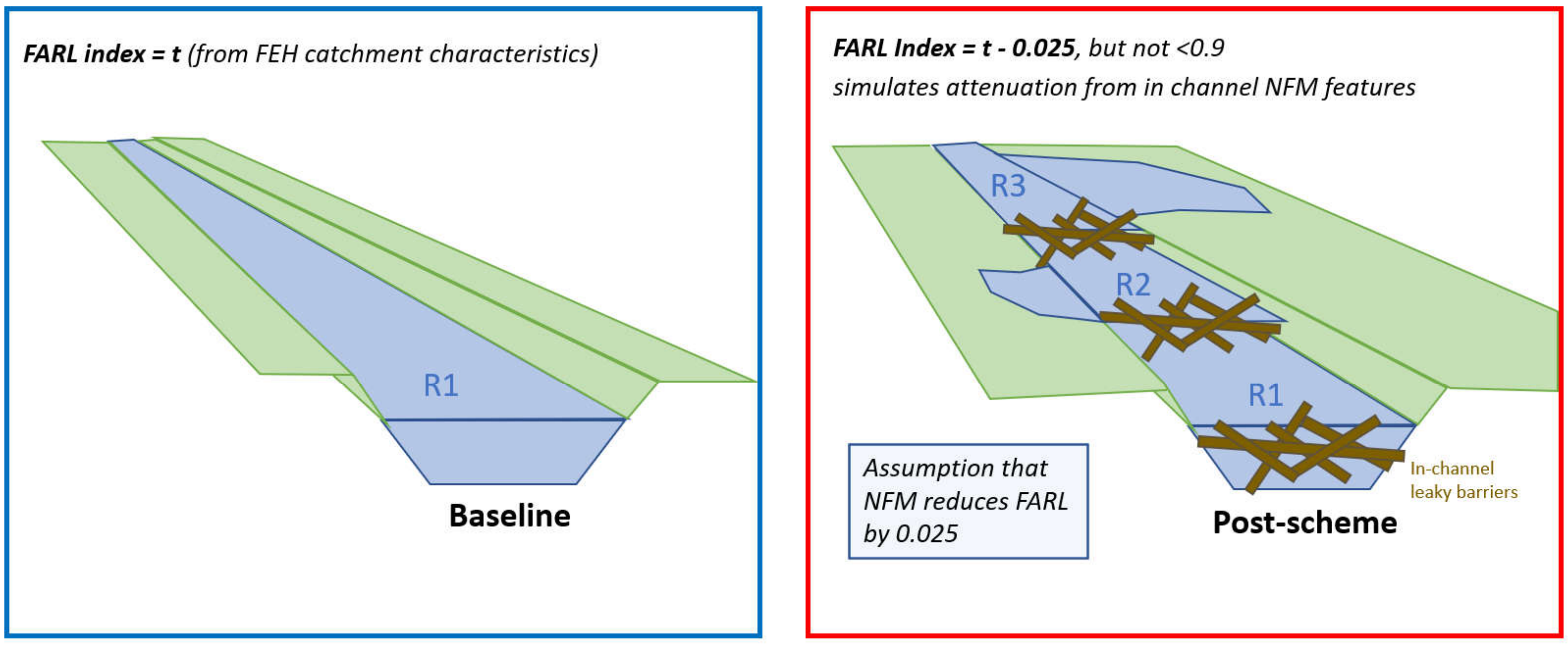
In-channel attenuation measures refer to actions that reduce flow velocities within watercourses and reconnect floodplains in rural areas, for example woody features in a watercourse. The methodology used to estimate the in-channel attenuation of watercourses in NFM Studio uses the FARL index in the industry-standard Flood Estimation Handbook (1999)[5]. The FARL index is a catchment descriptor that identifies the flood attenuation provided by online reservoirs and lakes. To calculate the effect of in-channel measures, NFM Studio uses the upstream river length, sub-catchment area, total catchment area and characteristics data from the OSMM water dataset for watercourse reach. NFM Studio assumes that the effect of in-channel attenuation measures such as woody features reduces the FARL index by 0.025, to a minimum value of 0.9.

The hydrograph is re-calculated to account for the updated FARL and the difference in total volume under the hydrograph (m^3) before and after the change in FARL is considered the temporary volumetric storage for the catchment. The hydrograph for the 1 in 2 year event (50% AEP) is used for the in channel volumetric assessment as it is approximately bank full conditions. The Muskingum flow routing method is used to route the adjusted Qmed[6] to generate the attenuated hydrograph and account for the attenuation of any in-channel interventions.

Within NFM Studio, the total catchment attenuation potential is proportioned out to individual watercourse reaches depending on the upstream catchment area and watercourse width, with wider reaches lower in the catchment having more attenuation potential. The Environment Agency's Working With Natural Processes (WWNP) floodplain reconnection potential dataset is also incorporated into the calculation to account for the potential floodplain reconnection capacity of each watercourse reach. Therefore, the resulting in-channel attenuation volumetric outputs estimate the total potential additional storage across the river corridor.

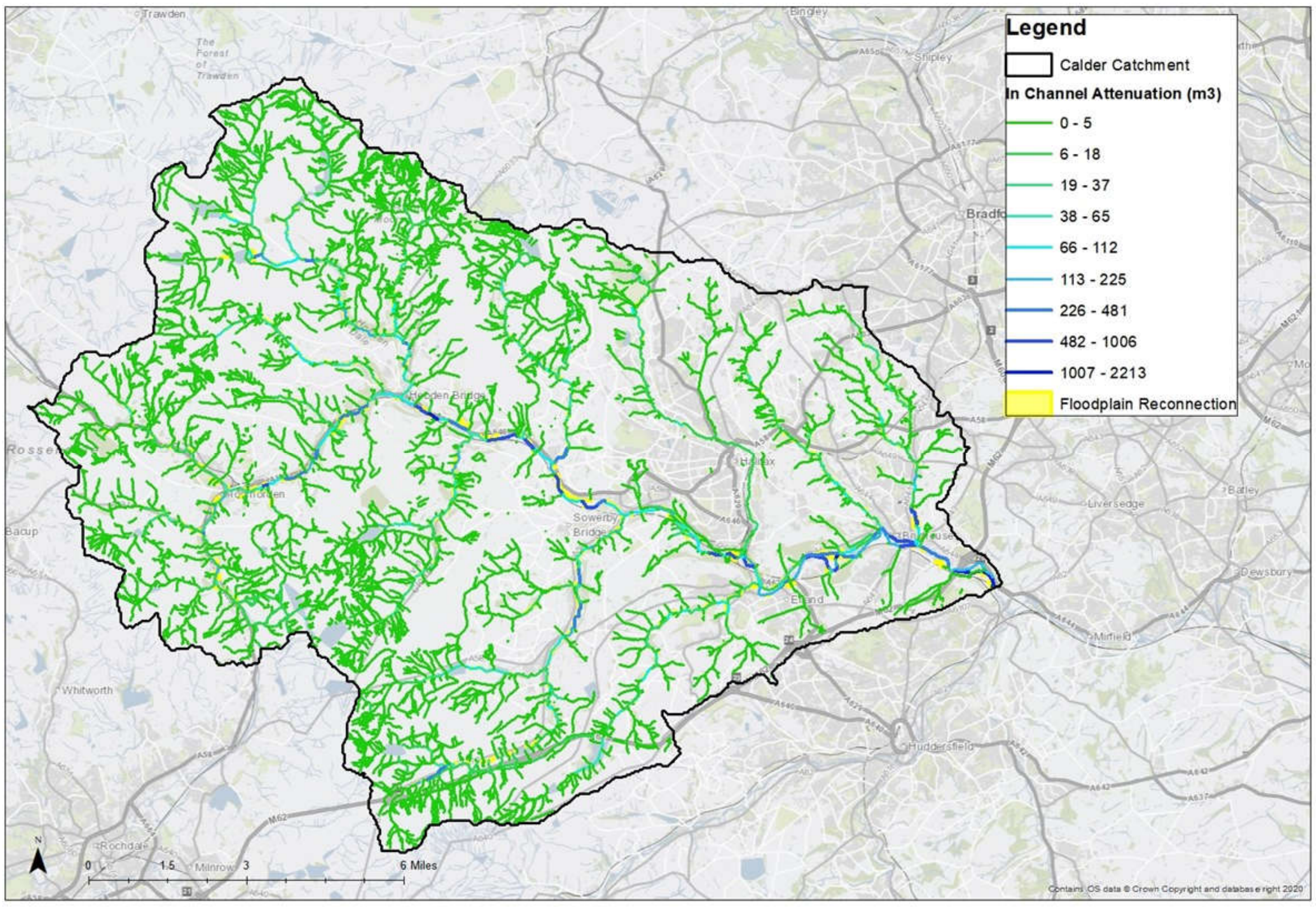
The volumes from the top 10% have also been calculated and are available in Appendix F.

Method to calculate in-channel attenuation and floodplain storage



0.9 is the minimum value which the Qmed equation is considered acceptable. Lower FARL values highlight catchments with high attenuation for which NFM interventions are not the recommended measures.

In-channel attenuation and floodplain storage map



Total in-channel storage 79,217m^3

The map on the left shows the best places in the Calder catchment for in-channel attenuation measures, including the likely volumes attenuated. The colour scheme is plotted onto the river network that is presented as a series of river reaches defined by OSMM segments.

NFM Studio estimates that **a maximum volume of 79,217m^3 can be attenuated in-stream across the Calder catchment**. A number of hotspots for instream attenuation are visible on the map, including the River Calder between Hebden Bridge and Sowerby Bridge. The high density of the stream network in the Hebden Water catchment also indicated that this sub-catchment also has in-channel potential.

The WWNP floodplain reconnection layer has also been included on the map (in yellow) to show that these areas coincide with NFM Studio potential. Floodplain reconnection areas tend to be on the main channel in the mid to lower sections of the catchment.

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[5] The Flood Estimation Handbook Centre for Ecology & Hydrology, 1999 https://www.ceh.ac.uk/services/flood-estimation-handbook

[6] QMED - The mean annual maxima flood. QMED has an annual exceedance probability of 0.5 and a return period of 2 years.

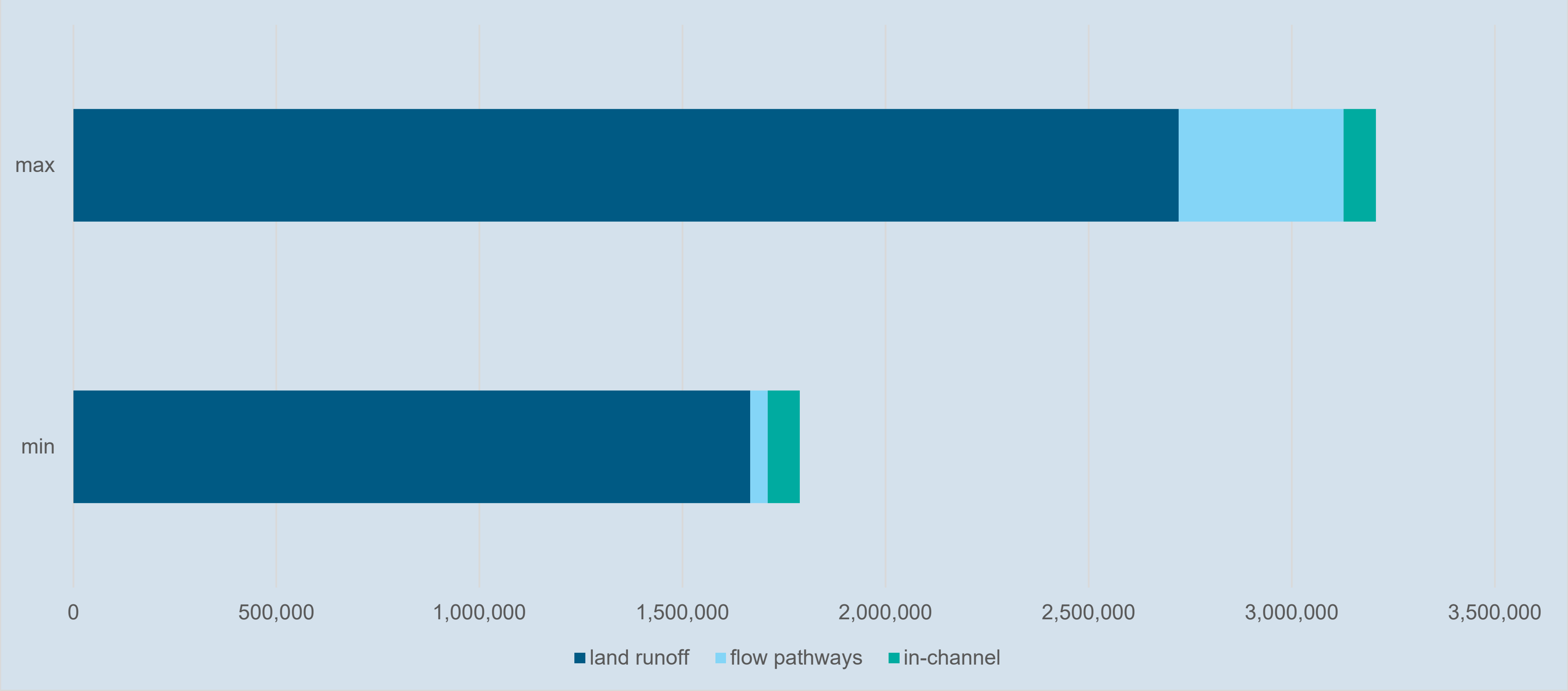
D. In-Combination Assessment

The ‘in-combination’ assessment in NFM Studio considers the total volumetric storage and attenuation that could be provided catchment-wide if all measures on individual fields and river segments were implemented simultaneously. Whilst this is likely to be a potentially unrealistic scenario, it does fulfil the project scope and provides an indicative, no-constraints volume to scale and contextualise the benefits associated with NFM in the Calder catchment.

The ‘in-combination’ assessment is simply the total estimated runoff reduction from land runoff, flow pathway and in-channel measures added together. The table and chart below provide the catchment scale results for a 1:100 year flood (1% AEP), presenting a maximum and minimum range. It is clear that the land use change and management intervention provides the greatest benefit in terms of volumetric reduction/storage across the whole catchment.

NFM Studio Results – In-Combination Catchment Summary

Scenarios and measures applied		**Land runoff (m^3)**	**Flow pathway (m^3)**	**In-channel (m^3)**	**Total (m^3)**
Maximum	Combining the (a) land runoff Option 2 (Woodland Creation); (b) maximum (multiple) bunds and (c) in-channel measures.	2,721,731	406,150	79,217	3,207,098
Minimum	Combining the (a) land runoff Option 3 (Soil recovery); (b) minimum (single) bund and (c) in-channel measures	1,666,718	42,839	79,217	1,788,774

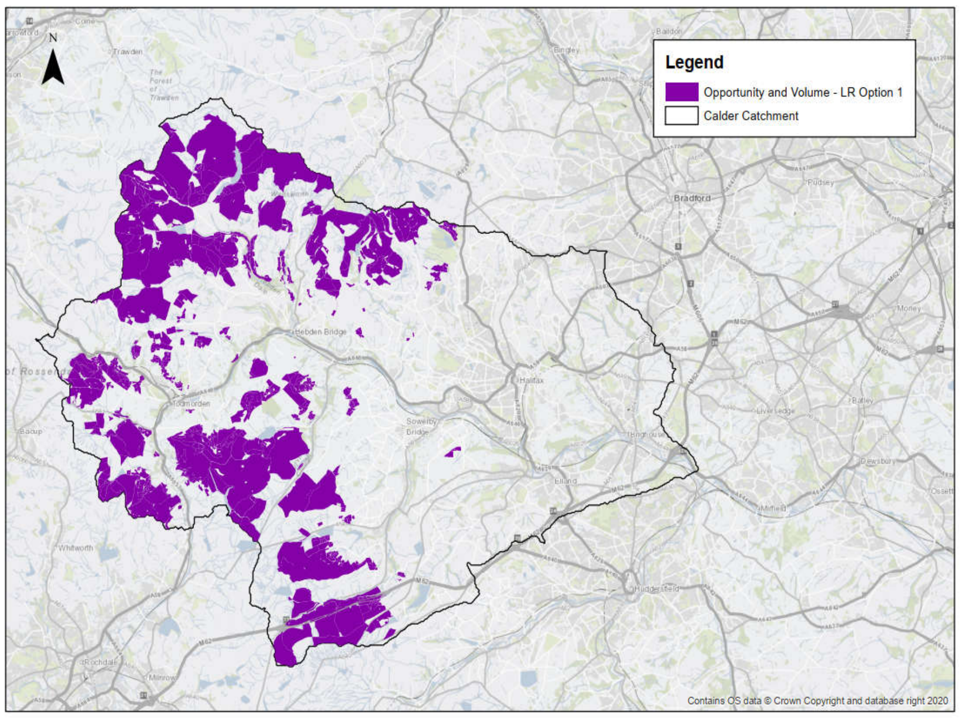


Prioritisation Maps

The NFM Studio hydrological (volumetric) assessment outputs can be used independently to prioritise NFM management in the catchment depending on local opportunities, landowner consent, funding or local volunteer groups etc. However, the volumetric outputs can also be used in combination with the opportunity mapping where stakeholders provided an indication of where NFM implementation is most likely to be undertaken in terms of land cover.

The top 10% of fields (highest total runoff reduction/attenuation potential) across the catchment, together with the top scoring opportunity areas is presented below for the 3 land use change and management options, flow pathways (minimum bund) and in-channel attenuation.

Priority map Option 1 land use change/management



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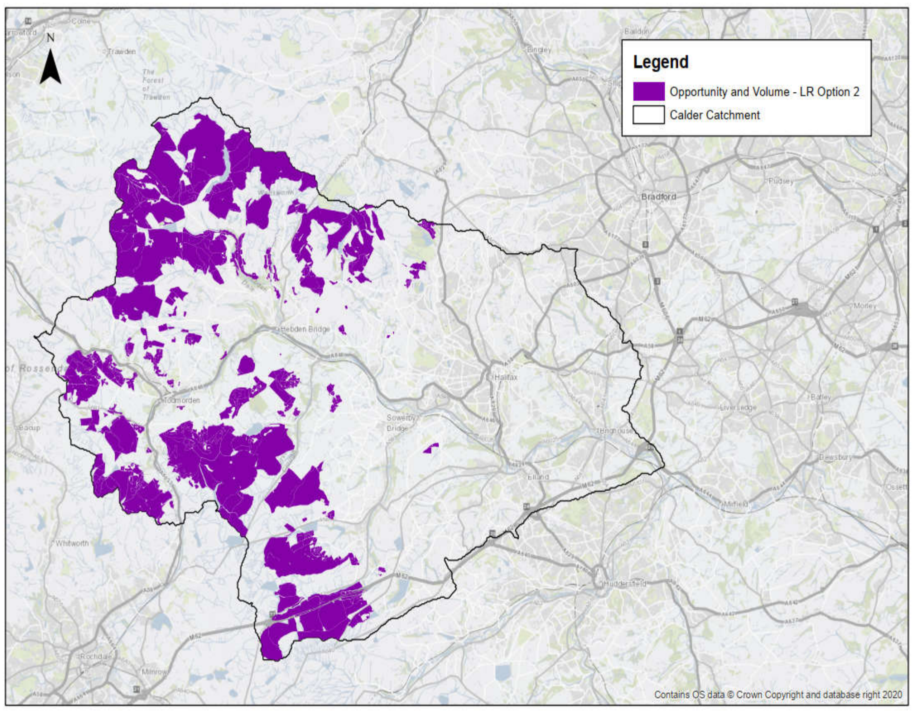
Priority map Option 2 woodland creation and peat restoration



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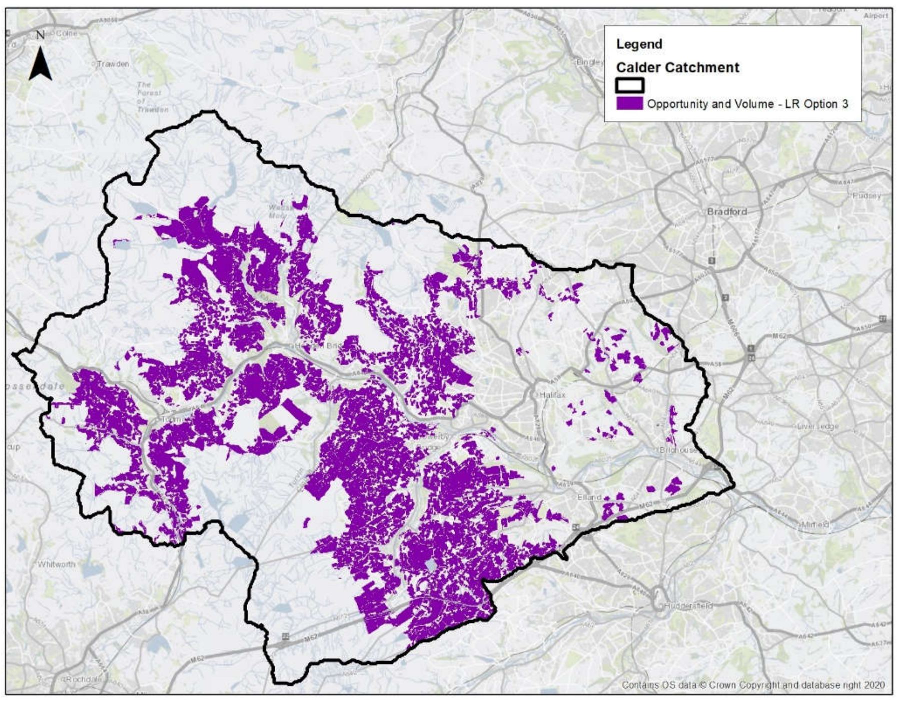
Priority map Option 3 soil recovery



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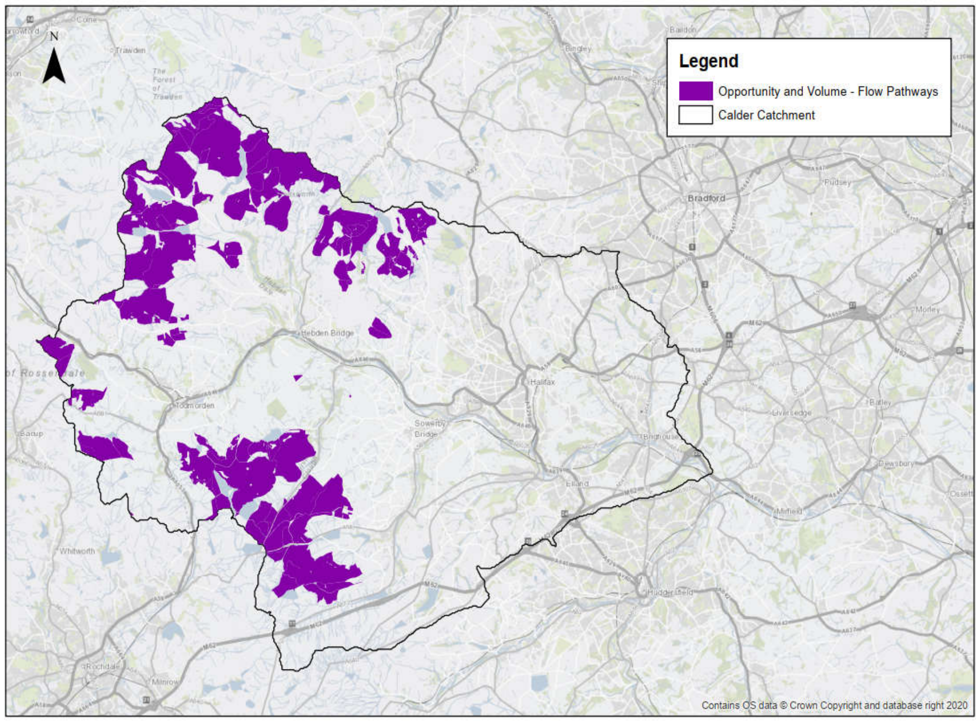
Summary priority maps

The maps combining the volumetric assessment (top 10% and the opportunity scoring) show that the upper catchment is the priority target for land use change and management including woodland creation and peat and moorland restoration. Restoration of the upland areas above Todmorden, Hebden Bridge and Mytholmroyd would provide the greatest runoff reduction potential (as runoff total per field parcel), and an area where stakeholders feel there is viable potential for implementation. Soil recovery is focused on the moorland, grasslands and pastures where improving soil health such as lowering grazing densities to reduce compaction, aerating, subsoiling or/and crop and livestock rotation would provide runoff benefits.

The uplands are also a suggested priority area for flow pathway intervention reducing overland flow through construction of bunds. The in-channel attenuation prioritisations map, when the volumetric NFM Studio outputs are combined with the opportunity map suggest that the Hebden Water catchment (Hardcastle Crags) is a focus area alongside Crimsworth Dean Beck. The area around Gorpley Clough upstream of Todmorden is also highlighted as a good opportunity to implement in-channel measures.

Flow pathways (minimum bund)



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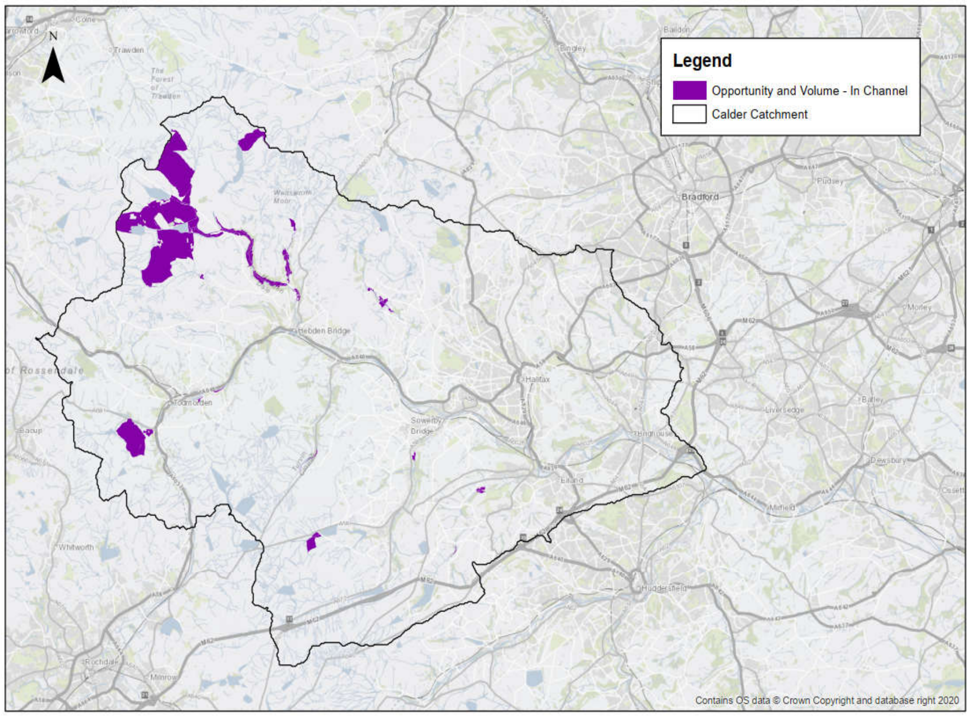
In-channel attenuation



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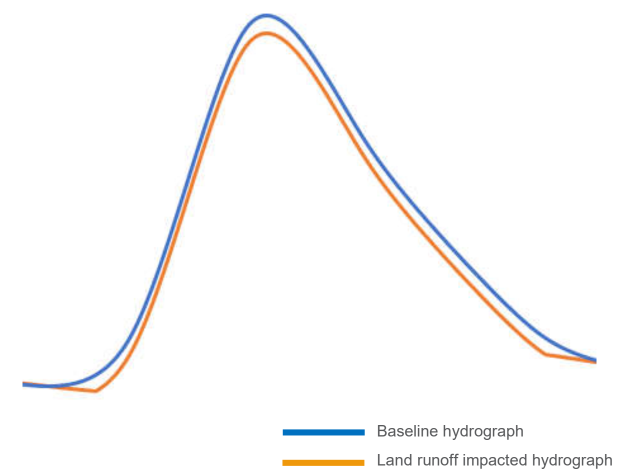
7. Hydrological Benefits

Methodology

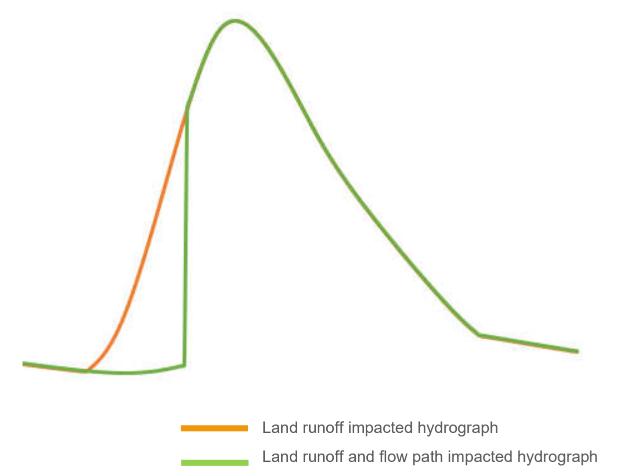
In NFM Studio, the effects of NFM on the flood hydrograph are estimated using a step-wise cumulative process method based on a series of assumptions describing the way runoff is generated and moves through the catchment during flood events. The visualisations below show and describe how this is done in NFM Studio and the main assumptions made.

Step 1 – Land runoff



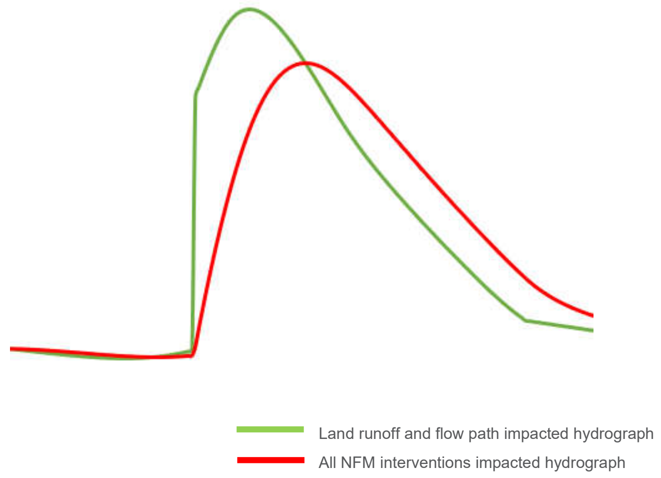
The estimated volumetric runoff reductions from the **land runoff interventions** are equally distributed across the hydrograph, having the effect of lowering peak flows. It is also assumed that infiltration to the deeper soil stores is added onto the baseflow.

Step 2 – Flow pathway

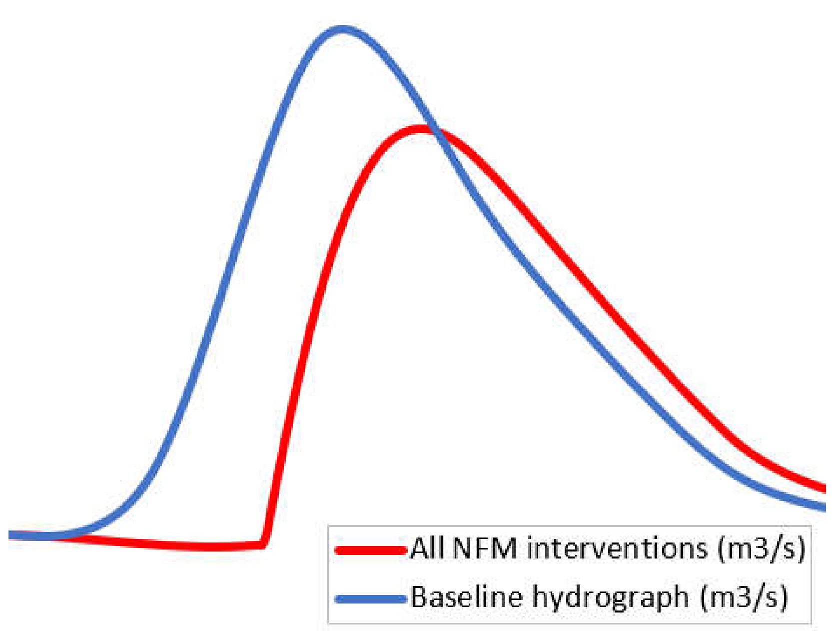


The storage provided by **flow pathway** bunds is removed from the rising limb of the hydrograph resulting from Step 1. This simulates the way flow pathway bunds fill at the beginning of a flood event. It is also assumed that the bunds are empty at the start of the event, and that they slowly drain after it.

Step 3 – In-channel



The **in-channel attenuation** volumes are applied using the Muskingham flow routing methodology to model the temporary attenuation and slowing the flow provided by in channel measures. This results in a decreased peak and increased time to peak.



Step 4 – Combined measures hydrograph

The resulting summary hydrograph (red) shows the impact of catchment wide implementation of all three NFM intervention types, assuming that all interventions can be applied simultaneously.

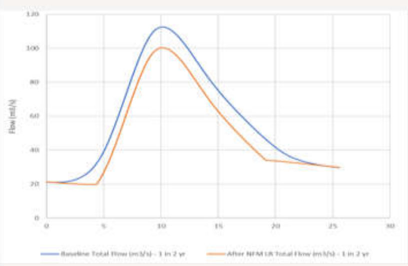
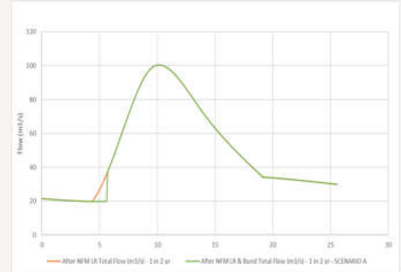
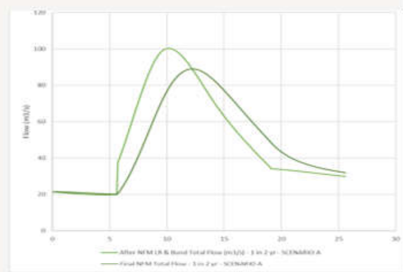
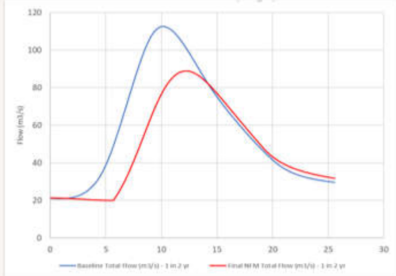
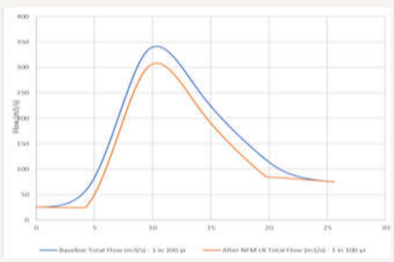
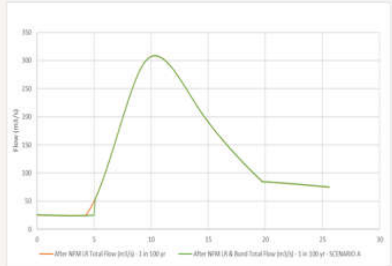
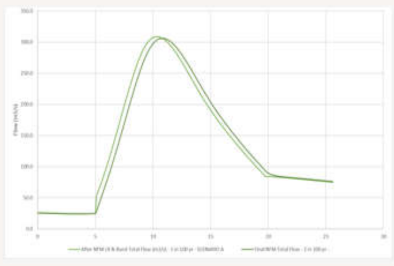
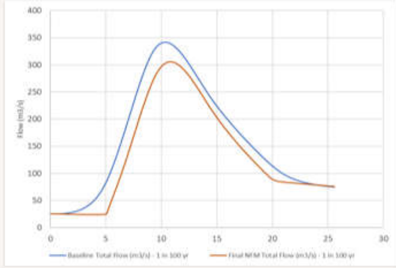
This step supports the visualisation of outputs, allowing modelled volumetric benefits to be put in the context of different return period flood volumes.

The results are indicative and based on the assumptions set out in this panel and in Appendix B.

The panels below show the estimated post-NFM hydrographs for different land use scenarios for the Calder catchment. Each panel shows a different land use scenario, estimating the hydrological effects of each at the 1 in 2 year (50% AEP) and 1 in 100 year (1% AEP) return periods.

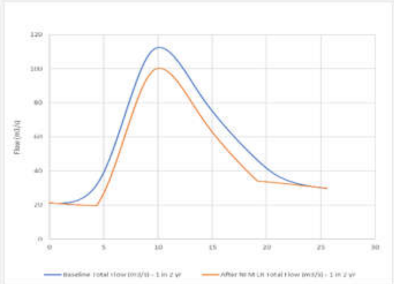
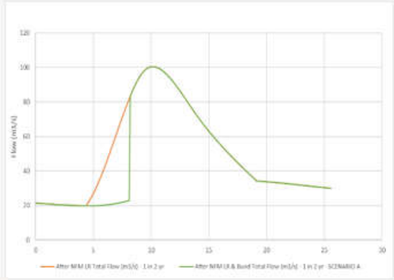
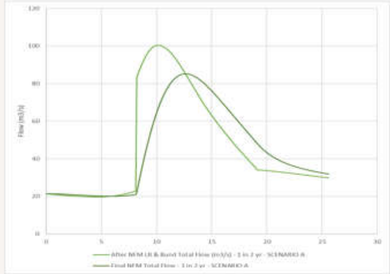
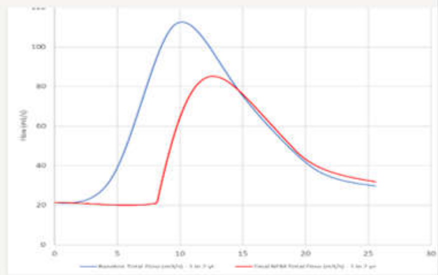
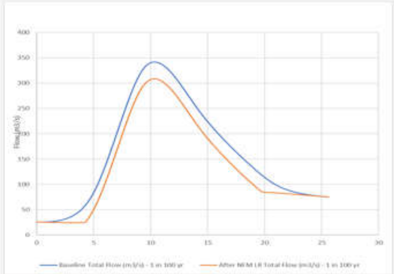
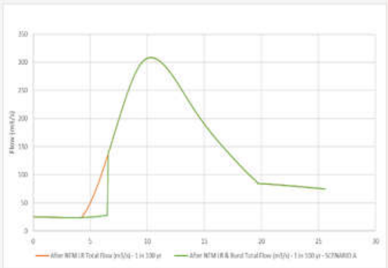
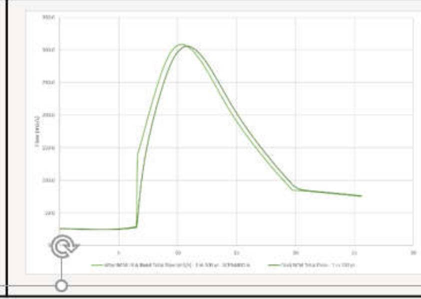
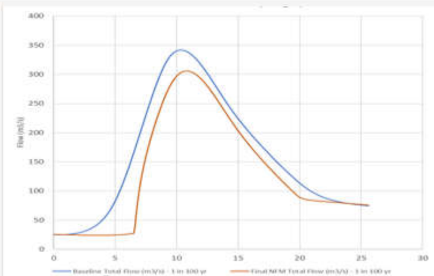
Results

Impacted hydrographs – Land use change and management (Option 1), minimum (single) bund option and in-channel

	Land-use change interventions	Flow pathway interventions	In-channel interventions	Final Post NFM Hydrograph	% change in peak flow
T2 1:2 year event					-21%
T100 1:100 year event					-10%

Sequential reduction in flood volumes from different NFM intervention types

Impacted hydrographs – land use change (Option 1), maximum bunds option and in-channel

	Land-use change interventions	Flow pathway interventions	In-channel interventions	Final Post NFM Hydrograph	% change in peak flow
T2 1:2 year event					-24%
T100 1:100 year event					-11%

Sequential reduction in flood volumes from different NFM intervention types

Peak flow reductions combined (land use change, flow pathways and in-channel interventions)

	Single Flow Pathway Bund							Maximum Flow Pathway Bund					
	Peak Flow (m^3/s)				% Change in Peak Flow			Peak Flow (m^3/s)			% Change in Peak Flow		
	Baseline	OPT1	OPT2	OPT3	OPT1	OPT2	OPT3	OPT1	OPT2	OPT3	OPT1	OPT2	OPT3
T2 1:2 yr 50% AEP	113	89	88	91	-21%	-22%	-19%	85	84	87	-24%	-25%	-22%
T10 1: 10 yr 10% AEP	190	163	161	168	-14%	-15%	-11%	162	160	167	-15%	-16%	-12%
T20 1:20 yr 5% AEP	228	199	197	206	-13%	-14%	-10%	198	196	205	-13%	-14%	-10%
T50 1:50 yr 2% AEP	287	255	252	264	-11%	-12%	-8%	255	252	264	-11%	-12%	-8%
T100 1:100 yr 1% AEP	342	306	303	318	-10%	-11%	-7%	306	303	318	-11%	-11%	-8%

The peak flows presented above are after all three NFM intervention types have been applied across a range of return periods. Since there are multiple options available for the land runoff and flow pathway intervention types the table also contains a summary of each combination of options. The biggest impact on peak flow is at the smaller return periods across all options with a gradual decrease in % peak reduction as the return periods increase.

8. Hydrology of Observed Events

Methodology

The volumetric outputs from the NFM Studio tool were also applied to the observed hydrographs of the selected storm events. The volumes of water that could be stored or reduced through the catchment wide implementation of NFM were applied to the hydrographs using the same methodology as explained above. The observed storm events studied were:

- June 2012 (Summer flooding, with levels at Hebden Bridge, Mytholmroyd and Sowerby Bridge highest. Estimated flow return period between 1:50 year and 1:70 year at Mytholmroyd, but this can not be applied catchment wide[7]).
- December 2015 (Boxing Day Floods during Storm Desmond but wet December so reduced storage and lower catchment still responding to earlier rainfall events[8]. EA estimate this was at least a 1:100 year event).
- March 2019 (Storm event mid March followed prolonged rainfall in the preceding weeks resulting in a saturated catchment, estimated as a proxy 1:50 year event when comparing to the NFM design event flow).
- February 2020 (Consecutive storms in quick succession, Storm Ciara and Storm Dennis followed by a period of heavy rain although river levels in upper catchment not historically significant in terms of river response[9] Estimated as a proxy 1:100 year event when comparing to the NFM design event flow).

The hydrology spreadsheet in which the calculations were performed is available in the accompanying documentation (Appendix H). In the spreadsheet the NFM volumes from different options and return periods can be applied to the observed hydrographs. Additionally, selected NFM volumes can be applied to the observed hydrographs to visualise the impact of selected NFM schemes.

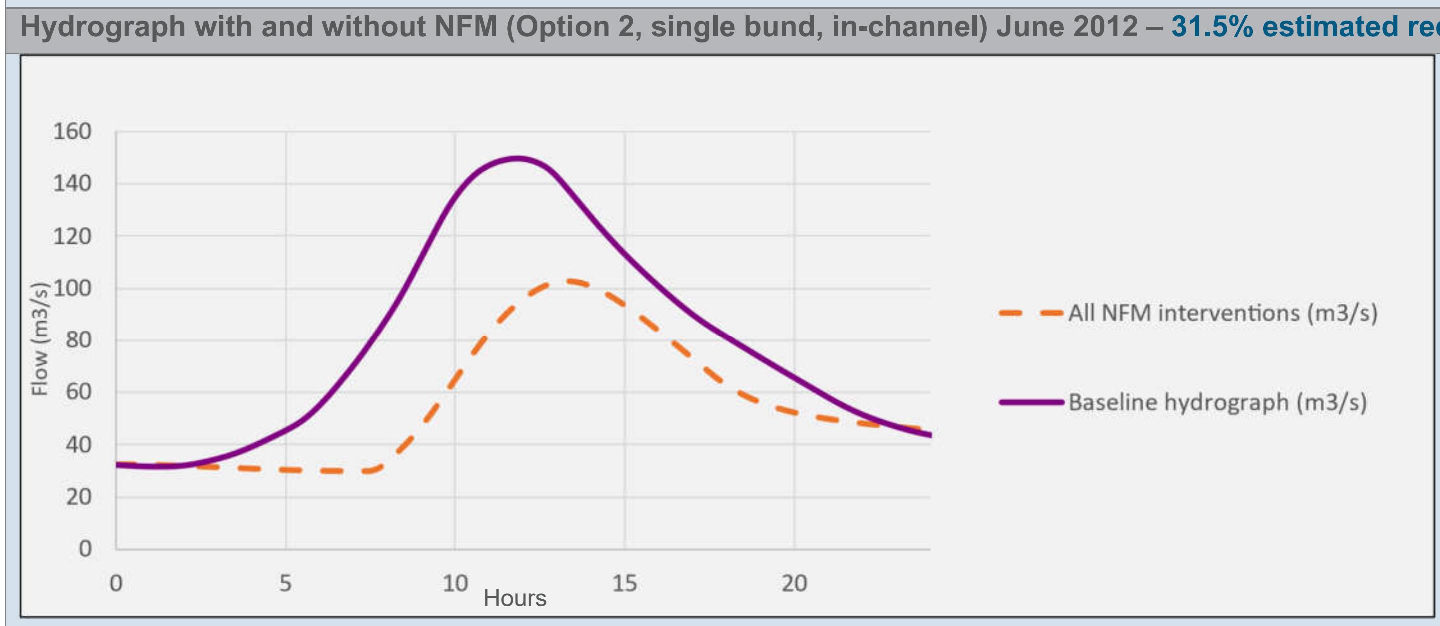
Observed Events

The volumetric outputs from NFM Studio were applied to the observed storm events. As several combinations of options are available for the NFM intervention types, plotted below are the volumetric reductions for catchment wide implementation of **woodland creation and peat and moorland restoration (Option 2) and the single bund per field flow pathway option as well as in-channel.**

The baseline hydrographs (in purple) were generated using the observed rainfall at Brighouse applied to the ReFH methodology. This was validated against the river level data converted to flow at Brighouse. The river level data was not used directly as we did not have as high a confidence in the polynomic relationship between river level and flow, additionally the ReFH method exports the baseflow which we would have had to calculate separately.

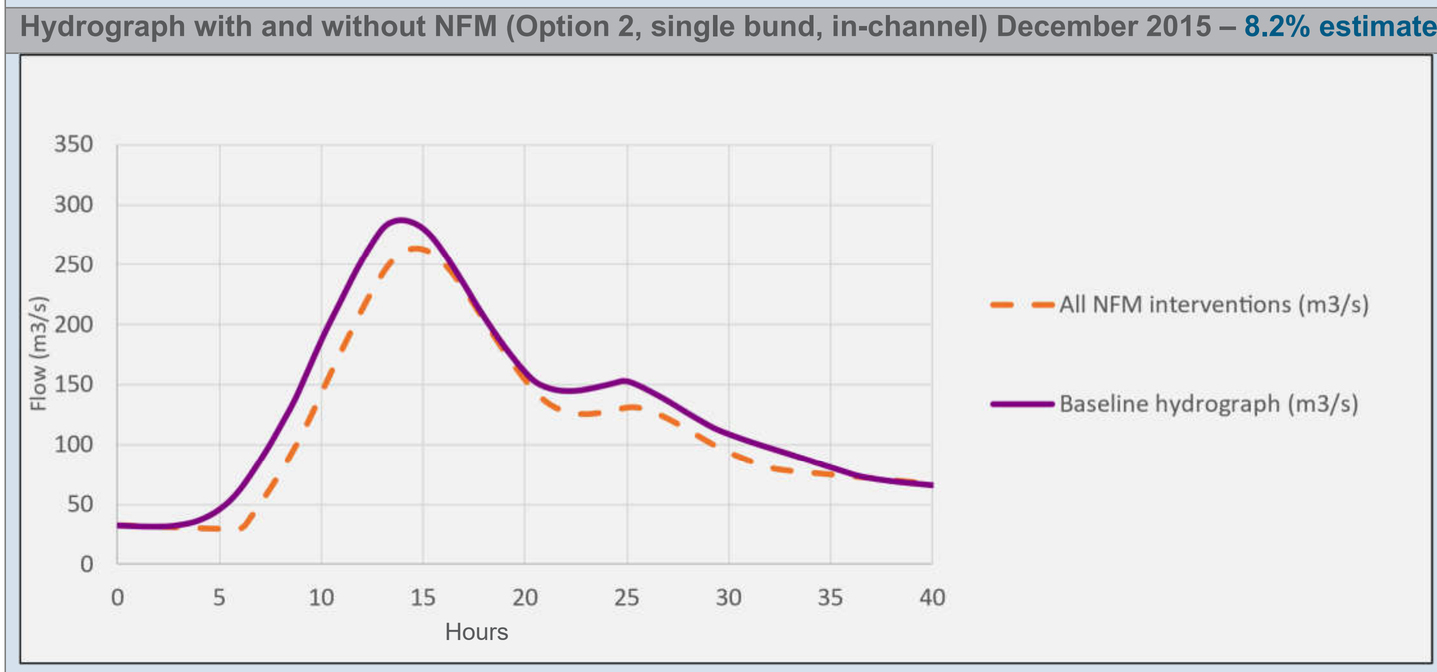
There is a clear benefit to the flood peak when all the NFM interventions are applied in the catchment across all 4 observed events. The 2012 event with NFM intervention applied shows a large reduction (31.5% reduction in peak flow), but the peak discharge was much lower than the other 3 events (4-8% reduction) so the impact is intensified, corroborating the NFM outputs above. The accompanying spreadsheet (Appendix H) can be manipulated to show one type or a combination of interventions and flow pathway types (minimum or maximum bunds) to see how the impact of NFM has on the 4 observed events of interest.

Hydrograph with and without NFM (Option 2, single bund, in-channel) June 2012 – 31.5% estimated reduction in peak flow



2012 event

Hydrograph with and without NFM (Option 2, single bund, in-channel) December 2015 – 8.2% estimated reduction in peak flow



2015 event

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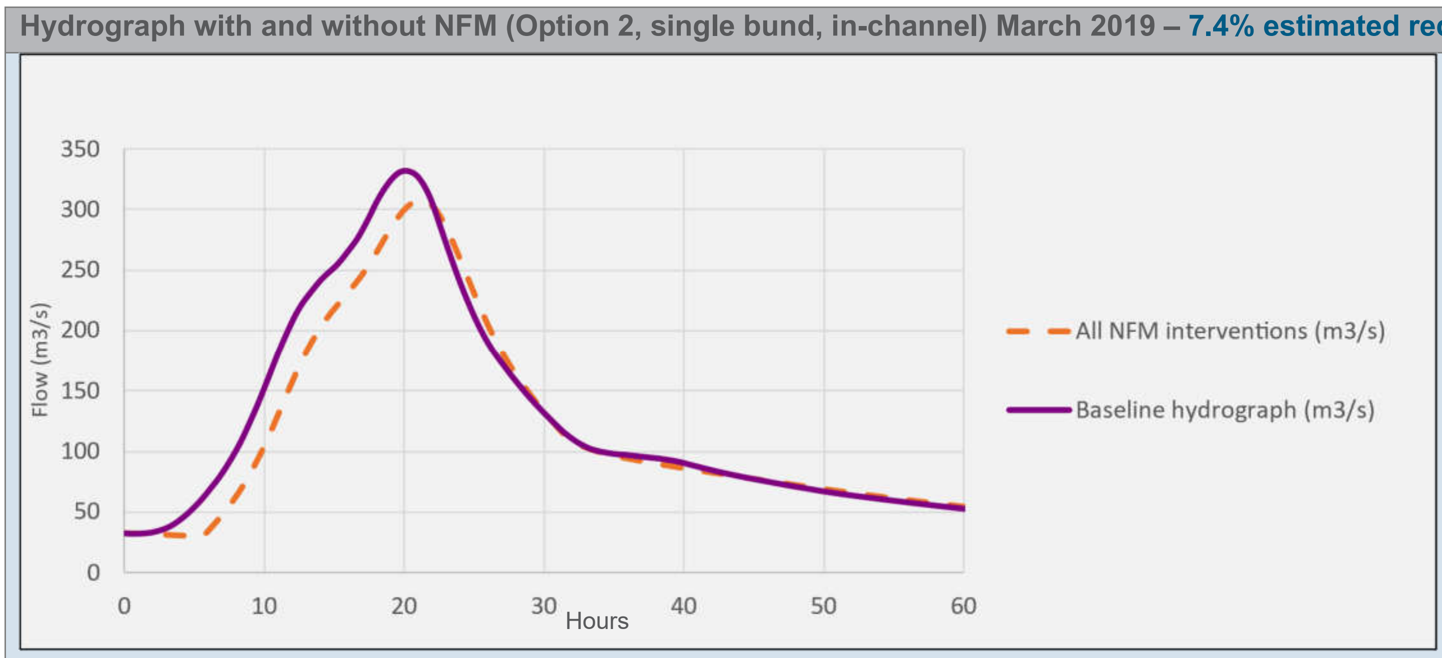
[7] EA June 2012 flood hydrology facts

[8] EA 26-28th December 2015 flood hydrology facts. Yorkshire Area: Factsheet 17

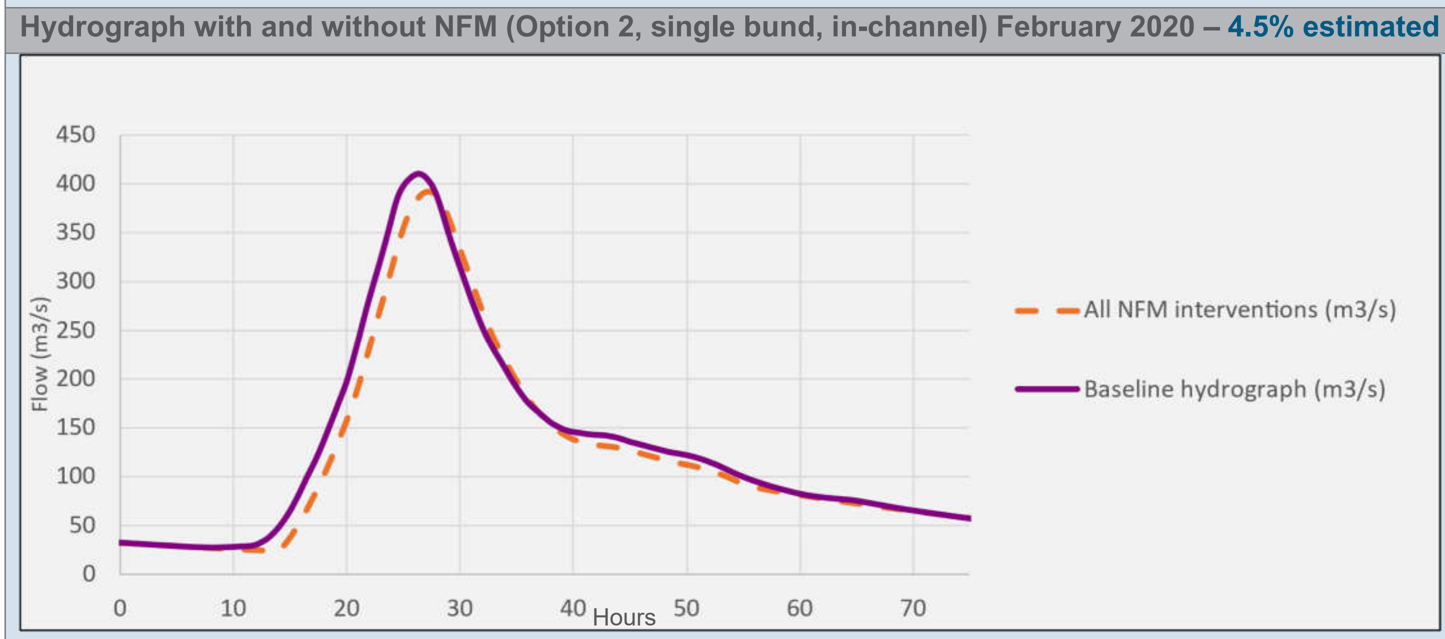
[9] EA 15-17th February 2020 flood hydrology facts. Yorkshire Area: Factsheet 38

Hydrograph with and without NFM (Option 2, single bund, in-channel) March 2019 – 7.4% estimated reduction in peak flow



2019 event

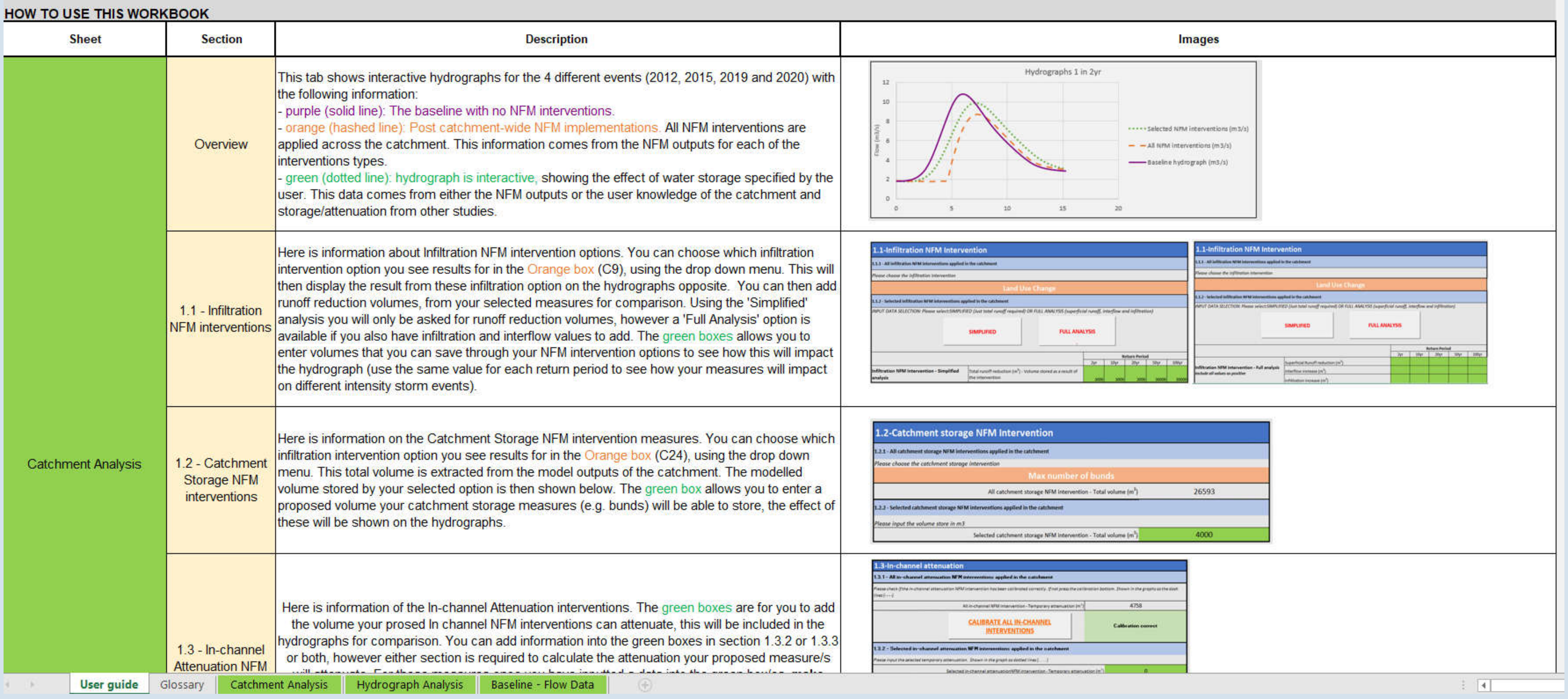
Hydrograph with and without NFM (Option 2, single bund, in-channel) February 2020 – 4.5% estimated reduction in peak flow



2020 event

Hydrology spreadsheet (Appendix H) is Calder specific but a more general user guide (Video 4) is available here. There is also a user guide tab in the Calder hydrology spreadsheet.

NFMStudio User Guide Videos - YouTube or please search for “Atkins NFMStudio User Guide” in YouTube



HOW TO USE THIS WORKBOOK

Sheet	Section	Description	Images
Catchment Analysis	Overview	This tab shows interactive hydrographs for the 4 different events (2012, 2015, 2019 and 2020) with the following information: - purple (solid line): The baseline with no NFM interventions. - orange (hashed line): Post catchment-wide NFM implementations. All NFM interventions are applied across the catchment. This information comes from the NFM outputs for each of the interventions types. - green (dotted line): hydrograph is interactive, showing the effect of water storage specified by the user. This data comes from either the NFM outputs or the user knowledge of the catchment and storage/attenuation from other studies.	
	1.1 - Infiltration NFM interventions	Here is information about Infiltration NFM intervention options. You can choose which infiltration intervention option you see results for in the Orange box (C9), using the drop down menu. This will then display the result from these infiltration option on the hydrographs opposite. You can then add runoff reduction volumes, from your selected measures for comparison. Using the 'Simplified' analysis you will only be asked for runoff reduction volumes, however a 'Full Analysis' option is available if you also have infiltration and interflow values to add. The green boxes allows you to enter volumes that you can save through your NFM intervention options to see how this will impact the hydrograph (use the same value for each return period to see how your measures will impact on different intensity storm events).	
	1.2 - Catchment Storage NFM interventions	Here is information on the Catchment Storage NFM intervention measures. You can choose which infiltration intervention option you see results for in the Orange box (C24), using the drop down menu. This total volume is extracted from the model outputs of the catchment. The modelled volume stored by your selected option is then shown below. The green box allows you to enter a proposed volume your catchment storage measures (e.g. bunds) will be able to store, the effect of these will be shown on the hydrographs.	
	1.3 - In-channel Attenuation NFM	Here is information of the In-channel Attenuation interventions. The green boxes are for you to add the volume your prosed In channel NFM interventions can attenuate, this will be included in the hydrographs for comparison. You can add information into the green boxes in section 1.3.2 or 1.3.3 or both, however either section is required to calculate the attenuation your proposed measure/s	

9. Outline Costings

Methodology

Initial costings have been calculated for both the implementation of the measures from the NFM Studio outputs and the maintenance of the measures for a 5 year and 50 year period as agreed with the Environment Agency. These have been calculated as a total per field for land use changes and flow pathway measures combined, and per river segment for in channel features as per the NFM studio outputs. Furthermore, the costs per m^3 of storage have been calculated based on the total cost of implementation plus 5 years maintenance and total cost of implementation plus 50 years maintenance and the storage provided, this helps to understand which options are more cost effective. The values used to calculate these costs have primarily been based on the costs provided via organisations in the catchment that have already implemented measures and supplemented by open-source data from the National Highways NFM Handbook, further details on this can be found in the table below and Appendix I. It is important to note that these costs are indicative, as the implementation and maintenance costs will vary based on a number for factors such as density of features, location and size, but also access and volunteer/equipment availability.

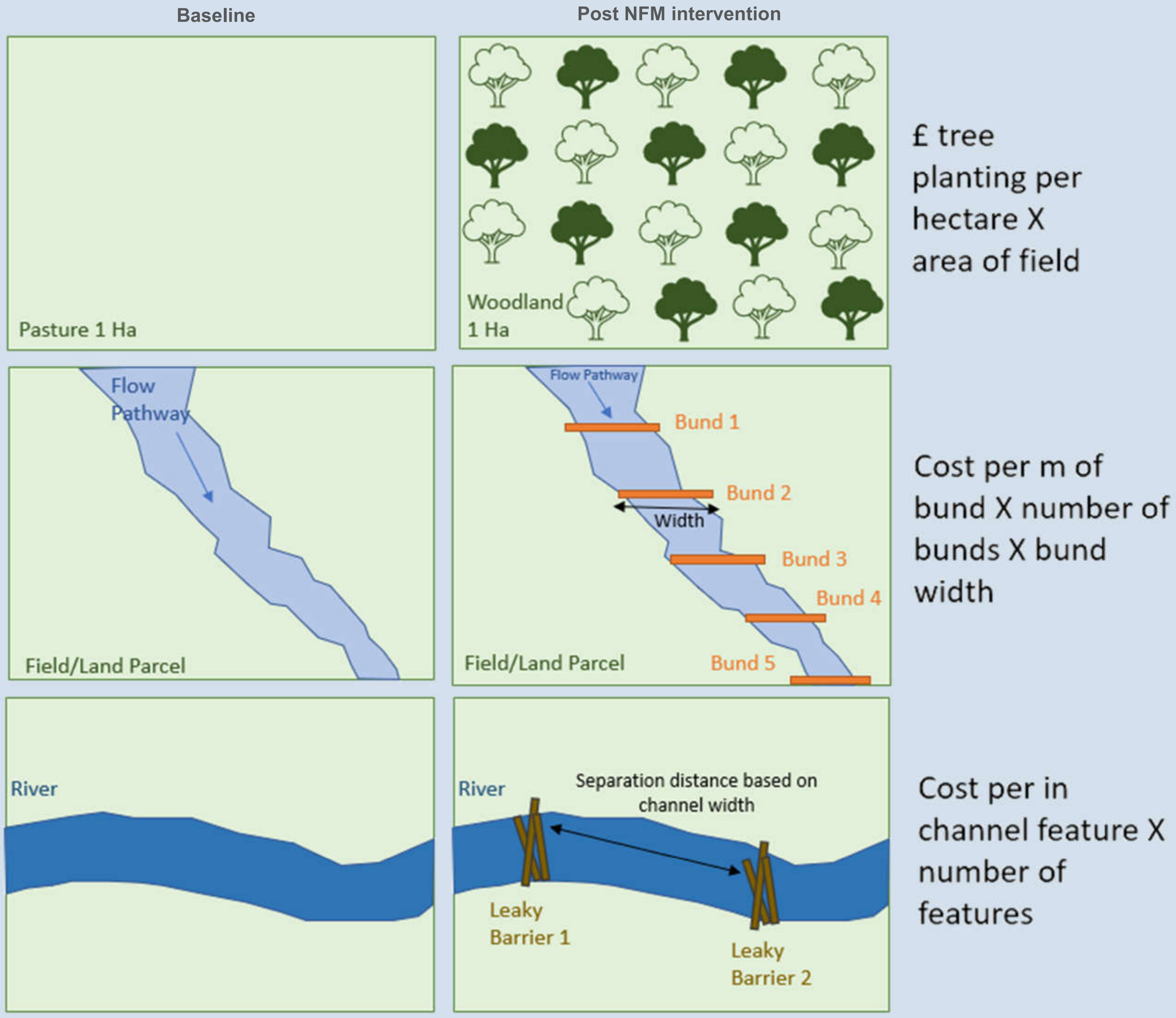
The construction costings for the three NFM intervention types for which storage is calculated in NFM Studio are as follows:

- The **Land use change** costs were calculated by applying a cost per m^2 for different land use change scenarios to the area of each field, again in m^2. The land used changes included are:
    - Arable to Pasture
    - Moorland to Shrubland
    - Pasture to Natural Grassland
    - Peatland to Restored Peatland
    - Arable to Woodland
    - Moorland to Woodland
    - Natural Grassland to Woodland
    - Pasture to Woodland
    - Soil recovery
    - Moorland to Restored Moorland
- The **flow pathway** costs were calculated by using the metre width of the bund as per NFM Studio output and cost per metre width of construction, scaled up for the number of bunds per field again indicated by the NFM studio outputs.
- The **in-channel** costs were calculated by assuming an in-channel feature could be implemented with a separation distance of 5 times the channel width. Once the number of in channel features was calculated this was multiplied by the indicative cost per in channel feature to give the total cost per river segment.

A maintenance period of 5 years and 50 years was then added to the construction costs to give a total cost over 5 and 50 years. The maintenance costs for some measures have been assumed to be 10% of the construction cost per year (as suggested by the Calder catchment organisations). The values and justifications for the maintenance costs are again provided in full in the table below.

Costs for landowner engagement have not been included but are estimated to be approximately up to 15-20% of capital cost (*pers. comm* Environment Agency).

Method to estimate costs of NFM interventions



Costings Breakdown

Measure	Capital cost	Capital cost + 5 year maintenance	Capital cost + 50 year maintenance	Average cost per m^3 over 5 years	Cost per m^3 over 50 years	Costs used
Land use – Option 1						
Arable to Pasture	£588,681	£3,532,083	£30,022,707	£2,811	£23,896	SW7 (£321 per ha) + £100 per ha for implementation (https://www.gov.uk/countryside-stewardship-grants/arable-reversion-to-grassland-with-low-fertiliser-input-sw7)
Moorland to Shrubland	£47,860,513	£71,790,769	£287,163,077	-£16,583[10]	-£66,331	Woodland planting costs from Calderdale Grant Scheme with shelter and stake (£1.65 per m^2)
Natural Grassland to Woodland	£27,737,799	£41,606,699	£166,426,796	£61,701	£246,804	Woodland planting costs from Calderdale Grant Scheme with shelter and stake (£1.65 per m^2)
Pasture to Natural Grassland	£4,813,824	£28,882,946	£245,505,037	£361	£3,064	AB8 (£628 per ha)+ £100 per ha for implementation (https://www.gov.uk/countryside-stewardship-grants/flower-rich-margins-and-plots-ab8)
Peatland to Restored Peatland	£24,605,524	£36,908,287	£147,633,146	£5,387	£21,547	Peat revegetation costs from MFFP (£0.567 per m^2)
Land use Option 1 Total	**£105,606,341**	**£182,720,784**	**£876,750,764**	**£4,956**	**£21,356**	
Land use – Option 2						
Arable to Woodland	£24,283,072	£36,424,608	£145,698,433	£25,831	£103,322	Woodland planting costs from Calderdale Grant Scheme with shelter and stake (£1.65 per m^2)
Moorland to Woodland	£47,860,513	£71,790,769	£287,163,077	£45,591	£182,365	Woodland planting costs from Calderdale Grant Scheme with shelter and stake (£1.65 per m^2)
Natural Grassland to Woodland	£27,737,799	£41,606,699	£166,426,796	£61,966	£247,863	Woodland planting costs from Calderdale Grant Scheme with shelter and stake (£1.65 per m^2)
Peatland to Restored Peatland	£24,605,524	£36,908,287	£147,633,146	£5,423	£21,690	Peat revegetation costs from MFFP (£0.567 per m^2)
Pasture to Woodland	£113,468,715	£170,203,072	£680,812,288	£1,890	£7,560	Woodland planting costs from Calderdale Grant Scheme with shelter and stake (£1.65 per m^2)
Land use Option 2 Total	**£237,955,623**	**£356,933,435**	**£1,427,733,740**	**£11,614**	**£46,455**	
Land use – Option 3						
Soil recovery	£213,356	£320,034	£1,280,135	£16	£64	Soil aeration cost from Calderdale Grant Scheme (£0.002 per m^2)
Moorland to Restored Moorland	£16,446,613	£24,669,919	£98,679,675	£6,231	£24,926	Peat revegetation costs from MFFP (£0.567 per m^2)
Land use Option 3 Total	**£16,659,968**	**£24,989,953**	**£99,959,810**	**£461**	**£1,844**	
Flow pathway bunds						
Minimum (single bund)	**£659,253**	**£988,879**	**£3,955,517**	**£13**	**£52**	Costs for earth bund from Calderdale Grant Scheme (£10 per m width and 1m high) N.B. NFM Studio bund height 0.5m
Maximum (multiple bund)	**£30,812,244**	**£46,218,366**	**£184,873,462**	**£16**	**£64**	Costs for earth bund from Calderdale Grant Scheme (£10 per m width) N.B. NFM Studio bund height 0.5m
In channel						
In channel feature	**£19,225,325**	**£28,837,988**	**£115,351,950**	**£2,071**	**£8,283**	Costs for leaky barrier from Calderdale Grant Scheme (£175 per feature)

The table above shows the capital cost, capital costs plus a 5-year maintenance period, capital cost plus a 50-year maintenance period and cost per cubic metre of storage for both 5 and 50 year periods for each land use option type, minimum and maximum bunds and in channel features. The results show that soil recovery and flow pathway bunds are the most cost-effective measures in terms of cost per m^3 of storage. Whilst the NFM studio outputs show that land use change as a whole is more effective for storage, implementation costs of these can be high in comparison to other measures.

In terms of land use, the most cost-effective measures, apart from bunds and soil recovery, are pasture to natural grassland and pasture to woodland followed by arable to pasture and peatland to restored peatland. The least cost-effective measures presented are moorland to shrubland (increase in runoff), natural grassland to woodland and moorland to woodland. The cost per m^3 of storage for in channel features is lower than the majority of the land use changes, however substantially higher than flow pathway bunds and soil recovery.

It is important to note that with rising energy costs and inflation that capital costs of constructing many of these features is likely to be greater going forwards.

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[10] A change of moorland to shrubland is presenting a negative value for cost per m^3 as for some areas this measure results in an increase in run-off.

10. Natural Capital and Multiple Benefits

Methodology

A catchment wide natural capital assessment has been undertaken to estimate the potential wider environmental benefits to society. The outputs provided for each NFM option/intervention type are the predicted change in annual monetised value across a set of ecosystem service categories based on 2020 price levels. The method for generating the values is consistent with Defra's Enabling a Natural Capital Approach (ENCA) guidance[11] on monetary valuation of ecosystem services and natural capital in project/policy appraisal. The assessment is not a formal natural capital account as the quantity and monetary value of the environmental assets (woodland, peatland, waterbodies etc.) themselves are not explicitly measured; only the annual change ('flow') is captured. This assessment is not a cost-benefit appraisal, nor does the monetisation represent a direct capital gain to a landowner. Nevertheless, the outputs can be used as part of a standardised assessment across catchments to further inform prioritisation, to help target further investigations and primary data collection or to provide the starting point for a site-specific assessment if required.

For the Calder catchment, the multiple benefits provided by NFM have been calculated for the three land use options used as follows (with more detail provided on Page 15):

- **Option 1 - Land use Change and Management**: a land-based scenario where arable fields would revert to low-input grassland and livestock would be removed from grassland fields during the winter season.
- **Option 2 - Woodland Creation:** a land-based scenario where fields without a woodland land cover currently would be converted to woodland and the peat and moorland areas are restored.
- **Option 3 - Soil Recovery:** this option simulates the potential improvements in soil health that arise from soil recovery measures such as aeration in all but the peat areas.

Alongside these three land use scenarios, the multiple benefits from specific NFM measures have also been calculated as follows:

- **Flow Pathway Bunds (wetland creation) –** a flow pathway-based scenario where the maximum number of bunds are placed within a field to store water. For this assessment, it is assumed that the flow pathway area behind the bunds becomes temporary wetland habitat.
- **In-Channel Restoration –** a channel-based scenario where the channel is restored to a high standard using features to naturalise the watercourse including slowing the flow (e.g. woody dams) and floodplain reconnection. For this element, one of the main assumptions is that the measures are significant enough to improve the WFD status of the reach. This is an overly optimistic assumption but there is inadequate data and information on the efficacy of in-channel work to reasonably scale it back.

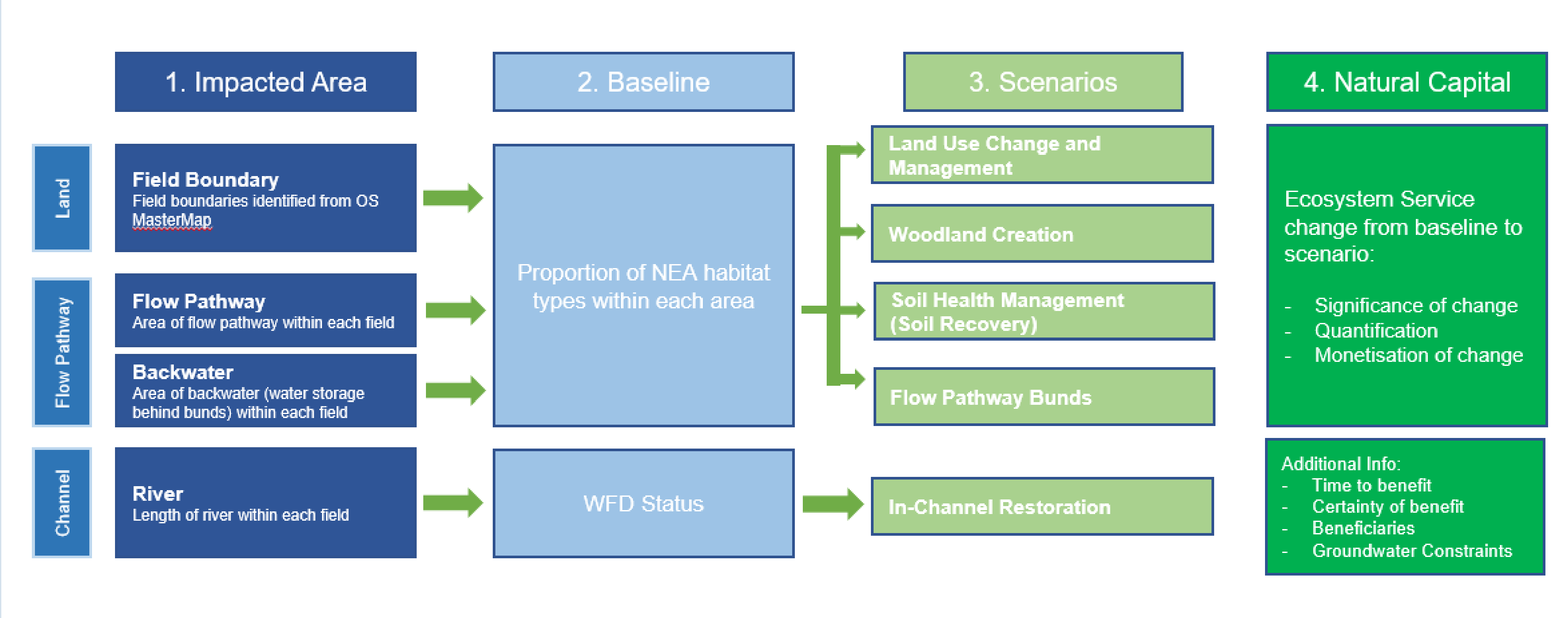
It is important to note that the assessments presented in this section refer to the complete catchment scale application of different land use options and NFM measures. The results are indicative for a no-constraints outcome to help contextualise the multiple benefits associated with NFM in the Calder catchment. The data can be used in the same way as the NFM Studio data to broadly scale and help prioritise areas and measures.

The assessment is also based on a series of assumptions that have necessarily been made to calculate the value of different ecosystem services (see Appendix B and J). For example, the carbon calculation assumes that there is an immediate land-use change when implementing each option, and thus carbon benefits reflect those of a mature measure (e.g. dense woodland). In the absence of site-specific data for the Calder catchment, for other services ecosystem services, transfer values from elsewhere are used. Further specifics of the methods used for each ecosystem service are provided in Appendix J together with a confidence rating.

The list of ecosystem services considered in the assessment of the Calder catchment is shown below. Flood benefits have not been included as these are quantified by separate methods using NFM Studio and the flood economics.

Ecosystem services assessed for the Calder catchment and flow chart detailing approach

Biodiversity	Food	Recreation
Water Quality	Carbon	Air Quality



Natural Capital Assessment Summary Table (further detail in Appendix J)

	Option 1 Land use change and management (£/yr)	Option 2 Woodland creation (except peat and protected moorland) (£/yr)	Option 3 Soil recovery (£/yr)	Flow pathway (Maximum bunds) (£/yr)	In channel interventions (£/yr)
Air Quality	3,881,137	4,886,086	-383,907	74,672	0
Biodiversity	5,233,628	20,671,336	0	0	18,680,398
Carbon	55,329,857	90,106,455	304,410	2,401,628	0
Food	787,457	-10,467,098	0	-1,846,571	0
Recreation	4,521,241	4,502,401	0	0	6,226,799
Water Quality	767,559	916,329	95,997	628,587	6,226,799
Total Benefit	**70,520,879**	**110,615,509**	**16,500**	**1,258,316**	**31,133,996**

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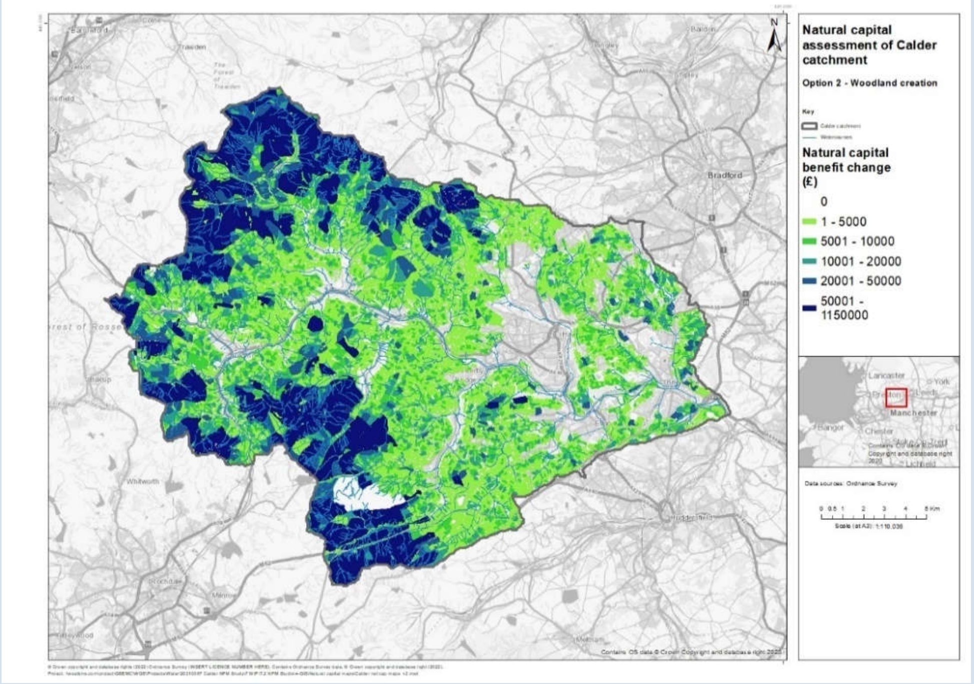
[11] Enabling a Natural Capital Approach guidance - GOV.UK (www.gov.uk)

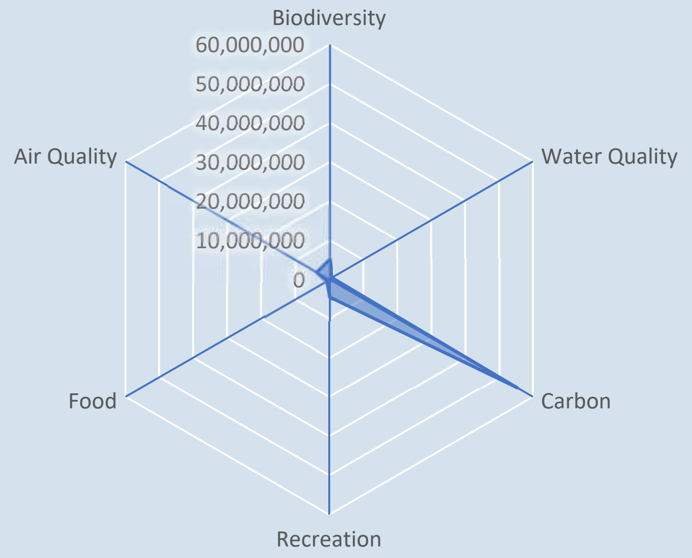
Total Benefit Maps

Option 1 Land use change and management

The results show that the greatest estimated Natural Napital (NC) benefit from land use change and management option is by far carbon (£55,329,857), and then biodiversity (£5,371,912) and recreation (£4,521,241) ecosystem services. The total potential NC benefits within the catchment is **£70,520,879 per year.** The natural capital benefit hotspots in the catchment are shown to be the peat/moorland areas in the upper catchment relating to the carbon sequestration potential.

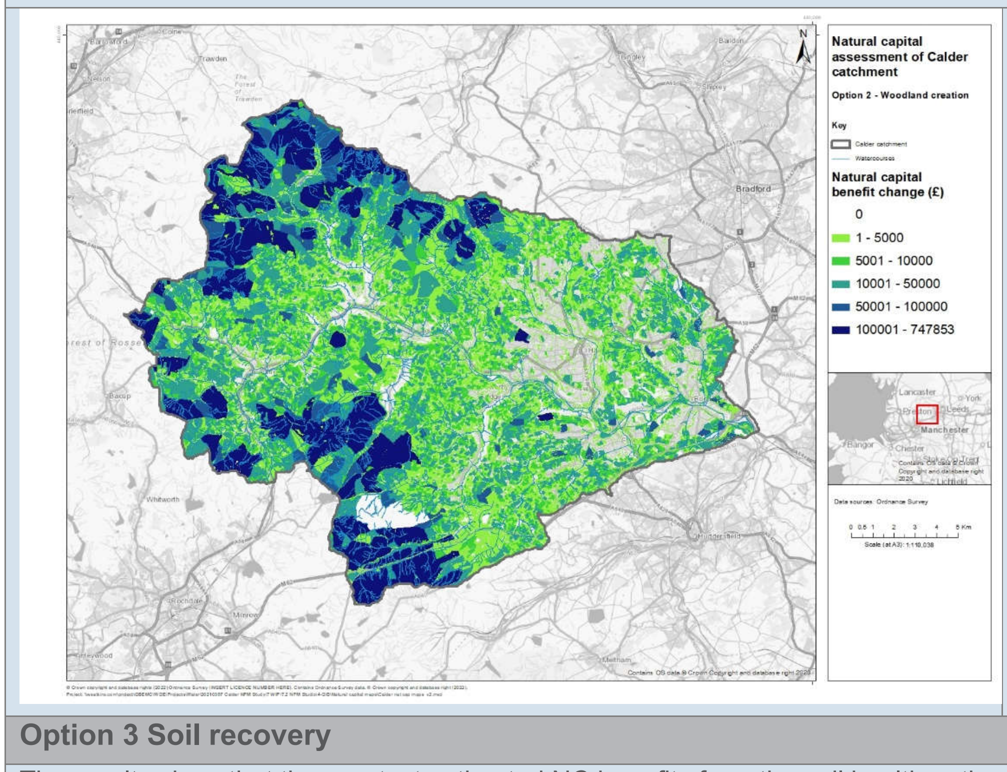


Total Benefit = £70,520,879

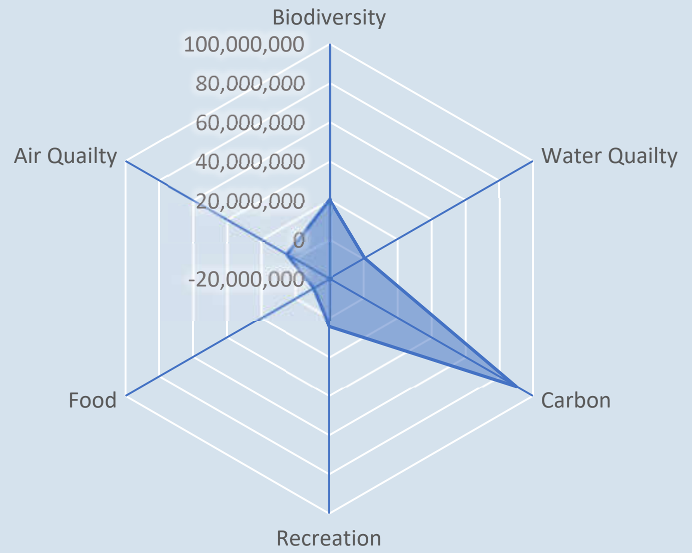


Option 2 Woodland creation and peat restoration

The results show that the greatest estimated NC benefits from woodland creation (with peat and protected moorland being restored) are within the carbon (£90,106,455) and biodiversity (£20,671,336) ecosystem services. The reduction in NC benefits within the food (- £10,467,098) ecosystem service can be explained by the loss of agricultural land. The woodland scenario has the largest potential total NC benefit **(£110,615,509**) in this assessment. This is driven by the large carbon benefits from peat/moorland restoration and woodland creation, alongside the comparatively large benefits to biodiversity.

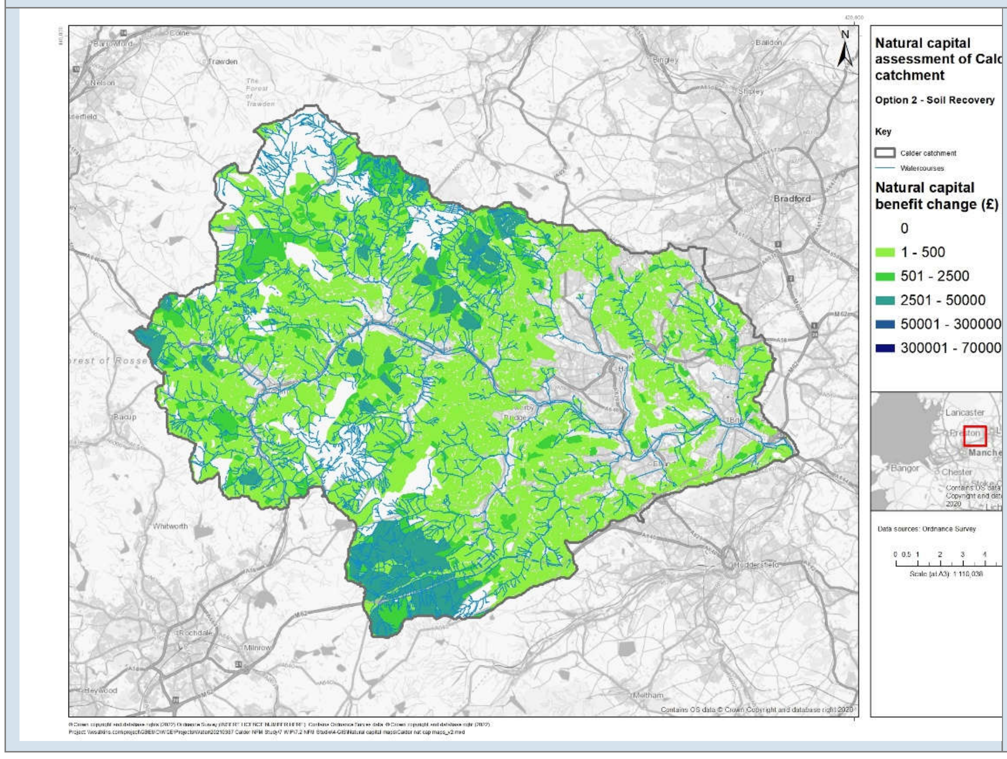


Total Benefit = £ 110,615,509

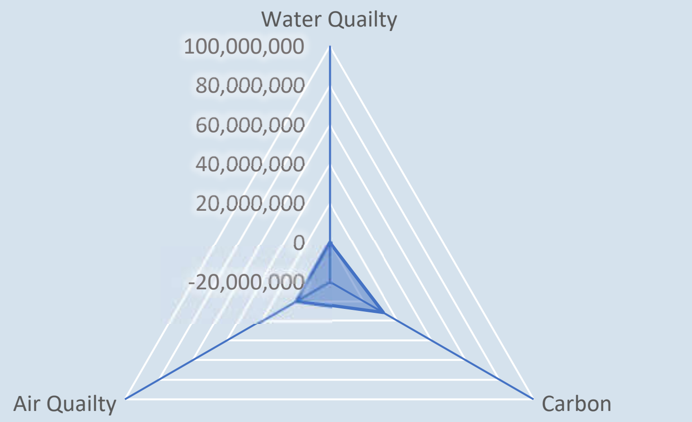


Option 3 Soil recovery

The results show that the greatest estimated NC benefits from the soil health option are within the carbon (£304,410) and water quality (£95,997) ecosystem services. There is a reduction in NC benefit within the air quality ecosystem service (-£383,907) as it is assumed that there is some degree of seasonal livestock removal to reduce poaching and compaction risks to soils. This increases the amount of time stock are housed indoors which has an adverse impact on ammonia emissions. The total potential NC benefits within the catchment are therefore only **£16,500.** To match the Option 3 volumetric outputs and for comparison with Option 1 and 2, this option does not include peatland restoration.

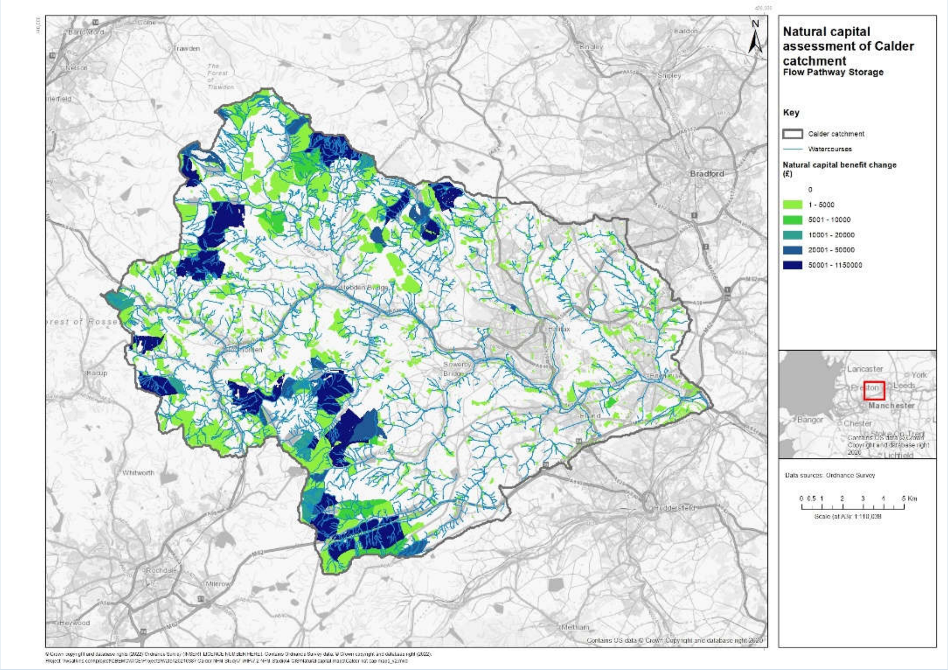


Total Benefit = £ 16,500

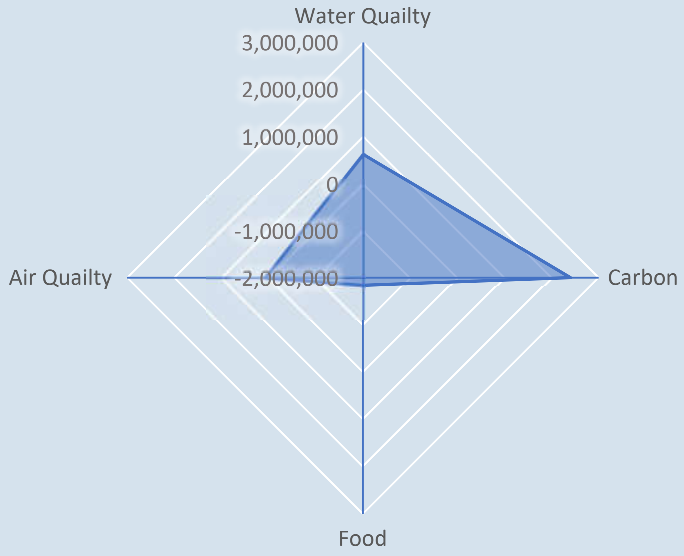


Flow pathway (maximum bunds option)

The results show that the greatest NC benefit from flow pathway (maximum bunds option) is within the carbon service (£2,401,628) and water quality (£628, 587), but yields a -£1.8 million for food production. The total potential NC benefit from this measure is **£1,258,316**, the spatial distribution of this benefit is shown in the figure to the left below.



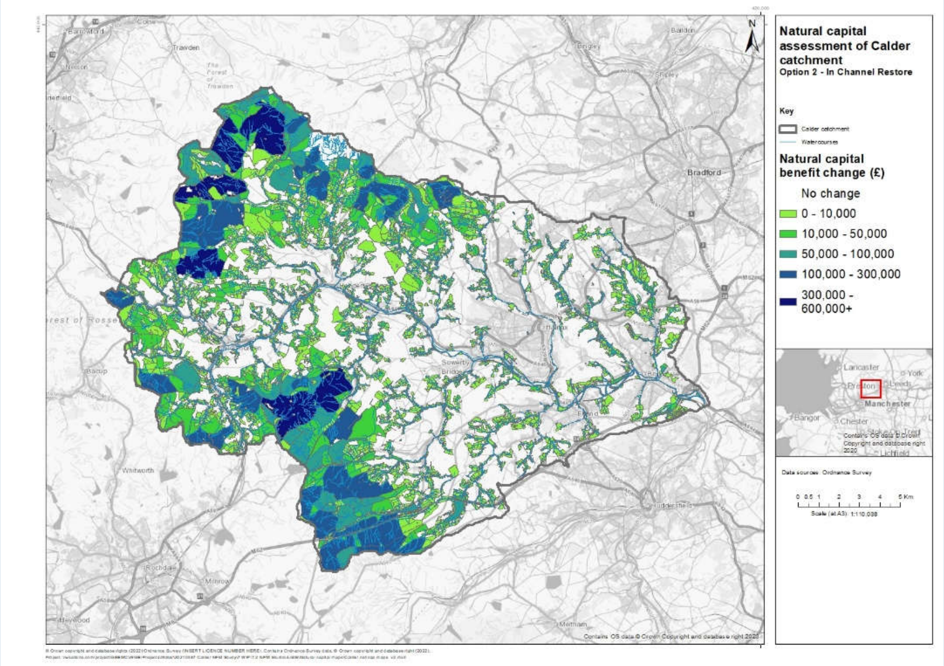
Total Benefit = £ 1,258,316



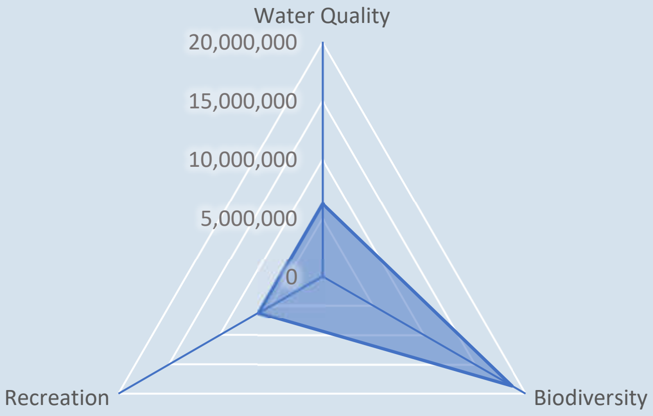
In-channel

The results show that the greatest NC benefits from the in-channel scenario are within the biodiversity (£18,650,398), water quality (£6,226,799) and recreation (£6,226,799) ecosystem services. It is important to note that this assessment assumes that the channel (and surrounding floodplain) is morphologically (and in-turn ecologically) enhanced to increase the reach by an equivalent of one WFD class. These benefits are not likely to be realised with leaky dams alone[12].

The total potential NC benefit from this measure is **£31,133,996**. The main channels and areas with high density of watercourses show the greatest benefit.



Total Benefit = £ 37,360,796



Insallation of stone dams (© Moors for the Future)

Willow living dam (© Treesponsibility)

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[12] The values are based on the NWEBS study as recommended in ENCA guidance and the willingness to pay as one of the main means of measuring value. There is currently inadequate evidence to scale it back.

11. Hydraulic Modelling

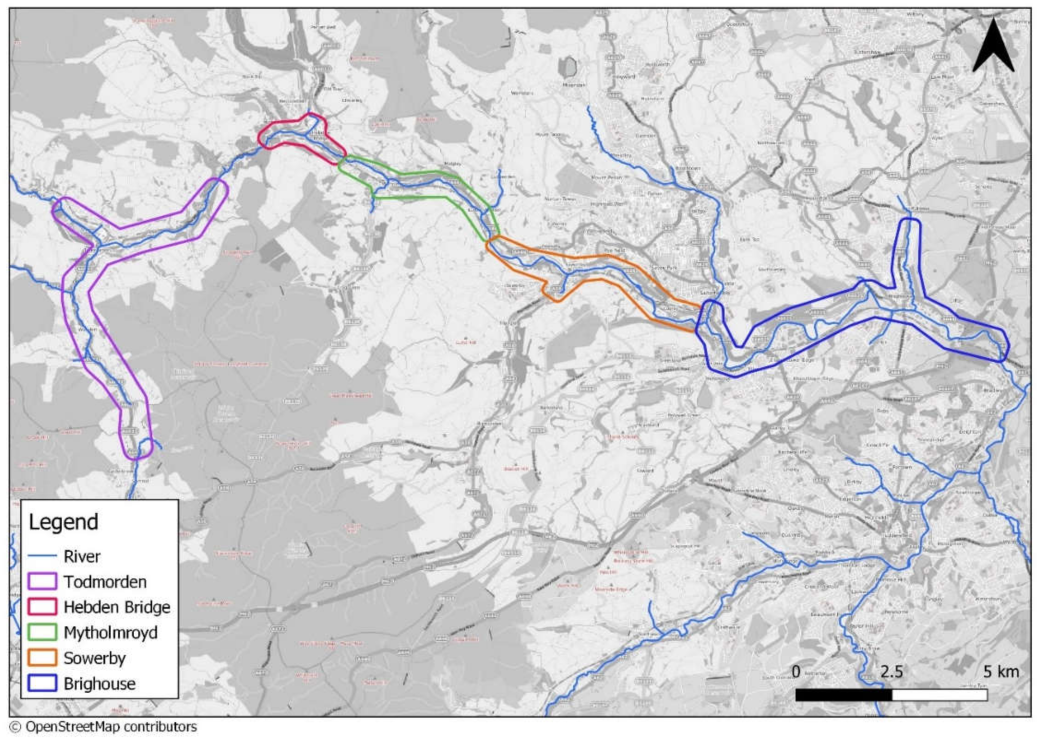
Methodology

Hydraulic models for the assessment were provided by the Environment Agency. Five hydraulic models, all 1D/2D FM-TUFLOW models, have been used for the Baseline. All Flood Alleviation Schemes that have been constructed (or proposed and have been modelled) have been utilised for this study. In summary:

- The Todmorden model represents the Baseline scenario, with scheme, in this part of the catchment.
- The Hebden Bridge scenario is based on the option 4a preferred scheme model but does not have the Mytholmroyd FSA included and therefore has only been used for the Hebden Bridge property list.
- Mytholmroyd scenario includes the scheme as built at Mytholmroyd and the baseline representation of Hebden Bridge (including representation of an earlier version of the scheme). Mytholmroyd model depths have only been used for the Mytholmroyd property list and properties which are impacted by the Mytholmroyd scheme only.
- The Sowerby Bridge scenario is a defended scenario, without a scheme.
- The Brighouse scenario includes the refurbishment of defences along the Calder and a Flood Storage Area (FSA) along Clifton Beck and some NFM measures – this is representative of the situation in the near future once these have been constructed.

The model coverage is limited to the River Calder, the Rochdale Canal and the Calder and Hebble Navigation Canal and is shown on the map below. Appendix K provides a more detailed summary of the hydraulic models used and provides justification of the models selected where duplication occurred within the same reach (e.g. Hebden Bridge and Mytholmroyd).

Model coverage



© OpenStreetMap contributors

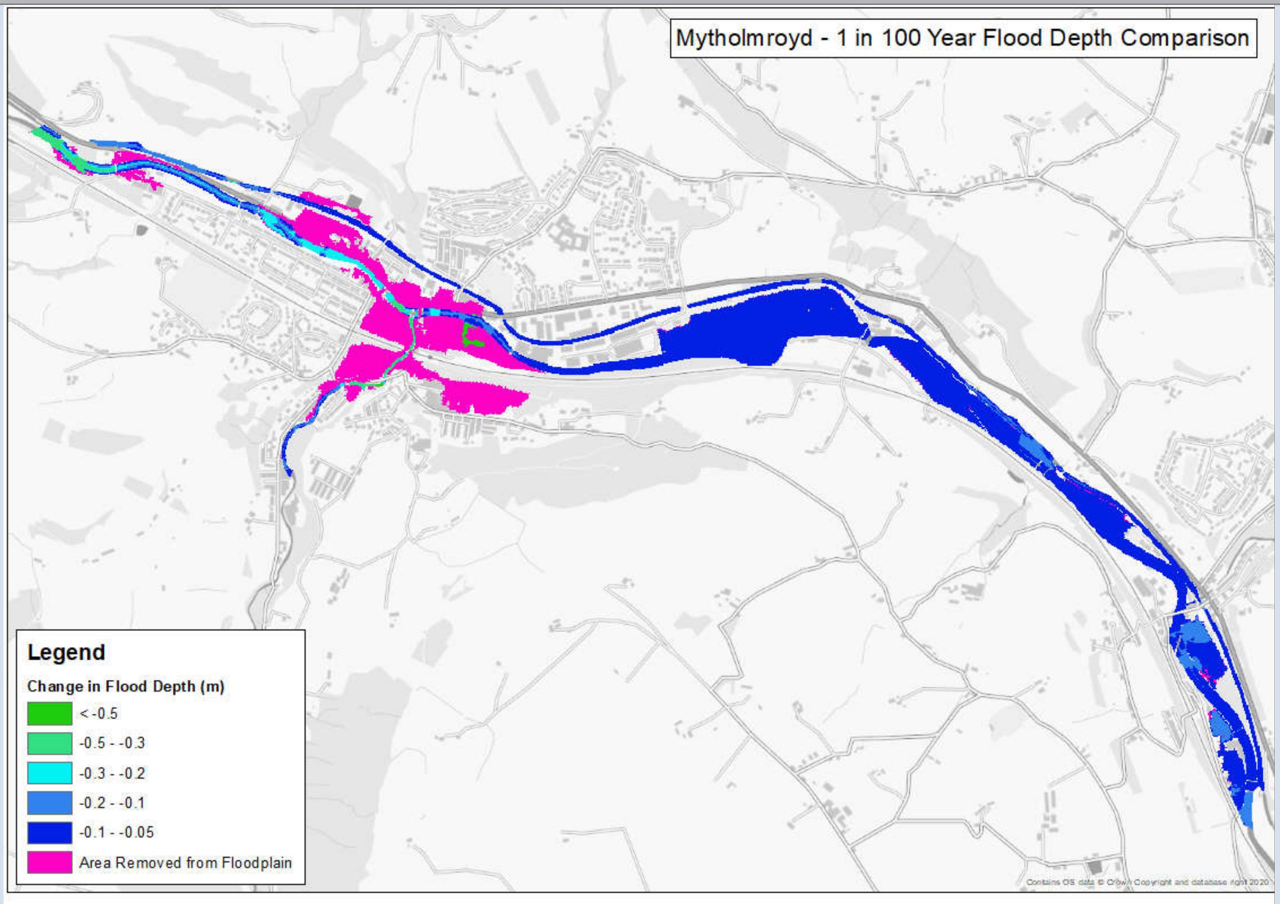
Integration from NFM Studio to hydraulic models

NFM Studio uses a single set of catchment descriptors to generate flow hydrographs for a suite of return periods and then generates the same set of hydrographs with the implementation of NFM measures. These NFM Studio results produce a reduction in peak flow and the percentage change for each return period was calculated. The average of the three land use change and management options and minimum and maximum bunds was used (see table below, as agreed with the Environment Agency). All the inflows within the hydraulic models have then been scaled by the same percentage reduction to peak flow to create and run 'with NFM' model scenarios. More information is provided in Appendix K on the integration method.

	% change in peak flow Minimum (single bund)			% change in peak flow Maximum (multiple bunds)			Ave % change peak flow
	Option 1	Option 2	Option 3	Option 1	Option 2	Option 3	Average
T2 50% AEP	-20.9%	-21.7%	-19.2%	-24.4%	-25.4%	-22.5%	-22.4%
T10 10% AEP	-14.2%	-15.1%	-11.4%	-14.7%	-15.6%	-11.7%	-13.8%
T20 5% AEP	-12.7%	-13.6%	-9.7%	-12.8%	-13.7%	-9.8%	-12.0%
T50 2% AEP	-11.3%	-12.2%	-8.1%	-11.4%	-12.3%	-8.1%	-10.6%
T100 1% AEP	-10.5%	-11.5%	-7.1%	-10.5%	-11.5%	-7.1%	-9.7%

Results

Change in flood depth in Mytholmroyd between Baseline and 'With NFM' modelling



The 'with NFM' model run results in a reduced flood depth across the catchment and at all return periods.

The model results at Mytholmroyd show how the reduction in peak flow results in an improved Standard of Protection (SoP) offered by the existing flood defences, effectively increasing the SoP to properties from a 1:50 year event (2% AEP) to a 1:100 year event (1% AEP) at current day flows. The change in flood depth (from Baseline to 'With NFM') is illustrated for a 1:100 year event across the catchment in a series of maps in Appendix K with an example here for Mytholmroyd. The pink area illustrates the approximate area which would be removed from the 1:100 year floodplain area with catchment wide NFM implementation. However it should be noted that the results presented are based on present day hydrology and it is likely that the frequency of the event shown will have increased by the time NFM measures are implemented across the catchment. The effect of climate change on flood risk has been assessed in the economic section and Appendix L. The economic assessment provides more details on the number of individual properties benefitting from NFM interventions across the catchment and present value benefits.

12. Economics Assessment

Methodology

A high-level economic assessment of damages comparing the Baseline model run (constructed or proposed FAS's with models included) and the 'With NFM' run included the following steps:

- Development of a property list;
- Assign depths of flooding to each property from a range of return period flood events;
- Calculate the direct and indirect damages relating to these properties and their inhabitants as an Average Annual Damage (AAD); and
- Build up a present value damage value for all properties at risk of flooding, over the standard 100-year appraisal period.

Appendix L provides a more detailed account of the approach and explains about the AAD and the incorporation of climate change. The rate of damage increases over the 100 year appraisal period as a result of climate change using the method documented and in the Environment Agency, 2020 guidance[13]. For the purposes of this appraisal the central estimates have been applied.

Change to peak flows compared to a 1961 – 1990 Baseline			
Applies across Calder catchment	**Total potential change anticipated for '2020s' (2015 – 2039)**	**Total potential change anticipated for '2050s' (2040 – 2069)**	**Total potential change anticipated for '2080s' (2070 – 2115)**
Central estimate	**11%**	**13%**	**23%**

The future change in flood risk due to climate change is incorporated into the economic appraisal stage by amending the probability of an event causing a certain amount of damage. This was completed for each of the three climate change epochs but is demonstrated for the long-term '2080s' epoch in Brighouse below. For consistency and simplicity across the five areas it has been assumed that the baseline scenario is representative of the situation in 2021.

Incorporating climate change by changing event probability			
2021 AEP (return period shown in brackets)	**Present day peak flow (m^3/s)**	**Assumed 2080 peak flow (m^3/s) (23% increase on present day)**	**Calculated '2080s' event probability**
50% (1 in 2)	142	174	100% (1 in 1)
20% (1 in 5)	183	225	40% (1 in 2.5)
10% (1 in 10)	210	258	24% (1 in 4.1)
5% (1 in 20)	233	287	16% (1 in 6.3)
2% (1 in 50)	264	325	8.3% (1 in 12)
1.3% (1 in 75)	274	337	6.4% (1 in 16)
1% (1 in 100)	289	355	4.7% (1 in 21)
0.5% (1 in 200)	322	396	2.1% (1 in 48)

The fluvial model results from each of the model domains along the Calder Valley were used to understand depths of flooding at properties at different return period or Annual Exceedance Probability (AEP) events. Using the model results, the AAD for property, evacuation costs, emergency services, vehicle damages and mental health damages were calculated for the present day. The same event damages were then applied to the increased event probabilities to calculate the AADs for the three future epochs: '2020s' (11%), '2050s' (13%) and '2080s' (23%).

As per the EA's guidance, using the Central allowances, present day AADs (2021, with no modelled climate change) were linearly interpolated to the 11% AADs in year 2030, which then stayed constant until year 2040, when there was a step up to the next climate change epoch (13% AADs). These then stayed constant until year 2070 until the end of the appraisal when there was a final step up to the 23% AADs.

For the purpose of the economic assessment, the Present Value damages (PVd) of a property cannot exceed the current market value. More information is provided in Appendix L.

Results – Property Counts

The table below presents the difference in property counts between the Baseline and the 'With NFM' scenario and relates to flooding both above ground level (external) and above internal floor level for each of the study areas under a selection of the range of modelled events. The Baseline scenario represents properties at risk of flooding with no inclusion of property counts with climate change. The models ran different events so the ones most common to all model areas are presented here. Appendix L provides all the data for comparison. One of the greatest reductions in properties at risk of external flooding is in Mytholmroyd where 312 (231 residential and 81 non-residential) or 96% of properties at risk of external flooding in the 1% Annual Exceedance Probability (AEP) (or 1 in 100 year event) in the Baseline are no longer at risk in that event with NFM in place. The other highest reduction in properties at risk of external flooding is in Todmorden where 31% or 315 properties (269 residential and 46 non-residential) are no longer at risk of flooding in the 1% AEP (1 in 100 year) with NFM in place when compared to the Baseline.

Difference in property counts by study area - Baseline minus 'with NFM' (present day)															
Study Area	**Flooding Type**	**50% AEP (1 in 2)**		**20% AEP (1 in 5)**		**10% AEP(1 in 10)**		**2% AEP (1 in 50)**		**1.3% AEP (1 in 75)**		**1% AEP (1 in 100)**		**0.5% AEP (1 in 200)**	
		Res	**Non-Res**	**Res**	**Non-Res**	**Res**	**Non-Res**	**Res**	**Non-Res**	**Res**	**Non-Res**	**Res**	**Non-Res**	**Res**	**Non-Res**
Todmorden	External					6	3	243	66			269	46		
	Internal					13	4	195	64			275	47		
Hebden Bridge	External	1	0	7	0	1	1	6	1	14	0	7	0	44	35
	Internal	2	0	1	0	1	1	10	2	11	0	15	0	32	39
Mytholmroyd	External							1	2	180	66	231	81	88	13
	Internal							1	2	141	59	200	78	99	14
Sowerby Bridge	External	0	8	3	23	13	23	2	19	0	10	0	21	3	14
	Internal	0	8	0	21	4	21	9	18	0	8	0	20	3	14
Brighouse	External	1	21	6	8	2	23	15	65	24	92	33	64	29	40
	Internal	1	15	1	10	1	20	16	73	21	90	40	74	29	37

Results – Present Value Damages and Benefits

The economic damages calculated for each of the 5 study areas for the Baseline and NFM options are shown below in the table alongside the PV benefits provided by NFM as modelled. The Baseline across the 5 study areas (in total) has £336m Present Value (PV) damages, with 65% of this coming from non-residential property damages. The 'with NFM' option across the 5 areas has £245m PV damages (with 70% still coming from non-residential property damage), meaning that it has £91m PV benefits compared to the Baseline. Comparing the Baseline with the NFM, there is a 42% reduction in the direct damages associated with residential properties, versus a 21% reduction in the direct damages associated with non-residential properties. There are some places along the valley floor where modelled flood extents can be seen to reduce (such as Hebble End Bridge in Hebden Bridge), however in most places the benefit of NFM is in terms of the depth of flooding reduced, and the probability of events which impact property flood risk. Much of the valley floor remains at risk of flooding, and in many locations, this is where the bulk of properties are non-residential and which remain impacted by flood risk, with NFM in place, however the risk of flooding is much reduced.

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[13] Environment Agency, 2020 Flood and coastal risk projects, schemes and strategies: climate change allowances.

One of the greatest reductions in properties at risk of flooding with NFM in place, as described above, is in Mytholmroyd, however in the table below the PV benefits are the second lowest when compared with the other catchments. This is in part due to the SoP offered by the Mytholmroyd FAS which means that in the economics, no benefits are claimed for the more frequent flood events which this FAS provides protection from. It is also in part due to the smaller depth changes experienced between the flood depths of the Baseline versus NFM scenario in the flood events modelled when compared to the other catchments.

Present Value damages (PVd) (£) by study area - Baseline (taking climate change into account)

Damage type	Todmorden	Hebden Bridge	Mytholmroyd	Sowerby Bridge	Brighouse	Total
PV residential property damage	£25,651,000	£6,555,000	£5,478,000	£5,458,000	£4,347,000	£47,488,000
PV non-residential property damage	£33,349,000	£7,683,000	£13,348,000	£51,332,000	£111,131,000	£216,842,000
PV evacuation loss	£7,061,000	£1,499,000	£1,662,000	£1,633,000	£1,111,000	£12,966,000
PV emergency services loss	£6,318,000	£1,408,000	£1,980,000	£5,120,000	£10,215,000	£25,042,000
PV vehicle damage	£4,154,000	£751,000	£1,232,000	£1,411,000	£560,000	£8,109,000
PV mental health flood losses	£15,096,000	£2,910,000	£2,904,000	£2,529,000	£2,237,000	£25,677,000
Total PV Damages	**£91,629,000**	**£20,806,000**	**£26,604,000**	**£67,484,000**	**£129,601,000**	**£336,124,000**

Present Value damages (PVd) and PV benefits (PVb) (£) - with NFM (taking climate change into account)

Damage type	Todmorden	Hebden Bridge	Mytholmroyd	Sowerby Bridge	Brighouse	Total
PV residential property damage	£13,594,000	£5,362,000	£2,720,000	£2,862,000	£2,839,000	£27,376,000
PV non-residential property damage	£26,496,000	£4,789,000	£8,544,000	£39,251,000	£92,893,000	£171,973,000
PV evacuation loss	£3,485,000	£1,151,000	£837,000	£868,000	£745,000	£7,086,000
PV emergency services loss	£4,326,000	£984,000	£1,140,000	£4,248,000	£9,736,000	£20,434,000
PV vehicle damage	£1,751,000	£474,000	£691,000	£626,000	£276,000	£3,818,000
PV mental health flood losses	£7,638,000	£1,896,000	£1,470,000	£1,421,000	£1,574,000	£14,000,000
Total PV Damages	**£57,290,000**	**£14,656,000**	**£15,403,000**	**£49,277,000**	**£108,062,000**	**£244,688,000**
Total PV Benefits	**£34,339,000**	**£6,150,000**	**£11,201,000**	**£18,207,000**	**£21,539,000**	**£91,436,000**

With the maximum possible implementation of NFM across the catchment, the potential PV benefits are significant, particularly in comparison to the total PV damages and provide a 27% reduction in the total PV damages across the catchment over the 100 year appraisal period. There is therefore benefit in implementing NFM across the catchment, in terms of flood risk benefits.

Whilst there is an economic benefit of implementing NFM when considered over the 100 year appraisal in terms of flood risk reduction, it is anticipated that the benefit that NFM provides would deteriorate over time due to increasing flows due to climate change. However it is worth noting that if nothing was done, then flood risk would increase significantly in the catchment due to climate change.

Please note no economic damages or benefits of the proposed NFM from surface water flooding have been taken account of in this study due to the limitations of the models provided, nor do the models cover all the incoming tributaries. Therefore the damages and benefits are likely to be an underestimate.

Results - Climate Change Resilience

NFM in the Calder catchment may be able to contribute towards improving the resilience of the catchment to flood risk and improving the resilience of FAS assets already in place. Without a comprehensive suite of climate change model runs for all events and all epochs (this is usually conducted at detailed design for FAS's), it is difficult to quantify exactly what benefit NFM may provide in terms of an extended duration of the Standard of Protection (SoP) which is currently provided. It is likely that there will continue to be benefits from NFM implemented (as modelled) over the next 100 years with climate change as a result of reduced flows reaching the river, both in terms of sustaining the SoP and/or extending the life of assets due to reduced pressure on the structures or assets themselves, however this can't be quantified with this high level catchment appraisal. What can be concluded from the assessment is that with NFM in place there are fewer properties at risk (see property count tables), and that the probability of internal flooding for some properties is reduced in the present day. Where this reduction is significant e.g. from a 20% AEP to 5% (1 in 5 to a 1 in 20) event causing flooding in the present day with NFM then it can be inferred that these properties have a greater amount of resilience in place to increasing flood risk as a result of climate change, compared to those properties where the change in probability of internal flooding is smaller. As part of visualising the impact of NFM, properties at risk of flooding presently have been mapped (provided in a separate document due to sensitive information) to show the change in probability of internal flooding and how this changes between the Baseline and with NFM interventions in place.

Taking Todmorden as an example; several terrace properties in Todmorden have a decrease in the probability of internal flooding from a 1% AEP (or 1 in 100) event in the baseline to less than 1% AEP with NFM. It can't be quantified, with the available modelled events, how much lower the probability of internal flooding is as 1% AEP was the largest magnitude / lowest probability event modelled. For many properties in central Todmorden the change in probability of internal flooding is a single jump between 1 event in the Baseline and the next lowest probability event with NFM in place, such as a jump from a probability of internal flooding in a 1 in 25 or 4% AEP event in the baseline to a 1 in 50 or 2% AEP event with NFM in place. Please note that the mapping and the AEP events discussed in this section are for the present day risk of flooding only and takes account of 2021 flood depths not increased depths or extents of flooding associated with climate change. Please also note the 'with NFM' scenario is the maximum possible NFM measures implemented across the entire catchment as per project scope.

13. Rates of Delivery

Methodology

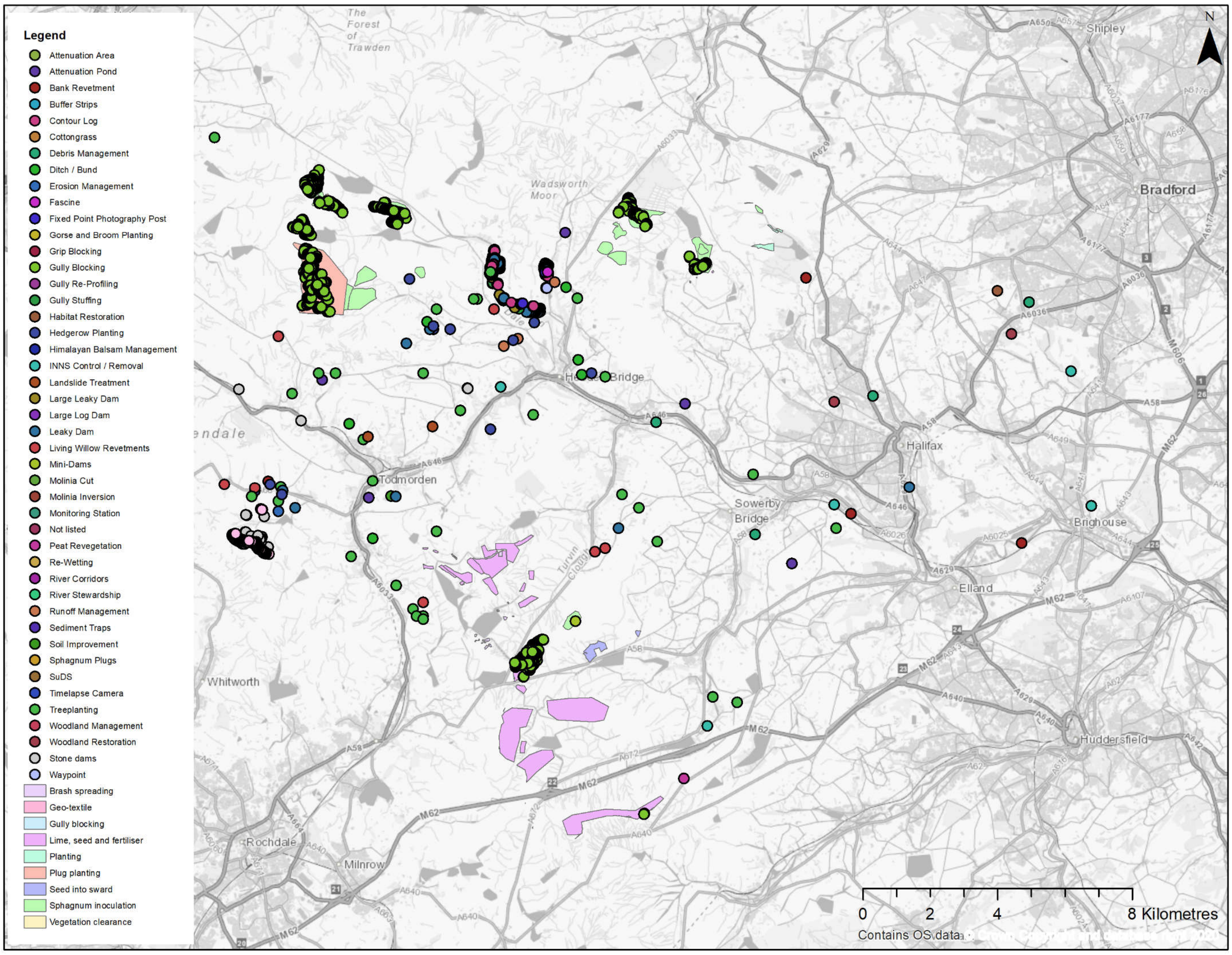
A large number of NFM measures have been implemented across the Calder Valley, by a range of organisations, over the last 5 years. This information was provided by the Environment Agency and comprised a spreadsheet of measures[14] and several shapefiles from Hardcastle Crags and Gorpley works and Moors for the Future.

The storage provided by these NFM measures has been calculated to understand the amount of storage these provide against the amount required for flood protection across the valley for both the 1 in 50 and 1 in 100 year events. This has then been used to calculate the percentage of the required storage this would provide by 2030, 2040 and 2050 should the current rate of delivery continue.

In order to calculate the rate of delivery, a number of steps were undertaken:

- Map the current features based on available data
- Calculate the scale, size and number of features (where possible)
- Calculate the storage provided by each feature (where possible)

NFM interventions implemented over the past 5 years



The table below shows the type of feature for which an estimated storage has been calculated, spilt into three main categories: in-channel, land use change and flow pathway, the storage provided by each type of feature, and the assumptions/limitations of the methodology used to calculate the storage. It was not possible, based on the available data to calculate a storage for all types of measures have that been implemented such as bank revetments, habitat restoration, Invasive and Non Native Species (INNS) control and others. It may also be that not all NFM interventions have been captured and utilised here so this assessment may be a slight underestimation.

Estimated storage per feature

NFM measure	Estimated storage provided (m^3)	Assumptions
In channel		
Large leaky dam	23,586	Calculated using height of feature, width of channel and gradient of channel. Height assumed to be 1m. Gradient and width extracted from nearest flow pathway using ArcGIS.
Leaky dam	2,159	Calculated using height of feature, width of channel and gradient of channel. Height assumed to be 0.5m. Gradient and width extracted from nearest flow pathway using ArcGIS.
Mini-Dams	25,111	Calculated using height of feature, width of channel and gradient of channel. Height assumed to be 0.5m. Gradient and width extracted from nearest flow pathway using ArcGIS.
In-channel Total	**50,856**	

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[14] 2021 08 26 FINAL_MASTER spreadsheet

Land use		
Buffer Strips	1	Length provided and assumed to be 10m to calculate area. Average storage for grassland from NFM Studio used.
Cottongrass	19	Area provided. Average storage for grassland from NFM studio used.
Gorse and Broom Planting	24	Area provided. Average of grassland and woodland planting storage from NFM Studio used
Hedgerow Planting	9	Hedgerow length provided and assumed to be 1m wide to calculate area. Average storage of woodland and grassland from NFM Studio used.
Peat Revegetation	154	Area provided. Average peat restoration storage from NFM Studio used.
Soil Improvement	415	Area provided. Average soil improvement storage from NFM Studio used.
Sphagnum Plugs	33,836	Area provided. Average peat restoration storage from NFM Studio used.
Treeplanting	499	Number of trees provided, assumed 2m spacing of trees. Average woodland storage from NFM Studio used. This assumes storage capacity of mature trees.
Land use Total	**34,957**	
Flow pathway		
Attenuation Area	122	Assumed to be flow pathway storage, with 2m channel width. Average flow pathway storage from NFM Studio used.
Attenuation Pond	22,018	Area provided in m^3.
Contour Log	762	Assumed to be flow pathway storage, with 2m channel width. Average flow pathway storage from NFM Studio used.
Ditch / Bund	3,149	Assumed to be flow pathway storage, with 2m channel width. Average flow pathway storage from NFM Studio used.
Grip Blocking	4	Assumed to be flow pathway storage, with 2m channel width. Average flow pathway storage from NFM Studio used.
Gully Blocking	12,817	Assumed to be flow pathway storage, with 2m channel width. Average flow pathway storage from NFM Studio used.
Gully Stuffing	496	Assumed to be flow pathway storage, with 2m channel width. Average flow pathway storage from NFM Studio used.
Stone Dams	436	Assumed to be flow pathway storage, with 2m channel width. Average flow pathway storage from NFM Studio used.
Flow pathway Total	**39,803**	
Total for all features	**125,616m^3**	

Rate of delivery

Using the estimated total storage provided by the current measures in Calderdale in the table above, and the volumetric storage required for protection against the 1 in 50 (2% AEP) and 1 in 100 (1% AEP) year events, the rate of delivery by 2030, 2040 and 2050 has been calculated. For each of these events, the average storage provided by a combination of Option 1, Option 2 and Option 3, minimum and maximum bunds and in-channel features subtracted from the baseline storage from NFM studio was used to provide a target storage. The percentage of this target storage provided by the current NFM measures was then calculated and is presented in the table below.

Projected delivery based on current rate of delivery

Event	Target storage (m^3)	Last 5 years	2030	2040	2050
1 in 50 year (2% AEP)	2,327,482	5.4%	8.6%	19.4%	30.2%
1 in 100 year (1% AEP)	2,600,036	4.9%	7.8%	17.5%	27.3%

This shows that for both events, the current rate of delivery needs to increase to meet the target storage by 2030, 2040 or 2050. At the present rate it will take approximately 100 years to broadly achieve the target storage for both the 1 in 50 year (2% AEP) and the 1 in 100 year (1% AEP). Our approach currently assumes there is no lag for tree growth and the planting undertaken over the past 5 years (and in the future) is fully effective immediately. Realistically, there is likely to be a lag of between 10-30 years.

Cost

In order to understand the costs associated with this rate of delivery, the capital cost for the construction of the NFM measures across the Calder Valley has been calculated based on costs provided by the Environment Agency for the Calder valley. Furthermore, the maintenance cost associated with these features has been calculated for 5 and 50 year maintenance periods. The results of this exercise, plus the costs and assumptions used for the calculations are presented in the following table. The costs of the features for which a storage has not been calculated are not included in the costings exercise.

Capital and maintenance costs for NFM measures applied in the Calder catchment over the last 5 years and cost per NFM feature

NFM measure	Capital cost	Capital cost + 5 year maintenance	Capital cost + 50 year maintenance	Cost used	Source	Assumptions
In channel						
Large leaky dam	£3,325	£4,988	£19,950	£175 per feature	Calderdale Grant Scheme	Maintenance cost per year is equal to 10% of capital cost
Leaky dam	£181,650	£272,475	£1,089,900	175 per feature	Calderdale Grant Scheme	Maintenance cost per year is equal to 10% of capital cost
Mini-Dams	£351,200	£526,800	£2,107,200	£200 per feature	MFFP	Maintenance cost per year is equal to 10% of capital cost
In channel Total	**£536,175**	**£804,263**	**£3,217,050**			
Land use						
Buffer Strips	£41	£62	£248	£0.055 per m^2	Highways England NFM handbook	Maintenance cost per year is equal to 10% of capital cost
Cottongrass	£550	£825	£3,300	£0.055 per m^2	Highways England NFM handbook	Maintenance cost per year is equal to 10% of capital cost

Gorse and Broom Planting	£1,107	£1,661	£6,642	£0.074 per m^2	MFFP	Maintenance cost per year is equal to 10% of capital cost
Hedgerow Planting	£43,155	£64,733	£258,930	£9 per m length	Calderdale Grant Scheme	Maintenance cost per year is equal to 10% of capital cost
Peat Revegetation	£39,690	£59,535	£238,140	£0.567 per m^2	MFFP for brash	Maintenance cost per year is equal to 10% of capital cost
Soil Improvement	£804	£1,206	£4,824	£0.002 per m^2	Calderdale Grant Scheme	Maintenance cost per year is equal to 10% of capital cost
Sphagnum Plugs	£1,135,027	£1,702,540	£6,810,161	£0.074 per m^2	MFFP	Maintenance cost per year is equal to 10% of capital cost
Treeplanting	£663,574	£995,361	£3,981,443	£1.65 per m^2	Calderdale Grant Scheme (£3.3 per tree)	Maintenance cost per year is equal to 10% of capital cost
Land use Total	**£1,883,948**	**£2,825,922**	**£11,303,688**			
Flow pathway						
Attenuation Area	£2,640	£3,960	£15,840	£80 per feature	MFFP (Timber Dam)	Maintenance cost per year is equal to 10% of capital cost
Attenuation Pond	£220,180	£330,270	£1,321,080	10 per m^3	Calderdale Grant Scheme	Maintenance cost per year is equal to 10% of capital cost
Contour Log	£16,480	£24,720	£98,880	£80 per feature	MFFP (Timber Dam)	Maintenance cost per year is equal to 10% of capital cost
Ditch / Bund	£17,495	£26,243	£104,970	£10 per m width	Calderdale Grant Scheme	Maintenance cost per year is equal to 10% of capital cost
Grip Blocking	£65	£98	£390	£65 per feature	National Trust	Maintenance cost per year is equal to 10% of capital cost
Gully Blocking	£154,095	£231,143	£924,570	£65-£200 per feature depending on material	MFFP	Maintenance cost per year is equal to 10% of capital cost
Gully Stuffing	£8,710	£13,065	£52,260	£65 per feature	National Trust	Maintenance cost per year is equal to 10% of capital cost
Stone Dams	£13,750	£20,625	£82,500	£27 per feature	National Trust	Maintenance cost per year is equal to 10% of capital cost
Flow pathway Total	**£433,415**	**£650,123**	**£2,600,490**			
Total of all interventions	**£2,853,538**	**£4,280,307**	**£17,121,228**			

Using the costs provided where possible, it has been estimated that the current interventions have cost approximately £2.8 million, and if a 5 year maintenance cost is applied, the spend to date has been approximately £4.28 million. Taking this latter value, knowing that 5% of the possible NFM interventions have already been applied, it can be inferred that approximately £86 million is required to fulfil the catchment potential. The costs are likely to be higher if more woodland planting or/and peat restoration is implemented across the catchment. Costs are also likely to increase with time, in line with inflation.

Woodland planting (© Calderdale Grant

Leaky Dam implemented in Calderdale (© Stuart Bradshaw)

Installing gully blocks above Mytholmroyd (© Moors for the Future)

Installation of peat bunds above Hebden Bridge (© Moors for the Future)

14. Summary and Conclusions

NFM Studio Findings

- **Reducing land runoff through land use change is the most beneficial type of NFM intervention measure in terms of volumes**, especially land use change and management (Option 1) and woodland creation and peat and protected moorland restoration (Option 2). The most suitable areas for these land use interventions from purely a hydrological perspective are in the uplands.
- **Flow pathway interventions through construction of bunds and in-channel measures such as woody dams are effective, but only form between 7% (minimum bund plus in-channel) and 15% (maximum bunds plus in-channel) of the total potential attenuation volume of the catchment**. This is mainly due to more opportunity (area) in the catchment to modify the land use and the way it is managed.
- The NFM Studio volumetric outputs can be viewed as a total or standardised, per mm volume reduction over a unit area. Clearly **the bigger the field parcel, generally, the greater the runoff reduction/volume of flow attenuated**. From a strategic perceptive it would make sense to target the larger fields, but there are opportunities in the mid-lower catchment where the field sizes are smaller. Being able to interrogate the data and prioritise the most productive fields in and around a specific location will be very helpful.
- The NFM Studio hydrological (volumetric) outputs provide a means to help focus NFM intervention types and area, but a priority map was also produced which combined the opportunity mapping (stakeholder contribution to prioritise datasets/land cover) with the top 10% of fields/channels in terms of total volume stored. **The uplands, specifically the peat/moorland areas were illustrated as the most favourable areas to undertake NFM land use interventions.** The in-channel intervention priority map illustrated that the tributaries upstream of Hebden Bridge as being an ideal target area together with a few tributaries upstream of Todmorden. Both these areas (Hardcastle Crags and Gorpley) have been the focus of recent NFM works including in-channel measures.
- The combined impact of unconstrained NFM measures across the entire catchment can be presented as a peak flow reduction on the hydrographs for a range of return periods. **The greatest impact is on peak flows of smaller return periods (e.g. 1 in 2 year event, 50% AEP) with a reduction of between 19 and 25% across the NFM measure types**. There is then, as expected, a decrease in % peak reduction as the return period increases but the results still show a **7-11% reduction in peak flow for a 1 in 100 year event (1% AEP)**.
- It is estimated that with catchment wide NFM measures implemented (taking Option 2 woodland creation, minimum bund and in-channel measures as an example), **the peak flow experienced during the 2015 Boxing Day floods during Storm Desmond may have been reduced by 8%.**

Modelling and Flood Economics

- The reductions in peak flow generated by the NFM Studio outputs for each of the three land use change options and minimum and maximum bunds and in-channel attenuation type was averaged for each of the return periods. **These peak flow values were then scaled and used across a series of modelled return periods within the 5 hydraulic 1D/2D TUFLOW models** which covered the Calder catchment within Calderdale.
- **The model runs 'with NFM' show a reduced flood risk across the catchment.** Depth grids were extracted pre and post NFM intervention to allow for a change in flood extents and depths to be calculated and flood economics to be generated for the different return periods. A climate change uplift was applied to the flood damages, and respective benefits.
- **The results show that there is significant economic flood risk benefit from implementing catchment wide NFM measures.** Over a 100 year appraisal period, the catchment would benefit by a total of £91.4 million with Todmorden benefiting the most with a present value of £34.3 million (38%). Mytholmroyd has 96% of properties at risk of external flooding in the 1 in 100 year event in the baseline which are no longer at risk in that event with NFM in place. Todmorden shows that 31% of the properties are no longer at risk in a 1 in 100 year event and 50% in a 1 in 50 year event. Brighouse shows there is a reduction of 30% of properties in a 1 in 50 year event with catchment wide intervention compared to without. These figures are also likely to be underestimates due to model coverage (not all tributaries included) and not accounting for surface water runoff.
- NFM in the Calder catchment will be able to contribute towards improving the catchment's resilience to climate change. **With NFM in place there are fewer properties at risk and the probability of internal flooding for some properties is reduced**. Where this is significant in the present day e.g. from a 20% to 5% AEP (1 in 5 to a 1 in 20 year event) it is likely that there will continue to be benefits from NFM implemented (as modelled) over the next 100 years with climate change as a result of reduced flows reaching the river, both in terms of sustaining the standard of protection and/or extending the life of assets due to reduced pressure on the structures or assets themselves.
- **The assessment therefore shows there is a great benefit in implementing NFM across the catchment**. If no further NFM measures were constructed, then flood risk would increase significantly in the catchment due to climate change.

Natural Capital and Multiple Benefits

- As well as the flood risk benefits, there are **significant natural capital benefits** associated with implementing NFM across a catchment. Indicative natural capital assessment values suggest that the highest benefits are generated from Option 1 (land use change and management) and Option 2 (woodland creation and peat restoration), £71 million and £111 million per year respectively.
- **Overall significant benefits were estimated particularly for carbon storage** through peat and moorland restoration and tree planting (£55 million and £90 million for Option 1 and 2 respectively). This helps to illustrate the potential role NFM might play in helping deliver Net Zero targets.
- **Flow pathway interventions such as hillslope bunds provide £1.3 million natural capital per year, with carbon and water quality elements making significant contributions.**
- **The in-channel intervention benefits (£31 million per year**) are likely to be an overestimate with relatively high biodiversity figures. It is assumed in the assessment that natural processes are restored including floodplain reconnection and that ecological habitats are enhanced to allow for a relative improvement in WFD class. This is not likely to be achievable with leaky dams alone, especially in the steeper headwater streams, however it is difficult to robustly scale this natural capital assessment down with the current evidence available.

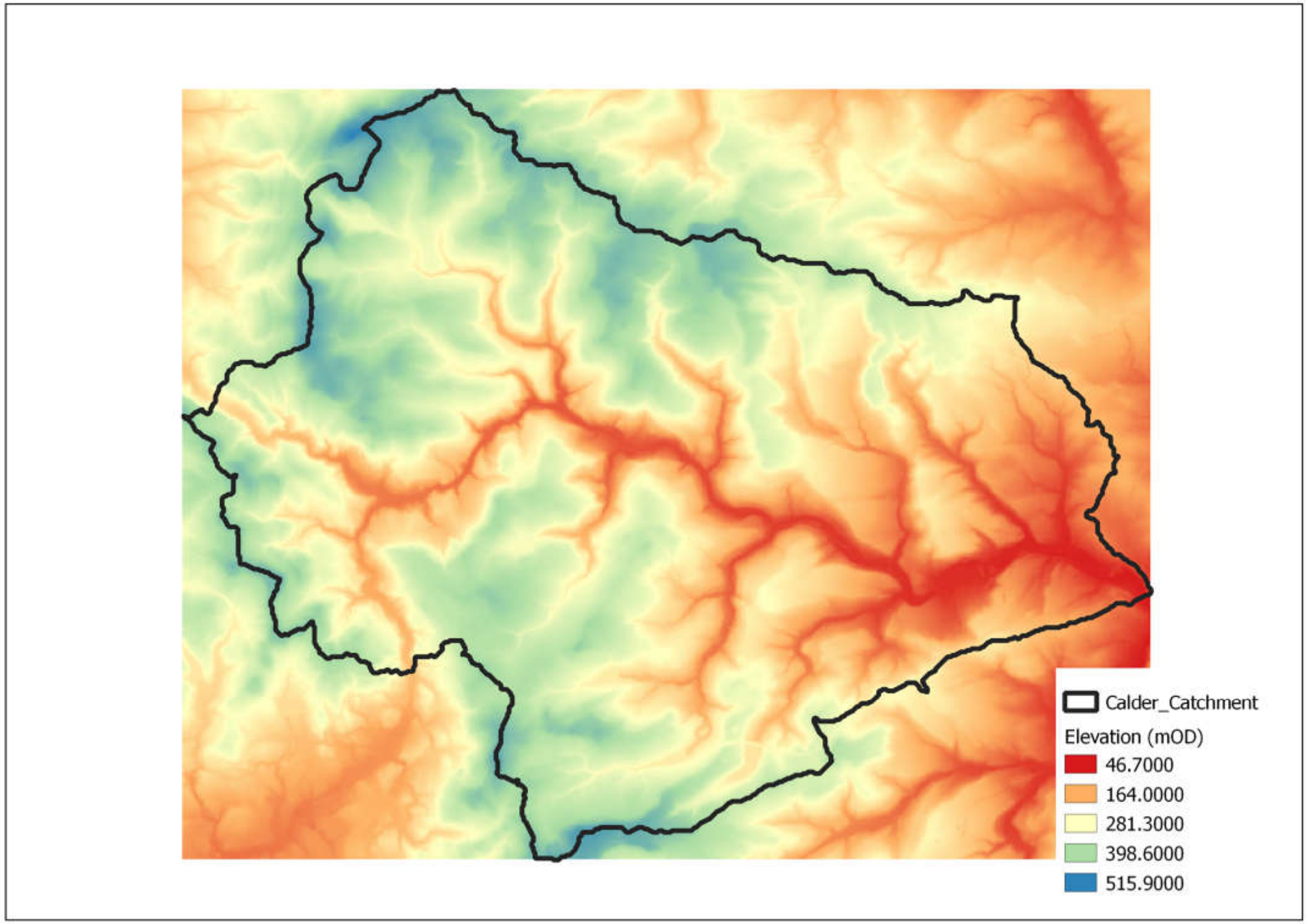
Cost and Rate of Delivery

- The results show that **soil recovery** (improving soil health across the catchment such as lowering grazing densities to reduce compaction, aerating, subsoiling or/and crop and livestock rotation) and **flow pathway bunds are the most cost-effective measures** in terms of cost per m^3 of storage at around £16 per m^3 over a 5 year maintenance period although they yield much less wider benefits.
- **Woodland planting is the most expensive**, especially from natural grasslands to woodland (£61,966 average cost per m^3 over 5 years with maintenance) but woodland planting offers higher multiple benefits. It appears that a transition from pasture to natural grassland is much more economical (£361 m^3 over 5 years with maintenance). Peat to restored peat in comparison is approximately £5,500 per m^3 over 5 years.
- The NFM measures implemented in the Calder catchment over the past 5 years have been mapped and quantified to evaluate the rate of delivery in terms of volumetric storage achieved to date compared to the catchment wide total target. **Estimations suggest that over the past 5 years approximately 5% of the target storage has been achieved** so with the current rate of delivery, it would take approximately 100 years to maximise the catchment NFM intervention potential equating to approximately 10% reduction in peak flows.
- Costs have also been estimated using the information provided by Calderdale NFM implementation groups and open source data**. It is estimated that it would cost over £86 million** to achieve the number of measures and area of land use change/management required to reduce the peaks flows as modelled. This figure is likely to be higher if a greater proportion of woodland planting and peat/moorland restoration is implemented, however we have deduced that these measures also provide the greatest multiple benefits, both in terms of reduced runoff and (in turn flood risk), and the wider natural capital benefits especially in the form of carbon storage.

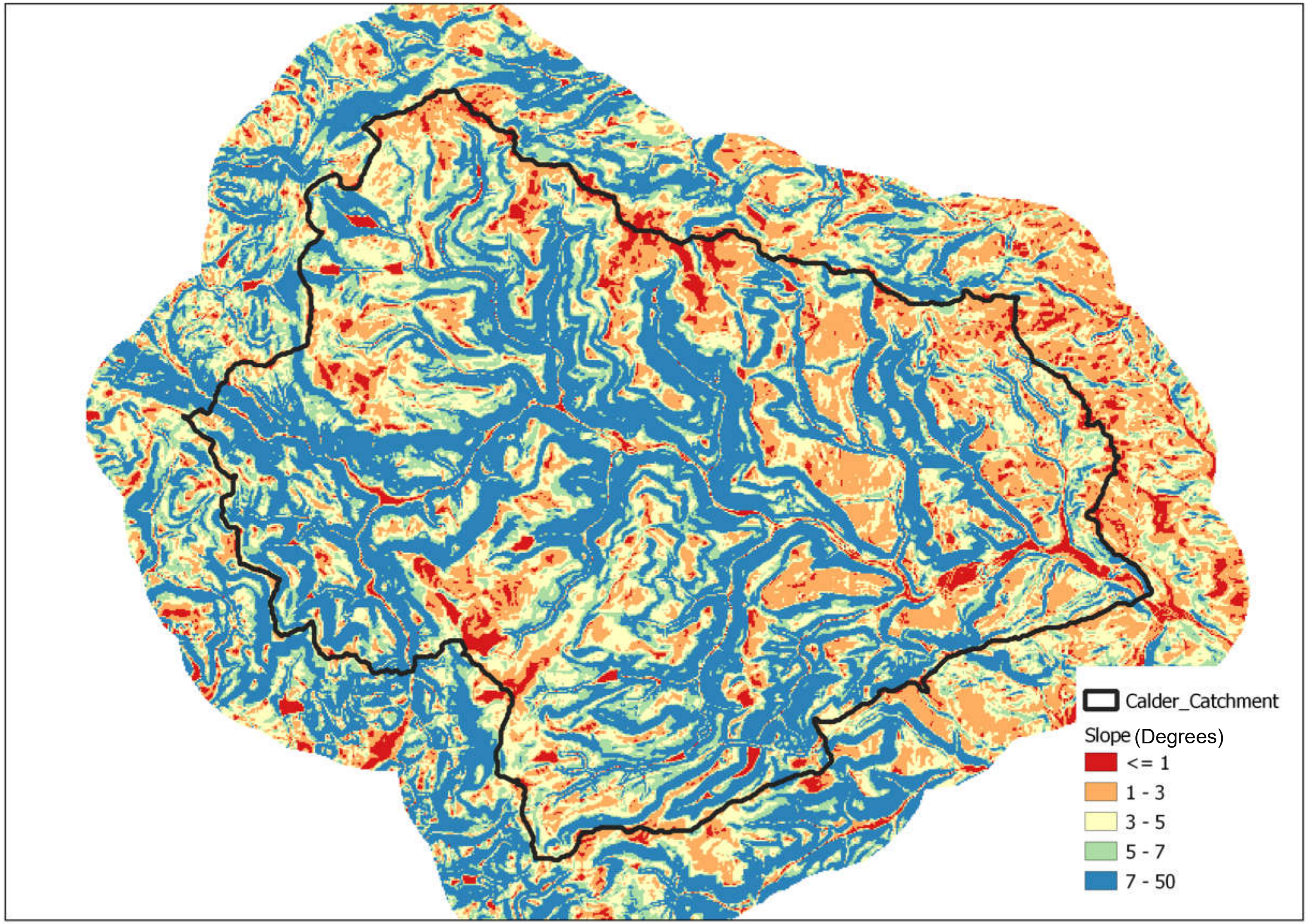
Appendices

Appendix A. Catchment Characteristics

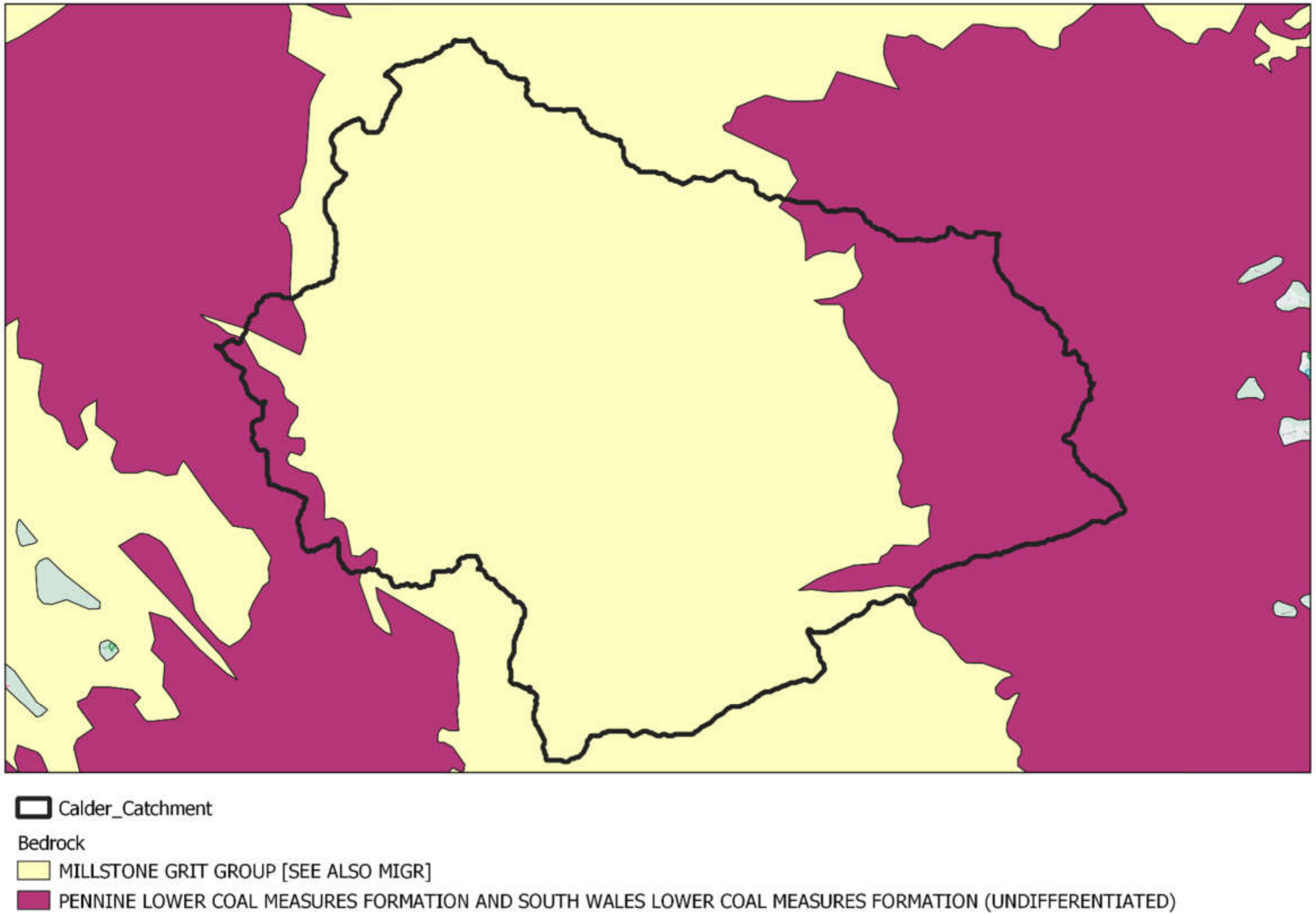
A.1. Elevation



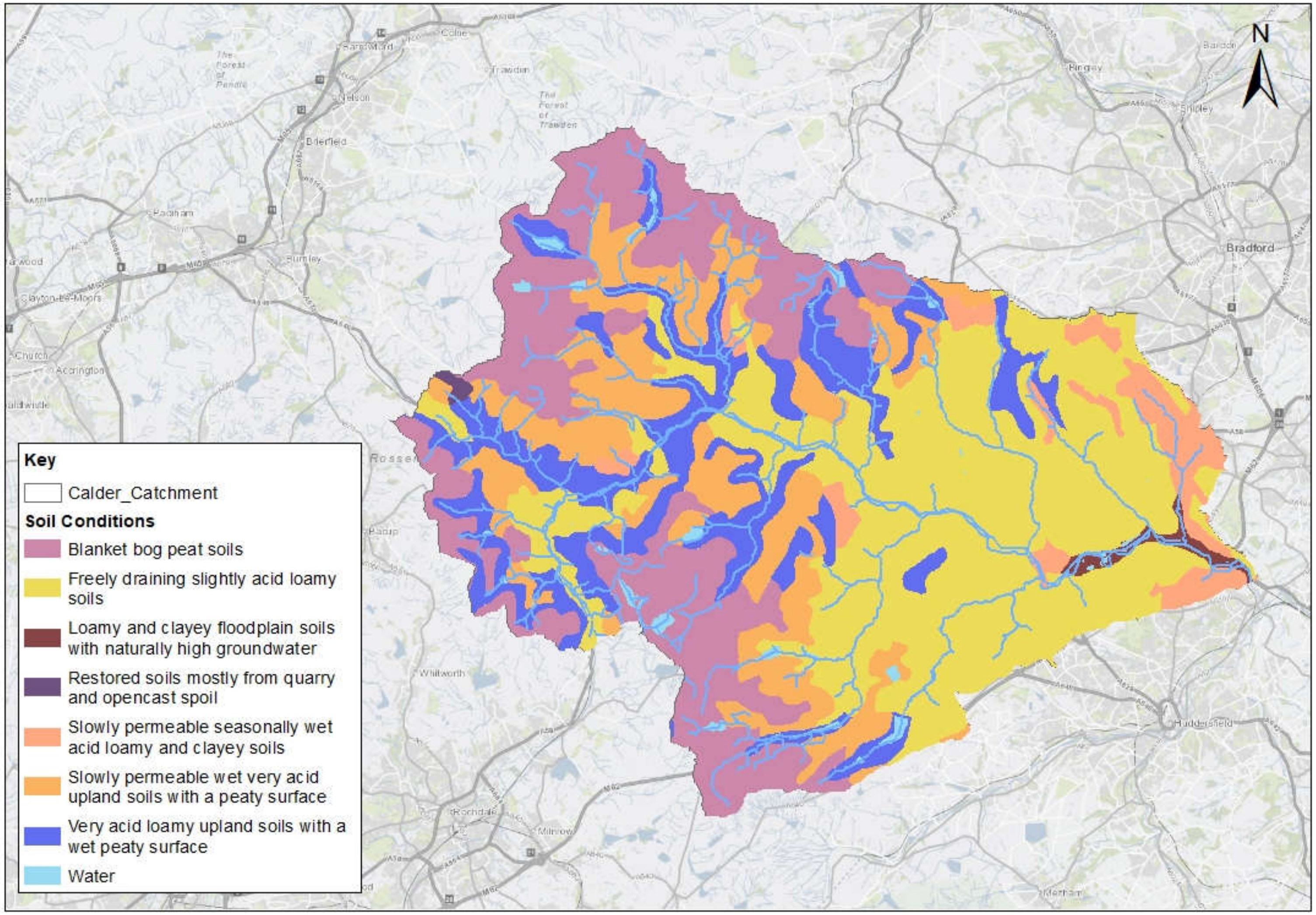
A.2. Slope



A.3. Bedrock


Calder_Catchment
Bedrock
MILLSTONE GRIT GROUP [SEE ALSO MIGR]
PENNINE LOWER COAL MEASURES FORMATION AND SOUTH WALES LOWER COAL MEASURES FORMATION (UNDIFFERENTIATED)

A.4. Soils


N
Key
Calder_Catchment
Soil Conditions
Blanket bog peat soils
Freely draining slightly acid loamy soils
Loamy and clayey floodplain soils with naturally high groundwater
Restored soils mostly from quarry and opencast spoil
Slowly permeable seasonally wet acid loamy and clayey soils
Slowly permeable wet very acid upland soils with a peaty surface
Very acid loamy upland soils with a wet peaty surface
Water
Barrowford
Colne
Trawden
The Forest of Pendle
Nelson
The Forest of Trawden
Brierfield
Padiham
Burnley
Bingley
Shipley
Bradford
Clayton-Le-Moors
Church
Accrington
Bacup
Whitworth
Rochdale
Milnrow
Huddersfield
Meltham

Appendix B. Limitations of the NFM Modelling Approach

There are several limitations to the NFM Studio modelling study. The table below outlines the main limitations and provides identification of any mitigating actions undertaken and comments on how the limitation should be understood.

	Limitation	**Response**
General	It is likely that there have been land cover changes since the latest version of Corine (2018) was produced.	Despite these changes Corine 2018 remains the most current land cover dataset available and any undocumented land cover changes are likely to be a very small percentage. Therefore Corine 2018 is a suitable land cover dataset.
	SPR values may not identify the heterogeneity of the soils at small scales.	To improve the SPR values both the BGS Soil Parent Material Model and the BGS 625k superficial layer are used this helps improve granularity of the outputs. Although local variations in the soil may not be represented in the model.
Opportunity	Land holder engagement is not able to be included in the assessment	Engagement in stewardship is used as a proxy for overall engagement in NBS Schemes.
	Although Multi-Criteria Decision Analysis (MCDA) is a standard tool used across multiple industries it can often be quite a subjective and biased process.	To help minimise the risk of subjectivity and bias the Analytic Hierarchy Process (AHP) developed by Thomas Saaty (Saaty, 1994) can be used within NFM Studio.
	This is the subjective part of the NFM assessment, where the opportunity scores developed in the opportunity workshop are applied, this simply considered perceived opportunity for NFM, the volumetrics are not considered here.	The workshop enables local knowledge of the catchment to be utilised where possible to make the results as catchment specific as possible.
Land runoff	The total runoff generated by the land runoff model used (Daily based Morgan Morgan-Finney model, DMMF) is matched to the total runoff from the ReFH model.	This increases confidence in the DMMF model as the outputs are matched to the industry standard ReFH method.
	The calculated and calibrated baseline initial soil moisture/ antecedent conditions are the same in the baseline and the scenarios. This assumes that the initial/ antecedent conditions are unaltered regardless of the intervention applied.	This enables comparison between the baseline and options to allow the user to determine the reduction in runoff.
	The initial conditions are calculated separately for each return period and therefor the initial water content of the soils can vary across return period.	To calculate an accurate estimation of the initial conditions a comparison of total runoff from the DMMF model is made to the total runoff from the ReFH model. The initial conditions are then altered to ensure the model outputs match and therefore gives confidence in the model outputs. Changes to

	Limitation	**Response**
		the initial conditions across the return periods are very slight and often near to saturation.
	The DMMF characteristics consider average conditions over the year and therefore provide an overall output for the temporal variability of environmental variables.	The land runoff volumetric outputs are able to be made return period specific by altering the amount of rainfall applied to the DMMF model.
Flow pathway	The volumetric calculations performed here simply calculate the storage provided by 1 or the maximum bunds, no infiltration is considered in this calculation	It is assumed that the bunds slowly release the water stored after the flood event. Under intense rainfall conditions which generate over land flow, the soil is already likely saturated, resulting in the overland flow, therefore any infiltration is likely to occur after the rainfall event.
	Bunds are assumed to be 0.5 m high	The SEPA NFM guidance[15] mentions bunds should not exceed 1.3m, with slopes of 1 in 4 or gentler, 0.5m was chosen to be modelled in NFM Studio as it seemed an appropriate and conservative middle ground. In addition, any bund greater than 0.5m required more detailed design rather than landowner/self build because of the construction risk.
	The maximum bund option assumes that the entire length of the flow pathway in the field is covered in bunds, found by dividing the back water length by the total length of the flow pathway in the field.	By providing the min and max volumes it enables a no constraints consideration of what may be possible. Realistically the number of bunds likely to be implemented will sit somewhere in between and will depend on the size of the bunds.
In-channel	It is assumed that after the in-channel interventions within the catchment are applied, FARL can be reduced by 0.025 down to a minimum value of 0.9.	Qmed is therefore re-calculated with the updated FARL and the difference in total volume (m^3) before and after the change in FARL for the 1 in 2 yr event (which is approximately bank full) is considered the temporary volumetric storage.
	In Channel measure types that are considered by the tool include in channel leaky barriers and measures that encourage floodplain reconnection.	Stage 0 assessments, which aim to identify suitable locations for Stage 0 river restoration measures, can be completed for the catchment to increase the granularity of the in-channel intervention types considered in NFM studio.
Hydrology	It is assumed that the shallow interflow that infiltrates goes into the baseflow and hence there are no losses/recharge into the groundwater system.	
	Standard hydrographs for chosen return periods are generated using ReFH to provide indicative flood volumes and visualise the impact of NFM across the catchment.	
	All measures can be applied simultaneously, and all measures are	

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[15] sepa-natural-flood-management-handbook1.pdf
https://www.sepa.org.uk/media/163560/sepa-natural-flood-management-handbook1.pdf

	Limitation	Response
	applied across the whole catchment, in every land parcel.	
	Bund volumes are applied to the hydrograph by taking the volume from front of hydrograph, they are assumed to be empty at start of event. Therefore, how these volumes have been applied means there is no impact to the peak.	
	Volumetric reductions are calculated for each individual land parcel separately and are applied to the hydrograph without considering implications of connectivity between individual fields and watercourses.	
Natural capital	This is not a pure B£ST assessment.	This assessment uses components of B£ST assessments. Values which are used and not B£ST are representative and up to date values in the field.
	The indicative natural capital outputs at this stage will not be used as part of a full cost-benefit appraisal and the monetisation provides relative values for the benefits of NFM interventions across a catchment, not direct capital gain to a landowner.	The outputs can be used to prioritise further investigation and feed into a site-specific natural capital assessment using primary data if desired.
	Flood ecosystem service	This was removed from the assessment as the method is separate to the outputs from the NFM Studio and flood economics, both of which evaluates flood risk benefit in a more detailed way for this study.
	Inflated values for in-channel NFM measures	The values are based on the NWEBS study. For biodiversity, willingness to pay is usually the only means of measuring value. It may be that people actually assign more value to the ecological conservation of watercourses than to terrestrial habitats. In addition, there is a lack of literature on in-channel measures so there is an assumption that interventions will lead to a 1 category uplift in WFD status. For water quality, this is also based on the NWEBS study and so reflect willingness to pay rather than damage avoidance approaches that are generally used for water quality. More information on efficacy of in-channel works is needed to reasonably scale it back.
Outline Costings	Baseline land cover is based on Corine 2018	
	The width of flow pathway bunds is assumed to be the same width as the flow pathway, according to the RoFSW layer.	
	For in channel measures, we have assumed the spacing of leaky barriers to be 5 times the channel width. The channel widths have been taken from OSMM Water and where channel	

	Limitation	**Response**
	widths are missing, we have assumed that the width is 3m.	
	Where possible we have taken the upper range of costings to provide a conservative approach.	
	Costings have been taken from the Calderdale projects where possible, others from the National Highways Design Specification[16] document.	
	Costed for capital costs only and applied 10% maintenance per year for all options. Operational costs have not been included.	
Hydraulic modelling and Economics assessment	Included in Appendix K and L respectively	

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[16] Design-Specification-Catalogue.pdf (catchmentbasedapproach.org) https://catchmentbasedapproach.org/wp-content/uploads/2021/03/Design-Specification-Catalogue.pdf

Appendix C. Datasets

The datasets included in the NFM Studio metrics (hydrology, natural capital and opportunity).

Dataset	Hydrology	Natural Capital	Opportunity	Summary of how the Dataset is Applied
FEH Catchment descriptors	✓			Catchment descriptors are utilised to calculate peak flows and obtain hydrographs with ReFH.
Agricultural Land Classification (ALC)			✓	Land quality and ease of removing land from productive agriculture can be inferred from the grades.
OS Greenspace	✓	✓	✓	Used to exclude greenspaces where NFM interventions are very unlikely to be applied (i.e. golf course, tennis courts, etc.).
BGS 50k, 625k and soil parent material data	✓		✓	Used to derive standard percentage runoffs and soil characteristic in the runoff modelling.
Enhanced Corine Land Cover 2018	✓	✓	✓	Describes land-use / landcover in each metric. The dataset has been enhanced and extended using Priority Habitat Inventory data.
Environment Agency Floodplain Woodland			✓	Catchment with floodplain woodland potential used to target areas of land-use change.
Environment Agency Floodplain Reconnection	✓		✓	Target areas of floodplain reconnection next to the river and increasing volumetric storage attenuation potential.
Soil Characteristics e.g Standard Percentage Run-off (SPR)	✓		✓	SPR provides information about the runoff generation. Interventions can be targeted according to high/low runoff percentages.
Risk of Flooding from Surface Water (RoFSW) 1 in 1000 years and 1 in 100 years	✓		✓	Areas at risk from flooding used to target NFM intervention types, and also to identify flow pathways for volumetric calculations.
Runoff Attenuation			✓	Areas with runoff used to target NFM intervention types.
Manmade Features in the Floodplain			✓	Areas around manmade features are less suitable for NFM interventions as may increase local flood risk.
Countryside Services Stewardship			✓	Countryside Stewardship areas may infer that the landowner is likely to be receptive to and capable of implementing NFM interventions depending on the prescriptions being applied.
Environmental Services Stewardship			✓	Environmental Stewardship areas may infer that the landowner is likely to be receptive to and capable of

Dataset	Hydrology	Natural Capital	Opportunity	Summary of how the Dataset is Applied
				implementing NFM interventions depending on the prescriptions being applied.
Conservations sites (i.e. SSI, LNR, SAC, SPA, PHI, etc.)		✓	✓	These datasets identify the conservation sites and how they influence the likelihood of interventions being implemented. They are also flagged up in the natural capital metric to steer intervention types.
Scheduled Monuments		✓	✓	Dataset that indicates where the monuments in the catchment are and how they constrain intervention delivery.
Historic Landfill and Waste sites		✓	✓	Dataset that indicates where the waste management issues in the catchment are and how they constrain intervention delivery.
Source Protected Zones (SPZ)		✓	✓	SPZ 1 (not 1c) are used to identify potential constraints to NFM intervention delivery.
Flood Zone 3	✓	✓	✓	Used to differentiate between flow pathway and in-channel intervention types in the assessments.
OS MasterMap	✓	✓	✓	Used to divide up and summarise the metric outputs into land parcels (denoted as fields in this report).
Terrain 50 – Slope	✓			The slope is calculated with terrain 50 data and utilised in the Infiltration and flow pathways calculations.
Standard Annual Average Rainfall (SAAR)	✓			SAAR data identifies the variability of rainfall across the catchment and is used to develop spatially variable rainfall statistics in the hydrology metric outputs.
Nitrate Vulnerable Zones and Environment Agency Aquifer Designations		✓		Used to identify potential constraints to NFM intervention delivery in the natural capital metric.
Defra (2021). Air quality appraisal: damage cost guidance		✓		Air quality monetisation
BEIS (2021). Valuation of greenhouse gas emissions: for policy appraisal and evaluation		✓		GHG emission and C sequestration monetisation
National Water Environment Benefits Survey		✓		Channel intervention monetisation

Dataset	Hydrology	Natural Capital	Opportunity	Summary of how the Dataset is Applied
Woodland Trust by Europe Economics 2017 report		✓		Raw materials monetisation
Christie, M. et al (2011): Economic Valuation of the Benefits of Ecosystem Services (BAP)		✓		Biodiversity value monetisation
Hanley & Craig (1991). Wilderness development decisions and the Krutilla-Fisher model: the case of Scotland's flow country. Ecol Econ 4, 145-164		✓		Recreational value monetisation (peatland)
ONS UK natural capital accounts: 2019		✓		Groundwater resources monetisation Recreational value monetisation
Agriculture in the UK 2020		✓		Food production value monetisation
iCASP (2019). A user guide for valuing the benefits of peatland restoration		✓		Peatland restoration carbon sequestration estimation
Farmscoper: ADAS		✓		Estimate impacts of scenarios on reduction of diffuse pollution (water quality, air quality, greenhouse gas (GHG) emissions)
ONS (2021). GDP Deflators		✓		Adjustment of historic monetary values to reference year (2020).
EA Peaty Locations	✓			Locating peatland areas for the peatland restoration and use change option
Moors for the Future – locations of works	✓			Locating peatland areas for the peatland restoration and use change option

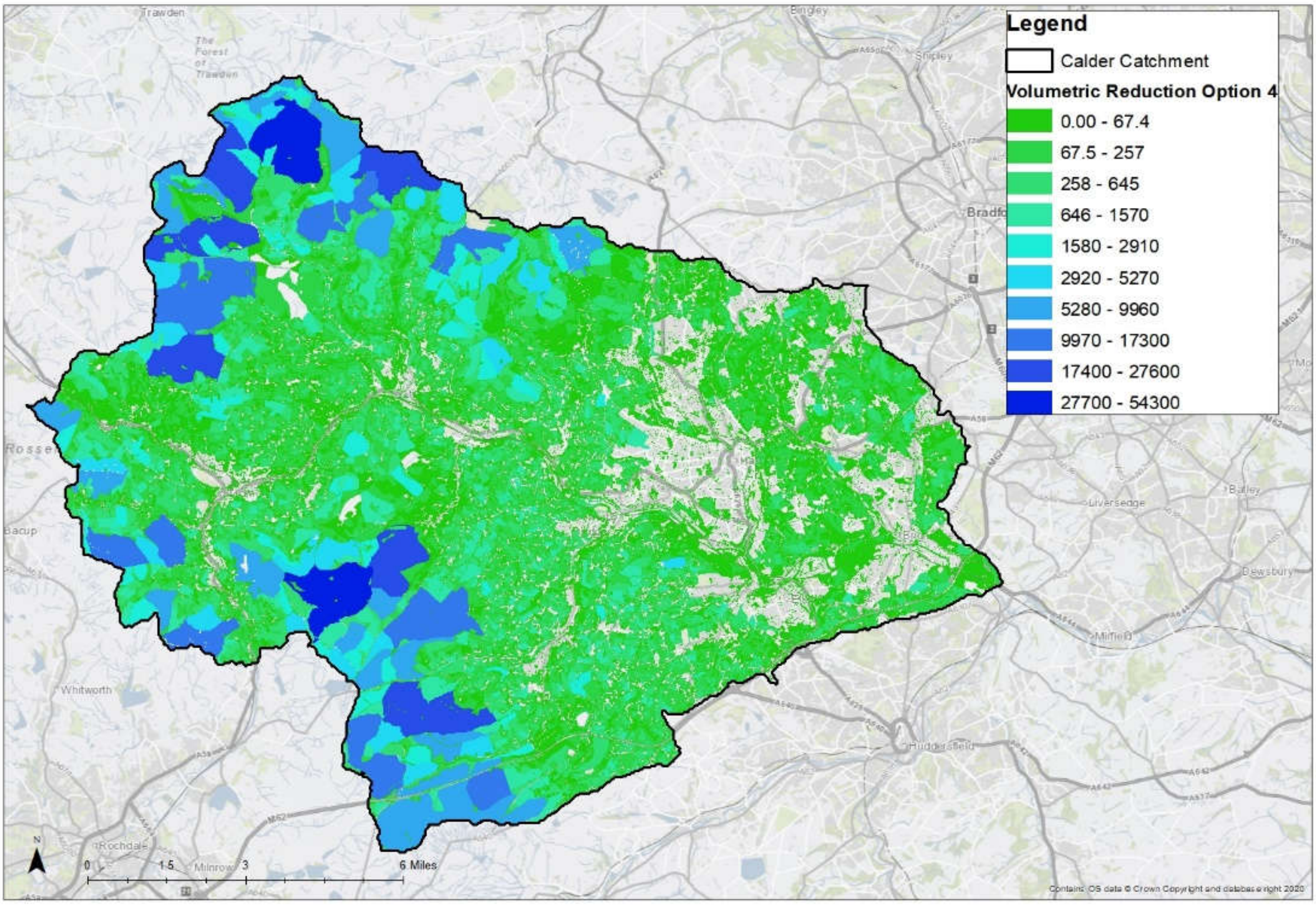
Appendix D. Opportunity Scores (normalised average after Partner Consultation)

Data	Enablers and Constraints	Land Runoff	Flow Pathways	In Channel
Agricultural Land Classification (ALC)	Non-agricultural, Grade 4 and 5	2	1.5	N/A
	Grade 1, 2 and 3	1	1	N/A
	Urban	0	0	N/A
Standard Percentage Run-off (SPR)	<0.41 (low)	0	0	2
	>=0.41 and <0.64 (medium)	1	0.5	1
	>0.64 (high)	2	1	0.5
EA Floodplain Woodland	Catchment with floodplain woodland potential	1	N/A	N/A
Land Cover (CORINE data)	Natural grassland	1	2	2
	Moors and heathland	2	2	2
	Peatbogs	2	2	2
	Coniferous forest	2	2	2
	Pastures	1.5	1	1.5
	Non-irrigated arable land	1	0.5	1
	Permanently irrigated arable land	1	0.5	0
	Annual crops associated with permanent crops	1	0.5	0.5
	Rice fields	1	1	0.25
	Mixed forest	1	1	1.5
	Agro-forestry areas	1	1	1
	Complex cultivation patterns	1	1	1
	Land principally occupied by agriculture and mix forest	1	1.5	1
	Transitional woodland	1	1	1
	Broadleaf forest	0	1.5	1.5
	Vineyards, fruit trees or olive groves	0	1	0.5
	Green urban areas	0.5	0.5	0
	Sports and leisure facilities	0.5	0.25	0.5
	Continuous urban fabric	-2	-2	-2
	Discontinuous urban fabric	-2	-2	-2
	Road and rail networks	-2	0	-2
	Industrial or public facilities	-2	-2	-2
	Airports, ports, construction sites, dumps and mineral extraction sites	-2	-2	-2

Risk of Flooding from Surface Water (RoFSW)	Areas at Risk of Flooding from Surface Water 1:1000	2	2	N/A
Environmental Services Stewardship (Stewardship codes in each group listed in 'Stewardship Prescription' tab, Table A-1)	Catchment with higher level stewardship	1	1.25	1
	Catchment with stewardship options that:	1.5	1	1
	· Manages habitats for water voles, dragonflies, newts and toads			
	· Manages land for cleaner water and healthier soil	2	1	1
	Catchment with historical landscapes stewardship	-1	-1	-1
Countryside Services Stewardship (selected option listed in 'Stewardship Prescription' tab, Table A-2)	Higher tier stewardship	1	1	1
	Water management related mid-tier options	2	1	1
	Historical landscape options	-1	-1	-1
Priority habitats and areas of conservation	Areas within Local nature reserves, SSSIs, Special Areas of Conservation, Special Protection Areas and All priority habitats except:	2	2	1
	Traditional Orchards	0	0	0
	Upland Calcareous Grassland	-2	0	0
	Lowland Calcareous Grassland	-1	0	0
	Lowland Dry Acid Grassland	-1	0	0
Scheduled Monuments		-1	-1	-1
EA Historic landfill sites	Defines the location of any known historic (closed) landfill sites	0.1	-1	-1
EA permitted Waste Sites		-1	-1	-1
EA Source protection zones	Where large and public potable groundwater abstraction sites are.	-1	-1	-1
WWNP Runoff Attenuation		N/A	2	N/A
Mademade features in Floodplain		N/A	N/A	-1
WWNP floodplain reconnection potential		N/A	N/A	2

Appendix E. Unconstrained Woodland

E.1. 1 in 100 year unconstrained woodland planting



1 in 100 year	Baseline – Total Runoff (m^3)	Option 4 – Woodland Creation – Total Runoff (m^3)	Reduction in runoff (m^3)	Percentage decrease in runoff from baseline
Whole Catchment	5,609,038.9	1,865,371.9	3,743,667.00	66.7%
Top 10%	4,266,530.7	1,538,072.6	2,728,458.10	64.0%

Appendix F. Volumetric Outputs Top 10%

Land runoff Volumetrics – 1 in 2 year return period

	Total Volume (m^3) for each option in 1 in2 year event				% Difference between the baseline and the options (m^3)		
	Baseline (BL)	**OPT 1**	**OPT 2**	**OPT 3**	**BL – OPT 1**	**BL – OPT 2**	**BL – OPT 3**
Top 10%	1,223,279	957,742	907,807	1,041,014	21.7%	25.8%	14.9%

Land runoff Volumetrics – 1 in 100 year return period

	Total Volume (m^3) for each option in 1 in 100 year event				% Difference between the baseline and the options (m^3)		
	Baseline (BL)	**OPT 1**	**OPT 2**	**OPT 3**	**BL – OPT 1**	**BL – OPT 2**	**BL – OPT 3**
Top 10%	5,161,354	3,236,087	3,074,040	4,062,929	37.3%	40.4%	21.3%

Flow Pathway Volumetrics

Option	Total Volume (m^3) Top 10% Fields
Minimum Bunds	24,085
Maximum Bunds	240,681

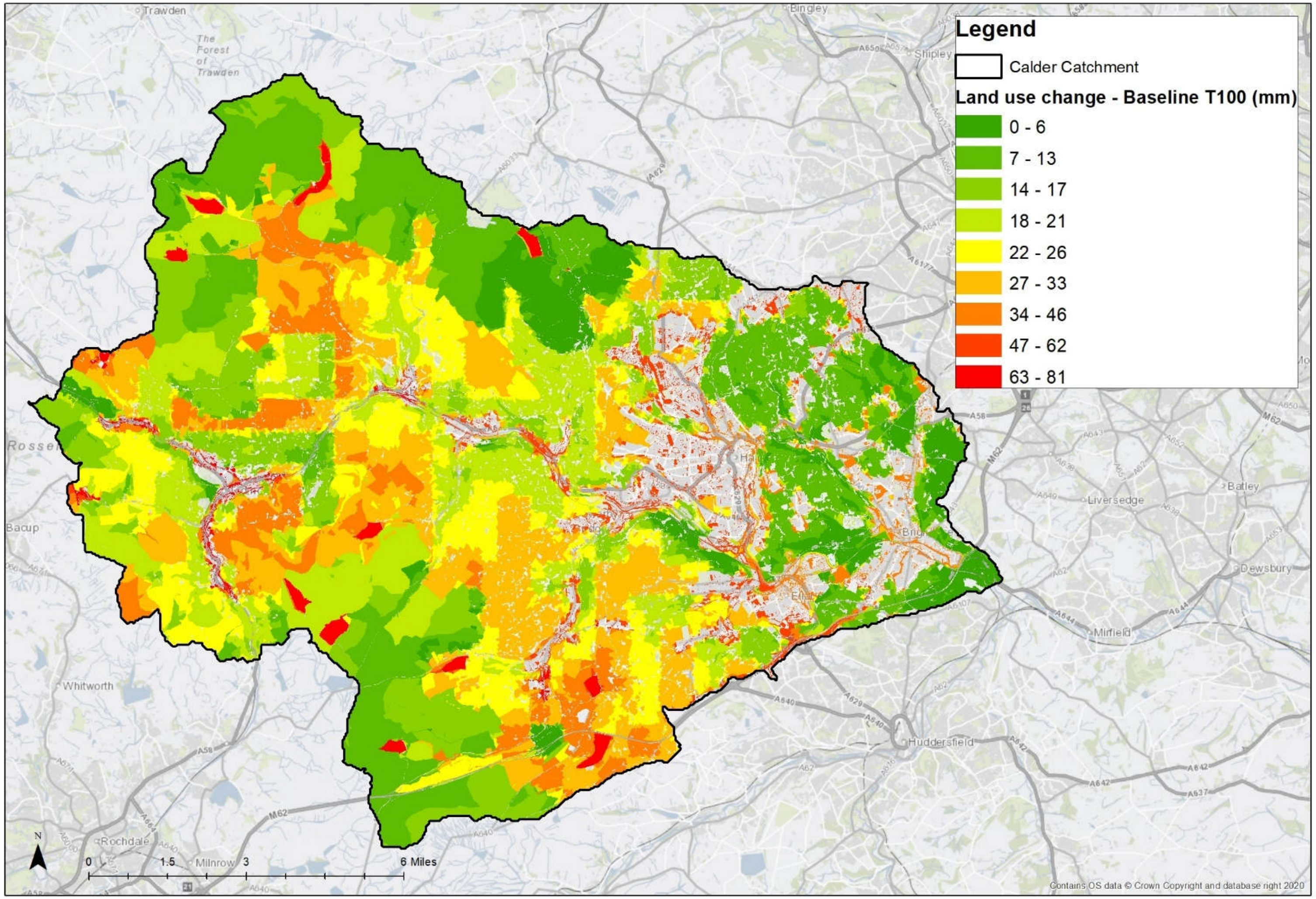
In Channel Volumetrics

	Total Volume (m^3) with In-Channel Interventions Applied
Top 10% Fields	57,620

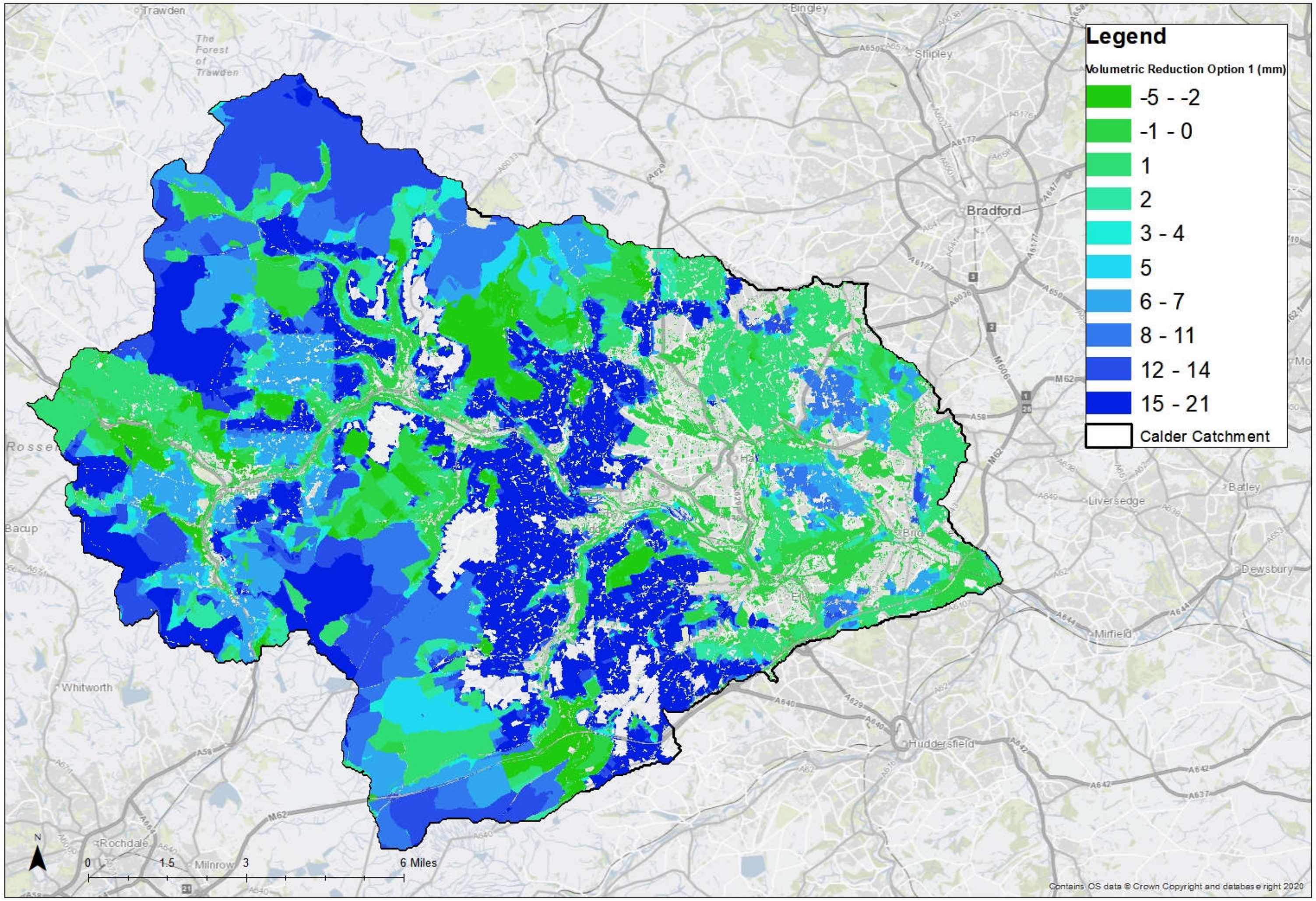
Appendix G. Standardised Land Runoff Maps in mm per m^2

Below are maps of the volumetric land use change NFM Studio output in mm. This shows a standardised outputs as the volumes do no take field size into account. The 1 in 100 year return period has been mapped as an example.

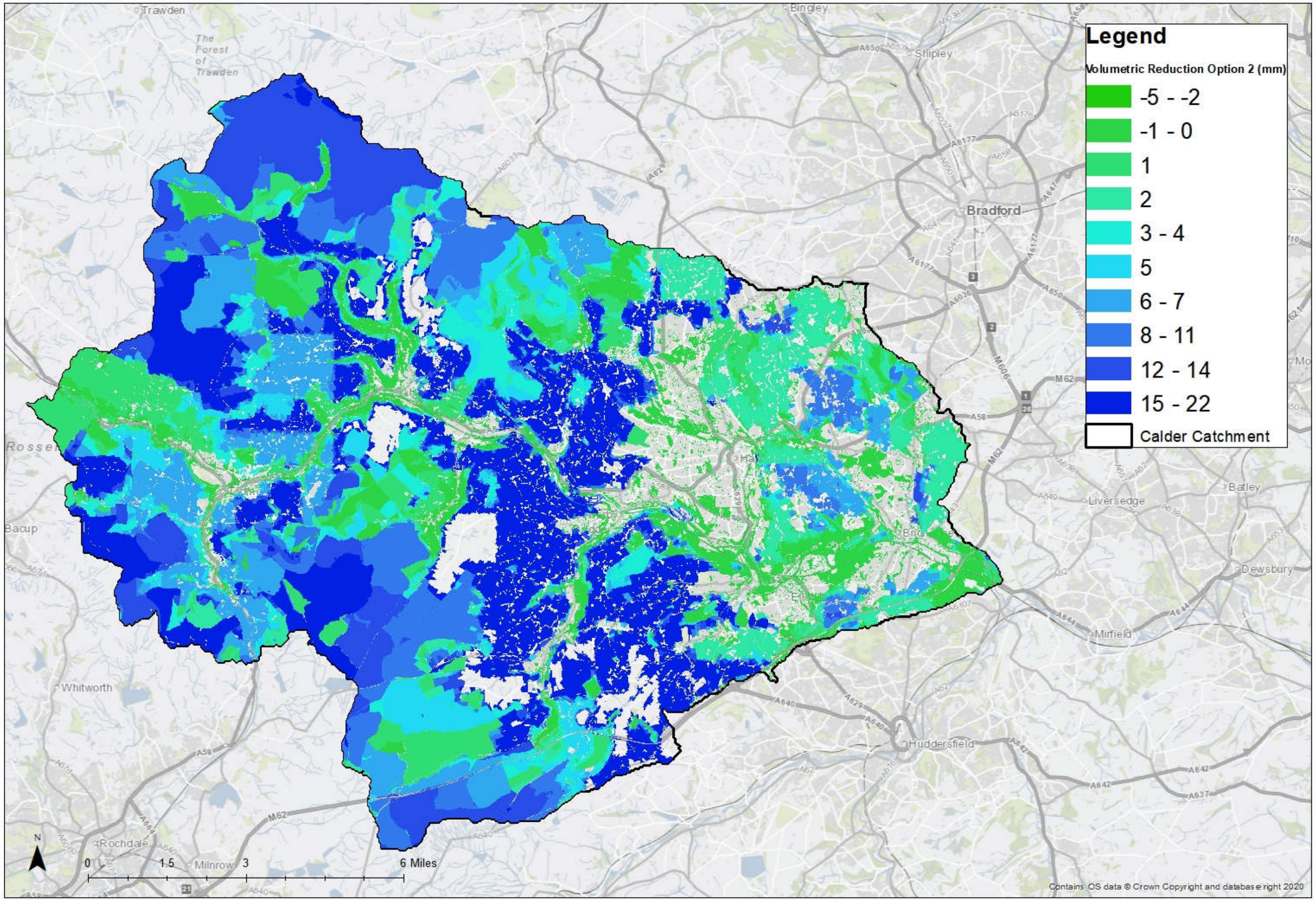
G.1. Baseline (mm per m^2)



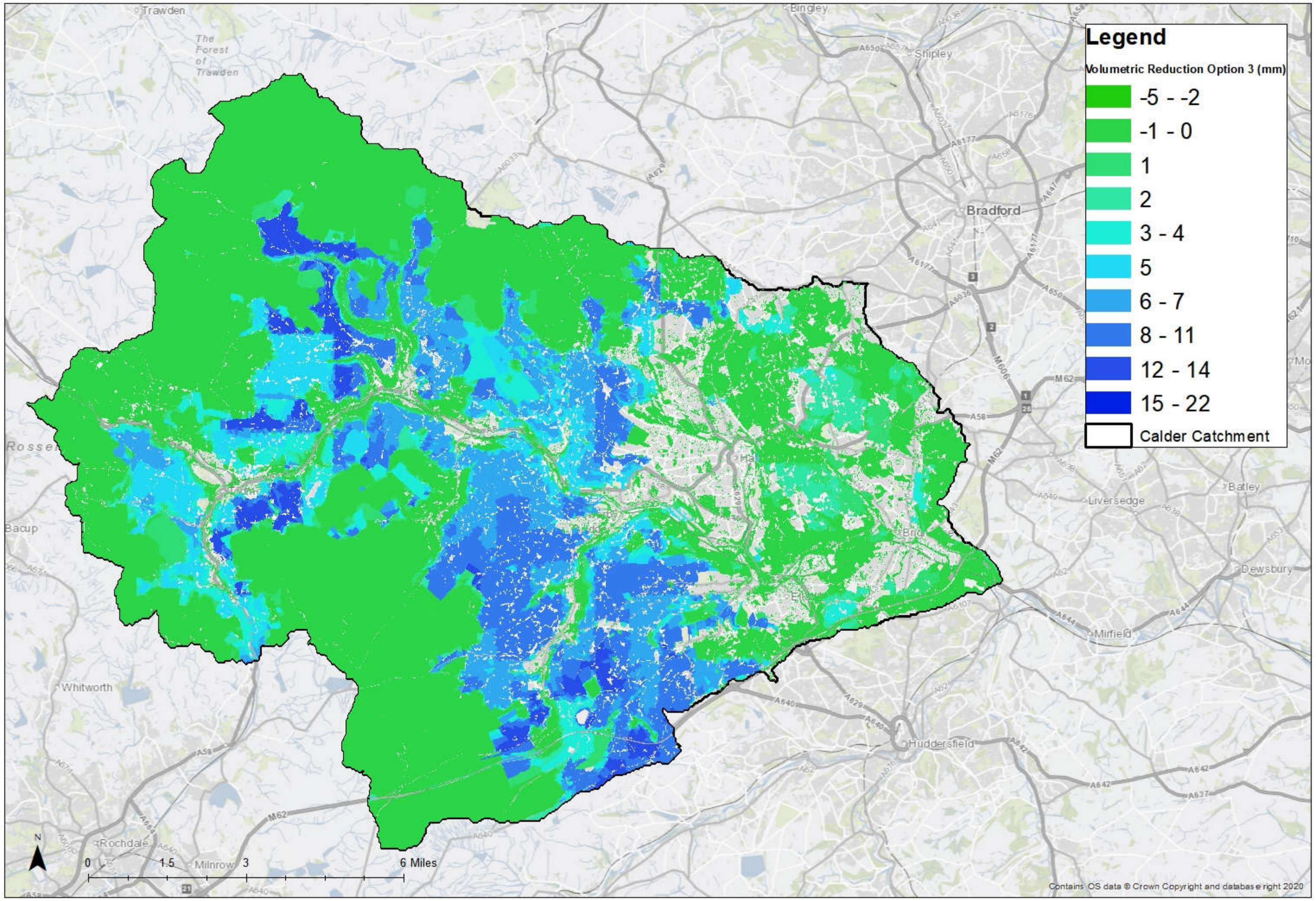
G.2. Option 1 – Land use Change and Management (mm per m^2)



G.3. Option 2 - Woodland Creation (except peat and protected moorland which is restored) (mm per m^2)



G.4. Option 3 – Soil Recovery (excluding peat but including restored moorland areas) (mm per m^2)



Appendix H. Hydrology Spreadsheet

Excel spreadsheet to be provided as a separate output

Calder_Hydrographs_v18_Appendix_H

Appendix I. Outline Costings Reference Table

Description	Cost (£)	Unit	Assumptions	Source
Capital Costs				
Pasture to Natural Grassland	0.07	m^2	AB8 (£628 per ha)+ £100 per ha for implementation	https://www.gov.uk/countryside-stewardship-grants/flower-rich-margins-and-plots-ab8
Arable to Pasture	0.04	m^2	SW7 (£321 per ha) + £100 per ha for implementation	https://www.gov.uk/countryside-stewardship-grants/arable-reversion-to-grassland-with-low-fertiliser-input-sw7
Arable to Woodland	1.65	m^2	Woodland planting costs from Calderdale Grant Scheme with shelter and stake. Assumed 1 tree every $2m^2$.	Calderdale Grant scheme
Pasture to Woodland	1.65	m^2	Woodland planting costs from Calderdale Grant Scheme with shelter and stake. Assumed 1 tree every $2m^2$.	Calderdale Grant scheme
Moorland to Woodland	1.65	m^2	Woodland planting costs from Calderdale Grant Scheme with shelter and stake. Assumed 1 tree every $2m^2$.	Calderdale Grant scheme
Natural Grassland to Woodland	1.65	m^2	Woodland planting costs from Calderdale Grant Scheme with shelter and stake. Assumed 1 tree every $2m^2$.	Calderdale Grant scheme
Moorland to Shrubland	1.65	m^2	Woodland planting costs from Calderdale Grant Scheme with shelter and stake. Assumed 1 tree every $2m^2$.	Calderdale Grant scheme
Moorland to Restored Moorland	0.567	m^2	Peat revegetation costs from MFFP	MFFP
Peatland to Restored Peatland	0.567	m^2	Peat revegetation costs from MFFP	MFFP
Soil aeration	0.002	m^2	Soil aeration cost from Calderdale Grant Scheme	Calderdale Grant scheme

Flow pathway bund	10	per m width	Costs for earth bund from Calderdale Grant Scheme. This assume a 1m high bund with additional 300mm freeboard.	Calderdale Grant scheme
In channel woody barrier	175	per feature	Costs for leaky barrier from Calderdale Grant Scheme	Calderdale Grant scheme
Maintenance costs				
Description	Cost (£) over 5 years			
Pasture to natural grassland	0.35	m^2	Maintenance cost assumed to equal capital cost per year. Calculated over 5 years	https://www.gov.uk/countryside-stewardship-grants/flower-rich-margins-and-plots-ab8
Arable to Pasture	0.2	m^2	Maintenance cost assumed to equal capital cost per year. Calculated over 5 years	https://www.gov.uk/countryside-stewardship-grants/arable-reversion-to-grassland-with-low-fertiliser-input-sw7
Arable to Woodland	0.825	m^2	10% of construction cost per year	
Pasture to Woodland	0.825	m^2	10% of construction cost per year	
Moorland to Woodland	0.825	m^2	10% of construction cost per year	
Natural Grassland to Woodland	0.2835	m^2	10% of construction cost per year	
Moorland to Shrubland	0.2835	m^2	10% of construction cost per year	
Moorland to Restored Moorland	0.825	m^2	10% of construction cost per year	
Peatland to Restored Peatland	0.825	m^2	10% of construction cost per year	
Soil aeration	0.001	m^2	10% of construction cost per year	

Flow pathway bund	5	m^2	10% of construction cost per year	
In channel woody barrier	87.5	per m width	10% of construction cost per year	
Arable to Woodland	0.825	per feature	10% of construction cost per year	

Appendix J. Natural Capital Valuation Approach Summary

The table below shows all of the ecosystem services that were assessed, identifying key metrics and approaches and data used to calculate them. Natural capital valuation is an evolving discipline and detailed data describing individual services on every site may not always be available. As a result, there may be gaps in metrics for specific site settings and services. In the table below, a confidence score for each ecosystem service has been presented, reflecting data availability and the assumptions made to value them.

Ecosystem Service	Metric	Approach	Methodology	Confidence* (Key below)	Main assumptions	Sources of information
Food production	Change in agricultural farm gross margin (£ / ha / year)	Value transfer (Resource rent)	Monetisation of agricultural production was estimated using a simplified resource rent approach, defined as the value of agricultural production after all agriculture costs such as fertilisers, pesticides, machinery, fuel and labour have been removed (agricultural gross margin). Farm gross margins (£ / ha / yr) were obtained from the Farm Business Survey by farm type and NUTS2 region for the most recent available year (2019). Miscellaneous revenues not related to food production (e.g. subsidies, agri-environment payments, non-farm income) were removed. Arable, improved grassland, semi-natural grassland and moorland related revenues were calculated by farm type (Cereals, Gen Cropping, Dairy, Lowland Grazing, LFA Grazing) and land apportionment (Defra 2020). For offline storage, impact on food production calculated with reference to ADAS (2014).	🟩	Farm Business Survey values represent averages for NUTS2 regions. Production values may vary within a region depending on catchment dynamics.	1, 2, 3
Air pollutant removal	Pollutant emission reduction (kg NH_3 / ha / year) * £ / kg reduced	Value transfer (Damage cost)	Baseline and scenario nitrate, P and sediment loss figures obtained using FARMSCOPER and are based on representative farm types for each NUTS2 region. These are converted into kg / ha for arable, improved grassland, semi-natural grassland and moorland based on the farm type land apportionment (Agricultural Census data). Damage costs per kilogram of pollutant derived from UK government guidance on air quality damage costs (Defra 2021).	🟩	UK/national air quality monetisation approaches apply to the local context. FARMSCOPER methods are close approximations of actual NFM scenarios rather	2, 8, 9

Ecosystem Service	Metric	Approach	Methodology	Confidence* (Key below)	Main assumptions	Sources of information
				🟩	than bespoke applications.	
Water quality regulation	Pollutant losses avoided (kg nitrate, P, sediment / ha / year) * £ / kg avoided	Value transfer (Damage cost)	Baseline and scenario NH_3 emission figures obtained using FARMSCOPER and are based on representative farm types for each NUTS2 region. These are converted into kg / ha for arable, improved grassland, semi-natural grassland and moorland based on the farm type land apportionment (Agricultural Census data). Damage costs per kilogram of phosphorous were derived from Chadwick et al. (2006) as used in FARMSCOPER.	🟩	UK/national water quality monetisation approaches apply to the local context. FARMSCOPER methods are close approximations of actual NFM scenarios rather than bespoke applications.	2, 8, 10
Water quality regulation (in-channel)	Length of channel providing improved regulation (£ / km / year)	Value transfer (Stated preference)	National Water Environment Benefits Survey (NWEBS). Average of Central willingness to pay (£ / km) for 1 unit (Bad -> Poor, Poor -> Mod, Mod -> Good) increase in WFD status for a given Management Catchment. Component value for ‘Clarity of water’	▨	In-channel works will deliver a 1 unit change in WFD status and that the site affected is equally likely to be currently in Bad, Poor or Moderate condition.	7
Climate regulation	Carbon sequestered and GHG emissions reduced (t CO_2 e / ha / year) * £ / t sequestered / reduced	Value transfer (Damage cost)	Baseline and scenario N_2O, CH_4 and CO_2 emission figures obtained using FARMSCOPER and are based on representative farm types for each NUTS2 region. These are converted into tCO_2e / ha for arable, improved grassland, semi-natural grassland and moorland based on the farm type land apportionment (Agricultural Census data) and conversion factors for N_2O and CH_4. C sequestration values by land use are based on Natural England’s (2021) review of Carbon Storage and Sequestration by Habitat except for peatland which are based on iCASP (2019) and restored moorland (Quin et al 2014). All greenhouse gas sequestration and emissions were monetised using the UK	▨	FARMSCOPER methods are close approximations of actual NFM scenarios rather than bespoke applications. Assumes instant change in C sequestration rate, rather than a gradual transition.	2, 6, 8, 11, 12, 13

Ecosystem Service	Metric	Approach	Methodology	Confidence* (Key below)	Main assumptions	Sources of information
			Government's latest figures for valuation of greenhouse gas emissions (BEIS, 2021).	🟩		
Biodiversity	Area (type) of land with greater biodiversity (£ / ha / year)	Value transfer (Stated preference)	Christie et al (2011).	🟩	Impacts can only be judged for scenarios/measures involving land use change between categories referred to in Christie et al.	14
Biodiversity (in-channel)	Length of channel providing improved regulation (£ / km / year)	Value transfer (Stated preference)	National Water Environment Benefits Survey (NWEBS). Average of Central willingness to pay (£ / km) for 1 unit (Bad -> Poor, Poor -> Mod, Mod -> Good) increase in WFD status for a given Management Catchment. Component value for 'Fish' + 'Invertebrates and other animals' + 'Plants'.	🟩	In-channel works will deliver a 1 unit change in WFD status and that the site affected is equally likely to be currently in Bad, Poor or Moderate condition.	7
Recreation	Area (type) of land receiving greater visitation (£ / ha / year)	Value transfer (Travel cost; direct spending)	ONS (2021).	🟨	Impacts can only be judged for scenarios/measures involving land use change between categories referred to in ONS. Apportionment is by proportion of land use and does not reflect preferential spending associated with habitats.	15
Recreation (in-channel)	Length of channel	Value transfer	National Water Environment Benefits Survey (NWEBS). Average of Central willingness to pay (£ / km) for 1 unit (Bad ->	🟩	In-channel works will deliver a 1 unit	7

Ecosystem Service	Metric	Approach	Methodology	Confidence* (Key below)	Main assumptions	Sources of information
	providing improved regulation (£ / km / year)	(Stated preference)	Poor, Poor -> Mod, Mod -> Good) increase in WFD status for a given Management Catchment. Component value for 'Safety for recreation'	🟩	change in WFD status and that the site affected is equally likely to be currently in Bad, Poor or Moderate condition.	
Not calculated for this study						
Flood regulation	Area (type) of land storing more water or slowing flow (£ / ha / year)	Value transfer (Damage cost)	Value of woodlands: Broadmeadow et al (2018). Used for land use change -> woodland. Value of wetlands: Morris & Camino (2011). Used for offline storage areas. Value of peatlands: Ferré & Martin-Ortega (2019). Storage value of restored fen. Central value used where there is no flow pathway. Upper value used where there is a flow pathway indicating greater potential for impact. Run-off pathway measure or conversion to semi-natural grassland deemed to have half the effect of wetland. Soil health scenario and arable reversion deemed to have half the effect of woodland.	🟨	Value transfer approach here does not reflect spatial dynamics and contains many assumptions.	4, 5, 6
Flood regulation (in-channel)	Length of channel providing improved regulation (£ / km / year)	Value transfer (Stated preference)	National Water Environment Benefits Survey (Environment Agency, 2012). Average of Central willingness to pay (£ / km) for 1 unit (Bad -> Poor, Poor -> Mod, Mod -> Good) increase in WFD status for a given Management Catchment. Component value for 'Channel condition/flow'	🟩	In-channel works will deliver a 1 unit change in WFD status and that the site affected is equally likely to be currently in Bad, Poor or Moderate condition.	7

Confidence Category definitions	Confidence level
We may have used some assumptions or estimation but these are in line with current industry standard approaches.	🟩
We have used some assumptions or estimation and some of these would benefit from additional data collection.	🟩
We are confident that the number is in the right order of magnitude. Order of magnitude implies that for an estimate of 5 that we are confident that the real figure is within the range 0.5 to 50.	🟨
We can't offer a number which is likely to be in the right order of magnitude. This is due to unquantifiable uncertainty in the science, valuation or the relationship between them. What we do know, and our confidence, is discussed qualitatively.	-

*Adapted from the Environment Agency confidence category definitions.

1) Farm Business Survey Region Reports 2019/20 http://www.farmbusinesssurvey.co.uk/regional/Reports-on-Farming-in-the-Regions-of-England.asp
2) Defra (2020). The Structure of the Agricultural Industry in England. Breakdown by region – 2019.
3) ADAS (2014). The impact of the 2014 winter floods on agriculture in England.
4) Broadmeadow, S., Thomas, H., Nisbet, T., & Valatin, G. (2018). Valuing flood regulation services of existing forest cover to inform natural capital accounts. Forest Research.
5) Morris, J. & Camino, M (2011). Economic Assessment of Freshwater, Wetland and Floodplain Ecosystem Services. UK National Ecosystem Assessment Working Paper.
6) Ferré, M & Martin-Ortega, J. (2019). A user guide for valuing the benefits of peatland restoration. iCASP. https://icasp.org.uk/resources/peat-resources/
7) Environment Agency (2012). National Water Environment Benefits Survey.
8) ADAS (2014) FARM SCale Optimisation of Pollutant Emission Reductions (FARMSCOPER) Defra project WQ0106. Available from: http://www.adas.uk/Service/farmscoper
9) Defra (2021) Air quality appraisal: damage cost guidance [online], available at: https://www.gov.uk/government/publications/assess-the-impact-of-air-quality/air-quality-appraisal-damage-cost-guidance#table-3-level-of-change-in-nox-emissions-t
10) Chadwick, D., Chambers, B., Harris, D., & Crabtree, R. (2006) Benefits and pollution swapping: Crosscutting issues for catchment sensitive farming policy. Final report for Defra project WT0706, 29 pp + Appendices.
11) R Gregg, J. L. Elias, I Alonso, I.E. Crosher and P Muto and M.D. Morecroft (2021) Carbon storage and sequestration by habitat: a review of the evidence (second edition) Natural England Research Report NERR094. Natural England, York.
12) Quin S. et al (2014). Restoration of upland heath from graminoid to a Calluna vulgaris dominated community provides a carbon benefit. *Agriculture, Ecosystems & Environment* 185, 133-143
13) BEIS (2021) Valuation of greenhouse gas emissions: for policy appraisal and evaluation [online]. Available at: Valuation of greenhouse gas emissions: for policy appraisal and evaluation - GOV.UK (www.gov.uk)
14) Christie. M et al (2011). Economic valuation of the benefits of ecosystem services provided by the Biodiversity Action Plan.
15) ONS (2021). Tourism and outdoor leisure accounts, natural capital, UK: 2021

Appendix K. Hydraulic Modelling Tech Note

K.1. Introduction

This Technical Note provides an overview and assessment of the modelled impacts of NFM measures and the potential reduction in flood risk and frequency.

This modelling exercise has also informed the Economics Analysis and the assessment of the economic benefits of the implementation of the NFM measures. The modelling exercise has developed outputs in term of flood extents and flood depths for both a 'baseline' and 'with NFM' models for a range of return periods from hydraulic models of the Upper Calder catchment

This technical note provides details of the models used for this assessment and how the proposed NFM measures within the catchment have been represented.

K.2. Upper Calder Catchment

The extents of the upper Calder catchment considered for this study is shown on Figure 1. It includes the entire river Calder catchment from its upstream limits at Todmorden to the lower limit of the catchment where it crosses the M62 downstream of Brighouse.

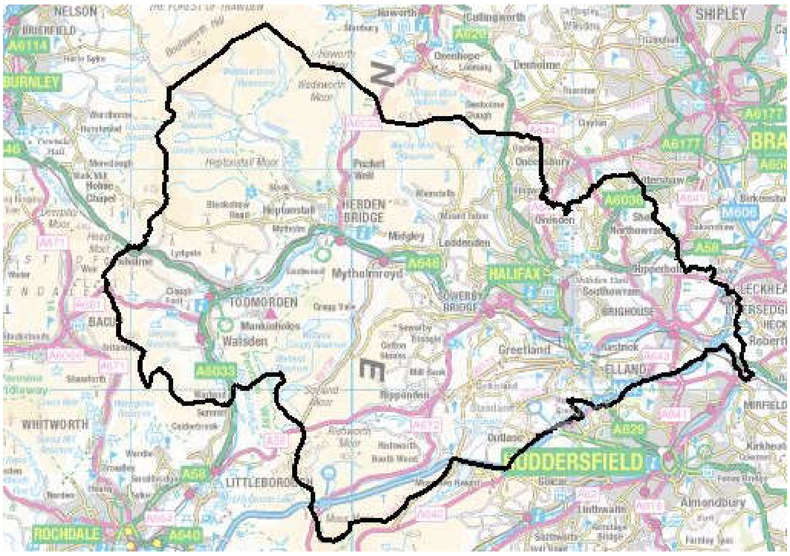


Figure 1 - Catchment Extents

K.3. Hydraulic Models

Hydraulic models for the assessment were provided by the Environment Agency. In total five hydraulic models have been used. All models are 1D/2D FM-TUFLOW models. The model coverage is generally limited to the River Calder, the Rochdale Canal and the Calder and Hebble Navigation Canal. The majority of the tributaries to the Calder are not included in these models. The model coverage is shown on Figure 2

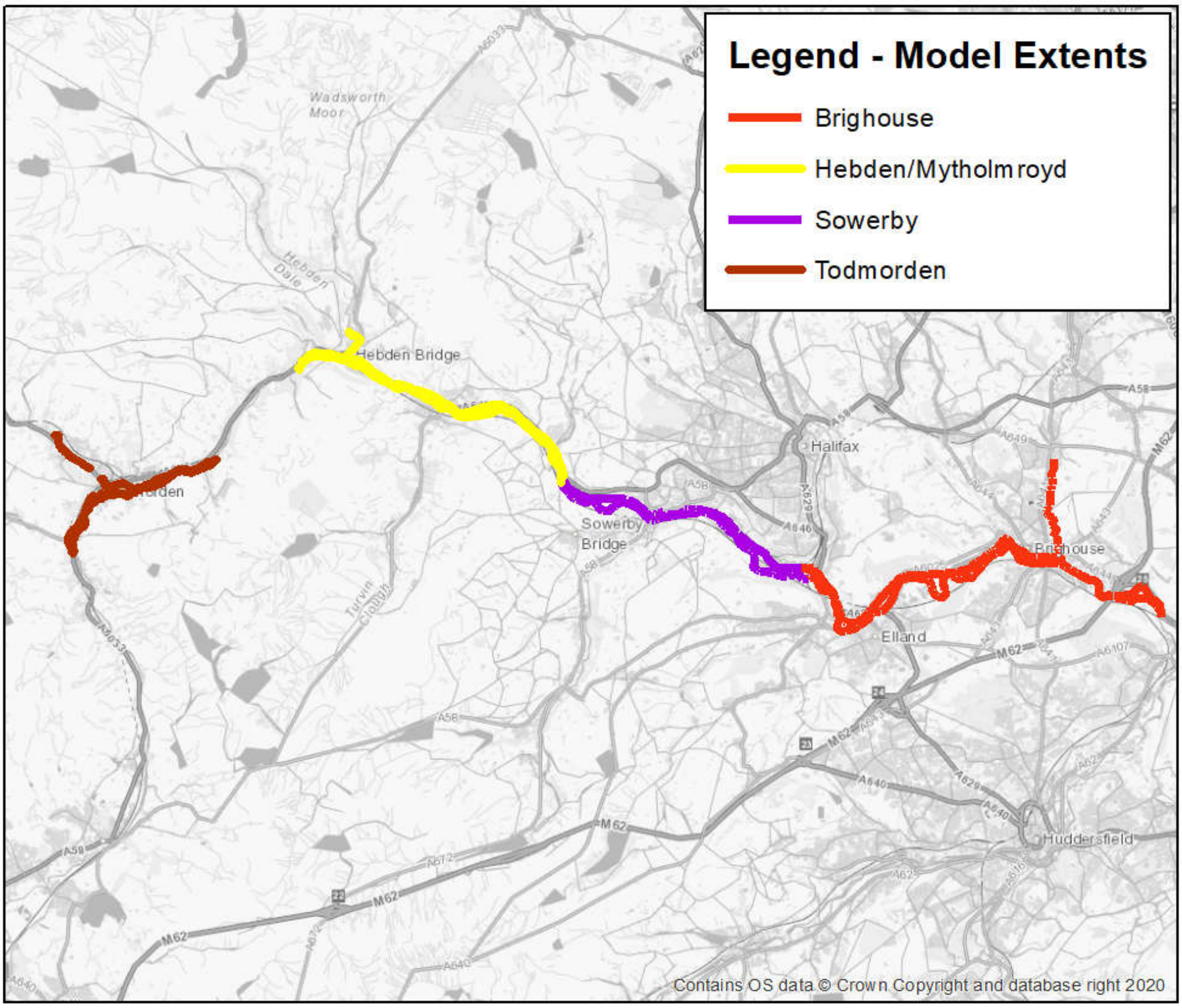


Figure 2 – Hydraulic Model Extents

A summary of each of the hydraulic models used for this study is provided below. Where several models were provided for the same reach, justification of the model selected for the assessment has been provided.

The models provided by the EA form the baseline condition against which the 'With NFM' model results are compared. The models are defended models and include existing flood alleviation schemes where available.

Buildings within the models have been represented using blockage polygons with a blockage ratio of 90% (i.e. 2D cells within the building boundaries are blocked by 90%). Roughness polygons have also been used with a Manning's n roughness value of 0.05.

K.3.1. Todmorden

The Todmorden model used for this study is the Flood Model Investigation Study Model. The model includes the River Calder from Lydgate to Springside and Walsden Water from Gauxholme to its confluence with the River Calder. Also included in this model is the Rochdale Canal from Gauxholme to Springside. The model covers a combined length of approximately 12.5 km over the two waterbodies. The model includes 974 nodes which define the channel topography and hydraulic structures.

K.3.2. Hebden Bridge

The Hebden Bridge model used for this study is the Hebden Bridge Flood Alleviation Scheme Model 2020 and covers the River Calder and Rochdale Canal from Calderside down to Luddenden Foot. It also includes a 900m reach of Hebden Beck upstream of where it flows into the Calder. The model includes 656 nodes which defines the channel topography and hydraulic structures. In total a combined reach of 16.5 km in length has been modelled.

For the purposes of this assessment, only model results upstream of Machpelah have been used in the assessment of flood risk for this NFM study. The reason for this is that the Hebden Bridge model overlaps with the Mytholmroyd model in the lower limits and as such, the results from the Mytholmroyd have been used downstream of Machpelah.

K.3.3. Mytholmroyd

The Mytholmroyd model consists of the same extent and general model schematisation as the Hebden Bridge model but includes representation of the Mytholmroyd Flood Alleviation Scheme. For the purposes of this assessment, model results from the Mytholmroyd model downstream of Machpelah have been used in the assessment, rather than those from the Hebden Bridge model. The model is based on a previously modelled “preferred scheme” option for Mytholmroyd and is the best model available to represent future flooding in Mytholmroyd.

K.3.4. Sowerby Bridge

The Sowerby Bridge model used for this study covers the River Calder, Rochdale Canal and the Calder and Hebble Navigation Canal from just downstream of Luddenden Foot to Salterhebble. The model contains 369 nodes which define the channel topography and hydraulic structures. A combined length of 13.5 km of watercourse is modelled.

K.3.5. Brighouse

The model used in the assessment is the Brighouse Flood Alleviation model May 2021. This model includes flood alleviation scheme as designed at the outline business case stage. The Brighouse model includes the river Calder, Calder and Hebble Navigation Canal and Clifton Beck. The Calder reach of the model extends from Salterhebble to just downstream of where it passes beneath the M62 downstream of Brighouse. The Clifton Beck part of the model extends from upstream of Bailiff Bridge to its confluence with the Calder. The model contains 957 model nodes which define the channel topography and hydraulic structures. The model includes representation of the proposed refurbishment of defences along the Calder and a Flood Storage Area along Clifton Beck. This model is the most suitable model available to represent future flooding along the modelled reach.

K.4. NFM Studio Outputs

NFM Studio is a strategic tool that quantifies NFM effectiveness relative to runoff reductions at the field scale, as well as identifying priority opportunity areas within a catchment. For the purposes of this assessment the upper Calder Catchment has been considered as a whole with a single set of catchment descriptors used to generate flow hydrographs for a suite of return periods. NFM Studio then generates the same set of hydrographs but with the implementation of NFM measures. Table 1 shows the reduction in peak flows for the selected current day return periods from NFM Studio.

Table 1 – Reduction in Peak Flow (Output from NFM Studio)

Event	Averaged Reduction in Peak Flow Due to NFM
1 in 2 year (50% AEP)	22.35%
1 in 10 year (10% AEP)	13.79%
1 in 20 year (5% AEP)	12.04%
1 in 50 year (2% AEP)	10.57%
1 in 100 year (1% AEP)	9.69%

K.5. Application of NFM to Hydraulic Models

To assess the impact of NFM measures and the resultant reduction in peak flows, a simplified approach has been used. The reduction in peak flow calculated in NFM Studio has been calculated as a percentage for each return period. All the inflows within the hydraulic models have then been scaled by the same percentage to create a 'with NFM' model scenario with reduced inflows.

The simplified approach has been used due to many factors. NFM Studio considers the Calder as a single catchment with a single set of physical parameters that define the catchment. In reality (and within the hydraulic models) there are many sub-catchments, each of which have their own set of physical characteristics. Given the broadscale nature of the project and the NFM Studio outputs, it was decided that it was not proportional to define individual scaling factors for each sub-catchment per return period based on its size and location relative to the NFM measures defined within NFM Studio, and that doing so would imply a level of detail which did not fit with the high level approach used with NFM Studio. If a more detailed approach were to be adopted, 575 unique individual scaling factors would need to be calculated and entered manually. Figure 3 shows the location of all the inflows across the Calder model reaches.

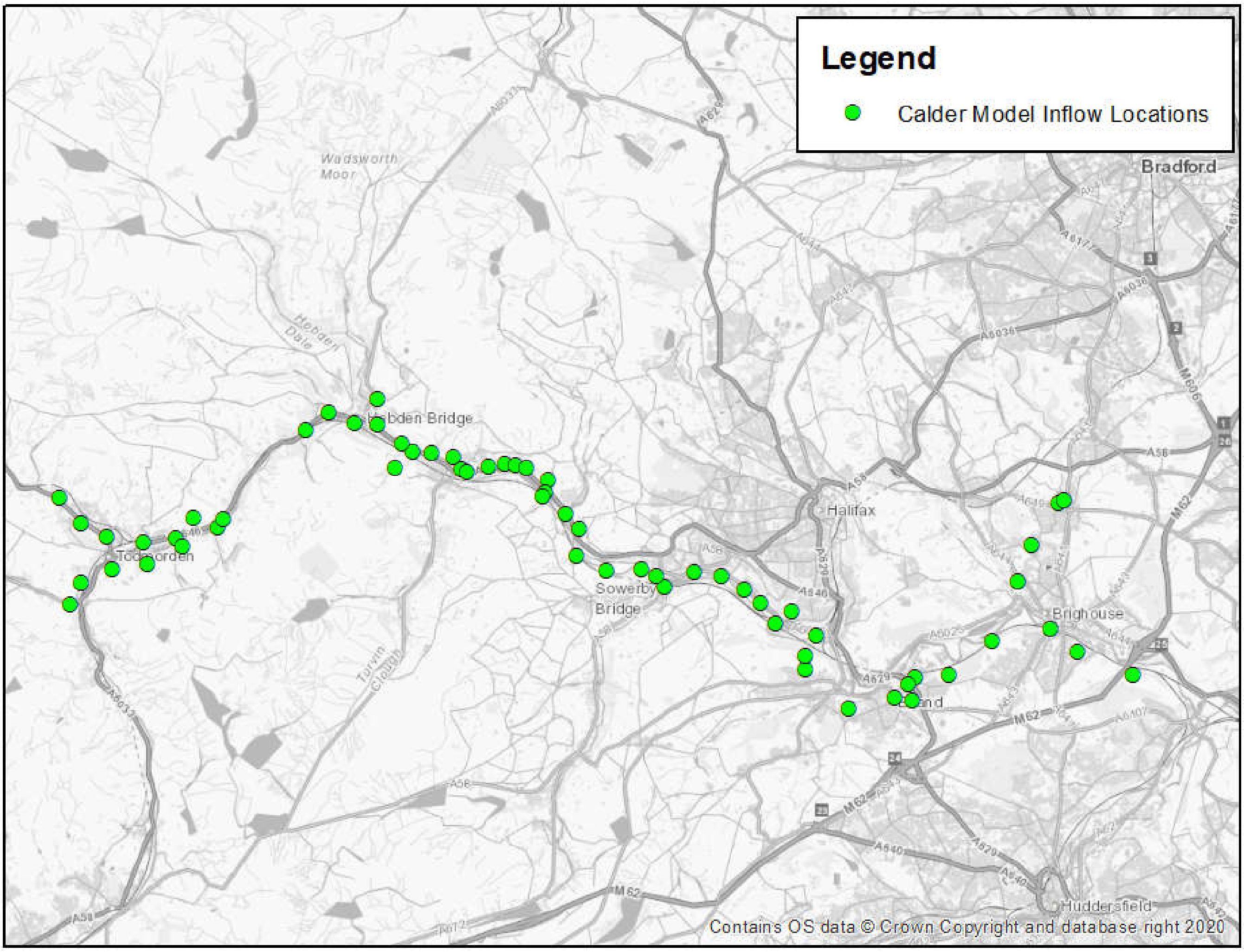


Figure 3 – Calder Model Inflows

In addition to the complexities of applying individual scaling factors, the models would also have to have been run sequentially, for example the Todmorden models would need to be run first, with the outflows from these models then applied as an inflow to the next model downstream. This approach would not have been feasible as a standard set of return periods had not been provided for all of the models. This would have meant that the economic damage calculations would be limited to a few return periods as hydrology was not provided for all return periods. It would also mean having to re-baseline the hydraulic models as this approach (running the models sequentially to inform inflow of the model downstream) had not been adopted for the baseline Calder models provided. The simplified approach adopted means that the models could be run in parallel and be run independently of each other such that any error identified could be fixed without impacting all of the other model runs. It allows for a catchment wide assessment of changes in flood risk to be assessed at a catchment wide level, and allows through economic assessment, areas which would benefit most from reductions in flood depth and extent as a result of the reduction in flow to be identified.

The hydraulic models and economic analysis consider additional return periods than those considered by NFM Studio. Interpolation has been used to calculate the percentage reduction in peak flow for these return periods. This is shown in Table 2. Figure 4 shows the relationship between reduction in peak flow and return period.

Table 2 – Reduction in Peak Flow (All Return Periods)

Event	Reduction in Peak Flow Due to NFM	Notes
1 in 2 year (50% AEP)	22.4%	NFM Studio
1 in 5 year (20% AEP)	19.1%	Interpolated
1 in 10 year (10% AEP)	13.8%	NFM Studio
1 in 25 year (4% AEP)	11.8%	Interpolated
1 in 30 year (3.33% AEP)	11.6%	Interpolated
1 in 50 year (2% AEP)	10.6%	NFM Studio
1 in 75 year (1.33% AEP)	10.1%	Interpolated
1 in 100 year (1% AEP)	9.7%	NFM Studio
1 in 200 year (0.5% AEP)	7.9%	Interpolated

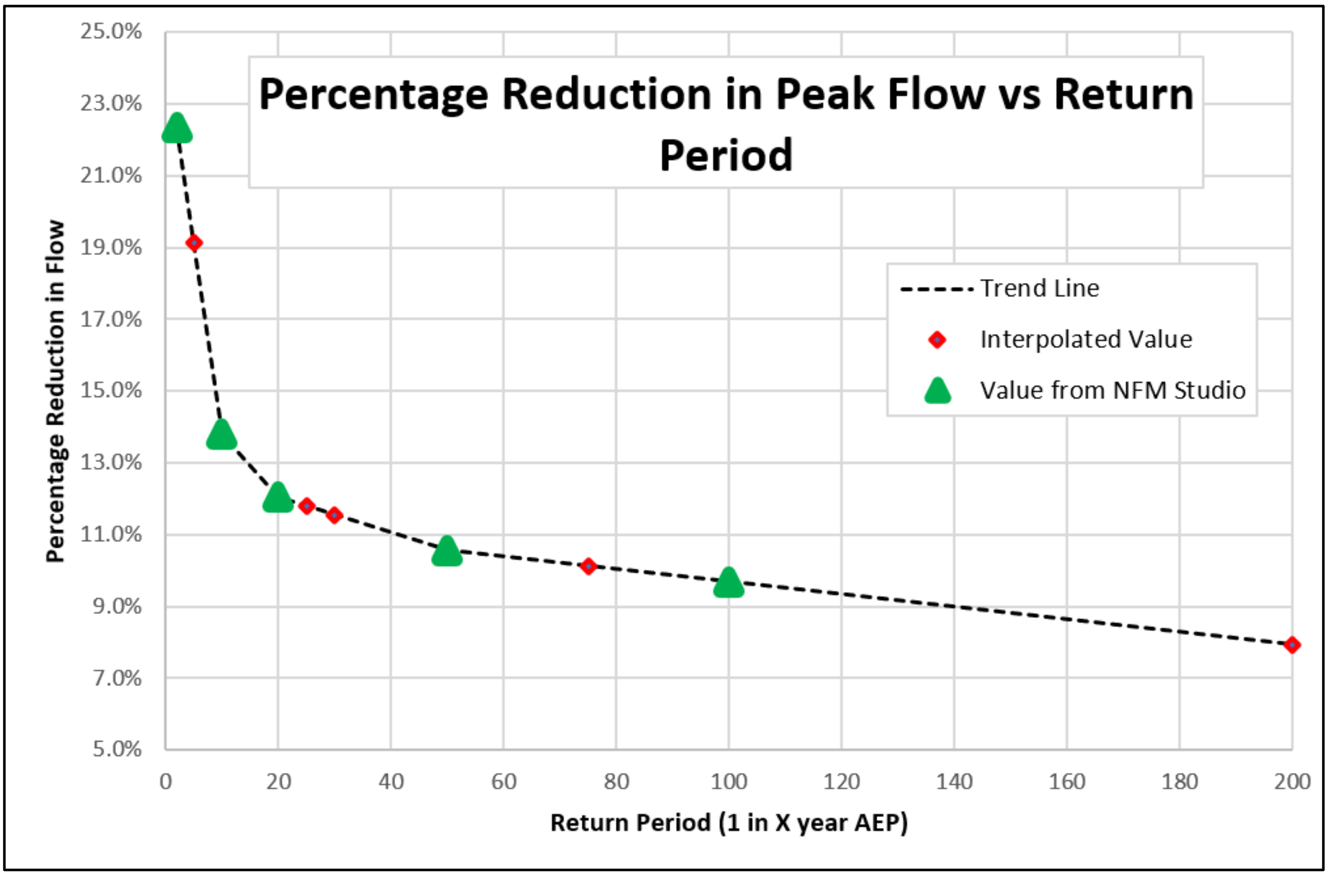


Figure 4 – Calculated Reductions in Peak Flow

Each model has a series of hydrological inflows which represent inflow into the River Calder and the canal system from tributaries and contributing lateral flows from the catchment. To represent the reduced inflow as a result of the implementation of NFM measures, these inflows were automatically scaled by the factors shown in Table 2 for each return period. In total there are 87 model inflows across the five models and a total of 34 NFM model runs have been undertaken. The total number of inflows that have been automatically scaled for the NFM model runs is 575. The model inflow locations are shown on Figure 3.

An example of the scaling of the inflows can be seen in Figure 5, which shows the Baseline Q100 main Calder flow for the Brighouse model and the reduced inflow for the NFM scenario (a reduction in peak flow of 9.7%).

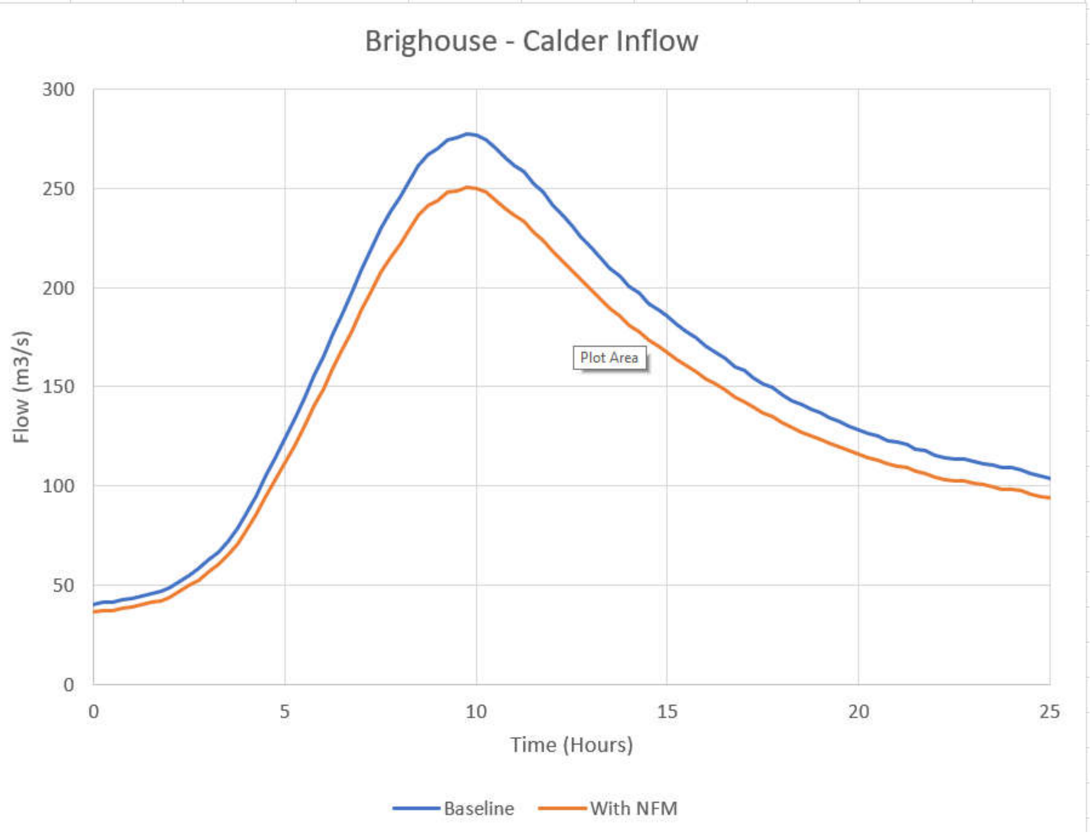


Figure 5 – Brighouse Model "Baseline" and 'with NFM' Inflow Hydrographs

Table 3 below details which return periods have been simulated through the hydraulic models.

Table 3 – Modelled Return Periods

	Event									
Model Name	**1 in 2 year (50% AEP)**	**1 in 5 year (20% AEP)**	**1 in 10 year (10% AEP)**	**1 in 25 year (4% AEP)**	**1 in 30 year (3.33% AEP)**	**1 in 50 year (2% AEP)**	**1 in 75 year (1.33% AEP)**	**1 in 100 year (1% AEP)**	**1 in 200 year (0.5% AEP)**	**1 in 2 year (50% AEP)**
Todmorden			✓		✓		✓		✓	
Hebden Bridge			✓		✓		✓		✓	
Mytholmroyd							✓	✓	✓	✓
Sowerby Bridge	✓	✓	✓		✓	✓	✓	✓	✓	✓
Brighouse	✓	✓	✓	✓			✓	✓	✓	✓

K.6. Results

K.6.1. Depth Grids

The reduction in peak inflow due to NFM measures results in a reduction in flood depth and flood extent across the catchment and at all return periods. Figure 6 to Figure 10 show the general reduction in flood depth across the upper Calder catchment when comparing flood depths for the 1 in 100 year (1% AEP) flood for Baseline and With NFM scenarios. It is to be noted that the results presented are based on present day hydrology only, it is likely that the frequency of the event shown will have increased by the time NFM measures could be implemented across the catchment. The effect of climate change on catchment flows have been assessed in the economic assessment.

In particular the model results at Mytholmroyd show how the reduction in peak flow results in an improved SOP offered by the existing flood defences, effectively increasing the SOP to properties from 1 in 50 year (2% AEP) event to a 1 in 100 year (1% AEP) event at current day flows.

The Economics Assessment provides more detail on individual properties benefiting from NFM interventions across the catchment and the likely effects NFM has on improving the resilience to future flood risk across the upper Calder catchment at a property level scale.

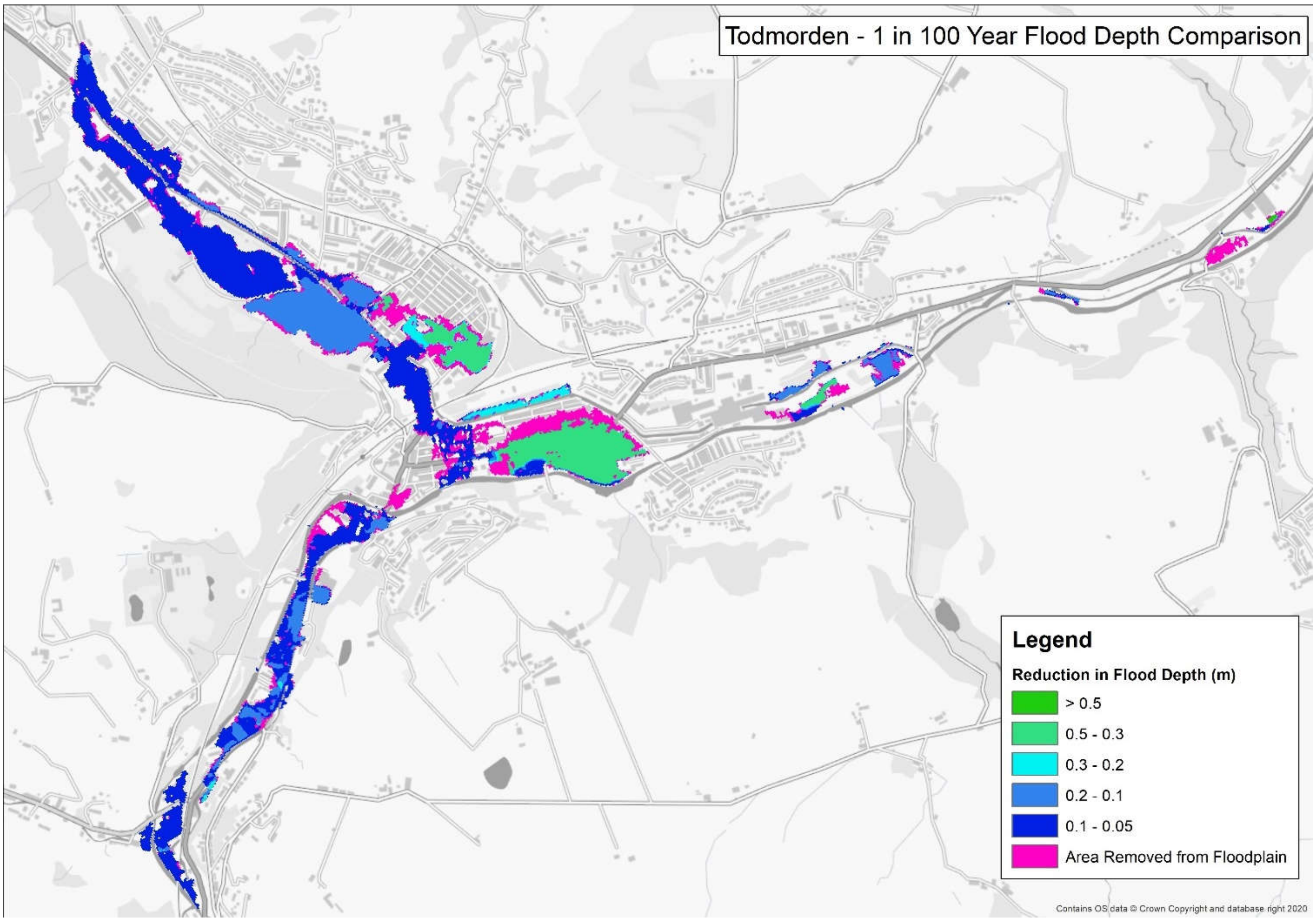


Figure 6 – Todmorden Model Flood Depth Change

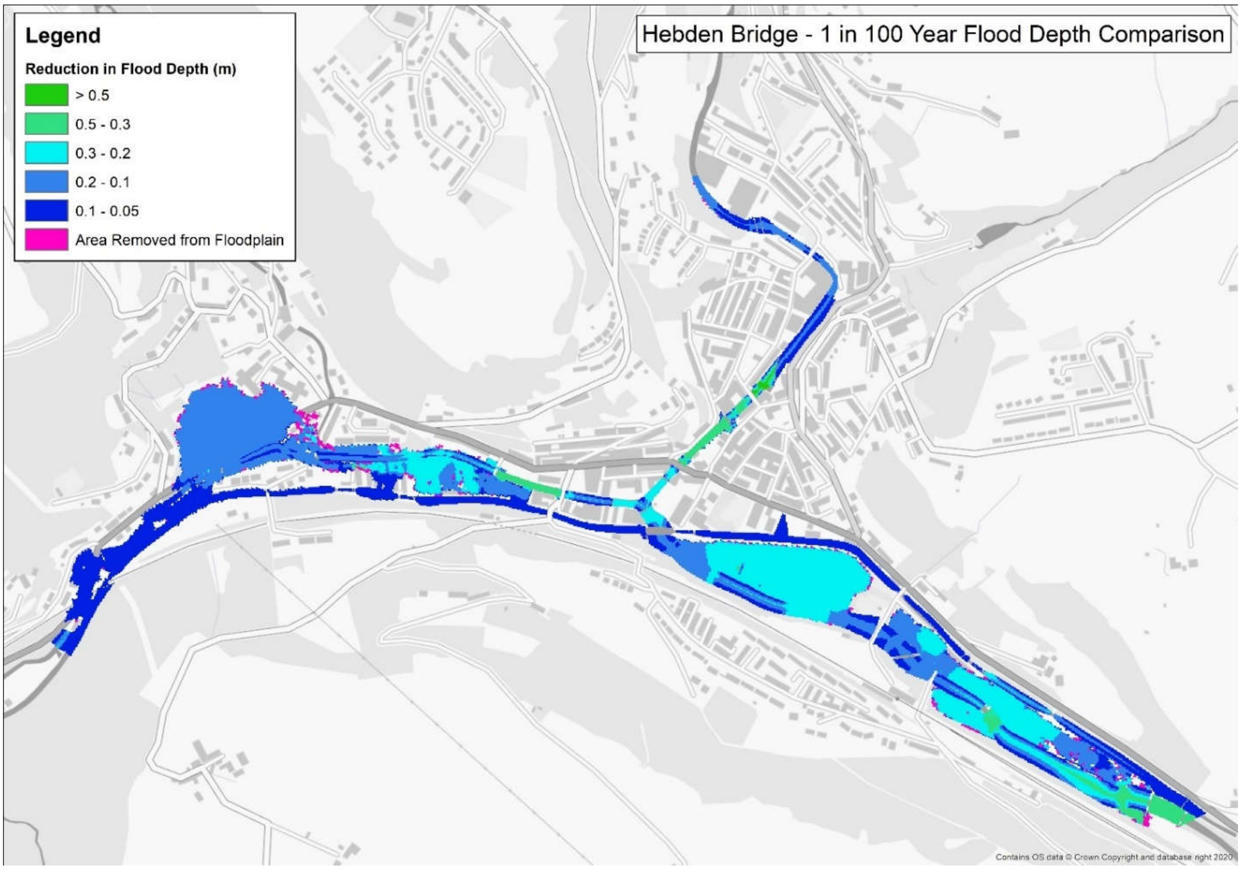


Figure 7 – Hebden Bridge Model Flood Depth Change

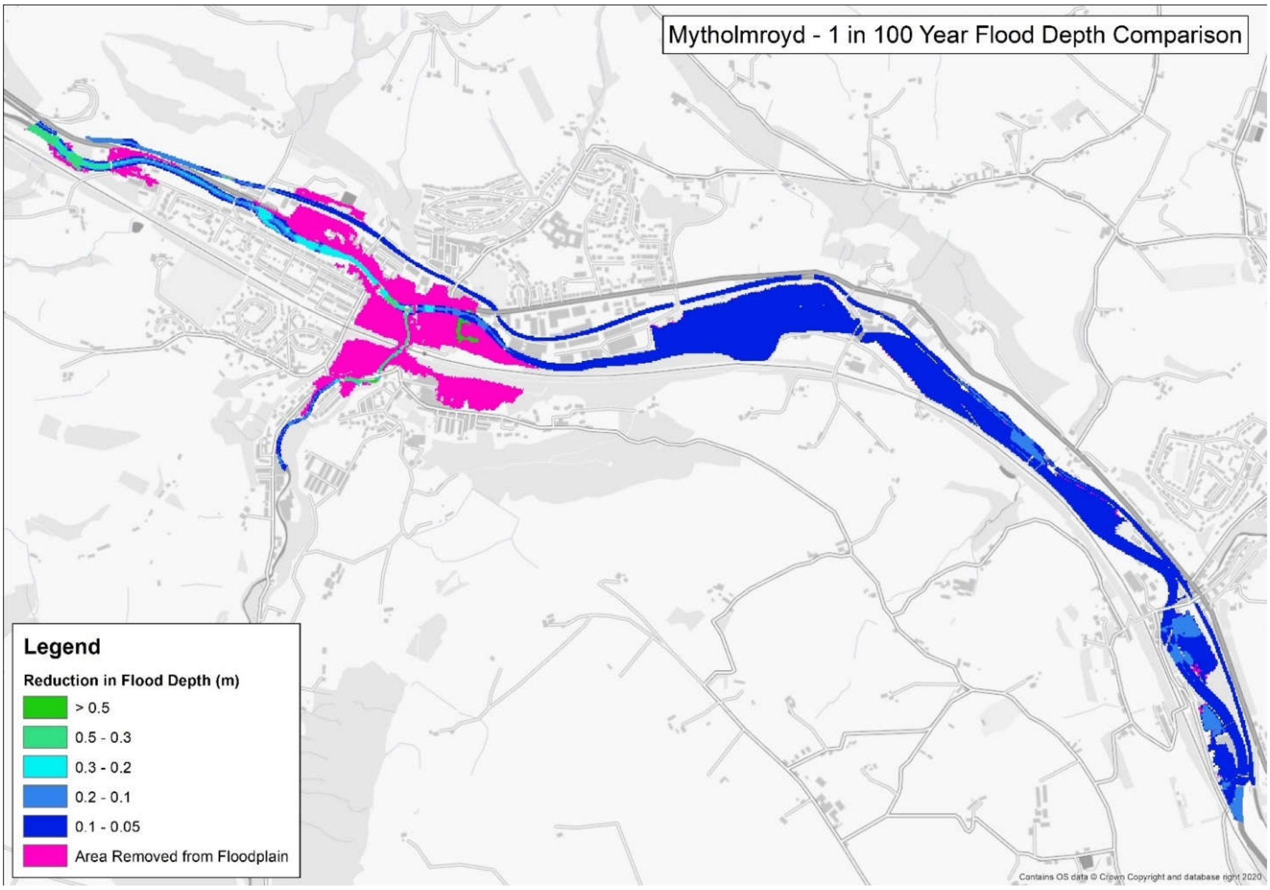


Figure 8 – Mytholmroyd Model Flood Depth Change

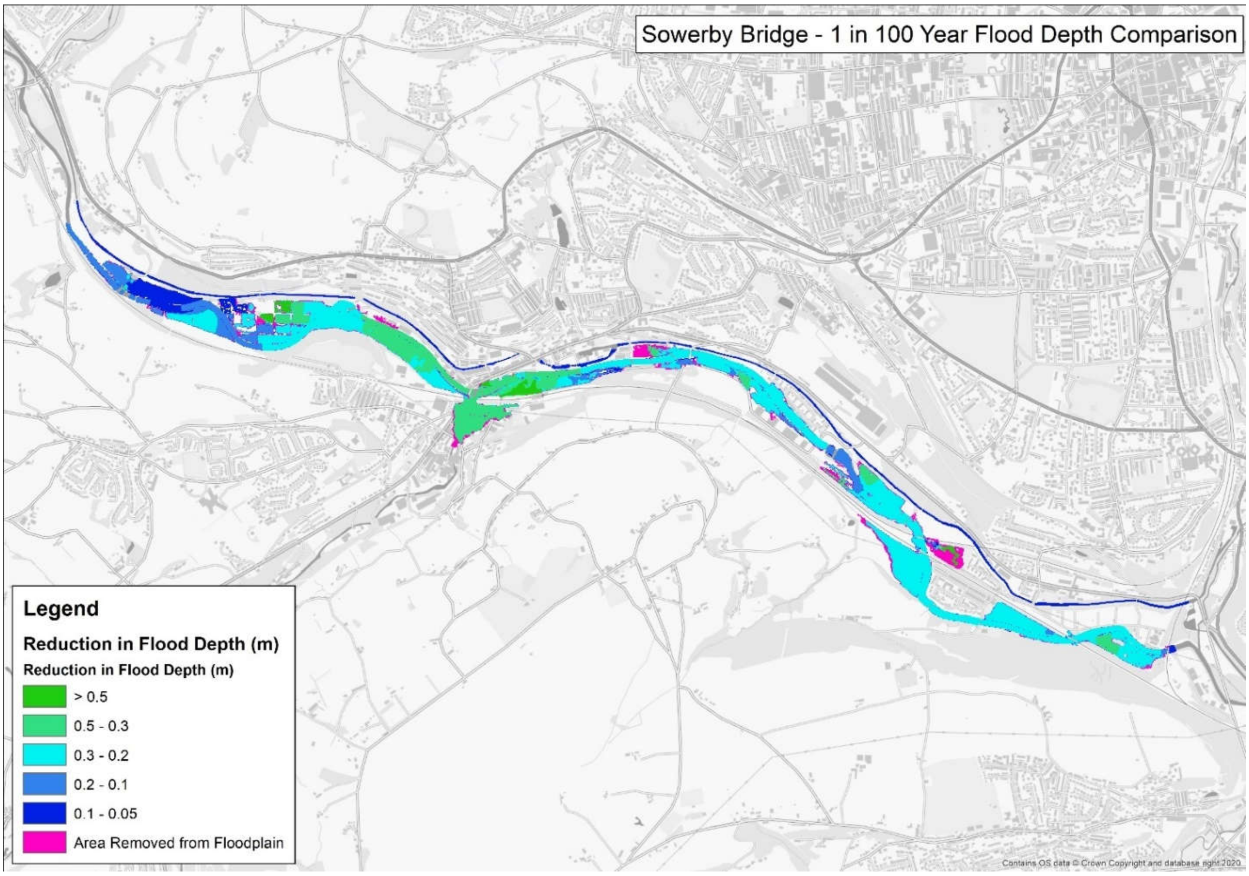


Figure 9 – Sowerby Bridge Model Flood Depth Change

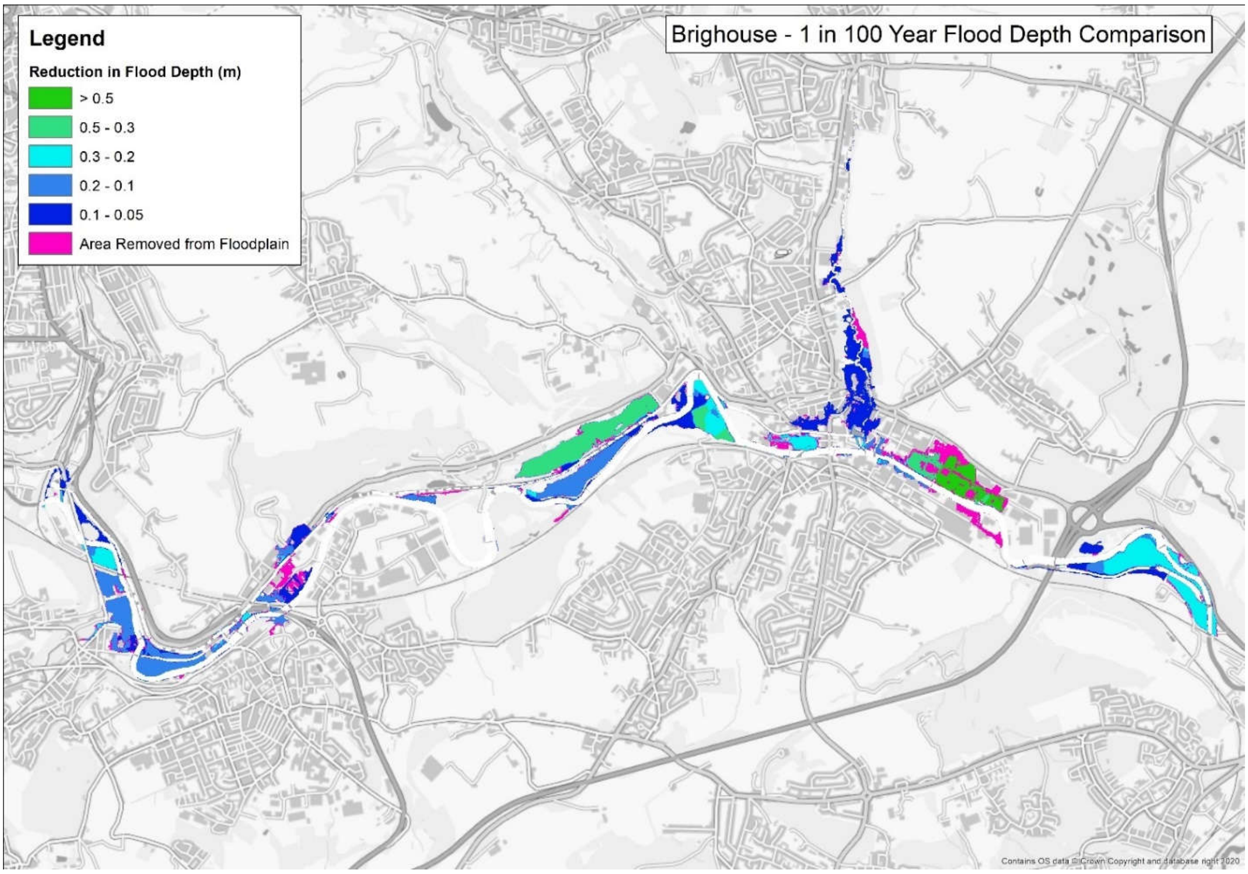


Figure 10 – Brighouse Model Flood Depth Change

The impacts of the change in flood extents and depths with relation to properties at risk are discussed in Appendix L.

K.6.2. Downstream Hydrographs

Table 4 shows the potential effectiveness of the NFM measures in reducing in-channel peak flows, and whether the net decrease in peak inflow translates to the same reduction in river flow at the downstream boundary of the hydraulic models.

Table 4 – Modelled Reduction in Downstream Peak Flow

	Percentage Reduction in Peak Flow		
	Calculated in NFM Studio	Observed at Model Downstream Boundary	Difference
Todmorden	9.7%	5%	4.9%
Hebden Bridge		10%	-0.6%
Mytholmroyd		4%	6.1%
Sowerby Bridge		11%	-1.5%
Brighouse		6%	3.4%

Flow at the downstream boundaries of the models is reduced by between 4% and 11% compared to the 9.7% in model inflow calculated within NFM studio. The difference in peak flow at the downstream boundaries in the hydraulic models from running the NFM models with reduced inflows from NFM Studio differs from the calculated reductions from NFM for a number of reasons. It is likely mainly due to the physical characteristics of the catchment inflows and the differences in catchment response and the hydraulic conditions of the Calder through the models. A reduction in the peak flow of a tributary may not impact the peak flow along the River Calder with the same degree of effectiveness if the peak flow occurs before the peak of the main modelled inflow. It is also the case that the inflow as a total volume is not distributed evenly along the watercourse, so the reduction in peak flow will vary along the watercourse. There are also a significant number of hydraulic structures such as weirs and bridges which may limit the pass forward flow which may mean that a more significant reduction in flow and flood depth is observed upstream of these structures, but this may not be the case downstream.

K.7. Assumptions, Limitations and Recommendations

- The reduction in peak flow has been assumed to be evenly distributed across the catchment for this modelling exercise. There will likely be areas in the catchment which are better suited to the application of NFM, and there will also be reaches of the Calder which are more sensitive to reductions in peak flow (and resultant change in flood frequency) than others.
- The tributaries of the Calder have not been modelled other than Clifton Beck and Hebden Beck. There will likely be many communities along these tributaries which will benefit directly from the NFM measures which have not been considered in this assessment.
- The model results show that the reduction in peak model inflow does not result in the same reduction at the downstream extent of the model. The modelling undertaken does not consider this and assumes that the main Calder inflow at the upstream extent of each model is reduced by the same fixed percentage as all the other model inflows. The models do not consider the effects of the implementation of NFM in the modelled reach immediately upstream.
- The modelling does not include representation of the main tributaries to the River Calder. It is likely that there are structures on these watercourses that act as hydraulic controls which limit the pass forward flow during high flow events into the Calder. It therefore may be the case that a reduction in peak flow due to the implementation of NFM does not have as a significant effect on flow in the River Calder as the modelling shows.

- The models represent fluvial flooding not surface water runoff, therefore the modelling and economic assessment to determining the impact of NFM in the Calder valley may well be an underestimate.
- The modelling only considers the reduction of peak flow. It does not consider the potential change to hydrograph shape.
- The modelling does not include an assessment of critical duration for the upper Calder catchment as a whole.
- It is recommended that any further work undertaken is done on a sub-catchment basis, with all main tributaries modelled and with the outline design of proposed, viability and buildability of NFM measures for that catchment considered. It should include representation of the spatial distribution of the NFM measures with regard to model inflows and should include an assessment of hydrograph timing, and how changes to the inflow hydrographs (whether it be shape or duration) affect flows in areas of known flood risk.

Appendix L. Economics Assessment

L.1. Introduction

Atkins have been commissioned by the Environment Agency to undertake the Calder Natural Flood Management (NFM) study for five areas of interest. The economic appraisal has followed the principles of the Flood and Coastal Erosion Risk Management – Appraisal Guidance (FCERM-AG) (Environment Agency, 2010), as updated by supplementary guidance on the Environment Agency website. Depth damage data has been taken from the Multi-Coloured Manual Handbook (MCM) (Flood Hazard Research Centre, 2021). In accordance with Treasury guidance a 100-year appraisal period has been used and the Treasury variable discount rate has been applied.

This economic appraisal report comprises the Baseline economics element and with NFM element. This high-level assessment of the Baseline and with NFM economic damages of flooding, has been based on Baseline fluvial models which include scheme information, which have then been modified to demonstrate the impact of NFM on flood risk.

L.2. Purpose

The purpose of this report is to outline the methods used in generating a high-level economic assessment of the flood risk damages in Brighouse, Sowerby Bridge, Mytholmroyd, Hebden Bridge & Todmorden which form the areas of interest for an economic appraisal of the benefits of NFM compared to the Baseline scenario. The report will also summarise the results of the economic assessment and provide recommendations for developing this assessment further to enable the Environment Agency (EA) to explore potential Natural Flood Management (NFM) schemes in these areas.

The results presented in this report can be used to understand where the most economic benefits may be present, and therefore aid in informing recommendations for further development and refinement of NFM options. It will also provide an initial, high level understanding of the potential scale of funding that may be required and therefore an indication of the cost limitations of any potential schemes.

L.3. Method

A high-level economic assessment of damages such as this is carried out with the following steps:

- •Development of a property list;
- •Assign depths of flooding to each property from a range of return period flood events;
- •Calculate the direct and indirect damages relating to these properties and their inhabitants as an average annual damage; and
- •Build up a present value damage value for all properties at risk of flooding, over the standard 100-year appraisal period.

This method has been applied to each of the five study areas, for the Baseline scenario, which are shown in Figure 1.

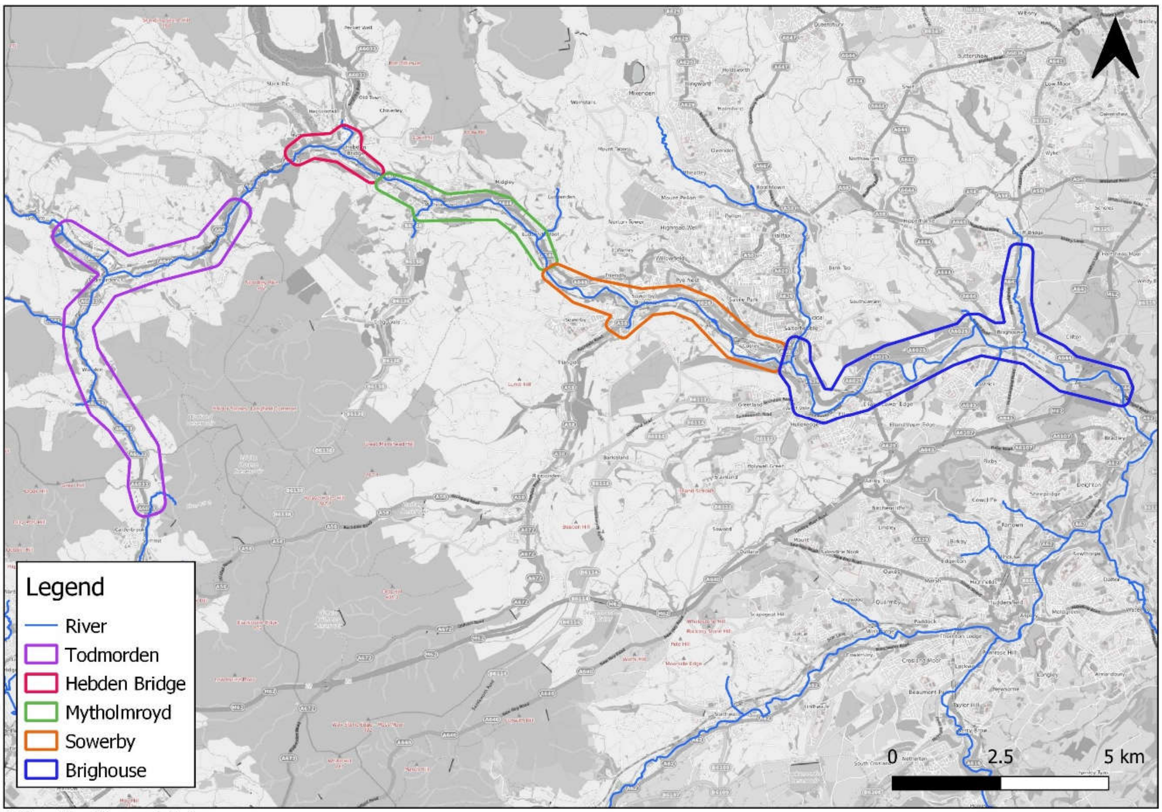


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Figure 1 - Study Areas

L.3.1. Property list development

The following datasets are required to develop a property list appropriate for an economic appraisal of flood damages:

- Ordnance Survey Master Map (OSMM) to provide outlines of buildings, as issued by the client.
- National Receptor Database (NRD) (2014) to provide further details on the buildings such as their use (residential or non-residential), floor area and whether they are ground level or first floor / upper level properties.

There are a number of filters which are applied to the property dataset in order to ensure it is appropriate for use in an economic assessment, namely these are:

- Ensure only ground floor properties are considered, all first floor and upper flats are removed.
- Remove non-residential properties with a floor area of less than 25m^2 as it is assumed that these are not used and therefore, they are removed under advice from the MCM.

Under the National Planning Policy Framework developments built after 2012 are required to demonstrate that they are appropriately flood resilient and resistant. Therefore, any properties built after 2012 are not considered to be at risk of flooding and are excluded from economic appraisals where this is known.

Depth damage data is based on the flood depth above internal floor level. This internal floor level is called the threshold level. Property threshold levels were based on LiDAR ground levels with an increase of 150mm for residential properties and 50mm for non-residential properties. No properties were surveyed for threshold levels at this stage of the appraisal, however information on thresholds and property use from previous appraisals undertaken by the Atkins team, such as from Mytholmroyd and Brighouse, was incorporated.

L.3.2. Assign flood depths

The fluvial model results from each of the model domains along the Calder Valley were used to understand depths of flooding at properties at different return period or annual exceedance probability (AEP) events. All models include Flood Alleviation Schemes (FASs) where available. The below points summarise the modelled scenario for each area which is being used as the Baseline;

- The Brighouse scenario includes the refurbishment of defences along the Calder, a Flood Storage Area (FSA) along Clifton Beck and some NFM measures – this is representative of the situation in the near future once these have been constructed.
- The Sowerby Bridge scenario is a defended scenario, without a scheme.
- Mytholmroyd scenario includes the scheme as built at Mytholmroyd and the Baseline representation of Hebden Bridge (including representation of an earlier version of the scheme). Mytholmroyd model depths have only been used for the Mytholmroyd property list and properties which are impacted by the Mytholmroyd scheme only.
- The Hebden Bridge scenario is based on the option 4a preferred scheme model but does not have the Mytholmroyd FSA included and therefore has only been used for the Hebden Bridge property list.
- The Todmorden model represents the Baseline scenario in this part of the catchment.

Further information on the modelling used as part of this work can be found in Appendix K in the main Calder NFM Study report.

Each property was intersected with the Baseline and NFM model results and attributed the maximum external and internal depths of flooding within the area covered by the building polygon (from the OSMM) for all AEP events modelled. Internal flood depths are based on the threshold assumptions stated above.

L.3.3. Annual Average Damage calculations

The MCM methodology was applied to the property list and flood depths using the May 2021 depth damages to calculate the direct damages to both non-residential and residential properties within the study area for each of the AEP events modelled in the Baseline. The damages for each event were plotted against their annual probability and the area under the curve calculated. This area represents the Average Annual Damages (AAD) for the present day.

The rate of damage increases over the 100-year appraisal period as a result of climate change using the method documented in the current guidance, as described below.

L.3.3.1. Incorporation of climate change

A copy of the changes in peak flows from the climate change guidance is provided in Table 1. The guidance suggests that appraisal of flood risk management options should include allowance for the Central estimates, but with sensitivity testing to determine the impact of using the Upper estimate. For the purposes of this initial appraisal we have just applied the central estimates. At the point where the NFM options have been refined then sensitivity testing may be more appropriate.

Table 1 - Change to peak flows compared to a 1961 – 1990 Baseline

Applies across Calder catchment	Total potential change anticipated for '2020s' (2015 – 2039)	Total potential change anticipated for '2050s' (2040 – 2069)	Total potential change anticipated for '2080s' (2070 – 2115)
Higher estimate	15%	18%	31%
Central estimate	11%	13%	23%

The impact of climate change was not fully included in the hydraulic model simulations undertaken. The future change in flood risk because of climate change was instead incorporated at the economic appraisal stage by amending the probability of an event causing a certain amount of damage. This was done for each of the three climate change epochs but is demonstrated for the long-term '2080s' epoch in Brighouse in Table 2. For consistency and simplicity across the five areas it has been assumed that the Baseline scenario is representative of the situation in 2021.

Table 2 Incorporating climate change by changing event probability – Brighouse peak flows

2021 event annual exceedance probability (AEP)	Present day peak flow (m^3/s)	Assumed 2080 peak flow (m^3/s) (23% increase on present day)	Calculated '2080s' event probability
50% (1 in 2)	142	174	100% (1 in 1)
20% (1 in 5)	183	225	40% (1 in 2.5)
10% (1 in 10)	210	258	24% (1 in 4.1)
5% (1 in 20)	233	287	16% (1 in 6.3)
2% (1 in 50)	264	325	8.3% (1 in 12)
1.3% (1 in 75)	274	337	6.4% (1 in 16)
1% (1 in 100)	289	355	4.7% (1 in 21)
0.5% (1 in 200)	322	396	2.1% (1 in 48)

Using the model results, the AAD for property, evacuation costs, emergency services, vehicle damages and mental health damages were calculated for the present day. The same event damages were then applied to the increased event probabilities to calculate the AADs for the three future epochs: '2020s' (11%), '2050s' (13%) and '2080s' (23%).

As per the EA's guidance, using the Central allowances, present day AADs (2021, with no modelled climate change) were linearly interpolated to the 11% AADs in year 2030, which then stayed constant until year 2040, when there was a step up to the next climate change epoch (13% AADs). These then stayed constant until year 2070 until the end of the appraisal when there was a final step up to the 23% AADs.

L.3.3.2. Capping

For the purpose of the economic assessment, the Present Value damages (PVd) of a property cannot exceed the current market value.

Residential properties

Residential properties were capped at the current market value, by property type, as detailed in Table 3. The market value prices are based on average house prices, taken from data on property sales prices across West Yorkshire, over a three-month period to Feb 2021[17], which is in line with MCM guidance.

Table 3 - Typical residential property prices within the study area

Study Area	Property Type	Average Property Price (£k)
West Yorkshire	Detached	368
	Semi-Detached	203
	Terraced	139
	Flat	122

Non-residential properties

For non-residential properties, the market value or capping value was derived from the rateable value multiplied by a factor that reflects the rental yield from that property. Rateable values (per m^2) were taken from MCM Table 5.4 May 2021. This was converted into a £/m^2 for a range of business types using yield multipliers taken from MCM Table 3.4 May 2021. Floor areas were extracted from the NRD and checked against the geometric area of the OSMM polygons representing buildings, to provide a total expected rateable value per non-residential property. No verification was undertaken at this stage of the appraisal.

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[17] House price data obtained from www.home.co.uk. Accessed 3rd August 2021.

L.3.3.3. Evacuation costs

The appraisal included costs associated with evacuation, including renting of temporary or alternative accommodation, food, transport costs and loss of earnings. The cost of evacuation depends on many variables, one of the most important being evacuation duration. Evacuation of flooded properties can range from a short-term requirement (to limit loss of life, injury and stress) to a much longer-term measure (to allow flood damage to be repaired). The MCM makes a direct link between the internal property flood depth and the evacuation rate and time. In this appraisal therefore, and in accordance with the MCM methodology, evacuation costs for individual properties have been estimated as a function of the flood depth and property type using the 2021 published Multi-Coloured Handbook (MCH) data. Evacuation costs have only been included for residential properties experiencing above floor level flooding. Additionally, evacuation costs are only included for residential properties where the losses are still below the capping threshold.

L.3.3.4. Emergency services

Flood incidents need to be managed when they occur. These emergency costs come from active services from the police, fire and ambulance services, local authority emergency response team, and the Environment Agency’s flood incident teams. The MCM guidance estimates that the emergency costs are 5.6% of the total direct property damages. This is the percentage applied in this appraisal and it is suitable for urban areas.

L.3.3.5. Vehicle damages

Vehicle damages were assessed by using the MCM methodology, which assumes that:

- The average value of a UK motor vehicle is £5,600;
- The average number of vehicles per (residential) household is 1.21; and
- Vehicles are most likely to be damaged (and written off) when flood depths exceed 0.39m.

Vehicle damages were therefore calculated by: £5,600 x 1.21 x number of residential properties where external flood depth > 0.39m.

L.3.3.6. Mental Health damages

Mental health flood risk damages are estimated by determining the number of adults in each residential property, multiplying this by the mental health costs per adult for each flood event.

Mental health impacts per property per flood

= number of adults per property (Table 4) x loss per adult per flood (Table 5)

Table 4 - National average number of adults per property in England (Environment Agency, 2020)

Property type	Number of adults per property
Average (all categories)	1.85
Detached	2.01
Semi-detached	2.00
Terraced	1.95
Flat	1.45

Table 5 - Mental health impacts of flooding, per adult, per flood event (assumes 2 years of impact for each flood), updated to 2021 price date using the GDP deflator. (Environment Agency, 2020)

Flood depth band above internal floor level	Mental health losses per adult per flood event
> 0 cm < 30 cm	£2,022
30 – 100 cm	£3,260
> 100 cm	£4,453

L.3.3.7. Human intangibles

The benefits of the human intangible effects on health and stress have not been incorporated into this appraisal. This is based on the change in Standard of Protection offered by each option to each individual residential property according to modelling results in accordance with Defra Supplementary Guidance. These benefits are measured directly as a benefit of an option as compared to the Do Nothing scenario which has not been modelled for the purpose of this assessment.

L.3.4. PV Damages

Under 2018 Treasury guidance, a variable discount rate (starting at 3.5%) was then applied to a majority of the AADs to generate the Present Value Damages for each option over an appraisal period of 100 years. The revised Green Book published in 2018 introduced a new lower discount rate (starting at 1.5%) applicable for 'risk to health and life'. This lower discount rate has been applied in this appraisal to emergency services, and mental health damages in line with the updated appraisal guidance.

The whole life direct damages and benefits at properties are thematically mapped in a separate document (contains sensitive information) alongside maps which show how the probability of internal flooding changes between the Baseline and NFM.

L.3.5. Limitations and assumptions

The following limitations and assumptions are pertinent to understand and to provide context to the results;

- The flood risk information available is equivalent to the economic scenario 'Baseline' as modelling has been undertaken which represents the Calder Valley and flood schemes as they have presently been modelled, and so a 'Do Nothing' scenario has not been developed for this work, however this would be required for a business case.
- The generation of AAD curves is most accurate when a wide range of events are included, particularly those more frequent events. The number of events available for each area varied from four to ten events. This limits the accuracy of the annual average damages applied to the properties, particularly in Mytholmroyd and Todmorden which have a limited range of events that have been modelled. Based on the flood risk information for the highest annual probability event for each area, we have assumed that no properties flood in events up to the zero damage event. These are outlined for each area in Table 6 below. The impact of this limitation is that where properties are at risk of flooding in events more frequent than these then the damages calculated as part of this work are an underestimate. For Mytholmroyd there is a scheme in place with a Standard of Protection provided and so this is less of a limitation here however for Todmorden it may be a significant underestimate depending on how many properties are at risk of flooding from events more frequent than a 1 in 10 (10% AEP).

Table 6 - Zero damage event annual exceedance probabilities (AEP)

Area	Zero damage event annual probability (2021)
Brighouse	100% (1 in 1)
Sowerby Bridge	100% (1 in 1)
Mytholmroyd	3.3% (1 in 30)
Hebden Bridge	100% (1 in 1)
Todmorden	20% (1 in 5)

- The five different areas each have different model scenarios, which are being used as the Baseline scenario for the purpose of the economics and comparing the impact of NFM to, these scenarios are outlined in section L.3.2. The scenarios used as the ‘Baseline Scenario’ for each of the areas in the model is based on information provided by the EA. It is assumed that these scenarios are representative of present day or the very near future and further details are provided below.
- The NFM scenarios has been assumed to be applied from year 0 in the appraisal, i.e. all NFM options are implemented now in the present day, not in the future or phased over a number of years. Whilst in reality this would not occur, it was applied as an assumption in lieu of further information being available on phasing of delivery.
- This phase of the project is about understanding the potential available benefits in order to decide whether the development of a business case for NFM options in the Calder Valley is feasible/required in order to seek funding or whether there could be other ways of taking these NFM options forward. As part of later stages of business case, if this phase is successful, Outcome Measure 2 (OM2) (residential properties which move from one risk band to another due to the option) will need to be calculated. It is known that many of the OM2s in the Calder valley have been ‘claimed’ already by the numerous flood schemes present. Work will be required to try to understand whether any OM2s remain for the NFM options which will depend on their performance in the modelling also. In addition there are a total of 1324 OM2s due to be claimed by other EA schemes which are proposed between 2022 and 2028 onwards (data provided by Julia James of the EA on 20/12/2021). The availability of remaining OM2s may limit or constrain the potential Grant in Aid funding available for NFM options if these are carried forward. That said, it is important to note that there are many other funding streams from multiple sources that have been both secured and could be sought for further NFM implementation, for example, DEFRA and Yorkshire Water, with delivery over the last five years securing more than £5m from funding streams other than Grant in Aid.
- Similarly, there have been a number of other business cases developed throughout the Calder valley and it is not known which properties were capped in these other business cases. Once a property becomes capped, an economic appraisal can't include any further damage from that property. It may be the case that the PV damages calculated as part of this study are an overestimate of what is available in the catchment due to capping.
- It is important to state that this study is only considering additional benefits, provided by the proposed NFM, on top of the Baseline scenario as many of the areas include a FAS within the model setup.
- There is ongoing work with Yorkshire Water and the EA to consider drawdown of reservoirs in the upper Calder valley, which will have impacts as far as Brighouse. The economics as part of the reservoir work are based on the benefits provided in each town (Hebden Bridge, Mytholmroyd, Sowerby Bridge and Brighouse) above the benefits which would be provided by the FASs in each of these towns already. The benefits calculated by this study for potential NFM is also based on those benefits above what is already provided by the existing FASs (as described above in the reporting). Therefore there may be double counting between the reservoirs project and this study and this is worth being aware of when considering next steps of both projects.
- Due to the method of modelling and the software, there is an inherent limitation. This is due to the fact that the modelling is fluvial only. Part of the flood mechanism in the Calder valley, due to the steep slopes, is surface water runoff. No economic damages or benefits of the proposed NFM from this flood risk mechanism have been taken account of in this study due to the limitations of the models provided. Therefore the damages and benefits may be an underestimate in comparison to reality.

L.4. Results

L.4.1. Property Counts

Tables 7,8 and 9 presents the property counts for properties flooding both above ground level (external) and above internal floor level for each of the study areas under a selection of the range of AEP events that were simulated as part of the modelling. The models ran different AEP events and so the ones most common to all model areas have been presented below. A property is counted as being at risk of internal flooding if the modelled flood depth at any point directly adjacent to or within the building footprint is greater than 0.15m for residential properties or 0.05m for non-residential properties unless property-specific threshold information was available. A property is counted as being at risk of external flooding if the modelled flood depth at any point directly adjacent to or within the building footprint is greater than 0m.

The counts are cumulative i.e. the **9** residential properties in Brighouse at risk of external flooding in the 50% (1 in 2) AEP event are included in the **16** residential properties at risk of external flooding in the 20% (1 in 5) AEP event.

Table 7 - Property Counts by Study Area - Baseline

Study Area	Flooding Type	50% (1 in 2)		20% (1 in 5)		10% (1 in 10)		2% (1 in 50)		1.3% (1 in 75)		1% (1 in 100)		0.5% (1 in 200)	
		Res	Non-Res	Res	Non-Res	Res	Non-Res	Res	Non-Res	Res	Non-Res	Res	Non-Res	Res	Non-Res
Todmorden	**External**					63	34	475	146			805	207		
	Internal					38	25	308	131			637	192		
Hebden Bridge	**External**	31	20	41	21	42	22	63	25	77	25	82	25	175	225
	Internal	12	12	17	13	18	14	37	17	46	17	58	17	135	207
Mytholmroyd	**External**							4	5	184	70	236	89	384	123
	Internal							2	4	143	61	204	82	352	117
Sowerby Bridge	**External**	0	28	3	52	13	63	56	108	56	115	56	127	59	141
	Internal	0	28	0	49	4	61	55	107	55	113	55	126	58	140
Brighouse	**External**	9	22	16	46	18	72	49	218	65	280	93	317	122	379
	Internal	7	15	8	39	9	62	30	214	45	266	74	310	110	359

Table 8 - Property Counts by Study Area - NFM

Study Area	Flooding Type	50% (1 in 2)		20% (1 in 5)		10% (1 in 10)		2% (1 in 50)		1.3% (1 in 75)		1% (1 in 100)		0.5% (1 in 200)	
		Res	Non-Res	Res	Non-Res	Res	Non-Res	Res	Non-Res	Res	Non-Res	Res	Non-Res	Res	Non-Res
Todmorden	**External**					57	31	232	80			536	161		
	Internal					25	21	113	67			362	145		
Hebden Bridge	**External**	30	20	34	21	41	21	57	24	63	25	75	25	131	190
	Internal	10	12	16	13	17	13	27	15	35	17	43	17	103	168
Mytholmroyd	**External**							3	3	4	4	5	8	296	110
	Internal							1	2	2	2	4	4	253	103
Sowerby Bridge	**External**	0	20	0	29	0	40	54	89	56	105	56	106	56	127
	Internal	0	20	0	28	0	40	46	89	55	105	55	106	55	126
Brighouse	**External**	8	1	10	38	16	49	34	153	41	188	60	253	93	339
	Internal	6	0	7	29	8	42	14	141	24	176	34	236	81	322

The numbers in Table 9 represent the subtraction of NFM property counts from the Baseline counts i.e. 9 residential properties in Brighouse are at risk of external flooding in the Baseline scenario 50% (1 in 2) AEP event, 8 residential properties in Brighouse are at risk of external flooding in the same NFM scenario event and there is a difference of 1 property shown below.

Table 9 - Property Counts by Study Area – Difference (Baseline minus NFM)

Study Area	Flooding Type	50% (1 in 2)		20% (1 in 5)		10% (1 in 10)		2% (1 in 50)		1.3% (1 in 75)		1% (1 in 100)		0.5% (1 in 200)	
		Res	Non-Res	Res	Non-Res	Res	Non-Res	Res	Non-Res	Res	Non-Res	Res	Non-Res	Res	Non-Res
Todmorden	**External**					6	3	243	66			269	46		
	Internal					13	4	195	64			275	47		
Hebden Bridge	**External**	1	0	7	0	1	1	6	1	14	0	7	0	44	35
	Internal	2	0	1	0	1	1	10	2	11	0	15	0	32	39
Mytholmroyd	**External**							1	2	180	66	231	81	88	13
	Internal							1	2	141	59	200	78	99	14
Sowerby Bridge	**External**	0	8	3	23	13	23	2	19	0	10	0	21	3	14
	Internal	0	8	0	21	4	21	9	18	0	8	0	20	3	14
Brighouse	**External**	1	21	6	8	2	23	15	65	24	92	33	64	29	40
	Internal	1	15	1	10	1	20	16	73	21	90	40	74	29	37

Across the catchments, different levels of flood risk and exposure of residential versus non-residential properties can be seen from the property count tables above. Brighouse, Todmorden and Sowerby Bridge have more non-residential properties at risk, when compared to the other catchments. Todmorden has the highest number of total properties at risk in the Baseline, with a total of 1012 properties (805 res and 207 non-res) at risk of external flooding in the 1% AEP event, with most of these being residential properties. Brighouse has the second highest total at 410 properties (93 res and 317 non-res) in the Baseline at risk of external flooding in the 1% AEP event, with most of these being non-residential properties. Mytholmroyd has the second highest total of residential properties (236) in the Baseline at risk of external flooding in the 1% AEP event, with 89 non-residential properties at risk.

One of the greatest reductions in properties at risk of external flooding is in Mytholmroyd where 312 (231 res and 81 non-res) or 96% of properties at risk of external flooding in the 1% AEP event in the Baseline are no longer at risk in that event with NFM in place. The other highest reduction in properties at risk of external flooding is in Todmorden where 31% or 315 properties (269 res and 46 non-res) are no longer at risk of flooding in the 1% AEP event with NFM in place when compared to the Baseline.

The only other event where property counts are comparable across all the catchments is the 2% AEP event. In this event Todmorden and Brighouse still have the highest number of properties at risk of flooding externally in the Baseline (621 (475 res and 146 non-res) and 267 (49 res and 218 non-res) respectively). However with NFM in place Todmorden has the highest reduction in properties at risk of flooding externally in the 2% AEP event with a 50% reduction or 309 properties (243 res and 66 non-res) no longer at risk of external flooding in that event. The second highest reduction in number of properties at risk of external flooding in the 2% AEP event is in Brighouse where there is a reduction of 80 properties (15 res and 65 non-res) or 30% compared to the Baseline.

L.4.2. Present Value Damages and Benefits

The economic damages calculated for each of the 5 study areas for the Baseline and NFM options are shown below in Tables 10 and 11 alongside the PV benefits provided by NFM as modelled. The Baseline option across the 5 study areas (in total) has £336m Present Value (PV) damages, with 65% of this coming from non-residential property damages. The NFM option across the 5 areas has £245m PV damages (with 70% still coming from non-residential property damage), meaning that it has £91m PV benefits compared to the Baseline option. Comparing the Baseline with the NFM, there is a 42% reduction in the direct damages associated with residential properties, versus a 21% reduction in the direct damages associated with non-residential properties. This is as a result of the extent of flood risk in the majority of the valley floor not reducing significantly with NFM in place. There are some places along the valley floor where modelled flood extents can be seen to reduce (such as Hebble End Bridge in Hebden Bridge), however in most places the benefit of NFM is in terms of the depth of flooding reduced, and the probability of events which impact property flood risk. Much of the valley floor remains at risk of flooding, and in many locations, this is where the bulk of properties are non-residential and which remain impacted by flood risk, with NFM in place.

One of the greatest reduction in properties at risk of flooding with NFM in place, as described above, is in Mytholmroyd, however in Table 11 below the PV benefits are the second lowest when compared with the other catchments. This is in part due to the SoP offered by the Mytholmroyd FAS which means that in the economics, no benefits are claimed for the more frequent flood events which this FAS provides protection from. It is also in part due to the smaller depth changes experienced between the flood depths of the Baseline versus NFM scenario in the 1 in 100 event when compared to the other catchments.

Table 10 - Present Value Damages (PVd) (£k) by Study Area for the Baseline Scenario

	Present Value Damages (PVd) (£k) - Baseline					
Damage type	**Todmorden**	**Hebden Bridge**	**Mytholmroyd**	**Sowerby Bridge**	**Brighouse**	**Total**
PV residential property damage	£25,651	£6,555	£5,478	£5,458	£4,347	£47,488
PV non-residential property damage	£33,349	£7,683	£13,348	£51,332	£111,131	£216,842
PV evacuation loss	£7,061	£1,499	£1,662	£1,633	£1,111	£12,966
PV emergency services loss	£6,318	£1,408	£1,980	£5,120	£10,215	£25,042
PV vehicle damage	£4,154	£751	£1,232	£1,411	£560	£8,109
PV mental health flood losses	£15,096	£2,910	£2,904	£2,529	£2,237	£25,677
Total PV Damages	**£91,629**	**£20,806**	**£26,604**	**£67,484**	**£129,601**	**£336,124**

Table 11 - Present Value Damages (PVd) and PV Benefits (PVb) (£k) by Study Area for the NFM Scenario

	Present Value Damages (PVd) and PV benefits (PVb) (£k) - NFM					
Damage type	**Todmorden**	**Hebden Bridge**	**Mytholmroyd**	**Sowerby Bridge**	**Brighouse**	**Total**
PV residential property damage	£13,594	£5,362	£2,720	£2,862	£2,839	£27,376
PV non-residential property damage	£26,496	£4,789	£8,544	£39,251	£92,893	£171,973
PV evacuation loss	£3,485	£1,151	£837	£868	£745	£7,086
PV emergency services loss	£4,326	£984	£1,140	£4,248	£9,736	£20,434
PV vehicle damage	£1,751	£474	£691	£626	£276	£3,818
PV mental health flood losses	£7,638	£1,896	£1,470	£1,421	£1,574	£14,000
Total PV Damages	**£57,290**	**£14,656**	**£15,403**	**£49,277**	**£108,062**	**£244,688**
Total PV Benefits	**£34,339**	**£6,150**	**£11,201**	**£18,207**	**£21,539**	**£91,436**

As part of visualising the PV damages and benefits across the catchments, a range of maps have been produced for all areas, which are provided in a standalone report, however, due to sensitive information they contain and in line with General Data Protection Regulation (GDPR) guidelines, these cannot be shared. However, Todmorden and the results these maps show, are discussed below as an example.

By comparing the scale of damages in the two PV damages maps above it is possible to identify which buildings are receiving the greatest reduction in damages as a result of the NFM options in place directly. So for example it can be noted that several terrace properties go from receiving between ~ £55k - £105k of PV damage per property in the Baseline, to less than ~ £19k PV damage per property over the 100 year appraisal with NFM in place. The reduction in damage is also referred to as the benefit of implementing NFM, as modelled. The PV benefits mapping can also be used to inform where NFM could be located to maximise the benefits available in terms of flood risk reduction – so for example certain areas of Todmorden are shown to benefit greatly from the implementation of NFM in the catchment and therefore measures may wish to be targeted here, although there are other drivers that could influence this aside from flood risk, for example landowner collaboration or permission to undertake NFM on their land.

In a very small number of instances there are properties which show flood depths in the NFM scenario which are either a few mm or cm higher than in the Baseline. In some cases, this is because in the Baseline, the property is out of the flood extent and in the NFM scenario it lies just within it, therefore, these have been removed from the assessment on the basis that it is unlikely to flood in either scenario. There are also cases where the property features in both the Baseline and NFM scenario extents and has a small increase in flood depth in the NFM scenario. These were discussed with the modelling team who confirmed that in some locations, there are areas of model instability which causes these depths to fluctuate slightly between scenarios. Where these were significant and unrealistic, they were either addressed in the modelling or by amending the flood depths of the properties in question. Where these were not significant, the depths were left unchanged (to avoid unnecessary work) and have been highlighted in red for full transparency, however, in reality, it is likely that depths may stay the same or slightly decrease at these properties as a result of NFM. That said, as these properties contribute <0.001% of total benefits, they would be considered insignificant at this stage of appraisal. Further refinement of the model/option conceptualisation and design to confirm these properties do not receive increased flood depths in the NFM scenario would be recommended when further assessment is undertaken.

L.4.3. Costs

The costs of NFM that have been developed as part of the NFM Studio process are based on the hydrograph input into that process which allows the NFM solutions to be sized and therefore costed. NFM Studio takes a single hydrograph which is representative of the whole catchment, however the hydraulic modelling uses many individual hydrographs across the catchments developed as catchment specific inflows. The two different approaches used mean that the benefits of NFM in relation to flood risk (calculated by hydraulic modelling and this economic appraisal) are not directly comparable to the outputs of NFM Studio. This is due to the differences in the hydrographs used by NFM studio compared to hydraulic modelling. NFM Studio uses a single hydrograph to size and cost solutions. Hydraulic modelling uses many more hydrographs, which are more representative of the sub-catchments across the Calder. The hydraulic modelling has adjusted all these individual hydrographs to simulate the impact of NFM across the catchment. This means that the volumes of water removed from the hydrographs by NFM differ in the hydraulic modelling (a standard percentage reduction in peak flow) because they are applied to different peak flows across many sub-catchments, when compared to a single change in one hydrograph. However the benefits calculated above in Table 11 can be used to inform the upper limit of PV costs for NFM options to be considered as part of the next, more detailed refinement of the work done to date. Further information on the NFM Studio process and costing can be found in the main Calder NFM Study report.

L.4.4. Climate change resilience

NFM in the Calder catchment may be able to contribute towards improving the resilience of the catchment to flood risk and FAS already in place. Without more detailed information available on the schemes, or the ability to model these and a comprehensive suite of climate change model runs for all events and all epochs, along with the NFM options more explicitly, it is difficult to quantify exactly what benefit NFM may provide in terms of an extended duration of the Standard of Protection (SoP) which is currently provided. It is likely that there will be benefits from reduced flows reaching the river, both in terms of sustaining the SoP and/or extending the life of assets due to reduced pressure on the structures or assets themselves, however this can't be confidently quantified at this early stage of appraisal.

In terms of the properties at risk, mapping has been provided in the standalone report (which shows the change in probability of internal flooding and how this changes in the present day between the Baseline and with NFM options in place It is important to remember that the NFM option presented is the maximum possible NFM implemented across the catchment, and that in reality it may not be possible to progress with this option as it stands and it may have to be refined. With regards to how the probability of flood risk changes over time for individual properties, this would have to be modelled for each climate change epoch and a full suite of climate change allowances applied to all AEP events in the hydraulic modelling to enable a more confident assessment of the potential of NFM to provide resilience benefits in this way. What can be concluded from the assessment that has been done is that with NFM in place there are less properties at risk (see property count tables in section L.4.1), and that the probability of internal flooding for some properties is reduced (as shown in the mapping in the Appendix) in the present day. Where this reduction is significant in the present day e.g. from a 20% (1 in 5) to 1% AEP (1 in 100) event then it could be inferred from this that these properties have a greater amount of resilience in place to increasing flood risk as a result of climate change, compared to those properties where the change in probability of internal flooding is smaller with NFM in place in the present day.

As part of visualising the change in probability of internal flooding at properties across the catchments, a range of maps have been produced which are located in the Appendix for all areas. Todmorden and the results these maps show are discussed below as an example. Todmorden mapping has been split up into three areas due to the spatial extent of the modelling and economic analysis undertaken. The examples below show the central area of Todmorden only.

For several terrace properties it can be seen that the probability of internal flooding goes from a 1% AEP (or 1 in 100) event in the Baseline to less than 1% AEP with NFM. It can’t be quantified, with the available modelled events, how much lower the probability of internal flooding is as 1% AEP was the largest magnitude / lowest probability event modelled. For many properties in this section of Todmorden the change in probability of internal flooding is seen in the mapping below as a single jump between 1 event in the Baseline and the next lowest probability event with NFM in place. Please note that this is for the present day risk of flooding only and takes account of 2021 flood depths.

L.5. Conclusions and Recommendations

The following conclusions can be drawn from the economic analysis of the benefits of NFM across the Calder;

- Due to the application of NFM across the Calder in the modelling, in determining the maximum possible implementation of NFM solutions, the potential PV benefits are significant, particularly in comparison to the total PV damages and provide a 27% reduction in the total PV damages across the catchment over the 100 year appraisal period. There is therefore benefit in implementing NFM across the catchment, in terms of flood risk benefits.
- Whilst there is an economic benefit of implementing NFM when considered over the 100 year appraisal in terms of flood risk reduction, it is anticipated that in reality, the benefit that NFM provides would deteriorate over time due to increasing flows due to climate change. However it is worth noting that if nothing was done, then flood risk would increase significantly in the catchment due to climate change. Due to the method of modelling and the software, there is an inherent limitation. This is due to the fact that the modelling is fluvial only. Part of the flood mechanism in the Calder valley, due to the steep slopes, is surface water runoff. No economic damages or benefits of the proposed NFM from this flood risk mechanism have been taken account of in this study due to the limitations of the models provided. Therefore the damages and benefits may be an underestimate in comparison to reality.
- It is not known whether these NFM solutions are cost beneficial based on the limitations described above around the costing approach, however the benefits provided by NFM, as modelled, can be used to provide an indicative maximum PV cost which would provide a benefit cost ratio of 1.
- The PV benefits will vary according to the types and spatial scale of the NFM implementation. This study assumes all NFM measures implemented across the catchment.

In order to refine this assessment, the following recommendations include;

- Hydraulic modelling should incorporate more upper catchment flow paths in order to better understand the potential benefits of NFM across the whole catchment, not predominately in the valley floor. Hydraulic modelling should also model a consistent and more comprehensive suite of AEP events.
- Whole life costing (PV costs) should be developed in line with a refinement of where NFM options should be further investigated, appraised and designed, and targeted to locations where there is the

most significant benefit to be gained. This can be in terms of flood risk, or in terms of other wider environmental benefits. Consideration of potential funding routes is currently ongoing by the EA.

- Further consideration of whether more targeted NFM measures could have an impact on the properties most at risk, for example the non-residential properties along the valley floor, alongside an improved understanding of other schemes currently being investigated and locations / properties that these may benefit would be required as part of any business case. A more detailed analysis of available and claimable OM2s and OM4s can be undertaken at this point once the NFM strategy has been developed.

L.6. Reference list

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