Working with natural processes: Evidence directory update

FCERM Research & Development Programme

Research report

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This report is the result of research commissioned and funded by the Joint Flood and Coastal Erosion Risk Management Research and Development Programme. Our vision is that the nation is recognised as a world leader in researching and managing flooding and coastal change.

The Joint Programme is overseen by Defra, the Environment Agency, Natural Resources Wales and Welsh Government on behalf of all risk management authorities in England and Wales.

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If you have any comments or questions about this report or the Environment Agency's other flood and coastal erosion risk management work, please contact fcerm.evidence@environment-agency.gov.uk.

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Executive summary

Working with natural processes (WWNP) aims to protect, restore and emulate the natural functions of catchments, floodplains, rivers and the coast to reduce flood risk. The term can be used interchangeably with natural flood management (NFM).

In 2017, the Environment Agency published an evidence base which set out the current state of the scientific evidence underpinning WWNP. This was completed under the Flood and Coastal Erosion Risk Management (FCERM) research and development programme, supported by the Department for Environment, Food & Rural Affairs (Defra), Natural Resources Wales (NRW), the Welsh Government and the Environment Agency. The Scottish Environment Protection Agency (SEPA) and the Woodland Trust were also involved in the 2017 edition. The purpose was to provide flood risk management practitioners and other responsible bodies with information that explains 'what we know' and 'what we don't know' about the effectiveness of different measures. This information is viewed from both a flood risk and ecosystem services perspective.

Several years on from the first evidence base, there is a need to summarise newly emerged evidence in this fast-moving area. This report is intended to be read in conjunction with the 2017 evidence directory. It follows a similar structure, with changes made in places to reflect advances in the science and practice of WWNP.

The evidence base was one part of 3 interlinked projects. This update includes a new evidence directory document, a literature review and a series of summaries.

New within the update are chapters on the evidence where a 'catchment-based approach' was used; this is where several different types of WWNP were implemented in a single catchment and, therefore, the effect on flooding cannot be associated with a single WWNP measure alone.

This update also includes some new natural flood management measures including habitats restored through beaver reintroduction in Chapter 4, and coastal reefs and submerged aquatic vegetation (for example, sea grass and kelp) in Chapter 7. Table 1 lists the measures from both 2017 and 2024. The new measures are bolded.

Table 1 - WWNP measures included in the 2024 evidence directory adapted from Environment Agency (2017) - new measures are bolded

Chapter 4. River and floodplain management	Chapter 5. Woodland management	Chapter 6. Run-off management	Chapter 7. Coast and estuary management
River restoration Floodplain/wetland restoration Leaky barriers **Beavers** Offline storage areas	Catchment woodland Cross-slope woodland Floodplain woodland Riparian woodland	Soil and land management Headwater drainage management Run-off pathway management	Saltmarsh and mudflat management Beach nourishment Sand dune management **Reefs** **Submerged aquatic vegetation**

New evidence was found for all measures, although the volume of new evidence varies between the measures. Information covering multiple settings, scales and benefits was considered. Many studies included modelled information, while less information on modelling was available. The measures studied generally can provide flood risk and multiple other benefits, but specific dependencies for each measure must be carefully considered and are provided. General agreement across new literature was found. Research gaps persist, but centre on more precise information because we now understand the big picture. The main findings for each measure are provided in the associated summary documents.

The outputs can be used by those planning projects, which include WWNP measures to help understand:

- their potential FCRM benefits and multiple benefits
- any gaps in knowledge
- where it has been done before and any lessons learnt
- where in a catchment they might be most effective

This report provides a new evidence baseline for NFM. It can help inform future investment decisions and support the selection of measures on the ground. The findings are already being used; they shaped the Environment Agency's £25 million NFM Programme and can help further build a base of NFM examples.

1 Introduction

1.1 Introduction to the report

Working with natural processes (WWNP) aims to protect, restore and emulate the natural functions of catchments, floodplains, rivers and the coast to reduce flood risk. The first 'Working with natural processes evidence directory' was published in 2017. Since then, there has been considerable progress in the implementation of and research into WWNP.

This report presents an update to the evidence base for WWNP, setting out the current state of the scientific evidence underpinning it and assessing how the evidence has evolved. Its purpose is to build on and complement the 2017 WWNP evidence directory and provide flood risk management practitioners with information about 'what we know' and 'what we still don't know' about the effectiveness of WWNP measures from a flood risk and ecosystem services perspective.

This chapter explains:

- what WWNP is
- its current policy context

Chapter 2 provides a recap of the 2017 WWNP evidence directory.

Chapter 3 explains how to use this report and how readers can find information quickly. It explains how to use this update alongside the 2017 evidence base and provides links to other useful guidance documents for WWNP, for example, those that provide guidance on implementation and design.

Chapters 4 to 7 look in detail at each of the WWNP measures, summarising new research and case study evidence available on their effectiveness from a flood risk and ecosystem services perspective.

Chapter 8 considers research which cuts across multiple WWNP measure types, encompassing the catchment-based approach to flood risk management.

Chapter 9 looks at new approaches to and advances in the modelling and monitoring of WWNP projects.

1.2 What is working with natural processes?

WWNP aims to protect, restore and emulate the natural functions of catchments, floodplains, rivers and the coast to reduce flood risk. It takes many different forms and can be applied in urban and rural areas, and on rivers, estuaries and coasts. Some of the measures restore natural processes (for example, woodland planting), while some work with natural processes but rely on more engineered structures to function or improve functioning (for example, bunds, offline storage areas and leaky barriers). WWNP measures can be either stand-alone or in combination with traditional engineered schemes. Figure 1 is a schematic from the National Flood and Coastal Erosion Risk Management Strategy for England. It shows how different NFM techniques from the headwaters of the river catchment down to the sea might look.

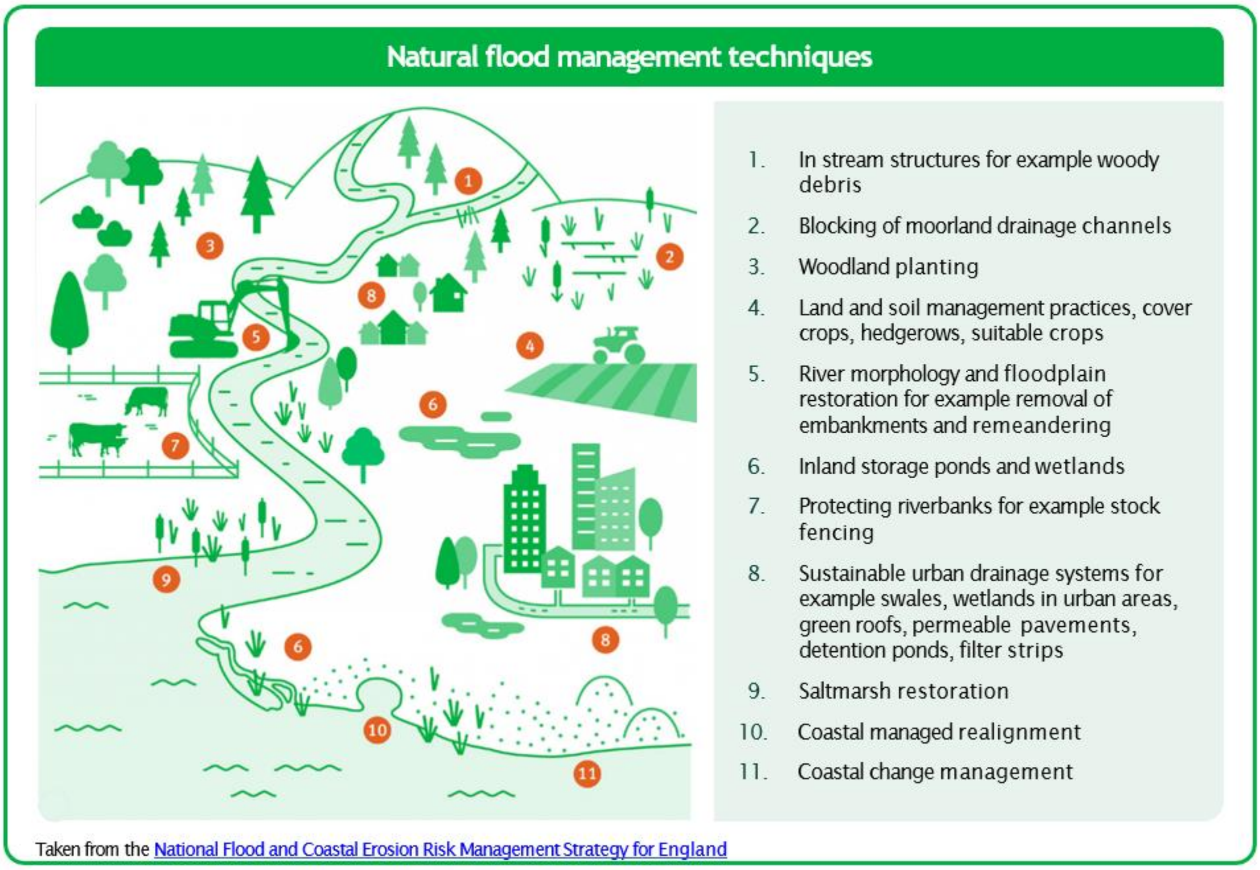

Figure 1 - Working with natural processes – from source to sea (taken from the National Flood and Coastal Erosion Risk Management Strategy for England)

Globally, many different terms are used to refer to this form of flood and coastal risk management (FCRM). The 2017 evidence base uses the terms WWNP and natural flood management (NFM) in recognition that these terms are the most used in the UK context. This is still the case; however, nature-based solutions (NBS) is increasingly used in the UK. This is a broader umbrella term which also covers measures aimed at other outcomes, including biodiversity and water quality improvements, for example. This reflects the move towards greater working with nature and restoration of nature to mitigate and adapt to climate change.

Figure 2 shows the alternative terms. Working with natural processes is in a larger hexagon at the centre of the figure and is surrounded by 6 smaller hexagons with natural flood management, nature-based solutions, engineering with nature, green/bio/eco/soft engineering, natural water retention measures and catchment based flood management.

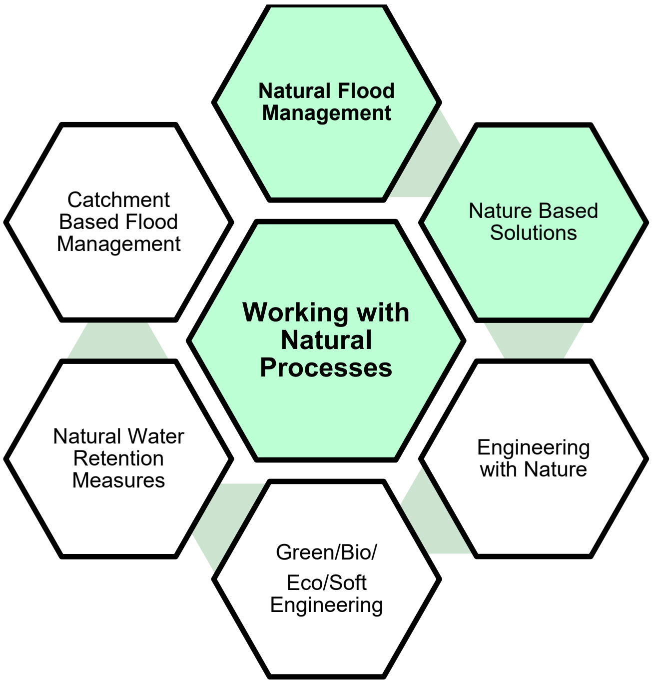

Figure 2 - Alternative terms used to describe WWNP, NFM or NBS reproduced from Environment Agency (2017)

1.3 What does it include?

A wide range of techniques can be used to reduce flood risk by slowing and attenuating flow while achieving other benefits. Within this evidence directory, NFM measures have been categorised into 4 main themes which were retained from the 2017 evidence directory:

- river and floodplain management
- woodland planting
- run-off management
- coastal and estuary management

These techniques can be used in combination with more traditional hard engineering options. The effectiveness of NFM measures is site-specific and depends on many factors, including the location and scale at which they are used. NFM may be the only or most suitable option for small communities where a more traditional scheme may not be financially viable.

It is often not possible to guarantee that NFM measures alone will provide a specified level of flood risk reduction even though they do enhance wider flood and coastal resilience. Instead, they can be used in conjunction with traditionally constructed hard defences to increase the resilience of communities to flooding. It is important to note that WWNP and hard engineering solutions should not be viewed as being in conflict with one another and should instead be carefully designed and considered to offer complementary and effective solutions.

Consequently, flood risk management measures are normally chosen from a range of options, from natural systems through to more traditional forms of engineering, with a wide range of measures in between. Figure 3 shows this continuum of flood risk management techniques. On the left, it starts with natural recovery, followed by assisted natural recovery, significant natural restoration, soft engineering and ending on the right with hard engineering.

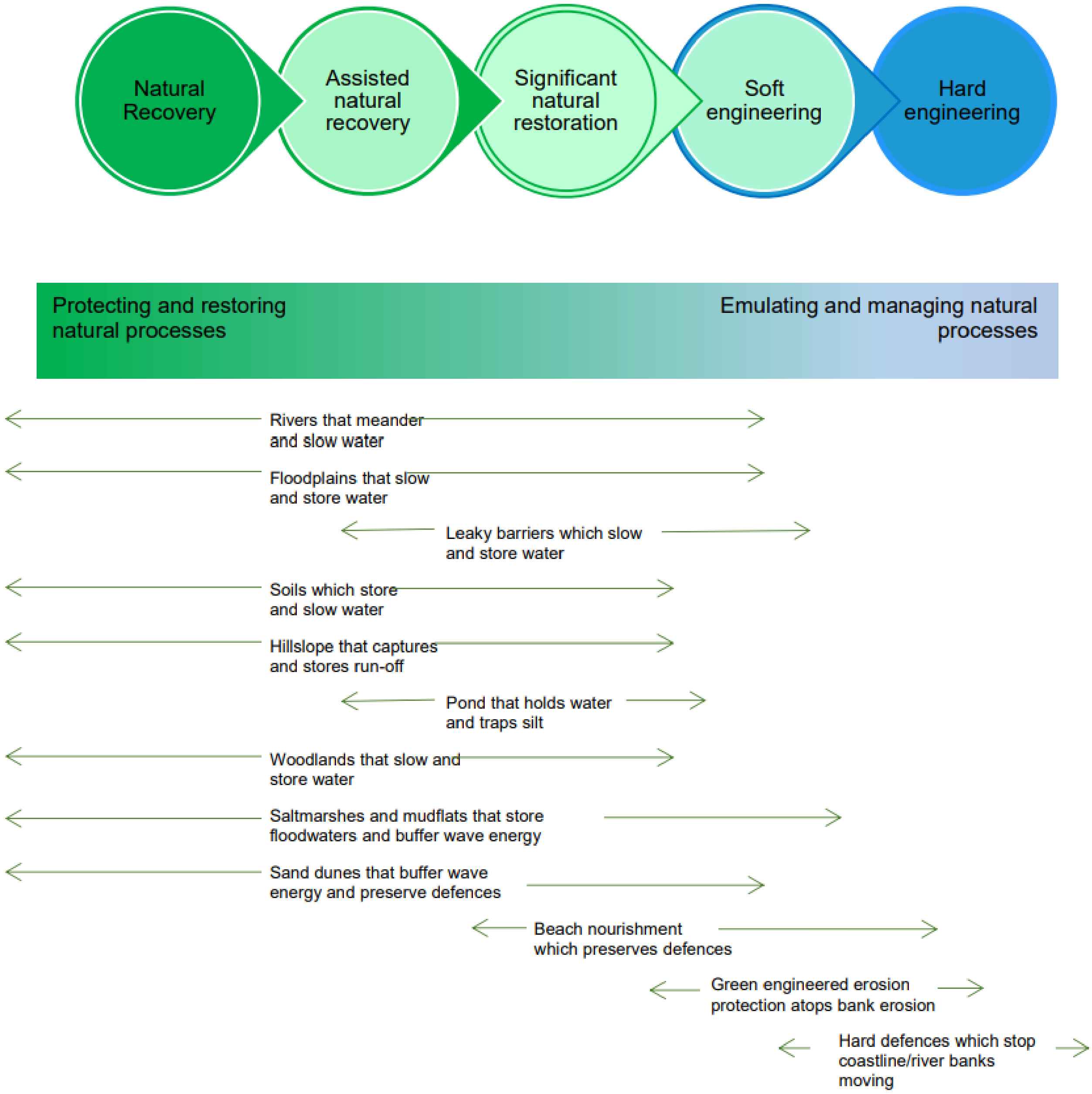

Figure 3 - The FCRM continuum (adapted from Environment Agency 2012a)

WWNP measures that are included within this review are:

- river restoration

- floodplain/wetland restoration
- leaky barriers
- beavers
- offline storage areas
- catchment woodland
- cross-slope woodland
- floodplain woodland
- riparian woodland
- soil and land management
- headwater drainage management
- run-off pathway management
- saltmarsh and mudflat management
- beach nourishment
- sand dune management
- reefs
- submerged aquatic vegetation (SAV)

Adopting WWNP techniques will help achieve more sustainable flood risk management schemes, often with significant additional environmental and social benefits. Using the right combination of measures in the right places can help to lower and slow flood peaks and reduce the depth and duration of flooding as well as achieve other benefits. These other benefits include:

- reducing soil erosion and sedimentation of lakes and rivers
- increasing carbon capture and storage
- improving water quality
- reconnecting rivers with species-rich floodplain wetlands
- enhancing recreation opportunities
- creating new habitat to help restore biodiversity
- providing amenity space
- improving the well-being of local communities

A better environment can improve human health and well-being and make a significant contribution to the local economy. WWNP is, and should be, an integral part of the sustainable management and reduction of flood risk. Sometimes it will be the whole solution and sometimes it may have a smaller role.

1.3.1 The scope of this evidence directory

As far as possible, the same scope and structure as the 2017 edition of the evidence directory was kept. This includes an update to the narrative literature review completed for the 2017 edition. Some changes were made to reflect the advances in the science and practice of WWNP.

The scope of this evidence directory includes:

- both academic and grey literature
- literature from 2017 until 2023
- studies focusing on all points of the project lifecycle (for example, modelling and design through to implementation, effectiveness and monitoring)
- international studies deemed relevant to understanding in a UK context

An important addition to the 2024 evidence directory is the inclusion of beavers, reefs and submerged aquatic vegetation as WWNP measures. This is due to the large increase in studies and introduction of these measures in a UK context since 2017.

Sustainable drainage systems (SuDS) were excluded from the scope of this evidence directory as with the original evidence directory.

It is important to recognise that effectiveness of particular measures will vary widely based on a range of location specific characteristics including geography, geology, antecedent conditions and existing catchment conditions.

This directory is intended as a collation of scientific knowledge and necessarily requires some generalisation and summary of findings. Specific context is included around study sites, where possible, to aid in understanding.

This guide is not intended as a practical handbook and application of these measures in practice will require careful consideration of the specific location and understanding of any constraints that might apply.

1.4 Policy and legislative context

Policy, regulation and legislation are important factors influencing NBS and help to establish the aspirations for WWNP across the UK. Grounding NBS within legal frameworks can help overcome some barriers associated with WWNP and facilitate implementation.

1.4.1 Summary of NFM policy relevant to UK government

A summary of UK government policy and legislation relevant to NFM is provided below. Policy that is applicable to multiple countries within the UK is also included.

Future flood prevention (House of Commons Environment Food and Rural Affairs Committee 2016)

Farmland should be used in some places to store flood water. The National Farmers' Union and Defra must develop storage approaches with low impact on farm productivity and appropriate incentives to recompense farmers.

A Green Future: Our 25 Year Plan to Improve the Environment (HM Government, 2018)

The UK government will take action to reduce the risk of harm from flooding and coastal erosion, including greater use of NFM solutions. The plan includes a commitment to test, encourage and embed NFM solutions in the appropriate places alongside more traditional defences where needed, including new ways of financing schemes.

National Infrastructure Strategy (HM Treasury 2020)

The government is committed to harnessing the opportunities of rural landscapes to increase the resilience of rural communities to flooding. The government will maximise good land management and implement nature-based solutions through the latest flood and coastal defence programme.

The Third National Adaptation Programme (NAP3) and the Fourth Strategy for Climate Adaptation Reporting (HM Government 2023a)

Using NBS will reduce society's vulnerability to climate risk and contribute to species recovery by providing more high-quality habitat.

New legislation and supporting implementation programmes are addressing climate risk and supporting the natural environment to adapt.

1.4.2 Summary of NFM policy relevant to England

The principles of NFM are reflected in the Environment Agency's responsibilities derived from English policy, regulation and legislation. The Environment Agency is developing the appraisal process to better facilitate a range of complex resilience projects such as NFM and implement the below policy.

Appraisal of flood and coastal erosion risk management (Department for Environment, Food & Rural Affairs 2009)

In sections 3.2 and 5.4, it was noted that strategic plans should help to identify viable opportunities for WWNP.

National Flood Resilience Review (HM Government 2016)

Engineered hard flood defences can only ever be part the solution. Catchment leaders will coordinate planning, taking an integrated approach to the environment and valuing interventions such as NFM.

National Flood and Coastal Erosion Risk Management Strategy for England (Environment Agency 2020)

Risk management authorities will work with partners to make greater use of NBS that take a catchment-led approach to managing the flow of water to improve resilience to both floods and droughts.

Strategic objective 1.4 - Between now and 2030, risk management authorities will use nature-based solutions and improve the environment through their investment in flood and coastal resilience.

Measure 1.4.1 - From 2021 risk management authorities will work with catchment partnerships, coastal groups, land managers and communities to mainstream the use of nature-based solutions.

Using the power of nature to increase flood resilience (Environment Agency 2021)

The Environment Agency is currently implementing the flood and coastal investment plan for 2021 to 2027. This will invest £5.2 billion of government funding in new projects to better protect 336,000 properties from flooding and coastal erosion.

Environmental Land Management schemes: Overview (Department for Environment, Food & Rural Affairs and Rural Payments Agency 2021)

ELMS will support farmers and land managers to provide NFM to protect themselves and other farm businesses in the catchment.

FCERM Strategy Roadmap to 2026 (Environment Agency 2022)

WWNP was highlighted in the Roadmap including:

- between now and 2030, risk management authorities will use nature-based solutions to improve the environment through their investments in flood and coastal resilience
- the number of NFM projects delivered as part of the Flood and Coastal Erosion Risk Management Investment Programme will be doubled
- risk management authorities will work with partners on Local Natural Recovery Strategies to identify where actions for nature could benefit flood and coastal risk management
- by 2030, risk management authorities will work with farmers and landowners to help them adapt their businesses and practices to be resilient to flooding and coastal change
- the Environment Agency will continue to enhance its appraisal guidance for flood and coastal erosion risk management projects, in line with government policy

The Third National Adaptation Programme (NAP3) and the Fourth Strategy for Climate Adaptation Reporting (HM Government 2023a)

Supporting farmers and land managers to provide NFM through the Environmental Land Management schemes (ELMS) to protect themselves and other farm businesses in the catchment.

£25 million fund for Natural Flood Management (Environment Agency and Defra 2023)

The Environment Agency and Defra launched a £25 million fund to accelerate investment in NFM. This is benefitting 38 projects, delivered by a range of organisations, that will carry out a mixture of NFM measures at a range of scales and across a variety of communities and landscapes. The fund will run until March 2027. It aims to:

- reduce local flood risk using NFM
- provide wider benefits to the environment, nature and society
- accelerate new and existing opportunities for NFM delivery and financing
- further improve evidence of NFM by filling knowledge gaps

It also includes some important innovations to support the mainstreaming of NFM alongside other resilience measures.

1.4.3 Summary of NFM policy relevant to Northern Ireland

An overview of Northern Ireland's NFM legislative context is provided below.

Draft Environment Strategy (Northern Ireland Executive, 2021)

Develop and implement nature recovery plans and programmes, including NBS as an important action and target, such as increased woodland cover.

2nd Cycle – Flood Risk Management Plan 2021-2027 (Department for Infrastructure 2021)

In the plan, it was noted that the Department for Infrastructure will:

- consider the use of NFM on all flood alleviation schemes/works to complement the traditional hard engineered solutions
- create opportunities to work with others, through partnership arrangements, to implement sustainable flood risk management measures at a catchment level including NFM in rural areas

The Third National Adaptation Programme (NAP3) and the Fourth Strategy for Climate Adaptation Reporting (HM Government 2023a)

Northern Ireland departments recognise the role that NBS will have for both climate change mitigation and adaptation.

1.4.4 Summary of NFM policy relevant to Scotland

An overview of Scotland's NFM legislative context is provided below.

The Flood Risk Management (Scotland) Act 2009 (Scottish Government 2009)

The Act includes a requirement to examine where working with natural features could contribute to the management of flood risk and to assess where the removal of existing natural features could increase flood risk.

Identifying opportunities for Natural Flood Management (Scottish Environment Protection Agency 2015)

A key element of sustainable flood risk management involves finding ways to manage the source and pathway of flood waters, rather than solely focusing on traditional hard engineering further down the catchment.

The Flood Risk Management (Scotland) Act 2009 - Delivering Sustainable Flood Risk Management (Scottish Government 2019)

Flood risk management to deliver rural and urban landscapes with space to store water and slow down the progress of floods.

The Environment Strategy for Scotland (Scottish Government 2020)

The strategy includes adaptive measures to be used, including NFM.

1.4.5 Summary of NFM policy relevant to Wales

Natural resource management, including NFM is an important part of the Welsh Government's flood and coastal risk management approach. Welsh NFM legislative context is outlined below.

Natural Resources Policy (Welsh Government 2017)

Delivering NBS is listed as one of the 3 national priorities in the policy.

Flood and Coastal Erosion Risk Management – Business Case Guidance (Welsh Government 2019)

The guidance notes that an investment objective relevant to NFM should be included in nearly all FCERM business cases.

Risk management authorities (RMAs) should identify all possible long list measures that work with natural processes first and always develop a 'do something' option that incorporates NFM for shortlist consideration.

The National Strategy for Flood and Coastal Erosion Risk Management in Wales (Welsh Government 2020)

In line with the Flood and Water Management Act 2010, reducing the risk of flood and coastal erosion can include WWNP or NFM. This approach is in line with the Natural Resources Policy and is encouraged in all FCERM interventions.

The government wants to encourage the take-up of NFM in Wales. It will support pilot studies and interventions designed to reduce flood and coastal erosion risk to better understand its benefits.

It wants to see NFM as an option for every FCERM scheme as set out in its FCERM Business Case Guidance.

Welsh Government, Programme for Government (Welsh Government 2022)

The programme includes commitments to:

- deliver nature-based flood management in all major river catchments to expand wetland and woodland habitats
- fund additional flood protection for more than 45,000 homes
- establish a targeted scheme to support restoration of seagrass and saltmarsh habitats along our coastline

2 Recap: the 2017 WWNP evidence base

The 2017 WWNP evidence base was made up of 3 interconnected projects. This section outlines the previous outputs and what is and isn't being updated out of these 3 workstreams.

The Venn diagram in Figure 4 shows the 3 workstreams: the evidence directory in a circle at the top, research gaps in a circle on the right and mapping the potential for WWNP in a circle on the left. The elements under the evidence directory circle include using the evidence base, flood risk matrix, 14 one-page summaries, 65 case studies and literature review. The research gaps elements include filling R&D gaps by monitoring Defra funded NFM projects, monitoring evaluation plan for Defra funded NFM projects, Natural Environment Research Council (NERC) research call. The elements under the mapping the potential for WWNP circle include GIS maps, PDF maps, user guide and technical report.

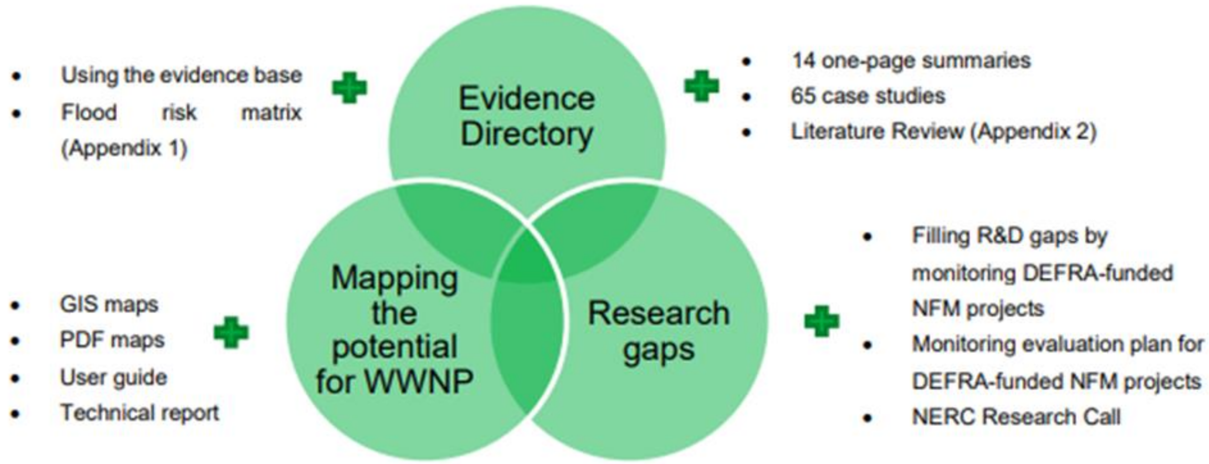

Figure 4 - The 3 interconnected workstreams which made up the original WWNP evidence base - reproduced from Environment Agency (2017)

2.1 Evidence directory

The evidence directory summarised what was known about the effectiveness of different measures from a flood risk management and ecosystem services perspective. The original directory included chapters covering 14 different types of WWNP measures. These were sorted into 4 groups, with a chapter covering each. Each chapter also identified evidence gaps that existed at the time the directory was collated.

2.1.1 Summary findings

The 2017 evidence directory found that WWNP:

- is not new, there are many examples of its application across the UK

- it can reduce flood risk, by slowing, storing and filtering water
- it complements rather than replaces traditional engineering
- typically reduces flood risk for smaller magnitude floods, across small to medium catchment scales
- almost always achieves multiple environmental benefits
- is currently reliant on modelled data, more observed data is needed to help validate model findings

It highlighted that the understanding needed to be further developed in:

- the effectiveness of WWNP measures across different catchment scales for a range of return period events (observed and modelled data)
- how to design and construct different measures so they perform as designed (this includes engineering design standard)
- how different measures function in different catchment types and different geologies
- the role WWNP could play in making catchments more adaptable/resilient to climate change
- more fully understanding the ecosystem service benefits of different measures

More detailed summaries of the measure-specific findings from the 2017 evidence directory can be found in Chapters 4 to 7.

2.1.2 Literature review

The evidence directory was underpinned by a detailed literature review which summarised the state of knowledge on WWNP to reduce flood and coastal erosion risk. It was made up of 4 separate literature reviews which looked in detail at the 4 categories of measures and the individual interventions included within them. Table 2 includes the 4 categories and 14 measures from the 2017 report.

Table 2 - Interventions included within the 4 categories of measures in the 2017 evidence directory - reproduced from Environment Agency (2017)

River and floodplain management	Woodland management	Run-off management	Coast and estuary management
River restoration Floodplain/wetland restoration Leaky barriers Offline storage areas	Catchment woodland Cross-slope woodland Floodplain woodland Riparian woodland	Soil and land management Headwater drainage management Run-off pathway management	Saltmarsh and mudflat restoration Sand dune management Beach nourishment

2.1.3 Case studies

In addition to the literature review, the evidence directory was linked to real world examples through 65 standalone case studies. Summaries of these case studies were included in each chapter to bring the science to life using real world examples. Detailed case study reports were also produced. They included:

- main driver
- project stage
- project summary
- main facts
- contact details
- location and catchment description
- background summary of the catchment (socio-economic/historic contact; flood risk problem(s); other environmental problems)
- defining the problem(s) and developing the solution (evidence to define the flood risk problem(s) and solution(s); design rationale; effectiveness of the project
- project construction (how individual measures were constructed; how long measures were designed to last; landowner and legal requirements considerations)
- funding
- wider benefits
- maintenance, monitoring and adaptive management
- lessons learnt
- bibliography

The case studies were split across the 4 categories of measures shown in Table 3.

Table 3 - Case studies from 2017 Working with natural processes evidence directory - these have not been updated or added to in this update

Category	Number of case studies
Rivers and floodplains	23
Woodlands	7
Run-off	15
Coasts and estuaries	20

2.1.4 One-page summaries

14 one-page summaries of each of the measures covered in the evidence directory were produced. They provided a high-level summary of the main findings and pointed users to where they could find more information.

Each one-page summary included:

- an introduction to the measure
- a description of what it is
- examples from literature
- a summary of the findings
- an assessment of the level of confidence in flood risk benefits and the main source of the evidence
- a summary of the research gaps
- examples of flood risk benefits at different catchment sizes and flood magnitudes
- multiple benefit information
- a benefits summary
- examples of multiple benefits from case studies and literature
- a benefits wheel
- further reading, case studies and maps

2.2 Mapping the potential for WWNP

A set of national-scale, strategic maps were created to be used alongside the evidence directory to help practitioners think about the types of measure that may work in a catchment and the best places in which to locate them. They identified potential for WWNP across England. The maps are indicative and signpost a range of areas for managing flood risk by protecting, restoring and emulating the natural regulating function of catchments and rivers.

They were developed using entirely open, national data sets such as the Environment Agency maps showing the risk of flooding from rivers, the sea and surface water.

The maps did not cover a comprehensive list of WWNP measures and do not prescribe how the measures could be designed. Wider environmental and societal benefits were not included in the maps but need to be considered in addition to flood risk mitigation. A constraints data set also based on open data was developed to help users further refine potential areas. It included roads and rail, urban areas, existing woodland, peat and water bodies, which may restrict the potential for implementation of some interventions.

The maps identified potential areas for:

- floodplain reconnection
- run-off attenuation features and gully blocking
- woodland planting covering floodplain planting, riparian planting, and wider catchment woodland

They are provided in spatial data and PDF format and are supported by a user guide and a detailed technical guide. These can be accessed online. The maps can also be viewed online via the JBA Trust website.

These maps were not modified for the 2024 WWNP evidence directory project.

2.3 Research gaps

The final element of the 2017 evidence base identified important knowledge gaps common across most types of measures. It also detailed an action plan to address these. This plan included monitoring outcomes from a £15 million Defra funded pilot scheme for NFM projects and working with the Natural Environment Research Council (NERC) to shape an NFM research call.

2.3.1 Summary findings

The research gaps were categorised across 4 areas.

Gap 1: The flood risk impact of WWNP measures across different scales

The effectiveness of WWNP measures alone, in clusters or in combination with other forms of FCRM for a range of return periods and a range of different catchment scales on:

- flood level/flow
- flood peak (including synchronisation and backwater effect)
- flood storage

Including understanding of:

- what scale/extent a WWNP measure is needed in a catchment to reduce flood risk

- how effective measures are when soils are fully saturated

Gap 2: Performance and design life

The whole life performance and engineering design standard of WWNP measures need to be understood. Specifically, information is required on:

- whole life costs of measures
- standard of protection (SoP) to downstream communities
- comparative assessments between WWNP/NFM and traditional measures
- how long it takes for the measures to work
- how long the measures last (design life)
- how frequently they need to be maintained

Gap 3: Typology, geology, sediment management and conveyance

How do WWNP measures function in different catchment typologies/geologies and what effect do they have on sediment management and conveyance? Specifically:

- what are the flood risk effects of proposed measures in groundwater-fed catchments?
- what are the flood risk effects of your proposed measures in lowland catchments? (including pumped catchments and perched river systems)
- do the measures affect channel conveyance?
- do the measures trap sediment and reduce the need for channel maintenance?

Gap 4: Wider benefits

More information is also needed on:

- ecosystem service benefits of different measures, including quantitative information if possible
- the role of WWNP/NFM in making catchments more adaptable/resilient to climate change

3 User guide

3.1 Introduction

This updated evidence directory summarises the advances in the scientific evidence base that underpin WWNP since 2017.

It is expected that this updated evidence directory is read alongside the original, to provide the reader with a well-rounded understanding of different WWNP measures. Short synopses have, however, been included for each measure.

3.2 What's different in this update?

This document is an update to the 2017 evidence directory and not a replacement for it. It follows a similar structure to the previous directory to reflect and highlight newly emerging evidence. The number of papers reviewed is shown in Table 4. Some changes to the structure have been made to reflect advances in the science and practice of WWNP.

Table 4 - Numbers of papers reviewed per category

NFM category	Number of papers reviewed
River and floodplain management	>250
Run-off management	~200
Woodland management	~150
Coastal management	~200
Total	~800

The case studies and WWNP mapping have not been updated as part of this update, which is focused on updating users on new evidence through an update report on the evidence base and new, updated summaries.

3.3 What information is included?

The updated evidence directory research report (this document) summarises what more has been learnt about the effectiveness of different measures from a flood risk management and ecosystem services perspective. It is underpinned by a narrative literature review; the findings from which are detailed in a separate document.

The literature review was completed by searching publication databases using terms relevant to the NFM measures in the context of flood risk management. The search covered literature published between 2017 and 2023. This included academic journal articles, including those published internationally where they incorporated measures relevant to the UK context, and grey literature. The process resulted in a large number of returns, with more than 800 being reviewed in detail. This review was consistent with the approach adopted in the 2017 edition and sought to balance a broad search of the literature with the use of expert knowledge.

Whilst the search may not be fully exhaustive, it reflects the evidence base available which is more developed in some areas than others. Some research may have been missed due to the nature of the search process and the prevalence of unpublished supporting evidence.

Within the literature review, each reference includes basic contextual information where supplied. For example, "In the Eynsham catchment (1,616 km^2) of the River Thames, broadscale woodland planting (a mixture of riparian and catchment woodland over 73% of the catchment, replacing all arable land and grassland)…". The user is advised to read the source of information for full contextual information.

While the majority of the literature included within the review has come from peer-reviewed academic journals, a variety of grey literature is also included, therefore the reader is advised that there will be different levels of scientific rigour across the literature.

3.3.1 Which measures?

This report looks in detail at 17 measures. They are covered in each chapter in the order shown in Table 5.

Table 5 - WWNP measures covered in the evidence directory

Chapter 4. River and floodplain management	Chapter 5. Woodland management	Chapter 6. Run-off management	Chapter 7. Coast and estuary management
River restoration Floodplain/wetland restoration Leaky barriers Beavers Offline storage areas	Catchment woodland Cross-slope woodland Floodplain woodland Riparian woodland	Soil and land management Headwater drainage management Run-off pathway management	Saltmarsh and mudflat management Beach nourishment Sand dune management Reefs Submerged aquatic vegetation (SAV)

It is also recognised that most WWNP schemes include a wide range of measures implemented together. Chapter 8 assesses the evidence and research into the use of multiple measures in a catchment area.

3.3.2 Effects of measures

Each chapter outlines a summary of the evidence on the effect of WWNP measures on:

- flood flows, peaks and storage
- different catchment scales (NB: this is primarily literature that looks into different scales as part of one study)
- different watercourse typologies
- sedimentation and geomorphology
- design life and effectiveness
- maintenance

As part of the review, we have not inferred site understanding given site location, literature has only been included in different sub-sections (for example, catchment scales, types) if the information needed was stated in the literature. For example, despite knowing where a catchment is in the UK, we have not assumed the catchment type (for example, groundwater dominant) unless it was stated in the literature.

For coastal measures, the outline covers:

- overall understanding on flood and coastal erosion risk

- effect on wave attenuation
- effect on sediment and geomorphology
- design life and effectiveness
- maintenance

Within the literature review, evidence was further subdivided (where appropriate) into:

- process understanding
- observed evidence
- modelled evidence

Each WWNP measure section ends with a summary of the changes in the evidence since 2017 and the remaining research gaps.

The following terms of reference were used throughout.

Small catchment is ~10 km^2.

Medium catchment is ~100 km^2.

Large catchment is ~1,000 km^2.

Local scale impact is an impact that is not catchment wide; it is localised where the measure was implemented.

Small flood is <10-year return period events.

Medium flood is from 10 year to 100-year return period events.

Large flood is >100-year return period events.

However, where a piece of literature only states a size of event or catchment, for example, ‘small catchment’ or ‘large event’, this has not been cross-checked against the definitions.

3.3.3 Multiple benefits

For each measure, there is an assessment of the evidence for the multiple benefits which the measure could provide alongside FCRM. The categorisation of these benefits changed since 2017 to reflect Defra's Enabling a Natural Capital Approach (ENCA) guidance (Defra, 2023), which was used to standardise categorisation and theory behind different benefits. However, the term ‘flood risk reduction’ is used instead of ‘flood regulation.’ This guidance has been widely adopted and accepted across the UK.

In recognition that WWNP measures do not contribute to all types of ecosystem services, as in the first evidence directory, a condensed list of 8 relevant benefits is outlined below.

Water resources means the preservation of water for the purposes of supporting habitats, preventing drought and providing drinking water.

Air quality means the removal of harmful air pollutants from the atmosphere through both direct deposition onto leaves and bark, and internal absorption of pollutants through stomatal uptake.

Climate regulation means the sequestration and storage of greenhouse gases by vegetation, soils and sediments and/or the reduction in air temperature from vegetation by green and blue spaces.

Flood risk reduction means regulating water flow. Retaining water and releasing it slowly, or absorbing wave energy.

Amenity is a bundling of cultural services which arise from people being close to natural assets. Amenity is taken to include other cultural benefits, including recreation, physical health, mental health, education and volunteering. It also includes landscape, which here refers to improvements to landscapes that give rise to a range of cultural and aesthetic and visual amenity benefits.

Biodiversity means the variability among living species from all sources, including terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part.

Soil means the undegraded and uncontaminated soils. Note this was removed from coastal measures where this would not apply.

Water quality means clean water for safety, recreation and thriving biodiversity.

The 8 benefit types can be defined into 3 broader categories:

- social – flood risk reduction, water resources, air quality
- environmental – biodiversity, soil, climate regulation, water quality
- cultural – amenity value

It should be noted that the update to the WWNP evidence directory was created with a focus on flood risk. Where other benefits were identified, these have been explored, however terms relating to the multiple benefits have not been explicitly included within the review. Therefore, we acknowledge that there will be other literature available that highlights multiple benefits in much more depth, and that additional research gaps may have been identified by other authors that are not included within the evidence directory.

The multiple benefits assessment and associated wheels are only intended to be used as a visual tool to suggest where additional benefits may be sought when implementing the measures for flood risk. They should not be used as part of detailed quantitative analysis or optimisation of options.

3.3.4 Scientific confidence levels

As in the 2017 evidence directory, an approach adapted from the Living with Environmental Change (LWEC) score cards are used to attach a confidence level (high, medium or low) based on the potential effectiveness of each measure at reducing flood risk and providing wider benefits. These confidence limits are relative within WWNP and may not be reflective of our overall understanding compared to our confidence with engineered FCRM measures. It is highlighted where these confidence levels have changed in relation to the 2017 evidence directory.

The confidence level, assigned by scientific experts, reflects both the degree of agreement of scientific studies and the amount of information available. The confidence bandings were developed through a detailed literature review and were peer-reviewed. Low levels of agreement or low volumes of evidence result in low overall confidence and high levels of agreement. High volumes of evidence result in high overall confidence. A combination of medium and high result in medium overall confidence. If there is high confidence in a measure, it does not necessarily mean there are not still knowledge gaps in this area.

Figure 5 shows the confidence level using a 9 square matrix grid. The horizontal axis is level of evidence, and the vertical axis is level of agreement. This means the square in the bottom left corner indicates low amount of evidence and a low amount of agreement. The centre square in the matrix grid is medium for level of evidence and level of agreement. The top right square is high for level of evidence and level of agreement.

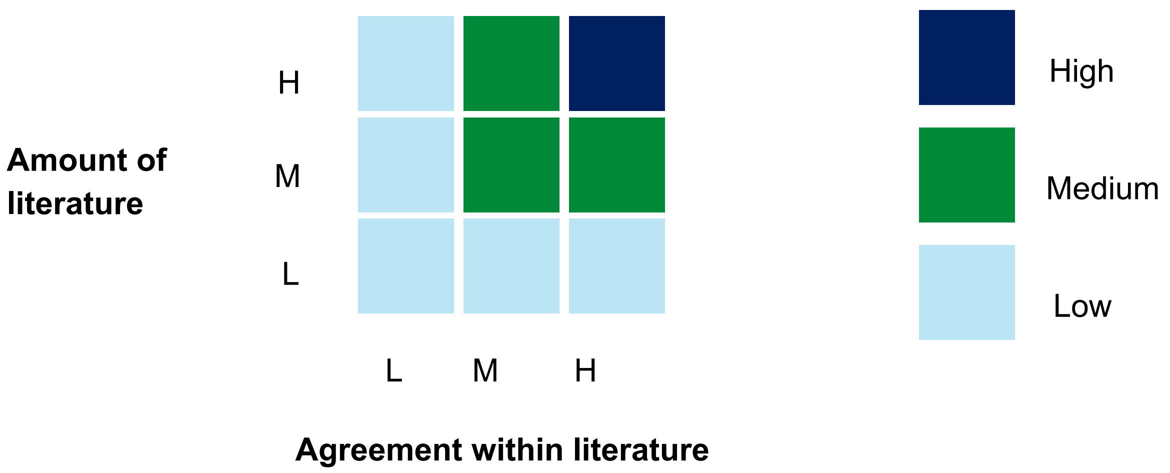

Figure 5 - Approach used to help define confidence in evidence based on level of consensus around science and amount of evidence (source: Adapted from LWEC score cards)

3.3.5 Cross-cutting

A cross-cutting chapter was added to the update to recognise that many WWNP schemes seek to implement a variety of NFM measures to increase effectiveness. It summarises the evidence around the effectiveness of mixed NFM schemes, whereby multiple NFM measures are used in combination. It does not consider integrated flood risk management, which combines traditional flood risk management, property flood resilience and NBS as a strategy.

Within the literature review, **Cross-cutting** has been used to identify papers that have used a range of measures.

3.3.6 Quantifying the evidence

Chapter 9 summarises the advances made in the monitoring and modelling of WWNP since 2017. For monitoring, this includes new technologies or existing technologies that have been used in the WWNP field for the first time since 2017. For modelling, this includes evidence relating to new types of models available, how to model WWNP within those models, and discussion around uncertainty and confidence in the modelling of WWNP.

3.4 Using the 2024 and 2017 evidence directories

It is intended that the original 2017 and this updated 2024 evidence directory be used concurrently.

However, in appreciation of the volume of both documents together, each measure has a 'findings from the 2017 evidence base' section that details the summaries of 'what we know' and 'what we don't know' that were in the 2017 directory; this sits prior to the new evidence.

The new evidence is then summarised, followed by a 'what are the changes?' and 'research gaps' section.

3.5 Caveats

While much research and implementation of WWNP has taken place since 2017, the science and our understanding are still evolving and developing. Some measures may have been tested during extreme flood events; however, their effectiveness may not yet have been appraised. This means that we are still learning where and how to design and construct these measures. There is also still a need for more long-term monitoring of sites to fully understand their effectiveness.

Evidence was categorised where possible into broad themes, however some studies cross multiple themes and, therefore, to avoid duplication, these have only been included in the most relevant theme.

Effects at different catchment scales can be based on both monitored and modelling understanding. Wherever possible, the type of evidence used has been indicated in the text.

Monitoring at large catchments scales is challenging, therefore, our understanding is often limited by this.

As with all FCRM schemes, it is incumbent on those who design and construct them to ensure that they are competently designed to optimise possible flood risk benefits, and do not pose a public safety risk to downstream communities. This evidence directory does not seek to be a design guide, other resources that focus on design have been signposted in 'further reading' sections throughout the evidence directory. Design is mentioned only when there is scientific understanding that changes in design affect the efficacy of the measure.

Throughout this document we have used the following annotation **Important** to alert the reader to circumstances where a particular measure could potentially increase flood risk, cause a blockage, synchronise peaks or create a backwater effect.

3.6 Further reading and resources

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ENVIRONMENT AGENCY, 2017. Working with Natural Processes – Evidence Directory [Online]. Environmental Agency, Report No. SC150005. Available from: https://assets.publishing.service.gov.uk

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ENVIRONMENT AGENCY, 2021. Achieving Net Zero carbon emissions: a review of the evidence behind carbon offsetting. Available from: Achieving Net Zero carbon emissions: a review of the evidence behind carbon offsetting - GOV.UK (www.gov.uk). [Accessed 12/06/24].

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ENVIRONMENT AGENCY, 2022. Natural Flood Management Programme: evaluation report. Available from: Natural Flood Management Programme: evaluation report - GOV.UK. [Accessed 01/14/25].

FOREST RESEARCH, 2022. UK Forestry Standard Practice Guide: Designing and managing forests and woodlands to reduce flood risk. Forestry Publishing Group: Roslin.

FORESTRY COMMISSION, 2019. Managing forest operations to protect the water environment. Forestry Commission: Edinburgh.

NATURAL ENGLAND, 2021. Carbon storage and sequestration by habitat 2021 (NERR094). Available from: Carbon Storage and Sequestration by Habitat 2021 - NERR094 (naturalengland.org.uk). [Accessed 12/06/24].

RIVER RESTORATION CENTRE, 2023. Practical river restoration appraisal guidance for monitoring options (PRAGMO). Available from: https://wiki.therrc.co.uk/index.php/PRACTICAL_RIVER_RESTORATION_APPRAISAL_GUIDANCE_FOR_MONITORING_OPTIONS_(PRAGMO). [Accessed 12/06/24]

WOODLAND TRUST, 2022. Trees for Water. Wood Wise, Spring 2022. Available from: https://www.woodlandtrust.org.uk/publications/2022/06/wood-wise-trees-for-water/. [Accessed 12/06/24]

WREN, E., 2022. The natural flood management manual. CIRIA.

4 River and floodplain management

4.1 Introduction

This chapter summarises the evidence around the effectiveness of the following river and floodplain management measures in reducing flood risk:

- river restoration
- floodplain and floodplain wetland restoration
- leaky barriers
- Eurasian beavers
- offline storage areas

Restoring and working with the natural processes and features within rivers and floodplains can provide a wide range of benefits for the environment and people. From an FCRM perspective, these types of measures can increase the hydraulic roughness and morphological complexity of rivers and floodplains, which, in turn, slows floodwaters and reconnects rivers to their floodplains to store water. Of all the measures covered in this chapter, offline storage areas are seen to be the most engineered, sometimes involving the construction of flow control structures and other grey infrastructure to enable their full operation.

Please note that any new literature that assesses the impacts of combinations of NFM measures is covered in Chapter 8 (Cross-cutting).

4.2 River restoration

4.2.1 What is river restoration?

Rivers have been physically modified over time through a variety of means for the purposes of navigation, agriculture, drainage and industrial development. River restoration can be defined as ‘the reinstatement of the natural physical processes (for example, renaturalising flow and sediment supply regimes by removing weirs) and features (for example, adding wood, altering river shape and introducing sediment gravel) that are characteristic of a river’.

Figure 6 shows an example of river restoration with assisted natural recovery. The river has been reshaped to curve and there are trees and shrubs on the riverbanks.

Figure 6 – River restoration near Carlisle (image credit: David Kennedy, Environment Agency)

River restoration does not necessarily mean restoring river forms and processes to their pre-industrial state, as this can be difficult or impossible due to societal constraints and the ever-changing nature of rivers. However, restoring hydraulic and sediment transport processes directly or indirectly by reinstating the physical form of a channel may help a river adjust towards a more natural form.

River restoration can take many forms; in some cases, very little effort is needed (assisted natural recovery), whereas in other cases more extensive engineering and earthworks are needed. From a flood risk perspective, river restoration can alter many of the primary processes rivers use to transport water and sediment through the catchment. This can include increasing or reducing channel roughness, changing conveyance and water storage times, changing energy states in different reaches and providing flexible solutions that change with the environmental factors over short or long time periods. River and floodplain restoration usually occur in tandem so as to give the greatest flood risk benefits.

4.2.2 Findings from the 2017 evidence base

What we knew about river restoration in 2017

From the 2017 evidence base, we know that river restoration:

- does not work instantaneously, it takes time to adjust morphologically, and pace of adjustment will vary depending on flow and sediment supply
- can reduce flood risk, but the extent of this effect depends on the length of river restored relative to the catchment size
- can slow flood flows and decrease conveyance through the reintroduction of features that:
    - encourage the river to reconnect with its floodplains
    - enable the storage of floodwaters on floodplain
    - increase floodplain inundation depth
    - attenuate peak flows downstream
- techniques selected must be appropriate to the river typology
- should require limited maintenance

What were the research gaps?

In 2017, the research gaps identified that more information is needed on:

- field-based evidence that demonstrates its flood risk benefit
- the potential flood reduction benefits provided by river restoration
- FCRM benefits of different types of river restoration at different spatial scales
- conveyance capacity of restored rivers
- water storage effects of restoration

4.2.3 New flood risk evidence

For more detailed information relating to the studies used to formulate the following summaries, please see the literature review.

We have **medium** confidence in the effect that river restoration has on flood risk. This remains unchanged from the original evidence directory as not enough new literature was identified to increase our confidence in our understanding.

A review of the latest evidence has found that river restoration:

- can increase surface water area (Champkin and others, 2018; Ioana-Toroimac and others, 2022)
- can increase river morphological complexity and alter sediment size, although this may vary temporally (Groll, 2017; Martínez-Fernández and others, 2017; Champkin and others, 2018; Williams and others, 2020)

- can slow flows, delay peak flows and store water (Rogers, 2017; Levi and McIntyre, 2020; Gilbert, 2021a). However, effectiveness depends on:
    - the length of the channel restored; with evidence suggesting it is more effective across entire river segments (Martínez-Fernández and others, 2017)
    - catchment size; with evidence suggesting it is more effective in smaller catchments (Levi and McIntyre, 2020)
    - the level of impoundment within the reach (Groll, 2017; Levi and McIntyre, 2020)
- one paper suggested some interventions require maintenance, including routine maintenance as well as reactive/remedial maintenance after a flood event. (Moore and Rutherfurd, 2017)

Effects at different scales

We have **medium** confidence in the effects of river restoration at different scales. This remains unchanged from the original evidence directory due to a lack of new literature. The limited new literature suggests that:

- river restoration may be more effective over entire river segments rather than small sections (Martínez-Fernández and others, 2017)
- at the catchment scale, larger effects are seen in smaller catchments (Levi and McIntyre, 2020)
- **Important -** our understanding of the effectiveness of river restoration at larger catchments sizes may be limited due to the challenges of monitoring at larger scales. Additionally, there are few large-scale restoration projects in the UK, with most being smaller in scale

Effects on different watercourse typologies

We have **medium** confidence in the effects of river restoration on different watercourse typologies. This has been lowered from the original evidence directory as there is limited new evidence. This evidence suggests that:

- the benefits of river restoration have been found to be less pronounced in a weir-impounded reach compared to a free-flowing reach (Groll, 2017)
- following river restoration in a tidally influenced floodplain, erosion occurred after rainfall where the sea meets the land, whereas the area above the tide was more stable (Medel and others, 2022)

Effects on sediment and geomorphology

We have **high** confidence in the effects of river restoration on sediment and geomorphology. This is an improvement from the original evidence directory due to the large quantity of new literature and level of consensus in that literature. The new literature suggests that river restoration:

- increases surface water area and river feature complexity; this varies with time, with more active processes observed in sections which had been naturalised for less time (Heritage and Entwistle, 2020), with bank erosion being a significant driver for channel volume change (Williams and others, 2020)
- may also change sediment size, decreasing silt and increasing gravel content (Champkin and others, 2018)

Design life and effectiveness

We have **medium** confidence in the design life and effectiveness of river restoration. This remains unchanged from the original evidence directory as there is limited new evidence. A lab-based experiment of how vegetation types alter flow resistance found long grass slowed the flow the most compared to reed, stick, short grass and algae (Meng and others, 2021).

Maintenance

We have **low** confidence in our understanding of the maintenance requirements of river restoration. This has been lowered from the original evidence directory as there is limited new evidence that conflicts with that in the original. The new evidence suggests that successful river restoration relies on consistent, well managed maintenance (Moore and Rutherfurd, 2017).

4.2.4 New multiple benefits evidence

Evidence prior to 2017 suggested that river restoration results in water quality improvement, habitat provision, climate regulation, resilience to low flows, health access, and contributions to flood risk reduction.

New evidence suggests that river restoration:

- may have minimal effects on water resources (Aghajani and others, 2023a; Aghajani and others, 2023b)
- may have the potential to increase carbon stocks (Sear and others, 2023)
- can reduce the distance travelled by nutrients due to longer residence times and lower water velocities (Levi and McIntyre, 2020)
- may improve biodiversity through the introduction of different habitat types (Agócsová and others, 2020) and increased species diversity (Seele-Dilbat and others, 2022), however changes may be small (Martínez-Fernández and others, 2017; Champkin and others, 2018)

The multiple benefits of river restoration are reflected in Figure 7. River restoration may result in improvements to water quality, habitat provision and biodiversity, climate regulation, health access, and contributions to flood risk reduction. While it is thought that river restoration may improve resilience to droughts, new evidence suggests that it can have minimal impact on water resources.

The multiple benefits wheel tool is only intended to be used as a visual aid to suggest where additional benefits may be sought when implementing the measures for flood risk. It should not be used as part of detailed quantitative analysis or optimisation of options.

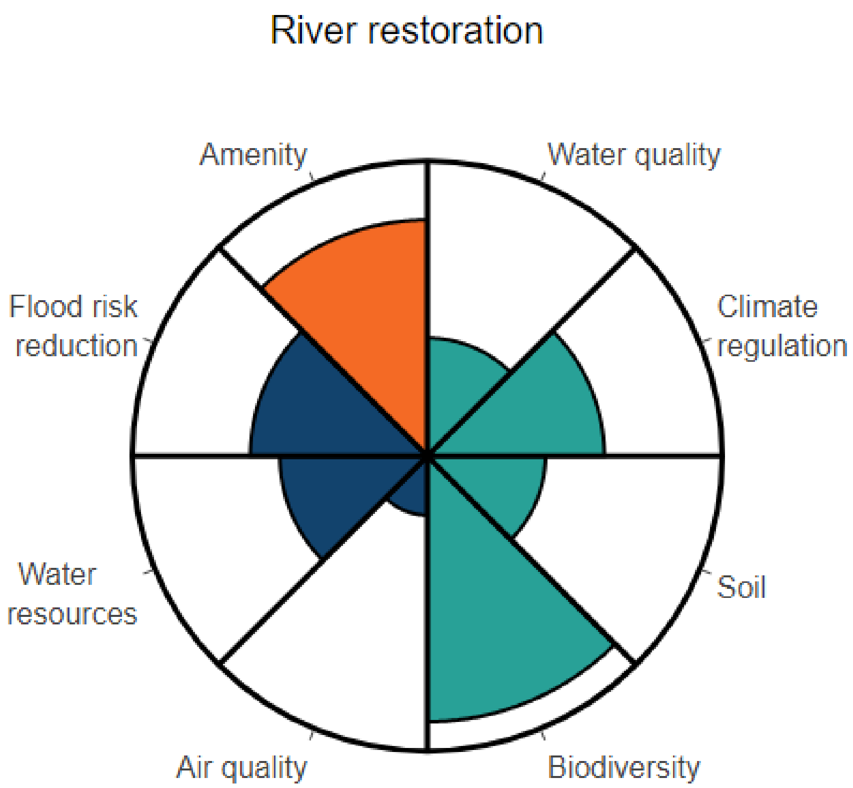

Figure 7 - Multiple benefits wheel for river restoration

4.2.5 What are the changes in evidence from 2017?

The main changes in evidence since 2017 are:

- a small increase in the number of field-based studies assessing the relationship between river restoration and flood risk, however, further assessment would still be beneficial, there is minimal conflict among the literature that has been identified
- it remains clear that effects change with time
- more evidence on the multiple benefits has been presented
- more evidence on how the changes may vary within the catchment is presented, such as the differences between the lower and upper catchment

4.2.6 Research gaps

Despite new evidence coming to light since the original evidence directory, there are remaining research gaps to allow us to continue to improve our understanding of river restoration. We still need:

- to understand the potential flood reduction benefits, conveyance capacity and water storage effects provided by river restoration
- long-term monitoring and evaluation of flood risk and multiple benefits
- future efforts in river restoration to focus on catchment-wide factors that can boost ecosystem recovery
- the impact of different types of river restoration at greater spatial scales to be assessed further
- understanding around the difference between active versus passive intervention
- assessments to identify optimal design of river restoration

4.3 Floodplain and floodplain wetland restoration

4.3.1 What is floodplain and floodplain wetland restoration?

Floodplains and floodplain wetlands can be restored or created to store large volumes of water for flood risk and ecological benefits.

Floodplain restoration aims to restore the hydrological connection between rivers and floodplains so that floodwater, sediment and biological material inundate the floodplains and store water during times of high flows. This can involve removing flood embankments and other barriers to floodplain connectivity.

Figure 8 shows an example of a floodplain attenuation wetland at Gissing. Water is pooling in the centre of a green wetland and there are trees around the edges of the wetland.

Figure 8 - Floodplain attenuation wetland, Gissing (image credit: Norfolk Rivers Trust)

In recent years, ‘Stage Zero’ or ‘Stage 0’ restoration has developed. Stage 0 floodplain reconnection considers the natural pre-disturbance ('Stage 0') state of rivers. This approach involves landscape-scale restoration, completely altering the recognised norm of a single thread channel and allowing the river to reconnect with the floodplain and a raised water table. This helps return natural hydromorphological and ecological processes, habitat availability and biodiversity, and a more resilient mosaic of habitats, than in-channel restoration (River Restoration Centre, no date). Eurasian beavers have a significant positive effect in creating and sustaining floodplain wetland restoration.

Wetlands are dynamic and changing habitats that include fens, dune slacks, grazing marsh and swamp, upland and lowland peat bog, reedbed and saltmarsh, wet woodland, wet grassland and wet heathland. This chapter considers floodplain wetlands.

4.3.2 Findings from the 2017 evidence base

What we knew about floodplain and floodplain wetland restoration in 2017

From the 2017 evidence base, we know that floodplain restoration:

- does not usually work instantaneously, there can be delays before full floodplain connectivity is re-established and it is able to attenuate peak flows
- can reduce or delay flood peaks, but these benefits are site-specific and hard to predict

- **Important** - can increase flooding downstream (for example, due to peak synchronisation in the river network)
- can reduce flood risk, but the extent of this effect depends on the length of river restored relative to the catchment size, and the river and floodplain type
- can potentially reduce or delay flood peaks, capture and store sediment
- may attenuate high frequency, low return period floods
- may require maintenance

What were the research gaps?

The research gaps identified that more evidence is needed on:

- site-based observations that demonstrate its flood risk benefit
- effectiveness (positive and negative) of floodplain and floodplain wetland restoration from an FCRM perspective
- hydraulic performance of restored floodplains and wetlands and impacts on downstream receptors
- impacts of floodplain and floodplain wetland restoration in different watercourse types across different spatial scales
- impacts of floodplain and floodplain wetland restoration on channel conveyance and whether it increases/decreases the need for in-channel maintenance
- floodplain roughness (for example, parameterising drag coefficients) to ensure flood models are accurate
- role of groundwater in floodplain restoration
- effectiveness of different types of wetland and the FCRM benefits they provide

4.3.3 New flood risk evidence

For more detailed information relating to the studies used to formulate the following summaries, please see the literature review.

We have **low to medium** confidence in the effect that floodplain and floodplain wetland restoration, including emerging restoration techniques, have on flood risk. This remains unchanged from the original evidence directory as not enough new literature was identified to increase our confidence in our understanding.

A review of the latest evidence has found that floodplain and floodplain wetland restoration:

- effects vary spatially across the catchment, with different results in the upper and lower catchment (Åhlén and others, 2022)
- one paper showed floodplain connectivity and increased overspilling does not necessarily mean changes in the flood hydrograph are seen (Addy and Wilkinson, 2021)

- modelling shows floodplain restoration can reduce peak flow; this is consistent among the literature as reported by multiple studies, and the effect has also been noted over a variety of return periods (Chappell and others, 2023; Hankin and others, 2021; McKenna, 2021; Chappell and Beven, 2023)
- one modelling study also showed wetland removal can increase stream peak flow (Ameli and Creed, 2019)
- a few studies showed floodplain and wetland restoration can reduce groundwater recharge and baseflow (Aghajani and others, 2023b; Aghajani and others, 2023a; Aghajani and others, 2023c)
- can increase river complexity and sedimentation (Maaß and Schüttrumpf, 2019; Williams and others, 2020; Pierce and others, 2022; Hinshaw and others, 2022)
- design should reflect the typology of the catchment and local environment (Noon, 2020)
- one paper demonstrated maintenance is required (Ioana-Toroimac and others, 2022)

Effects at different scales

We have **low to medium** confidence in the effects of floodplain and floodplain wetland restoration at different scales. This remains unchanged from the original evidence directory due to a lack of new literature or long-term monitored sites. A study from Sweden found that wetlands have different storage patterns based on the landscape, with upland catchment wetlands showing variable water levels and complex flooding, while downstream wetlands maintain capacity for buffering of extreme floods (Åhlén and others, 2022).

Effects on different watercourse typologies

We have **low** confidence in the effects of floodplain and floodplain wetland restoration on different watercourse typologies due to limited new evidence in all but groundwater dominant catchments. This evidence suggests that:

- the loss of historic wetlands has decreased groundwater discharge, baseflow discharge and increased stream peak flow (Ameli and Creed, 2019)
- restoration and floodplain reconnection increased groundwater levels (Pierce and others, 2022)

Effects on sediment and geomorphology

We have **medium** confidence in the effects of floodplain and floodplain wetland restoration on sediment and geomorphology. This remains unchanged from the original evidence directory due to a lack of new literature. The new literature suggests that:

- floodplain restoration and bank lowering may lead to erosion, including on the lowered banks, opposite banks and bank protection measures (Williams and others, 2020; Addy and Wilkinson, 2021)

- sedimentation can increase post restoration, and sediment size may change (Maaß and Schüttrumpf, 2019; Pierce and others, 2022; Hinshaw and others, 2022)

Design life and effectiveness

We have **low** confidence in the design life and effectiveness of floodplain and floodplain wetland restoration. This remains unchanged from the original evidence directory as there is limited new evidence. Reflections from a study in Delaware, USA showed a well-designed restoration approach should encompass optimised channel width-to-depth ratios, planting of native species, and use of woody shrub planting to address unstable banks (Noon, 2020).

Maintenance

We have **medium** confidence in our understanding of the maintenance requirements of floodplain and floodplain wetland restoration. This has been lowered from the original evidence directory as there is limited new evidence. The new evidence suggests that insufficient maintenance of wetland areas during restoration may result in limited success (Ioana-Toroimac and others, 2022).

4.3.4 New multiple benefits evidence

Evidence prior to 2017 suggested that floodplain and floodplain wetland restoration results in water quality improvement, habitat provision, climate regulation, resilience to low flows and contributions to flood risk reduction.

New evidence suggests that floodplain and floodplain wetland restoration may:

- increase summer baseflow (Hunt and others, 2018)
- increase infiltration and groundwater flows, cooling down baseflow temperatures (Noon, 2020)
- store excess precipitation, however the location is important for whole system functioning at low flows (Åhlén and others, 2022)
- result in habitat variations over short timescales due to complex and patchy inundation (Åhlén and others, 2022)
- change plant community composition (rise in moisture-tolerant species) due to increase in flood frequency (Richards and others, 2020)
- lead to an improvement in water quality (Shrestha and others, 2017)

The multiple benefits of floodplain restoration and floodplain wetland restoration are reflected visually in Figure 9 and Figure 10. Floodplain and floodplain wetland restoration may result in improvements to water quality, habitat provision, climate regulation, resilience to low flows and contributions to flood risk reduction.

Wetland restoration offers particularly high climate regulation and biodiversity benefits, but floodplain restoration also scores well for these categories. Water resources and air quality benefits can be more limited for both types of restoration.

The multiple benefits wheel tool is only intended to be used as a visual aid to suggest where additional benefits may be sought when implementing the measures for flood risk. It should not be used as part of detailed quantitative analysis or optimisation of options.

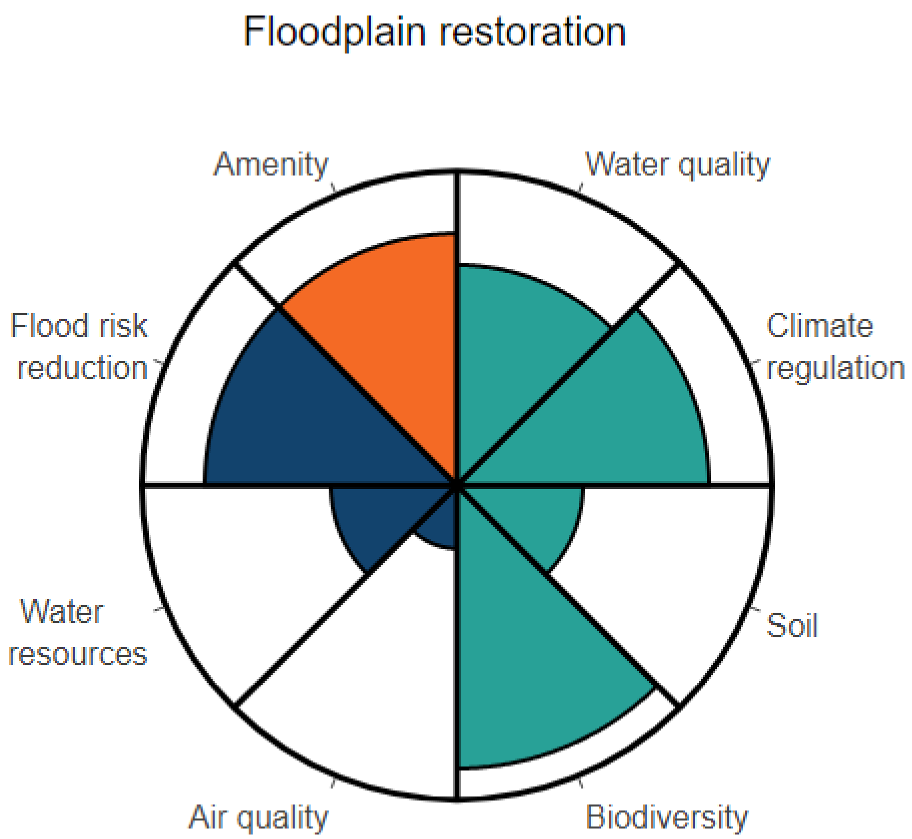

Figure 9 - Multiple benefits wheel for floodplain restoration

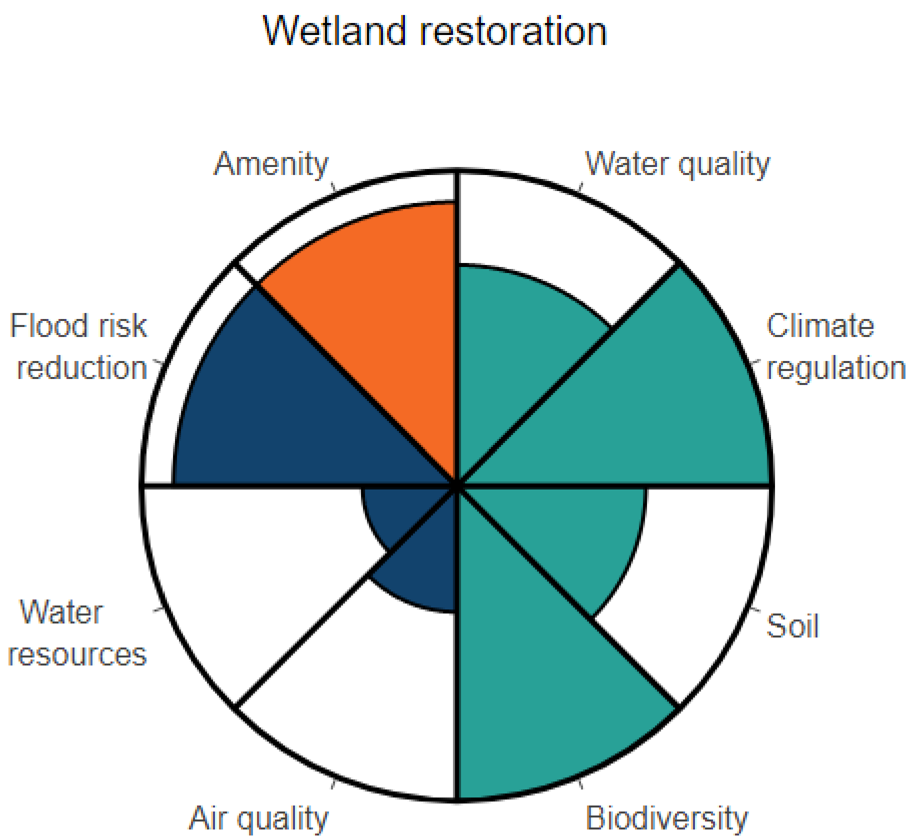

Figure 10 - Multiple benefits wheel for floodplain wetland restoration

4.3.5 What are the changes in the evidence from 2017?

The main changes since 2017 are:

- there is still limited site-based evidence that demonstrates flood performance and most evidence is modelled
- no new literature discussing the process evidence was identified
- more evidence on the impact at different return periods is presented
- more evidence on the multiple benefits is presented

4.3.6 Research gaps

Despite new evidence coming to light since the original evidence directory, there are remaining research gaps to allow us to continue to improve our understanding of floodplain and floodplain wetland restoration. We still need:

- evidence to suggest how flood peak flow reductions translate into flood risk reductions and how floodplain and floodplain wetland restoration may help reduce wider flood risks (for example, help in hard engineered asset control)

- site-based evidence that demonstrates its flood risk benefit
- to understand the effectiveness (positive and negative) of floodplain and floodplain wetland restoration from an FCRM perspective
- to understand the benefits of emerging techniques such as Stage-0 restoration
- to understand the hydraulic performance of restored floodplains and wetlands and impacts on downstream receptors
- to develop understanding of riparian processes at different temporal and spatial scales post restoration
- to understand the impact of scaling projects from the local, wetland scale to larger, catchment scales
- more information on the role of groundwater in floodplain restoration and other different watercourse types
- more research to consider wetland hydrological functioning across the variety of wetland types
- to understand how assemblages of different networked wetlands function together over seasons and annually
- more information on maintenance requirements and whether it increased or decreased the need for in-channel maintenance
- to better understand floodplain roughness (for example, parameterising drag coefficients) to ensure flood models are accurate
- work to improve mapping, projection and modelling capabilities that help to understand how to prioritise potential sites for wetland restoration and what controls wetland buffering potential
- information on optimising design of solutions, including which features can be sited within the floodplain to further enhance flood risk benefit

4.4 Leaky barriers

4.4.1 What are leaky barriers?

Leaky barriers usually consist of accumulations of wood, occasionally combined with some living vegetation, in river channels as well as on riverbanks and floodplains. Although the word ‘barrier’ evokes thoughts of hard engineering, leaky barriers can occur naturally along rivers as a result of trees, or parts of trees, falling locally into watercourses through snagging of natural wood. Leaky barriers emulate similar responses to beaver dams. Beaver dams contribute to other measures in this chapter. Similar structures can also be engineered by humans to restore rivers and better connect them to floodplains to slow and store flood water.

Figure 11 below shows an example of a leaky barrier with sticks and logs laying across a stream in the Cotswolds.

Figure 11 - An example of a leaky barrier in the Cotswolds (image credit: Jenny Broomby, JBA Consulting)

Leaky barriers are known by many other names such as:

- coarse woody debris
- large woody debris
- logjams
- wood accumulations
- wood jams/barriers
- beaver dam analogues
- leaky dams
- woody material

When engineered, they are often referred to as ‘wood placements’, ‘engineered log jams’ or ‘flow restrictors.’ The term ‘leaky barriers’ is used here because it has fewer negative connotations than the word ‘dam’.

4.4.2 Findings from the 2017 evidence base

What we knew about leaky barriers in 2017

From the 2017 evidence base, we know that leaky barriers can:

- work instantaneously
- have limited evidence in relation to flood risk benefits

- generally show flood risk reduction for small floods in small catchments (<10 km^2) depending on design and placement
- reduce flood risk locally for small flood events
- increase hydraulic roughness
- reduce and slow flow velocities
- create temporary storage and attenuate flood flows
- increase floodplain connectivity
- trap fine sediment
- create areas of sediment scour and deposition
- encourage sediment sorting
- create in-channel features
- require maintenance, particularly when there is no natural wood supply

What were the research gaps?

The research gaps identified that more evidence is needed on:

- their effectiveness at mitigating flood peaks at the catchment scale for larger events
- flood risk impacts alone (in isolation from other WWNP measures)
- understanding the role of leaky barriers in reducing flood risk across a range of different catchment sizes and catchment types
- modelling tools to assess their impacts on flood risk and for guidance on how to correctly use parameters (such as Manning's n values) to model their effect
- understanding how woody structures built by beavers could mitigate flood risk
- leaky barrier flood and coastal erosion risk management (FCRM) design guidance
- decomposition rates
- whole life costs and engineering performance
- how to inspect leaky barriers to decide if maintenance is needed
- ownership, maintenance and liability
- the hydrological effect of beaver dams compared to leaky barriers

4.4.3 New flood risk evidence

For more detailed information relating to the studies used to formulate the following summaries, please see the literature review.

We have **medium** confidence in the effect that leaky barriers have on flood risk. This remains unchanged from the original evidence directory as despite an increase in the evidence available, it often contradicts itself depending on site and design characteristics.

A review of the latest evidence has found that leaky barriers can:

- reduce peak flow, but overall volume stored is often modest (Hankin and others, 2020; Chadwick, 2021a; Pang Valley Flood Forum, 2021; Norbury and others,

2021; Mulligan and others, 2023; Van Leeuwen and others, 2024; Phillips, and others, no date)
- result in limited storage created by present designs which is often too small to generate significant impact in reducing flood risk for higher return period events (Metcalfe and others, 2018; Black, 2020; Geertsema and others, 2020; Norbury and others, 2021; Follett, Hankin, and others, 2023; Muhawenimana and others, 2023; Norbury and others, no date; Phillips, and others, no date)
- be effective in creating a rise in upstream water depth and backwater length which can be linked to barrier physical structure (Taylor and Clarke, 2021; West Cumbria Rivers Trust, 2021a; Follett, Beven, and others, 2023; Muhawenimana and others, 2023)
- increase upstream water depth, and corresponding backwater volume, is often proportional to the number, size, and packing density of the wood pieces in the barrier and extent of lower and lateral gaps (Schalko and others, 2019; Follett and others, 2020; Schalko and others, 2023)
- fail, but this is site specific (Hankin and others, 2020; Lo and others, 2022)
- cause peak synchronicity effects as suggested by one paper and that the potential for this increases with catchment size (Metcalfe and others, 2018)

Effects at different scales

We have **low** confidence in the effects of leaky barriers at different scales. This remains unchanged from the original evidence directory due to limited new literature which often contradicts itself. The limited new literature suggests that:

- the potential for peak flow to align after the introduction of leaky barriers may increase with catchment size; making sure flood peaks are not synchronised across sub-catchments may improve the effectiveness of schemes using leaky barriers (Metcalfe and others, 2018)

Effects on different watercourse typologies

We have **low** confidence in the effects of leaky barriers on different watercourse typologies which remains unchanged from the original evidence directory due to no new evidence being identified as part of this review.

Effects on sediment and geomorphology

We have **high** confidence in the effects of leaky barriers on sediment and geomorphology. This remains unchanged from the original evidence directory due to an increase in the volume of literature with limited contradiction. The new literature suggests that:

- leaky barriers can lead to erosion and sedimentation (Harvey and others, 2018; Follett and others, 2020; Chadwick, 2021a; Gilbert, 2021b; Pang Valley Flood Forum, 2021; Powell and others, 2021; Deane and others, 2021; Lo and others, 2022; Muhawenimana and others, 2023; Schalko and others, 2023; Phillips and others, no date); (Ismail and others, 2021; Schalko and others, 2021; Livers and Wohl, 2021; Follett and others, 2021; Wohl and Iskin, 2022), with one study finding that accumulation of silt over one year upstream of a barrier potentially contributed to observed overtopping of the barrier (Chadwick, 2021a)

- leaky barrier sites may have reduced sediment concentration compared to a control site for very high flow events; this was found in 1 study (Taylor and Clarke, 2021)
- erosion can lead to the formation of pools (Lo and others, 2022). Sedimentation can occur in these pools and there can then be an increase in gravel-pebble sized material (Gilbert, 2021b; Powell and others, 2021)

Design life and effectiveness

Overall, we have a **medium** level of confidence in the design of leaky barriers. In 2017, we had a **low** level of knowledge about design life of woody barriers, **medium** confidence in understanding how long naturally forming leaky barriers take to become effective and **high** confidence in how long it takes woody barriers to be effective. These remain unchanged from the original evidence directory. However, there was an increase in the volume of literature as we are confident that design is site specific and important for efficacy, however we are less confident about whether there is an optimal design and how long the effects of certain designs last. The evidence suggests that leaky barriers:

- need to be designed to drain and vacate storage before subsequent events (Metcalfe and others, 2018; Van Leeuwen and others, 2024)
- effectiveness increases with retention time (Follett, Beven and others, 2023)
- storage is dependent on design and site character, including structure, width of lower and lateral gaps, barrier height, and channel slope, bed roughness, and depth ((Pearson, 2020; Follett and others, 2021; Follett and Hankin, 2022; Chappell and others, 2023; Follett, Beven, and others, 2023), and can vary with time depending on debris accumulation and loss (Muhawenimana and others, 2023)
- extending out of the channel and onto the floodplain may locally increase storage but this may not lead to a reduction in peak flow (Pearson, 2020)
- design can affect the need for maintenance (Mulligan and others, 2023) and can impact the amount of additional material accumulated behind barriers (Pang Valley Flood Forum, 2021)

Maintenance

We have **low** confidence in our understanding of the maintenance requirements of leaky barriers. This has been lowered from the original evidence directory due to no new evidence being identified as part of this review compared to the overall number of new studies and sites that have implemented leaky barriers.

4.4.4 New multiple benefits evidence

Evidence prior to 2017 suggested that leaky barriers result in water quality improvement through sediment retention and habitat provision (although they may present a barrier to fish passage), climate regulation, resilience to low flows and contributions to flood risk reduction.

New evidence suggests that leaky barriers may:

- have limited effects on hydrological variables at low flows (Taylor and Clarke, 2021)
- have limited long-term effects on water quality (Bickley and others, 2021)
- improve biodiversity through increased abundance, richness and diversity of species (Deane and others, 2021; Adams, n.d.), however other studies did not find notable changes (Pinto and others, 2019; Pang Valley Flood Forum, 2021) or variation and decreased with time (Harvey and others, 2018; Hinshaw and others, 2022)
- affect fish movement, which is dependent on the design of the leaky barrier (Müller and others, 2021)

The multiple benefits of leaky barriers are reflected in Figure 12. Leaky barriers may result in water quality improvement through sediment retention (although this may be limited), habitat provision (although this may present a barrier to fish passage), climate regulation, resilience to low flows and contributions to flood risk reduction. There are very limited benefits for amenity, air quality and soil identified from leaky barriers.

The multiple benefits wheel tool is only intended to be used as a visual aid to suggest where additional benefits may be sought when implementing the measures for flood risk. It should not be used as part of detailed quantitative analysis or optimisation of options.

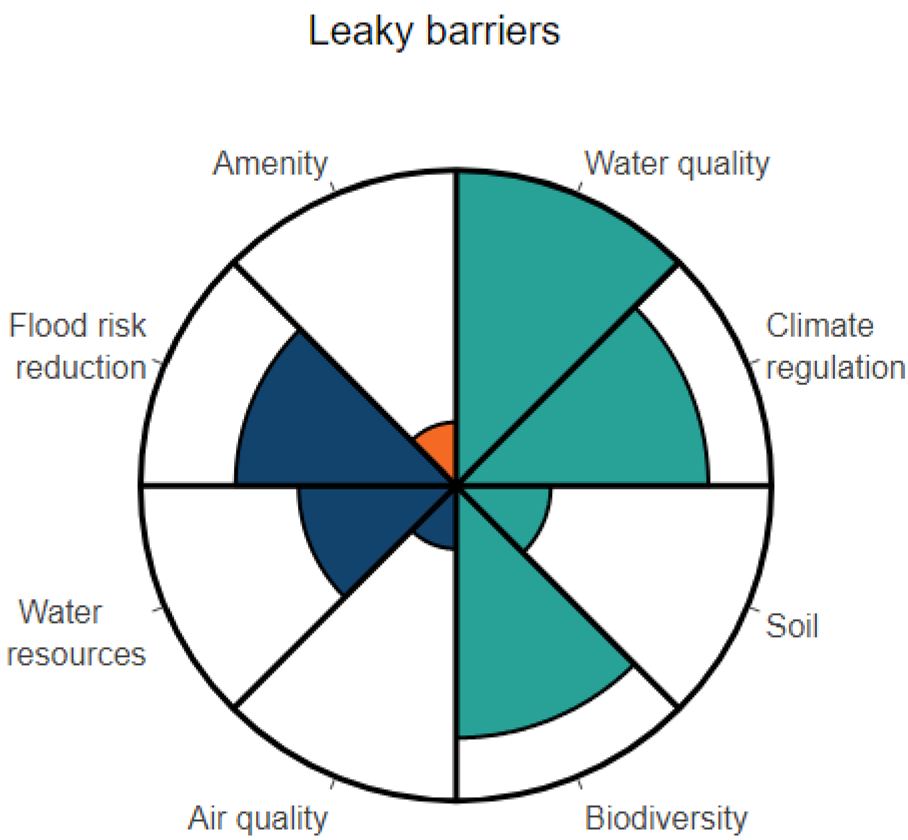

Figure 12 - Multiple benefits wheel for leaky barriers

4.4.5 What are the changes in the evidence from 2017?

The main changes in evidence since 2017 are that:

- studies have fundamentally advanced the science of understanding the relationships between head loss and the physical characteristics of leaky barriers
- no new evidence on the impact of leaky barriers on different watercourse typologies was identified
- the effectiveness of leaky barriers at different catchment scales has been further studied
- more evidence on multiple benefits is presented

4.4.6 Research gaps

Despite new evidence coming to light since the original evidence directory, there are remaining research gaps to allow us to continue to improve our understanding of the effectiveness of leaky barriers. They reflect the large increase in literature since 2017, meaning they are often more detailed and specific. However, this does not mean that they are more effective than other measures, simply that we know more about them overall. We still need:

- evidence to suggest how flood peak flow reductions translate into flood risk reductions and how leaky barriers may help reduce wider flood risks (for example, the benefits of debris dams working in conjunction with hard defences)
- further research to focus on the effectiveness of leaky barriers at greater flow magnitudes to understand in particular when leaky barriers become overwhelmed
- studies at a range of catchment settings and at larger spatial scales
- more work across a range of UK climates and geological environments
- research covering longer time scales, to help understand impacts in the long term on both flood risk and wider impacts
- the influence of storm type, antecedent conditions and seasonality to be assessed
- assessments of a larger range of artificial and natural leaky barriers features with different wood characteristics (such as wood density) in the field. This may include specific design features such as the inclusion of branches or root wads or characteristics such as barrier surface area or angle of barrier placement in relation to channel
- studies on a range of bedload transport conditions and materials to develop understanding of the impacts of leaky barriers on sedimentation
- further work to consider the impact of sediment loading volume and material
- future studies to aim to work to improve leaky barrier representation with models, including at varying magnitudes
- future research to further examine the impact of leaky barriers on fish migration
- design guidance which considers decomposition rate, how to check if maintenance is required, whole life costs and engineering performance
- more information on ownership, maintenance and liability
- evidence on the life span of debris dams and whole life costs

4.5 Eurasian beavers

4.5.1 What are Eurasian beavers?

Beavers are often referred to as ecosystem engineers because they have the ability to modify ecosystems profoundly to meet their ecological needs. This brings with it considerable associated hydrological, geomorphological, ecological and societal effects. Beaver dams extend beyond channels, creating durable berm-like structures which can hold back water. Figure 13 shows an aerial image of a beaver dam that is built alongside the River Otter. The dam is blocking some of the water from flowing into the river.

Figure 13 - Beaver pond on the River Otter (image credit: Alan Puttock, University of Exeter)

Castor fiber is the European species, with Castor canadensis being the North American species. Both species behave in the same way and so evidence and studies for both species are considered to be applicable and relevant to this report. The expansion of the Castor fiber population has led to an increase in the number of scientific studies and evidence, including the effect on hydrology, both low and high flows. This is of particular relevance to this report, together with the wider ecosystem benefits that the presence of beaver in a landscape can bring.

Alongside a suite of ecosystem services creating complex and biodiverse habitat, the presence of beavers can significantly mitigate peak flows during large storms. Beaver dams can decrease flood levels even in saturate environments. This indicates that beavers play a role in providing NFM (Puttock, Graham, and others, 2021).

4.5.2 Findings from the 2017 evidence base

The original directory did not have a section on beavers and so the scientific papers are from after 2017, while noting that there is substantial evidence before this period. A summary of the earlier papers can be found in:

- a review of evidence on the interactions of beavers with the natural and human environment in relation to England (NEER017) (Howe, 2020)
- Beaver: Nature’s ecosystem engineer (Brazier and others, 2021)

- Dam Builders and Their Works: Beaver Influences on the Structure and Function of River Corridor Hydrology, Geomorphology, Biogeochemistry and Ecosystems (Larsen and others, 2021)

To summarise, beaver:

- reintroduction can help reduce flooding for small flood events either locally or at a small catchment scale
- dams can reduce longitudinal (downstream) connectivity, while at the same time increasing lateral floodplain connectivity
- dams increase surface water storage and elevate water tables
- dam sequences and wetlands can attenuate flow in low and high flow periods
- dams work well in locations where they create complex wetlands, often in headwaters and tributaries and encompass benefits realised from leaky woody barriers, river and floodplain restoration, offline storage areas
- dams may not be created by beavers if the existing water depth is deep enough for them to be safe
- dam benefits may increase as features develop
- dams may increase hydraulic roughness
- dams may reduce and slow flow velocities
- dams create temporary storage and attenuate flood flows
- dams increase floodplain connectivity
- dams may trap fine sediment
- dams may create areas of sediment
- dams may encourage sediment sorting
- reintroduction can lead to the creation of new channels and in-channel features

The dams beavers create to slow flood flows:

- encourage the river to reconnect with its floodplains
- enable the storage of floodwaters on the floodplain
- increase floodplain inundation depth

Beavers may also:

- result in challenges with FCRM objectives, although there are management and mitigation measures that reduce or remove these
- adapt to different environments, using both rural and urban watercourses
- build dams against infrastructure, including culverts, bridges and trash screens
- build dams that may erode with time and block infrastructure and adjacent agricultural land
- burrow into river banks, affecting their structural integrity
- build dams whose performance may vary,
- build dams that are not in a desired location for FCRM benefit

The research gaps at the time were a need for:

- a greater mechanistic understanding of the hydrological impacts (and cumulative impacts) of beaver dams and beaver dam cascades across different catchment scales, rivers, and as their populations increase
- understanding of the conditions of dam failure and associated consequences
- greater understanding of the impacts of beaver landscape engineering on low flow conditions and wetland maintenance during drought
- evidence to suggest whether beaver dam analogues/leaky woody debris dams could function as 'starter dams' to encourage beaver damming in locations that optimise the potential benefits of beavers in NFM, while minimising the potential conflict

4.5.3 New flood risk evidence

For more detailed information relating to the studies used to formulate the following summaries, please see the literature review.

We have **medium** confidence in the effect that beavers have on flood risk. While there has been much research in North America and Europe, there is less research in the UK, although this is a rapidly growing body of evidence.

A review of the latest evidence found that:

- beaver dams can reduce flow velocities and increase storage capacity; this was shown in several papers (Puttock and others, 2017; Neumayer and others, 2020; Westbrook and others, 2020; Graham and others, 2022)
- beavers can reduce peak flows, but more research at different catchment scales is needed (Puttock and others, 2017; Smith and others, 2020; Puttock, Graham, and others, 2021; Graham and others, 2022)
- beavers can increase groundwater storage but may not affect discharges (Karran and others, 2018; Smith and others, 2020)
- beaver dams lead to sediment storage; multiple papers agree with this (Puttock and others, 2017; Puttock and others, 2018; Levine and Meyer, 2019)
- beavers can improve floodplain connection (Graham and others, 2022)
- beaver presence can positivity influence other wildlife and provide drought resilience (Karran and others, 2018; Brown and others, 2018; Willby and others, 2018; Law and others, 2019; Puttock, Graham, and others, 2021; Graham and others, 2022; Wikar and others, 2023)

Effects at different scales

We have **low to medium** confidence in the effects of beavers at different scales. This is from understanding before the original evidence directory as no new literature was identified regarding different catchment scales as part of this review, and there is limited understanding of the impacts of beavers at larger (100 km^2 to 1,000 km^2) catchment scales within the UK.

Effects on different watercourse typologies

We have **medium** confidence in the effects of beavers on different watercourse typologies due to the limited new literature to improve our understanding. It should be noted that catchment type has not been inferred from knowing the catchment location, therefore, unless the literature has stated the type of catchment studied, it has not been included in this section. The new literature suggests that:

- beaver reintroduction can increase groundwater storage and leakage
- the presence of beaver dams can improve water table stability
- a study in Alberta, Canada found the water table to lower when beaver dams had been breached (Karran and others, 2018; Smith and others, 2020)

Effects on sediment and geomorphology

We have **high** confidence in the effects of beavers on sediment and geomorphology. This confidence has been derived from both evidence prior to the original evidence directory and new literature. The new literature suggests that:

- beaver dams and ponds can accumulate sediment (Puttock and others, 2017; Puttock and others, 2018)
- ponds with larger surface areas tend to accumulate more, and this builds over time, with older ponds containing more sediment than new ponds (Puttock and others, 2018)
- beavers have been seen to increase lateral channel erosion (Gorczyca and others, 2018)

Design life and effectiveness and maintenance

Beaver dams are dynamic, ephemeral natural features. There is guidance available on the management of beaver populations in the UK. We, therefore, have **medium** confidence in our understanding of the maintenance requirements. Guidance available in the UK includes:

- Beavers: how to manage them and when you need a licence - GOV.UK (www.gov.uk)
- Advice and recommendations for beaver reintroduction, management and licensing in England. Second edition. Natural England NEER019. York. POUGET, D. & GILL, E.L. 2021

4.5.4 New multiple benefits evidence

Evidence prior to 2017 suggested that beavers and the dams they build result in water quality improvement through sediment retention, habitat provision, climate regulation, resilience to low flows and contributions to flood risk reduction.

New evidence suggests that beavers and the dams they build:

- can increase surface and groundwater storage (Karran and others, 2018) and reduce the frequency of low flows (Graham and others, 2022) and, therefore, mitigate against drought (Fairfax and Whittle, 2021)
- may have the potential to store carbon (Puttock and others, 2017; Larsen and others, 2021) and increase carbon sequestration (Karran and others, 2018; Puttock and others, 2018), however anoxic conditions may slow carbon cycling (Larsen and others, 2021)
- may prefer native softwoods over invasive wood species (Juhász and others, 2020)
- can increase species richness and abundance (Wikar and others, 2023), increasing the variety of species (Karran and others, 2018), creating a more biodiverse environment (Willby and others, 2018)
- can result in spatial heterogeneity of water temperature (Ecke and others, 2017; Majerova and others, 2020; Hafen and others, 2020), which may, however, be buffered by groundwater interactions and relate to the number of dams (Larsen and others, 2021)
- often trap sediment in beaver ponds (Puttock and others, 2018), however excavation, activity and dam collapse may lead to an export of sediment (Brazier, Elliott and others, 2020), with pond size being the greatest control on storage of sediment (Puttock and others, 2017)
- can store nutrients (phosphorus, nitrogen) (Puttock and others, 2017; Puttock and others, 2018), with retention more likely if hydraulic gradient or flow is low (Wegener and others, 2017), however others have suggested that overall water quality improvements are limited (Smith and others, 2020)
- may impact nutrient storage, however there are mixed views on whether age relates to improved nutrient storage (Murray and others, 2021)
- may impact heavy metal contamination but there is conflicting evidence around the benefits of beavers to heavy metal contamination (Briggs and others, 2019; Murray and others, 2021)

The multiple benefits of beavers are reflected in Figure 14. The presence of beavers may result in improvements to water quality by storing sediment and associated nutrients, improve biodiversity by creating new habitat, increase groundwater storage and, therefore, mitigate against drought and increase carbon storage and sequestration.

The multiple benefits wheel tool is only intended to be used as a visual aid to suggest where additional benefits may be sought when implementing the measures for flood risk. It should not be used as part of detailed quantitative analysis or optimisation of options.

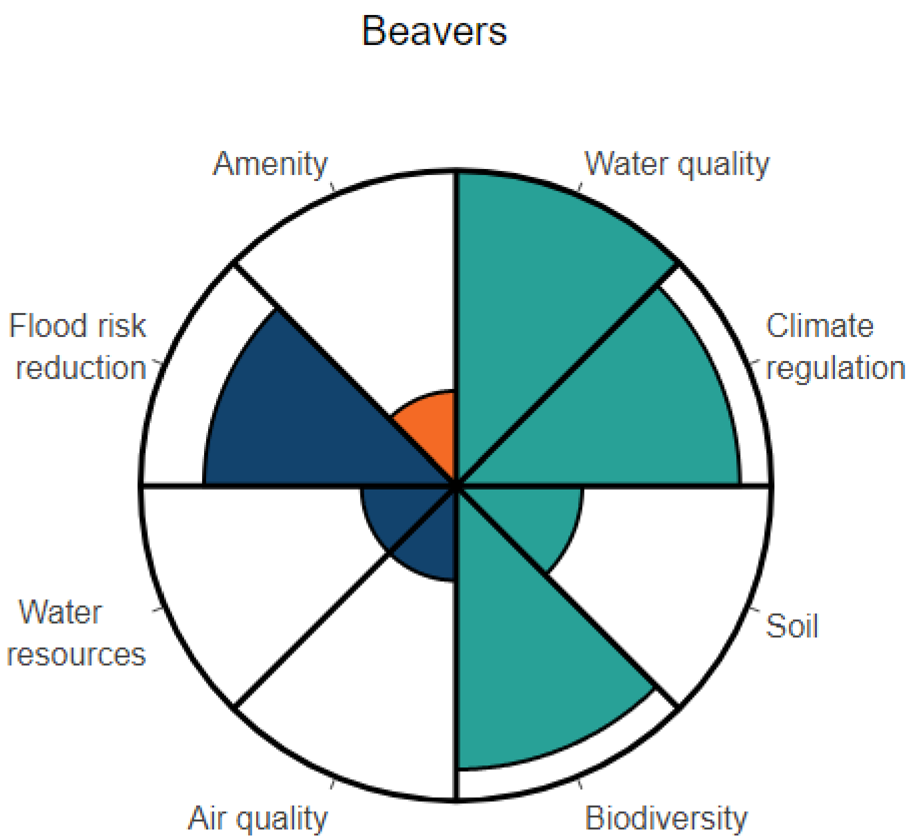

Figure 14 - Multiple benefits wheel for Eurasian beavers

4.5.5 Research gaps

Despite new evidence coming to light since the original evidence directory, there are remaining research gaps to allow us to continue to improve our understanding of Eurasian beaver dams. We still need:

- further examples from both real-world data and modelled scenarios to build further confidence in the evidence, particularly from the UK
- understanding around the hydrological impacts of beaver dams and sequences of beaver dams across scales and land uses
- understanding around the conditions of dam failure and consequences
- research into how beaver dam sequences affect water flow under different conditions
- further information on dam structure, number and location of dams in catchments required to have significant downstream flood reduction benefits
- to build further confidence in the evidence, especially densely populated and intensively managed European landscapes

- greater understanding of beaver landscape engineering on low flow conditions and wetland maintenance during drought
- evidence to suggest whether beaver dam analogues/leaky woody debris dams could function as ‘starter dams’ to encourage beaver damming in optimal locations
- to understand how to best represent within models
- to understand the most effective management and maintenance techniques for beavers

4.6 Offline storage areas

4.6.1 What are offline storage areas?

Offline storage areas are floodplain areas that have been adapted to retain and attenuate floodwater in a managed way. They usually require the construction of a containment bund which increases the amount of water that can be stored on a floodplain and may also require an inlet, outlet and potentially a spillway mechanism.

Figure 15 shows an example of an offline storage area in Cottesbrooke with water being retained in a field and trees in the distance.

Figure 15 - Cottesbrooke offline storage area (image credit: Ryan Jennings, JBA Consulting)

Many different terms are used internationally to describe offline storage areas. However, the important difference between these definitions is the size and amount of engineering involved in the design. For example, the terms washlands (larger scale) and run-off attenuation features (smaller scales) are frequently used.

This section focuses on small to medium scale offline storage areas rather than engineered flood storage areas. The latter are typically online and built to reservoir safety standards, with an outflow controlled by flow control devices.

4.6.2 Findings from the 2017 evidence base

What we knew about offline storage areas in 2017

The 2017 evidence base showed that offline storage areas:

- work instantaneously
- can reduce flow velocities and create temporary storage which attenuates flood flows
- can reduce flood risk locally for small flood events
- can trap fine sediment during flood flows
- need to be bigger or more numerous as catchment size increases because a greater volume of storage is needed to reduce flood risk
- may require maintenance

What were the research gaps?

The evidence gaps identified for offline storage areas showed that there is limited information on:

- their effectiveness at mitigating flood peaks at the catchment scale for larger flood events
- their cumulative effects, including upscaling the impacts of using many smaller scale offline storage areas distributed throughout a catchment
- how to identify best locations for potential storage areas
- how these types of features affect peak synchronisation during a series of events, including any diminishing flood store benefits
- how effective they are in different watercourse types
- how quickly storage will fill with sediments and require maintenance
- how these types of feature function in groundwater-fed catchments
- their maintenance requirements
- whether a cascade of small offline storage areas counts as a reservoir under the Reservoirs Act

4.6.3 New flood risk evidence

For more detailed information relating to the studies used to formulate the following summaries, please see the literature review.

We have **medium** confidence in the effect that offline storage areas have on flood risk; this remains unchanged from the original evidence directory as despite an increase in the evidence available, it often contradicts itself depending on site and design characteristics.

A review of the latest evidence has found that offline storage areas:

- can reduce peak flow (Chappell and others, 2023) according to some modelled studies
- can create storage, but the rate of drainage impacts the available storage and the ability to mitigate flood events which come in quick succession (Nicholson and others, 2020; West Cumbria Rivers Trust, 2021b; Lockwood and others, 2022; Pearson, 2023a)
- remain full or overspill during minor flood events, reducing the flood attenuation function (West Cumbria Rivers Trust, 2021c; Majeed, 2023)

Some studies found outlet design is important to ensure sufficient and timely drainage (West Cumbria Rivers Trust, 2021c; Lockwood and others, 2022).

Effects at different scales

We have **medium** confidence in the effects of offline storage areas at different scales. This remains unchanged from the original evidence directory due to limited new literature. The limited new literature suggests that:

- offline storage areas can provide temporary storage to help reduce flood risk; this has been demonstrated through modelled evidence
- modelling at the catchment scale showed a series of large ponds on the floodplain can reduce flow peak; this can also cause delays to the peak (by 6 hours) (Nicholson and others, 2020)

Effects on different watercourse typologies

We have **low** confidence in the effects of offline storage areas on different watercourse typologies, which remains unchanged from the original evidence directory due to no new evidence being identified as part of this review.

Effects on sediment and geomorphology

We have **medium** confidence in the effects of offline storage areas on sediment and geomorphology. This remains unchanged from the original evidence directory due to no new evidence being identified as part of this review.

Design life and effectiveness

We have **high** confidence in the design life and effectiveness of offline storage areas. This remains unchanged from the original evidence directory. This evidence suggests that:

- the design of offline storage areas can impact the measure's effectiveness
- for inlet-filling ponds, fill thresholds must be at a level which allows direct filling from the channel during major events; in some instances, flows might not be high enough to fill ponds via the inlet
- the rainfall required to allow inlet filling may vary seasonally; adjusting inlet heights or mechanisms to management inflows throughout the year is, therefore, essential (Lockwood and others, 2022)
- correctly designing pond outlets is crucial for ensuring sufficient spilling and, therefore, the availability for the pond to store water during the peak of a flood event
- drainage can take time after events and so this should be carefully considered in design (Lockwood and others, 2022)
- there are some issues with water storage areas overflowing even in relatively modest flood events; increasing the size of outflow pipes or adding a second outflow pipe to improve water outflows may be required - this would help offline storage areas operate effectively during multiple flood events in quick succession (West Cumbria Rivers Trust, 2021c)

Maintenance

We have **medium** confidence in our understanding of the maintenance requirements of offline storage areas. This remains unchanged from the original evidence directory due to no new evidence being identified as part of this review.

4.6.4 What are the changes in the evidence from 2017?

The main changes in the evidence since 2017 are:

- more information on the importance of outlet design has been presented
- evidence on the ability to attenuate flows and store water has been developed, although there is some conflict within the literature
- no new evidence on the maintenance requirements for offline storage areas was identified
- no evidence on the multiple benefits of offline storage areas was identified

4.6.5 New multiple benefits evidence

Evidence prior to 2017 suggested that offline storage areas result in water quality improvements, habitat provision depending on how the storage areas are managed, enhancement of long-term supply of water, and improvements to amenity if designed for recreation and flood risk benefits.

There was no new literature identified which looked into the multiple benefits of offline storage areas created for WWNP flood risk benefits. The multiple benefits of offline storage areas are reflected in Figure 16. Offline storage areas have significant associated flood risk reduction benefits and can result in long-term water resources benefits.

Improvements to biodiversity and water quality will depend on how they are managed. There may also be some amenity benefits if they are designed for recreation.

The multiple benefit tool is only intended to be used as a visual aid to suggest where additional benefits may be sought when implementing the measures for flood risk. It should not be used as part of detailed quantitative analysis or optimisation of options.

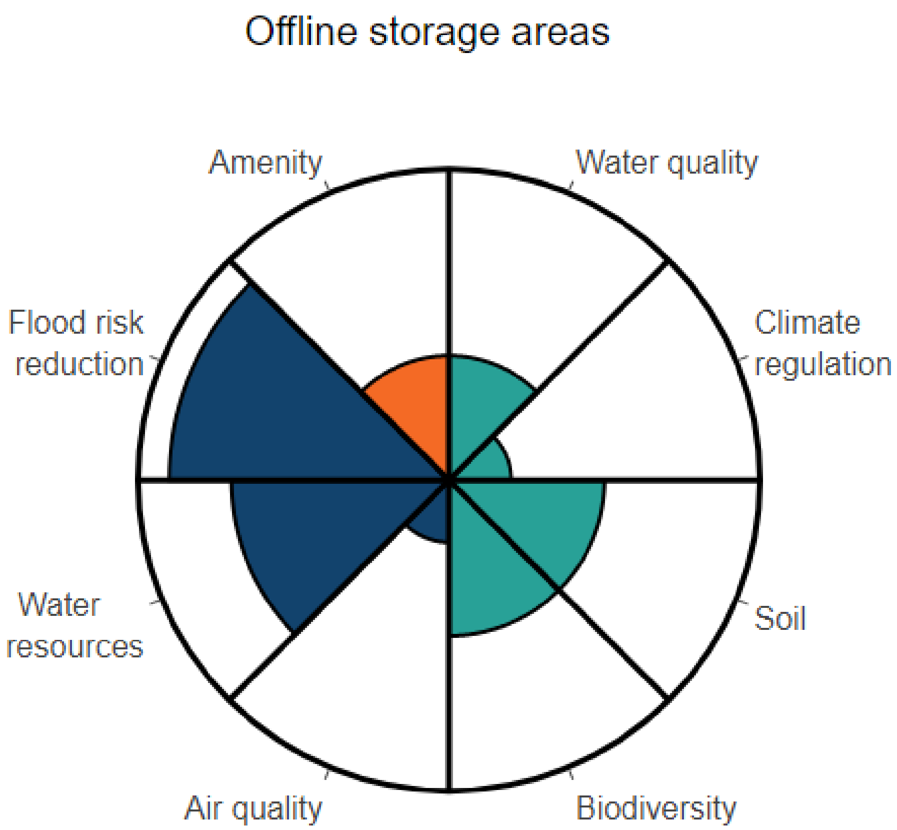

Figure 16 - Multiple benefits wheel for offline storage areas

4.6.6 Research gaps

Despite new evidence coming to light since the original evidence directory, there are remaining research gaps to allow us to continue to improve our understanding of offline storage areas. We still need to improve our understanding of:

- evidence to suggest how flood peak flow reductions translate into flood risk reductions and how offline storage areas may help reduce wider flood risks (for example, help in hard engineered asset control)
- their effectiveness at mitigating flood peaks at the catchment scale for larger flood events
- their cumulative effects, including upscaling the impacts of using many smaller scale offline storage areas distributed throughout a catchment

- how to identify best locations for potential storage areas
- how these types of features affect peak synchronisation during a series of events, including any diminishing flood store benefits
- how effective they are in different watercourse types
- how quickly storage will fill with sediments and require maintenance
- how these types of feature function in groundwater-fed catchments and other alternative catchment types and models to allow for their representation in such catchments
- the difference between more natural features and more engineered features
- their maintenance requirements
- the risk that a cascade of small offline storage areas could be considered a reservoir under the Reservoir Act
- how to design offline storage areas to provide a wider range of benefits

5 Woodland management

5.1 Introduction

This chapter summarises the evidence around the effectiveness of the following woodland management measures in reducing flood risk:

- catchment woodland
- cross-slope woodland
- floodplain woodland
- riparian woodland

The term ‘woodland’ is used to describe land predominantly covered in trees (with a canopy cover of at least 20%), whether in large tracts (generally called forests) or smaller areas known by a variety of terms (including woods, copses, spinneys, or shelterbelts). The terms woodland and forest are used interchangeably throughout this chapter.

Please note that any new literature that assesses the impacts of combinations of NFM measures is covered in Chapter 8 (Cross-cutting).

5.2 Catchment woodland

5.2.1 What is catchment woodland?

Catchment woodland is defined as the total area of all woodland within a catchment. It combines general woodland cover of all types and species, including plantations, plus specific forms where present, such as cross-slope, riparian and floodplain woodland.

Figure 17 shows an example of a catchment woodland at the Broughton Park Estate. There are small trees planted in a field surrounded by fencing.

Figure 17 - Catchment Woodland, Broughton Park Estate (image credit: Caitlin Rees, JBA Consulting)

5.2.2 Findings from the 2017 evidence base

What we knew about catchment woodland in 2017

The 2017 evidence base identified that catchment woodland:

- can reduce flood risk, although the extent of this reduction decreases as flood magnitude increases
- can reduce peak flows, with studies of new planting showing reductions ranging from 5% to 65%, with the largest reductions seen for smaller events in smaller catchments
- can reduce peak flows according to modelling studies which predict reductions ranging from 3% to 70%, with a main factor being the scale of woodland planting or felling within a catchment
- can affect flood generation and conveyance through increased interception, wet canopy evaporation, soil permeability and storage, and increased surface roughness
- can increase peak flow between 20% and 172% according to 16 out of 50 studies which looked at the FCRM impacts of felling at catchment scale

- tends to have a greater impact on peak flows when planting or felling conifer compared to broadleaved woodland
- has greatest effect on peak flows for small and medium flood peaks
- impacts on peak flows are very difficult to detect when the extent of planting or felling is <15 to 20% of the catchment; and catchment size is greater than 100 km^2 due to limited scale/area of change in woodland cover usually involved; this does not necessarily mean that catchment planting on smaller scales or in larger catchments may not influence flood risk

What were the research gaps?

The research gaps identified were:

- the effect on large flood flows and the contribution it makes to reducing flood flows generally
- how the standard of flood protection provided varies according to the amount and type of woodland, its placement in the catchment, and the size of the catchment
- appropriate parameter ranges to ensure catchment woodland processes are modelled effectively to help predict their flood risk benefits
- the need to improve the way that hydrology, hydraulic and coupled models represent woodland hydrological processes and to test the upscaling of these to the catchment level
- understanding whether there is a greater flood risk benefit if the catchment woodlands are more connected/less fragmented
- understanding the different designs, management methods and maintenance types of agro-woodlands and the efficacy of these for flood risk

5.2.3 New flood risk evidence

For more detailed information relating to the studies used to formulate the following summaries, please see the literature review.

We have a **medium to high** level of confidence in the effect that catchment woodland has on flood risk because there have been significant updates to evidence, but there still remains a lack of evidence in large catchments and for large events.

A review of the latest evidence has found that:

- woodlands can reduce the risk of downstream flooding through increased interception, soil permeability and storage, and surface roughness (Mawdsley and others, 2017; Soulsby, Dick and others, 2017; Mawdsley and others, 2017; Fahey and Payne, 2017; Soulsby, Braun and others, 2017; Chandler and others, 2018; Bathurst and others, 2018; Zabret and Šraj, 2019; Page and others, 2020; Bathurst and others, 2020; Murphy and others, 2021; Ponte and others, 2021; Ponte and others, 2021; Monger, Spracklen and others, 2022; Xiao and others, 2022; Revell and others, 2022; Monger, Bond and others, 2022)

- wet canopy evaporation occurs from both broadleaved and evergreen woodlands (Soulsby, Braun and others, 2017; Zabret and Šraj, 2019; Page and others, 2020; Ponte and others, 2021; Xiao and others, 2022); one study suggests that coniferous interception is higher than broadleaved (Zabret and Šraj, 2019)
- benefit from woodland (all species types) declines as flood magnitude increases (Soulsby, Dick and others, 2017; Fahey and Payne, 2017; Iacob and others, 2017; Bathurst and others, 2020; Ferguson, 2020; Bond and others, 2022; Xiao and others, 2022; Collins and others, 2023); the limited evidence suggests benefit could be insignificant for extreme events, however, 2 papers suggest that catchment woodland can still be effective in larger storms (Monger, Spracklen and others, 2022; Kingsbury-Smith and others, 2023)
- woodland is more effective in smaller catchments, mainly due to higher percentage woodland cover in smaller catchments, but this may also be due to a lack of data in larger catchments (Bezak and others, 2021; Hankin, Page, Chappell and others, 2021; Buechel and others, 2022; Xiao and others, 2022; Acuña-Alonso and others, 2022)
- the extent of woodland within the catchment is more important than location (Barnsley, 2021; Gilbert, 2021a; Hankin, Page, Chappell and others, 2021; Bond and others, 2022; Buechel and others, 2022): this is supported by modelling studies that look at higher percentage woodland cover scenarios than can be practically implemented (Iacob and others, 2017; Dittrich and others, 2019; Ferguson, 2020; Barnsley, 2021; Collins and others, 2023), however, some papers do suggest that location is an important factor (Chappell and others, 2017; Iacob and others, 2017; Buechel and others, 2022; Acuña-Alonso and others, 2022); the impact of these factors may be influenced by catchment size
- soils and geology play a dominant role in storm run-off, particularly in upland catchments and for larger events; 2 papers suggest this (Peskett and others, 2021; Peskett and others, 2023), but the research around this impact is limited
- the nature of woodland management impacts the efficacy of the measure (understory management, roads, ditches (particularly in peat catchments), soil health, grazing) (Chandler and others, 2018; Hernández-Morcillo and others, 2018; Bathurst and others, 2018; Bathurst and others, 2020; Murphy and others, 2021; Peskett and others, 2021; Ponte and others, 2021; Monger, Bond and others, 2022; Yu and others, 2022)
- soil hydraulic conductivity is higher under coniferous forest than under broadleaved, although this can depend on the age of trees and management (grazed versus ungrazed); both are higher than pasture (Chandler and others, 2018)
- planting conifer woodland tends to have a greater impact on peak flows than broadleaved woodland, however, the study on which this is based only differentiated between the 2 woodland types by attributing coniferous woodland with higher evapotranspiration rates than broadleaved woodland; hydraulic roughness

was not considered, nor were potential soil differences between the 2 woodland types (Iacob and others, 2017)

- coniferous woodland could be more effective for reducing peak flow than broadleaved woodland (Iacob and others, 2017; Chandler and others, 2018), but ditching and/or road networks may result in coniferous woodland being less effective than pasture/grassland (Bathurst and others, 2020)
- catchment woodland could be less effective in winter, with some papers suggesting that this may be because soils are already saturated (Soulsby, Dick and others, 2017; Iacob and others, 2017; Revell and others, 2022)
- woodland can reduce peak flow and increase time to peak, and is more effective when a higher proportion of the catchment is afforested and in smaller events (Chappell and others, 2017; Iacob and others, 2017; Dittrich and others, 2019; Ferguson, 2020; Barnsley, 2021; Gilbert, 2021a; Hankin, Page, Chappell and others, 2021; Bond and others, 2022; Buechel and others, 2022; Acuña-Alonso and others, 2022; Kingsbury-Smith and others, 2023; Collins and others, 2023)
- woodlands can provide multiple environmental benefits, including biodiversity, climate regulation, recreation/health, and volunteering (Scridel and others, 2017; Moseley and others, 2018; Blackstock, 2020; Barnsley, 2021; Chadwick, 2021b; Dartmoor National Park and Environment Agency, 2021)
- forests reduce baseflows, meaning that water resources are reduced (Fahey and Payne, 2017; Iacob and others, 2017; Bentley and Coomes, 2020; Buechel and others, 2022; Yu and others, 2022; Aghajani and others, 2023c; Collins and others, 2023), although one study found a partial flow recovery after initial decreases (Bentley and Coomes, 2020)
- in catchments where woodland was felled, baseflows increased, with the scale of impact being dependent on the size of area felled; this was based on 1 study (Xiao and others, 2022)

Effects at different scales

We have varying levels of confidence in the effects of catchment woodland at different scales. We have **high** confidence in the effects of catchment woodland in small catchments, **medium** confidence in the effects of catchment woodland in medium sized catchments and **low** confidence in the effects of catchment woodland in large catchments. This remains unchanged from the original evidence directory due to a lack of new literature. The new literature suggests that:

- findings from small catchments might not directly apply to very large catchments (Bezak and others, 2021; Xiao and others, 2022), primarily because the affected portion in larger basins is relatively small, and variations are dampened by combined sub-catchment outflows
- in larger UK catchments (over 500 km^2), the extent of afforestation holds greater significance than the specific location of afforestation efforts; this was suggested by modelled evidence from 1 study (Buechel and others, 2022)

Effects on different watercourse typologies

We have **low to medium** confidence in the effects of catchment woodland on different watercourse typologies. This remains unchanged from the original evidence directory due to a lack of new literature. In one study, afforestation has shown promise in generating flood peak reductions in chalk-dominated groundwater catchments, although substantial trade-offs arise, given the need to convert extensive areas of land to woodland for these effects to materialise (Barnsley, 2021).

Effects on sediment and geomorphology

We have **medium** confidence in the effects of catchment woodland on sediment and geomorphology. This has been reduced from the original evidence directory due to a lack of literature around the ability of woodland to modify and/or reduce sediment pathways. The new literature suggests that:

- in a medium catchment with low baseline erosion rates in Maine, forestry best management practices can reduce severe erosion events, but as events become more extreme and frequent, especially under climate change, significant sediment mobilisation events will occur more often (Cook and others, 2020)

Design life and effectiveness

We have **medium** confidence in the design life and effectiveness of catchment woodland. This has been reduced from the original evidence directory as there is not enough evidence around effective design. The new literature suggests that:

- catchment woodland in UK upland headwater catchments can take around 15 years to show soil changes significant enough to reduce flows (Murphy and others, 2021)
- mature, unmanaged, semi-natural woodlands with varied structures have greater surface roughness than those with spare understorey vegetation; this results in the former exhibiting reduced overland flow; this was suggested by 1 study (Monger, Bond and others, 2022)
- diverse forests may be more resilient to climate change (Hernández-Morcillo and others, 2018), with one paper suggesting that diverse forests may be more effective for regulating annual run-off (Yu and others, 2022)
- excluding livestock may be important to ensure that the maximum flood risk benefits are achieved, to ensure survival of saplings, increase surface roughness, and to increase soil infiltration (Dartmoor National Park and Environment Agency, 2021; Murphy and others, 2022; Monger, Bond and others, 2022)

Maintenance

We have **high** confidence in our understanding of the maintenance requirements of catchment woodland. This remains unchanged from the original evidence directory due to a lack of new literature.

5.2.4 New multiple benefits evidence

Evidence prior to 2017 suggested that catchment woodland results in water quality improvement, habitat provision, climate regulation, resilience to low flows, health access, and contributions to flood risk reduction.

New evidence suggests that catchment woodland:

- may reduce low flows and/or baseflow (Fahey and Payne, 2017; Iacob and others, 2017; Bentley and Coomes, 2020; Buechel and others, 2022; Yu and others, 2022; Aghajani and others, 2023c; Collins and others, 2023), although one study found a partial flow recovery after initial decreases (Bentley and Coomes, 2020)
- may reduce peak flows in future climates (Barnsley, 2021) and sequester carbon (Chadwick, 2021b)
- that is native broadleaf is advantageous to native bird species, providing shelter, shade, perches and song posts (Scridel and others, 2017; Dartmoor National Park and Environment Agency, 2021)

The multiple benefits of catchment woodland are reflected in Figure 18. Catchment woodland may result in many multiple benefits, with particularly large benefits relating to climate regulation and biodiversity. Catchment woodland also has strong benefits for amenity, water quality, soil health, flood risk reduction and air quality. Evidence has, however, suggested that catchment woodland can reduce low flows and/or baseflow, negatively affecting water resources.

The multiple benefits wheel tool is only intended to be used as a visual aid to suggest where additional benefits may be sought when implementing the measures for flood risk. It should not be used as part of detailed quantitative analysis or optimisation of options.

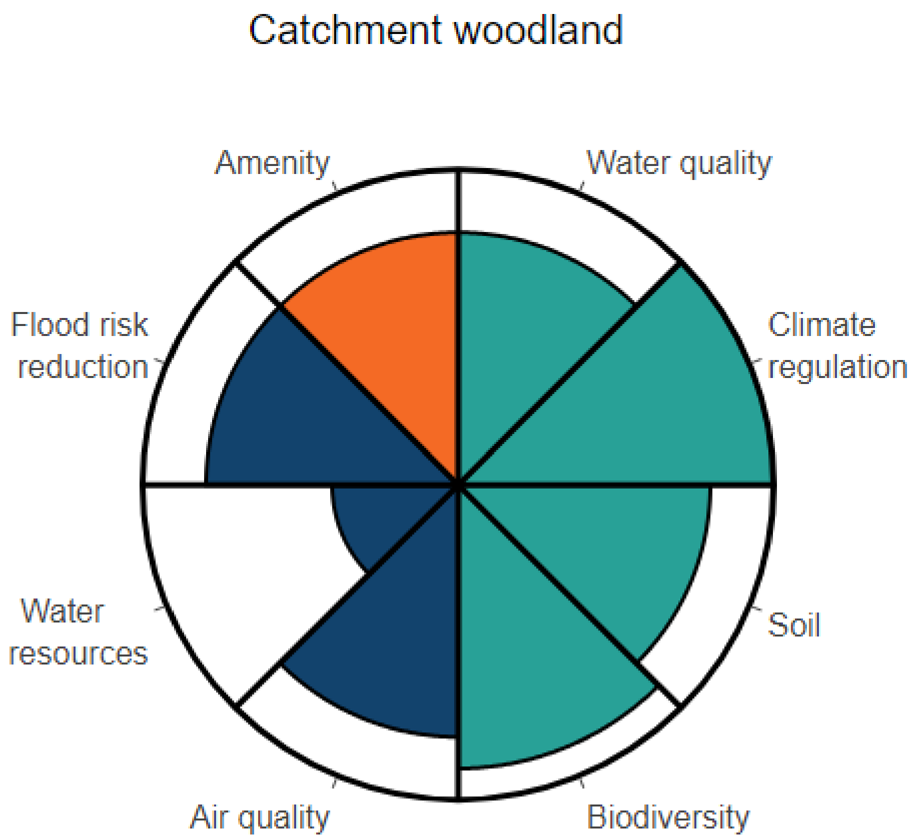

Figure 18 - Multiple benefits wheel for catchment woodland

5.2.5 What are the changes in evidence from 2017?

The main changes in evidence since 2017 are:

- there is more evidence that wet canopy evaporation remains a significant process even in increasing storm event magnitudes; observed evidence from Page and others, (2020) shows that evaporation from both woodland types can be much higher than previously observed, although it remains higher for coniferous woodland
- there is now evidence of the improvements in soil hydrology following woodland creation, although some studies suggest that this impact can be limited if grazing under trees continues
- that it has expanded

5.2.6 Research gaps

Despite new evidence coming to light since the original evidence directory, there are remaining research gaps to allow us to continue to improve our understanding of catchment woodland. Many of these more general research gaps would also be relevant to the other types of woodland within the evidence directory. These are:

- evidence to suggest how flood peak flow reductions translate into flood risk reductions and how catchment woodland may help reduce wider flood risks (for example, help in hard engineered asset control)
- a need to better quantify how the type of woodland, its placement in the catchment and catchment size affects the flood risk impact
- the impacts of woodland creation in large catchments; these are less well studied with studies still largely confined to small to medium sized catchments
- the impact of woodlands reducing peak discharge during large events which is still not fully understood, with studies often struggling to demonstrate a significant impact
- understanding of the significance of wet canopy evaporation for flood risk mitigation with a potential disparity between flow data collected from catchment studies and measurements from forest plot studies
- understanding the impact of wet-canopy evaporation during significant events; one meta-study shows that it could be significant, but more evidence is needed

Difference in woodland types and placement

Further work is required to establish:

- the difference in impact on flood peaks and run-off between different woodland types, such as ancient woodland, wet woodland and wood pasture
- whether alternative designs for woodlands would provide better flood risk benefits compared to conventional practices, including the significance of their placement within the catchment
- whether there is a greater flood risk benefit if the catchment woodlands are more connected/less fragmented

Woodland management

Further work is needed on woodland management to establish:

- the impact of different management methods (drainage during site preparation in particular) on run-off and flood peaks, particularly with increasing catchment scale. The impact of these methods also varies significantly depending on design such as drain spacing, gradient and connectivity, soil type, and antecedent conditions
- the impact of micro-topographies, wheel ruts and vehicle tracks, including how they affect the efficacy of riparian woodland buffer strips
- the impact of different grazing intensities, and different species (sheep versus cows) on tree regeneration, soil properties, and surface roughness in wood pasture
- the effect of tree stocking density on soil permeability and surface roughness through measurements

- the relative benefits of semi-natural woodland versus wood pasture, in upland pasture in particular
- the long-term impact of reduced grazing levels, natural regeneration and woodland creation on streamflow and soil properties using monitoring

The impact of woodland/deforestation on peatlands

The impact of woodland on peatlands needs further work as:

- the impact of peat deforestation and restoration on run-off, peak flows, and the hydrograph is poorly quantified in literature
- to how the flow/hydrograph changes in the short and long term after forest-to-bog restoration
- the long-term, wider societal and environmental benefits of restoring afforested areas to functioning peatlands (including removing conifer plantation) are not well understood, particularly quantitatively (biodiversity, carbon, water quality)
- the greenhouse gas implications of forestry on peatland (including over shallow versus deep peat) are not well understood
- natural capital values for open, afforested and restored peatlands of various ages are not known

Modelling requirements

Further work on modelling requirements needs to establish:

- that the Manning's n roughness coefficient is ‘far from’ constant in shallow overland flows; the creation of more robust Manning's n data sets, covering different vegetation types, vegetation structure and management regimes, would be beneficial for improving modelling
- better model parameters and data to validate these are required for representing woodland hydrological processes to assess their flood risk impacts and to test the upscaling of these to the catchment level
- the daily balance of rainfall and throughfall (combined with stemflow) beneath tree canopies; the data should be collected at better time resolutions so that more reliable rates of wet canopy evaporation specific to extreme events can be used in modelling; data for sites with different characteristics (regional climate, altitude, aspect and slope) and different woodland designs (including tree species) would be beneficial

Impacts of climate change

Climate change impacts need to be better understood, particularly:

- the impact on the efficacy of woodland for NFM
- how trees will react to climate change (increased temperature, pests, fire, disease)

Impact in groundwater catchments

Very little is known on how woodland can be used as effective NFM in catchments that experience groundwater flooding, due to limited woodland cover and larger scale of groundwater catchments, which are more difficult to represent within modelling. More detailed flood maps and understanding of groundwater emergence is needed.

5.3 Cross-slope woodland

5.3.1 What is cross-slope woodland?

Cross-slope woodland is defined as the placement of smaller areas or typically belts of woodland across hill slopes. It can comprise all woodland types and species and can be managed as either productive or unproductive woodland.

The main purpose of cross-slope woodland from a WWNP perspective is to intercept and reduce rapid run-off from upslope land. This draws on the higher infiltration rates, potentially greater soil water storage capacities and higher surface roughness of woodland.

Figure 19 shows an example of cross-slope woodland planting in Kenwith with small trees planted along a grassy slope and mature trees in the distance.

Figure 19 - Cross-slope woodland planting, Kenwith (image credit: Sophia Craddock, Environment Agency)

5.3.2 Findings from the 2017 evidence base

What we knew about cross-slope woodland in 2017

The 2017 evidence base showed that:

- the localised nature of this woodland type makes it difficult to measure its impact on flood flows at the catchment scale (there is an absence of measured data for this type of woodland)
- soil infiltration rates can be 67 times higher within woodland plots and shelterbelts planted on improved grassland compared with grazed pasture, which reduced measured run-off volumes by an average of 78% compared with the control. Soil hydraulic conductivity values were also higher beneath the woodland (2.4 times) due to a greater proportion of larger soil pores and flow pathways provided by the tree roots. These were findings from the Pontbren study
- planting tree strips across 7% of a 12 km^2 headwater catchment could reduce a severe flood event (0.5% AEP) by an average of 5%. These were findings from a modelling study drawing on the process measurements at Pontbren
- the contribution of hydraulic roughness to slowing run-off is dependent on the structural characteristics of the individual woodland
- alignment/width/placement of cross-slope woodland in relation to surface run-off pathways has a big influence on its effectiveness at reducing flood run-off, the narrower the woodland, the larger the upslope area contributing run-off, and the shallower the soil, the smaller the expected effect

What were the research gaps?

More work was needed to establish:

- how to calculate the most effective width of the woodland to reduce flood risk
- how transferable the results from Pontbren are to other locations
- how woodland design/management alters the effectiveness of cross-slope woodland, for example, what size, width, type, density and age of woodland is needed to have greatest FCRM benefit
- the effect of a targeted and integrated network of cross-slope woodland across a range of catchment sizes on flood risk
- how to improve and test the ability of hydrology models to upscale process understanding from the plot/site level to the catchment scale to better predict the effects of cross-slope woodland on flood risk
- the impact of cross-slope planting on water retention during a sequence of storm events

5.3.3 New flood risk evidence

For more detailed information relating to the studies used to formulate the following summaries, please see the literature review.

We have a **low** level of confidence in the effect that cross-slope woodland has on flood risk because of the lack of recent observed data. A review of the latest evidence found that for cross-slope woodland:

- the effect may be localised; 1 study showed soil moisture dynamics returning to those similar to grassland 15 m downslope of the woodland (Peskett and others, 2020)
- in the wettest conditions, the storage capacity of a forest strip could be easily overwhelmed if the surrounding land cover is less permeable (Peskett and others, 2020) according to one study
- flood peaks can be moderately reduced, with it being more effective in lower magnitude events or intense summer storms, this is seen in both observed evidence (Peskett and others, 2020) and in modelling studies (Mason-McLean, 2020; Ferguson and Fenner, 2020; Willis and Klaar, 2021)
- most studies look at smaller catchments, where percentage woodland coverage is higher; there is a lack of evidence for the efficacy in larger catchments
- there are limited new studies, particularly including observed data

Effects at different scales

We have **low** confidence in the effects of cross-slope woodland at different scales which has been reduced from the original evidence directory due to low confidence in other parts of the review and no new evidence being identified as part of this review.

Effects on different watercourse typologies

We have **low** confidence in the effects of cross-slope woodland on different watercourse typologies which has been reduced from the original evidence directory due to limited understanding in different types of catchment, low confidence in other parts of the review of cross-slope woodland and no new evidence being identified as part of this review.

Effects on sediment and geomorphology

We have **low** confidence in the effects of cross-slope woodland on sediment and geomorphology which remains the same as the original evidence directory as no new evidence was identified as part of this review.

Design life and effectiveness

We have **low** confidence in the design life and effectiveness of cross-slope woodland which has been reduced from the original evidence directory as no new literature was identified as part of this review, particularly around width, planting density and placement.

Maintenance

We have **high** confidence in our understanding of the maintenance requirements of cross-slope woodland. This remains the same as the original evidence directory as no new literature was identified as part of this review.

5.3.4 New multiple benefits evidence

Evidence prior to 2017 suggested that cross-slope woodland results in water quality improvement, biodiversity and surface water flood benefits. There was no new literature identified which looked into the benefits of cross-slope woodland created for WWNP flood risk benefits. The multiple benefits of cross-slope woodland are reflected in Figure 20.

The multiple benefits wheel tool is only intended to be used as a visual tool to suggest where additional benefits may be sought when implementing the measures for flood risk. It should not be used as part of detailed quantitative analysis or optimisation of options.

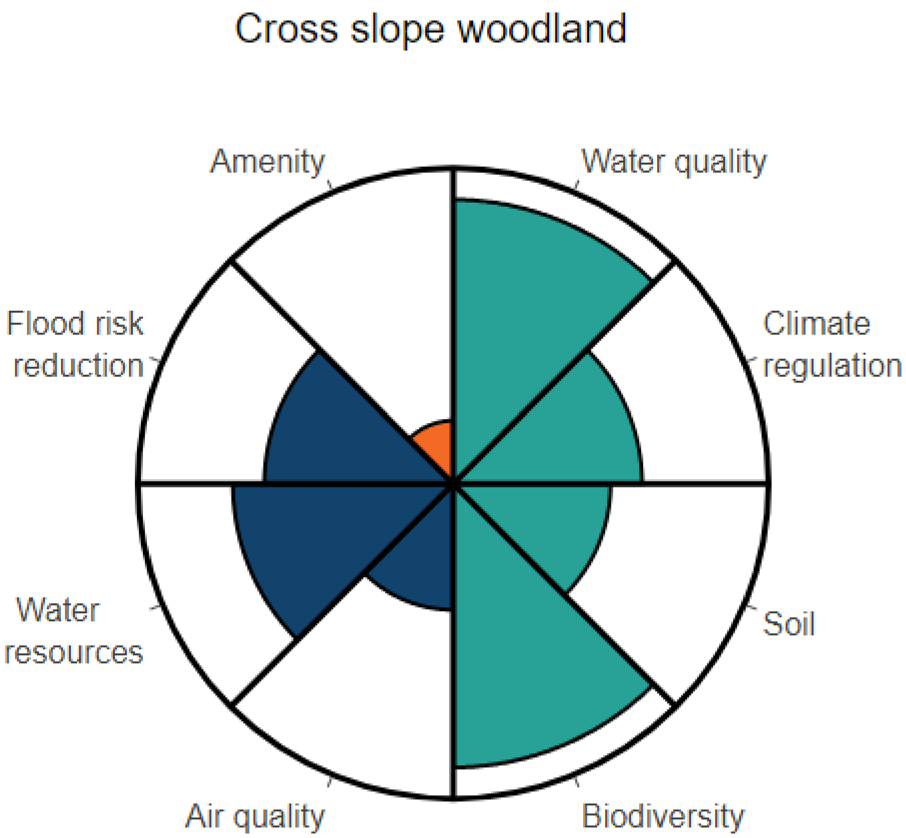

Figure 20 - Multiple benefits wheel for cross-slope woodland

5.3.5 What are the changes in evidence from 2017?

There are no changes to what the 2017 evidence suggested, but the evidence base has expanded, with more modelling studies carried out. Observed evidence is still sparse for this woodland type.

5.3.6 Research gaps

Despite some new evidence coming to light since the original evidence directory, there are remaining research gaps to allow us to continue to improve our understanding of cross-slope woodland. We still need:

- evidence to suggest how flood peak flow reductions translate into flood risk reductions and how cross-slope woodland may help reduce wider flood risks (for example, help in hard engineered asset control)
- to know the impact of differing slope angle and slope length on the efficacy of cross-slope woodland for NFM
- further research on what the optimal soil/geological conditions, extents, and locations of forest cover are in order to have a larger catchment-scale influence
- to know how woodland design/management alters the effectiveness of cross-slope woodland, for example, what size, width, type, density and age of woodland is needed for the greatest benefit
- more studies of large catchments, as studies are still largely confined to small to medium sized catchments
- measurements on the effect of tree stocking density on soil permeability and surface roughness
- studies on the relative benefits of semi-natural woodland versus wood pasture, in upland pasture in particular
- to know how to improve and test the ability of hydrology models to upscale process understanding from the plot/site level to the catchment scale to better predict the effects of cross-slope woodland on flood risk
- to know the impact of cross-slope planting on water retention during a sequence of storm events

5.4 Floodplain woodland

5.4.1 What is floodplain woodland?

Floodplain woodland is defined as all woodland lying within the fluvial floodplain that is subject to an intermittent, regular, planned or natural flooding regime. It typically comprises broadleaved woodland and can range from productive woodland on drier, intermittently flooded, areas to unmanaged, native wet woodland in wetter areas. While the terms ‘riparian woodland’ and ‘floodplain woodland’ can often be used interchangeably, floodplain woodland usually covers a larger area than riparian woodland, often extending >5 m on either side of watercourses.

Figure 21 shows a floodplain woodland at Fforestganol, Caerphilly with water flowing in between mature trees and the ground beneath covered with leaves.

Figure 21 - Natural floodplain woodland, Fforestganol, Caerphilly (image credit: Eleanor Pearson, JBA Consulting)

The main role of floodplain woodland from an NFM perspective is to slow down and hold back flood flows within the floodplain, as well as to enhance sediment deposition and thereby reduce downstream siltation. This draws on the higher hydraulic roughness presented by floodplain woodland in the form of trees, shrubs and deadwood, as well as the potential additional floodwater storage provided by associated multiple water channels and backwater pools.

5.4.2 Findings from the 2017 evidence base

What we knew about floodplain woodland in 2017

The 2017 evidence base showed that floodplain woodland:

- influences flood flows in a similar way to riparian woodland but with a larger footprint
- has the potential to reduce flood risk which is usually greatest in the middle and lower river reaches in medium to large catchments
- affects both floodplain and channel hydraulic roughness by the physical presence of the trees, undergrowth and deadwood, as well as by the influence of these on diverting floodplain flows and driving the formation of multiple channels and backwater pools
- suffers from a lack of catchment studies measuring impact on flood peaks, and so modelled data provide the best source of evidence at the catchment level
- reduces water velocity and raises water levels on the floodplain with laboratory-based flume and process modelling studies demonstrating how its size/placement/orientation affects energy loss by resistance and turbulence
- has the greatest hydraulic roughness of all vegetation types, with a Manning's 'n' value 5 times greater than grassland
- can significantly reduce water velocities and increase water levels on the floodplain, but with a relatively small reduction in flood peak (0 to 6%), but with a significant delay to flood peak timing (by up to 2 hours or more), providing significant scope to desynchronise sub-catchment flood waves and further reduce peak height
- can have a high water use, which can significantly increase the capacity for below-ground storage of floodwater
- can capture/filter river sediments, reducing downstream siltation and maintaining channel conveyance
- **Important** - can increase flood risk (via peak synchronisation/backwater effect), although this impact can be reduced through careful design/placement

What were the research gaps?

In 2017, more work was needed to establish:

- the effect of creating a large floodplain woodland across a range of catchment sizes on flood flows and the standard of protection

- how important the different effects of floodplain woodland (for example, water use and evaporation, soil infiltration and storage, soil erosion and sediment delivery) are at reducing flood risk and how these vary between different types of woodland and catchment
- improvements to the way that models represent floodplain woodland in terms of woodland processes and appropriate parameter values
- how we can better capture the effects of floodplain woodland on local energy losses (for example, drag forces) and on floodplain geomorphology to incorporate into user-friendly models
- the effect of floodplain woodland on low flows/droughts
- how terrestrial woodlands compare with wet woodlands from an FCRM perspective
- how best to use floodplain woodland combined with leaky dams to avoid flood synchronisation effects

5.4.3 New flood risk evidence

For more detailed information relating to the studies used to formulate the following summaries, please see the literature review.

We have a **low to medium** level of confidence in the effect that floodplain woodland has on flood risk; this remains unchanged from the original evidence directory due to the lack of research at catchment scale.

A review of the latest evidence has found that floodplain woodland:

- mainly impacts flood flows by increasing surface roughness on the floodplain, slowing the flow and retaining water on the floodplain (Carling and others, 2020; West Cumbria Rivers Trust, 2021b)
- is more effective at reducing peak flows in smaller events; 1 modelling study suggest this (Carling and others, 2020)
- has the ability to retain and slow flood flows but that this diminishes with increasing flood depth/flow. This was suggested by 1 lab study (Carling and others, 2020)
- has a greater impact on reducing peak flow than upstream afforestation; 1 study suggests this (Dittrich and others, 2019)
- can provide a multitude of environmental co-benefits, including biodiversity, water quality and cultural services (Cosgrave, 2017; Stutter and others, 2020; AECOM and The Nature Conservancy, 2021; Spray and others, 2021; West Cumbria Rivers Trust, 2021b)
- has limited new studies

Effects at different scales

We have **low to medium** confidence in the effects of floodplain woodland at different scales. This remains unchanged from the original evidence directory as no new literature was identified as part of this review.

Effects on different watercourse typologies

We have **low to medium** confidence in the effects of floodplain woodland on different watercourse typologies. This has been lowered from the original evidence directory as no new literature was identified as part of this review.

Effects on sediment and geomorphology

We have **medium to high** confidence in the effects of floodplain woodland on sediment and geomorphology. This remains unchanged from the original evidence directory as no new literature was identified as part of this review.

Design life and effectiveness

We have a **medium to high** confidence in the design life and effectiveness of floodplain woodland. This remains unchanged from the original evidence directory as there is limited new evidence. This evidence suggested that planting short rotation willow coppice on floodplains has a greater impact on increasing hydraulic roughness when planted in rows that run across the direction of flow (West Cumbria Rivers Trust, 2021b).

Maintenance

We have a **medium to high** confidence in our understanding of the maintenance requirements of floodplain woodland. This has been lowered from the original evidence directory as no new literature was identified as part of this review.

5.4.4 New multiple benefits evidence

Evidence prior to 2017 suggested that floodplain woodland results mostly in improvements to habitat and climate regulation.

New evidence suggests that floodplain woodland:

- can provide thermal refugia habitat for a range of species, and specialised habitats for wet woodland in particular (Cosgrave, 2017; Stutter and others, 2020; AECOM and The Nature Conservancy, 2021; Spray and others, 2021; West Cumbria Rivers Trust, 2021b)
- provides foraging habitat for birds and improves habitat connectivity (West Cumbria Rivers Trust, 2021b)
- can foster community involvement in environmental conservation (Cosgrave, 2017) where student, corporate and volunteer groups conduct invasive species control and plant native tree species

The multiple benefits of floodplain woodland are reflected in Figure 22. Floodplain woodland may result in significant benefits to biodiversity. It can also have water quality, soil and climate regulation benefits. New literature suggests that wet woodland can break down and slow the transport of pollutants and provides specialised habitat. Floodplain woodland can provide thermal refugia and also foraging habitat, improving habitat connectivity. Water resources benefits are relatively limited from floodplain woodland.

The multiple benefits wheel tool is only intended to be used as a visual aid to suggest where additional benefits may be sought when implementing the measures for flood risk. It should not be used as part of detailed quantitative analysis or optimisation of options**Error! Reference source not found.**.

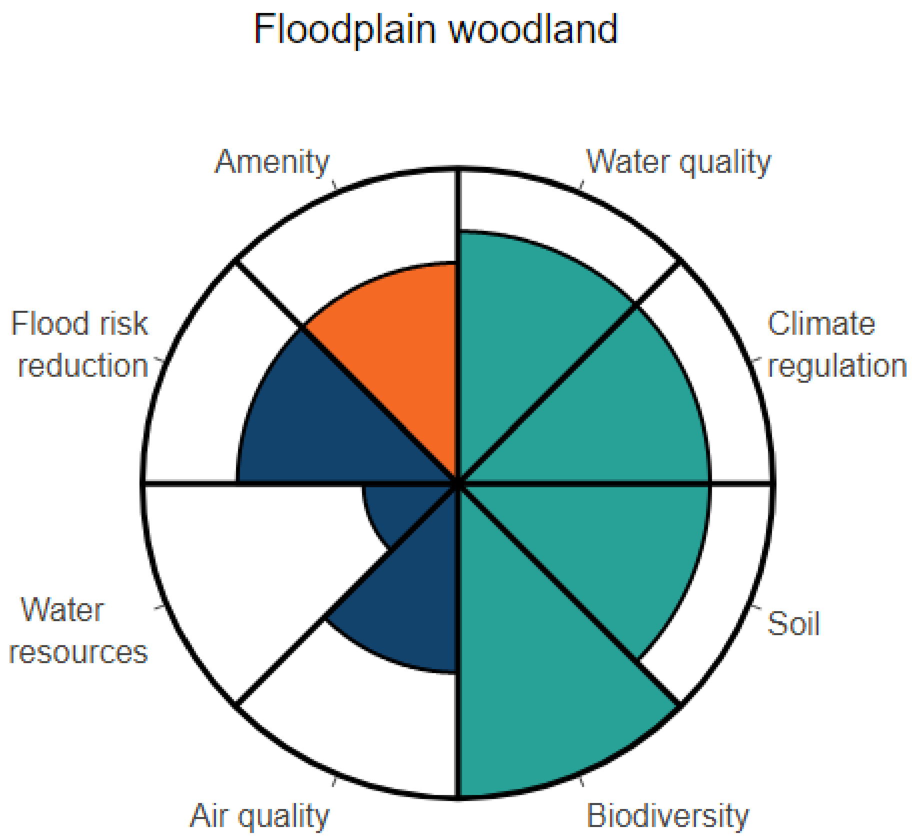

Figure 22 - Multiple benefits wheel for floodplain woodland

5.4.5 What are the changes in evidence from 2017?

There are no changes to what the 2017 evidence suggested, but the evidence base has expanded. There are still a lack of catchment studies measuring floodplain woodland impact on flood peaks, and modelling studies since 2017 are also sparse.

5.4.6 Research gaps

Despite new evidence coming to light since the original evidence directory, there are remaining research gaps to allow us to continue to improve our understanding of floodplain woodland. We still need:

- evidence to suggest how flood peak flow reductions translate into flood risk reductions and how floodplain woodland may help reduce wider flood risks (for example, help in hard engineered asset control)
- to improve our understanding of the effect of creating a large floodplain woodland across a range of catchment sizes on flood flows and flood peak reduction
- to improve our understanding of how important the different effects of floodplain woodland are (for example, water use and evaporation, soil infiltration and storage, soil erosion and sediment delivery) at reducing flood risk and how these vary between different types of woodland and catchments
- to improve the way that models represent floodplain woodland in terms of woodland processes and appropriate parameter values, particularly floodplain roughness data
- to understand how we can better capture the effects of floodplain woodland on local energy losses (for example, drag forces) and on floodplain geomorphology to incorporate into user-friendly models
- to understand how terrestrial woodlands compare with wet woodlands from an FCRM perspective
- to understand how best to use floodplain woodland combined with leaky barriers to avoid flood synchronisation effects

5.5 Riparian woodland

5.5.1 What is riparian woodland?

Riparian woodland is described as woodland located within the riparian zone, defined here as the land immediately adjoining a watercourse or standing water. While the terms riparian woodland and floodplain woodland can often be used interchangeably, the riparian zone is usually relatively narrow, often extending 5 to 10 m on either side of watercourses. This, therefore, allows for the natural addition of large woody debris into the watercourse. It typically comprises native broadleaved woodland and is often unmanaged. In the past, conifer plantations extended into riparian zones, but most of these areas have now been cleared and are being restored to native woodland or more open semi-natural vegetation.

Figure 23 shows a riparian woodland with a stream running through a field in Oughtershaw in the Yorkshire Dales. Small trees are planted along the edge of the stream.

Figure 23 - Riparian woodland planting, Oughtershaw in the Yorkshire Dales (image credit: Jenny Broomby, JBA Consulting)

The main role of riparian woodland from an NFM perspective is to slow down and hold back flood flows within the riparian zone, as well as to reduce sediment delivery and bankside erosion. This draws on the higher hydraulic roughness presented by riparian woodland in the form of trees, shrubs and deadwood, including associated large woody structures within water channels, which deflect and encourage out-of-bank flows. Studies have demonstrated that planting trees along watercourses effectively decreases the rate of water entry into these channels. This is achieved by enhancing surface resistance to overland water flow and increasing the soil's capacity for water infiltration (Willis and Klaar, 2021).

Riparian buffer strips, which are strips of vegetation that provide a barrier between fields and watercourses and can contain long grasses, trees or shrubs, are covered in the run-off management chapter under 'run-off pathway management'.

5.5.2 Findings from the 2017 evidence base

What we knew about riparian woodland in 2017

The 2017 evidence based showed that for riparian woodland:

- benefits at reducing flood flows have been well studied at the reach level

- above-ground water storage is increased by the friction created by riparian trees and the barrier effect of ‘leaky’ woody dams/structures within channels; this slows flows and stores water
- leaky dams can be used to reduce flood risk, with these potentially making a greater contribution to the reduction in flood risk
- high evaporation losses can create additional below-ground water storage
- which slows water, it is effective at enhancing sediment deposition in the riparian zone, reducing downstream in-channel siltation
- the impact on flood flows is much less researched at the catchment scale; as a result, modelled data provide the best source of evidence at the catchment level
- modelling studies provide a range of results, with most predicting that riparian woodland can reduce flood peaks by 2 to 8% for events smaller than 1% AEP
- modelling has demonstrated that the placement of it in a catchment has a pronounced influence on its flood risk impact; the largest reductions in peak flows resulted from planting arrangements which help desynchronise flood flows – typically in the middle and upper catchment
- modelling studies underestimate the impact of it on flood flows by not fully incorporating the full range of woodland processes
- **Important** - washout of woody material can potentially increase flood risk by downstream blockage, this risk can be managed by appropriate design/maintenance

What were the research gaps?

In 2017, more work was needed to establish:

- the effect of creating an extended network of riparian woodland across a range of catchment sizes on flood flows and standard of protection
- how important the various effects of riparian woodland (for example, water use and evaporation; soil infiltration and storage; soil erosion and sediment delivery) are at reducing flood risk, and how these vary between different types of woodland and catchment (including interactions with leaky woody structures)
- improvements in the way that models represent riparian woodland processes, in terms of woodland processes and appropriate parameter values
- appropriate parameters and calibrated models to explore the effects of different woodland design/management on flood risk, including extent and placement within catchment

5.5.3 New flood risk evidence

For more detailed information relating to the studies used to formulate the following summaries, please see the literature review.

We have **medium** confidence in the effect that riparian woodland has on flood risk; this has been increased from the original evidence directory due to an increase in the amount of literature available.

A review of the latest evidence has found that for riparian woodland:

- mature trees can add large woody debris to watercourses, increasing hydraulic resistance and channel complexity, but there may be a lag time of 45 to 50 years before the benefits are fully realised, to account for trees maturing; this was found in 1 study (Dixon and others, 2019)
- younger trees may not delay lag time, with older/denser forests offering higher hydraulic resistance in one study (Antonarakis and Milan, 2020; Black and others, 2021)
- tree species and canopy should be considered, as canopy height and density may impact hydraulic resistance, according to 1 study (Antonarakis and Milan, 2020)
- unmanaged, older, semi-natural riparian woodland is likely to exert greater roughness than evenly spaced and young pine plantation; 1 study suggests this (Antonarakis and Milan, 2020)
- Manning's n is seen to increase in simulated lab experiments (compared to grassland), with a staggered arrangement being more effective than a regular grid arrangement (Jumain and others, 2018; Jumain and others, 2021)
- flood peaks can be reduced; this was based on modelling in 2 studies (Willis and Klaar, 2021; Hankin, Page, McShane and others, 2021), with the impact being marginally higher in smaller catchments than in larger catchments in 1 study (Willis and Klaar, 2021)
- additional storage can result on the floodplain as a result of the increased riparian friction and that this is crucial to the peak flow reductions; this was highlighted by 1 study (Hankin, Page, McShane and others, 2021)
- it appears to be more effective in shorter return period events; this was based on 1 modelling study (Willis and Klaar, 2021)
- gullying can be reduced by reducing erosion; this was found in 1 monitoring study (Marden and Seymour, 2022)
- flow resistance can be increased, which leads to a reduction in velocity of the channel flow; this was shown in 1 laboratory study (Jumain and others, 2018; Jumain and others, 2021)
- establishment time can be particularly important, as it is vulnerable to being washed away during high flow events; 1 study showed this (Blackstock, 2020)

Effects at different scales

We have **low to medium** confidence in the effects of riparian woodland at different scales. This remains unchanged from the original evidence directory, with no new literature being identified as part of this review.

Effects on different watercourse typologies

We have **low to medium** confidence in the effects of riparian woodland on different watercourse typologies. This remains unchanged from the original evidence directory, as no new literature was identified as part of this review.

Effects on sediment and geomorphology

We have **medium to high** confidence in the effects of riparian woodland on sediment and geomorphology. This remains unchanged from the original evidence directory due to limited new evidence being available. The new literature suggests that:

- 35,000 ha of afforestation on gully-prone pastureland in New Zealand led to a 45% net reduction in the number of eroding gullies; however, this success was tempered by a significant increase in the number of new gullies formed in unplanted areas (both in unplanted pastoral land and remnant areas of indigenous forest) during the study period - therefore, the present hill country area affected by gullies is only slightly reduced by 5% compared to pre-1960s levels (Marden and Seymour, 2022).
- riparian vegetation increases flow resistance, leading to reduced channel flow velocity; 2 lab simulations implied this (Jumain and others, 2018; Jumain and others, 2021)

Design life and effectiveness

We have **medium to high** confidence in the design life and effectiveness of riparian woodland. This remains unchanged from the original evidence directory as there is limited new evidence. This evidence suggests that:

- woodland needs sufficient time to establish itself before a significant flood event occurs - without this, the planting could be vulnerable to being washed away by high rainfall events, potentially undermining its effectiveness in stabilising the bank (Blackstock, 2020)
- there is a delay of about 40 to 50 years between the initiation of riparian forest growth and the delivery of woody debris to the channel in a size that can enhance channel complexity and hydraulic resistance; the benefits of NFM may not be fully realised unless additional interventions are employed; this was found in 1 study (Dixon and others, 2019)
- to optimise deadwood delivery to the channel, especially sizeable and stable pieces, locally suitable mixed deciduous woodland species should be prioritised (Dixon and others, 2019)
- it may take over 100 years from the establishment of a new riparian forest to reach the necessary maturity for achieving maximum benefits in NFM; this encompasses the development of a complex floodplain surface and an ample supply of in-channel deadwood (Dixon and others, 2019)

Maintenance

We have **medium to high** confidence in our understanding of the maintenance requirements of riparian woodland. This remains unchanged from the original evidence directory, with no new literature being identified as part of this review.

5.5.4 New multiple benefits evidence

Evidence prior to 2017 suggested that riparian woodland results in water quality improvement, habitat provision, climate regulation, cultural activities and contributions to flood risk reduction.

New evidence suggests that riparian woodland:

- creates marginal habitats (Blackstock, 2020)
- provides thermal refugia (Drayer and others, 2017; Stutter and others, 2020; AECOM and The Nature Conservancy, 2021; Spray and others, 2021)
- potentially reduces nitrate concentrations (Kowalska and others, 2021)

The benefits of riparian woodland are reflected in Figure 24. Riparian woodland may result in amenity benefits as well as benefits to water quality and biodiversity, with new literature suggesting that riparian woodland provides thermal refugia, creates marginal habitats and potentially reduces nitrate concentrations. It also provides climate regulation benefits. Water resources, air quality and soil benefits are more limited from riparian woodland.

The multiple benefits wheel tool is only intended to be used as a visual aid to suggest where additional benefits may be sought when implementing the measures for flood risk. It should not be used as part of detailed quantitative analysis or optimisation of options.

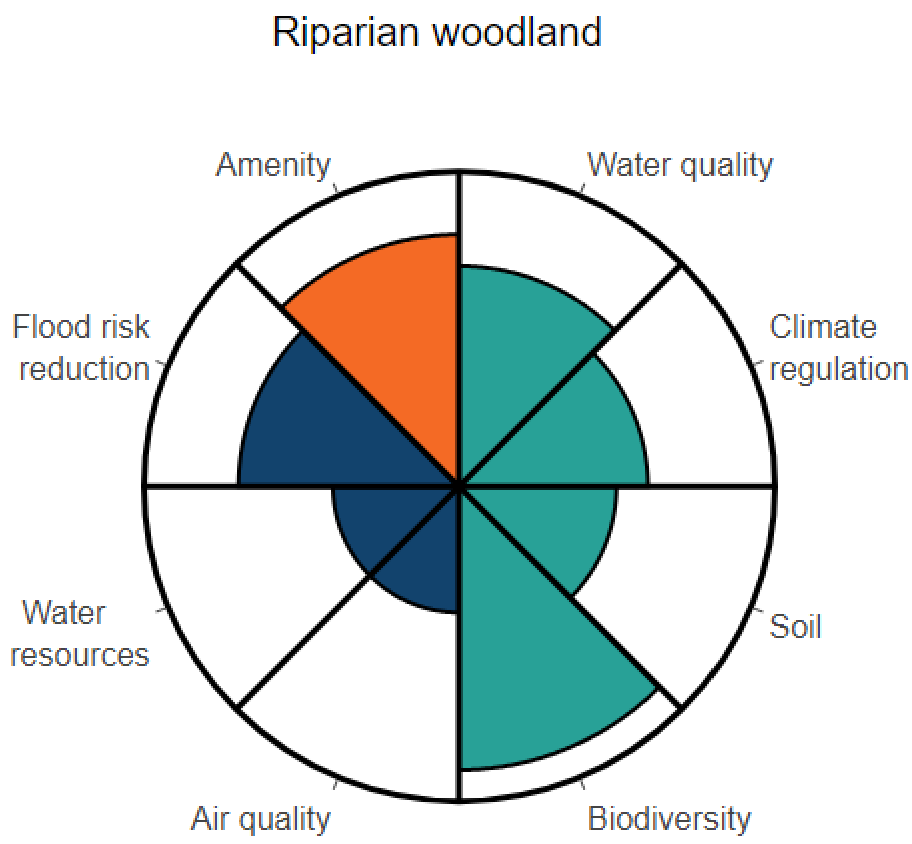

Figure 24 - Multiple benefits wheel for riparian woodland

5.5.5 What are the changes in evidence from 2017?

There are no changes to what the 2017 evidence suggested, but the evidence base has expanded. There is still a lack of catchment studies measuring riparian woodland impact on reducing flood risk, and modelling studies remain sparse.

5.5.6 Research gaps

Despite new evidence coming to light since the original evidence directory, there are remaining research gaps to allow us to continue to improve our understanding of riparian woodland. We still need:

- evidence to suggest how flood peak flow reductions translate into flood risk reductions and how riparian woodland may help reduce wider flood risks (for example, help in hard engineered asset control)
- to understand the effect of creating an extended network of riparian woodland across a range of catchment sizes on flood flows and standard of protection
- to understand the effectiveness of riparian woodland in extreme events
- to know how important the various different effects of riparian woodland (for example, water use and evaporation; soil infiltration and storage; soil erosion and

sediment delivery) are at reducing flood risk, and how these vary between different types of woodland and catchment, including interactions with leaky woody structures

- to understand the effect of different woodland designs while considering existing land management practices (for example, drainage) and ecohydrology
- to understand the difference in riparian woodland efficacy in different watercourse morphologies
- more evidence of the impact of riparian woodland in rapid response catchments
- more evidence of the effects of different species on the efficacy of riparian woodland
- to improve the way that models represent riparian woodland processes, in terms of woodland processes and appropriate parameter values
- to use appropriate parameters and calibrated models to explore the effects of different woodland design/management on a flood risk, including extent and placement within catchment

6 Run-off management

6.1 Introduction

This chapter summarises the evidence around the effectiveness of run-off management measures in reducing flood risk include soil and land management, run-off pathway management and headwater peatland restoration. This reflects a change in structure from the original evidence directory.

Restoring natural processes across the rural landscape can provide a wide range of benefits for the environment and people. From an FCRM perspective, these types of measures can intercept overland flow, restore soils to help store water, encourage infiltration and increase the hydraulic roughness and morphological complexity of rivers and floodplains. This, in turn, slows floodwaters and reconnects rivers to floodplains to temporarily store floodwaters.

Of the measures covered in this chapter, some of the run-off pathway management measures are seen to be the most engineered, often involving the construction of flow control structures to enable their full operation.

6.2 Soil and land management

6.2.1 What is soil and land management?

This section summarises the evidence around the effectiveness of soil and land management measures in reducing flood risk. Soil and land management practices can increase the amount of surface storage, increase surface roughness, the rate of infiltration, and the capacity of the soil to store water. The size of the effect that these measures have on flood risk depends on the initial soil wetness, location and area of land managed relative to the size of the catchment.

Soil and land management includes:

- soil aeration, subsoiling and measures to reduce soil compaction
- for grassland systems, stocking density and vegetation cover
- arable systems (including machinery use)
- conservation tillage
- cover cropping
- crop rotations
- regenerative agriculture

Figure 25 shows an herbal ley of mixed grasses growing in Shipton-under-Wychwood with a building in the distance.

Figure 25 - Herbal ley, Shipton-under-Wychwood (image credit: Eleanor Pearson, JBA consulting)

6.2.2 Findings from the 2017 evidence base

What we knew about soil and land management in 2017

Soil aeration and subsoiling

In 2017, the evidence base for soil aerating and subsoiling showed that:

- there was high confidence that soil aeration and subsoiling does increase the ability for water to infiltrate and be stored in soil, but there is currently low confidence in the measure itself significantly reducing flood risk downstream
- there was conflict in the literature over whether land management in itself will provide a reliable solution to the flood problems at catchment scale with an increasing frequency and magnitude of extreme rainfall events, particularly given climate change projections (Fowler 2005)

Arable systems

In 2017, the evidence base for arable systems showed that:

- there was limited evidence or peer-reviewed literature from the UK which shows that changes in crop management reduce flood risk locally or at the catchment scale; the evidence that was available is also conflicting
- soil cultivation or tillage can, in the short term, have positive effects on soil water retention capacity by decreasing soil bulk density and increasing porosity (BIO Intelligence Service and Hydrologic 2014)
- early sowing and cover crops have a flood risk benefit; however, there was limited peer-reviewed literature available and it was conflicting

Grassland systems

In 2017, the evidence base for grassland systems showed that:

- there were limited findings from scientific experiments showing the impacts of stocking/destocking on run-off generation
- findings from scientific studies on this topic were conflicting, in some cases, it is assumed that trampling will cause compaction and reduce infiltration, while in other studies no significant difference was witnessed between soil infiltration rates on grazed and ungrazed plots

What were the research gaps?

Further work was needed to establish:

- how these measures reduce flood risk at a catchment scale
- more evidence (qualitative and quantitative) that takes into account the complexity of catchment hydrological connectivity, flood generating processes and land management across vast areas to determine the type of land management required to create an impact of flood risk on a catchment scale
- the uncertainties associated with hydrological science and how they compare to uncertainties in the potential benefits of the WWNP measures
- the effectiveness of land/soil management measures on flood risk at catchment scales (most are at the plot scale and upscaling these results is hard to do because the impacts are highly uncertain and spatially and temporally dependent; for example, the way in which weather moves across the catchment and the timings of tributary contributions to the main channel)
- the impacts of increasing flow attenuation in one tributary depends on the tributary's relationship with water delivered from other tributaries, consequently, determining whether land management will have an impact downstream is strongly scale dependent
- better modelling and prediction of the hydrological impacts of land use change
- the effect of soil and land use management measures on flood risk, further data and assessments were required
- how increasing measures on a larger scale impact other complex tributary interactions and flood risk downstream

- the dynamic nature of soil structure and its effects on hydrology, particularly how the seasonal variations of soil hydraulic properties are modified by tillage, compaction, cracking by repeated shrinking and swelling and soil sealing processes

6.2.3 New flood risk evidence

For more detailed information relating to the studies used to formulate the following summaries, please see the literature review.

We have **varying levels** of confidence in the effect that soil and land management have on flood risk. We have 'medium' confidence in soil aeration and subsoiling; this has been reduced from the original evidence directory as we have good process understanding, but limited evidence to support the impact of flood risk. We have 'high' confidence in techniques suited to grassland systems this is an increase from the original evidence directory due to an increase in the amount of literature available, and 'low to medium' confidence in techniques suited to arable systems; this remains unchanged from the original evidence directory. Overall, there is further evidence to show that soil and land management increases hydraulic conductivity and infiltration rates, but there is limited evidence showing a reduction in risk downstream.

A review of the latest evidence has found that:

- soil aeration and subsoiling can increase hydraulic conductivity and the ability for water to infiltrate and be stored in soil, and there is evidence to show the effect of soil compaction on run-off at a catchment scale; however, there is low confidence in its ability to significantly reduce flood risk downstream (Chalise and others, 2019; Wallace and Chappell, 2019; Blake and others, 2022; Mulligan and others, 2023); a lab study has confirmed this, but minimal research has been undertaken at a catchment scale (Lockwood, 2022)
- reducing stocking density can reduce peak flow; multiple observed and modelled studies have shown this (Gao and others, 2017; Bond and others, 2020; Willis and Klaar, 2021; Kingsbury-Smith and others, 2023)
- increasing vegetation cover slows the flow of run-off by increasing surface roughness; multiple studies have shown this (Gao and others, 2017; Rak and Steinman, 2019; Razmand and others, 2019; Peskett, 2020; Wallace and Chappell, 2020; Bond and others, 2020; Ellis, 2021a; Ellis, 2021b; Bond and others, 2022; Aghajani and others, 2023b; Aghajani and others, 2023d; Aghajani and others, 2023a; Aghajani and others, 2023c)
- reverting arable land to pasture showed increased evapotranspiration; 2 modelled studies showed this (Aghajani and others, 2023d; Aghajani and others, 2023c)
- culm grassland is particularly effective in reducing flood peaks, reducing them by an average of 6% in a catchment with 30% restored culm grassland (Ellis, 2021b)
- there is strong evidence to suggest that seasonal changes in vegetation mean that overland flow peaks vary over the course of a year (Bond and others, 2022)

- reducing stocking density reduces sediment erosion, and revegetation can restabilise the ground (Thomas and Abbott, 2018)
- maintenance of land following reduced stocking density and revegetation should focus on preventing single species dominance to improve surface roughness (Ellis, 2021b)
- there is limited evidence which shows that changes in crop management reduce flood risk locally or at the catchment scale; the evidence that is available is also conflicting (Berdeni and others, 2021)
- plants with deeper and more vertically oriented roots tend to improve soil infiltration more than other plants; laboratory studies investigating the impact of roots on soil infiltration found this which backs up existing understanding on soil infiltration (Zhang and others, 2020)

Effects at different scales

We have **varying levels** of confidence in the effects of soil and land management at different scales. We have ‘high’ confidence in soil aeration and subsoiling in small catchments, ‘medium’ confidence in medium sized catchments and ‘low’ confidence in large catchments. We have ‘low to medium’ confidence in techniques suited to grassland systems and ‘low to medium’ confidence in techniques suited to arable systems. These confidence limits remain unchanged from the original evidence directory as no new literature was identified as part of the review.

Effects on different watercourse typologies

We have **varying levels of** confidence in the effects of soil and land management on different watercourse typologies. We have ‘low to medium’ confidence in soil aeration and subsoiling. We have ‘low to medium’ confidence in techniques suited to grassland systems and ‘medium’ confidence in techniques suited to arable systems. This remains unchanged from the original evidence directory due to a lack of new literature. The new literature suggests that:

- in the Test catchment (862 km^2), modelled arable reversion to pasture resulted in increased evapotranspiration, decreased groundwater recharge, and decreased in baseflow; this became more pronounced as the proportion of land converted increased (Aghajani and others, 2023c).
- in a Thames sub-catchment (1,616 km^2), herbal ley crop rotations produced less than a 1% reduction in flow for return periods greater than 2 years; their effect on flooding in groundwater-dominated catchments should not be overstated (Collins and others, 2023)

Effects on sediment and geomorphology

We have **varying levels of** confidence in the effects of soil and land management on sediment and geomorphology. We have ‘high’ confidence in soil aeration and subsoiling. We have ‘medium to high’ confidence in techniques suited to grassland systems and ‘low’ confidence in techniques suited to arable systems. This remains unchanged from the original evidence directory due to a lack of new literature. The limited new literature suggests that:

- in 1 long-term study in New Zealand, land sliding and, therefore, sediment supply is disproportionately high in locations where livestock grazing occurs on steep hillslopes (Thomas and Abbott, 2018)
- cover cropping can reduce erosion, despite heavy rainfall (Robertson and Maddock, 2019)

Design life and effectiveness

We have **varying levels of** confidence in the effects of soil and land management on design life and effectiveness. We have 'high' confidence in soil aeration and subsoiling. We have 'medium to high' confidence in techniques suited to grassland systems and 'high' confidence in techniques suited to arable systems. This remains unchanged from the original evidence directory due to a lack of new literature. The new literature suggests that:

- combining soil and land management measures with other nature-based solutions (NBS) leads to efficiencies, but improved soil management means that fewer run-off attenuation features (RAFs) will be required, as less run-off is generated to fill them according to a modelling study (Aghajani and others, 2023a)
- introducing a diverse mix of vegetation which builds a rough surface will help to restore unimproved grassland; a study on culm grassland, comparing improved and unimproved grassland found this (Ellis, 2021a)

Maintenance

We have **varying levels of** confidence in the maintenance of soil and land management. We have 'high' confidence in soil aeration and subsoiling. We have 'medium to high' confidence in techniques suited to grassland systems and 'high' confidence in techniques suited to arable systems. This remains unchanged from the original evidence directory due to a lack of new literature. A study in Devon concluded that lower intensity management will preserve the benefits of aeration (Ellis, 2021a).

6.2.4 New multiple benefits evidence

Evidence prior to 2017 suggested that soil and land management results in water quality improvement, surface water flood risk reductions and improvements to habitat.

New evidence suggests that:

- stabilised water tables under culm grassland increased baseflow and slowed the release of water, contributing to drought resilience (Ellis, 2021a)

- soil organic carbon is likely to increase, but this is variable depending on measures implemented (Paustian and others, 2019; Chalise and others, 2019; Kühnel and others, 2019; McClelland and others, 2021)
- grass leys may reverse structural degradation, increase earthworm numbers, infiltration rates, macropore flow and saturated hydraulic conductivity, reduce bulk density and improved wheat yields (Berdeni and others, 2021)

The multiple benefits of soil and land management are reflected in Figure 26. Soil and land management may improve water and soil quality and can be beneficial for water resources. New evidence suggests that culm grassland stabilises the water table, increasing baseflow and slowing the release of water, contributing to drought resilience, and grass leys may reverse structural degradation and increase wheat yields. There is conflicting understanding on the impact on soil organic carbon, depending on the measure implemented. There was no new evidence for wider grassland types. There are potential biodiversity, climate regulation and air quality benefits. Amenity benefits are more limited.

The multiple benefit wheel tool is only intended to be used as a visual aid to suggest where additional benefits may be sought when implementing the measures for flood risk. It should not be used as part of detailed quantitative analysis or optimisation of options.

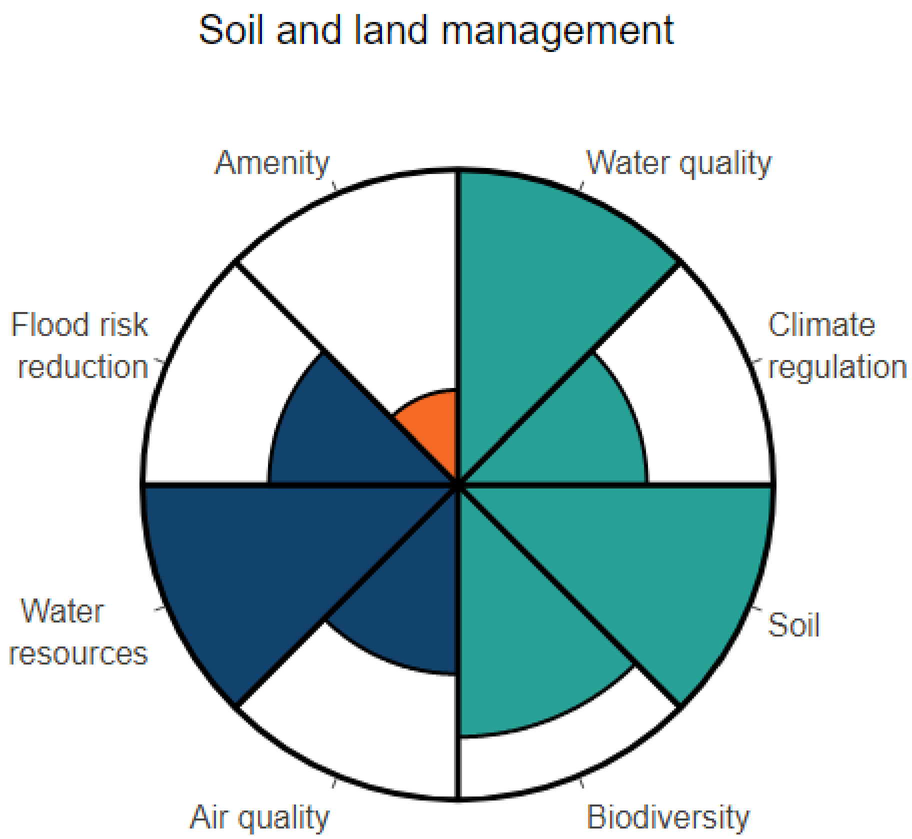

Figure 26 - Multiple benefits wheel for soil and land management

6.2.5 What are the changes in evidence from 2017?

The main changes to the evidence since 2017 are that:

- there is minimal new evidence to show that soil aeration and subsoiling reduces flood risk, although there is further confirmation that this increases the ability of water to infiltrate
- there is still limited evidence or peer-reviewed literature from the UK which shows that changes in crop management reduce flood risk locally or at the catchment scale, the evidence that is available is also conflicting, however, the impact of these measures on sedimentation has been studied in greater detail, and they have been shown to reduce erosion
- there has been more evidence for the benefits of regenerative agriculture
- there has been further research into the impacts of stocking density on flood peaks, with minimal conflict in the recent literature
- more evidence has been found for improving vegetation cover, with minimal conflict in the literature
- several laboratory studies have been carried out to investigate the impact of roots on soil infiltration, these back up existing understanding on soil infiltration

6.2.6 Research gaps

Despite new evidence coming to light since the original evidence directory, there are remaining research gaps to allow us to continue to improve our understanding of soil and land management. These is a need for:

- more evidence (qualitative and quantitative) that takes into account the complexity of catchment hydrological connectivity, flood generating processes and land management across vast areas to determine the type of land management required to create an impact on flood risk at a catchment scale
- evidence to suggest how flood peak flow reductions translate into flood risk reductions and how soil and land management may help reduce wider flood risks (for example, help in hard engineered asset control)
- more complex, long-term field experiments evaluating multiple alternative agricultural systems in whole catchments rather than individual practices
- further research to understand the potential synergies between optimal water outcomes and other ecological benefits at several scales, such as in relation to soil biology, nutrient cycling, and drought and flood impacts; more studies into the benefits of regenerative agriculture and rewilding are also needed
- more studies into the impact of degraded compared with healthy habitats on flood risk management
- more catchment scale evidence on the effectiveness of land/soil management measures on flood risk. Most of the evidence is at the plot/field scale. Upscaling these results is hard to do because, at the catchment scale, the impacts are highly

uncertain and spatially and temporally dependent (for example, the way in which weather moves across the catchment and the timings of tributary contributions to main channel) determining the impacts of increasing flow attenuation in one tributary depends on the tributary's relationship with water delivered from other tributaries, consequently, determining whether land management will have an impact downstream is strongly scale dependent

- better understanding of the dynamic nature of soil structure and its effects on hydrology, particularly how the seasonal variations of soil hydraulic properties are modified by tillage, compaction, cracking by repeated shrinking and swelling, and soil sealing processes
- greater understanding of the role of micro-topography and artificial drainage within soil and land management
- examination of sediment run-off following floods, for example, using tracers to understand how poor land management can lead to sedimentation throughout a catchment
- understanding of the benefit duration, and, therefore, the optimal management regimes, of soil and land management measures (particularly grass leys and subsoiling maintenance)
- evidence of the effects of soil aeration and subsoiling in different soil types, conditions, geologies and depth for both arable and grassland systems particularly studies showing the initial degradation state of soils and the subsequent efficacy of improvements
- future studies to test large-scale soil management improvements on wider catchment scales
- understanding of whether there is a difference in flood reduction depending on if a species native to the area or a more productive species is used on grassland
- more evidence of the length of rest period in rotational grazing to establish the optimum duration; this will require more observed study
- research into how unimproved grassland will interact with quick-to-implement NFM measures such as leaky barriers and storage ponds, as this may alleviate the issue of unimproved grassland taking several years to make changes to flood risk
- a quantitative relationship to be established between surface roughness and vegetation density which will continue to aid model development in future
- further study of land cover interventions to examine their impact on different catchment sizes and the topographic configurations of different land cover patterns
- exploration of further opportunities for expanding practices such as perennial crop use into agroecosystems will facilitate improvements to water infiltration
- further evidence of the impact of agroforestry and companion cropping on flood peaks
- further research on arable systems, specifically the influence of crop type, herbicide treatment, veterinary medication, land use intensity, capping and panning
- a better understanding of the link between diverse types of root systems and worms burrowing vertically, as well as the role of eco-hydrology, micro-organisms, biofilms,

- dung beetles, fungi and anecic worms in a variety of habitats, in the context of flood risk management
- a better understanding of the role that glomalin production from roots plays in soil aeration in terms of soil hydrology and linking to flood attenuation

6.3 Run-off pathway management

6.3.1 What is run-off pathway management?

Run-off pathway management measures are intended to mimic natural hydrological regimes to minimise the impact of human activity on surface water drainage discharge, reducing flooding and pollution of waterways and groundwater. They have the potential to regulate run-off through the temporary storage of floodwater, disconnection and lengthening of flow pathways, or increasing travel time, and roughening the floodplain during flood events.

This section describes some of the measures that can be added to farmed landscapes to slow and store flood the flow of water across the landscape. These features are described collectively and referred to as run-off attenuation features (RAFs). Some of the measures included restore natural processes (for example, buffer strips), while some work with natural processes but rely on more engineered structures to function or improve functioning (for example, hedges, track management and swales).

This section summarises the evidence around the effectiveness of run-off pathway management measures in reducing flood risk. These measures are:

- swales, scrapes and sediment traps
- ponds, run-off attenuation features and bunds
- hedges and buffer strips
- headwater management (flow paths in fields, tracks, paths, roads, farms and ditches)

Figure 27 shows an example of what run-off attenuation features look like at Smithills Estate with water pooling in a grassy field.

Figure 27 - Run-off pathway management features at Smithhills Estate (image credit: Eleanor Pearson, JBA Consulting)

6.3.2 Findings from the 2017 evidence base

What we knew about run-off pathway management in 2017

The 2017 evidence showed that run-off management features:

- have been found to slow, store and filter water, reducing flood risk locally for small events and disrupting and attenuating overland flow
- have been found to have a positive flood risk management benefit, especially at source, within hours of the flow being generated
- work best when many clusters of features are included throughout the landscape, working as a network of measures rather than one dominant measure
- can become filled with water, after this they have minimal impacts on flow
- trap fine sediment, reducing the amount that enters the watercourse
- are unlikely to provide significant flooding benefits on their own; in conjunction with other run-off management features they can help to control the release of sediment to the river network and maintain the capacity of rivers to convey floodwaters
- run-off attenuation features are effective as soon as they are installed
- run-off pathway management measures need maintenance; this is usually sediment removal

- agricultural landscape features can slow, store, filter and attenuate flow, but there is limited evidence to demonstrate their flood risk benefits locally and at a catchment scale

What were the research gaps?

The research gaps were:

- the evidence that individual run-off pathway management measures operate efficiently during the peak of storms
- evidence to demonstrate the effects of run-off management measures for big flood events at large catchment scales
- evidence to demonstrate the flood risk benefits of run-off attenuation measures trapping fine sediment, reducing the amount that enters the watercourse, although it may reduce the need for in-channel maintenance activities and have a positive impact on conveyance
- information on the effectiveness of run-off attenuation features in different catchment types or different geologies
- limited UK-based peer-reviewed papers looking at the role of rural swales in reducing flood risk
- evidence of the effectiveness and performance of sediment traps in regard to their ability to reduce flood risk
- limited literature available to determine how farm ponds can increase flood storage in the landscape or increase travel time to surface water bodies
- data in ponds and run-off attenuation features during storm events to understand how they function in storm events so that their design can be optimised from a flood attenuation perspective
- evidence to help understand how run-off attenuation features affect flood flows when they are full
- the need for a new breed of hydraulic models to enable the assessment of clusters of WWNP features throughout a catchment
- top-down analysis that can determine, for any catchment, the amount of flood storage and the number and type of features needed to gain a specified peak flow reduction at a flood impacted site, while also addressing the potential issue of flow synchronisation
- research to establish the flood risk impacts of multiple on-farm features (this is difficult as the measures have different degrees of storage and attenuation effects)
- quantifiable evidence of how altering hydraulics within a ditch will reduce flood risk

6.3.3 New flood risk evidence

For more detailed information relating to the studies used to formulate the following summaries, please see the literature review.

We have a **high** level of confidence in the effect that run-off pathway management has on flood risk. There is further evidence to show that run-off management measures store water and slow the flow downstream, but there is limited evidence showing a reduction at a catchment scale. This has been increased from the original evidence directory due to an increase in the volume of new evidence. A review of the latest literature has found:

- further evidence and examples of run-off management measures successfully intercepting run-off, strong, peer-reviewed evidence is available to support this (Boardman and others, 2017; Richet and others, 2017; Champion, 2018; Coates, 2018; Evans and others, 2018; Ibrahim and Amir-Faryar, 2018; Bathurst and others, 2018; Razmand and others, 2019; Wells, 2019; Holden and others, 2019; Zak and others, 2019; Blanusa and Hadley, 2019; HR Wallingford, 2020; Mason-McLean, 2020; Stutter and others, 2020; Nicholson and others, 2020; Chadwick, 2021; Cook and Byers, 2021; Gilbert, 2021a; Lewis and Hodges, 2021a; Puttock and others, 2021; Severn Gorge Countryside Trust, 2021; Wallace and others, 2021; Wallace and others, 2021; West Cumbria Rivers Trust, 2021b; West Cumbria Rivers Trust, 2021c; West Cumbria Rivers Trust, 2021d; West Cumbria Rivers Trust, 2021a; Willis and Klaar, 2021; Robotham and others, 2022; Beven and others, 2022; Pearson, 2023a; West Cumbria Rivers Trust, 2023; Pearson, 2023b; Kingsbury-Smith and others, 2023; Adams, n.d.; Birkinshaw and Krivtsov, no date; George and Todd, no date)
- several studies show that RAFs are most effective in reducing local flood peaks for small, common, flashy events (Ibrahim and Amir-Faryar, 2018; Nicholson and others, 2020; West Cumbria Rivers Trust, 2021b; West Cumbria Rivers Trust, 2021d)
- the location of RAFs and ponds in a catchment influences peak flow, and can sometimes increase it, so this must be considered in their design and modelling (Wells, 2019; HR Wallingford, 2020; Gilbert, 2021a; Birkinshaw and Krivtsov, no date)
- hillslope storage measures are most likely to show results on a small reach, immediately downstream of features (Metcalfe and others, 2018)
- for smaller capacity ponds relative to catchment size, larger outflow pipes are likely to prevent premature filling before the storm's peak (West Cumbria Rivers Trust, 2021d; Pearson, 2023a)
- hedges and buffer strips slow flows, storing water upslope through improved infiltration in nearby soils, however there is limited evidence for hedges reducing flood risk at a catchment scale (Boardman and others, 2017; Richet and others, 2017; Coates, 2018; Holden and others, 2019; Zak and others, 2019; Blanusa and Hadley, 2019; Stutter and others, 2020; Mason-McLean, 2020; West Cumbria Rivers Trust, 2021b; Severn Gorge Countryside Trust, 2021; Wallace and others, 2021; Willis and Klaar, 2021; Kingsbury-Smith and others, 2023; Adams, n.d.)
- buffer strips reduce flood risk further when implemented over a greater area, integrated buffer zones (with storage and outflow) perform more effectively and wider buffer strips are more effective at reducing peak flow and time-to-peak (Richet

and others, 2017; Zak and others, 2019; Mason-McLean, 2020; Stutter and others, 2020; Ellis, 2021a)
- hedges and buffer strips trap sediment and can improve water quality. Both require minimal maintenance (Richet and others, 2017; Thomas and Abbott, 2018; Hille and others, 2019; Blackstock, 2020; Stutter and others, 2020; West Cumbria Rivers Trust, 2021f; Yorkshire Wildlife Trust, 2021; Frankl and others, 2021)
- blocking ditches may redirect water onto the hillslope surface and subsurface, reducing discharge and slowing downstream flows (Champion, 2018; Evans and others, 2018; Bathurst and others, 2018)

Effects at different scales

We have **varying levels** of confidence in the effects of run-off pathway management at different scales. We have 'high' confidence in run-off pathway management in small catchments, 'medium' confidence in medium sized catchments and 'low' confidence in large catchments. These confidence limits remain unchanged from the original evidence directory as limited new literature was identified as part of the review. The new literature suggests that:

- the most beneficial effect of additional hillslope storage is likely to be seen on a small scale in reaches immediately downstream of a feature
- scaling up results from bunds on a sub-catchment to their impact on a full catchment may not show as high a reduction in peak flows, however, there has been limited new evidence regarding this (Metcalfe and others, 2018; Wells and others, 2020)
- at a catchment level, vegetative barriers seem to be most effective when placed immediately downstream of erosion sources, across channels of concentrated run-off, or immediately upstream of local assets at risk
- the potential benefits of buffering rivers from their floodplains may increase with catchment area, making the case for restoring unimproved grasslands on a larger scale than buffer strips (Ellis, 2021a)

Effects on different watercourse typologies

We have a **low** level of confidence in the effects of run-off pathway management on different watercourse typologies. This remains unchanged from the original evidence directory due to a lack of new literature. In a chalk catchment in Norwich, surface RAFs had a slightly greater impact on groundwater flows than in-channel RAFs (Aghajani and others, 2023a; Aghajani and others, 2023c; Aghajani and others, 2023d; Aghajani and others, 2023b).

Effects on sediment and geomorphology

We have a **medium** level of confidence in the effects of run-off pathway management on sediment and geomorphology. This remains unchanged from the original evidence directory due to a lack of new literature. Ponds will retain nutrients and suspended solids during average baseflows, but net losses of these can occur during higher magnitude storm events. They are most effective at capturing nutrients and materials during smaller to medium events typically experienced during winter (Robotham and others, 2021).

Design life and effectiveness

We have a **high** level of confidence in the effects of run-off pathway management on design life and effectiveness. This remains unchanged from the original evidence directory due to a lack of new literature. The new literature suggests that:

- for smaller capacity ponds relative to catchment size, larger outflow pipes are crucial to prevent premature filling before the storm's peak (Pearson, 2023a)
- effective functioning of riparian buffers to achieve multiple benefits relies on good soil and crop management in upslope fields to minimise water and pollutant transport to the buffer area (Stutter and others, 2020)
- a 6-metre buffer is likely to be a minimum, 10 to 12 metres is more suitable for higher burden upslope pollution and peak flow scenarios (Stutter and others, 2020)

Maintenance

We have a **medium** level of confidence in our understanding of the maintenance requirements of run-off pathway management measures. This remains unchanged from the 2017 evidence directory due to a lack of new literature. The new literature suggests that:

- maintenance of ponds should be considered biennially, and the removed sediment can be reapplied to arable land as an organic soil conditioner (Robotham and others, 2021)
- in the early years of hedge establishment, minimal pruning and effective weed control is necessary, however plastic protective sheeting should be avoided as a control measure, as it would hinder the emergence of new shoots (Richet and others, 2017)
- regular access and disturbances to buffer strips can reduce their effectiveness for flood and pollution control (Stutter and others, 2020; Yorkshire Wildlife Trust, 2021)

6.3.4 New multiple benefits evidence

Evidence prior to 2017 suggested that run-off pathway management results in water quality improvement, surface water flood risk reductions and improvements to habitat.

New evidence suggests that:

- swales may provide good habitat for birds (Adams, n.d.)
- roots in woody buffer strips may strengthen banks, provide shelter and contribute to the accumulation of deadwood, increasing structural diversity (Stutter and others, 2020)

- fencing of buffer strips to prevent stock access may allow for more varied vegetation to flourish (Miles and others, 2021)
- retention ponds may provide water quality enhancement through settling of water-borne sediment and biological degradation of pollutants (Mulligan and others, 2023)
- the degree to which these benefits are provided depends on the size of the pond, the geophysical context as well as the at risk asset distribution downstream (Mulligan and others, 2023)
- hedgerows may be effective at removing nitrates from shallow groundwater when compared with pasture vegetation or arable crops; this could ameliorate groundwater contamination and transport of nutrients to streams (Thomas and Abbott, 2018)

The multiple benefits of run-off pathway management are reflected in Figure 28**Error! Reference source not found.**. Run-off pathway management may be beneficial for water resources, flood risk reduction and water quality. Depending on the type of run-off pathway management, there may also be benefits to biodiversity, and it can promote wider ecological resilience. New literature suggests that run-off management techniques often provide good and varied habitat, with hedges and buffer strips additionally allowing for improved habitat connectivity. Ponds allow water-borne sediment and associated pollutants to settle, however the degree of benefit depends on the size and geophysical context. Run-off pathway management provides limited climate regulation and soil benefits. It has very limited air quality and amenity benefit.

The multiple benefits wheel tool is only intended to be used as a visual aid to suggest where additional benefits may be sought when implementing the measures for flood risk. It should not be used as part of detailed quantitative analysis or optimisation of options.

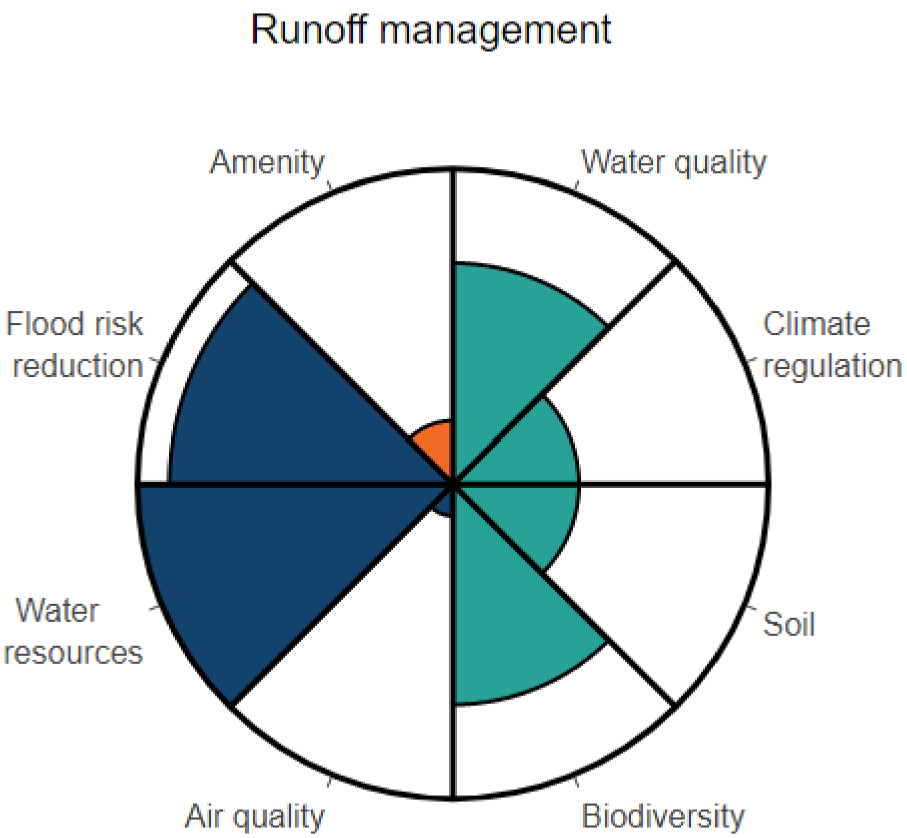

Figure 28 - Multiple benefits wheel for run-off pathway management

6.3.5 What are the changes in evidence from 2017?

The main changes to the evidence were:

- further research has confirmed process understanding of run-off management measures
- local evidence of measures shows that they are likely to reduce flood risk, mainly through slowing the flow of run-off, however most studies suggest that this is at a local scale, and there is limited evidence for impact at a catchment scale
- strong evidence that buffer zones are very likely to reduce flood peaks by reconnecting rivers to their floodplains

6.3.6 Research gaps

Despite new evidence coming to light since the original evidence directory, there are remaining research gaps to allow us to continue to improve our understanding of run-off pathway management. These are:

- evidence to suggest how flood peak flow reductions translate into flood risk reductions and how run-off pathway management may help reduce wider flood risks (for example, help in hard engineered asset control)
- the need for a top-down analysis that can determine, for any catchment, the amount of flood storage and the number and type of features needed to gain a specified peak flow reduction at a flood impacted site, while also addressing the potential issue of flow synchronisation
- the need for UK-based peer-reviewed papers looking at the role of rural swales in reducing flood risk
- evidence on the effectiveness and performance of sediment traps
- a need to determine the storage-discharge relationships for a range of RAF types and more research is needed at larger catchment scales
- further investigation of the implications of adding new RAFs into catchments with lighter soils and more significant groundwater interactions particularly in larger catchments
- evidence to demonstrate the flood risk benefits of run-off attenuation measures trapping fine sediment reducing the amount that enters watercourses.
- information on the effectiveness of run-off attenuation features in different catchment types or different geologies
- research into the multiple benefits of banked hedges/kested hedges/Devon banks
- further investigation to ascertain the methodologies and tools that can be used to identify the location of wider riparian buffer strips is needed
- quantifiable evidence of how altering hydraulics within a ditch will reduce flood risk
- further research to understand the role of run-off attenuation measures in increasing infiltration across different catchment types and geologies

6.4 Headwater peatland management

6.4.1 What is headwater peatland management?

This section looks at drainage management measures suitable in headwater peatland catchments. Headwater catchments are loosely defined as typically small catchment areas up to several square kilometres in size. Within these headwater drainage networks, there are potential opportunities to intervene to change the storage and the travel time of water within them by slowing the flow of water before it reaches the drainage network. Headwater peatland management aims to retain water within peatland habitats to reduce run-off downstream. Although it is recognised that there may be opportunities to implement WWNP measures in lowland raised mire and fen settings, the focus of this assessment is on upland peat management techniques. It looks at the following techniques:

- vegetation management
- grip and gully blocking
- pipe blocking

Other techniques such as burning and grazing management are not covered here.

Figure 29 shows an example of peatland restoration in Broughton Hall Estate with logs and rocks placed on the ground to slow the movement of water.

Figure 29 - Peatland restoration, Broughton Hall Estate, Skipton (image credit: Jenny Broomby, JBA Consulting)

Vegetation management is the deliberate planning and maintenance of the plant life within the peatland. This includes re-establishing natural conditions, planting native plants and controlling invasive plants.

Gully and grip blocking is the placement of structures such as dams or barriers within channels or grips to slow the movement of water within them. This allows water to be absorbed by peatland habitats instead of flowing downstream. While gullies are naturally occurring features, grips are man-made drainage channels.

Natural soil piping occurs across a range of landscapes, including peatlands. Soil piping can also be a significant factor in soil degradation and pipes can erode to form gullies, a common feature of degraded landscapes. Pipe blocking is the obstruction of pipe outlets or pipe ends, either by placing a vertical screen at the pipe-outlet or by inserting plug-like structures in the pipe-end. This prevents water from flowing out of the pipe and allows water to be absorbed by peatland habitats instead of flowing downstream (Regensburg and others, 2021).

6.4.2 Findings from the 2017 evidence base

What we knew about headwater peatland management in 2017

The 2017 evidence base showed that:

- restoration of peatland slows stormwater as it moves through the catchments, attenuating flow and altering the storm hydrograph, with potential flood risk benefits downstream
- evidence for the effectiveness of grip blocking at reducing flood risk is not consistent; it can either increase or decrease discharge rates at a hill slope scale
- grip blocking can be effective in reducing peak flows and restoring peatland habitat, but it is never as effective as intact peat
- there is significant evidence at a range of scales that restoration techniques, which replace bare peat with vegetation, can reduce run-off rates through increased hydraulic roughness
- there have been limited studies into the impact of gully blocking on run-off rates to determine with confidence its flood risk benefits
- headwater peatland measures take time to bed in and become effective, their effectiveness is not static as over time as soil properties change and adapt to the restoration measures with positive and negative effects on the discharge rate

What were the research gaps?

Limited information was found on the need to maintain headwater peatland management features. This is not to say maintenance is not needed, as clearly to function effectively, these sorts of measures may need to be maintained or adapted over time.

6.4.3 New flood risk evidence

For more detailed information relating to the studies used to formulate the following summaries, please see the literature review.

We have a **medium** level of confidence in the effect that headwater peatland management has on flood risk because of the lack of catchment-scale studies. This remains unchanged from the original evidence directory. A review of the latest literature has found that:

- revegetating peatland increases surface roughness and delays flood peaks; several studies show significantly longer lag times and reduced peak discharge under revegetation scenarios, which increases with the addition of gully and grip blocking

(Gao and others, 2017; Shuttleworth and others, 2019; Alderson and others, 2019; Brazier, Benaud and others, 2020; Goudarzi and others, 2021; Howson and others, 2023)

- establishment of sphagnum clumps is important and a crucial step in revegetating peatland, as shown on Kinder Scout; much faster growth is observed when sphagnum is located in areas with a higher water table and better protection from becoming very dry (Gao and others, 2017; Moors for the future, 2018; Gao and others, 2018; Howson and others, 2023)
- the amount of peatland undergoing restoration, the topography and the placement of restoration projects significantly impacts the downstream flood risk (Moors for the Future, 2018; Gao and others, 2018; Shuttleworth and others, 2019)
- experimental problems arise due to the large scales involved and the lack of control catchments able to be used due to the complexity of restoration (Shuttleworth and others, 2019)
- there is conflicting evidence on the impacts of pipe blocking on streamflow, although this appears to be small based on limited evidence (Holden and others, 2018; Brazier, Benaud, and others, 2020; Regensburg and others, 2021; Goudarzi and others, 2021)
- gully blocking forces water to leave moorlands via multiple pathways, diffusing the sources of run-off, promoting rewetting and slowing the flow; this has been shown in many observed and modelled studies (Moors for the Future, 2018; Alderson and others, 2019; Brazier, Benaud and others, 2020; Goudarzi and others, 2021; Gatis and others, 2023; Howson and others, 2023; MoorLIFE2020, no date)

Effects at different scales

We have **varying levels** of confidence in the effects of headwater peatland management at different scales. We have ‘high’ confidence in headwater drainage management in small catchments, ‘medium’ confidence in medium sized catchments and ‘low’ confidence in large catchments. These confidence limits remain unchanged from the original evidence directory as limited new literature was identified as part of the review. The extent to which downstream flood risk is reduced depends on the area of peatland restoration and the placement of it within the topography of the landscape. However, there are limited studies on the effect of this at different catchment scales (Shuttleworth and others, 2019).

Effects on different watercourse typologies

We have a **low** level of confidence in the effects of headwater peatland management on different watercourse typologies. This remains unchanged from the original evidence directory due to a lack of new literature. The limited new literature suggests that:

- sphagnum moss growth is maximised in areas with a high water table and better protection from becoming very dry (Moors for the Future, 2018)
- alterations in land cover from cotton grass to sphagnum moss within riparian zones and on gentle slopes had a more pronounced impact on peak river flows compared

to changes in other areas of the catchment; 1 study indicated this (Gao and others, 2018)

Effects on sediment and geomorphology

We have a **low** level of confidence in the effects of headwater peatland management on sediment and geomorphology. This remains unchanged from the original evidence directory due to a lack of new literature. Peat restoration via vegetation cover establishment can rapidly reduce particulate carbon loss (Alderson and others, 2019).

Design life and effectiveness

We have a **low to medium** level of confidence in the effects of headwater peatland management on design life and effectiveness. This remains unchanged from the original evidence directory due to a lack of new literature. The new literature suggests that:

- blocking peat pipes upslope rather than at outlets can cause spill on the surface before flowing through vegetation with a lower velocity, reducing peak flow downstream (Regensburg and others, 2021)
- blocking pipes at outlets exacerbates pipe development on edge zones, increasing peak flow downstream (Regensburg and others, 2021)
- to combine the objectives of peatland restoration and flood management, a trade-off between gully blocking to create static storage and allowing more water to flow downstream can be achieved through creating semi permeable blocks, or by creating water storage features elsewhere (MoorLIFE2020, no date)

Maintenance

We have a **low** level of confidence in the effects of headwater peatland management on maintenance. This remains unchanged from the original evidence directory due to no new literature being identified as part of this review.

6.4.4 New multiple benefits evidence

Evidence prior to 2017 suggested that headwater peatland management results in provision of habitat, surface water flood risk benefits, and climate regulation.

New evidence suggests that:

- grip and gully blocking has limited empirical data as to the carbon benefits; benefits could be realised over longer timeframes as the peatland ecosystem adapts to wetter conditions (Evans and others, 2018)
- upland peatland restoration can sequestrate 2 to 20 tCO_2e/ha/year (Beechener and others, 2021)

The multiple benefits of headwater peatland management are reflected in Figure 30.

Headwater peatland management may result in benefits to biodiversity, climate regulation, water resources, soil and water quality. New research suggests that there is limited data for the carbon benefits of grip and gully blocking, however benefits could be realised over longer timeframes as the peatland ecosystem adapts to wetter conditions. Benefits from amenity and air quality improvements are thought to be more limited.

The multiple benefits wheel tool is only intended to be used as a visual aid to suggest where additional benefits may be sought when implementing the measures for flood risk. It should not be used as part of detailed quantitative analysis or optimisation of options.

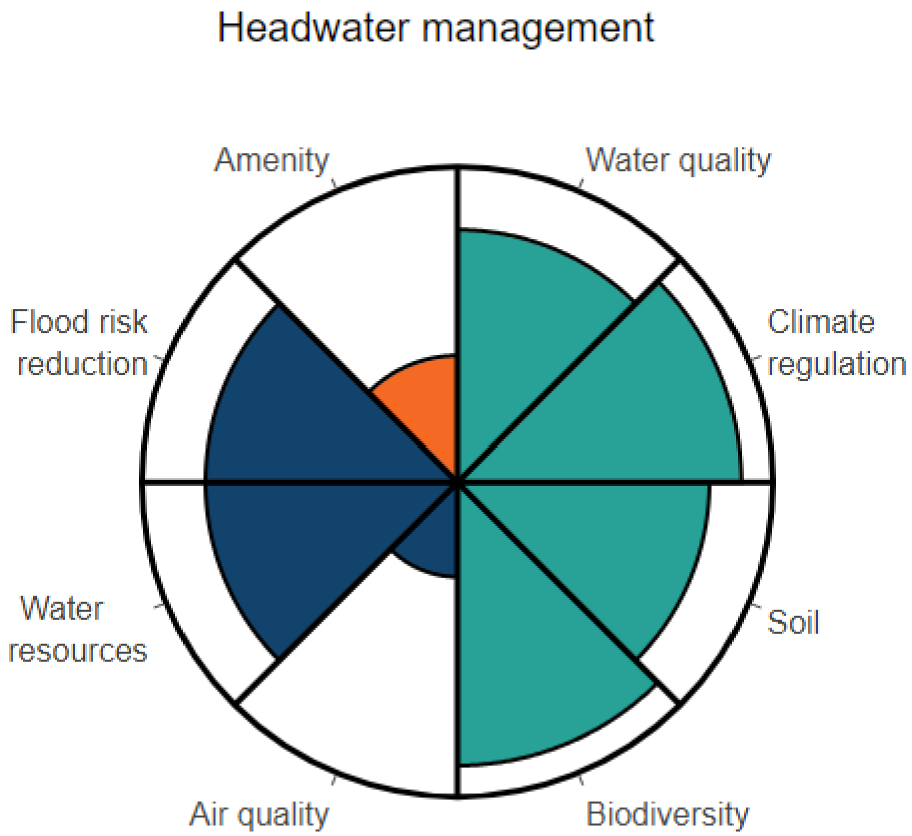

Figure 30 - Multiple benefits wheel for headwater management

6.4.5 What are the changes in evidence from 2017?

The main changes to the evidence were:

- there is more evidence supporting revegetation of peatlands as a method for reducing flood risk; these results are compounded when combined with grip and gully blocking
- there was significant research into the role of sphagnum on peatland, including how best to implement it, and the ways in which the moss alleviates flood risk

- there has been further research investigating how individual catchment influence affects the results of peatland restoration
- although more studies have taken place looking into the impact of grip blocking, there is still conflicting evidence over their efficacy
- there was further research into the effectiveness and longer term function of gully blocking, evidence has demonstrated potential storage 8 to 9 years post installation
- while there is a small but growing evidence base for pipe blocking, evidence over its efficacy is conflicting
- the kinematic storage (temporary) provided by gully blocks and revegetation is as important as the static (fairly stationary) storage for reducing storm peaks and increasing lag times, through increased surface roughness and slowing overland flow velocities

6.4.6 Research gaps

Despite new evidence coming to light since the original evidence directory, there are remaining research gaps to allow us to continue to improve our understanding of headwater peatland management. These are:

- evidence to suggest how flood peak flow reductions translate into flood risk reductions and how headwater peatland management may help reduce wider flood risks (for example, help in hard engineered asset control)
- long-term monitoring of peat restoration is required to establish if there are lasting effects or more pronounced impacts
- research on vegetation burning on peat soils in different types of catchments and at all peat depths is required, deep peat soils within protected areas are legally protected from being burned, however shallower peats and those outside protected sites are still at risk and could still impact flood risk/peak flows
- demonstration of headwater management measures for bigger flood events at larger catchment scales
- research to help understand how flood flows are affected when headwater management features are full
- information on the need to maintain headwater peatland management features; this is not to say maintenance is not needed
- further justification and evidence for when and how to restore peatland, this is of key importance alongside the Peat and Trees guidance (Forestry Commission, n.d.)
- evidence on the permeability of stone dams clogged with sediment and/or peat
- further research to investigate how grip and gully blocking function on a larger scale
- further work to establish whether the hydrological function of pipe-connected pools is different from those disconnected from peatland pipe networks
- further evidence to determine the effectiveness of natural peat pipes as results are currently mixed; case study evidence is required to back up theory from Regensburg and others, (2021) that increasing water storage higher in the pipe

network will be successful, and further information on how best to implement this and the impacts is required

- research to test upslope pipe blocking impacts, away from outlets, to establish if this has greater impacts than only blocking of outlet locations; this will require more precise mapping of pipe networks using more recent advances in ground penetrating radar detection so that peat pipes <10 cm in diameter can be mapped
- further work to understand the effects on flood risk of different design approaches with regards to vegetation management, as well as gully, grip and pipe blocking
- further research on wider peatland management practices, including the effects of burning on peatland habitats and flood risk is required
- greater detailed understanding of the temporal changes in flood risk following peatland restoration

7 Coastal management

7.1 Introduction

This chapter summarises the evidence around the effectiveness of the following coastal management measures in reducing flood risk. These include:

- saltmarsh and mudflat management
- beach nourishment
- sand dune management
- reefs
- submerged aquatic vegetation (SAV)

The 2017 WWNP evidence directory focused on saltmarsh and mudflat management, beach nourishment and sand dune management only. However, a growing interest in 'nature-based defences' was also identified. This included the use of various ecomaterials, including coir logs and oyster reefs to reduce wave energy impacts at shorelines and enhance existing saltmarsh habitats. It was stated that the application of such interventions within the UK required further investigation and highlighted a need for monitoring of schemes where such measures had been implemented to determine the level of success.

In response to this, and the development of research into the use of NBS, Defra published the Coastal Nature-Based Solutions: A Quick Scoping Review document in November 2021 (Defra, 2021). This review was conducted to reflect the growing evidence base and the increasing opportunities relating to the use of NBS to mitigate coastal erosion and flood risk. The published document aims to provide an initial scoping assessment of the coastal NBS evidence and main developments from 2017 to 2021. The case studies incorporated within the 2021 Defra review, which reflect the 3 main existing areas of the WWNP coastal component (saltmarsh and mudflat management, beach nourishment and sand dune management) have been incorporated within this evidence directory update.

The U.S. Army Corps of Engineers (USACE) has recently published the International Guidelines on Natural and Nature-Based Features (NNBF) for Flood Risk Management (Bridges and others, 2021). This is a comprehensive assessment of the growing knowledge, experience and technical practice of applying NBS as adaptive approaches towards resilient and sustainable coastal, estuarine and fluvial systems. From a coastal perspective, the main areas addressed in the NNBF guideline document are beaches and dunes, coastal wetlands and tidal flats, islands, reefs, plant systems (submerged aquatic vegetation and kelp) and enhancing structural measures for environmental, social and engineering benefits.

In response to the growing research interest and application of nature-based solutions which was reflected in a review of the literature, 2 additional habitats were introduced: reefs and submerged aquatic vegetation (SAV).

7.2 Saltmarsh and mudflat management/restoration

7.2.1 What is saltmarsh and mudflat management/restoration?

Saltmarsh and mudflats reduce and dissipate wave and tidal energy in front of flood defences and can extend their design life. They can reduce the forces impacting on flood defences and reduce tidal surge propagation, leading to slightly lower water levels at defence structures. To date, most schemes in the UK to restore mudflat and saltmarsh habitats have involved managed realignment (MR), which has been achieved through the breaching of existing embankments and/or the use of regulated tidal exchange (RTE) structures.

Figure 31 shows an example of saltmarsh restoration at Calstock wetlands. In the foreground is an area of water meeting a grassy slope with mature trees in the distance.

Figure 31 - Saltmarsh restoration at Calstock wetlands (image credit: Sophia Craddock, Environment Agency)

The term ‘living shorelines’ is commonly used in the United States to describe an approach to erosion protection which uses vegetation or low sills such as oysters to stabilise shorelines such as saltmarshes (Bridges and others, 2021). This technique, and its application to UK saltmarshes, is discussed throughout the following section.

The increased knowledge and understanding of the benefits and processes relating to the creation and protection of saltmarshes is evident through the publications of the Saltmarsh Restoration Handbook (Hudson and others, 2022) and Restoring Estuarine and Coastal Habitats with dredge sediment: A Handbook (Manning and others, 2021). These publications should be referred to further understand these measures.

7.2.2 Findings from the 2017 evidence base

What we knew about saltmarsh and mudflat management/restoration in 2017

The 2017 evidence base showed that:

- saltmarshes and mudflats reduce wave and tidal energy; this can contribute to reducing flood and coastal erosion risk, particularly by reducing the forces having an impact on flood defences
- saltmarshes and mudflats tend to occur in sheltered areas where the main cause of flooding is high water levels (in these settings, large areas of marshes can reduce tidal surge propagation and lead to slightly lower water levels at defences)
- a range of measures are available for the restoration of mudflats and saltmarshes, each with their own issues and benefits, however decisions on the most suitable solution will be site-dependent
- to date, the main mechanism for restoring these habitats has been managed realignment, and most aspects are now relatively well understood; most managed realignment schemes have been carried out to provide compensatory habitat, but local FCRM benefits have also been provided through the provision of new embankments
- flood storage areas are similar to managed realignments (and may be combined with them), but these schemes actively reduce flood risk by reducing water levels in the wider estuary – they are an excellent example of WWNP
- saltmarshes and mudflats have many wider benefits beyond FCRM, and, in many cases in the UK, they are currently restored or managed for biodiversity and amenity purposes rather than for their FCRM role

What were the research gaps?

The research gaps identified were:

- how to better apply the concepts of ‘standard of protection’ and ‘design life’ to natural environments such as saltmarshes and mudflats; the assessment of wave and water level reductions gained from the creation or restoration of these habitats can be assessed using a range of approaches including numerical modelling

- prediction of the long-term evolution (50 to 100 years) of existing habitats and habitats created within managed realignment schemes (these are subject to large levels of uncertainty due to the high number of controlling factors)
- understanding of the progression of mudflat to saltmarsh within managed realignment schemes; this is of particular interest for compensatory habitats schemes and is likely to require improved modelling techniques for siltation and vegetation development

7.2.3 New flood risk evidence

For more detailed information relating to the studies used to formulate the following summaries, please see the literature review.

We have a **high** level of confidence in the effect that saltmarsh and mudflat management have on flood and coastal erosion risk. This has been increased from the original evidence directory as there has been an increase in the literature, including both academic and grey sources.

A review of the latest evidence has found that:

- saltmarshes reduce wave energy, with vegetation increasing the level of attenuation (Rupprecht and others, 2017; Paquier and others, 2017; Davidson and others, 2017; McKee Smith and Anderson Bryant, 2018; Silinski and others, 2018; Foster-Martinez and others, 2018; Schoutens and others, 2019; Schoutens and others, 2020; National Trust and others, 2021; Zhang and others, 2022)
- saltmarshes can be further protected by restoring other habitats seaward that attenuate forces and reduce erosion of the saltmarsh edge, for example, oyster sills, while also creating living shorelines and habitat mosaics that benefit connectivity (Safak and others, 2020; Polk and others, 2022)
- flexible marsh species attenuate less wave energy; however, they are more likely to survive under storm conditions (Rupprecht and others, 2017; Silinskiand others, 2018; Zhang and others 2022; Zhang and others 2020; Zhu and others, 2019; Schoutens and others, 2020)
- storm events may cause erosion to saltmarshes but can also provide sediment (Dale and others, 2018; Nowacki and Grossman, 2020; Polk and others, 2022)

Effects on wave attenuation

We have **medium** confidence in the effects of saltmarsh and mudflat management/ restoration on wave attenuation due to a growing body of evidence. The new literature suggests that:

- saltmarsh has been found to reduce wave energy, current velocities and attenuate high-water levels (Paquier and others, 2017; Silinski and others, 2018; National Trust and others, 2021)

- greater wave attenuation was observed when saltmarsh vegetation was emergent rather than submerged (Foster-Martinez and others, 2018)
- laboratory experiments have also shown saltmarsh can reduce wave energy and height (Gillis and others, 2022; McKee Smith and Anderson Bryant, 2018)

Effects on sediment and geomorphology

We have **medium** confidence in the effects of saltmarsh and mudflat management/ restoration on sediment and geomorphology. The new literature suggests that:

- saltmarsh and mudflat restoration can lead to sediment accumulation (Dale and others, 2018; Osorio and others, 2020; Nowacki and Grossman, 2020; Oosterlee and others, 2020; McClenachan and others, 2020; Tognin and others, 2021; Polk and others, 2022; Mossman and others, 2022) and a reduction in erosion (Silliman and others, 2019; McClenachan and others, 2020; Polk and others, 2022; Schoutens and others, 2022), but this is dependent on a number of factors
- net change in elevation is dependent on the design/type of restoration (Osorio and others, 2020; Oosterlee and others, 2020) and storm and tidal conditions (Dale and others, 2018; Nowacki and Grossman, 2020; Tognin and others, 2021)
- the depth of inundation affects sedimentation rates, with deeper inundations leading to higher rates (Oosterlee and others, 2020; Tognin and others, 2021), with sedimentation continuing until there is an elevation equilibrium (Oosterlee and others, 2020)
- vegetation, particularly roots, plays a vital role in stabilising sediments and soil and reducing erosion rates (Baptist and others, 2017; Silliman and others, 2019; Schoutens and others, 2022)
- living shorelines can help reduce erosion and may also allow for sediment accumulation (McClenachan and others, 2020; Polk and others, 2022)
- managed realignment schemes can result in spatial varied geomorphological processes, with both erosion and deposition occurring (Dale and others, 2018; Pontee and Serato, 2019; Mossman and others, 2022)
- fair weather conditions lead to organic sediment deposition, while storm surges contribute mainly sand and silt (Tognin and others, 2021)
- beneficial use of dredged sediment (BUDS) can be used to help create/restore marsh (Baptist and others, 2017; Szimanski and others, 2019; McQueen and others, 2020; Dartez and others, 2020; National Trust and others, 2021; Davis and others, 2022), however the wider negative impacts of dredging means it should only be used where excess sediment is available from management for other primary aims

Design life and effectiveness

We have **high** confidence in the design life and effectiveness of saltmarsh and mudflat management/restoration. This evidence suggests that:

- vegetated saltmarsh is more effective in dissipating wave energy than non-vegetated saltmarsh (National Trust and others, 2021)
- exposed vegetation develops stress-avoidance traits and tends to be more flexible (Schoutens and others, 2020; Silinski and others, 2018), however stiffer vegetation typically better reduces wave energy and height
- wave attenuation provided by saltmarsh varies seasonally, with more attenuation occurring in summer when there is more biomass (Schoutens and others, 2019; Zhang and others, 2022; Silinski and others, 2018; Foster-Martinez and others, 2018)
- marshes with a leading mudflat can perform better than channelled and ponded marshes and nearly as well as the fully vegetated scenarios (Castagno, 2022)
- managed realignment in isolation may not be sufficient for the development of saltmarsh habitat; additional structures or interventions may also be needed to increase the probability of success
- sediment installation may be required in some instances to help improve the structure (Vuik, 2019; Tedesco, 2019; National Trust, 2021)
- managed realignment schemes can effectively replicate natural saltmarshes (Rezek, 2017)
- pre-breach landscaping should be designed higher in the tidal frame (Chirol and others, 2024)
- the inclusion of man-made creeks in design may encourage the erosion process (Pontee and Serato, 2019)

Maintenance

We have **high** confidence in our understanding of the maintenance requirements of saltmarsh and mudflat management/restoration. This remains unchanged from the original evidence directory due to limited new evidence being identified as part of this review. The new literature suggests that:

- grazing on saltmarsh could limit the ability for saltmarsh to reduce wave attenuation (Davidson and others, 2017)
- grazing can compact the ground and encourage growth of species with high root density, which can make saltmarsh more resistant to erosion (Marin-Diaz and others, 2021)

7.2.4 What are the changes in the evidence from 2017?

The main changes in the evidence were:

- further physical and computational models, as well as on-site evidence to show that saltmarshes attenuate wave energy
- additional evidence around the geomorphological changes following restoration
- additional examples of hybrid schemes, including living shorelines and engineering with nature

- improved understanding into the differences between vegetation species, for example, flexible vegetation attenuates less wave energy, however, are more likely to survive under storm conditions

7.2.5 New multiple benefits evidence

Evidence prior to 2017 suggested that saltmarsh and mudflat management/restoration results in the removal of nutrients and trapping of pollutants, improving water quality, habitat provision, heat absorption and carbon sinks, additional water storage providing a water reserve in times of drought and reduces erosion.

New evidence suggests that saltmarshes:

- have been recognised for their ability to regulate climate by storing large quantities of carbon (MacDonald and others, 2020; National Trust and others, 2021; Mossman and others, 2022)
- and managed realignment sites can lead to increased local tourism (MacDonald and others, 2020; Schernewski and others, 2018; National Trust and others, 2021)
- can have wider amenity benefits such as walking paths, and educational sites are often associated with saltmarsh (, 2017; Szimanski, 2019; Schernewski, 2018; Kurth, 2022; Rahman, 2019; Burgess-Gamble, 2023)
- can increase bird populations and create island for nesting birds

The multiple benefits of saltmarsh and mudflat management/restoration are reflected in Figure 32. Saltmarshes and mudflats provide a wide range of benefits across most of the ecosystem services. The greatest ecosystem service benefits associated with this measure are biodiversity, climate regulations and flood and coastal risk management.

New literature suggests that saltmarshes and mudflats are able to regulate climate by storing large quantities of carbon. They are widely recognised as being able to filter sediments and nutrients, therefore, improving water quality. They also provide potential amenity benefit. Water resource benefits are not relevant due to salinity.

The multiple benefits wheel tool is only intended to be used as a visual aid to suggest where additional benefits may be sought when implementing the measures for flood risk. It should not be used as part of detailed quantitative analysis or optimisation of options.

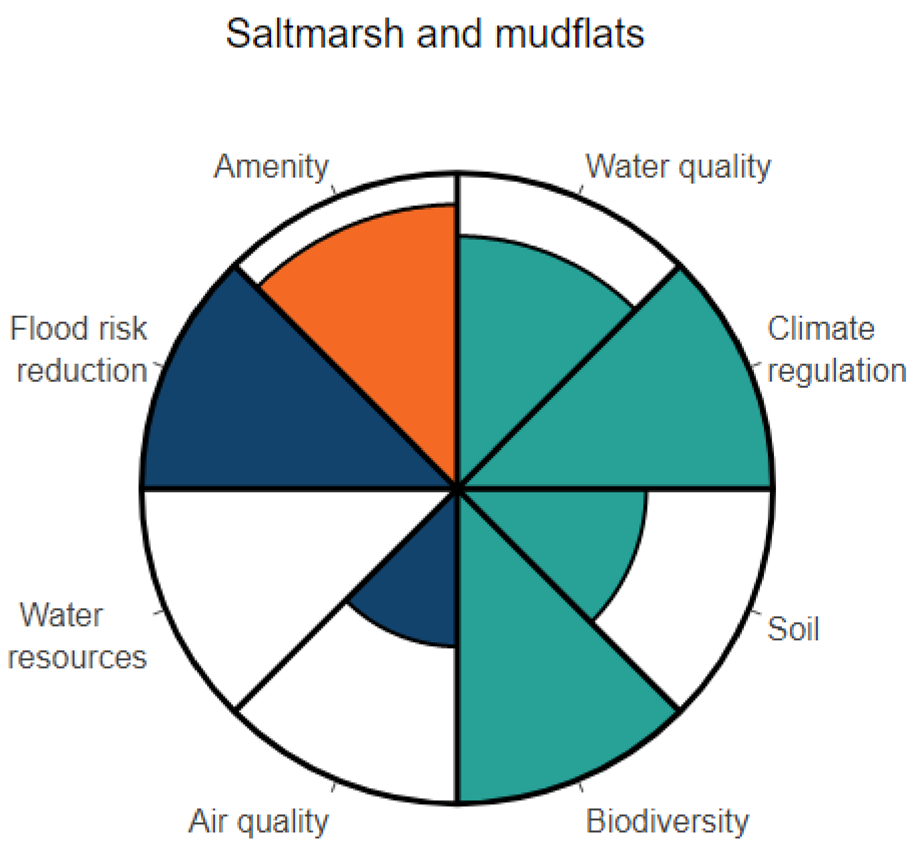

Figure 32 - Multiple benefits wheel for saltmarsh and mudflat management/restoration

7.2.6 Research gaps

Despite new evidence coming to light since the original evidence directory, there are remaining research gaps to allow us to continue to improve our understanding of saltmarsh and mudflat management/restoration. We still need:

- long-term monitoring across managed realignment schemes; the long- term impacts on the wider coastal system are, therefore, not fully understood
- understanding on the influence of tidal flats on flood risk and the best management practices for this
- further research for small scale living shorelines
- further evidence on whether UK-specific species follow the same stress-avoidance or ecosystem engineering strategies as those identified internationally, including advice for which species are to be used during plantation of restoration schemes
- further understanding on the characteristics of different types of vegetated marshes, for example, minerogenic and organogenic
- further understanding of estuarine and coastal sediment loads and processes, and the relationship between sediment change and vegetated marshes

- studies on the cumulative impacts of winter storms on saltmarshes and tidal flats
- further understanding on the pressures resulting in the erosion of existing saltmarshes and tidal flats
- further understanding around methods to protect saltmarshes and tidal flats, including features such as oyster-based substrates and considering this as a holistic environment
- further understanding of estuarine and coastal sediment loads and processes, and the relationship between sediment change and vegetated marshes
- further methods to be developed to allow for the inclusion of the dynamic interactions of saltmarshes rather than using LiDAR which considers saltmarshes as static systems in models, including simplified modelling methods for business cases
- modelling techniques which also consider vegetation characteristics such as flexibility
- decision-support tools to be developed for evaluating economic and environmental costs and benefits of saltmarsh restoration projects

In addition to the research gaps identified in this review, Pétillon and others (2023) undertook a study using expert opinions from an international network of multi-disciplinary researchers, policymakers and practitioners to understand the top research questions in global research to date. The research questions are included below.

1. How has the rate of change in areal extent varied globally over time?
2. Where and how can saltmarshes be realistically restored?
3. How does ecosystem service delivery vary with important marsh features and climate change?
4. How are saltmarsh ecosystem services valued among different groups across the globe?
5. What are the cultural ecosystem services of saltmarshes and what factors drive spatial-temporal variation in these services and benefits?
6. What are the global drivers of saltmarsh ecosystem structure and function?
7. How can integration of biological processes into physical models improve understanding of saltmarsh dynamics?
8. Do invasive marsh species contribute to ecosystem services and how does this contribution vary globally?
9. What are the challenges and opportunities to the effective management of saltmarsh ecosystem services?
10. What management actions can be used to enhance the protective function of saltmarshes?

7.3 Beach nourishment

7.3.1 What is beach nourishment?

Beaches provide an effective form of coastal defence, but only if they are of sufficient width and level. When beach systems become depleted there is a decrease in the flood risk management value and protective function. Beach nourishment is the process of adding material to the shoreline and allowing natural processes to incorporate it into the beach system to help retain the required standard of flood protection. It is undertaken to improve or restore the beach and coastal defence function; it helps retain the standard of flood protection to the section of coast where it is implemented. To be effective, beach nourishment is a long-term maintenance activity, usually repeated annually.

Beach nourishment is addressed within the context of this summary and the wider WWNP evidence directory, as the deposited beach material is subject to transport via exposure to wind, wave and tidal action. This allows natural processes to be maintained and uses the natural function of the beach to provide the necessary flood risk and erosion protection. However, the extraction from off/onshore sediment sources and the placement of material on the beach is a heavily industrialised process that may conflict with what are considered natural processes.

Figure 33 shows an example of beach nourishment at Poole Bay with people walking along the sandy beach and buildings on the coast in the distance.

Figure 33 - Beach nourishment at Poole Bay. Image credit: Dave Robson, Borough of Poole

7.3.2 Findings from the 2017 evidence base

What we knew about beach nourishment in 2017

The evidence base in 2017 showed that:

- beaches play a significant function in coastal flood and erosion defence, as well as being important for nature conservation, recreation and a range of other reasons
- beaches are dynamic features, which is part of their benefit as a buffer zone, however this does mean that changes can be unpredictable and rapid; where beach systems become depleted of sediment, a reduction in their flood defence value is likely unless remedial works are carried out
- nourishment through the import of sediment, sediment bypassing or recycling achieves FCRM objectives while working within the principles of WWNP, however decisions on the most suitable solution will be site-dependent due to the range of different beach systems and environments along the coastlines of England and Wales
- the scale and extent of nourishment schemes vary considerably, and this, in turn, affects how often nourishment needs to be undertaken; mega-nourishment schemes are intended to have a much longer design life (20 to 30 years), while elsewhere nourishment is necessary at least annually
- commonly, beach nourishment is carried out in combination with other forms of coastal management where good sediment husbandry cannot be achieved in isolation, for example, backing seawalls or groyne systems that are designed to improve retention of sediment

What were the research gaps?

The research gaps identified were:

- the prediction of long-term evolution (50 to 100 years) of beaches; this is subject to high levels of uncertainty due to the large number of controlling factors
- improved knowledge to inform site specific suitability and design of a beach nourishment scheme; each site is unique, and decisions about the suitability and/or design of a nourishment scheme depend on a number of factors, including physical setting, environmental impact, and the availability of suitable sediments, costs and aesthetics (in places, the root cause of the erosion will remain unknown and monitoring will be required to determine whether it has been a success)
- improved knowledge of the fate of nourishment sediment and how to build uncertainties in this into beach nourishment scheme design to maximise beach resilience to storms; the fate of nourishment sediment depends on prevailing conditions (although there may be data relating to past behaviour, there will always be uncertainty about future change therefore design should be able to incorporate some variability; however, the resilience of the beach to a storm or series of storms remains less predictable compared to an engineered hard structure)

- a need for models that can predict system behaviour over the meso-scale change (>10 km and >10 years); process-based models for open coastlines can only forecast coastal change over short time scales (days to a few weeks) and small spatial scales (<1 km)
- improved evidence of the long-term suitability of the mega-nourishment approach, particularly around the UK coastlines; it is still in its infancy, with only one test site currently underway
- improved monitoring of the nearshore subtidal part of the beach to support improved understanding of the fate of nourished material and of the applicability of shoreface nourishment, as more commonly performed in the Netherlands
- improved knowledge of the sources of suitable nourishment sediment (these are finite) and the sustainability of nourishment over the very long term particularly as forecast sea level rise may increase demand in the future

7.3.3 New flood risk evidence

For more detailed information relating to the studies used to formulate the following summaries, please see the literature review.

We have a **high** level of confidence in the effect that beach nourishment has on flood and coastal erosion risk, which is largely based on a number of local studies undertaken as part of various business cases that have modelled the flood risk impacts of beach nourishment. This remains unchanged from the original evidence directory. New literature suggests that:

- beach nourishment creates a wider beach, providing a more effective source for aeolian transport and subsequent deposition (Vikolainen and others, 2017; Kaczkowski and others, 2018; Nordstrom and others, 2018; Vouk and others, 2021)
- hybrid structures integrated into beach systems can assist in stabilisation (Almarshed and others, 2020)
- improved understanding of the influence of beach nourishment on the formation of beach scarps which can be prevented by altering nourishment volumes dependent on expected runup (Nordstrom and others, 2018; Van Bemmelen and others, 2020)
- the placement of sediment above the storm berm favours aeolian processes (Nordstrom and others, 2018)

Effects on wave attenuation

We have **medium to high** confidence in the effects of beach nourishment on wave attenuation. There are many practical applications of beach nourishment, however there is less academic literature looking into the wave attenuation effects of beach nourishment. The new literature included:

- a study that looked at 344,000 m^3 of sand nourishment that was being used to protect properties in a low-lying coastal region, and found that it reduced coastal

flooding by wave overtopping but elevated the water table, leading to groundwater flooding (Ludka and others, 2018)
- a study that looked at a 2011 beach nourishment campaign which was found to be too high to be overtopped by waves; this resulted in the development of a prominent scarp in the foreshore at the beach as it had not yet achieved an equilibrium slope as late as 5 months after nourishment (Nordstrom and others, 2018)

Effects on sediment and geomorphology

We have **medium to high** confidence in the effects of beach nourishment on sediment and geomorphology. There are many practical applications of beach nourishment, and natural geomorphological processes of beaches are well understood, however there is less academic literature looking into the effects specifically of beach nourishment on sediment and geomorphology. Although nourishment may provide habitat space, it can bury or displace the flora and fauna within the tidal zone or at the borrow site. Increased sedimentation can harm intertidal habitats and seagrasses (Raynie and others, 2020).

Design life and effectiveness

We have **high** confidence in the design life and effectiveness of beach nourishment due to a number of practical applications available within the UK, however there is a limited number of academic papers. In the US, most federal beach nourishment programmes are now designed for a 50-year life cycle, with multiple, planned nourishments that address losses due to background erosion and episodic storm events (Elko and others, 2021).

Maintenance

We have **high** confidence in our understanding of the maintenance requirements of beach nourishment. This remains unchanged from the original evidence directory. The new literature suggests that:

- maintenance can be performed relatively easily by placing or moving sand to the areas that are most critical; longshore sediment balance should be incorporated within a maintenance programme, for instance, before sand bypassing takes place, replenishment should be performed by the import of sand from elsewhere (Van Der Spek and others, 2020)
- there is no guideline for the design or maintenance of hybrid coastal defence systems because a myriad of types and intended functions exist (Almarshed and others, 2020)

7.3.4 What are the changes in the evidence from 2017?

The main changes in the evidence since 2017 are:

- improved understanding of the formation of beach scarps

- additional data gathered on examples of beach nourishment schemes

7.3.5 New multiple benefits evidence

There is little literature which specifically explores the wider benefits of beach nourishment. That which is available points to this measure having mainly a flood and coastal erosion risk benefit.

New evidence suggests that:

- economic activity, often driven by tourism-related expenditures, significantly increases in areas with nourished beaches (Porro and others, 2020)
- an additional 40 species of birds were regularly observed within the first 4 years of monitoring of a beach nourishment project in The Netherlands (Vouk and others, 2021)
- even if sea level rise induced erosion is less than projected, nourishment still offers the benefits of sustaining visitor activity (Porro and others, 2020)

The multiple benefits of beach nourishment are reflected in Figure 34. Maintaining beaches is also likely to have amenity value. New literature suggests that beach nourishment may increase local bird populations and sustain visitor activity, providing some biodiversity benefits.

The multiple benefits wheel tool is only intended to be used as a visual tool to suggest where additional benefits may be sought when implementing the measures for flood risk. It should not be used as part of detailed quantitative analysis or optimisation of options.

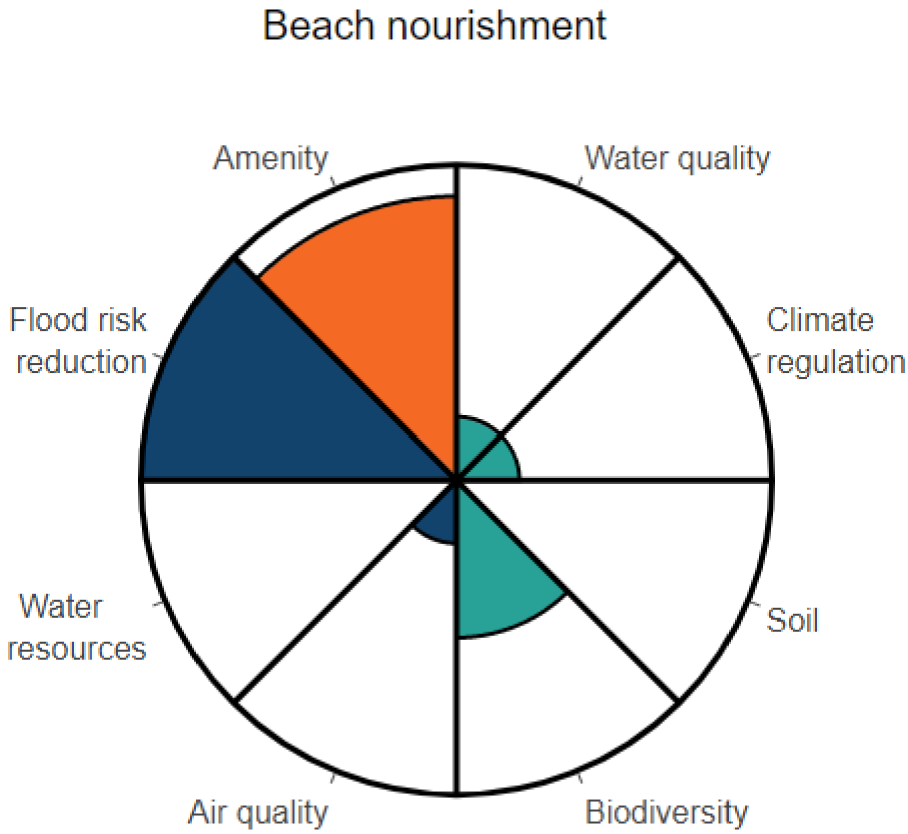

Figure 34 - Multiple benefits wheel for beach nourishment

7.3.6 Research gaps

Despite new evidence coming to light since the original evidence directory, there are remaining research gaps to allow us to continue to improve our understanding of beach nourishment. We still need:

- monitoring of UK examples of beach nourishment across a wide range of sites, for example, sand, gravel and sand-gravel (mixed) beaches
- to understand the fate of nourishment sediment depending on prevailing conditions and how this may change in the future
- monitoring of mega-nourishment schemes to understand their long-term suitability for UK coastlines
- monitoring of the nearshore, shallow subtidal environment adjacent and both up and downstream of the renourishment site, to improve understanding of the fate of nourished material
- further understanding of the sustainability of nourishment over the very long term, particularly as forecast sea level rise may increase demand in the future
- to improve the knowledge of hybrid approaches to protection against flooding, surge and wave attack by combining aspects from functional design of hard coastal

structures and knowledge of morphodynamic evolution of beach and dune systems under hydrodynamic forcing conditions

- improvements in our ability to predict long-term evolution (50 to 100 years) of beaches
- models that can predict system behaviour over the meso-scale change (>10 km and >10 years)

7.4 Sand dune management

7.4.1 What is sand dune management?

Coastal sand dunes provide a natural flood defence and erosion protection from storm surges, along with many other functions and benefits. By fully adopting WWNP, sand dunes would be left unmanaged to evolve in response to prevailing winds, tides and waves. However, many dune systems in the UK accommodate some form of human development and, therefore, erosion management is required to reduce the level of risk to backshore assets.

The relationship between morphology of dunes and the ecology they support means there is a significant overlap between the management of ecological features and flood and coastal erosion risk management. The inter-relationship between the beach and dune systems also means that management of dunes commonly involves the management of fronting beaches.

Figure 35 shows an example of sand dune restoration in Instow, Devon with the dunes being supported with fencing along a paved pathway.

Figure 35 - Sand dune restoration in Instow, Devon (image credit: Sophia Craddock, Environment Agency)

7.4.2 Findings from the 2017 evidence base

What we knew about sand dune management in 2017

The 2017 evidence base showed that:

- coastal sand dunes play a significant function in coastal flood and erosion defence, as well as being important for nature conservation, recreation and a range of other reasons
- sand dunes are dynamic features, which is part of their benefit as a buffer zone, however, this does mean that changes can be unpredictable and rapid
- where beach systems are depleted of sediment (as discussed in section 7.3), there is a risk that dunes will not recover following storm events and a reduction in their flood defence value is likely unless remedial works are undertaken
- a range of measures are available, each with their own issues and benefits, however decisions on the most suitable solution will be site-dependent due to the range of different dune systems and environments along the coastlines of England and Wales

- dunes have many wider benefits beyond FCRM, and in many cases in the UK they are currently restored or managed for biodiversity and amenity purposes rather than their FCRM role

What were the research gaps?

Research gaps included increasing understanding of:

- behaviour and management of dunes, there is less guidance on the best ways to employ the measures discussed above, such as the best positioning of fencing; often this is based on local experience and trial and error approaches; continued monitoring and knowledge sharing of experiences will improve understanding
- the response and, therefore, resilience of a dune system to a storm or series of storms; this is less predictable compared to an engineered hard structure, requiring continual monitoring at each individual site
- future evolution of dune systems remains; this remains uncertain, in part due to the uncertainty in predicting future changes to prevailing conditions, particularly at a local level, and the impact of future management both locally and along adjacent shorelines
- the long-term future role of sand dune systems in FCRM; this is uncertain and there is a risk that some dune systems could experience a catastrophic adjustment which will have major implications for flood defence, however not all sites are at risk and some are likely to be able to accommodate future change

7.4.3 New flood risk evidence

For more detailed information relating to the studies used to formulate the following summaries, please see the literature review.

We have a **high** level of confidence in the effect that sand dune management has on flood and coastal erosion risk. This has been increased from the original evidence directory as there has been an increase in the literature, including both academic and grey sources.

The increased knowledge and understanding of the benefits and processes relating to the management of sand dunes is evident through the publication of the Dynamic Dunescapes: Sand Dune Managers Handbook (UKCEH, 2021).

Additionally, Natural Resources Wales has restored 2,400 ha of sand dunes across 10 separate Welsh sites, through the Sands of LIFE project (Natural Resources Wales, 2024). This has investigated best management techniques for flood risk and improving Wales' well-being goals, as detailed in the Advice of Options for Sand Dune Management for Flood and Coastal Defence Volume 1: Main Report (Pye and others, 2017). These publications should be referred to for further understanding of these measures.

New literature suggests that:

- vegetated sand dunes are more effective than unvegetated sand dunes at dissipating wave energy (Biel and others, 2017; Jenks, 2018; Konlechner and others, 2019; Feagin and others, 2019; Fernández-Montblanc and others, 2020; Laporte-Fauret and others, 2021; Maximiliano-Cordova and others, 2021)
- plant roots contribute to strengthening the cohesiveness of sand dunes (Van Der Biest and others, 2017; Maximiliano-Cordova and others, 2021)
- species with greater belowground biomass reduce erosion rates (Walker and Zinnert, 2022)
- sand trapping fences can assist in developing sand dunes (Pinna and others, 2017; Carro and others, 2018; Conery and others, 2020; Laporte-Fauret and others, 2021; Eichmanns and others, 2021)
- silica-based grout was found to be effective at strengthening sand dunes along the Salento coast in southern Italy (D'Alessandro and others, 2020)

Effects on wave attenuation

We have **low to medium** confidence in the effects of sand dunes on wave attenuation due to limited literature. A study demonstrated how a new beach berm and foredune was created as a result of planting salt-tolerant coastal plants. The feature resisted the effects of storm surge run-up produced by massive cyclonic storm waves (maximum height 11 m) running up into the new plant protection zone (Jenks, 2018).

Effects on sediment and geomorphology

We have **medium to high** confidence in the effects of sand dunes on sediment and geomorphology. Vegetated dune systems play an important role in favouring a positive or near equilibrium coastal sediment budget. A sand dune reconstruction and revegetation study suggested that dune systems capture sediment during landward wind episodes, which reduces sediment erosion from overwashing and overtopping episodes during storm conditions (Fernández-Montblanc and others, 2020).

Design life and effectiveness

We have **medium** confidence in the design life and effectiveness of sand dunes as an FCRM measure. To improve the understanding of the behaviour of nature-based coastal defences by analysing the morphodynamic response of a dune-beach system with vegetation to storms, a study suggested that the presence of dune vegetation does not modify the beach profile dynamics nor the dune erosion regime; its role can be described as only reducing erosive processes by slightly attenuating waves (Mendoza and others, 2017).

Maintenance

We have **high** confidence in our understanding of the maintenance requirements of sand dunes. This remains unchanged from the original evidence directory. A study investigated the potential for beach and sand dune ecosystem-based adaptation (EbA) strategies to cope with extreme events and sea-level rise. They implemented several management approaches as a means of informing management decisions, including providing maintenance. They found that all measures were easy to implement and were low cost. Sand fencing had the most rapid results, helping to retain wind-blown sand (Carro and others, 2018).

7.4.4 What are the changes in evidence from 2017?

Silica-based grout is found to be an effective maintenance measure in strengthening sand dunes along the Salento coast in southern Italy.

7.4.5 New multiple benefits evidence

There is little literature which specifically explores the wider benefits of sand dunes. Existing research points to this measure having mainly a flood and coastal erosion risk benefit.

New evidence suggests that:

- coastal dunes provide a wealth of ecosystem services, including natural and efficient protection from eroding storms, limiting flood risk, pollutant filtration and providing bird nesting sites (Laporte-Fauret and others, 2021)
- sand dunes provide benefits to environmental and human issues such as education, community ownership and improved beach quality (Carro and others, 2018)

The multiple benefits of sand dunes are reflected in Figure 36. Sand dunes provide a wide range of benefits across most of the ecosystem services; the greatest benefit being biodiversity.

New literature suggests that sand dune management may provide natural and efficient protection from eroding storms, limiting flood risk, pollutant filtration and providing bird nesting sites. Sand dunes also provide benefits to education, community ownership and improved beach quality. Benefits to climate regulation and air quality are more limited.

The multiple benefits wheel tool is only intended to be used as a visual aid to suggest where additional benefits may be sought when implementing the measures for flood risk. It should not be used as part of detailed quantitative analysis or optimisation of options.

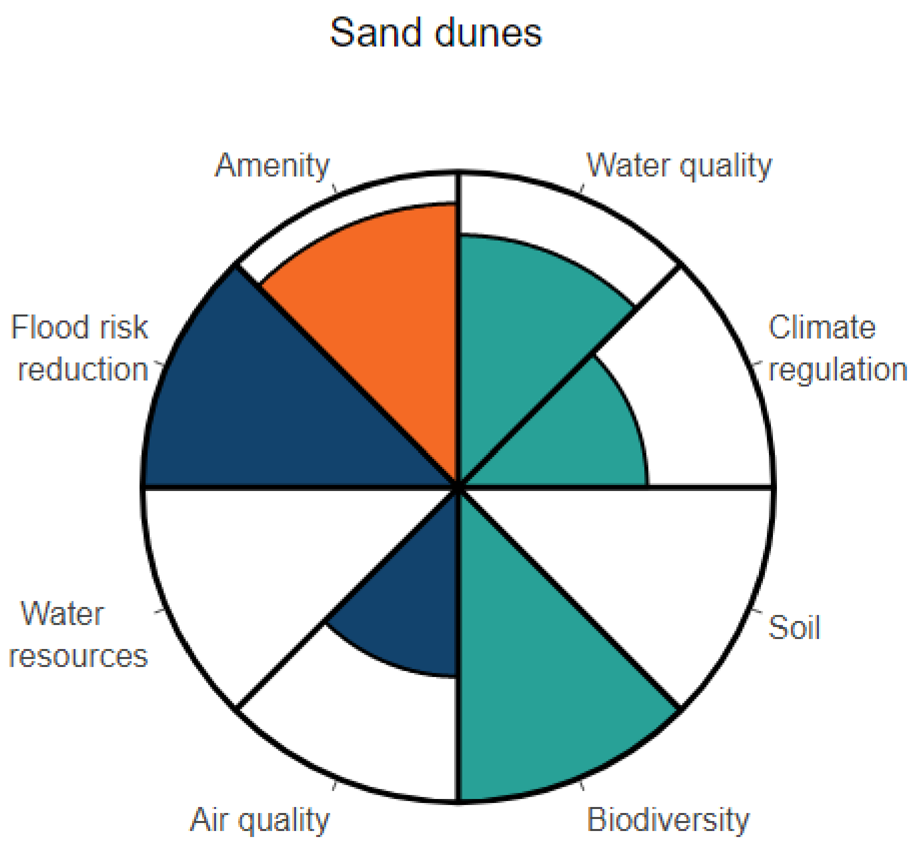

Figure 36 - Multiple benefits wheel for sand dunes

7.4.6 Research gaps

Despite new evidence coming to light since the original evidence directory, there are remaining research gaps to allow us to continue to improve our understanding of sand dunes. We still need:

- monitoring and knowledge sharing to determine whether a measure has been a success across a wide range of different sites in the UK
- design guidance on the best ways to employ sand dune management measures, such as the best positioning of fencing
- long-term, continual monitoring to understand the response and, therefore, resilience of vegetated versus non-vegetated dune systems to a storm or series of storms
- improvements in our ability to predict future changes to prevailing conditions, particularly at a local level, and the impact of future management both locally and along adjacent shorelines
- improved understanding of potential risk that some dune systems could experience a catastrophic adjustment with major implications for flood defence and whether is it possible to understand a site’s risk or whether it may be able to accommodate future change

- improved understanding of the appropriateness of silica-based consolidation techniques for coastal sand dunes restoration, including the behaviour over time and the environmental impacts

7.5 Reefs

7.5.1 What are reefs?

A ‘reef’ is a general term that describes shallow, submerged structures in the ocean and coastal areas. Biogenic reefs in the UK are made of bivalve molluscs, mostly species of oysters and mussels, and members of the Sabellariidae family such as the Ross worm. The rigidity of oysters enables the reef to act as an offshore breakwater, either submerged or emergent, and can dissipate wave energy through both depth-limited wave breaking and drag over the reef (Bridges and others, 2021). NBS research, therefore, tends to focus on oyster reefs due to their engineering potential. This review collates emerging research and features as a new inclusion to the WWNP evidence directory.

The broad term ‘reefs’ encompasses artificial, biogenic, geogenic and hybrid reefs, which combine elements of man-made structures to help mimic characteristics of natural reefs or encourage the accumulation of reef organisms. The different types of reefs covered in this section are detailed below.

Artificial reef is a man-made submerged structure which may mimic some of the characteristics of a natural reef – generally in coastal management schemes these are constructed from large rock and stone.

Biogenic reef is a solid, massive structure which is created by accumulations of organisms, usually rising from the seabed, or at least clearly forming a substantial, discrete community or habitat which is very different from the surrounding seabed. The structure of the reef may be composed almost entirely of the reef building organism and its tubes or shells, or it may to some degree be composed of sediments, stones and shells bound together by the organisms.

Geogenic reef is a natural reef formed of rock to which organisms can attach themselves.

Hybrid reef is a man-made structure which combines elements of an artificial reef with those of a biogenic reef.

Native oyster reef is a substrate with a veneer of living oysters, providing high surface complexity, on a substrate which may be dominated by dead oyster shell. It becomes ‘biogenic’ at densities >20 individuals/m^2.

Figure 37 shows a close up of oysters at an oyster nursery at Roker Marine in Sunderland. The nursery is a part of Stronger Shores’ Wild Oysters Project.

Figure 37 – Wild Oysters Project's oyster nursery, Roker Marina in Sunderland (image credit: Stronger Shores)

7.5.2 Findings from the 2017 evidence base

The original directory did not have a section on reefs and so the scientific papers are from after 2017, while noting that there is substantial evidence before this period. A summary of the earlier papers and case studies can be found in the following documents:

- European Native Oyster Habitat Restoration Handbook (Preston and others, 2020)
- Overview: International Guidelines on Natural and Nature-Based Features for Flood Risk Management (Bridges and others, 2021)
- The application of oyster reefs in shoreline protection: are we over-engineering for an ecosystem engineer? (R.L. Morris and others, 2019)
- Restoring the eastern oyster: how much progress has been made in 53 years? (Bersoza Hernández and others, 2018)
- Innovations in Coastline Management With Natural and Nature-Based Features (NNBF): Lessons Learned From Three Case Studies (Palinkas and others, 2022)
- Nature-Based Solutions: Protecting and Building Coastal and Ocean Ecological Infrastructure (Telesetsky, 2020)
- From grey to green: efficacy of eco-engineering solutions for nature-based coastal defence (Morris and others, 2018)
- Habitat Modification and Coastal Protection by Ecosystem-Engineering Reef-Building Bivalves (Ysebaert and others, 2019)

- Effects of Roughness Loss on Reef Hydrodynamics and Coastal Protection: Approaches in Latin America (Osorio-Cano and others, 2019)

To summarise:

- methods of creating biogenic reefs include using recycled oyster shells deployed as loose shell or within specialised bags, oyster larvae then recruit to the shells, forming a reef
- hybrid reef methods include oyster castles and living breakwaters with textured surfaces
- reef configurations include low and high relief loose planted 'cultch', constrained 'cultch', and precast concrete structures
- native oyster reefs in the UK (Ostrea edulis) are typically found in depths of less than 10m and form on mixed substrate; man-made structures should, therefore, be built as submerged breakwaters for oyster recruitment (however, the greatest wave attenuation is often realised when the crest of the structure is at or above still water level)
- oyster reefs increase bed friction, reducing wave energy and aiding wave attenuation; this can result in sediment accretion on the leeward side and may reduce edge erosion, reducing the overall sediment budget available
- reefs may reduce the annual rate of shoreline loss, with some examples of overall material gain
- effectiveness depends on the size of the wave, the depth of water over the reef structure, reef material, biophysical characteristics, reef design and oyster recruitment
- oysters are well adapted to variable estuarine conditions (salinity, temperature) but prolonged exposure to unfavourable conditions can lead to high mortality
- settlement rate of oyster larvae depends on substrate type and presence of suitable biofilm, with the quantity of oysters potentially decreasing in young reefs
- oyster reefs mature slowly and require time to become self-sustaining, while maturing, surface roughness is lower and subsequently, energy dissipation may be reduced
- winnowing, the process of water pulling bed material into reef voids, can cause sinking and structural failure, and is more likely in the first 2 years
- non-oyster filter-feeders (for example, sponges, tunicates, mussels, barnacles) may colonise substrates; such species may not provide the same ecological and attenuating services as oysters
- future considerations for reef survival include salinity changes due to climate change

7.5.3 New flood risk evidence

For more detailed information relating to the studies used to formulate the following summaries, please see the literature review.

We have a **low** level of confidence in the effect that reefs have on flood and coastal erosion risk. There is evidence to show that reefs increase bed friction and facilitate wave attenuation, but there is limited evidence on the optimum depth of a reef to dissipate wave energy and maintain oyster populations. New literature suggests that:

- reefs facilitate wave attenuation, with a great effect for shallower water (Wiberg and others, 2019)
- reefs can be used as sills or as stand-alone breakwaters to stabilise adjacent shorelines (Dunlop and others, 2017)
- oyster reefs can reinforce saltmarshes (Fivash and others, 2021)

Effects on wave attenuation

We have **low to medium** confidence in the effects of reefs on wave attenuation due to a growing number of modelled studies but limited empirical evidence. The new literature suggests that:

- oyster reef structures can attenuate waves, but effectiveness depends on distance from the shore and water depth (Chowdhury and others, 2019; Marin-Diaz and others, 2021; Vien, 2022; Ma and others, 2018)
- the ability for oyster reefs to attenuate waves decreases as water depths increases (Chowdhury and others, 2019; Vien, 2022)
- reefs attenuate waves more by dissipating rather than reflecting waves; this was found through flume testing (Ma and others, 2018)

Effects on sediment and geomorphology

We have **low to medium** confidence in the effects of reefs on sediment and geomorphology due to limited UK applications. The new literature suggests that:

- oyster reefs can help reduce erosion and retreat (McClenachan and others, 2020; La Peyre and others, 2022)
- the ability for oyster reefs to provide shoreline protection depends on the level of wave exposure (La Peyre and others, 2022)
- sediment accumulation can be higher behind oyster reefs than in front of them (Vien, 2022; Chowdhury and others, 2019; Marin-Diaz and others, 2021)

Design life and effectiveness

We have **low to medium** confidence in the design life and effectiveness of reefs due to growing understanding of different design requirements based on modelling, but there are limited UK applications. The new literature suggests that:

- intrusion of freshwater into oyster reef systems impacts reef production and their ability to attenuate waves (La Peyre and others, 2022)

- oyster reefs facilitate wave attenuation, but effectiveness varies between natural and restored reefs (Morris and others, 2021)
- oyster establishment on reefs depends on inundation duration, however reefs where oysters have not established can still attenuate waves (Morris and others, 2021; Hogan and Reidenbach, 2022)
- the location and position of the reef impacts the ability to attenuate waves, with nearshore likely to be more effective; reefs and structures placed parallel to wave action are more likely to resist displacement (Dunlop and others, 2017; Godfroy and others, 2017)

Maintenance

We have **low** confidence in our understanding of the maintenance requirements of reefs due to the limited overall volume of evidence and the limited number of UK applications. The new literature suggests that the number of new recruits to oyster reefs impacts oyster density. Regular monitoring is required to determine short and long-term responses to environmental variation (La Peyre and others, 2022).

7.5.4 New multiple benefits evidence

Reefs provide a wide range of benefits, particularly for water quality and biodiversity and new evidence suggests that:

- reefs can improve biodiversity by recruiting bivalves and supporting crustaceans and fish. Such species also act as food sources for other species (Geisthardt and others, 2022)
- oyster reefs can enhance mean organic matter content of shoreline sediments (Vien, 2022)

The multiple benefits of reefs are reflected in Figure 38. Reefs provide a range of benefits. The greatest ecosystem service benefits are associated with water quality and biodiversity.

New evidence suggests that reefs are designed to encourage oyster production, which supports both recreational and commercial fishing. Oyster reefs can increase sediment stability and organic matter content.

The multiple benefits wheel tool is only intended to be used as a visual aid to suggest where additional benefits may be sought when implementing the measures for flood risk. It should not be used as part of detailed quantitative analysis or optimisation of options.

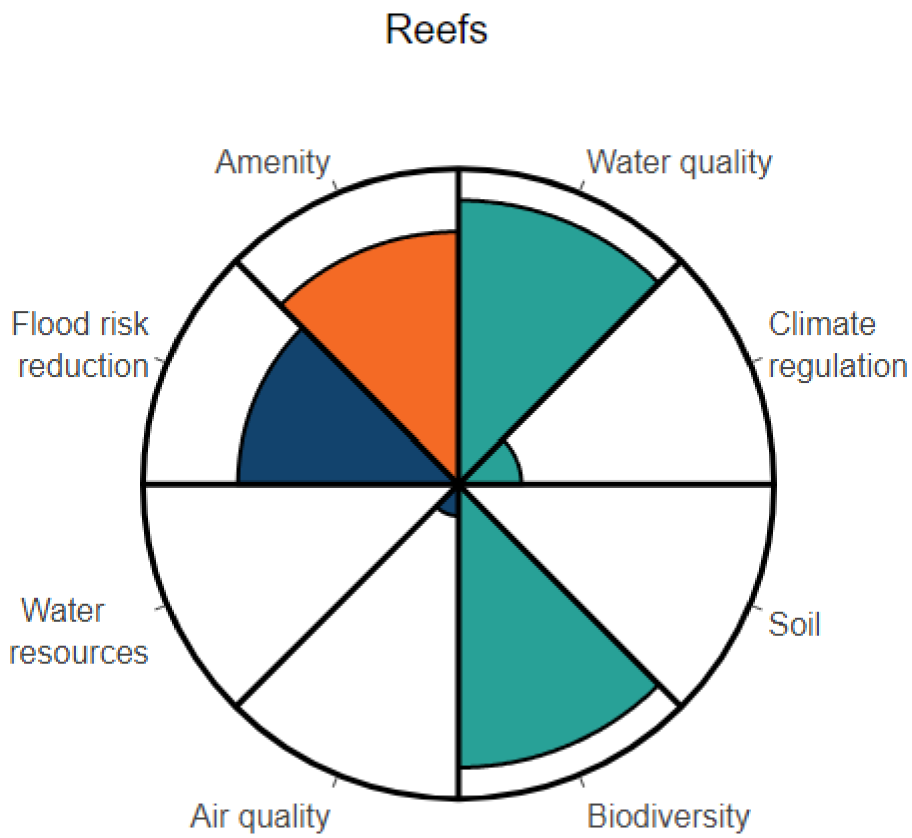

Figure 38 - Multiple benefits wheel for reefs

7.5.5 Research gaps

There are remaining research gaps to allow us to continue to improve our understanding of reefs. We still need:

- further understanding of the optimum depth of a reef to both effectively dissipate wave energy and maintain conditions for oyster recruitment
- methods for developing oyster reefs, such as the use of oyster castles versus gabions, including the design, performance and durability of materials for these
- an understanding of the long-term effects of oyster reefs for both recruitment and sedimentation
- an understanding of the conditions impacting oyster recruitment and survival (for example, temperature and salinity), including the impacts of climate change

7.6 Submerged aquatic vegetation (SAV) and kelp

7.6.1 What is submerged aquatic vegetation and kelp?

Submerged aquatic vegetation (SAV) is a term used to describe marine plants (for example, seagrass) and macroalgae (for example, kelp) and can be termed natural and nature-based features (NNBF). Seagrass is a subset of SAV which are found in intertidal zones in shallow coastal areas. The most recognised species in the UK are common eelgrass (Zostera marina) and dwarf eelgrass (Zostera noltei), 8,493 ha of which have been mapped across Scotland, Wales and the south coast of England (Gamble and others, 2021). Kelp grows on rocky reefs and artificial hard structures from the low water mark to depths in excess of 40 m, particularly along the wave-exposed south, west and north coasts. These species can absorb wave energy and induce drag, slowing water currents and providing shoreline protection (Bridges and others, 2021). The relevant terminology in this section is detailed below.

3D regenerative ocean farming means that 3D lattice of ropes and baskets are suspended just below the surface, enabling different species to grow at different depths.

Aquaculture is the farming of aquatic organisms, including fish, molluscs, crustaceans and aquatic plants.

Kelp is large brown seaweed of the Laminaria family. It can form dense underwater forests and is considered an ecosystem engineer.

Natural infrastructure (NI) is defined as a ‘strategically planned and managed network of natural lands, such as forests and wetlands, working landscapes, and other open spaces that conserves or enhances ecosystem values and functions and provides associated benefits to human populations’ (Benedict and McMahon, 2006).

Submerged aquatic vegetation (SAV) is a collective term for marine, estuarine and freshwater flowering plants that grow completely or predominantly submerged in the water column and reproduce through flowering on or above the water surface. SAV near shorelines can absorb waves and slow water movement.

Figure 39 shows an example of a kelp forest on submerged rocks from Stronger Shores in Wherry, South Tyneside.

Figure 39 - Kelp forest in Wherry, South Tyneside (image credit: Stronger Shores)

7.6.2 Findings from the 2017 evidence base

The original directory did not have a section on submerged aquatic vegetation and kelp and so the scientific papers are from after 2017, while noting that there is substantial evidence before this period. A summary of the earlier research and case studies can be found in the following documents:

- Seagrass Restoration Handbook UK & Ireland (Gamble and others, 2021)
- Overview: International Guidelines on Natural and Nature-Based Features for Flood Risk Management (Bridges and others, 2021)
- Nature-Based Solutions: Protecting and Building Coastal and Ocean Ecological Infrastructure (Telesetsky, 2020)

To summarise:

- SAV and kelp beds can slow and absorb unidirectional flow energy (for example, tides and flooding events)
- waves cause the leaves to move, with the amount of movement dependent on leaf stiffness
- SAV can also aid in sediment settlement, help stabilise sediment existing and may raise the sediment profile
- SAV habitats are spatially dynamic
- effectiveness is dependent on the height and rigidity of the canopy compared to water column height

- SAV is most effective when the canopy is the same height as the water column
- effectiveness is scale dependent, and SAV and kelp are often used in combination with other nature-based solutions
- SAV is likely to be most suitable in small scale, low energy environments
- identifying sites that are suitable for SAV and kelp is crucial; using SAV and kelp in unsuitable environments is likely to result in failure

7.6.3 New flood risk evidence

For more detailed information relating to the studies used to formulate the following summaries, please see the literature review.

We have a **low** level of confidence in the effect that SAV and kelp have on flood and coastal erosion risk. There is evidence to suggest that SAV and kelp increase sedimentation rates and attenuate wave energy by imposing a drag force, but there is limited evidence on the long-term influence of SAV and the different types of SAV. New literature suggests:

- SAV and kelp attenuate wave energy by imposing a drag force on incoming waves and currents (Bodycomb and others, 2023; Nowacki and others, 2017; James and others, 2021; Godfroy and others, 2017)
- seagrass meadows can trap sediment between plants, increasing sedimentation rates (Unguendoli and others, 2023)
- the ability of SAV and kelp to reduce wave energy increases with plant/macroalgae density (Chen and others, 2022; Sierra and others, 2023)
- wave attenuation was found to be greater in shallower water depths (Bodycomb and others, 2023)

Effects on wave attenuation

We have a **low** level of confidence in the effects of submerged aquatic vegetation on wave attenuation due to the limited evidence base. The new literature suggests that:

- wave energy dissipation rates recorded for a suspended kelp canopy were found to be reduced by as much as 94% (Bodycomb and others, 2023)
- wave modelling was applied to seagrass meadows within the Mediterranean, wave attenuation was found to be 10.5% greater on average over the meadow, with a maximum attenuation rate of 36.1% (Sierra and others, 2023)

Effects on sediment and geomorphology

We have a **low** level of confidence in the effects of submerged aquatic vegetation on sediment and geomorphology due to the limited evidence base. The new literature suggests that:

- erosion can be reduced; this was found through the modelling of seagrass meadows (Unguendoli and others, 2023; Chen and others, 2022)
- erosion has been observed to be the highest when seagrass shoot density and leaf length is at its lowest (Paquier and others, 2019)
- accretion can be enabled in front of seagrass meadows, with the slowest grain size being observed at the back of the seagrass meadow (Paquier and others, 2019)

Design life and effectiveness

We have a **low** level of confidence in the design life and effectiveness of submerged aquatic vegetation as there are limited academic applications, however the practical applications appear to be growing. The new literature suggests that:

- seagrass with greater leaf and shoot density provided the strongest wave attenuation, lowest rates of beach erosion and greatest seabed stabilisation (Chen and others, 2022; James, 2021)
- there is potential reduction in effectiveness during the initial seagrass growth stages; mature seagrass was found to be more effective (Chen and others, 2022)
- aquaculture farms, including mussels and kelps can attenuate waves more effectively than SAV meadows (Zhu and others, 2020)
- SAV reduced wave intensity more in shallow waters compared to vegetation height (Morris and others, 2019; Bodycomb and others; 2023)

Maintenance

We have **low** confidence in our understanding of the maintenance requirements of submerged aquatic vegetation due to the emerging nature of the measure for FCRM purposes. The new literature suggests that:

- planting is likely to be more successful if a tiered system is used, where rocks or geotextile bags are used to protect the vegetation from high wave energy while it matures (Pope, 2019)
- planting is more successful if more mature plants (plugs or larger) are used (Pope, 2019)

7.6.4 New multiple benefits evidence

Submerged aquatic vegetation and kelp provide a wide range of benefits, particularly for water quality and biodiversity and new evidence suggests that:

- greenhouse gas offset forecasts show carbon benefits from restoration of seagrass meadows (Oreska and others, 2020)
- restoring seagrasses provides habitat for fish (including those that are commercially important), supporting food security (Unsworth and others, 2019)

The multiple benefits of submerged aquatic vegetation are reflected visually in Figure 40. Submerged aquatic vegetation (SAV) provides a wide range of benefits, particularly for water quality and biodiversity. New evidence suggests that seagrass may store carbon, providing a climate regulation benefit. It also has some amenity benefit.

The multiple benefits wheel tool is only intended to be used as a visual aid to suggest where additional benefits may be sought when implementing the measures for flood risk. It should not be used as part of detailed quantitative analysis or optimisation of options.

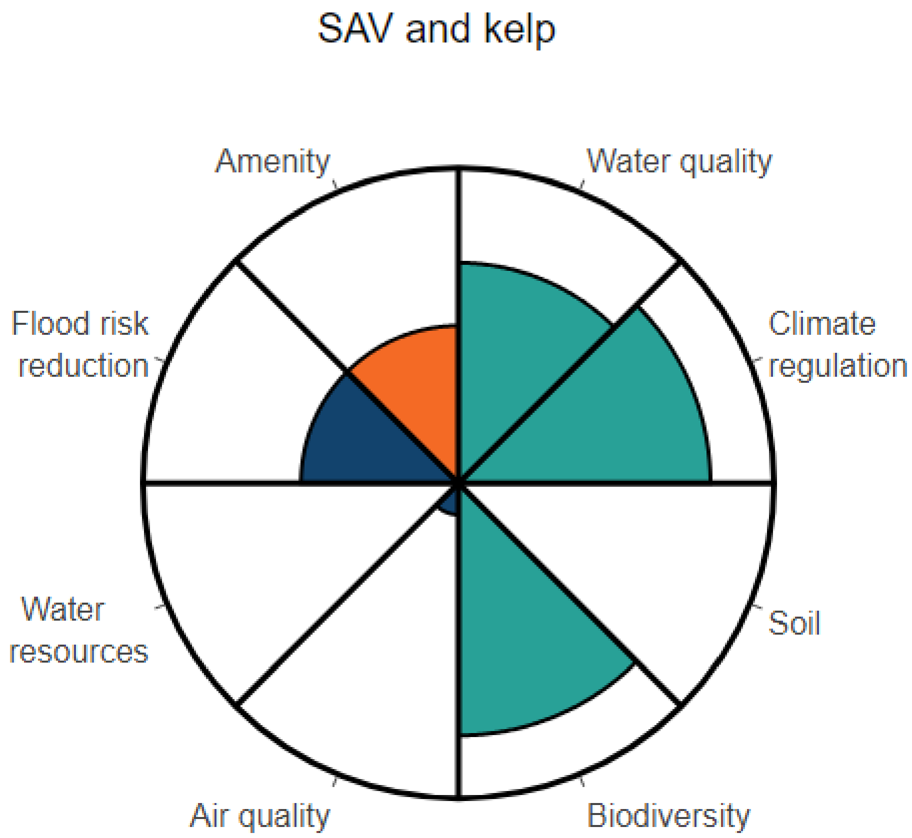

Figure 40 - Multiple benefits wheel for SAV and kelp

7.6.5 Research gaps

There are remaining research gaps to allow us to continue to improve our understanding of submerged aquatic vegetation. We still need:

- greater understanding of the species of SAV and kelp, including the differences between submerged and suspended kelp canopies
- quantification of wave attenuation capacity of seagrass and kelp
- further studies on the long-term influence of SAV and kelp in reducing flood risk
- further assessment of the impact of SAV on wave and tidal energy and how to incorporate this flood risk benefit of SAV into models

8 Cross-cutting NFM

8.1 Introduction

This chapter summarises the evidence around the effectiveness of mixed NFM schemes, whereby multiple NFM measures are used in combination in one scheme or study. Often, NFM schemes will use a variety of interventions to suit factors such as geography, flooding mechanisms and permissions. This chapter considers combinations of different NFM measures. It does not consider integrated flood risk management, whereby NFM measures are combined with traditional engineering flood risk management approaches or property flood resilience measures.

This chapter summarises the findings from studies that have used a combination of measures. It is split into 2 sections, results derived from modelling, and results derived from monitoring. The multiple benefits of a combination of measures are considered at the end of this chapter. To read about new evidence of multiple benefits of individual measures, please refer to the other chapters.

8.2 Monitored results of multiple NFM measures

8.2.1 Effect on flood flows, peaks and storage

A study quantifying the potential effectiveness of NFM for offsetting increases in peak river flows related to climate change, under the UKCP09 climate projections found that:

- assuming there is no time lag associated with the reduction in peak flows due to NFM (for example, installing a feature versus planting a tree which takes time to grow and reap benefits), NFM measures are more likely to offset the impacts of climate change for earlier time-slices and lower emissions scenarios
- NFM is likely to offset the impacts of climate change for a lower return period (for example, <10 years)

Summary statistics and flow duration curves calculated by the University of Exeter for the Ottery St Mary NFM project (120 ha) illustrated that peak flow levels were reduced by 14% following the implementation of 54 leaky dams, woodland renaturalisation, a retention pond and soil aeration. The flow duration curves also showed that the catchment is less flashy compared to pre-installation of the features (Puttock, Brown, and others, 2021).

The Littlestock Brook NFM trial, in a sub-catchment (16.3 km^2; underlain by clays, mudstones and limestones; average slope of 6.4%) of the River Evenlode in Oxfordshire, implemented measures over 5 years including:

- 27 in-channel, bank-full woody dams
- soil management measures on steep clay slopes and along overland flow pathways

- creation of nutrient retention ponds and sediment traps in fields
- 15 riparian field corner bunds to store over-land run-off
- de-culverting of 100 m of watercourse
- creation of 230 m of new watercourse
- 14.4 ha of new riparian woodland
- 900 m of field edge nutrient trapping swales

Results from an analysis of the monitoring network outputs (Robotham and others, 2022) showed:

- reductions in flood peaks across all storm events (14.2% to 55.2% reductions), with return periods of up to 5.5 years
- the greatest reduction in flood peak was seen during the most intense rainfall event, this was attributed to the greater potential for overbank flow into flood storage areas to be stored
- the least intense rainfall events still provided flood storage benefits, reducing the flood peak by over 20%
- the maximum flood peak reduction was observed during the longest duration and most intense rainfall event, which had 2 peaks. The flood storage areas were able to attenuate 19.1% of the second more intense peak, holding >8,000 m^3
- more than 40% of the total storage capacity of the NFM measures remained available throughout all events

A thesis paper analysing NFM impacts in the catchment of the Potwell Dyke (0.65 km^2) in Southwell, Nottinghamshire, where stage loggers recorded the effect of 2 bunds, leaky barriers, and a reach of river restoration, showed:

- stage decreased downstream of the interventions post restoration
- as event magnitude increases, benefits to stage and discharge decreases (Wells, 2019)

Monitoring of the upper Belford Burn catchment (5.7 km^2) in Northumberland was undertaken, where offline ponds, leaky dams, online ponds, overland flow interception ponds, sediment traps and riparian woodland had been installed. The results showed that offline storage areas reduce local flood peaks more effectively during small, flashy events (50% annual exceedance probability (AEP)) and that available storage is depleted before the arrival of the main flood peak during long duration events. Analysis of monitoring data noted that one set of features reduced peak flow by approximately 12% during a smaller storm event, filling to approximately 75% of its capacity (Nicholson and others, 2020).

Observations from the Stroud NFM project highlighted that there has been a reduction in average river stage height at 2 gauging stations in the 250 km^2 catchment since interventions (in-channel and floodplain large woody debris (LWD), gully stuffing, earth bunds, track management) have been implemented. One gauge measured an average reduction of 19%, and the other 13% (relative to the local stage datum). It is estimated that approximately 20% of the catchment (52.5 km^2) flows through the NFM interventions (Short and others, 2019).

8.2.2 Effect at different catchment scales

The ongoing Eddleston Water project in the Scottish Borders (69 km^2), which began in 2009, has been assessing the effectiveness of an integrated NFM approach to reduce flood risk and improve riparian habitats at a catchment scale. To date, working with farmers, it has provided:

- 207 hectares of woodland planting (>330,000 native trees)
- 116 large high-flow log structures, positioned on upper tributary streams
- 38 flow attenuation ponds (36 located in the headwaters and tributaries, and 2 large ones on the lower floodplain)
- 3 lengths totalling ~3.5 km of previously straightened river channel re meandered, with adjacent flood banks removed. This has added a total of ~362 m of new channel to the main river

Drawing on the results from the dense monitoring network (2 years baseline monitoring and 10 years post implementation), the study has sought to understand the total catchment response to the combined implementation of the NFM measures (as well as understanding the impacts of individual features, see other chapters). Its main findings are:

- headwater catchments up to 26 km^2 show increases in median lag times from 4 hours or fewer to 6 hours or more following the introduction of a mixture of flow restrictors, ponds, and riparian planting and in 50% AEP event (QMED); this is compared to 2 control catchments which showed median lag times of <4 hours in both the baseline period and in the years following the NFM interventions in the adjacent experimental catchments
- the greatest increases in lag time (up to 7.3 hours) were observed in the smallest catchments (2.21 km^2) that had the multiple NFM measures implemented
- in larger catchments greater than 26 km^2, median lag times are 5 hours or more in the period before NFM measures were introduced, while, in the period after measures, median lag time increases by at least 0.5 hours except in the furthest downstream site
- for catchments greater than 26 km^2, median lag time increases with catchment area, as would be expected given the increases in distance downstream
- in the 2.75 km^2 catchment where only riparian fencing and planting was implemented across 7.5 ha (2.7% catchment cover), no significant increases in lag were observed
- the 2 control catchments showed no changes in lag time (Spray and others, 2021; Black and others, 2021)

8.2.3 Effect on different watercourse typologies

A study of NFM in chalk groundwater-dominated catchments found that the results of the measures would be sub-optimal compared to other catchment types due to NFM interventions being less suited to catchments with less proportion of surface run-off processes. During periods of high level of groundwater emergence at hydrogeological features (for example, winterbournes or springs), NFM should be focused on small scale, in-channel measures to reduce small-scale disruptions such as the flooding of roads (Barnsley, 2021).

8.2.4 Effect on sedimentation and geomorphology

Restoration of 500 m of the 720 m study reach of the Allt Lorgy, Spey catchment, Scotland (21.6 km^2) took place in 2012 (Williams and others, 2020). This included removing and lowering embankments, gravel augmentation and large woody debris. Analysis after the restoration saw:

- a doubling in the total area of bowls and saddles (geomorphological features) between 2012 and 2016, demonstrating greater morphological complexity
- bank erosion was the most significant mechanism for volumetric change between 2012 and 2014 (52%) and between 2014 and 2016 (46%)
- the diversity index of the river increased from 1.4 to 2.04, near to the value for full diversity (2.64)
- an overall evolution of the study area from a plan-bed to a riffle-pool dominated morphology

The Littlestock Brook NFM trial's flood storage areas (combination of swales, ponds, bunds, leaky barriers) provided significant sediment trapping events, in particular during larger storm events. Studies showed that 2 to 3 years following construction, monitoring showed that the equivalent of 15% of sub-catchment sediment yield was trapped in the features, which covered only >1% of the catchment. This stored sediment accounted for 14% of the fine suspended sediment, 10% of the total phosphorous, and 8% of the particulate organic carbon yields. Given the accumulated sediment was generally enriched in nutrients and of a fine texture, it was identified as potentially being valuable for re-use in agriculture (Robotham and others, 2022; Robotham and others, 2023).

A combination of offline and online storage areas in agricultural catchments (3.4 km^2) amassed 47.8 t and 39 t of sediment respectively, with 14% of total sediment yield and 14.1% of fine (clay and silt) sediment yield being stored in all features (Robotham and others, 2023).

Sediment accumulation rates were 3.3 times higher in online features compared to offline features, with the difference thought to be due to the length-to-width ratio and contributing area, particularly the event contributing area, which clusters offline storage areas into those activated by leaky barriers and those that were not in Littlestock Brook. Using leaky barriers to encourage flow into offline storage areas enabled sediment-rich flows into the areas during storm peaks.

Despite designing ponds to below the optimum length-to-width ratio for trapping efficiency (5:1), Robotham and others, (2023) found that both online and offline storage ponds accumulated significant pollution masses, suggesting that gains can still be made without an ‘optimised’ design in Littlestock Brook, Oxfordshire.

8.3 Modelled results of multiple NFM measures

8.3.1 Effect on flood flows, peaks and storage

Ferguson and Fenner (2020) reported on integrated modelling of a mixture of NFM measures and their potential to reduce flows on urban drainage. They used a linked model (Dynamic TOPMODEL and HEC-RAS) to study the impact of hillslope tree planting and in-channel leaky barriers in the Asker catchment, Dorset (48 km^2; primarily silty mudstone and sandstone with alluvium deposits in the lower reaches; predominantly grassland with significant pockets of arable and woodland). The study found that during a storm with a 10% AEP event, the upstream NFM measures could reduce outfall inundation by up to 3.75 hours and reduce peak magnitude by 57%. During a 3.3% AEP event, the NFM measures reduced the maximum surface flooding extent within a housing estate downstream by 35%.

Modelling (SHETRAN) of the groundwater dominated River Test catchment (1,250 km^2) showed deciduous woodland creation with in-channel restoration (channel revegetation and large woody debris installation) results in a 5% flood peak reduction. It also decreases the time watercourse banks are overtopped (flood return period not stated), with an average reduction from 3.1% to 2.8% in bank overtopping compared to baseline scenarios (Barnsley, 2021).

Unconstrained modelling of Brimfield Brook in north Herefordshire (30 km^2) estimated that the flood could be reduced by a maximum of 13 to 33% if NFM measures were implemented in all areas of the catchment at 100% effectiveness. It found that the combination of the measures that were actually implemented through the project could reduce the flood peak by <1% on account of their relatively small percentage coverage of the catchment (Lewis and Hodges, 2021a).

In the Cam catchment (Norwich, 928 km^2), modelled results suggest that combining nature-based solutions (NBS) measures leads to improved results. For example, soil improvement and run-off attenuation features (RAFs) both retain run-off, but improved soils mean that fewer RAFs will be required, as less run-off is generated to fill them. Additionally, land use changes and soil improvement techniques affect different stages of the water cycle, so have compound effects (Aghajani and others, 2023a).

Modelling (SD-TOPMODEL with site-specific model parameters) of the combined effect of NFM measures in Bishopdale (38 km^2; predominantly rural catchment characterised by heavily gripped peat moorland and extensively grazed pastoral farmland) found that compared to single interventions such as increased soil infiltration, the application of multiple NFM measures was not as efficient (Figure 41). The effectiveness of multiple NFM interventions during the large storm event was restricted, leading to a 1% decrease in peak discharge and no change observed in time to peak compared to the 10% AEP event. This was attributed to potential synchronisation of flood peaks as a result of the decreased conveyance of overland flow across the catchment caused by NFM measures not being put in appropriate locations. It was, therefore, recommended that further study ought to be undertaken to identify the areas of synchronicity within the catchment and test different locations of NFM interventions to maximise their impact on the hydrograph (Kingsbury-Smith and others, 2023).

		10-year 12-h				100-year 12-h			
Scenario	Intervention	Peak runoff (mm)	Relative peak diff (%)	Time to peak (h)	Time to peak diff (%)	Peak runoff (mm)	Relative peak diff (%)	Time to peak (h)	Time to peak diff (%)
	Baseline	26.88	-	9.25	-	122.77	-	8.50	-
1	Woodland planting	27.58	3	9.50	3	109.56	−11	8.75	3
2	Hedgerow	26.96	0	9.50	3	122.77	0	8.75	3
3	Riparian buffer (grass)	26.88	0	9.50	3	121.99	−1	8.50	0
4	Buffer strip (young)	26.65	−1	9.50	3	121.99	−1	8.50	0
5	Buffer strip (developing)	26.73	−1	9.50	3	121.99	−1	8.75	3
6	Buffer strip (established woodland)	26.65	−1	9.50	3	121.99	−1	8.75	3
7	Buffer strip (mature woodland)	26.50	−1	9.50	3	121.99	−1	8.75	3
8	Increased soil infiltration	24.94	−7	10.00	8	112.67	−8	9.00	6
9	Moorland restoration	27.20	1	9.25	0	121.22	−1	8.50	0
10	All NFM	25.64	−5	10.00	8	121.22	−1	8.50	0

Figure 41 – Hydrological metrics from Kingsbury-Smith and others (2023)

Modelling of the combined impact of multiple NFM measures was undertaken as part of the Wye and Lugg NFM project, whereby it was assumed measures could be implemented ‘unconstrained’ in all areas of the catchment. The analysis estimated that the flood peak in the Cheaton, Cogwell and Ridgemoor brooks (total catchment area of 74 km^2) could be reduced by a maximum of 9 to 22% (range derived from comparison with a 50% and 1% AEP event in each catchment) if NFM measures were implemented in all areas of the catchment at 100% effectiveness. However, of the measures actually implemented, the combined impact was estimated through modelling to be <1% (Lewis and Hodges, 2021b). The measures modelled and implemented included:

- 17 ha grassland aeration
- 21.26 ha cover crops
- 2 sediment traps/attenuation areas (~2,300 m^3 storage)
- 72 leaky dams

- 595 m watercourse fencing
- 1.18 ha tree planting
- 120 m hedge planting
- 233 ha direct drilling
- 1 rainwater harvesting system (20 m^3)
- 20 m^2 bankside willow planting
- coppice scrub with small pond (500 m^2)
- a variety of other measures through mid-tier countryside stewardship

In the Upper Stour Valley in Warwickshire, a study modelled the impacts of a range of NFM measures, co-designed with land managers. Measures included:

- woodlands and hedgerows
- online storage
- offline storage
- leaky barriers
- river and floodplain restoration
- track drainage alteration
- buffer strips
- soil aeration, winter crops and zero tillage
- swales, ponds, bunds and sediment traps

It assumed that the interventions were fully matured (for example, fully established trees) and applied across the whole catchment. Modelling of the whole upper Stour Valley catchment and 5 sub-catchments was undertaken, ranging from 5.8 km^2 to 187 km^2. The storm events modelled were 1% AEP, QMED, 3.3% AEP and 1% AEP plus climate change allowance (35% increase in peak river flow) and each were modelled to a 12-hour storm duration. The smaller flood events (Index Flood (QMED) and the 3.3%) showed decreases in flood peaks across all the catchment sizes. As the storm magnitude rose, the impact of NFM measures on downstream peak response reduced significantly, in particular at the largest hydrological scales. The total catchment area of Shipston-on-Stour had the least change as a result of NFM: 4% at the QMED design event, 0% at the 1% AEP and 1% AEP + CCA. That said, delays in times to peak were noted at all hydrological scales. In some cases, flood peak was increased, which was attributed to the synchronisation of flows (Lavers and others, 2022).

Ramsbottom and others, (2019) modelled NFM measures in the Littlestock Brook catchment (16 km^2) using the InfoWorks ICM 2D hydraulic model. The measures were field corner bunds, online ponds, swales, woody dams and riparian vegetation. The hydrograph was delayed and the overall change in flood volume was about 50% of the storage volume created by the measures (about 10,500 m^3 for the 1 in 30 years event out of a total of about 20,000 m^3). The results for storm magnitudes are presented in Table 6 below.

Table 6 - Hydrological metrics from Ramsbottom and others, (2019)

Storm magnitude	Reduction in water level (m)	Reduction in peak discharge (%)	Reduction in volume (%)
1 in 10 year	0.19	22	10.3
1 in 30 year	0.24	27	9.8
1 in 50 year	0.21	23	8.4
1 in 75 year	0.18	21	7.6
1 in 100 year	0.16	19	6.6
1 in 75 year with climate change allowance	0.11	14	3.9
1 in 100 year with climate change allowance	0.09	12	3

SHETRAN modelling of the Coalburn catchment (1.5 km^2, covered predominantly by Sitka spruce and Lodgepole pine) indicated that flood frequency and magnitude were reduced through a combination of partial afforestation and leaky barrier installation in headwater catchments. Combining the 2 interventions resulted in a 10% peak discharge reduction, with only 35% afforestation and 20% dam installation, with a run-off reduction of only 7.5% (Barnes and others, 2023).

A modelling assessment of the combination impact of multiple measures (gully tree planting, cross-slope and field tree planting, and soil improvement) in 3 sub-catchments of the Calder River (Hebden Water, ~60 km^2; Jumble Hole, 5 km^2; Upper Calder, 19 km^2) found a positive impact on flood risk. The results showed a reduction in peak flow and volume as well as an increase in time to flood peak. Table 7 below shows average difference in peak, time to peak and change in volumes for all scenarios and for all catchments against the baseline expressed as a percentage value (Willis and Klaar, 2021).

Table 7 - Hydrological metrics from Willis and Klaar (2021)

Scenario	Average difference in peak value from baseline (%)	Average changes to timing of peak (minutes)	Average changes to flow volume (%)
Boundaries	-4.83	+5 -10	-1.38
Horse paddocks	+0.13	-	+0.29
Intensive livestock grazing	+2.01	-20 -30	+1.87
Riparian access	+0.40	-5 -10	+0.77
Moorland management	+0.77	-5 -10	+0.44
Gully planting	-1.01	+5 -10	-0.84
Tree planting	-2.08	+20 - 30	-2.83
Soil improvement	-1.52	+15 -20	-2.76
All land management	+5.61	-30 -40	+4.55
All NFM interventions	-6.10	+30 -40	-6.2

Modelling 2 scenarios for the Salmons Brook NFM project (Gilbert, 2021a) found that the combination of woodland planting (200 ha), channel width reduction (75% reduction in width to activate the rural floodplain) and 46 bunds in the rural catchment could potentially, during a 25 year AEP event, achieve a 50% reduction in peak flow and 10 to 30cm reduction in peak water levels in downstream urban areas (Table 8). This impact was expected to increase with the woodland's maturity. Increasing woodland planting to 415 ha and reducing channel width by 90% was expected to achieve a 65% peak flow reduction and a widespread reduction of 30 to 50 cm in the urban catchment.

Table 8 - Hydrological metrics from (Gilbert, 2021a)

Scenario	1 in 25 year AEP peak flow reduction	1 in 25 year AEP peak flood water heights in flood zone	1 in 100 year AEP peak flow reduction	1 in 100 year AEP peak flood water heights in flood zone
200 ha of woodland (as saplings) **75% channel width reduction** **46 rural permeable bunds**	50%	10 to 30 cm	35%	<50 cm
415 ha of woodland (as saplings) **90% channel width reduction** **46 rural permeable bunds**	78%	<30 cm	65%	>50 cm

A modelling study of the Rise Stream NFM project (2 km^2 catchment area) found a 28% reduction in peak flow compared to the baseline when simulating the combined effect of leaky barriers and a constructed wetland during an approximately 5% AEP event (Gilbert, 2021c; McKenna, 2021).

Modelling (HEC-RAS 2D) by Hankin and others (2021) of the range of measures implemented in the Eddleston Water catchment (69 km^2) found a small 5% reduction in peak flows across all design events modelled, as shown in Table 9.

The model was constructed and calibrated against the monitoring network developed by Dundee University for the Tweed Forum with Scottish Government funding, and represents one of the most detailed, multi-scale NFM monitoring catchments in the UK. The measures included leaky barriers extending onto the floodplain as lateral flow deflectors, combined with floodplain tree-planting, wider woodland, river re-meandering and additional pond storage. Additional floodplain storage was highlighted as being crucial to the results, with flow deflectors pushing higher flows into expandable areas of floodplain storage, and, for example, one section of re-meandering led to a 6% increase in flood volume stored.

Table 9 - Hydrological metrics from Hankin and others (2021)

Design event	Peak flow baseline	Peak flow (NFM)	% peak reduction	Time delay
Return period 1000	56.68	53.64	5.4%	00:00
Return period 200	35.19	33.42	5.0%	00:15
Return period 100	28.29	26.76	5.4%	00:15
Return period 75	25.77	24.34	5.5%	00:15
Return period 50	22.77	21.51	5.5%	00:15
Return period 30	19.67	18.51	6.3%	00:15
Return period 25	18.68	17.58	5.9%	00:30
Return period 10	14.63	13.69	6.4%	00:30
Return period 5	12	11.17	6.9%	00:30

8.3.2 Effect at different catchment scales

The Calderdale modelling study (Willis and Klaar, 2021) found peak flow and volume reductions and increases in time to flood peak as a result of the NFM measures scaled with catchment size. The NFM measures included a combination of:

- gully tree planting – conversion of identified planting areas to 'broad leaved woodland'
- cross slope and field tree planting – conversion of identified planting areas to 'broad leaved woodland'

- soil improvement – conversion of selected grazing fields to ‘improved soil’

The percentage in reduction of flow peaks were:

- 5 km^2 catchment, 25% NFM coverage – 9% reduction
- 19 km^2 catchment, 13% NFM coverage – 5.5% reduction
- 60 km^2 catchment, 10% NFM coverage – 3.5% reduction

The reductions to peak flow were observed to scale with catchment size and event size. The different reductions for the catchment sizes could be attributed to the greater percentage coverage of NFM interventions in the smallest 5 km^2 catchment (25%) compared to the largest 60 km^2 catchment (10% coverage). Overall, the smallest catchment was observed to produce the greatest variability in results, whereas the largest catchment had the lowest range as shown in Table 10. The greater impact on flow in the combined NFM scenario compared to the scenarios that implemented one type of measure was attributed to the complexity of feedback between the interventions.

Table 10 - Hydrological metrics from Willis and Klaar, (2021)

All NFM interventions	Upper Calder	Hebden Water	Jumble Hole
Catchment area (km^2)	19	60	5
% catchment modified	13%	10%	25%
% change in peak discharge 3-hour 1 in 10 year	-7%	-5%	-11%
% change in peak discharge 3-hour 1 in 100 year	-5%	-2%	-7%
% change in peak discharge 12-hour 1 in 10 year	-5%	-1%	-10%
% change in peak discharge 12-hour 1 in 100 year	-4%	-2%	-7%
Average of above scenarios % change in peak discharge	-6%	-2%	-9%
Observed June 2012 event % change in peak discharge	-5%	-3%	-5%
Observed December 2015 event % change in peak discharge	-4%	-2%	-3%

8.3.3 Effect on different watercourse typologies

A study of NFM in chalk groundwater-dominated catchments found that the results of the measures would be sub-optimal compared to other catchment types due to NFM interventions being less suited to catchments with less proportion of surface run-off processes. During periods of high level groundwater emergence at hydrogeological features (for example, winterbournes or springs), NFM should be focused on small-scale, in-channel measures to reduce small-scale disruptions such as the flooding of roads (Barnsley, 2021).

8.3.4 Multiple benefits

Climate regulation

A study of the multiple benefits of the Evenlode NFM project estimated that it would result in a substantial net removal of carbon dioxide to the atmosphere of 8,199 tCO_2. This was attributed to the creation of woodland and agroforestry, with smaller contributions from grassland and freshwater habitats (Miles and others, 2021).

Biodiversity

A biodiversity net gain (BNG) assessment carried out for the Evenlode NFM project estimated a 28.94% net gain for habitats and a 1.98% net gain for rivers. The assessment used the beta-test Biodiversity Metric 2.0. The measures included:

- implementing soil management measures on steep slopes and along flood pathways
- creating nutrient retention ponds and traps in fields
- constructing 15 bunds and scrapes to store up to 30,000 m^3 of floodwater in riparian field corners
- installing an additional 15 in-channel leaky dams using woody material
- planting approximately 12 ha of new riparian woodland on previous arable land supported by a Forestry Commission Woodland Grant scheme
- 900 m of field edge nutrient trapping swales
- 7.6 ha of arable land converted to No Till/cover crop production
- initiation of an agroforestry trial to supply the local community with produce
- installing new project interpretation boards to educate and engage with visitors

The assessment highlighted that the implementation of extensive sustainable land management provided significantly more biodiversity units than the implementation of discrete NFM features (Miles and others, 2021).

Water quality

Following the implementation of the NFM measures on the Eddleston Water project, the Water Framework Directive (WFD) status improved from bad in 2012, immediately before any measures had been implemented (the poorest category in WFD monitoring), to moderate potential in 2020 (Spray and others, 2021).

8.4 Headline findings

The 2017 evidence directory did not feature a chapter that focused solely on the evidence of WWNP measures being used in combination.

Gap 1 of the identified research gaps highlighted the need for more evidence of the effectiveness of WWNP measures **alone, in clusters or in combination** with other forms of FCRM for a range of return periods and a range of different catchment scales.

The evidence shows that:

- modelling studies that explore extensive implementation of WWNP measures across a catchment show positive results on flood peaks and flows, however it is often challenging to implement even a small percentage of the measures on the ground

- while modelling may show different combinations showing the best results, factors on the ground will play a crucial role in what combinations can ultimately be used
- modelling studies have found that a combination of measures is sometimes not as efficient in achieving flood risk benefits compared to the application of a single type of intervention applied extensively across a catchment (for example, improving soil infiltration)
- **Important** - the flood risk benefits of multiple NFM measures in a catchment can be reduced due to synchronisation of flood peaks resulting
- as with individual measures, the effectiveness of multiple WWNP interventions used in combination reduces as storm magnitudes increases

8.5 Research gaps

Research gaps include better understanding:

- how synchronisation of flood peaks can be avoided when using a combination of different measures across a catchment
- how combinations of WWNP measures can be best located in catchments (from source to sea) to achieve the greatest flood risk benefits
- which combinations of WWNP measures achieve the greatest benefits during larger return periods
- how much NFM needs to be implemented to achieve effective reductions and what could be appropriate common metrics across approaches to assess this (for example, equivalent volume removed by measures)
- what specific combinations of WWNP measures are used more frequently than others, why this is, and whether it's due to decisions based on maximising benefits or 'acceptability' on the ground
- how WWNP measures in catchments and on the coast interact with one another and can be used in combination to achieve flood risk and wider benefits
- what combination of measures work together best in different catchment and watercourse typologies
- what combination of measures work together best on different soil types
- how different combinations of measures can maximise multiple benefits
- how different coastal and estuarine NFM measures can be used in combination to improve the resilience of coastal communities
- what are the long-term, more sustainable nature-based alternatives to beach recharge and traditional forms of engineering on the coast, and how effective are they at improving coastal resilience in the face of sea level rise and climate change

9 Quantifying the evidence

9.1 Introduction

The previous chapters summarise the evidence base behind WWNP, explaining what we know and what we don't know about how effective different measures are at reducing flood risk, and the wider benefits they can bring for people and the environment.

The ‘Research gaps’ sections in Chapters 4 to 7 summarise the main areas of uncertainty where more research is needed to address these knowledge gaps and expand these areas of science. When developing a WWNP project and planning to undertake monitoring or modelling, it is suggested you look at these chapters and consider the measures you are planning to construct and whether you could potentially address any of these knowledge gaps.

This chapter provides some high-level understanding around developments to both monitoring and modelling since the original evidence directory. This chapter does not replace the guidance provided in the original evidence directory, where guidance on how to monitor and model are found in Chapter 6 and Chapter 2 of ‘Using the evidence base to make the case for natural flood management’ respectively and should be read in conjunction with the information below.

9.2 Monitoring

There have been few advances in the development of monitoring techniques for NFM or the application of novel monitoring techniques to NFM in the past few years, with no agreed framework for monitoring which is practical for the majority of applications across the UK. Many of the earlier sections have highlighted the lack of monitored data as a factor in our gap in understanding of the efficacy of NFM.

In September 2023, the Environment Agency and Defra announced £25 million of funding for improving flood resilience through a new NFM programme.

Recognising the importance of improving evidence on the effectiveness of NFM, all projects are required to carry out monitoring in line with the programmes minimum monitoring requirements which will be analysed centrally.

9.2.1 Extent of monitoring needed

Project monitoring

The monitoring of WWNP projects generally takes one of 2 approaches.

The ‘detailed’ approach looks at, for example:

- the extent of the effects of local-scale flow changes
- catchment-scale flow changes on flood risk
- before-after control-impact (BACI)

The 'lighter touch' approach looks at, for example:

- how, where and when a measure is working
- whether the effects of a measure can be used to inform modelling studies
- how the measures perform in non-flood and low flow conditions, for example, monitoring that lacks baseline data or a control site

Programme monitoring

The review of programmatic monitoring and evaluation approaches for restoration programmes by Roni and others (2018) highlighted various methods, each with strengths and weaknesses. These included:

- case studies offer detailed insights into individual projects but lack broad applicability, and meta-analysis was not recommended due to its reliance on compatible case studies
- the multiple before-after control-impact (mBACI) approach was deemed ideal for evaluating a few projects but proves challenging for broader applications
- the extensive post-treatment (EPT) approach, requiring no pre-project monitoring, has been increasingly used, although finding suitable controls often presents challenges
- a hybrid approach combining BACI and EPT designs may provide both quick and long-term insights; large-scale monitoring programmes may also benefit from rotating panel sampling where projects and years monitored are rotated to be more efficient and allow for collection of data at a large number of projects

Overall, the main considerations in any successful monitoring programme include effective project tracking, identifying suitable controls, using consistent protocols. Acknowledging contextual variables with the optimal design depends on programme goals, available projects and funding, with a hybrid approach likely to yield comprehensive and timely results for evaluating river restoration projects (Roni and others, 2018).

Monitoring for prediction modelling

If monitoring is required for prediction modelling of the effect of WWNP measures, Hinshaw and others, (2022) found that when sampling using 40 plots, a prediction power of 67% was realised for geomorphic change. It was assumed that 80 plots would be needed to increase the predicting power to 80%. However, there was little difference found between each plot's subplots, therefore Hinshaw and others, (2022) suggested that a random plot scale sampling technique could be tested to increase the number of plots with less field effort required (monitor 60 plots only instead of 40 plots with 4 subplots (160 subplots). It was assumed that 80 plots would be needed to increase the predicting power to 80%.

9.2.2 Monitoring techniques

The original evidence directory focused on monitoring techniques to measure flood storage and hydrometric monitoring equipment and its costs, time series and measurements. The information within the original evidence directory still stands and should, therefore, be read before the following information. The evidence in this update to the directory focuses on monitoring techniques that have advanced since 2017 and while the methods below are relevant to WWNP studies, the papers are not necessarily applying the approach specifically to flood risk monitoring/modelling.

Remote sensing and use of unmanned aerial vehicle (UAV) imagery

Sentinel-1 satellite synthetic aperture radar (SAR) data was used to assess changes in flooding through a change detection and thresholding (CDAT) technique along the Sussex Ouse, England. The process had a 75% accuracy when validated using footage from internet-published drone videos (Jarrett and Holbling, 2023).

Using multitemporal UAV imagery along the floodplain of the River Waal, Netherlands resulted in high overall accuracy of the object-based random forest classification, with 90% accuracy of floodplain land cover, with 6 different types of vegetation and 4 non-vegetation land covers identified. Using 2 or more time steps increases accuracy to up to 99.3% (Van Iersel and others, 2018).

Structure from motion

Rogers (2017) compared the use of airborne LiDAR and structure from motion (SfM) for generating non-bare earth digital terrain models (DTMs) of former meanders in the River Ure catchment. They found:

- SfM produces more accurate and higher-resolution DTMs than LiDAR, especially for meanders with areas of ~100’s to 1,000’s m^2
- imagery collected using a hand-held extended pole can result in better quality DTMs compared to ground-based camera photography, even though the pole extends the survey range, it was recommended to use ground-based imagery for other applications in geosciences
- point-to-point validation using control points (CPs) highlighted that SfM outperformed LiDAR at all 3 sites, SfM yielded smaller elevation errors compared to LiDAR, with LiDAR tending to underestimate ground surface elevation, especially in areas with tall and dense vegetation

An unmanned aerial vehicle (UAV)-SfM was tested to see the accuracy and precision of the method in agricultural settings where it was previously assumed that it would struggle due to a lack of features to stitch photos together. Over 3 separate flights, the maximum error compared to reference data (6 independent verification points (IVP), measured using differential global positioning system (dGPS)) was 0.24 m, with both accuracy and precision being a factor of crop height, flight height and the number of control points used. Although deemed acceptable on the basis of a linear regression analysis between UAV-derived digital elevation model values and IVP values, the authors note this regression analysis is not 100% accurate given the limited number of IVPs used (Robertson and Maddock, 2019).

Radio-frequency identification (RFID) passive integrated transponders (PIT) tags and tracers

Using RFID PIT tags to track the movement of sediment following sediment augmentation in the River Rhine, on the French-German border, Arnaud and others, (2017) found:

- monitoring of the position of the sediment wave front following gravel augmentation was consistent between airborne images, topo-bathymetric survey and RFID particle tracking
- high correlation between tracer position and areas of deposition in successive surveys
- using RFID PIT tags in large river (catchment size 34,500 km^2) can result in a low recovery rate (11 to 43%)
- mean travel distances when measured from individual tracers compared to tracer cloud centroids was relatively consistent, although through time, as tracer recovery rate lowers and tracer dispersion is at its highest, the consistency reduces
- due to not being dependent on identifying the same tracer between surveys, when there are enough particles to delineate tracer clouds, this technique should be used to assess travel distances over individual tracer analyses

The use of caesium-137 tracers in southern Italy to estimate soil erosion rates showed reference values which were similar to those found in other areas of southern Italy and depth distributions that conform to those expected in uncultivated soils. A 10% uncertainty band was used to account for equipment measurement error (Altieri and others, 2018).

9.3 Modelling

9.3.1 Introduction

This chapter focuses on advances in practical tools and models to help design or evaluate the effectiveness of WWNP.

The advice on modelling in the 2017 WWNP evidence directory still holds true, highlighting how we can use different levels of modelling to understand risk reduction from NFM better, especially where more calibration and greater process representation are included with proportionate evaluations of uncertainty. This must be in proportion to the scale of the NFM scheme (and budget) and the scale of risk being mitigated. Since 2017, there have been advancements in the tools, models and monitoring data at each scale and level of complexity that this chapter draws upon.

Figure 42 shows how increasing model complexity can help to improve representation of effectiveness of WWNP measures in models. It also demonstrates how confidence in results can be increased (and uncertainty reduced) through model calibration, sensitivity testing, performance tests, resilience tests and other checks.

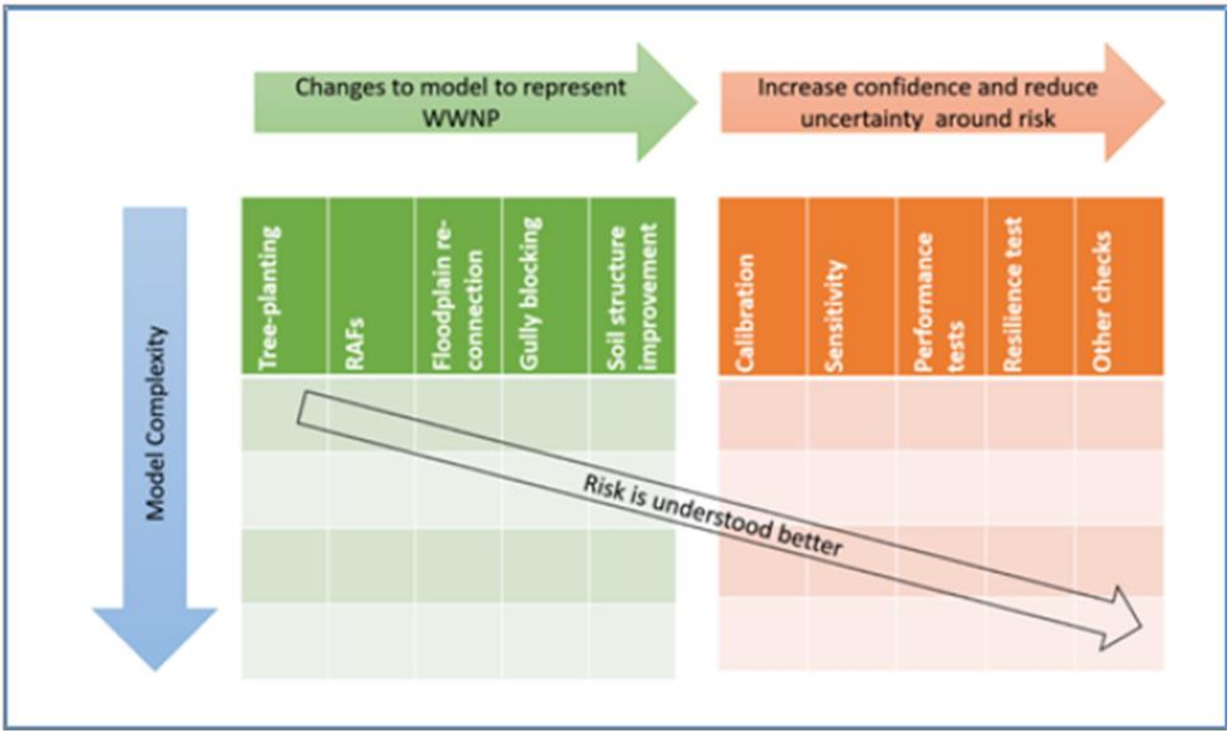

Figure 42 - Schematic of how to improve knowledge of the effectiveness of WWNP taken from Environment Agency (2017)

This chapter includes advances in process understanding from the UK Research and Innovation funded Natural Environment Research Council NFM Programme. The programme consisted of 3 projects which have been integral to the development of new modelling approaches since the 2017 WWNP evidence base. These were:

- LANDWISE - based at Reading University, focusing on land-use and soil change
- PROTECT-NFM - based at Manchester University, focusing on peat restoration
- Q-NFM - based at Lancaster University, focusing on diverse NFM across schemes in the predominantly managed grasslands (and woodland) of Cumbria

LANDWISE

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

PROTECT-NFM

The Protect-NFM team has been working for the last 11 years with Moors for The Future Partnership to monitor restoration of peatland micro-catchments on Kinder Scout and nearby moorland. The project has also set up restoration experiments on the moors above Stalybridge. Three main types of intervention have been deployed. The first is revegetation (grass seed spread onto bare upland peat alongside lime, fertiliser, and mulch). This stabilises the peat with a nurse crop, providing a surface for native plant species, like sphagnum moss, to re-establish. The second is gully blocking; over 6,000 dams across the Kinder plateau have been deployed into channels formed in the peat due to erosion. The team also evaluated a range of different dam types at Stalybridge Moor, including stone dams, peat dams and wooden dams and assessed the NFM optimisation of peat stone and wood gully blocks through the addition of pass-through pipes. The third restoration method was reintroducing sphagnum moss through plug planting.

Q-NFM

The primary aim of the Q-NFM project has been quantifying the effects of NFM interventions over scales ranging from micro-basins (about 1 km^2) that flood certain housing developments to the basins of large rivers that flood cities. The focus has been on 3 river basins in Cumbria (209 km^2 Kent, 667 km^2 Derwent and 2,287 km^2 Eden), although new observational evidence has been gained from a network of 1 km^2 micro-basins and plots located more widely across Cumbria (and elsewhere in the UK), and through the use of quality assured data sets collected within other temperate environments internationally. The micro-basin network (Cumbrian NFM effectiveness monitoring network (C-NFM project)) received additional funding from the Environment Agency as part of it's £15 million NFM pilot programme. This support has strengthened considerably the evidence base for the NERC NFM programme.

The NERC NFM programme identified, through the use of modelling guided by experimental data, that for more significant schemes, some model-led design can help improve the efficacy of the solutions designed to emulate natural processes. Fundamentally, this may help us move from the position that NFM effectiveness necessarily reduces with scale and storm magnitude, if there is considerably greater ambition to store flood water in the right place at the right time around the catchment (Chappell and others, 2023). To understand this potential further, it is worth considering recent advances in distributed modelling of NFM, particularly considering every catchment is unique in terms of climatology, hydrology, geology and distribution of people or receptors at risk.

The NERC NFM programme culminated in an important advancement that provides a more universal measure of efficacy, based on the volume of flood water avoided near the hydrograph peak (Chappell and Beven, 2023; Chappell and others, 2023). This can be computed in a directly observed or model-led situation by comparing hydrographs at a catchment outlet with and without any kind of NFM intervention.

Figure 43 shows this difference in the discharge (measured in metres cubed per second) with and without NFM. There is a reduction in peak flow (measured in metres cubed) in the window 2 hours either side of the peak.

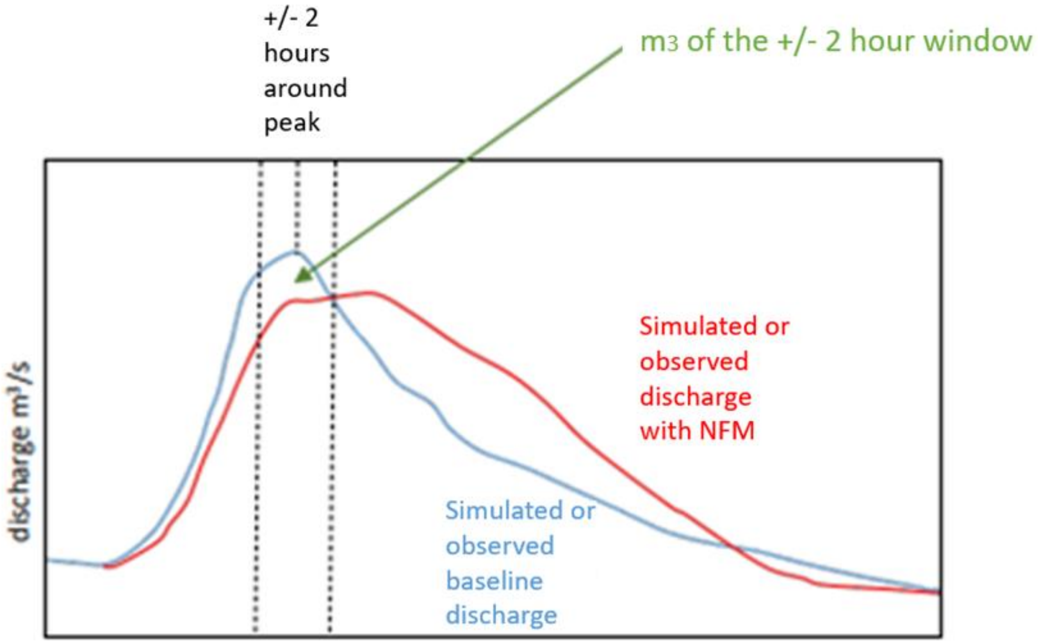

Figure 43 - NERC NFM programme measure of NFM efficacy based on an equivalent volume avoided at the peak

9.3.2 Advancements to modelling distributed process change due to NFM

The NERC NFM programmes have driven forward some important developments in distributed hydrological modelling described over the next sections, which are also now being adopted in some of the Environment Agency's [flood and coastal resilience innovation programme (FCRIP)] projects. The Environment Agency publication on modelling and mapping catchment processes (Environment Agency, 2021b) started from the position of asking which processes will be altered by NFM, and what tools or models can be used to represent the changes and evaluate the impacts. The 'Using the evidence base to make the case for natural flood management' chapter in the WWNP evidence directory (Hankin and others, 2018) built on this, but an important question remained on evidencing the changes made to model parameters at larger scales. The natural processes we are attempting to emulate are:

- increased wet-canopy evaporation (and soil drying) through woodland planting
- increased storage in different parts or compartments of the catchment, above ground, in the watercourses, floodplains and hillslopes
- increased friction typically to overland flow or channel pathways around the catchment through, for example, re-vegetation, land-use change or woodland
- enhanced infiltration

Note that representing spatial changes requires a 'distributed model' and that an 'unsteady model' is required to investigate temporal changes. Many of the Environment Agency's detailed hydraulic models can represent these distributed, unsteady process changes, so we can explore designing NFM in the right place at the right time. However, historically these detailed models have tended to represent upstream tributaries as a single 'lumped' response.

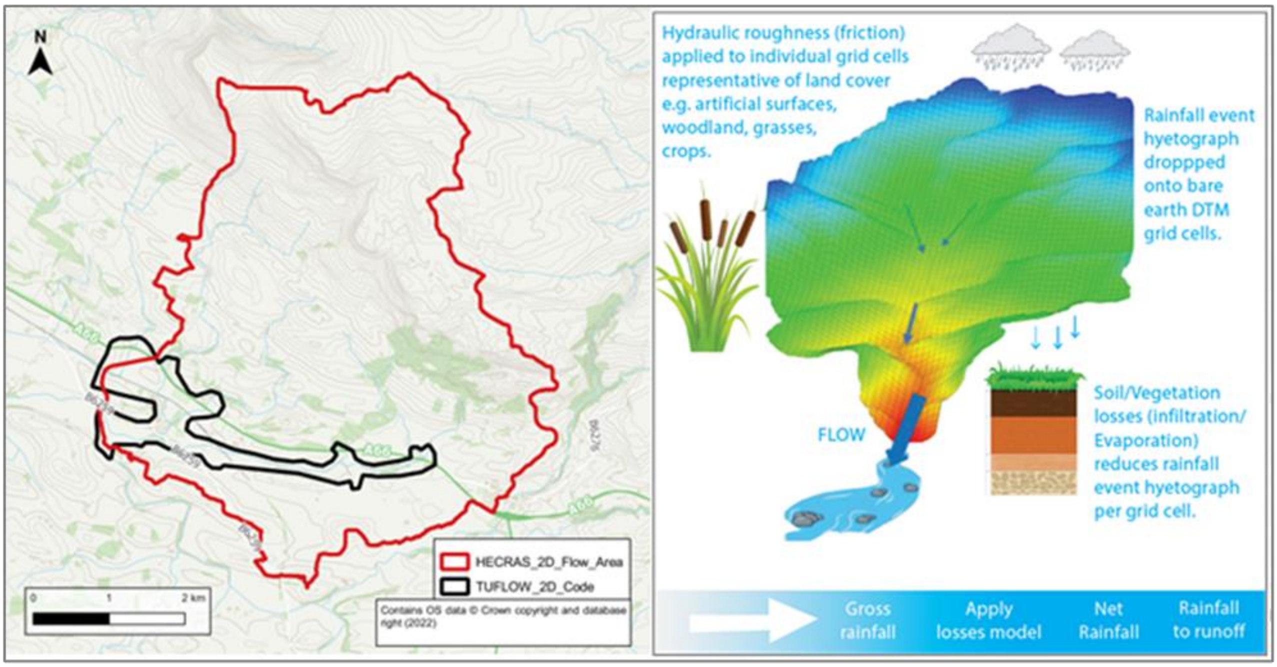

Figure 44 - Detailed model domain (black outline), whole catchment model (red outline) and modelling change at an inflow boundary

A useful approach has been to represent the catchment above a flood-affected community with a distributed, simplified model that can make use of new high-resolution topography data (such as a LiDAR bare earth DTM) and feed any relative changes in response due to NFM interventions, before evaluating changes in risk within a floodplain containing at-risk properties using the detailed hydraulic model.

This type of combination of models is powerful, and big advancements have been made in the availability of detailed open data sets needed to drive setting up a 2D model whether that is a 2D hydraulic model, or a distributed rainfall-run-off model (with routing of subsurface flows), or a model that can represent hillslope and hydrodynamics at the same time (for example, recent TUFLOW or hybrid modelling). Figure 44 shows an example of a detailed model boundary drawn in black that is nested within the wider catchment drawn in red. It is accompanied by a figure showing hydraulic roughness applied to individual grid cells, rainfall hyetograph and soil vegetation losses. This model allows for the estimate of gross rainfall - applying a losses model to estimate net rainfall and rainfall to run-off.

So, the advances also stem from the availability of observed data and models able to represent distributed changes to main processes in the landscape (Hill and others, 2023). They have also come from the development of models able to make use of sub-grid topography (for example, latest versions of HEC-RAS 2D, TUFLOW), enabling rapid modelling using cells of say 10 m resolution, while representing the sub-grid 1 m topography using LiDAR.

The hybrid approach of driving a hydrodynamic model with inputs from another model (Nicholson and others, 2020; Beven, Lane, and others, 2022; Bond and others, 2022; Quinn and others, 2022; Lavers and others, 2022) is computationally efficient, and has been mirrored in deep groundwater-dominated catchments, feeding in the predicted emergence from groundwater modelling into a 2D surface flow model. Progress has been made using a reduced dynamics (cellular automata) model since groundwater flooding is generally a slow process (for example, Collins and others, (2020)). The effectiveness of NFM measures in groundwater-dominated catchments has been assessed through the LANDWISE project and in other recent modelling studies (Barnsley and others, 2021).

Crucially, it is important to consider antecedent conditions (catchment wetness) before a modelled event, especially when investigating NFM-related soil improvement techniques such as agricultural aeration, de-compaction or, for example, use of herbal-leys (temporary grasslands made up of legume, herb and grass species). There are tools that can help with this to adjust flood estimation boundary conditions, such as the FEH Cini calibration, and models such as the distributed Dynamic TOPMODEL or the semi-distributed HYPE model that undertake soil-moisture accounting through time.

So, in addition to budget constraints and the scale of risk-reduction possible using NFM, selecting the appropriate model can also depend on the processes that dominate, the perceived role of antecedent conditions, and a requirement for computational efficiency.

9.3.3 Advances in representing uncertain change due to NFM

There are large uncertainties in distributed hydrological modelling, so assessing model fitness-for-purpose should come with an assessment of understanding uncertainties (Beven, Page and others, 2022). There are large knowledge-uncertainties in inputs such as the rainfall that drives the models (see, for example, Page and others, (2022)), or data used to prove the models such as gauged flow data for which peak flows might only be accurate to within 10%. Where catchments are ungauged, the design flood estimation process based on average catchment descriptors or pooled statistics from similar catchments also incurs large uncertainties. Accepting there will always be model errors, the aim should be to model observation data (where available) within ‘limits of acceptability' set at the outset of a study, given an understanding of data limitations (see Beven, Lane and others (2022); Beven, Page and others, (2022)).

Many studies will commence model-proving with a comparison of modelled hydrographs with gauged discharge data, design flow estimates, or flood mapping data, and the parameter combinations governing the shape of the hydrograph response are then calibrated to improve the fit. An important parameter in hydraulic modelling of channels and floodplains is the Manning's n roughness coefficient, controlling friction. In rainfall-run-off processes a similarly important parameter is the representation of infiltration and the downslope transmissivity of the soil profile. When these are allowed to be varied spatially, the numbers of parameters increase rapidly, and the combinations of model parameters yielding equally acceptable performance based on uncertain observation data increases. Recent advances in exploring uncertainties and sensitivities have been developed into an uncertainty toolbox (see Page and others, (2023)), where documenting and testing the sensitivity of major assumptions is part of the process of modelling.

Many NFM investigations will not have time or budget to investigate these uncertainties in detail. The Q-NFM project team developed estimates of the average effectiveness of different types of NFM interventions reported in earlier sections, while accounting for uncertainties (Chappell and Beven, 2023; Chappell and others, 2023). This was based on either direct observations at the 1 km^2 scale or upscaling of NFM via shifts to effective model parameters to represent observed NFM measure-scale behaviour (for example, see Hankin and others, (2017). For example, it has been possible to measure a change in topsoil permeability between soils on wooded slopes compared to immediately adjacent pastureland and apply this change to scale the effective parameter controlling the transmissivity function of the upper part of the subsurface in the model. This can then be generalised, and the parameter-shift used in larger catchments to represent more widespread tree-planting at a larger scale.

The modeller does, however, need to be aware that differences in point measurements of hydraulic properties (for example, infiltration capacity) attributed to land use may not reflect the magnitude of contrasts observed at field-scales or even local plot-scales. Where such larger scale observations (for example, 10 m^2 to 1,000 m^2) are available, these should be used to better represent the 'grid-scale' contrasts in parameters for distributed rainfall-run-off models (for example, Chappell and others, (2017)).This donor-parameter-shift approach can also be developed by calibrating models individually to paired catchments, and assessing if there are general shifts in important variables such as transmissivity across all the well-performing models, while accounting for model uncertainty (see (Goudarzi and others, 2021; Hankin, Page, Chappell and others, 2021). The range of predicted shifts can be used so a range of potential benefits are considered to reflect uncertainty. However, it is of course important to have a model that is capable of modelling the main processes, and that it is not right for the wrong reason (see Badjana and others, (2023)).

9.3.4 Advances in appraising risk-reduction for NFM

Advances in modelling water resource benefits for WWNP

The Environment Agency owns large detailed numerical water resource models of main aquifers, driven in part by recharge which can be modified by implementing NFM measures. There have been some advancements in tools for modelling these changes to recharge for different NFM. The Surface Water Accounting (SWAc) model was used as part of a recent Environment Agency project to understand the recharge characteristics in the Otter catchment in Devon. The model focuses on the vertical percolation of water to an aquifer and how this might change with different NFM measures. It helps understand how water is partitioned through processes between rainfall and recharge, surface flows and evaporation. The software recently had a number of modules added to help evaluate NFM, such as additional surface water storage. The output files include MODFLOW compatible recharge, stream, streamflow-routing and evapotranspiration files, alongside tabulated water balances for defined areas.

Advances in modelling hydro-morphological change due to NFM

There have been steps forward in broadscale modelling of geomorphological change (see, for example, Follett and others, (2020); Bowman and others, (2021)) and in the influence of longer-term change around NFM measures on NFM effectiveness. A number of hydraulic software packages have also added a 2D sediment-transport module since the previous evidence directory. A gap identified has been the modelling of mixed types of sediment where, for example, cohesive/non-cohesive sediments are present in rivers and estuaries.

9.3.5 Advances in modelling specific NFM measures across the evidence directory themes

Building on the modelling guide of the WWNP evidence directory, a recent modelling study by JBA Consulting, (2022) explored new learning in modelling the NFM benefits of catchment sensitive farming (CSF) measures, implemented for ecological benefit but recognising the potential for flood risk reduction co-benefits. This study built on a figure from the 2017 evidence directory resulting in Figure 45. The figure illustrates the importance of selecting the 'right model' to represent the 'dominant' hydrological processes. It also notes how local knowledge and new monitoring data can improve models, leading to improved intervention design.

It should be noted that while this figure focuses on spatial scales, temporal scales are also important, for instance designing storage with a long retention time will help slow down the wave speed in a flood and also enhance attenuation. This has been made easier for leaky barriers using a spreadsheet tool, but it should be recognised in general across different NFM types.

Figure 45 shows how effort and risk should be considered to inform an appropriate type of model analysis. The scale of models shown in the figure vary. At the lower cost end is GIS analysis, then simple tools and data analysis, and finally bespoke or large scale modelling (which may be appropriate for larger scale higher risk projects).

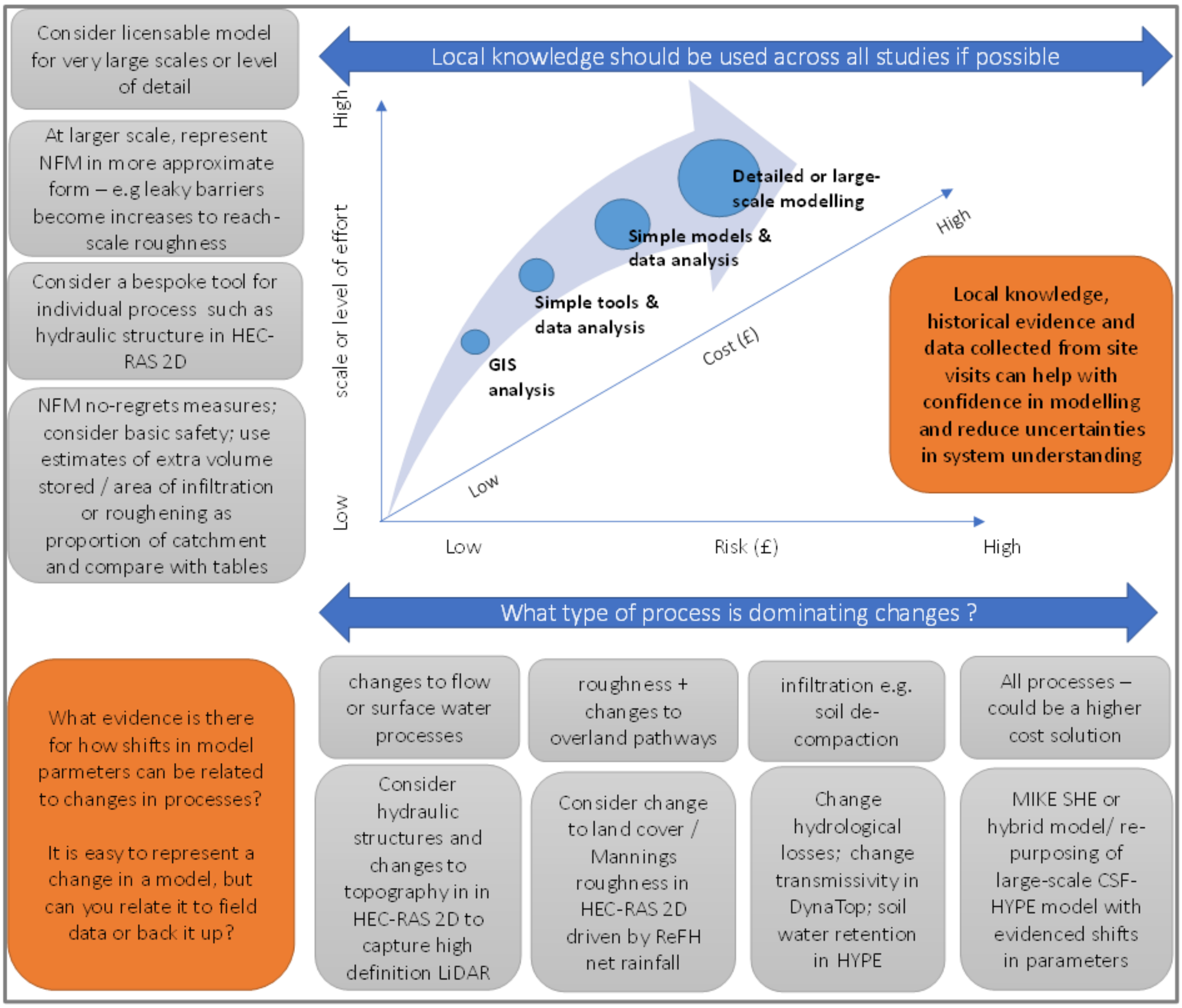

Figure 45 - What type of process is being considered for what type of NFM over what timescale? (JBA Consulting, 2022)

The following sections describe advancements in tools appropriate across this spectrum applied to the 14 types of NFM measure identified in the evidence directory. Many of these have been grouped where the advancements can be generally applied across measures. Examples of new resources since 2017 are included, although this is not exhaustive.

River and floodplain management: river restoration, river floodplain and floodplain wetland restoration, including offline storage

The NFM measure types under the heading of river and floodplain management cover restoration of river channels, floodplains and wetlands, which are generally all most effectively modelled using a 1D-2D or 2D only hydrodynamic model. This permits the hydrodynamic interactions between main channel and floodplain to be represented. It also permits the modelling of additional attenuation due to flood waters being stored temporarily, plus it allows an understanding of potential impacts on properties on the floodplain.

However, floodplain restoration will not necessarily reduce flood risk significantly, and it is more floodplain storage enhancement that facilitates the mechanism (Chappell and others, 2023; Chappell and Beven, 2023). Recognising this is important since the approach appears to provide some of the more significant improvements in resilience, especially when combined with some model-led design, as would be used in the development of an engineered flood storage area.

Modelling advancements that have already been discussed include the use of modern 2D hydraulics software to account for sub-grid topography based on a detailed LiDAR DTM, while using coarser scale computation cells, combined with mesh refinement around main features such as embankments. With this combination, the thresholds in bank levels that control pathways of large volumes of water can be better represented. These thresholds are essentially 'tipping points' (often responsible for 1D model instabilities), so the use of high-resolution LiDAR DTM plus a model with these capabilities represents a significant step forward.

There are still simplifications to process representation in mainstream 2D models using a lumped Manning's n roughness coefficient to represent friction, and not accounting for the complexities of channel-floodplain interactions, which is essentially a 3D process. Steps have been made to account for this in, for example, the Conveyance Estimation System (Knight and others, 2010) and other more recent studies (for example, Fernandes, 2021).

Models of offline storage have also been developed. For example, Nicholson and others, (2020), developed a Pond network model to demonstrate the potential peak flow reductions from offline storage in the Belford catchment (6 km^2) should significant offline storage be created (>10,000 m^3). This has been a common recommendation from across many modelling studies, that significant available flood-water capacity (freeboard) is needed for NFM measures to make a significant difference (Beven, Follett and others, 2022). The monitoring data for these measures has started to accrue, although generally for small flood events (for example, Lockwood and others, (2022)).

Examples of new modelling resources:

- high resolution LiDAR DTM data
- use of sub-grid topographic data in hydraulic schemes (HEC-RAS 2D / TUFLOW)
- open source distributed hydrological models
- Dynamic TOPMODEL Code and Help
- Water numbers – dynatop on github
- Water numbers – dynatopGIS on github
- Water numbers - Hydrological Response Unit (HRU) on github
- Distributed TOPMODEL (Gao and others, 2015)

- Generalized Multistep Dynamic (GMD) TOPMODEL (Goudarzi and others, 2023)
- HYPE Wiki
- HYPE Code
- for groundwater-dominated catchments see (Collins and others, 2020)

River and floodplain management: leaky barriers

Backwater rise upstream of leaky barriers depends on loss of momentum within the jam, and this can be represented by an adaptation of the law for drag in canopies (Follett and others, 2020). Advances have recently been made through laboratory experiments that permit characterisation of the losses based on measurable quantities - the frontal area and porosity of the woody debris to formulate a canopy resistance coefficient termed the 'debris factor'. This can be estimated by measuring head loss across the leaky barrier for a given flow, and then applied robustly across a range of flows. It has also been used to generate a rating curve and inserted as a hydraulic unit in a 2D model (Follett and Hankin, 2022).

In addition, new ways of formulating the problem in terms of whether a particular design increases retention time behind the NFM measure (Follett, Beven, and others, 2023) and so generates attenuation have been developed, with freely available software linked below. The associated software can be used as a design tool, providing estimates of retention time for a variety of instream barriers and channel characteristics. Retention time has been shown to be important, particularly when there is a period of prior wetting before a flood event (as is often the case in significant winter floods in the UK). If the storages drain too quickly or too slowly they will be ineffective in reducing flood peaks (Metcalfe and others, 2018).

At the wider scale, it is possible to represent leaky barriers in software such as Dynamic TOPMODEL, and as hydraulic units in standard 2D hydraulics packages. For larger scale NFM schemes where many leaky barriers are used (for example, over 40 in a small Black Brook reach of the Eddleston Water catchment), representing these all as individual hydraulic units within a large hydraulic model is impractical, so modellers have sought to represent these in terms of an uplift to reach-scale friction (Addy and Wilkinson, 2019), which has been linked to barriers structure and spacing (Follett and Hankin, 2022).

Recently rainfall-run-off software such as Dynamic TOPMODEL (Metcalfe and others, 2018) and developed by Paul Smith (see Beven and others, (2022)) have also developed ability to represent the impact of multiple enhanced hillslope storage with specified retention times. This has largely been done by changing the properties of an associated hydrologic response unit (HRU) to represent a store with a time delay between outflow and inflow.

Many models are now open source or freely licensable, driven by initiatives such as the flood hydrology roadmap, improving accessibility, which is being documented in further studies commissioned by the Environment Agency on open methods (Environment Agency, 2023).

New resources

New modelling resources include:

- environmental modelling and software link to R code in Follett and Hankin, (2022)
- GitHub - efollett/Leaky-Barrier-Advisor: Model files for Leaky-Barrier-Advisor
- JBA Trust link to retention time code
- Dynamic TOPMODEL, specifically hillslope storage
- Water numbers – Hydrological Response Unit (HRU) on github

Woodland management: advances in modelling catchment, cross-slope and riparian woodland

The NERC NFM programme projects Q-NFM and LANDWISE developed comparative observational data sets of changes to permeability between wooded and alternative land-covers. Some of this work has informed the effective parameters used in rainfall-run-off modelling. The way that downslope transmissivity of soil changes with soil moisture deficit strongly controls stream hydrograph shape. By using a 2-stage profile, one with a much-enhanced transmissivity in the upper profile to reflect soil permeability measurements (combined with measured contrasts in antecedent soil wetness), it has been possible to realistically represent the impact of woodland stream hydrographs.

This has been combined with new analyses of wet canopy evaporation (WCE) measurements (Page and others, 2020), which has shown that individual rainfall events as large as 50 to 300 mm may deliver significant removal of water from temperate catchment systems. It also demonstrated that through such events in Cumbria the relative humidity was, surprisingly, sufficiently below 100% to permit these high rates of loss, particularly in the lee of high mountains.

There have, however, been studies that showed contrasting results. For example, Carrick and others, (2019), concluded that from 7 eligible studies of 156 reviewed papers, increased tree cover only has a small statistically significant effect on reducing channel discharge. This contrasts with, for example (Monger, Spracklen and others, 2022), who highlight how semi-natural broadleaf woodlands can reduce streamflow generation significantly, including for flood magnitudes up to the 1% AEP event. These conflicting conclusions suggest that the benefit of woodland on flood flows is highly location specific, and, therefore, more work is needed, both monitored and modelled, in more geographic contexts to understand further the benefit woodland has on flood risk.

New resources

New modelling resources include:

- see above links to Dynamic TOPMODEL which has a method for representing the influence of woodland on downslope transmissivity (Beven, Lane and others, 2022)

Run-off management: soil and land management

LANDWISE was set up to evaluate the effectiveness of realistic and scalable land-based NFM measures to reduce the risk from flooding from overland flow and groundwater in groundwater-fed lowland catchments. The project evaluated measures like crop choice, tillage practices and tree planting, which have been suggested by people who own and manage land to have the greatest realisable potential. NFM measures were evaluated for their ability to increase infiltration capacity, evaporative losses and/or below-ground water storage, thereby helping to store precipitation deep underground to reduce overland flow and throughflow to slow down the movement of water to reduce peak river levels.

The LANDWISE project included measurements of soil permeability across different land-use/crop-types on different soils (Rameshwaran and others, 2021). An important finding was that soils with greater carbon content have significantly greater porosity and, therefore, potential storage.

One issue with seeking to reduce flooding with soil improvement measures such as agricultural aeration, de-compaction and organic content may be that the type of flooding that such measures can help mitigate are more associated with high intensity convective events, where the antecedent conditions are relatively dry. For many flood-causing events in catchments such as the Thames, soils might already be saturated at times of high river flow, so there would be limited potential for additional soil storage (Mulligan and others, 2023).

Another important issue with modelling land-use change is the difference between effective parameters used in a model numerical cell (perhaps 10, 100 or 1,000 m^2), and what can be measured in the field, typically at a point scale (perhaps less than 0.01 m^2). Typically, some kind of scaling should be undertaken to translate or upscale point measures to the transmissivity parameters used in a model like Dynamic TOPMODEL (Chappell and others, 2017). This approach was used by Kingsbury-Smith and others, (2023) to vary land management regimes to parameterise a physically based spatially distributed hydrological model (SD-TOPMODEL). This study found some significant reductions in peak flow for regimes improving infiltration rates (7 to 8% across 10% and 1% AEP events), although woodland was only effective at AEP 1%, reducing peaks by 11%. It was observed that the effect of implementing multiple NFM interventions was not additive.

New resources

New modelling resources include the Leaky-Barrier-Advisor for modelling efficacy with practical field-based data collection (see links earlier).

Run-off management: land and headwater drain management

As described in the introduction to this section, the PROTECT-NFM project aimed to demonstrate that upland restoration offers a low-cost way to reduce the risk of flooding in vulnerable rural communities, and to optimise multi-benefit restoration work for NFM. Three main types of NFM were deployed and monitored with BACI design. These were:

- revegetation (grass seed spread onto bare upland peat alongside lime, fertiliser and mulch), this stabilises the peat with a nurse crop providing a surface for native plant species, like sphagnum moss, to re-establish
- gully blocking: over 6,000 dams across the Kinder plateau have been deployed into channels formed in the peat due to erosion, the team also evaluated a range of different dam types at Stalybridge Moor, including stone dams, peat dams and wooden dams
- reintroduction of sphagnum moss through plug planting

The new results are reported (Shuttleworth and others, 2019) and a type of inverse modelling was undertaken that identified land surface roughness as the main determining factor enhancing attenuation in the systems that were monitored and modelled (Goudarzi and others, 2021).

New resources

New modelling resources include the Generalised Multistep Dynamic (GMD) TOPMODEL (Goudarzi and others, 2023), which is available on Github.

Run-off management: run-off pathway storage

There have been various advancements in modelling run-off attenuation measures on hillslopes (also called enhanced hillslope storage within the Q-NFM project), focusing on extending retention times (see parallel work in channels by Follett and others, (2023). Antolini and Tate, (2021) used network modelling to show that distributed attenuation can be an effective alternative to a single centralised flood mitigation approach, but that location matters. This is similar to Metcalfe and others, (2018), where the timing of storage and full utilisation was identified as important, along with the need to avoid slowing down flashy parts of a catchment that would then synchronise their peak with responses from elsewhere.

New resources

New modelling resources include:

- Environmental Modelling and Software link to R code in Follett and Hankin, (2022)
- GitHub - efollett/Leaky-Barrier-Advisor: Model files for Leaky-Barrier- Advisor
- [JBA Trust retention time code]
- [Dynamic Topmodel, specifically hillslope storage]

Advances in coastal NFM modelling

While there have not been significant advancements apart from numerical schemes permitting more efficient use of high-resolution LiDAR DTM, modelling packages have made improvements to visualisation. For example, understanding the duration of inundation of different vegetation species is important to ecological benefits of NFM, and this is now more easily visualised in TUFLOW.

The potential to model complex interactions with infrastructure has improved with 3D computational fluid dynamics (CFD) packages, which can help compute stresses in more detail to be used on, for example, bridge faces or to generate more accurate rating curves. These tools could all be used to improve NFM modelling in coastal areas.

Examples of current modelling approaches can be found in the literature review.

9.3.6 Summary

In addition to the NERC NFM programme, there have been developments elsewhere in the UK and internationally. These have included rapid expansion of high-resolution LiDAR DTMs, models capable of using this data efficiently to delineate complex flow pathways, and detailed modelling of leaky barriers based on physical properties.

There have been advances in distributed modelling to reflect changes to hydrological and hydrodynamic processes associated with NFM measures. This has included pragmatic approaches to combine rainfall-run-off models (and/or groundwater models) with rapid hydrodynamic flood modelling to understand floodplain flows and impacts. More complex integrated models have been developed, whereby the lateral flows from different soil layers are accounted for explicitly rather than being represented as losses.

Many of these models are now open source (see, for example, HYPE, DynaTop) or freely licensable, driven by initiatives such as the flood hydrology roadmap, improving accessibility, which is being documented in further studies commissioned by the Environment Agency on open methods (Environment Agency, 2023).

Many of these techniques are data-hungry, but high-resolution data has also become more widely available through the Environment Agency national LiDAR programme and advances in other remote sensing data such as Sentinel-2. Hydraulic software packages have also adapted to permit the use of sub-grid topographic data efficiently, representing another step forwards. It is likely that future advancements will come from improving extraction of physical data defining NFM using emerging remote sensing technologies, our understanding of performance, and feeding this into hydraulic models.

There remain gaps in understanding the influence of climate change on the effectiveness of NFM with increasing flows (for example, Connelly and others, (2020)), although some studies have identified that certain combinations of measures and anticipating the need to access larger areas for flood storage can help with future-proofing (Hankin, Page, McShane, and others, 2021). In addition, integrated urban modelling of urban/rural nature-based solutions (NBS) (such as mixed grey infrastructure and green infrastructure) is an area for future development, with some steps forward made in demonstrating how in combination NFM or SUDS could reduce the pressure on urban drainage (for example, Ferguson and Fenner, (2020)).

The distributed and integrated modelling approaches typically yield expensive model setups in relation to the budget or scale of project, so alternative approaches summarising efficacy have been reported upon. However, collecting place-specific monitoring data or using a local model and sensitivity analyses remains essential to improve NFM effectiveness.

The types of models and integrated approaches, and how they can be adapted to represent NFM, have taken a step forward. For example, the NERC projects, and are more widely available in practice to help with new schemes that incorporate NFM.

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