Department for Environment Food & Rural Affairs

Environment Agency

Cyfoeth Naturiol Cymru
Natural Resources Wales

Llywodraeth Cymru
Welsh Government

Working with natural processes: Evidence directory update

FCERM Research & Development Programme

Literature review

Date: February 2025

Report: FRS21232/LR

We are the Environment Agency. We protect and improve the environment.

We help people and wildlife adapt to climate change and reduce its impacts, including flooding, drought, sea level rise and coastal erosion.

We improve the quality of our water, land and air by tackling pollution. We work with businesses to help them comply with environmental regulations. A healthy and diverse environment enhances people's lives and contributes to economic growth.

We can't do this alone. We work as part of the Defra group (Department for Environment, Food & Rural Affairs), with the rest of government, local councils, businesses, civil society groups and local communities to create a better place for people and wildlife.

Published by:

Environment Agency
Horizon House, Deanery Road,
Bristol BS1 5AH

www.gov.uk/environment-agency

Further copies of this report are available from our publications catalogue: Flood and Coastal Erosion Risk Management Research and Development Programme or our National Customer Contact Centre: 03708 506 506

Email: fcerm.evidence@environment-agency.gov.uk.

Author(s): Eleanor Pearson, Mary Baldwin, Hannah Bard, Thomas Bromley, Jenny Broomby, Tom Burgess, Lydia Burgess-Gamble, Hannah Champion, Hannah Evans, Barry Hankin, Linley Hastewell, Matthew Hemsworth, Amber Humphries, Glenn Langler, Steve Maslen, Emily Prtak, Caitlin Rees, Steve Rose

Keywords: Flood and coastal erosion risk management, working with natural processes, natural flood management

Research contractor: JBA Consulting, 1 Broughton Park, Old Lane North, Broughton, Skipton, North Yorkshire, BD23 3FD. +44 (0)1756 799919

Environment Agency's Project Sponsor: Julie Foley, Project Executive: Eleanor Heron, Project Manager: Daniel Hine

Project number: FRS21232

Contents

1 Introduction

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 (Environment Agency, 2017). The term can be used interchangeably with natural flood management (NFM).

WWNP 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.

This literature review was written to support the update report to the WWNP evidence directory. The updated report was developed to help flood risk management practitioners and other responsible bodies inform their flood risk reduction work with knowledge of the effectiveness of a range of different measures from a flood risk and ecosystem services perspective. The content of this literature review is summarised within the update to the evidence directory, which is supported by summaries and should be read alongside the original evidence directory.

Considerable research was already carried out on this topic. This literature review summarises studies that looked at WWNP for flood risk since the development of the original evidence directory in 2017 until 2023. The literature review was completed by searching publication databases using terms relevant to the NFM measures in the context of flood risk management. 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.

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

The 4 chapters contain separate literature reviews covering:

- river and floodplain management
- woodland management
- run-off management
- coast and estuary management

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

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 literature review 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.

2 River and floodplain management

2.1 River restoration

2.1.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of river restoration from an FCRM perspective and the scientific confidence in what we know.

Rivers may take decades or centuries to physically and biologically adjust and so the magnitude of flood attenuation may change over time.

Effect on flood flows, peaks and storage: observed evidence

The relative area of storage was twice as large in the restored versus concreted reaches in 6 heavily urbanised catchments (Wisconsin, USA, studied catchments ranged from 3.0 km^2 to 55.4 km^2). Restoration of each reach had occurred 3 to 25 years prior to this study (Levi and McIntyre, 2020).

River restoration created a small extension to the surface water area of large wetland areas of the River Danube (within a 22 km^2 area, 35 km from the exit to the Black Sea) (Ioana-Toroimac and others, 2022).

Re-meandering within a chalk stream in Norfolk resulted in an increase in channel length (16%) and a decrease in mean channel width (0.5 m), increasing the channel surface area (Champkin and others, 2018).

The impact of river restoration in 6 catchments in Wisconsin, USA ranging from 3.0 km^2 to 55.4 km^2 was assessed at 3 to 25 years after the restoration. Mean residence times were 5 times larger in the restored reaches than the concreted reaches (Levi and McIntyre, 2020).

Re-meandering within a chalk stream in Norfolk resulted in an increasing trend in water depth, which was not statistically significant. However, variation in channel depths increased from between 10 to 52cm and 12 to 74cm, due to increased numbers of pools (Champkin and others, 2018).

Velocity was lowered 2- to 13-fold in restored reaches compared to concrete reaches (in Wisconsin, USA, studied catchments ranged from 3.0 km^2 to 55.4 km^2). Restoration of each reach had occurred 3 to 25 years prior to this study (Levi and McIntyre, 2020).

Effects of riparian regrading within a restoration project in North Carolina were seen up to 5 m away from the channel, where the bank slope moved from 12% to 5%, with frequent ponding within the clay-based soil riparian zone following rainfall (Welsh and others, 2020).

Effect on flood flows, peaks and storage: modelled evidence

ESTRY-TUFLOW 1D-2D hydraulic modelling was used to understand the benefit of channel restoration (Salmon Brook catchment, Enfield, London). Two-channel pinching scenarios were tested to reduce channel capacity and encourage out-of-bank flooding to activate floodplains. Gilbert (2021a) suggests that:

- a 75% reduction in channel width and a storage reduction factor of 0.25 resulted in a 15% reduction in peak flow for a 25-year return period observed event (October 2000) close to the downstream limit of restoration
- a 90% reduction in channel width and a storage reduction factor of 0.25 resulted in a 23% reduction in peak flow for a 25-year return period observed event (October 2000) close to the downstream limit of restoration
- both scenarios resulted in a ~2-hour delay to peak flow
- the effect of restoration reduced ~3.5 km downstream to 5% peak flow reduction
- both scenarios resulted in 10 mm to 50mm reduction in peak flood level heights at properties in the community at risk

Rogers (2017) showed across 14 reaches, paleochannels within a floodplain (on the River Ure) could store over 420,000 m^3, with a mean storage volume of 30,363 m^3 per channel. The majority of channels were no deeper than 3 m, with the maximum modelled water depth being 4.3 m. When creating link channels to the paleochannel and the main channel, storage could be increased to 445,000 m^3, and if paleochannels were excavated to the same elevation throughout too, storage may increase to over 650,000 m^3.

Effect at different catchment scales

Martínez-Fernández and others (2017) suggest that river restoration in the form of embankment and riprap removal is more effective across entire river segments (>20 km) than small sections (<1 km) in north-west Spain.

When comparing restored and concrete reaches in 6 catchments of different sizes (3 km^2 up to 55 km^2) in times of low flow in Wisconsin, USA, Levi and McIntyre (2020) noted that larger effects were seen in the smaller catchments, whereas in the larger catchments, effects were smaller. Velocity and residence time varied the most with catchment size. This was likely due to the relative scale of restoration compared to stream size. In headwater catchments, restoration increased stream width 7-fold, whereas in larger catchments restoration resulted in similar, if not smaller, channel widths.

Effect on different watercourse typologies

Restoration, including installation of channel spanning boulder flow deflectors, creation of a riffle-step-pool morphology, and lowering and regrading of banks in North Carolina saw (Welsh and others, 2020):

- in-channel and riparian water levels vary temporally, however they peaked at the same time, with the water table being within 0.5 m of the ground level frequently.

This was in contrast to the control reach where water table depths were consistently over 0.5 m below ground level in the riparian zone

- a groundwater flow gradient that increased with distance away from the channel laterally. During wet conditions, deflectors and reinstated riffle-step-pool morphology had a ground water table level zone of influence that accounted for 35% of the riparian area, increasing to 42% in dry conditions, and staying within 30 to 45% throughout the year
- during a wetter period, the restored site experienced upwelling in the mid-riparian zone where the hillslope water meets the displaced water from the boulder deflector zone of influence, resulting in downstream water table mounding. In summer, the lowered near-stream water table prompted a flow reversal from stream to near riparian zone, causing a down valley gradient next to the stream (Welsh and others, 2020)

A series of papers investigated the effect of nature-based solutions (NBS) in chalk catchments to understand where NBS may be best implemented, using MODFLOW.

In the Test catchment (862 km^2), river restoration had a limited impact on groundwater storage. There was also a limited impact on baseflow index, with only a slight reduction in river flows noted (Aghajani and others, 2023a).

The modelled restoration scenario in the Bure catchment led to a slight increase in maximum and minimum groundwater storage. There was no change in baseflow index in this scenario.

River restoration was carried out within a tidally influenced floodplain (in California, USA). Changes were observed in different zones following a 2-year return period rainfall. Within the intertidal zone, erosion of the main channel by 0.25 m had occurred, increasing the cross-sectional area by 12%. However, the supratidal zone was relatively stable and only 0.05 m of erosion occurred (Medel and others, 2022).

Groll (2017) found that the benefits from river restoration were much less pronounced in a weir-impounded reach compared to a free-flowing reach in Marburg, Germany (1,666 km^2 catchment upstream).

Effect on sedimentation and geomorphology: observed evidence

In Maryland, USA, 1,668 m of channels were reshaped by introducing meanders and pool-riffle forms, raising the stream bed and planting vegetation. This lowered flow velocities and shear stresses (Mattern and others, 2020).

Water depth and flow velocities were more dynamic in the main channel compared to the newly formed secondary channels in Marburg, Germany (1,666 km^2 catchment upstream) (Groll, 2017).

Restoration of a riffle-step-pool morphology with channel spanning boulder flow deflectors in North Carolina resulted in a pool upstream of one of the boulder deflectors to fill in with sediment, while a pool downstream of the deflector functioned as expected (for example, it did not fill with sediment). This shows the impact of river restoration on geomorphology isn't always as expected (Welsh and others, 2020).

Within an 11-year study (on the River Caldew, Carlisle), Heritage and Entwistle, (2020) identified that:

- within a reach which has been naturalising for less time, more active geomorphic processes were noted, but confined around the river edge, and associated with increasing channel sinuosity
- there was a net loss of material out of the partially naturalised reach, whereas a large net gain of material within the semi-braided reach, both naturalising reaches had larger relative active areas (40 to 41%) compared to the maintained control reaches (8 to 11%)

Verschoren and others (2017) found that removing vegetation in the Brzozówka River, Poland increased flow rates and decreased particulates held. Particulate retention varied by over 10% between non vegetated and 76% vegetation cover.

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

- that a substantial increase in vertical banksides post restoration was due to the steep, erodible banks present in 2014 and 2016
- bank profiles in 2012 were less steep and mainly classified as mounds, which decreased in area between 2014 and 2016
- bank erosion was the most significant mechanism for channel volumetric change between 2012 and 2014 (52%) and between 2014 and 2016 (46%) (Williams and others, 2020)

When monitoring restoration including the formation of secondary channels in Marburg, Germany (1,666 km^2 upstream catchment area), Groll (2017) identified that:

- there were more sand-dominated habitat types and much lower coverage of rock and gravel and artificial substrates in the restored reach compared to the control reach following the removal of bank protection (riprap)
- following a 50-year return period event, an increase in large wood was also noted
- in the secondary channels alone, following flooding, coarsening of sediment was observed, with sand-dominated habitats reducing from 75% to 61%, with some individual habitats reducing by greater than 50%

Re-meandering within a chalk stream in Norfolk, England resulted in sediment sizes changing, with silt decreasing by over 14% and gravel increasing by over 13%, silt continued to comprise the highest proportion at >46% and there was no change in the quantity of cobbles (Champkin and others, 2018).

Removal of embankments and ripraps along 13.4 km of river in north-west Spain resulted in widening of the active channel (Martínez-Fernández and others, 2017).

Re-meandering within a chalk stream in Norfolk, England resulted in an increase in channel length (16%) and a decrease in mean channel width (0.5 m), increasing the channel surface area (Champkin and others, 2018).

Restoration of 500 m of the 720 m study reach of Allt Lorgy (Spey catchment, Scotland, 21.6 km^2) in 2012, which included removing and lowering embankments, gravel augmentation and large woody debris, noted an expansion in the width of the active channel, creating an additional bankfull area (23% from 2012 [pre] to 2014 [post] and 6% from 2014 to 2016) (Williams and others, 2020).

Hajdukiewicz and others (2017) analysed 10 pairs of unmanaged and channelised river cross sections in Poland (983 km^2 catchment). They identified bank structure, channel mobility, geometry, erosional/depositional forms and lateral connectivity as features that changed the most during a restoration scheme. This assessment endorsed the erodible river corridor as a restoration approach, suggesting that enabling free channel migration within this corridor could notably enhance the identified features.

Removal of embankments and ripraps along 13.4 km of river in north-west Spain resulted in increases in river complexity, including channel sinuosity and braiding. However, while some improvements were made laterally, these were not recovered to pre-regulation levels, with a large area remaining as floodplain. The comparisons were made shortly after and 4 years after restoration. This limits the short-term effectiveness of this measure (Martínez-Fernández and others, 2017).

The creation of secondary channels and removal of bank fixation of 400 m reach in Germany showed increased diversity within microhabitat composition (not statistically significant), with one-third of habitats not being detected in the control reach (Groll, 2017).

Within the restored reach in Marburg, Germany, the secondary channels were more dynamic compared to the main channel, with a greater number of habitat changes. Following flooding, there was less difference in habitat type between the main channel and secondary channels, demonstrating change over time (Groll, 2017).

Heritage and Entwistle (2020) observed that a river reach on the River Caldew, Carlisle, which has been allowed to naturally recover from historic management to a wandering system, showed that due to the development of bar complexes and overbank splay deposits, the channel bed has raised over time as a result of natural sediment accretion.

Accumulation of sediment within a partially naturalised reach on the River Caldew, Carlisle formed as point bars and riffles, whereas in the wandering system there were large bar complexes where there was deposition in mid-channel and lateral bars where the channel has widened over time (Heritage and Entwistle, 2020).

Restoration of 500 m of the 720 m study reach of Allt Lorgy, Spey catchment, Scotland, (21.6 km^2) in 2012, which included removing and lowering embankments, gravel augmentation and large woody debris saw:

- the total area covered by in-channel geomorphic units increased by 23% pre to post restoration and by an additional 6% between 2014 and 2016
- notable changes included a doubling in the total area of pools and riffles between 2012 and 2016 and a significant increase in walls between pre- and post-restoration surveys
- increases in bowls and riffles indicated greater morphological complexity in the study area
- following restoration, in 2014, different geomorphic changes occurred in each of the sub-reaches, demonstrating the change and increase in geomorphic unit diversity, evenness, and a decrease in dominance
- diagonal bar complexes and bank-attached bar development were the most important mechanisms for reshaping topography at high flows (Williams and others, 2020)

Analysis of fine sediment dynamics following the restoration of 16 side channels of the Rhône River, France found fine sediment to be highly variable between- and within-channels. All but one channel exhibited fine sediment deposits (for at least one survey) and some showed thin patches of deposits. Sedimentation rates could be predicted from flooding patterns which may help guide project design *(*Riquier and others, 2017*)*.

Design life and effectiveness

A lab-based experiment of how vegetation types alter flow resistance found long grass slowed the flow the most when compared to reed, stick, short grass and algae (Meng and others, 2021).

Maintenance

One review paper agreed successful river restoration relies on consistent maintenance to avoid failure and achieve the expected outcomes. Some interventions need ongoing maintenance, while others are self-sustaining, however maintenance costs can be high and could lead to project failure (Moore and Rutherfurd, 2017).

Management of maintenance can also influence the success of the features. For example, voluntary monitoring instrumentation needs effective implementation, and independent oversight is necessary for all management arrangements. Robust legal measures are crucial for ensuring maintenance and eventual replacement occurs and that landowners uphold obligations (Moore and Rutherfurd, 2017).

2.1.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for air quality or soil derived from river restoration specifically.

Water resources

Modelling (MODFLOW) to simulate chalk stream restoration in the Cam catchment (928 km^2, covering Cambridge, Newmarket, Ely and Saffron Walden) showed minimal changes to water resources (Aghajani and others, 2023b).

Similarly, little change to water resources was noted during modelling on the River Wensum which raised side channels to levels seen before dredging. Additionally, raising stream beds in upland areas did not appear to greatly impact flows downstream (Aghajani and others, 2023c).

Climate regulation

A review of carbon storage within floodplains across Great Britain found river and floodplain restoration to have the potential to increase carbon stocks, especially through land management techniques which promote wetland and higher water tables (Sear and others, 2023).

Amenity

Despite offering significantly lower scores in terms of risk reduction, the extensive wider environmental and socio-economic benefits of the Isar River, Germany (8 km) restoration scheme meant that it was the preferred option among stakeholders over grey engineered solutions. This was determined through an analysis of 28 key performance indicators. Landscape, heritage and quality of life were multiple benefits which scored particularly highly. The scheme involved the creation of recreational space. Restoration measures implemented included lowering banks and adding riparian gravel structures and vegetation (Pugliese and others, 2022).

Biodiversity

Agócsová and others (2020) identified during a 570 m restoration scheme on the Hron River, Slovakia that river restoration favoured aquatic ecosystems, helping biodiversity in the region, and contributing to the revival of different habitat types that existed before the river channel became blocked.

Martínez-Fernández and others (2017) suggest that there were differences in riparian plant communities emerging on gravel bars between their restored reach (embankment and riprap removal) compared to the control reach in north-west Spain. It should, however, be noted that the differences in plant assemblages were greater between different bars with the same treatment than between treatments.

Removal of riprap (rock armour) in a 500 m reach of the Mulde River, Germany moved carabids (ground beetles), vegetation and bird indicators towards more natural habitat (Schulz-Zunkel and others, 2022).

When re-meandering a chalk stream in Norfolk, England, (Champkin and others, 2018) observed a decrease in the number of European eels. However, this was within a similar trend to the control reach and was, therefore, not statistically significant. The weight and biomass of brown trout increased following restoration. However, again this was not a statistically significant change.

Seele-Dilbat and others (2022) observed that within 2 years of removing bank fixation on the Mulde River, Germany, significant changes occurred in species composition and diversity. The shift was driven by the colonisation of 17 new species, making up 57% of the site's population. These species were absent at the control site. Species loss was minimal in both restored and control sites. Early re-colonisation-related species were more prominent in the restored site. The restored site exhibited higher species diversity than the control, but similar to a natural site, implying the restoration mimicked natural riverbank dynamics. Functional richness increased in the restored site, unlike the control or natural site.

An assessment of the impact of river restoration on sediment quality in the Johnson Creek catchment (Oregon, USA) showed an improved habitat quality to be directly linked to the increased removal of sediment bound pollutants. Natural sections were found to have a higher ability to remove pollutants. Several restoration projects have occurred along the 40 km river since 2006. However, the full length of the river has not been restored and no change in pollutant content across the whole reach was observed (Janes and others, 2017).

Restoration that included raising channels for floodplain connection and Oxbow Lake creation in Idaho, USA resulted, after 5 years, in:

- brown trout and rainbow trout redd counts increasing dramatically 6 to 7 years after restoration (515% increase), compared with pre-restoration redd counts
- salmonids (rainbow trout and brown trout), 3 native minnows (speckled dace, longnose dace, and redside shiner) and one native sucker (bridgelip sucker) being present after restoration that were not detected in original surveys
- brown trout and rainbow trout increasing from 0% before restoration to >90% after restoration in the restored reaches where only brook trout were present in original surveys
- increases in total trout relative abundance primarily due to post-restoration increases in age-0 rainbow trout and brown trout; the surveys also identified age-0 rainbow trout at all 3 monitoring sites where none were detected in pre-restoration surveys (Pierce and others, 2022)

The assessment of benthic invertebrate fauna in 3 mountain streams (<47.1 km^2), Germany revealed dynamic changes after restoration. Initially, restoration led to reduced species richness, particularly for certain insect groups, but positive effects emerged over 6 years. Abundances increased across all sites. These patterns were consistent in near-natural upstream reaches, except for an initial reduction in richness, suggesting other influences beyond restoration. Community composition shifted over time, indicating the impact of external factors. Floodplain restoration, including clear-cut logging, contributed to changes, replacing cold-adapted species with downstream ones and affecting water temperatures. The study highlights the influence of floodplain restoration and natural hydrology on shaping benthic communities, often surpassing the impact of in-stream restoration measures (Lorenz, 2021).

Water quality

When comparing restored reaches to concrete reaches in 6 catchments (in Wisconsin, USA) in times of low flow, Levi and McIntyre (2020) noted nutrients travelled for shortened distances in restored reaches due to longer residence times and lower water velocities. Other metrics, such as chlorophyll and nutrient demand did not differ between concrete and restored reaches. There was also no difference when increasing catchment size.

2.2 Floodplain and floodplain wetland restoration

2.2.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of floodplain and floodplain wetland restoration from an FCRM perspective and the scientific confidence in what we know.

Effect on flood flows, peaks and storage: observed evidence

The event-scale water volume buffering, which is the change in storage volume divided by the total precipitation input volume, shows average values (for the 3 events [35 mm, 26 mm, 38 mm]) of:

- 70% for Stordammen (a headwater wetland complex 4 km^2 in size within a 10.8 km^2 wetland catchment)
- 1% for Hällbomossen (a headwater swamp forest 0.3 km^2 in a 0.9 km^2 catchment)
- 4% for Lillabysjön (a headwater lacustrine marsh 0.7 km^2 in size in a 15.5 km^2 catchment)
- 4.5% for Rastmyran (a headwater wetland complex, 3.3 km^2 in size, in a 37.4 km^2 catchment in Sweden) (Åhlén and others, 2022)

The average residence time over the whole measurement period was higher in the headwater wetland than in the downstream wetlands (in Sweden) (Åhlén and others, 2022).

Restoring lakes to floodplain wetland meadows would help increase infiltration and groundwater flows which contribute to the watercourse in Delaware, USA across a 30-acre restoration site (Noon, 2020).

Restoration, which included relocating and raising 13.6 km of channels to connect the floodplain and channels being converted into oxbow lakes in Idaho, USA resulted, after 5 years, in:

- decreased bankfull widths (8.1 to 14.1 m before restoration to 6.0 to 6.7 m after restoration)

- decreased width-to-depth ratios (31.4 to 53.2 m before restoration to 14.4 to 18.3m after restoration)
- increases in mean depths (0.26 to 0.27m before restoration to 0.33 to 0.47m after restoration)
- increase in maximum depths (0.41 to 0.48m before restoration to 0.53 to 0.63m after restoration)
- channel floodplain connection was re-established at the bankfull stage elevation indicated by decreased bank height ratios (1.9 to 2.0 before restoration to 1.0 after restoration) and increased entrenchment ratios (1.2 to 1.3 before restoration to 15.1 to 16.3 after restoration)
- mean residual pool depths also increased dramatically (from 0.12 to 0.18m before restoration to 0.96 to 1.13 m after restoration) (Pierce and others, 2022)

However, little change was noted between 5 and 12 years after restoration (Pierce and others, 2022).

Effect on flood flows, peaks and storage: modelled evidence

Modelling (HEC-RAS) suggested that the geomorphological change observed following embankment lowering and bank reprofiling of the Allanmore floodplain, River Dee, near Braemar, Scotland (367 km^2 upstream catchment) resulted in:

- dramatic loss of channel conveyance capacity and a large decrease in required water level for overspill into a local backwater area
- threshold overspill discharge 50% lower than before restoration and boundary shear stress 71% lower, resulting in 20 more events spilling
- peak water levels higher on average by 0.25 m after restoration, with a statistically significant difference observed, although the difference varied depending on peak discharge
- flood levels higher than the mean annual maximum, the pattern tended to come together towards the highest peak discharge (400 m^3s^{-1}), this was except one cross section where there was a difference due to upstream flooding sources within the floodplain, overspill from the restoration and the declining inundation depth as the river water is dispersed
- rising and falling limb rates on the hydrograph that did not clearly change (Addy and Wilkinson, 2021)

Subsurface-surface flow modelling (of a 88 km^2 catchment in Alberta, Canada) (Ameli and Creed, 2019) suggested that when modifying the amount of riparian wetland:

- stream peak flow and cumulative stream flow at the catchment outlet increased as the area of non-riparian wetlands decreased
- the area of non-riparian wetland removal increased from 50% to 75%, while the relative increase in stream peak flow increased from 1.5% to 13% and in cumulative stream flow increased from 4.5% to 15% relative to the pre-loss model

- non-riparian wetlands were removed, total baseflow along the main stream network steadily increased, ranging from 3.2% (25% wetland loss) to 8.9% (100% wetland loss) compared to the pre-loss model
- removal of 8,959 ha of wetlands located over 2,000 m from the main stream network led to a relative 4% increase in stream peak flow and a 6% increase in cumulative stream flow relative to the pre-loss model
- removal of 11,391 ha of wetlands located more than 100 m from the main channel network led to relative increases of 5% in the stream peak flow and 6.8% in cumulative streamflow relative to the pre-loss model

Furthermore, modelling of wetland removal within 100 m of the main stream network:

- had a large impact on stream peak flow and cumulative flow at the watershed outlet
- increased stream peak flow at a rate of 268 m^3/day/ha
- increased cumulative streamflow at a rate of 6,863 m^3/ha

While removal of wetlands located more than 4,000 m from the main stream network:

- increased stream peak flow at a rate of 1.61 m^3/day per unit wetland area (ha)
- increased cumulative streamflow at the watershed outlet at a rate of 187 m^3/ha

Removal of wetlands located at different distances from the main stream network reduced total baseflow discharged into the entire length of the main stream network at an almost constant rate (from 0.0015 to 0.0017 m^3/day/ha) (Ameli and Creed, 2019).

Increasing riparian roughness or using leaky barriers was modelled to bring multiple natural flood management (NFM) benefits to the Eddleston Water catchment (70 km^2, in Cumbria, England) and Culm catchment (280 km^2, in Devon, England). Within these models, small-scale micro catchment measurements were used to calibrate the whole-catchment models. The analysis found consistent 5 to 7% reductions in peak flow across 9 different return periods ranging from 5 to 1,000 years (Hankin, Page, McShane and others, 2021).

The potential flood risk benefits of constructing a wetland near Rise Park Stream, (a tributary of the River Rom, Romford, London Boroughs of Havering) were modelled. After channelling water through the proposed constructed wetland, there is a 28% reduction in peak flow downstream. This lessens to a 24% reduction when it re-enters the Rise Park Stream. This reduction translates to a 10 mm to 50 mm reduction in flood levels for properties south of Rise Park for smaller events as seen during June 2020. Moreover, for 1 in 20-year return period events, the modelling showed a 9% reduction in peak flow downstream of the constructed wetland and a 15% reduction in peak flow for a 1 in 100-year event (McKenna, 2021).

A study using Dynamic Topmodel to assess the impact of enhanced floodplain storage in the Eggerslack basin found the peak downstream of the floodplain storage bund was 6 hours delayed and 16% lower. Similarly, using Dynamic Topmodel to assess the potential of larger-scale floodplain enhancement along the River Gowan, Cumbria (14.9 km^2

catchment size), an additional 145,000 m^3 of storage could be created (Chappell and others, 2023).

Effect at different catchment scales

Wetlands exhibit distinct storage patterns based on landscape position in Sweden, with upland headwater wetlands showing variable water levels and complex inundation, while downstream wetlands remain mainly dry. Therefore, the headwater wetland regions store excess water from regular summer rains, while downstream wetlands maintain capacity for extreme flood buffering (Åhlén and others, 2022).

Modelling of the Eddleston Water (70 km^2, in Cumbria, England), and Culm (280 km^2 in Devon, England) larger catchments found multiple techniques to show expandable field storage. This included applying both woody deflectors and increasing floodplain friction to improve floodplain connection and utilisation (Hankin, Page, McShane and others, 2021).

Effect on different watercourse typologies

Subsurface-surface flow modelling of an (88 km^2) catchment in Alberta, Canada suggested that the loss of historic wetlands has resulted in a decrease of groundwater discharge area from 15.6% to 15%. Baseflow discharge into the main stream network decreased by 6% and stream peak flow of a single event increased by 19%. Cumulative streamflow across the simulated period increased by 17% with wetland loss (Ameli and Creed, 2019).

Restoration in Idaho, USA resulted, after 5 years, in an average increase in groundwater elevations across 14 piezometers of 0.35 m, with the largest increase of 0.74 m and the lowest increase of 0.15 m (Pierce and others, 2022).

A series of papers investigated the effect of nature-based solutions (NBS) in chalk catchments to understand where NBS may be best implemented, using MODFLOW. These showed that:

- in the Test catchment (862 km^2), floodplain restoration led to a large, modelled increase in total evapotranspiration from the water table along valley floors, which subsequently affected total baseflow with slightly lower baseflow values
- a modelled floodplain storage scenario in the Bure catchment led to a slight increase in maximum and minimum groundwater storage (Aghajani and others, 2023d)
- along the River Wensum the conversion of arable floodplains to riparian grassland led to significant increases in evapotranspiration from groundwater, resulting in a loss in net recharge and baseflow compared to the long-term average according to modelling (Aghajani and others, 2023c)

Effect on sedimentation and geomorphology: observed evidence

Floodplain restoration involving the lowering of embankment height and bank re-profiling of the Allanmore floodplain (River Dee, near Braemar, Scotland, 367 km^2 upstream catchment) (Addy and Wilkinson, 2021), 5 storms greater than the mean annual maximum flood flow, resulted in:

- bed aggradation of +0.15 ± 0.0147 m^3 m^{-2} in the channel and +0.24 ± 0.02 m^3 m^{-2} in the backwater
- bed levels rose by over 1 m, adjacent to the original embankment
- erosion by up to 0.41 m in depth of reprofiled bank
- erosion of point bar on opposite bank to embankment lowering
- erosion of bank protection toe armour and geotextile completely washed out during December 2015 event despite earlier efforts to repair them
- net deposition in dry areas (+363 ± 69 m^3) despite significant bank erosion
- deposition in backwater and on floodplain over 200 m away from restoration site, with some of this sediment being from the eroded re-profiled bank and backwater

Restoration of 500 m of the 720 m study reach of Allt Lorgy, Spey catchment, Scotland (21.6 km^2) in 2012, included removing and lowering of embankments, gravel augmentation and large woody debris. Interventions were made in the upper section of the reach, but no interventions were made in the lower section of the reach. This included partial removal of an embankment along the outer bank of the first meander during restoration which led to bank erosion along this bend and the development of a pool. Monitoring showed that:

- between 2012 and 2014, there was bank erosion along the outer meander bends and extensive erosion, resulting in the formation of point bars and a diagonal bar complex in various parts of the reach
- by 2014, this reach exhibited a more complex and diverse spatial pattern of geomorphic units than in 2012
- between 2014 and 2016, the reach remained geomorphologically active, with localised erosion and deposition continuously reshaping geomorphic units (Williams and others, 2020)

Restoration that included raising channels for floodplain connection and oxbow lake creation in Idaho, USA resulted, after 5 years, in sediment coarsening, with increases in gravel (26% to 64% before restoration to 76% to 83% after restoration) and cobble (7% to 10% before restoration to 16% to 25% after restoration) in addition to decreases in silt/clay (16% to 22% before restoration to 0% after restoration) and sand (5% to 52% before restoration to 0% to 1% after restoration) (Pierce and others, 2022).

Monitoring between 1 and 2 years after 6 km of Stage 0 river and floodplain restoration in Oregon, USA, downstream of a dam in a 560 km^2 catchment resulted in (Hinshaw and others, 2022):

- significant difference in grain size between 1 and 2 years after restoration
- lower proportions of sediment <32 mm (coarse gravel and finer) in year 1 compared to year 2
- fine sediment increased significantly in year 2 compared to year 1

Effect on sedimentation and geomorphology: modelled evidence

Modelling (Delft3D) of floodplain lowering on Wurm River, Germany suggested that the floodplain was inundated at lower discharges compared to the baseline scenario. When increasing the width of the lowering from 20 m to 100 m wide, sedimentation of the floodplain increased from 5.5 cm to >6 cm respectively, however the shear stress on the floodplain increased from 2 N/m^2 to 4 N/m^2 (Maaß and Schüttrumpf, 2019).

Design life and effectiveness

Reflections from a study in Delaware, USA suggest a well-designed stream restoration approach encompasses several important aspects to enhance ecological resilience. Optimised channel width-to-depth ratios can accommodate current and future flow changes, minimising erosion and sediment transport. Addressing unstable banks and erosion through woody shrub planting supports stable habitats. Replanting with native species adapted to warmer climates ensures ecosystem resilience and diversity. Restoring lakes to floodplain wetlands helps groundwater flow and cooling baseflow temperatures, benefitting aquatic populations. Tailoring groundwater hydrology to native plants is vital, and planting trees near wetlands provides thermal regulation, sun protection and resilience against heatwaves (Noon, 2020).

Maintenance requirements

Insufficient upkeep, as seen by Ioana-Toroimac and others (2022) during restoration of a 22 km^2 area of the River Danube, 35 km from the exit to the Black Sea, could result in limited achievements when attempting to expand wetland areas through lateral reconnection. This might prompt a re-evaluation of riparian wetland restoration strategies in favour of more self-sustaining alternatives.

2.2.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for air quality, climate regulation or soil derived from floodplain and floodplain wetland restoration specifically.

Water resources

Wetlands situated in headwater regions in Sweden experienced fluctuating water levels during the summer season, which rose in reaction to rainfall events. In contrast, downstream wetlands reached their lowest seasonal water levels and remained unaffected by isolated summer precipitation events. This pattern suggests that excess event-level precipitation is mainly stored in headwater areas, reducing water flow to downstream wetlands, keeping them dry during the summer (Åhlén and others, 2022).

Large differences in residence times supports nature-based solutions and ecosystem services of wetlands like flow buffering/storage capacity and nutrient retention in wetlands in Sweden (Åhlén and others, 2022).

Hunt and others (2018) aimed to mitigate drought impacts through meadow restoration by refilling an incised channel in Sierra Nevada, USA to create floodplain wetlands. Restoration led to increased storage in spring and higher summer flows. Despite sustained drought conditions, summer baseflow from the meadow increased significantly, reaching 5 to 12 times the pre-restoration levels before restoration, with total summer outflow exceeding inflow by 5%; after restoration, this difference grew to 35 to 95%. Even during the severe 2015 drought with one month of no inflow, summer baseflow was at least 5 times greater than pre-restoration levels, and groundwater levels rose in 4 out of 5 sites near the stream channel. Therefore, filling the incised channel and reconnecting the meadow floodplain boosted water availability and streamflow, counteracting the effects of unprecedented drought conditions.

Amenity

The consistent, small reduction in peak flows noted from the modelling NFM features in the Culm (280 km^2) and Eddleston Water (70 km^2) catchments in Devon and Cumbria, England, respectively across a variety of return periods created a small economic saving from annual flood damages, which accumulated to larger benefits of £0.6 million over a 30-year period (Hankin, Page, McShane and others, 2021).

Complex and patchy inundation in headwater wetlands causes habitat variations over short time scales, in contrast to prolonged low-water conditions in downstream wetlands in Sweden (Åhlén and others, 2022).

Lowering flood banks led to a substantial increase in flood frequency within floodplains, with a rise from 1.7 to 571 floods per year in the Humberhead Levels, River Don, 1,800 km^2, Doncaster, England. This heightened flooding resulted in greater wetland submersion and hydrological diversity. The composition of plant communities showed significant differences before and after restoration, with a rise in moisture-tolerant plants. While the presence of target floodplain marsh grazing species didn't notably increase, this could be attributed to unsuitable conditions or insufficient propagules for colonisation. The ongoing restoration process may lead to environmental shifts and colonisation, eventually promoting the presence of desired floodplain grazing marsh indicator species over the coming decades (Richards and others, 2020).

After wetland conservation in the Lower Mississippi River Basin, a significant improvement in habitat was observed. However, no significant impact on the fish community was found (Shrestha and others, 2017).

Biodiversity

Monitoring (Hinshaw and others, 2022) between 1 and 2 years after 6 km of Stage 0 river restoration in Oregon, USA downstream of an engineered leaky barrier in a 560 km^2 catchment resulted in:

- canopy cover decreasing significantly (35% loss) between year 1 and year 2

- strong changes in organic cover with flow distance through the restoration site, with coarse particulate organic matter (CPOM) efficiently trapped in the upper portion of the study area but lost in the lower portion of the study area

Water quality

A moderate improvement in water quality was noted following wetland conservation in the Lower Mississippi River Basin (Shrestha and others, 2017).

2.3 Leaky barriers

2.3.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of leaky barriers from an FCRM perspective and the scientific confidence in what we know.

Effect on flood flows, peaks and storage: process understanding

The extent of increase in upstream water depth and corresponding backwater volume is 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, 2018; Follett and others, 2020; Schalko and others, 2023). Since 2017, these studies have fundamentally advanced the science of understanding the relationships between head loss and the physical characteristics of leaky barriers. Barriers are effective in creating a rise in upstream water depth and backwater region, which can be linked to the barrier's physical structure.

The scale of the storage created by present designs is often too small to generate significant impact in reducing flood risk for higher return period events (Metcalfe and others, 2018; Norbury and others, 2019; Norbury and others, 2021; Follett and others, 2023; Muhawenimana and others, 2023). Once the barrier becomes overtopped, with water flowing over the barrier, generation of new storage is limited (Geertsema and others, 2020; Hankin and others, 2020; Follett and Hankin, 2022; Follett and others, 2023; Muhawenimana and others, 2023).

For example, barrier designs with an upper edge at the channel bankfull depth will become overtopped at discharge levels below the bankfull discharge level (return period approximately every 1.5 years), so that they would fill and quickly become unable to provide significant storage for large events with higher discharge levels, such as a target flood event with a 100-year return period (Follett and others, 2023).

Leaky barrier pilot designs, which have demonstrated generation of effective storage during significant storms experienced since 2017, in particular Storms Dennis and Ciara, have used channel-spanning designs placed across a relatively wide, flat incised area, for example, an eroded peatland gully and a decommissioned reservoir at Smithills near Bolton (Norbury and others, 2021).

Modelling studies have indicated that natural flood management features should fill and drain in the order of 10 hours to provide an optimum balance of significant storage provision for larger events, while draining between successive storms (Metcalfe and others, 2018). Project designs which create a total target storage volume using successive areas of smaller storage should consider barrier performance during target storm levels.

Design tools linking the barrier physical structure to backwater volume and range of discharge for which the barrier is expected to impact storage can help target barrier design for site requirements (Follett and Beven, 2023).

Effect on flood flows, peaks and storage: observed evidence

5 engineered leaky barriers installed on a flat, wide (26 m) decommissioned reservoir resulted in an average 27.3% reduction in peak water levels across a range of precipitation events of varying magnitude. Water was attenuated and backed up behind the barriers (Norbury and others, 2021).

Leaky barriers installed in Flimby Gill, Cumbria were observed to retain water and fill only to a quarter of the maximum water depth during the highest flow event observed (1 in 2.4 years). While the barriers provided storage during the event peak, the overall volume stored was modest (319 m^3). Flimby Gill is incised with relatively little accessible floodplain storage, and very flashy. In all observed events, the leaky barriers filled most rapidly within the most intense period of rainfall and the effective storage corresponded to the peak water level at the culvert downstream. The leaky barriers also drain rapidly after the flood peak has passed, suggesting that they could be responsive to multiple peaks in rainfall intensity in short succession (Chadwick, 2021a).

Peak flow reductions (of an average of 10%) were observed for events up to 1 in 1-year return period following the installation of 8 leaky barriers in a 280 m reach with a 0.13 m/m stream gradient in Coverdale. This peak flow reduction reduced to 3% (+-7%) for events of higher return periods of 2 to 3 years (Van Leeuwen and others, 2024).

Hydrographs were noted to be less flashy downstream compared to upstream following the installation of 38 leaky barriers in the River Bourne, with a 4 hour increase in time to peak for a medium rainfall event (peak precipitation of 5 mm, peak flow downstream of <0.8 m^3/s) and a 5-hour increase for a larger event (peak precipitation of 17.5 mm, peak flow downstream of <0.35 m^3/s) (Powell and others, 2021).

In the Pang Valley, river monitoring suggests a delay and reduction in peak flow for the Bourne after major rainfall following leaky barrier implementation. Monitoring has taken place from 2019 and into 2022, however, further validation is needed across more flood events. Anecdotal evidence notes reduced peak flow in the overflow stream at Hogmoor Copse, likely due to a combination of leaky barriers and downstream channel improvements and no property flooding occurred during Storm Dennis (Pang Valley Flood Forum, 2021).

Leaky barriers were installed within the Thames Basin, (a 16,000 km^2 catchment), between London and Slough, with some implemented in the River Lee, covering semi-urban and urban areas. River level smart sensors placed upstream and downstream of the

31 barriers recorded lower peaks and longer recessions downstream relative to upstream of the barriers. Over one week, the river level rose 0.1 m upstream of the dams, mitigating approximately 25% of the peak flow. Over a whole month, the total amount of water slowed was 1.75 m^3 or 0.06 m^3 per barrier. The requirement to build at scale and the risk of barriers breaking up and blocking infrastructure such as culverts were noted within this study (Mulligan and others, 2023)**.**

Monitoring of 20 leaky barriers in the Merriott Stream catchments, Somerset (across a 625 m reach) found a 38-minute delay to peak flow downstream of some barriers during Storm Freya in 2019. However, other barriers within the same study showed little attenuation impact. Flood peaks were higher upstream of the barriers than downstream for the majority of barriers studied (Phillips, and others, no date).

At Hardcastle Crags, in the Calder Valley, West Yorkshire, flood peak delays of 1 hour and 1.5 hours were observed within a stream after passing through 9 leaky barriers over an 80 m stretch. Events with time to peak in excess of 10 hours were more likely to record delays (Bradshaw, 2023)**.**

On Flimby Gill, Buckbank Wood, Cumbria, the 29 formal leaky dams provided a maximum storage volume per barrier of 20 m^3 and a total site maximum storage volume of 319 m^3. The storage volume was estimated (ArcGIS surface volume tool) from pressure transducer water level records (February 2020 to March 2021) and topographical surveys using GPS or, when tree cover prevented use of GPS, publicly available 1 m resolution LiDAR data. The estimated storage volume varied significantly across the barriers, with the larger barriers on the main channel, connected to areas of flatter bank, storing up to 60 m^3, and smaller barriers on steep, incised areas of the tributaries storing as little as 6 m^3 (Chadwick, 2021b). The upstream barriers on the tributary streams remained utilised (see also Metcalfe and others, 2017), with water filling only a quarter of the potential maximum depth, during the highest return period event observed (1 in 2.4 years). The barriers located at the downstream end of the tributary streams filled to approximately three-quarters of their potential maximum depth during the analysis period (Chadwick, 2021b).

Slightly north of this site, in the incised Penny Gill, Hankin and others (2020) also estimated, through dynamic modelling, that the 8 largest horse-jump style leaky barriers coupled with in-stream large wood resulted in additional flood storage of up to 235 m^3 based on the 100-year return period (1% AEP) design event. It was found that this storage could be increased through optimum positioning of 20 modelled leaky barriers of the same design up to 355 m^3, but this did not necessarily help to remove volumes near the peak flow. The paper concluded that a good general principle is to site the barriers in low-lying areas or regions where the upstream area widens, so as to provide more storage per barrier. The gap below the barrier should be made high enough that it does not start to store water too early; if the barrier has filled before peak inflow conditions, it serves no further useful purpose in reducing the flow downstream. Barriers in locations with a large backwater region are worth building higher and making correspondingly stronger so as to avoid the risk of failure.

Muhawenimana and others (2023) estimated the bankfull storage volume upstream of one leaky barrier in Shropshire to be 80 m^3, with a net storage increase of 52 m^3 during events with a return period of less than 2 years, increasing to 102 m^3 during the 4-year return period event. The storage volume estimated found the volume between a surface at the upstream water level recorded by pressure transducers and surface DEM obtained from publicly available 1 m LiDAR and a fine-scale DEM obtained from photogrammetry. Backwater rise, cross-sectional average velocity, and net storage showed that the barriers rapidly filled during the rising limb of the storm. During the falling limb, upstream velocity remained lower than the pre-storm condition as the upstream storage provided by the leaky barrier gradually released downstream over several days.

Bokhove and others (2018) estimated that the 7,000 m^3 of storage from leaky barriers and plate weirs in Calderdale equated to 0.42% of the 1.65 Mm^3 flood volume of the Boxing Day 2015, 1 in 100-year flood event.

Time-lapse footage shows an upstream-downstream head difference for most barrier designs in Alder Stream, with surveying suggesting approximately 1,500 m^3 of storage. By using a rough approximation, this volume was estimated to be 8% of the total flow volume (19,000 m^3) around a 2-hour period during Storm Ciara (Cook and Byers, no date).

10 single logs were placed across the channel and floodplain in Matterdale, Cumbria, England. The barriers had a potential capacity of 697 m^3 in large events, with between 39 and 121 m^3 of storage for each leaky barrier depending on the topography of the floodplain and distance between next upstream barrier (West Cumbria Rivers Trust, 2021a).

In the Merriott Stream catchment, Somerset, monitoring of 20 barriers showed average storage per barriers to be 5.77 m^3, totalling 115.4 m^3 across the 625 m study stretch. This means the 20 barriers are able to store 1.9% of a 1 in 10-year return flood event. However, 100 barriers would be needed to reduce the hydrograph by 10% in a 1 in 10-year event, which would not fit within the stretch studied in this example. This demonstrates the need to implement multiple types of NFM measures (Phillips and others, no date).

Taylor and Clarke (2021) observed no difference between hydrological variables between 2 leaky barrier sites with a control site in Gloucestershire at low flows.

Taylor and Clarke (2021) observed a decrease in water velocity and an increase in water depth at higher magnitude events when comparing 2 sites with leaky barriers to a control site in Gloucestershire. Leaky barriers increased the active water width and depth upstream as water ponded behind the leaky barrier. Velocity increased immediately downstream of the leaky barrier, but water depth was lower due to the presence of another leaky barrier downstream. Therefore, this did not result in additional transportation of water out of the reach, highlighting the need for multiple small interventions in reducing flow out of the reach.

In the River Loddon catchment, mean velocity was increased and more variable in reaches with leaky barriers compared to their respective control sites, observed in both restored large wood and natural large wood sites. Vertical velocities displayed increased variability in restored reaches relative to controls, and stronger velocities were evident in large wood reaches, both natural and restored (Pinto and others, 2019).

When monitoring 105 leaky barriers over a 2-year period in Shropshire, changes in the relative backwater rise were observed to correspond to alterations in the physical properties and composition of the leaky barriers. The accumulation of wood material on the barrier increased backwater rise, while material depletion reduced it. The accretion of sediment increased the maximum backwater rise by factors ranging from 1.3 to 1.9, with barrier performance and resulting backwater rise changing cyclically following subsequent storm events.

10 single logs (35 cm high) were placed across the channel and floodplain in Matterdale, Cumbria, resulting in a depth increase of 22 cm upstream and less than 5 cm increase downstream. Levels returned within 6 hours following the peak of the event, in which 84 mm of rain fell within 24 hours (West Cumbria Rivers Trust, 2021a)**.**

Overbank flow frequency and leaky barrier effect on backwater rise varied depending on the presence and extent of the barrier lower gap, log number, diameter, spacing, barrier height, channel bankfull depth and width and local bathymetry (Muhawenimana and others, 2023)**.**

One study used HEC-RAS 2D modelling across 3 catchments and considered measures enhancing floodplain storage inundation. Eddleston Water, in particular, installed 'lateral deflector' leaky barriers and, using a post-scheme calibration incorporating data from high quality monitoring in Scotland, identified that lateral deflectors encourage increasing access to 'expandable' floodplain storage. It was shown that a small, but consistent peak flow reduction could be achieved across design events with increasing return period (Hankin, Page, McShane and others, 2021).

In the River Loddon catchment, the highest levels of retention were observed in the natural large wood reach, intermediate levels of retention were observed in the restored large wood reach containing barriers with a lateral gap and active channel-spanning barriers, while the control reaches showed the lowest hydraulic retention. Leaky barriers proved to be the most effective habitat at retaining water (60% to 71%), while marginal and emergent vegetation, as well as other channel margin areas, made smaller contributions (Pinto and others, 2019).

Leaky barriers exhibited an accumulation of vegetation around the original interventions within a study in Gloucestershire, UK. This was particularly noticeable at the upstream barriers. Notably, the first upstream leaky barrier in the sequence experienced the most significant increase in foliage build-up throughout the study period. Analysing the patterns of foliage accumulation during various flow events, there is a surge in build-up following substantial events. These high flows tend to mobilise materials, subsequently trapping them behind the leaky barriers. Subsequently, the trapped materials either become integrated into the structure and persist or get remobilised during subsequent flows (Taylor and Clarke, 2021).

Following installation, hydrological parameters changed quickly with decreased velocity and increased active water depth (for example, at Prinknash Abbey, there was a significant 37% reduction in velocity compared to the control site). Notably, both leaky barrier sites exhibited comparable average water depths and average velocities, suggesting that their effectiveness persisted for at least 5 years following installation (Taylor and Clarke, 2021).

Analysis of 15 sites which installed leaky barriers between 2010 and 2020 suggested that 2% had failed. Complete and/or partial failure had occurred at 5 sites across Yorkshire and in Buckinghamshire, and the probability of failure increased for high return period events. There was, however, variability within failure rates between sites within the same return period, thought to be due to site conditions, structure type and condition and loading conditions (van Leeuwen, 2021)**.**

With pooled data across 5 sites where leaky barrier failure had occurred, the probability of complete or partial failure based on defining a lognormal fragility curve for barrier failure was 6% for a 10-year return period event, increasing to 22% for a 50-year event, and 33% for a 100-year event (van Leeuwen, 2021).

An assessment in Coverdale, North Yorkshire which studied multi-peaked high flow events (with return periods ranging from <1 year to 6 years) found peak magnitude to be reduced following the installation of 8 leaky dams. The study found leaky dams to be effective for single peaked events or the first peak of multi-peaked events, but not for subsequent peaks of multi-peaked events (van Leeuwen and others, 2024).

Effect on flood flows, peaks and storage: modelled evidence

A range of modelling techniques and software packages have been used to represent leaky barriers (Addy and Wilkinson, 2019). Barriers have been represented by explicit inclusion of solid elements, local modification of bed roughness or hydraulic units to mimic dam impacts (Pearson, 2020; Gilbert, 2021a; Gilbert, 2021b), and reach-scale roughness modification (Follett and Hankin, 2022; Barnes and others, 2023). Physically-based backwater rise relationships (Follett and others, 2020; Follett and others, 2021) and relationship of jam structure and spacing (Follett and Hankin, 2022) allow choice of QH curve (showing the relationship between the flow rate and head) and elevation in reach-scale bed roughness to correspond to barrier structure and spacing.

In the Coalbrookdale catchment, Shropshire, for the event in February 2020 (75 to 100-year return period), hydraulic modelling suggested the 32 leaky barriers had no impact on peak flow, but did delay the peak flow by 10 to 15 minutes (Adams, no date).

A coupled Dynamic TOPMODEL and HEC-RAS model of Bin Brook (11 km^2) (calibrated to a summer storm (2012) with a 15-year return period) was used to understand the effect of large woody debris within a steep catchment (Ferguson, 2020). Large woody debris jams were applied to all watercourses crossing arable land over 50 m away from infrastructure. Ferguson (2020) found that:

- large woody debris resulted in up to a 3.1% reduction in peak flow and up to a 90-minute delay to peak flow for a flood with a 5-year return period
- peak flow reductions decreased with increasing return period (5 year to 100 year)
- peak flow delay decreased with increasing return period (5 year to 100 year)
- limited peak flow reduction but long peak flow delays, possibly due to model representation if increased roughness, which is not representing the backwater rise effect of leaky woody debris effectively

On the River Calder (18 km^2), Todmorden, West Yorkshire, a coupled Dynamic TOPMODEL and HEC-RAS model (calibrated to observed data between October and December 2017 which included the second highest peak on record) was used to understand the effect of both woodland planting and large woody debris in a steep catchment (Ferguson and Fenner, 2020b). It was found that large woody debris on its own resulted in:

- a peak flow reduction of 2.8% for an event estimated to be a 20-year return period (peak flow <25 m^3/s)
- a 3.2% reduction in peak flow for a smaller event (peak flow <15 m^3/s)
- a 2.2% reduction in peak flow for a multi-peaked small event (peak flow <15 m^3/s)

In a separate study, 63 leaky barriers with heights up to 40 cm above bankfull resulted in no change to the peak flow or timing of peak flow in Salmon Brook, Enfield. There was localised storage and attenuation, however, this was not translated to the community at risk, partially due to further inputs from other tributaries downstream of the dams (Gilbert, 2021a).

ESTRY-TUFLOW modelling of 50 leaky barriers and 11 tree trunk barriers in Edgware Brook and Silk Stream, Harrow resulted in a 3% reduction in peak flow for the October 2020 event, dropping to 2% for a 20-year return period event and no effect on the 100-year event immediately downstream of the leaky barriers. No effect was noted in the community at risk, further downstream (Gilbert, 2021c).

HEC-RAS 2D modelling of a single leaky barrier (with a lower gap measuring 0.3 m, a total barrier height of 1.3 m, and a width of 11.1 m) showed a reduction in peak discharge of 4.6% for a 100-year return period event and 13.8% for the even rarer 1,000-year return period event, 100 m downstream of the barrier. However, this benefit diminished further downstream when water initially pushed onto the floodplain had re-entered the channel. This study was carried out within Lothersdale, a steep-sided upland catchment (12.9 km^2) (Pearson, 2020).

SHETRAN modelling of the Coalburn catchment (1.5 km^2) showed a 31.7% reduction in peak flow (observed peak discharge 2.5 m^3/s) for the January 2005 event, with return period approximately 1 in 7.5 years when all possible streams were modified to reflect the implementation of leaky barriers. In the larger Irthing catchment (335 km^2), no effect was seen when converting 3% of the channel network, however, when converting between 50% and 100% of the channel network, peak flow reductions were observed (Barnes and others, 2023).

SHETRAN modelled leaky barriers in 100% of the headwaters of the Irthing catchment (335 km^2) resulted in a 38.8% reduction in peak flow for the mean of the 20 events analysed and 51.9% for the largest event analysed (Barnes and others, 2023).

2D Flood Modeller modelling of 33 leaky barriers in the steep sided Lyde Brook catchment, Coalbrookdale (5.66 km^2), showed a 10 to 20 minute delay to the onset of flooding, but no reduction in peak flows. Water depths increased from between 0.05 m to 0.6 m upstream of the leaky barriers (Jackson and Whittingham, 2021).

InfoWorksICM 1D-2D modelling of 39 leaky barriers and 11 tree trunk barriers in a tributary of Pinn Brook, in Park Wood, Ruislip, London resulted in a 5% reduction in peak flow for a 2-year event, a 4% reduction for a 5-year event, and a 3% reduction for a 30-year event. Modelling suggested that the current placement of barriers allows for alternative flow pathways to be used, reducing their effectiveness. When increasing the height and length of the leaky barriers by 1 m, a 21% reduction in the 2-year peak flow and a 14% reduction in the 30-year peak flow was seen (Gilbert, 2021b).

HEC-RAS 2D modelling of large wood at 3 cross sections in a 50 m reach resulted in an 8% reduction in peak flow, with negligible difference in peak flow delay. Hysteresis analysis of the hydrographs at the 3 cross sections suggests an effect of the increased floodplain residence time, which was greater during the rising limb compared to the falling limb of the hydrograph (Keys and others, 2018).

HEC-RAS 2D modelling of large woody debris at 3 cross sections in a 50 m reach increased the duration of floodplain inundation by 5 minutes and increased depths by 3 cm. Flooded area increased by 91 m^2, with an increase in the use of the floodplain with increasing return period up to a point of convergence, where afterwards, the floodplain dynamics were the same regardless of whether large wood was in place or not (Keys and others, 2018).

Analysis of 3 sites along the Oregon Coast, USA (5 to 16 km^2 catchment area) showed that the addition of large wood increased wetted area and floodplain connectivity, with added heterogeneity of flow fields. A wider distribution of velocities and shear stresses was seen, but with an overall decrease in mean values (Bair and others, 2019).

Using a 1D straight line network model of Penny Gill (West Cumbria, England, catchment less than 0.5 km^2), it was observed that the leaky barriers exhibited reduced effectiveness in lowering the height of the second peak in comparison to the first peak. This was attributed to the fact that they had already stored water, resulting in a reduced capacity to store and delay water from the second peak (Hankin and others, 2020).

Placement of the barriers on both the main trunk and side branches of a herringbone river network within a 1D network model of Penny Gill had a similar impact in terms of slightly delaying and decreasing the peak discharge. However, the branch barriers showed a slightly greater effectiveness. This is because the barriers located near the bottom of the central trunk overtopped and had reduced effectiveness, whereas the barriers on the side branches were not overtopped and, therefore, continued to perform as expected in the model (Hankin and others, 2020).

The volume of storage can be influenced by the location of leaky barriers within a network, with over 100 m^3 more storage being seen with randomly sited barriers compared to the real-world placement. However, the degree of peak flow reduction only increased by 1% (Hankin and others, 2020).

Building barriers on shallower gradients enhances storage and reduces underutilisation (Hankin and others, 2020).

Modelling (HEC-RAS 2D) of large woody debris at 3 cross sections (in a 50 m reach in Virginia, USA) suggested that geomorphic character had little impact on flooding dynamics (channel slope, width to depth ratio, sinuosity). However, floodplain connectivity was greatest when large wood was placed in shallow areas or in fast flowing areas (the study was within a 1 km^2 catchment area and assessed 12 return periods from 1 to 1,000 years) (Keys and others, 2018).

A 2020 study found that when using a 1D straight line network model across a range of rainfall event magnitudes, typically only one barrier experienced a collapse. However, the downstream peak discharge was notably influenced by which barrier failed. A larger peak discharge occurred when the barrier that collapsed was located further downstream. This is because if an upstream barrier fails (without causing a cascade of downstream failures), the sudden water release from that dam is moderated by the presence of barriers further downstream. When the failure of a single barrier triggers the collapse of 2 or more downstream barriers, the peak discharge can be substantially higher (Hankin and others, 2020). In this study, barrier failure depths were estimated. Failure required significant depth above the top of the leaky barrier: the critical depth was sampled from a normal distribution with mean 3.5 m and standard deviation 0.5 m (the top of the dam was at 1.5 m), so dam collapse usually occurs when the dam is already submerged significantly. Further research into the probability of failure with depth for a range of leaky barrier designs was carried out (van Leeuwen, 2021), developing a generic fragility curve for a more natural structure.

Within the modelling study, in nearly every simulation involving barriers positioned along the central trunk, cascade failures occurred, resulting in the collapse of 3 or 4 barriers. This, in turn, led to a brief but extremely high peak discharge. Conversely, when barriers were situated along the side branches, the possibility of cascade failure was eliminated since the individual branches operated independently, making it unlikely that more than one barrier would collapse. Therefore, while both barrier placements were similarly effective in reducing peak discharge, placement of barriers on branches of the network often led to a more resilient system, even though the resilience of the individual barriers remained consistent across both designs (Hankin and others, 2020).

Modelling of 16 leaky barriers along Rise Park Stream (a tributary of the River Rom, Romford, London Borough of Havering) for 6 different flood return periods between 1 in 20 years and 1 in 1,000 years was carried out. Modelling showed an increase in peak water levels upstream of the leaky barriers. However, modelling did not indicate any reduction in flood peak levels elsewhere in the catchment, suggesting that the leaky barriers do not effectively reduce flood risk in the area (McKenna, 2021).

Effect at different catchment scales

The potential for peak synchronicity effects increases with catchment size (Metcalfe and others, 2018). In some cases, desynchronisation of flood peaks across sub-catchments may increase the overall effectiveness of NFM schemes, adding to the impact of storage volume directly provided by the scheme (Metcalfe and others, 2018).

While modelling results suggest that model-led optimisation of barrier placement could lead to reduced costs of construction and maintenance, the advantages of optimisation at larger scales require further research (Hankin and others, 2020).

Effect on sedimentation and geomorphology: process understanding

Leaky barriers alter local flow conditions, in turn, impacting sediment transport and river geomorphology. Natural leaky barriers that span the channel width and depth have been observed to block progress of bedload sediment, resulting in upstream sediment accumulation (Livers and Wohl, 2021; Wohl and Iskin, 2022). In addition to the direct impact of the barrier in reducing sediment transport, the barrier-generated upstream backwater area of slower, deepened water reduces sediment transport capacity in the backwater region, promoting deposition of suspended sediment (Follett and others, 2020). Furthermore, the increase in upstream water depth in the backwater region increases hyporheic exchange, which may help to remove fine particles accumulated in pore spaces between larger sediment underneath the barrier (Huang and Yang, 2023).

Leaky barriers with lower and lateral gaps between the barrier and channel bed or banks concentrate flow within the gap region, which can generate areas of local scour underneath and immediately downstream of the barrier (Harvey and others, 2018; Schalko and others, 2021; Muhawenimana and others, 2023; Schalko and others, 2023). Increased velocity in the gap region increases bed shear stress and potential for sediment transport. The relative impact of the gap reduces as its width relative to the channel and barrier increases (Follett and others, 2021; Schalko and others, 2023).

Downstream of the barrier, a wake region forms as faster and slower flow streams exiting the gap and barrier regions mix. As distance downstream of the barrier increases, the flow profile becomes more uniform. In fixed-bed tests, a barrier with a lower gap generated a near-wake region over which the gap velocity was maintained for approximately 4 gap widths downstream of the barrier, followed by a far-wake region of gradual flow recovery (Huang and others, 2022; Müller and others, 2022).

Large wood barriers with one or more lateral gaps between the barrier and channel banks generate areas of faster flow in the gap region as flow diverges around the wood pieces. This can result in local scour at the upstream edge of the barrier, and a steady region behind the barrier, with reduced velocity downstream of the structure, which encourages sediment deposition (Ismail and others, 2021; Schalko and others, 2021; Follett and others, 2021; Schalko and others, 2023). The structure of the wake region has been linked to mechanisms generating longitudinal river islands in gravel-bed rivers (Follett and others, 2021). Large wood pieces that extend above the water surface generate approximately 10 times higher turbulent kinetic energy than wood pieces under submerged conditions, such as during a flood event (Schalko and others, 2021).

Natural leaky barriers in upland mountain settings are highly transient, though some persist for many years (Wohl and Scamardo, 2021; Wohl and Iskin, 2022). By altering 3-dimensional connectivity of flow and sediment transport, leaky barriers can influence channel bifurcations in unmanaged settings (Wohl and Iskin, 2022).

While multichannel upland sites are associated with a higher leaky barrier density, generation and maintenance of multi-thread sites also depend on local catchment geology and floodplain width (Wohl and Iskin, 2022).

Effect on sedimentation and geomorphology: observed evidence

Scour and sedimentation occurred within the series of barriers in Flimby Gill, Cumbria, England. Accumulation of ~13 cm of silt over a year upstream of one barrier potentially contributed to subsequently observed overtopping of the barrier (Chadwick, 2021b).

Areas immediately upstream of leaky barriers (Black Brook, River Dane, Cheshire, England) showed a higher percentage of fine silt and sediment than those immediately downstream (Deane and others, 2021).

Repeat surveys suggested an increase in silt present in Stanmore Country Park, London Borough of Harrow 2 years after the construction of leaky barriers (Gilbert, 2021c).

Emergent and submerged vegetation patches, which boost biodiversity, were more frequent at a restored wood reach containing barriers with a lateral gap compared to a natural wood reach (in the River Loddon catchment), which contained a variety of partial (lateral gap), active and complete barriers with substantial deposits of fine sediment (Pinto and others, 2019).

A restored wood reach containing barriers with a lateral gap and active channel-spanning barriers in the River Loddon catchment had a higher proportion of submerged vegetation and a lower proportion of riffle, pool and silt mesohabitats compared to the control reach. The majority of barriers were associated with very low proportions (<20% coverage) of silt. However, 2 partial barriers on a meander bend were linked to >60% silt coverage (Pinto and others, 2019).

In lowland chalk stream sites (River Bure, Norfolk, England), fine sediment storage was higher in the 2 restored reaches compared to the unrestored section, with the restored reaches also having statistically significantly different levels of sediment storage (Harvey and others, 2018). The percentage of fine sediment stored in wood patches placed adjacent to channel banks compared to other channel areas showed no trend through time for one reach, but increased linearly from ~30% to 40% in another (Harvey and others, 2018). Although not statistically significant due to high spatial variability, fine sediment depth and shear stress were similar between marginal and central channel areas before wood installation. After restoration patch types indicated more distinct sheltered depositional environments around the wood barriers and areas of higher shear stress and lower sediment depths in adjacent flow deflection patches in lowland chalk streams (Harvey and others, 2018).

Leaky barrier sites had reduced suspended sediment concentration compared to a control site for very high flow events (return period 1 in 9 years). Observed silt content sediment upstream of leaky barriers increased with time since installation (Taylor and Clarke, 2021).

Leaky barrier sites demonstrated a slight increase in the amount of suspended sediment during high-magnitude flow events compared to low-flow events. However, during the highest flow magnitude event, the control site experienced a significantly greater rise in suspended sediment levels. Therefore, leaky barriers continued to mitigate the transportation of suspended sediment in high-flow events, despite the greater volume of silt available in the bedload material upstream of the leaky barrier (Taylor and Clarke, 2021).

Cross-section profiles for each wood jam showed increased bed elevations in marginal areas around the wood jams (0.1 to 0.3 m higher and extending 2.5 to 5 m from the banks) and scour in adjacent areas where flow was concentrated between jams (0.05 m to 0.3 m at the deepest point) for 7 out of 11 wood jams through time on the River Bure, a chalk stream, in Norfolk). For 2 jams in each reach, this pattern was not observed. In one reach, these jams were both located on or near outer meander bend locations and in the other reach both comprised key wood pieces staked into the channel at some distance from the bank (Harvey and others, 2018).

At 2 engineered logjams in Coverdale, Yorkshire Dales, England, with a lower gap allowing passage of base flow, Lo and others (2022) observed formation of underflow pools spanning almost the full channel width, which became well-developed following 2 high flow events less than 2 years after installation. Pools with volume 0.56 m^3 and 0.96 m^3 developed directly beneath and downstream of the dams, with secondary erosion and pool formation (2 sites with 0.17 m^3 pool and 0.63 m^3 sediment removed, respectively) observed downstream laterally adjacent to deposition of sediment scoured from the initial underflow pools.

Muhawenimana and others (2023) observed the development of a 0.05 m gap at the upstream edge of a leaky barrier. A significantly deeper scour area developed downstream of the barrier (approximately 1 m deep which grew over time), followed by a deposition mound in Shropshire.

Two years after the construction of leaky barriers in Stanmore Park, Harrow, England, repeat surveying suggested an increase in gravel-pebble sized material within the reach in the form of a scour pool and subsequent downstream deposition (Gilbert, 2021c).

A survey of 34 leaky barriers noted plunge pool development under leaky barriers, with silt accumulation within the pools (on the River Bourne). Approximately 1 to 2 m downstream, shallow gravel deposits were observed (Powell and others, 2021).

Initial surveys show riverbed changes such as sorted gravels bars and minor erosion indicated a meandering flow associated with the in-channel leaky barriers implemented in the Pang Valley (Pang Valley Flood Forum, 2021).

Channel surveys observed bed aggradation at 2 of the 5 sites, with up to 67 cm of aggradation at one barrier. Particle size analysis revealed that this mainly consisted of silt and sand which smothered the gravel bed and may lead to a localised decrease in habitat quality (Phillips and others, no date).

Lo and others (2022) found that leaky barriers were associated with bank erosion (in Coverdale, Yorkshire Dales, England). For example, at one barrier, water flow concentrated on the left side of the channel, leading to erosion of the left bank within the 3 m downstream of the barrier, starting one month after barrier installation (0.20 m^3 eroded in 6 months and 0.17 m^3 in the following 6 months). At another, localised bank erosion occurred due to water flowing around the barrier, particularly evident in September 2020 when gravel-sized alluvium accumulated on the left bank at the original barrier location. At another, localised erosion of the right bank was observed at the original location of the dam, which had been displaced in the winter of 2018. At another, the slightly rotated barrier diverted water into the left bank, causing localised erosion.

Muhawenimana and others (2023) observed a reduction in backwater rise following the development of a lateral gap in the leaky barrier due to localised bank scour in Shropshire, UK.

Two years after the construction of leaky barriers in Stanmore Park, Harrow, England, surveying suggested bankfull width increased from 0.8 m before installation to 2.1 m 2 years after installation (Gilbert, 2021c).

Channel widening was observed up to 1 m upstream and downstream of leaky barriers on the River Bourne, Berkshire, England. Erosion was noted to be more severe for more naturally designed leaky barriers compared to horse-jump types (Powell and others, 2021).

Within a laboratory experiment at the University of Pisa, Italy, it was determined log-frame deflectors can protect riverbanks by diverting flows towards the middle of the channel, altering both depth and velocity of flow (Kurdistani and others, 2019).

An analysis in the Merriot Stream catchment, Somerset, England recorded bank erosion at 2 of the 5 man-made barriers. Up to 40 cm was lost at one barrier and up to 20 cm at another.

Lo and others (2022) identified the differing ability of leaky barriers to accumulate sediment in Coverdale, Yorkshire Dales, England. On one reach, the barriers had minimal sediment storage capacity. Some gravels accumulated, but the volume was small (0.14

m^3). While reach-wide aggradation occurred along the tributary in the winter of 2018/19, these deposits were transported by high flows the following year, suggesting that the barriers only had limited sediment retention ability. In contrast, on another reach where barriers had smaller clearance heights, gravels started to accumulate, clogging the gap between one barrier and the stream bed. Deposition extended further upstream through time, resulting in accumulation at the toe of the right bank, with the channel shifting laterally towards the left.

Lo and others (2022) observed that among 6 monitored leaky barriers, 2 experienced complete failure, one was rotated clockwise by 30 degrees, and another was pushed 0.4 m downstream. Of those that completely failed, one prevented further erosion of the outer bank of the downstream bend, protecting the bank from further erosion and the other allowed the left bank to shift towards the thalweg, resulting in a channel width that was 0.2 m narrower than the baseline condition.

At Pickering Beck, Yorkshire, 2 barriers were observed to fail after large flood events (November 2012) and within a straightened section of channel placed alongside a railway line, with limited floodplain storage. An upstream barrier was observed to fail, with a shift to the channel bank of the subsequent lower structure. Network modelling using a probabilistic barrier fragility function suggested siting logjams on smaller tributaries rather than the main stem (Hankin and others, 2020).

Effect on sedimentation and geomorphology: modelled evidence

Suspended sediment transport modelling using Caesar-Lisflood showed large wood generated 25% less suspended sediment compared to the baseline model over a 22-year period in an ephemeral stream (New South Wales (NSW), Australia). The rate of suspended sediment increase was highest in the first 7 years of simulation, before the model simulated stabilisation through vegetation (Walsh and others, 2020).

There was a large increase in the rate of suspended sediment increase when doubling the diameter or doubling the quantity of wood in the model across the first 7 years following a Q_2 discharge event (which represents the doubling of the baseline discharge volume), suggesting that channel adjustment to the new wood increases erosion. However, at the end of the 22-year simulation, there was no difference between the different scenarios. For a Q_{10} scenario, doubling the diameters of the wood simulated saw a reduced rate of increase in suspended sediment during the event (Walsh and others, 2020).

Sediment storage within a Caesar-Lisflood modelled ephemeral catchment in NSW, Australia) increased when large wood was simulated, with doubling the size of the large wood being more effective at storing sediment than doubling the quantity, with 0.61 m^3 of additional storage for the Q_2 scenario (Walsh and others, 2020).

Design life and effectiveness

Modelling results investigating NFM efficacy and uncertainty analysis (Dynamic TOPMODEL) of a variety of hillslope run-off attenuation features, including leaky barriers found within their study area features which were designed to drain out within 10 hours for target events, balanced desired water storage during a flood event, and had the greatest impact on flood peak. This design had the ability to drain and vacate potential storage before a subsequent event peak (Metcalfe and others, 2018).

Data-based modelling of monitored leaky barriers in Cumbria, England indicated that barriers were primarily effective by increasing the retention time of water entering the upstream backwater area, rather than in slowing the kinematic celerity of a flood wave (Follett and others, 2023). While the monitored leaky barriers provided storage, the storage volume generated was 2.8 to 128 times smaller than that required to achieve a retention time of 10 hours.

The storage volume provided by a barrier for a given discharge depends on the barrier structure, width of lower and lateral gaps, barrier height, and channel slope, bed roughness, and depth. Practitioner-focused modelling frameworks and design tools can be used to assess impact of design choices on barrier efficacy, such as storage and residence time (Follett and Hankin, 2022; Follett and Beven, 2023; Chappell and others, 2023).

Flow through the leaky barrier allowed for accumulation and depletion of debris (small twigs and leaves) over time. Due to accumulation and depletion of debris and changes in barrier wood pieces, the barrier impact on backwater rise varied over time, recorded by pressure transducers upstream and downstream of 3 monitored barriers in Shropshire (from observed evidence) (Muhawenimana and others, 2023).

No wider benefits were noted from leaky barriers installed in the Thames Basin (16,000 km^2) between London and Slough, which were designed with a gap between the barrier and the water surface as the barriers were not permanently storing water. Building dams from species such as willow which can continue to grow as a ‘living barrier’ can reduce maintenance costs. The greatest potential for successful leaky barrier implementation exists where barriers improved the connection with floodplains (Mulligan and others, 2023).

Understanding catchment peak magnitudes when designing leaky dams is important, however, designing to allow the system to recover between peak magnitudes is also important. This finding emerged following an assessment of the installation of 8 leaky dams in a stream in Coverdale, North Yorkshire. The dam’s effectiveness was assessed over various magnitude from >1 to 6-year return periods (van Leeuwen and others, 2024).

Increasing the gap beneath a single leaky barrier from 0.05 m to 0.3 m resulted in reductions in peak discharge by up to 14% for different return periods, 10 m downstream of the leaky barrier. Overtopping decreased between 28% and 80%, with the difference decreasing with increasing return period. Water stored on the floodplain decreased by up to 188 m^3 and water stored in the channel decreased by up to 96 m^3 (from modelled evidence) (Pearson, 2020).

Smaller lower gap heights increased the magnitude of backwater rise and backwater length, with outflow peak delay, reduction in peak magnitude and hydrograph skewness all increasing with decreasing gap height (Follett and Hankin, 2022).

Increasing the gap beneath a modelled leaky barrier from 0.05 m to 0.3 m resulted in an increase of up to 68 m^2 in the area estimated to be erosional, with a subsequent decrease of up to 124 m^2 in the area estimated to be depositional upstream (from modelled evidence) (Pearson, 2020).

The backwater rise and flow redistribution between the barrier and gap sections depend on the number, size and packing density of the logs in the barrier and height of lower gap and barrier. For the same vertical section, a smaller lower gap and greater barrier extent increases longitudinal velocities in the gap region, increasing bed shear stress and the potential for initiation of sediment transport, which could lead to development of local scour. A larger lower gap with reduced barrier extent reduces the velocity in the gap region and potential for sediment transport, but also reduces the potential magnitude of backwater rise and upstream water storage (Follett and others, 2021, Muhawenimana and others, 2023).

When increasing the height of a modelled leaky barrier so that it extended onto the floodplain, as the event magnitude increased and the flow interacted with the barrier, water accumulated upstream rapidly, with the extended barrier storing up to 90 m^3 more water than the wholly in-channel barrier. This extended barrier directed water onto the floodplain before overtopping, resulting in an additional 330 m^3 on the floodplain. Despite increased floodplain flow, there was, however, no reduction in water discharge downstream, leading to no attenuation or peak reduction at the downstream modelled boundary due to water re-entering the channel a short distance (<200 m) downstream (Pearson, 2020). There was little difference in the area estimated as erosional upstream of the barrier between the original and extended leaky barrier designs. However, extending the leaky barrier did increase the area estimated to be depositional by up to 124 m^2 (Pearson, 2020). Up to 50 m downstream, the extended barrier resulted in a decrease of up to 104 m^2 in erosion and an increase of up to 63 m^2 in deposition compared to the original barrier design; over 50 m downstream geomorphological processes were unaffected by barrier design.

The Pang Valley Flood Forum implemented natural flood management (NFM) initiatives across the Pang catchment in Berkshire from 2017 to 2021. It installed 63 leaky barriers of 2 different types of sites: large timbers set at right angles in deep channel sections, and timbers with brush set at angles in shallower sections. The leaky barriers placed within the channel are accumulating additional material like leaves and twigs, and often contain living elements like bushes. On the other hand, the leaky barriers positioned above the channel are not accumulating as much material, likely due to their greater height. The accumulation of materials and the presence of living elements in leaky barriers should be considered when assessing their design life, as they contribute to the maintenance and enhancement of the barriers through natural processes (Pang Valley Flood Forum, 2021).

2.3.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for air quality, climate regulation, amenity or soil derived from leaky barriers specifically.

Water resources

Taylor and Clarke (2021) observed no difference between hydrological variables between 2 leaky barrier sites with a control site in Stroud Frome and Twyver catchments (area of 8.37 km^2) in Gloucestershire at low flows.

Biodiversity

The presence of large wood debris (LWD) interventions led to an increase in macroinvertebrate abundance and taxa richness compared to control sites on the River Dane, UK. Higher biological monitoring working party (BMWP) scores also indicated greater taxa richness (Deane and others, 2021).

Analysis of invertebrate data using non-metric multidimensional scaling (NMDS) and hierarchical clustering revealed distinct community separations where LWD was present compared to areas without LWD (Deane and others, 2021).

SIMPER analysis identified the rapid establishment of taxa (riffle beetles [Elmidae], marsh beetles [Scirtidae], minute moss beetle [Hydraenidae], and Ryhacophillidae) in response to LWD additions, which were absent otherwise (Deane and others, 2021).

Ten months after LWD installation, downstream areas also exhibited improved biodiversity, indicating that the positive effects of LWD extended downstream (Deane and others, 2021).

Spatial organisation of mesohabitats appeared patchy in the restored large wood reach and natural large wood reach compared to a linear structure associated with a higher proportion of emergent and submerged macrophytes at the control reach in the River Loddon, SE England (Pinto and others, 2019).

At the site level, there were no significant differences observed in invertebrate abundance and diversity between large wood reaches (restored or natural) and their respective control sites (Pinto and others, 2019).

Large wood restored exhibited a 56 to 84% increase in vegetation cover through time on the River Bure, a lowland chalk stream, Norfolk (Harvey and others, 2018).

There was a notable increase in the cover of marginal/emergent species following restoration, which then declined but remained above 60% after a year. In a reach that had been restored for a longer period of time, the cover of marginal and emergent vegetation showed less variation over time, fluctuating between 40% and 60% (Harvey and others, 2018).

Clustering of marginal and emergent vegetation occurred around the wood jams (Harvey and others, 2018).

A flume study carried out to explore the influence of porous and non-porous leaky barriers with lower gaps on the behaviour of salmon in 2 different flow conditions indicated that the barrier porosity affected fish movement and spatial preferences. A higher rate of upstream passage was observed in the case of the non-porous design compared to the porous one. The study suggested the barrier design and porosity was more important than the difference in discharge on fish behaviour (Müller and others, 2021).

Areas with a high abundance of large woody debris saw hotspots of respiration by living organisms in a lowland forested stream in West Sussex (Blaen and others, 2018).

2D modelling suggested the introduction of large wood approximately doubled the size of coho salmon winter rearing habitat in Oregon, USA (Bair and others, 2019).

In the Coalbrookdale catchment in Shropshire, England) where 32 leaky barriers have been constructed, a statistically significant change in species assemblages adjacent to the dams was observed (Adams, no date).

Following the installation of leaky barriers in the Pang Valley, initial ecological assessments indicated no notable alteration in habitat quality in the short term. However, there may be improvements in the long term and anecdotal enhancements have been observed, such as clear signs of wildlife using the leaky barriers (Pang Valley Flood Forum, 2021).

Leaky barrier implementation in the Merriott Stream catchment, Somerset found 4 of the 5 leaky barriers created scour pools and outwash gravel bars, which benefits a range of fish and invertebrate species. However, depositions of silt and sand occurred at 2 of the 5 leaky barriers and smothered the gravel bed, which can negatively affect the local habitat (Phillips and others, no date).

Water quality

There were limited long-term effects of large woody debris introduction on water quality improvements in a catchment with low existing nutrient concentrations in a coastal plain region, Georgia, USA (Bickley and others, 2021).

2.4 Eurasian beaver

2.4.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of the presence of Eurasian beavers an FCRM perspective and the scientific confidence in what we know. The original directory did not have a section on beavers and so the scientific papers are those published after 2017, while noting that there is substantial evidence before this period.

Effect on flood flows, peaks, and storage: process understanding

Presence of beaver dams correlates with shallow channel gradients and wide, flat valley floors, reducing the likelihood of dam failure. This is due to the increased availability of cohesive clays in areas with flows onto floodplains as seen in Alberta, Canada (Westbrook and others, 2020).

Fuller ponds may also buffer flood wave power and protect downstream dams during high-magnitude flood events in Alberta, Canada (Westbrook and others, 2020).

Within the River Otter, in the Budleigh Brook catchment (6.3 km^2) in south-west England, the impacts of natural beaver colonisation were observed after 3 years in an unconfined valley. The observed delay to peak flow is believed to be associated with an increase in storage capacity and a reduction in flow velocities; both of which result from the increased roughness caused by beaver dams. In this particular scenario, the increased storage is primarily due to the temporary floodplain storage within the low-profile and gently sloping floodplain and valley. This underpins the significant influence of topography on the ability of beaver dams to attenuate flow (Graham and others, 2022).

In unfenced, low-gradient floodplain valleys, beaver dams can reconnect flow pathways between the channel and the floodplain following observations from the River Otter, SW England. This redirection of flow forces it laterally onto the floodplain, causing an increase in water levels within backwater beaver dam ponds. As flow intensifies, it is directed through, around or over the dam structures, lengthening the flow pathway and increasing factors such as roughness, depth and tortuosity. Generally, beaver dams and the associated wetlands expand the active floodplain area where floodplain processes are at play. Within this example, lag times increased by ~56% following beaver colonisation (Graham and others, 2022).

Effect on flood flows, peaks, and storage: observed evidence

The presence of beaver dams reduced discharges for the same storage levels compared to wetland rehabilitation (in a 66 km^2 catchment in Brandenburg, Germany). For example, at 17.5 mm of storage, discharge rates were 0.1 $mm \cdot hr^{-1}$ during wetland rehabilitation, but dropped to 0.05 $mm \cdot hr^{-1}$ during the period of beaver recolonisation. This shift in the dynamic between storage and discharge resulted in an extension of the mean hydrograph recession time of 30 hours during the period of beaver recolonisation (Smith and others, 2020).

Analysis of over 1,000 storm events showed statistically significant reductions in peak flows after beaver re-introduction, with estimated overall reductions ranging from 0.359 to 0.065 m^3s^{-1}. The impact of beavers on peak flow reductions appeared to be more pronounced in sites with well-established beaver activity, particularly those dominated by agriculture, resulting in larger reductions (0.065 to 0.211 m^3s^{-1}) during significant events, compared to smaller effects in woodland catchments with fewer dams (0.104 to 0.050 m^3s^{-1}). These impacts occurred over 4 sites across England (Puttock, Graham and others, 2021).

Within the same study, a BACI (Before-After-Control-Impact) analysis revealed that the mean peak flow remained unchanged (0.33 m^3s^{-1}) for the control site over the study period, whereas in the presence of beavers, the study site experienced a significant reduction in peak flow from 0.66 to 0.35 mm^3s^{-1} (47%) (on Budleigh Brook, River Otter, Devon, England). This effect was especially evident during large events above the Q5 exceedance rate (the flow that is expected to be exceeded 5% of the time), with a statistically significant 57% reduction in mean peak flow within the beaver-impacted site, compared to a 4% difference within the control site (Puttock, Graham and others, 2021).

In the headwaters of the River Tamar, Devon, total event discharges below the beaver-affected area were 34% (±9%) smaller than those above, with peak discharges also showing a 30% (±19%) reduction, both of which were statistically significant. Significant differences in flow parameters were also identified for the largest storm events (top 20%), which exhibited flows that were on average 37% (±15%) lower in terms of total event discharge and 35% (±14%) lower in peak discharges. The beavers were introduced in a 3-hectare area (Puttock and others, 2017).

Beaver dams led to a reduction in peak flows during rainfall events, with a more pronounced attenuation effect during larger magnitude events within the Budleigh Brook catchment, 6.3 km^2, River Otter, Devon. High flows occurred less frequently at the site with beavers, resulting in a 33% decrease in flows exceeded 5% of the time compared to a 15% decrease at the control site. Beaver dams' attenuation capacity was observed to increase with storm magnitude, achieving peak flow reductions of between 0.5 and 2.5 m^3s^{-1}, although this effect was not confidently evident beyond the 97^{th} percentile of events (Graham and others, 2022).

Attenuation effects were observed, with peak rainfall to peak flow lag times 29% longer and event durations 32% longer in a headwater catchment on the River Tamar, Devon, England. Significant differences in flow parameters were also identified for the largest storm events (top 20%), with 28 (±25%) longer lag times compared to flows above the beaver-affected area. In this example, 13 dam-pond structures have been established (Puttock and others, 2017).

The average event lag time increased by ~56% after the introduction of beavers compared to a ~18% decrease at a control site with no beavers in a study in the Budleigh Brook catchment, 6.3 km^2, River Otter, Devon, England. This change is reflected in the hydrograph shape, where minimal alterations occurred at the control site, but substantial changes were observed at the beaver-impacted site (Graham and others, 2022).

Q5:Q95 ratios, used as a measure of how quickly a river's levels responds to storm events, demonstrated that the attenuation effects of beaver dams were especially evident during higher magnitude events, with less pronounced changes for smaller hydrological events relative to the control site on the River Otter, Devon (Graham and others, 2022).

In a comprehensive study of beaver dams and their associated ponds (within a regional area spanning 5,826 km^2 in Alberta, Canada), observations were made before and after a major flood event with a >40-year return period. During this event, one of the 3 ponds examined in greater detail experienced a breach, releasing floodwater that did not breach the downstream dams. Surprisingly, the upstream beaver pond of the breached dam did not completely drain after the breach, retaining at least 1,135 m^3 of water, which was 13% of its capacity. Following a second flood wave, water level in the upstream pond increased by 0.11 m, storing an additional 486 m^3 of water (Westbrook and others, 2020).

A three-order-of-magnitude increase in surface water storage within ponds was observed following beaver re-introduction in the headwaters of the River Tamar, Devon, England. This increase included the creation of 13 dam-pond structures covering a surface area exceeding 1,500 m^2, with approximately 1,000 m^3 of water stored within them at any given time. Over the study period, there were further observed increases in storage, with the number of ponds growing from 7 to 13 between 2013 and 2014. Correspondingly, the water surface area expanded from 750 m^2 in 2013 to 1,832 m^2 in 2015. An overall significant upward trend in estimated storage volumes was evident (Puttock and others, 2017).

As indicated through more total water entering the area than leaving, the increase in storage with lateral redistribution at the site following beaver re-introduction in the headwaters of the River Tamar, Devon, England led to significant evapotranspiration, infiltration and transmission losses (Puttock and others, 2017).

Flow attenuation induced by beaver dams could persist through the wet season; 14 out of 16 of the largest events were observed during the wettest period and no significant reduction in attenuation was found when compared to all events of the River Tamar, Devon, England (Puttock and others, 2017).

Before a major flood event, when beaver dams were intact, the collective surface area of beaver ponds in the peatland area measured approximately 2.67×10^4 m^2 in a study in Alberta, Canada. However, following the summer flood, which resulted in breached dams, there was a notable reduction in the beaver pond surface area by 41%; a further 2 years later, the area had decreased again to just 21% of the initial storage area (Karran and others, 2018).

A notable seasonality effect was detected in the influence of beavers on peak flows, with the greatest reductions occurring during the wet season and the smallest during the dry season from beaver sites across England. For instance, the Budleigh Brook site in Devon, England exhibited a 50% reduction in peak flow during the wet season but only a 10% decrease during the dry season. In forested catchments, the seasonality effect was less pronounced, with an 11% decrease in the wet season and a 22% reduction in the dry season at the Yorkshire site. The seasonality effect held statistical significance, with no variation between seasons at the control site, while the beaver-impacted site exhibited a 17% decrease in mean peak flows during the dry season and a more substantial 62% reduction during the wet season (Puttock, Graham and others, 2021).

Post-flood, it was found that 42% of the cascades in the region remained, while 32% were breached, and 26% were affected but continued to exist in Alberta, Canada. Among the remaining yet affected cascades, it was most commonly observed that the upstream dam was breached while downstream dams remained intact (Westbrook and others, 2020).

Mean volume of stored water did not significantly vary between different dam intactness classifications, and there was no apparent correlation between dam intactness and the total amount of rainfall received in a study in Alberta, Canada. However, there was evidence of spatial clustering of cascades within the same persistence classification. For instance, 8 clustered sites in a flat, wide valley floor were classified as persistent, while 4 sites in the headwaters along a 20 km channel stretch were classified as breaches (Westbrook and others, 2020).

Dams that create a pond which inundates a lodge or food cache (a primary dam) were found to generally be taller than secondary dams (which increase inundation area to allow beavers to access food and building materials). The type of dam (primary or secondary) had the biggest impact on dam height. Secondary dams were much more common within this study of 500 dams in North America. Landscape characteristics such as slope, discharge and drainage area also had some impact on dam height. The likelihood of a dam being damaged was mainly due to which watershed the dam was in (Hafen and others, 2020).

Effect on flood flows, peaks, and storage: modelled evidence

Modelling (HYDRO_AS-2D) of 2 reaches in Germany indicated that beaver dam cascades (n=2, with 3 to 7 dams per cascade) have a significant impact on reducing flood effects up to the 2-year return period, with no substantial effect on events with return periods greater than 2 years. For events with a return period greater than 2 years, the peak discharge attenuation at the cascade was approximately 2%, with negligible downstream impact. These effects are strongly influenced by local catchment characteristics and flood magnitude. Dam cascades have little impact on peak discharge attenuation and translation in steep, v-shaped or u-shaped valleys (channel slope > 4.1%). In contrast, they can have considerable effects on peak discharge attenuation (up to 13.1%) and translation (up to 2.75 hours) in areas with wide floodplains and gentle river slopes (< 0.5%), but only during small magnitude events (Neumayer and others, 2020).

Beaver ponds resulting from dam construction were observed to encompass approximately 33.5% of the wetted channel area in Curits Creek (57 km^2 catchment), Utah, USA. Additionally, the construction of dams within the primary channel led to the formation of overflow channels and beaver canals, facilitating the reconnection of the active channel with an older one, adding 2,020 m^2 of wetted area (Majerova and others, 2020).

Effect in different watercourse typologies

Beaver dams extend beyond channels, creating durable berm-like structures across the peatland that increased the inundation area in a peatland (~1.3 km^2, in Alberta, Canada). Dams redirect groundwater flow away from channels and into longer down-valley flow paths, recharging peatland aquifers and increasing baseflow. Improving water table stability due to the presence of beaver dams is linked to the active maintenance of these structures, which maintains water levels near the dam crest. This maintenance sustains hydraulic gradients and ensures a consistent flow direction into the peat aquifer. Additionally, the elevation of the water table within the peat profile contributes to enhanced stability, as water tables in the upper layer experience reduced fluctuations due to the increased water volume needed to produce a specific change in water table height per unit area (Karran and others, 2018).

A study in Alberta, Canada compared water table elevations under peatland (~1.3 km^2) near beaver dams. In years with intact dams, water tables stayed in the range of approximately +5 cm to -20 cm relative to peat surface. After dams were breached, there was a substantial 135% median lowering of the water table and nearly a doubling of the median absolute deviation (MAD). Within a 150 m radius of dams, the median water table was consistently 12.8 cm higher on average when dams were intact, showing twice the level of stability. During a wet year with intact dams, all monitored wells showed high water table stability, which decreased to 78% during a dry year with intact dams. Conversely, with breached dams during a wet year, the number of wells displaying high water table stability declined to 62%, and this further decreased to 38% during a dry year. Beaver dams were attributed to the increase and stabilisation of groundwater table in peatland areas (Karran and others, 2018).

Beaver reintroduction increased groundwater storage and leakage but did not significantly affect average discharges due to a relatively small wetland area (1.7 km^2) within a 66 km^2 catchment in Brandenburg, Germany (Smith and others, 2020).

Effect on sedimentation and geomorphology: process understanding

In the upper reach of the Raba River (southern Poland), beaver dams increased lateral channel erosion by washing away bank sediments and reduced bed degradation by slowing flow velocity. In the lower reach, beaver activity directly causes bank fragmentation through slides and burrows (Gorczyca and others, 2018).

Effect on sedimentation and geomorphology: observed evidence

The introduction of beavers and their construction of engineered dams resulted in the formation of 13 new ponds in the headwaters of the River Tamar, Devon, England. These ponds collectively stored an estimated 101.53 (± 16.24) metric tons of sediment, signifying a total increase in sediment storage within the site of 88.14 tons over 5 years. When normalised per square metre of ponds, this averaged out to 74.40 (± 39.65) kilograms of sediment per square metre. Furthermore, it was calculated that the pond system still had a remaining potential storage capacity of 55.7%, assuming no changes to the site, representing an additional potential storage of 124.4 tons (Puttock and others, 2018).

The deposition of sediment within the upstream beaver ponds was believed to be a consequence of the reduced flow velocity linked to a decrease in stream power in the headwaters of the River Tamar, Devon, England. This was supported by the observation of lower concentrations of suspended sediment exiting the beaver site compared to the amount entering it, indicating that beaver dams and ponds can notably influence sediment budgets within the channel. Site visits further corroborated these findings, revealing that the majority of trapped sediment accumulates within the initial upstream ponds (Puttock and others, 2017).

The amount of sediment stored within the ponds was closely correlated with pond surface area, with larger ponds accommodating greater quantities of sediment in the headwaters of the River Tamar, Devon, England. Additionally, older ponds (4 to 5 years) tended to contain larger amounts of sediment compared to newer ponds (< 3 years) (Puttock and others, 2018).

An overall net reduction in suspended sediment downstream (trapping efficiency) was calculated at 65.17% in the headwaters of the River Tamar, Devon, England. Of the sediment trapped within beaver ponds, an estimated 70.43% was believed to originate from upstream, amounting to approximately 71.42 tons (Puttock and others, 2018).

Sediment accumulation and roughness can be increased as cuttings from beaver activity are deposited downstream of dams. The assessment of beaver dams in south-western Montana, USA found these cuttings deposits sprout and vegetation colonise as a result. The study also found breached beaver dams stimulate meander generation and, therefore, increase riparian habitat diversity (Levine and Meyer, 2019).

Effect on sedimentation and geomorphology: modelled evidence

An assessment of beaver dam complexes observed diverse geomorphic units within the modelling were driven by a wide range of hydraulic factors, particularly depth and velocity in Curits Creek (57 km^2 catchment, Utah, USA). The modelled pool depths varied from 0.50 m to 0.88 m, with an average of 0.62 m. Among these units, backwater areas exhibited the most substantial depth variation, averaging 0.32 m. In the entire modelled area, the distribution of geomorphic units included 13% pools, 21% backwaters, 10% margins and 10% riffles, encompassing a broad spectrum of velocities and depths (Majerova and others, 2020).

Design life and effectiveness

A comparison of beaver dam analogues and natural beaver dams in Red Canyon Creek Wyoming, USA found the nutrient cycling and water exchange processes to be similar for both types of dams in the short term. It is unclear if these similarities will continue in the long term. This may be an important consideration for design when working to maximise benefits (Wade and others, 2020).

2.4.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for air quality or soil derived from Eurasian beavers specifically.

Water resources

The dams increased both surface and groundwater storage, leading to a greater groundwater availability for release as baseflow. This could largely benefit water resource resilience during times of low flow in Alberta, Canada (Karran and others, 2018).

While Puttock and others (2021) focused on the impact on high flow periods, they note that the reduced hydrograph flashiness observed supports other research, suggesting the ability of beaver dams to maintain or elevate baseflows during dry periods through the slow release of water within a multi-site study across England.

The frequency of low flows (as indicated by the Q95 exceedance limit), showed a 10% decline at the impacted site after beaver colonisation, in contrast to a 12.5% increase at the control site in sub-catchments of the River Otter, Devon. It is suggested that this may be attributed to dam-induced loss increases through increased evapotranspiration and/or groundwater recharge (Graham and others, 2022).

Climate regulation

By altering the water table and enhancing its stability, beaver dams have the potential to increase carbon sequestration in peatlands and enhance these ecosystems' resilience to climate change in Alberta, Canada (Karran and others, 2018).

A total of 15.90 ± 2.5 tons of carbon were estimated to have been stored within the beaver ponds in the River Tamar headwaters, Devon, England. The mean concentrations of carbon in pond sediment, both upstream and downstream of beaver-affected sites, were significantly higher than those found in the channel bed sediment. Furthermore, mean concentrations were higher upstream of beaver sites than downstream, with an approximate decrease of 70% for carbon (Puttock and others, 2018).

A study in the USA found that beaver wetlands provide a significant mitigation to drought and wildfire, which is an increasing climate-related hazard across Europe (Fairfax and Whittle, 2021).

Accumulation of beaver cuttings over long timescales (thousands of years) can lead to increased carbon storage within the floodplain, as observed in Montana, USA (Levine and Meyer, 2019).

Amenity

One study found the ecosystem services (water purification, moderation of extreme events, habitat and biodiversity provision, nutrient cycling, greenhouse gas sequestration, recreational hunting and fishing, water supply and non-consumptive recreation) provided by beavers is worth millions to hundreds of millions of US dollars annually (Thompson and others, 2021).

One study in England found beaver reintroduction to provide economic benefits to local businesses through tourism. The extent of the benefit was dependent on businesses pursuing potential opportunities (Auster and others, 2020).

Biodiversity

Eurasian beavers were seen to use both softwood (willow and poplar) and invasive woody species (boxelder, Manitoba, dwarf and low maple and green ash), however softwoods were used in higher ratios than invasives, with notable avoidances of invasive wood species at several sites in lowland parts of Hungary (Juhász and others, 2020).

By altering the water table and enhancing its stability, beaver dams play a role in promoting the formation of unique plant communities within peatland ecosystems (Alberta, Canada) (Karran and others, 2018).

An assessment of the impact of beaver dams on other small mammals in Poland found both species richness and abundance to be higher on sections of streams which had been dammed by beavers. The number of species and individuals decreased with distance from the dam (Wikar and others, 2023).

Beaver-built ponds are far more biodiverse than other wetlands (Willby and others, 2018).

A study in Sweden found beaver reintroduction in areas where beavers are native should benefit freshwater biodiversity. The number of species unique to beaver ponds was 50% higher than the number of species found to be unique to other wetlands. The benefit, however, is context and taxon specific (Law and others, 2019).

Water quality

A study in Germany found dissolved oxygen tends to be higher in beaver ponds than upstream (Smith and others, 2020). On the River Tamar in Devon, dissolved organic carbon concentrations and loads were found to be higher downstream of beaver ponds (Puttock and others, 2017).

No unequivocal improvements to water quality were found, with negligible change to total phosphorus downstream of beaver colonisation (in a 66 km^2 catchment in Brandenburg, Germany) (Smith and others, 2020).

The study findings from the Logan River basin in Utah, USA indicate that beaver ponds resulting from dam construction have the potential to reduce heavy metal concentrations at a rate 2 to 4 times higher than that observed in riffle stream reach sections. This heavy metal attenuation was found to be proportional to both the age of the pond and the organic matter content in the sediment. Among the 3 ponds examined, the youngest and oldest sites did not exhibit significant attenuation effects on dissolved nutrients or total phosphorus. However, the intermediate-aged pond had a limited impact on total phosphorus loads but accumulated substantial amounts of phosphorus within its sediments. This suggests that the potential for beaver ponds to sequester phosphorus is primarily within the first few years of pond creation, with diminishing attenuation and storage effects over time (Murray and others, 2021).

Puttock and others (2017) propose that in the headwaters of the River Tamar, Devon, England deceleration of flow velocity leading to sediment and nutrient deposition and the increased wetness of the site affecting the biogeochemical cycling of nutrients resulted in substantial mean reductions in suspended sediment, total oxidised nitrogen and phosphate levels, accompanied by slight decreases in water pH downstream. Instantaneous loads, adjusted to account for the reduced downstream flow, also exhibited declines for suspended sediment, total oxidized nitrogen and phosphate. Consequently, it is suggested that, for a given discharge, the loads entering the site are higher compared to the loads leaving it. This effect was also observed for yields entering and exiting the site following events.

A total of 0.91 (+/- 0.15) tons of nitrogen was stored within beaver ponds in the headwaters of the River Tamar, Devon, England. The mean concentrations of nitrogen in pond sediment, both upstream and downstream of beaver-affected sites, were significantly higher than those found in the channel bed sediment. Furthermore, mean concentrations were higher upstream of beaver sites than downstream, with an approximate decrease of 56% for nitrogen (Puttock and others, 2018).

During periods of low flow, it was observed that the temperature difference between upstream and downstream locations at the reach scale was 2°C, resulting in a net daytime warming of 1°C and a net nighttime cooling of 0.5°C in Curtis Creek (57 km^2 catchment, Utah, USA). The presence of diverse geomorphic units created by beaver dams led to spatial temperature variations at the site scale, specifically within the dam cascade, reaching as high as 10.5°C, with daytime warming of 1.15°C and variable nighttime cooling (Majerova and others, 2020).

2.5 Offline storage areas

2.5.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of offline storage areas from an FCRM perspective and the scientific confidence in what we know.

Effect on flood flows, peaks and storage: observed evidence

There was a 7% reduction in peak flows for a 31% annual exceedance probability (AEP) event for a 2-pond network, representing 408 m^3 of flow and slight reduction in rising limb slope, suggesting lower 'flashiness' (6 km^2 catchment in Tone and Parrett catchments, Somerset, England). For a second 2-pond network, the peak flow reduction was 1.4% for a 41% AEP event, equating to 35 m^3 of storage (6 km^2 catchment in Tone and Parrett catchments, Somerset, England). Lockwood and others (2022) suggest the difference in efficacy between the 2 networks is due to the high inlet elevations reducing the ability of the ponds in the second network to fill from the channel during high-flow events.

Following installation of ponds in autumn 2021, only 2 relatively low-magnitude events occurred (events with a return period of less than 2 years). Pond 1 rapidly filled to approximately 90% of its capacity and exhibited a more immediate response to rainfall. In contrast, pond 2 filled gradually throughout the event, reaching only 45% of its capacity in the Glenderamackin catchment, Cumbria, England (Pearson, 2023a).

Monitoring of the Askew Rigg ponds was carried out exclusively during the late October 2021 and February 2022 events in the Glenderamackin catchment, Cumbria, England. During both of these events, the water levels in the ponds exceeded the overspill level, causing overflow into the adjacent fields. GIS analysis showed the storage volumes were nearly twice the overspill capacity. In the February event, both ponds surpassed the overspill level in the first 2 peaks of the event. Subsequently, they drained almost to the base level before experiencing a rapid and significant increase in volume during the third peak. This pattern indicates that the ponds were not overwhelmed during any of the peaks and continued to attenuate the flow throughout the event. Their offline design, directing flows above a threshold into the ponds, reduces premature overwhelming during events. Moreover, these features can drain from full capacity faster than online ponds as they stop receiving inflow once rainfall and stream levels decrease (Pearson, 2023a).

The floodplain scrape at Rogerscale within the River Cocker catchment, Cumbria, England had a storage capacity of 244 m^3, but this capacity was exceeded during the initial phases of a high-flow event, resulting in minimal reduction of peak flows downstream (West Cumbria Rivers Trust, 2021b).

The study identified a significant issue with the water storage area on Naddle Beck, Cumbria, England; overflowing even in relatively modest 1 in 2-year flood events. However, initial drainage through the overspill channel occurred swiftly in response to rainfall intensity, creating additional capacity during heavy rainfall periods (West Cumbria Rivers Trust, 2021c).

In a 2-pond network on the River Soar*,* Leicestershire, England during the wet season (September to April), the pond's water levels closely mirror the rapidly changing river water levels, suggesting that the pond remains consistently full during most significant events, leaving no available storage when needed the most. On-site pictures confirm the pond's high-water levels even during relatively minor events. Water level logging highlights the slow drainage rate of the pond due to the absence of an outlet. Following the addition of a new upstream logger, following a small event, the pond still slowly fills from the river, suggesting limited storage capacity for small events with favourable soil moisture conditions (Majeed, 2023).

Effect on flood flows, peaks and storage: modelled evidence

Cross-cutting Modelling of the Belford Burn catchment (5.7 km^2, in Northern England) has demonstrated that a network of 5 offline storage areas (providing typical temporary storage of 300 to 1,000 m^3) distributed along the floodplain of a channel reach may be effective in reducing downstream flooding at the small catchment scale (~10 km^2) for 1 in 12.5 to 1 in 100-year events. The modelling results have shown that peak flow can be reduced by more than 30% at downstream receptors (storage distributed between 35 run-off attenuation features and offline storage areas). Offline storage areas were the primary intervention in the catchment and point of investigation for the study, however 6 areas of riparian planting, 14 leaky barriers, 2 sediment traps and 15 overland flow interception ponds had also been constructed within the catchment (Nicholson and others, 2020).

Effect at different catchment scales

Cross-cutting A paper looking at the creation of well-designed large floodplain storage ponds in the Eddleston catchment (69 km^2) in the Scottish Borders (UK) showed they can provide temporary storage and help reduce flood risk, demonstrated through modelled and empirical evidence. For a 1.5-year return interval flow event, 5 such ponds in series on the floodplain could locally reduce the discharge peak by 18 to 20% and theoretically delay it by up to 6 hours (Spray and others, 2021).

Design life and effectiveness

Lockwood and others (2022) showed that for inlet-filling offline ponds, fill thresholds must be at a suitable level to accommodate direct filling from the channel during major events. In one offline pond, a flow of 0.75 m^3/s is needed for inlet filling, which is over 10 times higher than the mean downstream flow of 0.073 m^3/s in sub-catchments (of the Tone and Parrett catchments, Somerset, England). However, the required rainfall volumes for generating such high flows vary seasonally, with >12 mm needed in winter and >53 mm needed in summer. In contrast, a different pond did not experience high enough flows from even the largest recorded events to fill via the inlet. Historical data analysis highlighted that the monitored period was relatively wet in the context of previous years, with daily rainfall totals reaching 99.8% of previous daily rainfall totals (since 1961). Adjusting inlet heights or mechanisms to manage appropriate inflows throughout the year is essential, rather than relying on larger events to fill the upstream pond in Merriott.

Correctly designing pond outlets is crucial for ensuring sufficient spilling and, therefore, storage capacity availability at the peak of the flood event and during subsequent events. In the case of the pond network example of Lockwood and others (2022), an observed pre-event pond spilling in the upstream pond is inadequate, with pre-event storages typically 76% full, while downstream ponds allow better spilling, with only 5% storage pre-event. For another pond network, downstream spilling was generally sufficient (12% storage pre-event on average), but drainage can take up to 7 days after major events, longer than desired.

One study identified a significant issue with the water storage area overflowing even in relatively modest 1 in 2-year flood events. Complete drainage down to the base level was slow, taking 10 days, raising concerns about mitigating subsequent flood events in quick succession. This suggests increasing the size of the outflow pipe or adding a second outflow pipe to improve water discharge capacity before reaching maximum pond fill may be needed (West Cumbria Rivers Trust, 2021c).

2.5.2 Multiple benefits

No new evidence was found for offline storage areas since 2017 for benefits associated with water resources, air quality, climate regulation, amenity, biodiversity, soil or water quality.

3 Woodland management

3.1 Catchment woodland

3.1.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of catchment woodlands from an FCRM perspective and the scientific confidence in what we know.

Effect on flood flows, peaks and storage: process understanding

Semi-natural broadleaf woodlands (predominantly oak, ash, alder, birch and hazel) mitigate the risk of flood events caused by rainfall by enhancing interception, promoting soil infiltration, and providing additional storage capacity. Compared to pasture soils, woodland soils have higher permeability, contributing to their greater efficiency in lowering peak discharge and run-off in <0.2 km^2 catchments, for 1:10, 1:4 and 1:1.5-year events, near Haweswater, Lake District (Monger, Spracklen, and others, 2022).

Greater hydraulic conductivity, leading to enhanced drainage, removes water from the upper soil layer, reducing the likelihood of rapid overland flow formation within 0.5 m of alder saplings on Tebay Common, River Lune catchment headwaters, Cumbria (catchment size and return period not stated) (Mawdsley and others, 2017).

In Maryland, USA, among trees of the same species (red maple) in urban areas, higher transpiration rates are observed in more open environments and are more influenced by climatic conditions. While individual trees display the highest transpiration rates, urban forest areas with denser canopies or larger trees compared to open areas exhibit greater transpiration per unit ground area. Understory vegetation in forest patches can also contribute to overall transpiration (Ponte and others, 2021). Catchment size was not stated as these findings are from an urban study. The return period was also not stated.

Monitoring (BACI design) of the Hore catchment, Wales (3.1 km^2), Burrishoole catchment, Ireland (1.2 km^2), and Howan catchment, England (0.2 km^2) was carried out to study the impact of coniferous woodland on flow regimes. The results suggest that deforestation does not significantly increase the number of large peak flows, with the only impacts seen for minor peaks and only in catchments where over 50% of the catchment was changed. If activities like forest harvesting and biomass removal may have minimal effects on high flow rates, it is possible that reforestation's impact on peak flows may also be minimal (Xiao and others, 2022). However, other factors may have influenced these findings.

Effect on flood flows, peaks and storage: modelled evidence

For a 1-in-30 year, 6-hour duration flood event, planting broadleaf trees on acid grassland in the headwaters of Wasdale (catchment size unknown), excluding areas where peat depth exceeded 50 cm, reduced the overland flow peak by approximately 30%. Overland flow in the headwater basin was reduced by 15% and time to peak increased by 10 minutes following tree planting. Adding extensive conifer plantation in the downstream areas of Wasdale (approximately 50% of the catchment under conifer plantation) produced even greater benefits: for the same event, the overland peak flow was reduced by 59% and the total volume of water rapidly discharged during the event was also reduced by 40%. The time to peak increases by 45 minutes from 4 to 4.75 hours following the conifer planting (Chappell and others, 2017).

Dynamic Topmodel and JFlow modelling was carried out on 2 micro-catchments: Sware Gill (rough grazing; area 0.24 km^2) and Darling Howe (working conifer plantation (33% mature trees); area 0.46. km^2) in Cumbria, UK. The modelling was carried out to be scaled up to the macro-scale catchment, the Eden catchment (2,300 km^2), Mallerstang Valley, Cumbria. Modelling was carried out for Storm Ciara (peak flow of 1,000 m^3/s). In the micro catchments, a hypothetical conifer tree planting scenario on rough grazing in Sware Gill (~ 33% of the catchment, similar to Darling Howe) showed a potential peak flow reduction of 17% for Storm Ciara. At the macro-scale, a hypothetical tree planting scenario (area not specified) of targeted planting in small watersheds above communities at risk had a 0.5 to 5% peak flow reduction for Storm Ciara - a 1% median peak flow reduction (Hankin, Page, Chappell, and others, 2021).

A study assessed the impact of broadleaf afforestation on streamflow across 12 UK catchments (511 to 9,931 km^2) for the 1%, 5%, 50%, 90% and 95% quantiles of daily flows for 2000 to 2010. Findings show that the location of afforestation can impact extreme streamflow levels, particularly in smaller catchments. In larger catchments, the extent of afforestation matters more than the specific location, especially for median flows. However, there is no consistent national evidence of extreme flood reduction (definition of extreme not provided) due to afforestation. A 10-percentage point increase in catchment broadleaf woodland leads to a 2.8% ± 1.0 reduction in median modelled flow (equivalent to 10 mm/yr. ± 2.1). Catchments with low rainfall and deep soils show greater hydrological responsiveness to afforestation in these specific catchments (Buechel and others, 2022).

Hydrological modelling (HEC-HMS using information from Sentinel 2 satellite images) was carried out for the Umia Basin (44,591 ha), Galicia, NW Spain, for 3 events (237.3 m^3/s, 113.00 m^3/s and 109.9 m^3/s) showing that afforestation (mix of broadleaf and conifer) is most effective in headwaters and areas far from the river mouth. The modelling showed an average peak flow reduction of 9.3% in the case of afforestation in headwater areas (from 28.3% to 59.8% in the 12,285 ha sub-basin and from 49.9% to 71.3% in the 4,478 ha sub-basin), 8.6% for afforestation in downstream sub-basins (percentages not provided), and 13% for basin-wide afforestation (headwater afforestation, downstream afforestation and also afforestation of 44.09% and 75.28% in the 2 remaining basins of 12,344 ha and 1,561 ha respectively). Peak delay was also seen in all modelled afforestation scenarios (Acuña-Alonso and others, 2022).

In the Tarland Burn catchment (72 km^2), NE Scotland, WASIM-ETH modelling found that afforestation species and placement within the catchment have differing impacts on the scale of peak flow reduction. 10% new woodland planted in the lowland zone replacing cultivated agricultural land reduced high flows (Q5) by 8% for coniferous and 1% for deciduous woodland. In upland zones, 10% new woodland planting produced smaller results, with a 5% reduction in Q5 for coniferous and 0.5% for deciduous woodland. The different woodland types (coniferous versus broadleaved) were modelled by attributing coniferous woodland a higher evapotranspiration rate than broadleaved woodland (Iacob and others, 2017).

A HEC-HMS modelling study by Dittrich and others (2019) in the Eddleston Water catchment, Scottish Borders (69 km^2) modelled the effect of hillslope broadleaf afforestation of 30%, 64% and 100% of the catchment (corresponding to 2,070 ha, 4,416 ha and 6,900 ha, respectively). The gradient of the slope was not noted. Under the present day 1% AEP scenario, the difference in impact on peak flow reduction from 30% and 60% woodland was negligible (approximately 13% reduction for both scenarios), whereas on increasing woodland cover to 100%, the flood risk benefit increased (approximately 20% flood peak reduction). The same pattern is seen under the 2040 (approximately 8% reduction for the 30% and 64% afforestation scenarios versus 16% reduction for the 100% scenario) and 2080 (approximately 8% reduction for the 30% and 64% afforestation scenarios versus 15% reduction for the 100% scenario) climate change scenarios, although the benefit decreases with climate change. For all scenarios, there was a greater relative reduction in peak flow for the 5% AEP event than for the 1% AEP event, both under present day conditions in 2016 and under climate change (2040 and 2080). They also found that the benefits from hillslope afforestation were primarily derived from non-flood regulation ecosystem services, with flood regulation contributing only around 1% of total benefits (Dittrich and others, 2019).

SHETRAN modelling of Weston Colley sub-catchment (54 km^2), River Test, Hampshire showed flood peak reduction of up to 14% due to woodland planting. Woodland planting was most effective when the catchment had a higher proportion of woodland restoration (16.9% to 47%), but this reduction did not lead to a decrease in flood duration, suggesting that flooding in groundwater catchments may remain disruptive despite NFM efforts (Barnsley, 2021).

A modelling study was carried out on a groundwater dominated catchment of the River Thames to the town of Eynsham (1,616 km^2), with a baseline of 20% broadleaved woodland and 3% coniferous woodland. The study showed that broadscale woodland planting (a mixture of riparian and catchment woodland over 73% of the catchment, replacing all arable land and grassland) on top of the baseline woodland reduced median peak flows by 1.7% to 6.7% for broadleaved woodland and 16.0% to 24.7% for spruce woodland at return periods of 1 to 15 years. Peak flow reduction was largest for storms with shorter return periods (1 to 2 years for broadleaved and 2 to 3 years for spruce), with the smallest peak flow reductions seen for return periods of 5 to 15 years for both broadleaved and spruce. However, this scale of planting was estimated to reduce low flows (Q95) by ~39%. A more 'realistic' scenario of only a ~5% increase in woodland cover had limited impact on peak flows, with the greatest reduction seen in the 1 to 2-year return period scenarios: 0.2% to 0.9% for broadleaved and 1.5% to 2.6% for spruce woodland (Collins and others, 2023).

In Bin Brook (11 km^2), Cam and Ely Ouse River basin, Cambridgeshire, a coupled Dynamic TOPMODEL and HEC-RAS model, calibrated to a summer storm (2012) with a

15-year return period (NSE 0.83) was used to understand the effect of woodland planting (species not specified - modelling parameters detailed in Ferguson, 2020). Tree planting was represented as an increase in saturated soil conductivity, decrease in steepness of decline in soil conductivity, decrease in antecedent soil moisture, and decrease in overland flow. (Ferguson, 2020) found:

- that woodland planting across 45% of catchment area resulted in up to a 16.6% reduction in peak flow (10-year RP) and 30-minute delay to peak flow
- that woodland planting across 79% of catchment area resulted in up to a 33.2% reduction in peak flow (5-year RP) and a 45-minute delay to peak flow
- an overall decrease in peak reduction with increasing return period
- an overall decrease in peak delay with increasing return period
- a higher peak reduction and longer peak delays with larger areas of tree planting
- a difference between observed 15-year RP event (7.6% peak reduction, 0 min peak delay, 45% planting coverage) and design 20-year RP event (15.7% peak reduction, 30 min peak delay, 45% planting coverage) thought to be due to different hyetograph shape where the first quarter of the rainfall in the observed event fell within the first 30 minutes, which overwhelmed the soil's ability to absorb the water
- limited benefit to peak delay possibly due to the greater sub-surface flux created by tree planting in Dynamic TOPMODEL, creating storage but having less of an impact of slowing the time to peak

The Salmons Brook catchment (catchment size not stated), Enfield was modelled with ESTRY-TUFLOW and calibrated to an October 2000 event with a 1:25-year return period to understand the effect of differing coverage and maturity of woodland planting (species not stated). Woodland planting was represented by doubling soil hydraulic conductivity and applying a Manning's n roughness coefficient of 0.1. Mature woodland scenarios tripled the soil hydraulic conductivity. Peak flow was reduced by 10%, 30% and 45% for 200 ha, 415 ha, and 639 ha, respectively for saplings in the herb layer, increasing to 20%, 50% and 70%, respectively once the woodland matured. The model showed small areas of disbenefit due to the measures (deeper peak flood water depths in the urban catchment), which may have been due to unknowns in water inputs and the surface water drainage networks (Gilbert, 2021a). The study also modelled tree planting on individual farms in the catchment for the same October 2000 event. This showed that for:

- Plumridge Farm: 168 ha proposed woodland planting = 15% peak flow reduction
- Chase and Slopers Pond Farm: 119 ha proposed woodland planting = 10% peak flow reduction
- Parkside Farm: 128 ha proposed woodland planting = 8% peak flow reduction
- Beech Barn Farm: 85 ha proposed woodland planting = 6% peak flow reduction
- Ferny Hill Farm: 101 ha proposed woodland planting = 6% peak flow reduction
- Botany Bay Farm: 38 ha proposed woodland planting = 4% peak flow reduction

Hydrological modelling (SD-TOPMODEL) of the 38 km^2 Bishopdale catchment, Yorkshire Dales showed catchment-wide woodland planting (species not specified) reduced peak flow by 11% during the 100-year event, but was ineffective during the 10-year event, resulting in a 3% peak flow increase. Time to peak was delayed by 3% (15 minutes) in the 10-year and 100-year events due to catchment woodland (Kingsbury-Smith and others, 2023).

In an 80% broadleaf woodland/scrub cover scenario, when using SD-TOPMODEL of the River Calder from source to Walsden Water at Todmorden (Upper Calderdale catchment, 21 km^2), overland flow peaks were notably reduced, such as by 33.1% (13.03 m^3/s; 6-h, 1 in 50-year) and 41.0% (7.45 m^3/s; 24-h, 1 in 10-year). A 20% cover scenario also brought about peak reduction, albeit less significant. For both the 80% and 20% cover scenarios, a 15-minute delay in peak flow was observed during the 24-hour, 1 in 10-year storm event. In the 24-hour, 1 in 50-year event, a 15-minute peak delay occurred in the 80% cover scenario. However, no peak flow delays were projected for the 6-hour, 1 in 50-year storm event, irrespective of land cover (Bond and others, 2022).

WASIM-ETH modelling of the Tarland Burn catchment (72 km^2), NE Scotland, showed afforestation, particularly with coniferous woodland, can reduce peak high flows, although the reduction is less pronounced for higher magnitude extreme events and in typical winter conditions with saturated soils and lower evapotranspiration rates. This showed that:

- a 24% increase in new woodland can lead to up to a 19% reduction in a Q5 (used in this study as a ‘general’ high flow metric) peak flow
- afforestation can contribute to flood risk management by delaying time to reach peak flow
- coniferous woodland had a larger impact on reducing high flows; the highest reduction was with 100% coniferous afforestation
- high flow reduction was greater when the woodland was planted in lowland zones, replacing cultivated land (arable and improved grassland), with 10% new woodland reducing Q5 by 8% (coniferous) and 1% (broadleaved); in upland zones (where woodland replaced semi-natural habitats and unimproved grassland), the reduction was smaller, with 5% (coniferous) and 0.5% (broadleaved) reductions with the same proportion of new woodland
- for extreme high flows (7-hour 1 in 10-year return period), above the ‘general’ Q5 high flow metric, 100% coniferous afforestation decreased the peak flow by 30% (compared with a 60% reduction to the Q5 flow)
- smaller areas of afforestation did not show a proportional reduction in extreme high flows, suggesting that the impact of new woodland reduces as the intensity of the flood event increases (Iacob and others, 2017)

In the Tarland Burn catchment (72 km^2), NE Scotland, WASIM-ETH modelling found that afforestation with coniferous trees can delay flood peaks. The study also showed that:

- for full coniferous afforestation (100% cover), peak flow time was delayed by 2 hours in summer and one hour in winter for a 1 in 10-year return period 15-hour event

- with 75% afforestation, the time to peak flow was delayed by one hour for the same event, but only in summer; similar effects were observed for larger magnitude events, with little difference between full and 75% afforestation
- for larger magnitude events, a similar effect was seen, with the 1 in 100, 15-hour event taking one hour longer to reach peak in a 100% coniferous afforestation scenario, however, the 75% scenario made little difference to flood peak timing, suggesting that large and 'unrealistic' land use change is required to delay flood peaks for extreme events
- afforestation-based NFM, therefore, might have limited effectiveness against the largest extreme flood events in winter (Iacob and others, 2017)

JULES modelling of broadleaf afforestation has a streamflow-reducing effect across all flow quantiles in 12 large UK catchments (511 to 9,931 km^2) studied. The impact is more pronounced at median and low flows than at high flows (Buechel and others, 2022).

Effect at different catchment scales

Findings from small catchments might not directly apply to very large catchments, primarily because the affected portion in larger basins is relatively small, and variations are dampened by combined sub-catchment outflows. An observed impact on peak flows was detectable only when over 25% of the basin area was influenced in a 3.1 km^2 Welsh catchment. Afforestation and woodland cover (coniferous) have the potential to reduce flood peaks during smaller, frequent events and in smaller catchments in England and Ireland (0.2 km^2 and 1.2 km^2, which were 90% and 60% felled, respectively), however their impact diminishes in larger flood events and larger basins (Xiao and others, 2022).

A HEC-RAS model of the Glinščica river catchment (16.9 km^2), Slovenia, looking at 2, 10, and 25-year return period events, suggested that to achieve significant reductions in peak discharge and alter peak discharge timing through afforestation requires extensive forest cover. While afforestation can have noteworthy effects on a local scale, its impact on larger scales might be limited. In other words, the potential for afforestation to significantly reduce flood risk is more prominent in smaller catchments (Bezak and others, 2021).

In larger UK catchments (over 500 km^2), modelled evidence suggests that the extent of broadleaf afforestation holds greater significance than the specific location of afforestation efforts (Buechel and others, 2022).

Effect on different watercourse typologies

NFM shows diminished flood reduction effects in chalk groundwater sub-catchments within the River Test catchment, Hampshire, compared to non-groundwater dominant ones. Afforestation has shown promise in generating flood advantages 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. SHETRAN modelling showed flood peak reduction of up to 14% due to woodland planting, with the highest reduction seen when the catchment had a higher proportion of woodland restoration

(16.9% to 47%), but this reduction does not lead to a decrease in flood duration (Barnsley, 2021).

Effect on sedimentation and geomorphology: process understanding

In the moderately impacted Little Kennebago Lake watershed (135 km^2), NW Maine, USA, with low baseline erosion rates, logging and road construction led to greater sediment yield. Despite this, the implementation of effective forestry best management practices (BMPs) from the mid-1970s to 2017 - when timber harvesting was increasing - reduced severe erosion events under non-extreme rainfall events. However, an extreme event in 2018, resulting in culvert failure, triggered significant sediment mobilisation, fresh gravel bars and altered channels. While the 2018 event was exceptional, events such as this will become more frequent in the future, so existing BMPs may become inadequate. This emphasises that expanding road networks in forested areas increases the landscape vulnerability to future disturbances, potentially causing more such events (Cook and others, 2020).

In the Štavska river catchment (40.2 km^2), Serbia, there has been logging, deforestation, and the abandonment of meadows and pastures, facilitating unregulated logging practices. Consequently, erosion has risen, causing greater surface run-off and suspended sediment yields. This has led to changes in river flow regimes, highlighting the importance of good forest management practices (Potić and others, 2022).

Effect on sedimentation and geomorphology: observed evidence

Within the 135 km^2 Little Kennebago Lake watershed in Maine, USA, where tree species are mixed (coniferous and broadleaf), cores obtained before and after a 2018 intense rainfall event help in understanding earlier clastic layers. Event frequency rose after 1900, with 5 layers in ~1,100 years and 12 layers from 1900 to 2018. This coincided with suspended sediment yield rise (2.0 to 6.4 $Mg/km^2/yr.$) and heightened disturbance-related pollen taxa. The density of road systems within forested catchments and the onset of commercial timber harvest in 1981 appeared to correlate with higher levels of suspended sediment yield (Cook and others, 2020). Other related factors may also have impacted this correlation.

Design life and effectiveness

In 'flashy' upland headwater catchments (Erme, Colly Brook, Dean Burn, Holy Brook), Dartmoor National Park, oak and ash trees planted on former pastureland were an effective soil recovery option, doubling soil hydraulic conductivity, increasing the ‘wetness threshold’, and reducing surface soil compaction and bulk density within 15 years of establishment (Murphy and others, 2021).

The density of a woodland and, therefore, its canopy and understory vegetation impact flow and run-off resulting from differing levels of surface roughness and soil permeability.

Woodlands with closed canopies may have sparse understorey vegetation, leading to less surface roughness and faster overland flow. In contrast, mature semi-natural woodlands with varied age structures, canopy gaps and more understorey components tend to have increased surface roughness and reduced overland flow when looking at 20 m plots near Haweswater, Cumbria (Monger, Bond and others, 2022).

To enhance woodland resilience to climate change, it is recommended that a variety of different tree species are used within agroforestry. This approach increases adaptability and the ability to withstand the challenges posed by changing climatic conditions (Hernández-Morcillo and others, 2018).

A global meta-analysis of 496 watersheds across 36 countries over 25 years, looking at water resource management, found that natural forest growth (that is, forest free from human interference versus forest under afforestation) covering a span of 25 years could contribute to higher annual run-off and elevated run-off coefficients. The impact on run-off coefficient, particularly in less complex forest ecosystems, is influenced by external factors like thinning or felling. Diverse forests demonstrate greater resilience and effectiveness in regulating annual run-off, emphasising the role of ecosystem complexity in moderating these effects (Yu and others, 2022).

Dartmoor National Park and the Environment Agency (2021) found that planting trees within gorse and scrub areas, where burning is not a concern and grazing pressure is absent, leads to improved establishment compared to trees planted in open grazed areas.

A study in the pastoral uplands of Dartmoor, SW England found that to facilitate the natural growth of native oak (Quercus robur, Q. petraea) through seedling expansion, it is essential to exclude livestock during seedling establishment. Research shows that oak saplings aged 8 to 12 years had significantly better survival rates within enclosures where livestock were absent, as opposed to no survival outside enclosures. Moreover, saplings experienced the greatest increase in height where livestock were excluded (Murphy and others, 2022).

Decreasing stocking levels is likely to increase surface roughness and soil permeability. Woodlands with open canopies can combine higher soil permeability with greater understorey-induced surface roughness. Mature, semi-natural woodland soils have the highest soil water permeability and water storage capacity (Haweswater, Cumbria) (Monger, Bond and others, 2022).

Wood pasture, characterised by open canopies and dominated by bracken, exhibits less permeable soils but heightened surface roughness due to diverse grazing regimes, understorey vegetation, tree density and canopy cover. It, therefore, has the lowest overland flow (Haweswater, Cumbria) (Monger, Bond and others, 2022). This impact may depend on the grazing regime used.

It is advisable to retain trees in their current positions whenever feasible, allowing them to mature and reach their maximum infiltration potential. Infiltration capacity tends to rise as root systems develop over time (aspen and birch in a 2.2k m^2 clay site in Warwickshire) (Revell and others, 2022).

In the groundwater dominated Eynsham catchment (1,616 km^2) of the River Thames, it was shown that both broadscale woodland cover (~73% increase in broadleaved or spruce woodland cover on top of a baseline 20% broadleaved and 3% spruce woodland cover) and 'refined' (~5% increase of broadleaved or spruce) woodland cover was largely ineffective at reducing flood flows. However, the paper notes that locally, and in specific landscapes underlain by low permeability geology, some woodland NFM measures can significantly reduce flood risk, highlighting the need to understand underlying geology and apply woodland planting in suitable areas so that resources are not wasted (Collins and others, 2023).

3.1.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for air quality, soil or water quality derived from catchment woodlands specifically.

Water resources

When carrying out a global meta-analysis of 496 watersheds over 25 years, Yu and others (2022) suggest that a complex ecosystem is expected to be more resilient to external stresses and maintain stable processes, including water cycles. Highly complex forests have better compensation and mitigation capabilities.

In experimental coniferous forest sites in Hore (3.1 km^2), Hafren Forest, Mid-Wales; Howan (0.2 km^2), Kielder Forest, Scottish Borders; and Burrishoole (1.2 km^2), Nephin Forest, Ireland, there was a noticeable and consistent rise in baseflows following tree removal compared to control catchments. Baseflows increased by approximately 8% when the 3.1 km^2 catchment was 2% felled and by 41% with near-total (90%) clearing of a 0.2 km^2 catchment. This demonstrates that forests may decrease streamflow during dry periods. The removal of forests in this study led to an increase in baseflows, suggesting a shift in streamflow dynamics (Xiao and others, 2022). However, other factors may have influenced these findings.

A meta-analysis of 43 catchment studies (0.03 km^2 to 25,645km^2) spanning a global distribution of 13 countries, including the UK (Bentley and Coomes, 2020) identified that:

- following forest establishment (type not specified) there was a confirmed reduction in annual river flow, with a 23% decrease after 5 years and a 38% decrease after 25 years; this reduction is more pronounced in catchments with higher annual precipitation, greater forest cover increases, and those previously idle (grassland not used for agriculture) rather than used for agriculture
- the impact of forests on river flow is sensitive to annual precipitation and potential evapotranspiration, showing considerable variability; forests have a lesser effect on river flow in regions with low annual precipitation, and this sensitivity decreases as catchment aridity increases
- while most catchments experienced sustained river flow declines after forest establishment, 9 catchments showed partial flow recovery after an initial decrease

- recovery, observed at an average tree age of 15 years and across various tree species, occurred at a rate of 34 mm/year over 5 years, however, such partial flow recovery is not commonly expected, emphasising that changes in annual river flow are likely to persist for up to 5 decades in afforestation programmes
- changes in land cover can significantly affect evaporation, streamflow and water storage
- the impact of land cover change varies in forested ecosystems, depending on disturbance patterns
- it is important to note that land cover change does not have a uniform impact; the spatial distribution and frequency of these changes are crucial factors
- while fluctuations in evaporation due to land cover changes are important, precipitation fluctuations primarily influence the water balance in most forested ecosystems

In a study in the upper Waipori river basin, Glendhu, South Island, New Zealand, between 1991, when the planted catchment achieved canopy closure, and 2013, there was a significant annual reduction in water yield in the planted (Monterey pine) catchment (3.1 km^2) compared to the tussock (Chionochloa rigida) catchment (2.1 km^2), amounting to 273 mm or 33%. This reduction continued until 2010 when the difference in annual water yields between the 2 catchments began to narrow. Additionally, following canopy closure, afforestation led to an average 26% reduction in low flow (Q95) when compared to the tussock catchment (Fahey and Payne, 2017).

In the Tarland catchment study in Scotland (72 km^2), hydrological modelling indicated that afforestation, especially with coniferous woodland, can reduce low flows, even though its primary benefits are in reducing high flows. Specifically, in the case of low flows (Q95 flow), 75% conifer afforestation led to a reduction in low flow discharge of over 50%, while 100% afforestation resulted in a reduction of over 70% in low flow (Iacob and others, 2017).

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) in a groundwater dominated catchment reduced the 5th percentile flow (Q95) by 12% for broadleaved woodland and 39% for spruce woodland. The catchment has a baseline of 20% broadleaved woodland and 3% coniferous woodland. A more 'realistic' scenario of only a ~5% increase (78 km^2) in woodland cover had limited impact on Q95 flow (less than 5% for both spruce and broadleaved scenarios). As the broadscale spruce woodland planting scenario had the greatest reduction in peak flow (16 to 24.7% at return periods 1 to 15 years) but also the greatest reduction in Q95 flows, the impact on peak flows needs to be balanced against the need for water security and ecological river flows (Collins and others, 2023).

Widespread broadleaf afforestation may reduce water availability, particularly in drier areas: JULES modelling of afforestation has a streamflow-reducing effect across all flow quantiles in the 12 large UK catchments (511 to 9,931 km^2) studied. The impact is more pronounced at median and low flows than at high flows (Buechel and others, 2022).

A study using a mixture of recharge models and MODFLOW models looked at the impact on water resources from a variety of land use change scenarios within a chalk catchment, the Test, Andover. Changing land use from arable to woodland reduced base flows (by 4 to 17%) and groundwater storage (by 4 to 16%) for 25% to 100% land use change scenarios; conversion from arable to pasture had a comparatively lower impact on river flows and groundwater storage. Total river flow was 453.7 to 470.9 Ml/day compared to the baseline 477.2 Ml/day (Aghajani and others, 2023a).

Climate regulation

In terms of adaptation, there are moderate reductions in peak flow across various climate projections when modelling the Weston Colley sub-catchment of the River Test, Hampshire, which had 47% catchment broadleaf woodland cover, when compared to a non-NFM scenario. This implies that a significant increase in tree coverage can sustain these moderate benefits for up to 80 years under all UKCP18 climate scenarios. However, it's important to note that these modest peak flow reductions do not lead to measurable reductions in flood duration beyond the range of uncertainty. This presents a significant challenge for NFM function in the future, as future climate scenarios indicate extremely long flood durations, especially at the 90th percentile probability, under both RCP2.6 and RCP8.5[1]. These moderate peak flow reductions may not be enough to mitigate the major disruptions expected from these simulated floods. Nonetheless, these small benefits could serve as an adaptation strategy to complement the resilience of other hard engineering approaches to flood management that might be necessary in the future (Barnsley, 2021).

The Flimby catchment (4.5 km^2) NFM project, Cumbria, planted 11,000 trees which, according to the Woodland Carbon Code Calculator, will sequester approximately 2,500 tCO_2e (Chadwick, 2021a).

Amenity

Woodland areas (14 across England and Wales) offer recreational ecosystem services that, in turn, yield health benefits capable of improving overall life prospects and reducing the strain on public health budgets. The annual value of recreation services can vary significantly between woodlands, influenced by factors such as available facilities, activities, visit frequency and proximity to populations. Monetary estimates for the benefits of physical recreation range from £6 to £8,542 per person and from £2,581 to £70,832 per woodland. Smaller woodlands, although they may not draw large visitor numbers, offer valuable opportunities for informal physical recreation. These spaces are often underrated but can provide regular chances for physical activity, particularly when situated near urban areas (Moseley and others, 2018).

[1] Representative Concentration Pathways which represent the climate change scenario under very low (2.6 and very high (8.5) greenhouse gas emissions)

Tree planting for the Yarrow Meadows NFM programme involved 30 volunteers; tree planting and subsequent management can offer an easy way to get volunteers involved, providing social value by giving them experience and enabling them to source paid employment for this in the future (Blackstock, 2020).

Biodiversity

The establishment of new native woodlands in an approximately 700 km^2 study area, Tayside, Scottish Highlands, is particularly advantageous for bird species with high conservation concern, like the black grouse. The most significant benefits are observed in young woodlands, where black grouse populations increase notably when new native woodland covers around 30% of the land area within 1,500 m of their leks and has an average age of approximately 5 years (Scridel and others, 2017).

On Dartmoor National Park commons, in the River Erme catchment, native broadleaf trees and scrub planted for NFM play a vital role in open landscapes by offering valuable resources to both livestock and wildlife. They provide shelter from harsh weather conditions and offer much-needed shade during hot summers. Additionally, trees serve as perches and song posts for birds, enhancing their habitat and acting as a source of nectar and berries in an otherwise barren environment (Dartmoor National Park and Environment Agency, 2021).

3.2 Cross-slope woodland

3.2.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of cross-slope woodlands from an FCRM perspective and the scientific confidence in what we know.

Effects on flood flows, peaks, and storage: process understanding

Modelling for 3 sub-catchments of the Upper Calder Valley (Hebden Water, 60 km^2, Jumble Hole, 5 km^2, and the Upper Calder, 19 km^2), broadleaf cross-slope woodland (% of catchment modified: 1.5%, 8%, and 2.5%, respectively) disrupts, intercepts and absorbs surface water flow, leading to improved water infiltration and storage within the soil and reducing the speed of run-off (modelled for 3-hour and 12-hour 10-year and 100-year events, as well as the 2015 Boxing Day floods (maximum discharge = approx. 117 m^3/s) and a June 2012 event (maximum flow = approx. 37 m/s^3)) (Willis and Klaar, 2021).

Cross-slope woodland helps to reduce and delay rainfall run-off by absorbing rainfall directly and retaining water within its canopy (Blanusa and Hadley, 2019; Willis and Klaar, 2021).

Effects on flood flows, peaks, and storage: observed evidence

Observations from a catchment study of Eddleston Water, Scottish Borders (67 km^2), which implemented 27-year-old mixed coniferous and deciduous cross-slope woodland

(14 m wide strip on a hillslope ~100 to 200 m from Eddleston Water, rising to 30 m above the river with a relatively uniform slope of ~9°) found that soil moisture dynamics returned to those similar to grassland areas beyond 15 m downslope of the woodland. It also found that groundwater levels were lower downslope of the woodland compared to grassland areas, but evidence suggested upslope-downslope water table connectivity in the wettest conditions (Peskett and others, 2020). These results suggest that:

- storage capacity of the strip alone could be easily overwhelmed when surrounded by less permeable surroundings
- in temperate climates, during wetter winter periods, isolated mixed species (coniferous/deciduous) forest strips might have limited impact on subsurface moisture storage, however, these strips could modestly reduce catchment responsiveness in certain scenarios, like lower magnitude events or intense summer storms
- in temperate environments, mixed species (coniferous/deciduous) forest boundary strips might marginally heighten catchment storage due to evapotranspirative processes and tree interception that extends deeper and lasts longer than in grassland areas; this is most pronounced in summer and autumn, potentially mitigating summer flood events, although additional storage is limited in winter and spring, but this is likely to vary depending on forest type and age
- at the scale of storm events, mixed species (coniferous/deciduous) forest strips can locally dampen the response of soils and groundwater beneath them to rainfall events, particularly during summer and autumn
- forest soils respond similarly to rainfall as grassland does during larger events, and in winter, they seem to saturate less frequently, implying that forest strips could reduce run-off by combining intra-event evaporation and faster subsurface drainage

Effects on flood flows, peaks, and storage: modelled evidence

A modelling study (linking dynamic TOPMODEL, HEC-RAS and Infoworks ICM) in the Asker catchment (48 km^2), Dorset showed that cross-slope woodland planting (species not stated - modelling parameters detailed in Ferguson and Fenner, 2020) on areas of existing grassland with areas of underlying soils that were either free draining or slowly permeable, and with slopes between 10 and 30% gradient, reduced flood peak between ~43% for a 10-year return period event and 15% for a 100-year event. Peak flow was modelled for events with return periods of between 10 and 100 years, and peak reductions reduced with increasing storm severity (Ferguson and Fenner, 2020a).

A Soil and Water Assessment Tool (SWAT) model was used to study the effectiveness of hillslope 50 m deciduous tree buffer strips for peak flow reduction (for events: QMED (Median of annual maximum*);* 1 in 2 year; Q30; 1 in 5 year; Q10; 1 in 10 year) for the upper, middle and lower sub-catchments (25.3 km^2, 24.3 km^2, and 18.2 km^2, respectively) of the Tarland catchment of the River Dee, NE Scotland. Hillslope woodland was planted over 3.7 km^2 in the upper catchment (15% coverage), 1.9 km^2 in the middle catchment (8% coverage), and 1.6 km^2 in the lower catchment (9% coverage). This resulted in an average peak flow reduction (across all event scenarios) of 9.3%, 7.9%, and 7.9% upper, middle, and lower catchments respectively (Mason-McLean, 2020).

An SD-TOPMODEL study of 3 sub-catchments of the Upper Calder Valley (Hebden Water, 60 km^2, Jumble Hole, 5 km^2 and the Upper Calder, 19 km^2) modelled broadleaved cross-slope planting (1.5%, 8%, and 2.5% of catchment modified, respectively), with parameters based on mature woodland with comprehensive summer canopy (slope gradient not specified). The study modelled results for 3-hour and 12-hour 10-year and 100-year events, as well as the 2015 Boxing Day floods (maximum discharge = approx. 117 m^3/s) and a June 2012 event (maximum flow = approx. 37 m/s^3). The study by Willis and Klaar (2021) found that:

- cross-slope planting and catchment woodland planting (field-scale) approaches yielded positive outcomes in decreasing flood peaks and volumes
- the catchment woodland planting (field-scale) approach demonstrated a greater capability to reduce flood peak and volume values in comparison to cross-slope planting
- cross-slope planting saw average peak flow reductions of up to 2% and 4% and reduction in flood volumes of 2% to 7% for Upper Calder and Jumble Hole; this effectiveness was more pronounced for lower return period events
- for Hebden Water, reduction in flood peak was ~1% across all events

3.2.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for water resources, air quality, climate regulation, amenity, biodiversity, soil or water quality derived from cross-slope woodland specifically.

3.3 Floodplain woodland

3.3.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of floodplain woodlands from an FCRM perspective and the scientific confidence in what we know.

Effects on flood flows, peaks and storage: observed evidence

A study using experimental plots (45 m x 5 m) to mimic a channel and its floodplain found that sparse vegetation plays a substantial role in retaining water on forested floodplains during low flows; however, its impact diminishes as flow levels rise. As discharge increases, the capacity for water retention on forested floodplains decreases, reaching a similar value regardless of vegetation composition (bare ground, sparse vegetation with trees, or dense vegetation with trees, herbaceous plants and litter). With increasing vegetation density, the influence of lateral mixing (right angles to the flow direction) becomes more prominent, particularly in cases where vegetation is less dense. This suggests that vegetation density significantly affects the dynamics of water movement within floodplains, with lateral mixing becoming increasingly dominant as vegetation density rises (Carling and others, 2020).

In the Rogerscale floodplain restoration scheme in Cumbria (catchment size not stated), short rotation willow coppice planted perpendicular to the flow on the floodplain slowed the flow and captured debris. Comparing pre-NFM scenario modelled data for a 1 in 2-year event to the (qualitative) observed results in a similar magnitude event, the intervention led to a reduction in both the depth and velocity of water movement across the floodplain (West Cumbria Rivers Trust, 2021b).

Effects on flood flows, peaks and storage: modelled evidence

A HEC-HMS modelling study by Dittrich and others (2019) in the Eddleston Water catchment, Scottish Borders (69 km^2) modelled the effect of hillslope broadleaf afforestation, as well as the effect of existing 29 ha riparian/floodplain woodland. Under the present day 1% AEP scenario, riparian woodland gives an approximately 7% peak flow reduction. Under the 2040 and 2080 climate change scenarios, the percentage reduction is approximately 5%. For all scenarios, there was a greater relative reduction in peak flow for the 5% AEP event than for the 1% AEP event, both under present day (2016) conditions and under climate change (2040 and 2080). However, in the scenario assessing riparian/floodplain woodland, the reduced effect was less prominent, suggesting that afforestation on the floodplain had a greater effect on the resulting peak flow compared to upstream afforestation (Dittrich and others, 2019).

A modelling study (HEC-HMS) that assessed the cost-benefit ratio of woodland in the Eddleston Water catchment (69 km^2), Scottish Borders found that only riparian/floodplain woodland (compared to broadleaf hillslope woodland at 30%, 64% and 100% catchment coverage) showed benefits surpassing costs in the current climate when considering flood risk management alone. Flood risk reduction represented about 25 to 50% (depending on the climate change scenario) of the total benefits (cross slope was less than 1%) (Dittrich and others, 2019).

Design life and effectiveness

No new evidence found.

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).

3.3.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for water resources, air quality, climate regulation, soil or water quality derived from floodplain woodlands specifically.

Amenity

The Cleavelys Wet Woodland project, Worsley Brook, Salford site is being used as an educational resource, with ongoing research opportunities for University of Salford students. The site is actively engaging in volunteer efforts. It collaborates with student, corporate and volunteer groups to carry out invasive species control and plant native species, fostering community involvement in environmental conservation (Cosgrave, 2017).

Biodiversity

Planting trees along riparian areas offers a direct climate change adaptation strategy by establishing 'thermal refugia'. These refugia are created as the bankside trees eventually provide shading, helping to mitigate the effects of rising temperatures in these areas, which is particularly beneficial for salmonid species by reducing thermal stress on hot sunny days (Stutter and others, 2020; AECOM and The Nature Conservancy, 2021; Spray and others, 2021).

Wet and waterlogged woods play a vital role in supporting biodiversity. They provide habitats for various life forms, including lichens, mosses, sedges, rushes, ferns and numerous invertebrates. These invertebrates, in turn, serve as a food source for amphibians, mammals and birds. Dead wood associated with wet areas creates a specialised habitat not typically found in dry woodlands, supporting insects such as craneflies. These insects are an ideal food source for bats and other priority species like the willow tit, highlighting the interconnectedness of these ecosystems (Cosgrave, 2017).

Willow coppice is beneficial to a variety of insects and mammals, while also serving as a foraging habitat for birds. Floodplain woodlands play a crucial role in increasing biodiversity and fostering habitat connectivity, bridging the gaps between fragmented woodlands throughout the catchment area (West Cumbria Rivers Trust, 2021b).

3.4 Riparian woodland

3.4.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of riparian woodlands from an FCRM perspective and the scientific confidence in what we know.

Effect on flood flows, peaks and storage: process understanding

Mature riparian woodland adds large in-channel wood to watercourses, leading to increased hydraulic resistance and channel complexity by anchoring logjams – conceptual model. However, modelling suggests that there can be a lag of up to 40 to 50 years from the start of a woodland growing and the trees adding large enough wood to the channel to increase hydraulic resistance (Dixon and others, 2019).

Effect on flood flows, peaks and storage: observed evidence

A study using remote sensing found that older and denser forest plantations provide 30% greater resistance within the first 2 m flow depth compared to younger and sparser plantations. It compared 5 forest types (young poplar plantation, old poplar plantation, young pine plantation, old pine plantation, and unmanaged riparian forest) using 2, 4, 6 and 8 m flow depth events data from a gauging station upstream of the River Avon. The plantations were 5,930 m^2 in area and the riparian forest, 2,070 m^2. It found that forests with lower canopies, such as unmanaged riparian forests, exhibit higher resistance compared to forests with taller canopies like old plantations. Among different types of plantations, deciduous plantations like poplar tend to have higher roughness (measured as Manning's n) than pine plantations, especially when floodwater exceeds 6 m in flow depth. This difference is attributed to the placement of woody and leafy areas within the canopy, which is lower in the case of poplar trees (Antonarakis and Milan, 2020).

In a flume experiment, riparian vegetation (represented as 5 mm steel rods*)* was shown to create additional resistance to flows, leading to a reduction in velocity, an increase of flow depth and transportation of sediments. Riparian vegetation was observed to raise Manning's n by 20%. Among vegetation arrangements, staggered positioning resulted in the highest Darcy's f (a parameter related to flow resistance), increasing it by approximately 16% compared to a regular grid arrangement. The presence of riparian vegetation induced 20% more drag force than the main channel's roughness alone. These changes in bed morphology substantially elevated flow resistance within the channel (Jumain and others, 2018).

A monitoring study in the Eddleston catchment (69 km^2), Scotland, showed that 7.5 ha of riparian planting alone (rather than a group of NFM measures), in the School sub-catchment (6.89 km^2) did not result in any delays in lag time under mean annual floods. As the trees were between 5 and 8 years of age, it was suggested that this may be due to the immaturity of the trees at the time of monitoring or other local factors (Black and others, 2021).

A lab experiment carried out in a 12 m long flume (0.5 m wide, 0.1 m deep) with a 0.5 m wide floodplain studied the effect of 'trees' of 5 mm in diameter, placed in a regular grid (case B) and staggered (case C) array, 1 mm apart, 4 to 8 m from the channel inlet for a period of over 24 hours. Case A was a non-vegetated scenario. The study (Jumain and others, 2021) found that:

- the presence of 'vegetation' on the 'riverbank' decreased the water flow capacity and increased the water level in the channel
- the Manning’s n increased as the relative depth increased, for the regular grid scenario it was 9.2% higher than the non-vegetated scenario; and for the staggered scenario it was 14.3% higher than the non-vegetated scenario
- these results show that planting trees in a staggered arrangement has more impact than non-vegetation and regular grid planting on flow reduction

Effect on flood flows, peaks and storage: modelled evidence

A modelling study (SD-TOPMODEL) of riparian tree planting in 3 catchments in Calderdale (Hebden Water, 60 km^2, Jumble Hole, 5 km^2, and the Upper Calder, 19 km^2*;* 2.5%, 2%, and 2.5% of catchment modified, respectively) was completed (Willis and Klaar, 2021). This showed that:

- tree planting in gullies/cloughs resulted in a reduction of flood peaks ranging from 1 to 2% (in 2 sub-catchments, 19 km^2 and 60 km^2) to 2 to 3% (in one sub-catchment, 5 km^2) for all events
- the variation in reductions was partly attributed to differences in available planting areas among the catchments
- notably, the disparities between various events were more pronounced, particularly evident for the 3-hour events, where flood peaks decreased by approximately 2%, and flood volumes decreased by about 2.5% for both return periods (10-year and 100-year)
- similar effects were observed for the 12-hour 1 in 10-year event, however, the impact was less significant for higher return periods, resulting in a reduction of around 1% in flood peaks (Willis and Klaar, 2021)

A modelling study (HEC-RAS 2D) of the Culm catchment (280 km^2) found that an increase in riparian friction through woodland planting identified by the 2017 WWNP maps (area not stated, but the modelling was based on a theoretical maximum scenario) led to a reduction in peak flows for both a baseline 100-year return period event (peak flow reduction of approximately 10%) and the same event with a 20% increase in rainfall intensity to represent climate change (peak flow reduction of approximately 10%). Again, the additional storage on the floodplain as a result of the increased riparian friction was highlighted as being crucial to the peak flow reductions (Hankin, Page, McShane and others, 2021).

Effect on sedimentation and geomorphology: observed evidence

An extensive study of afforestation of actively eroding gullies on the east coast of North Island, New Zealand was carried out between the early 1960s and 2017. Planting was concentrated in an extensive area of gully-prone pastureland, totalling ~35,000 ha of planting. The planting 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).

A lab experiment carried out in a 12 m long flume (0.5 m wide, 0.1 m deep) with a 0.5 m wide floodplain studied the effect of 'trees' of 5 mm in diameter, placed in a regular grid (case B) and staggered (case C) array, 1 mm apart, 4 to 8 m from the channel inlet for a period of over 24 hours. Case A was a non-vegetated scenario. The study (Jumain and others, 2021) found that:

- depth-averaged velocity was higher for non-vegetated scenarios (0.34 m/s) than both vegetated scenarios (0.32 m/s and 0.29 m/s for regular grid and staggered planting, respectively) for the shallow depth
- for the deeper scenario, flow was more uniform (particularly for the non-vegetated scenario), and more floodplain flow occurred. Depth-averaged velocity was 0.37 m/s for the non-vegetated scenario and velocity decreased greatly at the channel-vegetation interface
- in shallower depths, the highest shear stress was observed for the non-vegetated scenario, the lowest shear stress was observed for the staggered scenario with greater variability in shear stress in the channel compared to the floodplain due to bed morphological changes and lower shear stresses at the channel boundaries (wall and bed)
- in deeper depths, shear stresses decreased from the non-vegetated scenario to the regular grid scenario and then to the staggered scenario, although there was limited difference between the regular grid and staggered scenarios; this was likely due to the limited lateral extent of the vegetation tested, with the difference expected to be greater if vegetation was applied across the entire floodplain; there was more uniform distribution of shear stresses in these scenarios (Jumain and others, 2021)

Design life and effectiveness

The Yarrow Meadows Project in Chorley concluded that for optimal bank stabilisation using willow in riparian areas, it is essential that the willow has enough time to establish itself before a significant flood event occurs. Without this establishment period, 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 considerable delay of about 40 to 50 years between the initiation of riparian forest growth and woody debris entering the channel in a size that can effectively anchor logjams, enhancing channel complexity and hydraulic resistance. During this initial growth phase, the benefits of NFM may not be fully realised unless additional interventions, like engineered logjams, are employed. Mixed deciduous and mixed deciduous/conifer forests yield higher volumes of deadwood biomass compared to beech or conifer forests. To optimise deadwood delivery to the channel, especially sizeable and stable pieces, locally suitable mixed deciduous woodland species should be prioritised. Results were modelled using 2 scenarios based on typical valley-bottom forest composition in temperate lowland rivers in north-eastern US and Europe, one representing commercial plantations and finally mixed forest cover. Results indicate that it may take over 100 years from the establishment of a new riparian forest stand 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).

In a riparian restoration project in Wilson Creek (1,200 ha watershed), Kentucky, USA, native riparian tree planting was carried out (Drayer and others, 2017). The study found that:

- American sycamore (Platanus occidentalis) and green ash (Fraxinus pennsylvanica*)* individuals had higher survival (80% and 79%, respectively) than individuals of Quercus palustris (pin oak; 22%)
- shelter and herbicide treatments had no effect on tree survival or height growth
- height growth varied by species (Platanus occidentalis exhibited a greater than 5-fold increase, F. pennsylvanica slightly increased, and Q. palustris decreased in height growth)
- there was significant natural colonisation of sycamore seedlings alongside the planted sycamore seedlings and the lack of available sunlight due to the spacing of their plantings and rapid growth of the sycamore seedlings (planted and naturally colonised) likely contributed to the low survival of pin oak seedlings and the stunted height growth of green ash seedlings
- rate of growth should be considered when choosing planting mixes (shade intolerant species may suffer if planted with faster growing species, leading to less biodiversity)

3.4.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for water resources, air quality, climate regulation, amenity or soil derived from riparian woodlands specifically.

Biodiversity

The Yarrow Meadows, Chorley project observed that riparian woodland planting has created marginal habitats (Blackstock, 2020).

Planting trees along riparian areas offers a direct climate change adaptation strategy by establishing ‘thermal refugia’. These refugia are created as the bankside trees eventually provide shading, helping to mitigate the effects of rising temperatures in these areas, which is particularly beneficial for salmonid species by reducing thermal stress on hot sunny days (Stutter and others, 2020; AECOM and The Nature Conservancy, 2021; Spray and others, 2021).

A study of a riparian restoration project in Wilson Creek (1,200 ha watershed), Kentucky, USA using native trees found that vigorous growth by Platanus occidentalis (American sycamore) provided thermal protection in the riparian area, lowering stream temperature (Drayer and others, 2017).

Water quality

A study of lowland riparian hardwood forests in Poland found the potential for water treatment, as indicated by the ratio of NO_3^- concentration in shallow groundwater outside versus inside the forest, varies significantly. Interestingly, the site with the highest groundwater level may have the highest potential for water treatment. This potential for water treatment is associated with the proximity of the water table to the root zone (high groundwater). The paper found that long-term enrichment of the ecosystem with nitrates can limit the nitrate uptake potential. These habitats, in turn, favour invasive plant species (supporting the study's finding of a negative relationship between water treatment versus share of invasive species). The age of the tree stand also has an impact: younger forests are less saturated and can, therefore, uptake more nitrate from the groundwater (Kowalska and others, 2021).

4 Run-off management

4.1 Soil and land management: soil aeration and subsoiling

This section sets out what we have learnt since 2017 about the effectiveness of soil and land management – specifically soil aeration and subsoiling – from an FCRM perspective and the scientific confidence in what we know.

4.1.1 Flood risk reduction evidence

Effect on flood flows, peaks and storage: observed evidence

In Brookings, South Dakota, Chalise and others (2019) showed that returning crop residue to silty, loamy soils resulted in 7% lower bulk density, 22% higher soil organic carbon (SOC) and infiltration 66% higher than non-treated areas. These improvements to the soil structure and function increased with time over the 16-year study period. However, this can result in increased emissions of N_2O, a potent greenhouse gas.

Effect on flood flows, peaks and storage: modelled evidence

Unconstrained modelling estimated that the flood peak in the Brimfield Brook in north Herefordshire (30 km^2) could be reduced by a maximum of 11% (1 in 2-year return period (RP)) to 17% *(*1 in 100-year RP) if all of the catchment had land management measures implemented on it, including arable subsoiling, reducing stocking densities and measures that reduce soil compaction. The modelling suggests that this could be reduced further to 26% in a 1 in 100-year event if all of the catchment had land use NFM measures, including arable reversion. Currently, NFM implemented on 3% of the catchment has reduced the flood peak here by 1% (Lewis and Hodges, 2021a).

Regenerative agriculture (minimising/avoiding tillage, eliminating bare soil and encouraging plant diversity) practices in 2 fields on a farm in Hertfordshire (Thames catchment, at the Stort upstream from Roydon), with the same soil, geology and climate were compared. Modelling showed that soils in the regenerative agriculture field responded more dynamically and had greater infiltration and drainage rates in these, in comparison to the adjacent control field where there was significantly less drainage and more waterlogged soils. The regenerative agriculture field (2.57 ha) stored up to 2,000 m^3 more water than the waterlogged control field (Mulligan and others, 2023).

Aeration: observed evidence

In Penrith, Cumbria, aeration increased hydraulic conductivity by up to a factor of 7.5 in stagnosols. Aeration decreased the occurrence of infiltration excess overland flow, reducing likelihood from 11.4% of all rainfall event periods during the study period pre-aeration, to 0.09% post-aeration, although this was dependent on natural soil variation (Wallace and Chappell, 2019).

A study of 164 fields with 5 soil types and 4 land uses on the West Thames catchment was carried out by Blake and others (2022). They found that if the organic matter content of soils is between 1 and 4%, modest increases in organic matter can significantly increase porosity. 2% organic matter in soils gave an average of 38% near-surface estimated porosity, while 5% organic matter gave a 51% porosity when an average was taken across all fields.

Subsoiling: observed evidence

Lockwood's (2022) study in Somerset based on single-ring infiltration experiments in loamy and clayey soils found increases in soil infiltration under subsoiling at 4 out of 5 sites assessed. 5 sites with different land uses (one grassland, one winter wheat, 3 miscanthus) were surveyed, each with a subsoiled area and a control area.

Design life and effectiveness

Cross cutting 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, 2023b).

Maintenance

A study in Devon (Ash Moor Nature Reserve) concluded that lower intensity management will preserve the benefits of aeration. Following aeration and other soil conservation measures, lower intensity management will preserve improved soil structures. This includes having low cattle stocking density and only using heavy machinery required for land management in seasons when the soil is not saturated and liable to compaction (Ellis, 2021a).

4.1.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for water resources, air quality, climate regulation, amenity, biodiversity, soil or water quality derived from soil aeration and subsoiling specifically.

4.2 Soil and land management: grassland systems

This section sets out what we have learnt since 2017 about the effectiveness of soil and land management – specifically grassland systems – from an FCRM perspective and the scientific confidence in what we know.

4.2.1 Flood risk reduction evidence

Stocking density: observed evidence

A study in Swindale, Cumbria used a hillslope flume to investigate overland flow velocities in 4 headwater grassland habitats: low density grazing, hay meadow, rank grassland and rush pasture. Overland flow visibly occurred for longer when habitat is ungrazed. This may be a consequence of enhanced storage in more highly vegetated ungrazed habitats, through which surface water cannot flow downslope as readily and, therefore, the time for which overland flow lasts is longer (Bond and others, 2020).

Stocking density: modelled evidence

Cross cutting In a modelled (SD-TOPMODEL) study in Bishopdale, Yorkshire (38 km^2), an area characterised by heavily gripped peat moorland and extensively grazed pastoral farmland reduced grazing intensity, improved soil structure and soil infiltration on a floodplain. The effectiveness of reduced grazing intensities (changing land use to riparian buffer strips and woodland planting) had a greater impact during a 100-year storm event. The peak flow was reduced by 8% during the 100-year event and 7% during the 10-year storm event. The model was calibrated against a synthetic storm based on catchment descriptors due to the absence of discharge and rainfall data in the catchment. This limitation meant that the uncertainty in the flow values could be up to 55% in some catchments. However, as this study aimed to understand the impact of land management against a baseline, the relative changes had a greater significance than observed values (Kingsbury-Smith and others, 2023).

A study in Coverdale suggested that grazing on Higher Level Stewardship (HLS) land results in more than twice the relative change to the baseline ungrazed condition scenario (considered to be a 'normal' land management scenario with a uniform Eriophorum surface cover and no soil compaction in this case) compared to grazing on Entry Level Stewardship (ELS) land. The modelled scenario with both ELS and HLS areas grazed has a large impact on river flow peaks with, for example, even just for the light grazing scenario, a predicted 18-minute earlier flow peak and a 32.9% increase in peak discharge for the 15 mm storm event. Heavy grazing scenarios had much greater influence on flow peaks than light grazing; for the same 15 mm storm with grazing across the ELS and HLS areas the peak was 42 minutes earlier and 82.2 % higher than baseline (Gao and others, 2017). There was a lack of river flow data in this catchment, so the parameters of the model were optimised using data from a nearby similar catchment. The simulation corresponded well to the observed flows used as calibration periods.

In a modelled (SD-TOPMODEL) study in Calderdale, a variety of NFM measures have been assessed. 3 sub-catchments were studied: Hebden Water (60 km^2), Jumble Hole (5 km^2) and Calder (19 km^2). The impact of intensive livestock grazing in selected fields is negative with increased peaks, volumes and a reduction in the typical time to peak for an event. The impact of livestock access to riparian zones on peak flows is poor, with an increase of around 0.5% of peak levels in all catchments studied. For Jumble Hole, this can be as high as 3% for the 3-hour 1 in 10-year event, where a greater percentage of the watercourse is accessible from the grazed areas. This model was calibrated against observed data, and the results were consistent with these (Willis and Klaar, 2021).

A study was completed in the Bishopdale (38 km^2) catchment with deep loam soils, and a vulnerability to slight seasonal waterlogging due to low permeability subsoils. Improved soil infiltration through converting improved grassland (26.3% of catchment) to a lower grazing density provided the greatest reduction of NFM scenarios measured in the intensity and delayed timing of the flood peak for a 1 in 10-year occurrence storm event (7% reduction in peak run-off and 8% increase in lag time), with similar reductions observed for a 100-year storm event (Kingsbury-Smith and others, 2023).

Vegetation cover: process understanding

Bond and others' (2021) one year study in Swindale, a 2.7 km^2 valley in the Lake District found that, on a hillslope scale, surface roughness plays a significant role in flood mitigation within shallow, high hydraulic conductivity (K), organic matter (OM)-rich soil grassland systems. Overland flow occurred up to 60% of the time, with longer durations in grassland excluded from grazing with higher density vegetation. The prevalence of overland flow and the strong hydrological differences between ungrazed and bracken habitats suggests that, at a hillslope scale, the largest influence on flood mitigation in these shallow, high Ks, OM-soil grassland systems is surface roughness. In areas characterised by significant overland flow in Cumbria, particularly in catchments with shallow soil profiles, it was observed that surface roughness played a more crucial role in flood reduction than soil permeability.

In rainfall simulations by Ellis (2021b) in Devon, moor grass-dominated fields showed more sinuous movement of water through dense vegetation tussocks, while improved grassland fields showed linear, slope-following water movement. The vegetation disrupts surface flow pathways and stores more surface water despite ground saturation. Bond and others (2020) found that surface roughness is strongly controlled by annual cycles of vegetation growth and decay at a plot scale.

A study was carried out in the Swindale catchment in the Lake District with upland organo-mineral soils, with samples taken every month for an 8-month period. Flows varied in rushes between 0.004 m/s in November, and 0.034 m/s in June. Velocities increased significantly following cutting in hay meadows, from 0.006 m/s in July to 0.054 m/s in September (Bond and others, 2020).

A study looked at the effects of the below vegetation management measures on the upland catchment of Coverdale (84 km^2) in the Yorkshire Dales National Park. It modelled the impacts of different vegetation management measures under 2 different rainfall scenarios: 15 mm/hr and 30 mm/hr. Livestock compacted soil and reduced soil water capacity, leading to enhanced and earlier occurrence of saturated excess overland flow on hillslopes. Hydraulic conductivity and infiltration rate in grazing areas is lower across hillslope than where grazing has been restricted (Gao and others, 2017).

Research into the volumetric wetness of semi-natural grassland compared to permanent pasture with slowly draining, till-derived stagnosols in the Lowther catchment northwest of Shap in Cumbria revealed that plot scale work is not representative at the landscape scale. It recommended that a body of further research is required before results can be applied to regional-scale models (Wallace and Chappell, 2020).

Applying mean overland flow velocities, obtained through a hillslope flume model, to a theoretical 100 m long hillslope suggests overland flow is delayed by >1 hour on rank grassland when compared to hay meadows in an 18 mm/hr storm event (Bond and others, 2020).

A series of papers (Aghajani and others, 2023d; Aghajani and others, 2023b; Aghajani and others, 2023c; Aghajani and others, 2023a) investigated the effect of nature-based solutions (NBS) on water resources in a chalk catchment in Norwich to understand where NBS might be implemented, using MODFLOW. In the Cam and Wensum catchments (928 km^2, no catchment size given for Wensum), land uses with lower evapotranspiration rates showed modelled higher baseflow and higher total river flow.

Vegetation cover: observed understanding

In Devon, with land management that prioritises limiting soil degradation, unimproved grassland was shown to reduce the run-off coefficient (a dimensionless coefficient relating the amount of run-off to the amount of precipitation received) and increase the storage of water within microtopographic depressions due to more diverse vegetation. Water storage was around 3 times higher in a 30% unimproved grassland scenario compared to a 10% unimproved grassland scenario (Ellis, 2021b).

Razmand and others (2019) modelled the effects of 100% conversion of agriculture to native vegetation in the Clear Creek Watershed (270 km^2), Iowa using a GHOST model. Results show that the adoption of native vegetation significantly reduced peak discharges across the catchment, for all the 15 years studied, and under both historic and increased precipitation conditions. Peak flow reduction decreased downstream.

Vegetation cover: modelled evidence

Peskett (2020) found that, at the catchment scale, soil type and superficial geology were found to be more dominant controls on catchment storage over seasonal timescales, with vegetation cover playing a secondary role.

A series of papers (Aghajani and others, 2023d; Aghajani and others, 2023b; Aghajani and others, 2023c; Aghajani and others, 2023a) investigated the effect of nature-based solutions (NBS) on water resources in a chalk catchment in Norwich to understand where NBS might be implemented, using MODFLOW. The approach used established Food and Agriculture Organisation (FAO) methods.

In the Bure catchment (no catchment size given), changing arable land to pasture resulted in increased modelled evapotranspiration and a decrease in groundwater recharge. Change from arable to horticulture resulted in a decrease in evapotranspiration and a corresponding increase in groundwater flow. Changing arable to riparian pasture (near watercourses) resulted in a large modelled increase in evapotranspiration, lowering baseflows.

In the Cam catchment (928 km^2), modelled results showed that changing 100% of arable land to pasture and changing just arable areas on chalk outcrop to grassland appear to have similar impacts, with a minor increase in run-off (1%) and decrease in recharge to the water table (-3%).

In the Test catchment (862 km^2), modelled arable reversion to pasture resulted in increased evapotranspiration, decreased groundwater recharge, and decreased baseflow. This became more pronounced as the proportion of land converted increased.

A study by Ellis and others (2020) in Devon used digital photogrammetry applied to the overlapping aerial images to produce a digital surface model (DSM) from which flow pathways were modelled using GIS. 2 field sites were studied, one (1.3 ha) with purple moor-grass (Molinia caerulea) dominated unimproved grassland field (MCUG) which has never been tilled, and one (2.7 ha) with perennial ryegrass (Lolium perenne) dominated improved grassland (LPIG) with a history of high stock density grazing. The MCUG field had longer, winding surface flow pathways through the dense tussocky network with a drainage density of 2.54 m/m^2. This was significantly greater than drainage density in the LPIG (1.82 m/m^2). This study showed the importance of not treating grasslands as a homogenous unit in modelling, and that roughness coefficients should be adjusted accordingly.

Lower hydraulic conductivity may also decrease subsurface flow volume and increase the possibility of saturated-excess overland flow generation. Reduction of infiltration capacities may induce infiltration-excess overland flow. However, on an improved pasture hillslope of a headwater peat catchment, infiltration excess overland flow would not be widespread across the hillslope and occur only where soils are ‘severely’ compacted. Heavy grazing may induce vegetation loss, reducing surface roughness, accelerating overland flow and may set off early and sharp flow peaks in watercourses (Gao and others, 2017).

Culm grassland is a type of unimproved purple moor-grass and rush pasture, with significantly deeper soils, lower bulk density and higher organic matter (OM) content when compared with intensively managed grassland soils. Ellis (2021b) found that culm grassland could reduce flood peaks by an average of 6% (range of -1.56% to -9.62% in a catchment covered by 30% restored culm grassland). The catchment became less flashy, and baseflow between events increased up to 7.65%. Culm grassland run-off never exceeded 85% of total rainfall input. The study took place in the upper Tamar catchment near Bude and used a rainfall-run-off response model. Suitability mapping was used to assess the best locations for culm grassland restoration, and this was used to model random restoration of various levels of culm grassland coverage.

Bond and others (2022) modelled seasonal changes in vegetation and the impacts on flooding in 2 catchments. Seasonal changes to vegetation increased overland flow peaks by up to +2.2% in winter (6 hour, 1 in 50-year event) and reduced them by -5.5% in summer (6 hour, 1 in 10-year event) compared to the annual average. Percentage changes in flood peak due to hillslope grassland management scenarios were more substantial; overland flow peaks were reduced by up to 41% in Calderdale (21 km^2 catchment, 1 in 10-year event), where 80% woodland development was the most effective mitigation strategy, and up to 35% in Swindale (15.3 km^2, 1 in 50-year event), where a conversion from grazed grassland to a rank grassland-dominated catchment was the most effective. However, 80% forest cover is unlikely to be practical in many catchments, so ground-level roughness should also be considered. The main conclusion of the study was that surface seasonal vegetation change should be incorporated into flood modelling, as cycles of surface roughness in grasslands modify overland flow, potentially having a large impact on downstream flood peak and timing.

A study on the Sava River in Slovenia using the MIKE FLOOD model investigated the influence of changing land use on different flood waves. The floodplain analysed was mostly meadows and agricultural fields, with some settlements, orchards and forest. If the whole floodplain of the 13 km reach of the river was devoted to agricultural land use, this would result in a 13.7% decrease in peak attenuation and a 7.1% decrease in propagation time. In a 100% forest scenario, peak attenuation increased by 63% and propagation time increased by 10.7%. The model was calibrated and validated on the basis of field measurements and results from a physical model (Rak and Steinman, 2019).

Effect on sedimentation and geomorphology: observed evidence

A study in the Oroua and Pohangina catchments in New Zealand spanning a decade showed that land sliding and, therefore, sediment supply is disproportionately high in locations where livestock grazing occurs on steep hillslopes (Abbott and others, 2018).

Following an extreme storm in New Zealand in 2004, suspended sediment loads were elevated for around 4 years following a landslide. Vegetation re-establishment may then make sediment less erodible (Abbott and others, 2018).

Design life and effectiveness

Ellis' (2021a) study on culm grassland (comparing unimproved grassland with improved grassland, more details above) found that introducing a diverse mix of vegetation, which builds a rough surface, will help to restore unimproved grassland.

Maintenance

Ellis' (2021a) study on culm grassland in Devon suggests that practices that prevent single species dominance and minimise overgrazing risk will promote biodiversity and surface roughness (Ellis, 2021a).

4.2.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for air quality, soil or water quality derived from grassland systems specifically.

Water resources

Ellis' (2021a) study on culm grassland in Devon showed that the stabilised water table created by improving culm grassland will be beneficial in the summer. There was, on average, an increase in baseflow of up to 7.65% from the current land use at 10, 20 and 30% unimproved grassland coverage. The increase in baseflow in the summer months was due to unimproved grassland storage, and slower release of water will contribute to drought resilience in the future.

Climate regulation

A study of grasslands in Bavaria, Germany, monitored over 27 years, reported the importance of organic matter being returned to grasslands via manure to maintain or increase soil organic carbon (Kühnel and others, 2019).

A study of agricultural estates in England found that, in spite of implementing conservation management grazing on rough permanent grasslands, these parts of the estates showed the greatest declines in soil organic carbon. This was attributed potentially to the historic management process (for example, drainage) and, therefore, highlighted the length of time required to restore soil functional process (Warner and others, 2020).

Vegetation cover species are an important consideration for multiple benefits. In a study on culm grassland in Devon, M. caerulea stored 3.8 times more soil organic carbon (SOC) (g cm^3) than L. perenne in the O horizon and 38% more SOC across a whole 0.15 m long soil core, reflecting the value of the vegetation cover as a potentially valuable store of SOC (Ellis, 2021a).

Biodiversity

In Littlestock Stream (2.2 km^2 area within the Evenlode catchment), Oxfordshire, biodiversity net gain (BNG) units generated from NFM were measured. Arable reversion from existing cropland or modified grassland to more natural grassland on 9.96 ha of land has resulted in an additional 104 biodiversity net gain units being generated (Miles and others, 2021).

4.3 Soil and land management: arable systems

4.3.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of soil and land management – specifically arable systems – from an FCRM perspective and the scientific confidence in what we know.

Effects on flood flows, peaks, and storage: process learning

In a laboratory setting using loamy soils, plants with deeper and more vertically oriented roots tend to exhibit a greater enhancement in soil infiltration (Zhang and others, 2019).

Conservation tillage: modelled evidence

Razmand and others (2019) modelled the effects of the adoption of no-till farming and cover crops in the Clear Creek Watershed (270 km^2), Iowa using a GHOST model. Cover crops/no-till practices reduce peak discharges for all the years, and for the largest floods (exceedance probability < 20%) simulation results also show reduced peak discharges. The model was calibrated and validated using a 15-year continuous simulation with hourly climatological data. Simulated hydrographs were compared against measurements taken at 2 USGS flow gauging stations.

Early sowing winter crops and cover crops: observed evidence

In comparison to arable soils, grass-clover leys in Yorkshire demonstrated several beneficial effects at a study site near Leeds with loamy, calcareous brown earth. These included an increase in earthworm populations, greater macropore flow, improved saturated hydraulic conductivity and a reduction in bulk density. Infiltration rates in arable soils were around 260 mm h^{-1}, 75 mm h^{-1} in leys and 740 mm h^{-1} in grass-clover leys. Grass-clover leys contribute to the rejuvenation of earthworm communities and the reversal of structural deterioration in intensively cultivated arable soil. This facilitates the adoption of no-tillage farming practices, breaking the cycle of soil degradation driven by repeated ploughing (Berdeni and others, 2021).

Effect on different watercourse typologies

Collins and others (2023) used a process-based soil–water vegetation model coupled with a semi-distributed groundwater model to explore the impact of converting land with conventional agriculture to regenerative agriculture (for example, crop-herbal ley pasture rotation) on peak and low flows. The model was calibrated by fitting simulated run-off to observed run-off at gauging stations. The catchment studied was a large (1,616 km^2) groundwater-dominated catchment of the River Thames. For a 1 to 2-year return period event, the regenerative agriculture scenario showed a 1.7%, 2.9% and 4.1% reduction in median peak flow for 25%, 50% and 75% conversion respectively. Percentage reductions in median peak flow for return periods between 3 and 15 years are all below 1% however. Therefore, it is important that although regenerative agriculture has significant environmental benefits, its effect on flooding in groundwater-dominated catchments should not be overstated.

Effect on sedimentation and geomorphology: modelled evidence

In laboratory hydraulic flume experiments, plant roots were more effective at reducing erosion from concentrated flow in sandy soils compared to bare soils without roots. The effectiveness depended on root system type: fine roots worked best in non-cohesive soils, while tap roots were more effective in cohesive soils. Higher soil bulk density appeared to reduce root effectiveness when fibrous roots were present. In soils with tap root systems, the roots' erosion-reducing power was influenced by sand content: more sand meant a smaller erosion reduction effect for the same number of roots, mainly due to increased vortex erosion around thick tap roots in non-cohesive soils. Additionally, the results confirmed that fibrous roots outperformed thick tap roots in erosion reduction (Vannoppen and others, 2017).

The 11.2 km^2 Castledockrell catchment observatory in Ireland was used to model the influence of land management on soil erosion, connectivity and sediment delivery in agricultural catchments. The catchment is low relief with predominantly well-drained soils, dominated by spring-sown cereal cropping through the study period. Caesium-137 activity concentrations and gross soil erosion rates were measured. Modelled net soil erosion from permanent pasture fields, 4.4 Mg ha^{-1} yr^{-1} (on predominantly low permeability soils), was greater than from cultivated fields, 1.5 Mg ha^{-1} yr^{-1} (on predominantly high permeability soils), due to the greater likelihood of overland flow initiation. In this study, historical field-scale erosion rates were likely to have been influenced by winter-sown sugar beet crops and harvest erosion. This now appears reduced by spring-grown cereal crops which are harvested without removal of the root system and associated soil. Permanent pastureland management on low permeability soils is a consistent high risk for soil erosion despite the limited extent in the catchment (Sherriff and others, 2019).

Conservation tillage: observed evidence

Kitch and others (2019) carried out a study in the Merriott Stream catchment (13.5 km^2) in rural Somerset. The dominant soil is a fine sandy loam topsoil and land cover is mainly cultivated using a combination of ploughing and minimum tillage. The dominant contributor to suspended sediment captured in transit was cultivated land (60 to 90%), linked to enhanced overland flow and increased erodibility of cultivated soils. The dominant contributor to channel bed sediment in the lower catchment was channel bank erosion (50 to 75%), linked to recent incision of the stream network driven by the increased magnitude and frequency of run-off events which is causing localised erosion and bank failure. These processes of incision and bank failure were worsened by winter die-back of Himalayan balsam. This exposed the bank surface to direct fluvial scour under winter high flows, preventing establishment of a perennial root structure from native plants that plays an important role in bank stability.

Early sowing winter crops and cover cropping: observed evidence

At Lower Hope Farms in Herefordshire (0.153 km^2), conservation agriculture and cover cropping (nitrogen-fixing vetch and rye grass) were used to reduce the risk of soil erosion in the winter of 2018/19. Structure from motion (SfM) photogrammetry was used to make digital elevation models (DEM) of the site. Following the interventions, a raising of the surface was evident on the DEM, caused by crop growth. Despite heavy rainfall in the summer following the survey, there was no impact on this site and no erosion was visible as a result (Robertson and Maddock, 2019).

Crop rotation: observed evidence

A study in the South Downs National Park analysed 400 sites. 79% of sites that underwent land use change resulted in a reduction in erosion risk, most notably at 28 sites with a shift to permanent grass from winter cereals. This has also reduced the risk of muddy floods (Boardman and others, 2017).

4.3.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for water resources, air quality, or amenity derived from arable systems specifically.

Climate regulation

Introducing ley crops along with adding livestock manure to arable fields can result in a net gain of soil organic carbon resulting from the reduction in tillage and quantity and quality of the soil organic matter (Paustian and others, 2019).

A global meta-analysis reported that the use of cover crops increased soil carbon stocks by 12% compared to a no cover crop control (McClelland and others, 2021).

Biodiversity

In the Evenlode catchment (2.2 km^2 area within the Evenlode catchment), Oxfordshire, BNG units generated from NFM were measured. Changing existing arable practices to no-till farming and cover cropping on 7.6 ha of land is predicted to generate 41 more biodiversity units (Miles and others, 2021).

Soil

In a laboratory study using clayey loamy soils from Yorkshire, grass leys, when compared to arable soils, increased earthworm numbers, infiltration rates, macropore flow and saturated hydraulic conductivity, and reduced bulk density, improving wheat yields by 42 to 95 % under flood and normal conditions. They reverse structural degradation of intensively cultivated arable soil, facilitating adoption of no-tillage practices (Berdeni and others, 2021).

Water quality

In a study by Boardman and others (2017) in the South Downs National Park, measures designed to prevent sediment erosion that causes muddy floods will also improve water quality, reducing the costs associated with making water fit for drinking.

4.4 Run-off pathway management: swales, scrapes and sediment traps

4.4.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of run-off pathway management (including swales, scrapes and sediment traps) from an FCRM perspective and the scientific confidence in what we know.

Effect on flood flows, peaks and storage: observed evidence

NFM interventions on the Weybourne/Spring Beck (3.5 km²) in north Norfolk included the creation of 3 scrapes and a swale along with the planting of 400 trees, creation of 11 leaky barriers and 3 large woody debris screens. The scrapes alone stored 2,400 m³ of water. The suite of measures created led to a reduction in peak discharge of 7% for a 50% AEP event (George and Todd, no date).

4.4.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for water resources, air quality, climate regulation, amenity, soil or water quality derived from run-off pathway management – swales, scrapes and sediment traps – specifically.

Biodiversity

A swale constructed in Corvedale (150 km^2) as part of the 'Shropshire Slow the Flow' project has provided a good habitat, with barn owls, buzzards, goldfinch and yellow hammer recorded feeding nearby (Adams, no date).

4.5 Run-off pathway management: ponds, run-off attenuation features (RAFs) and bunds

4.5.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of ponds, run-off attenuation features (RAFs) and bunds from an FCRM perspective and the scientific confidence in what we know.

Effect on flood flows, peaks and storage: observed evidence

Kingsnoad Pond is located in the Beult catchment (8.7 km²) part of the wider Medway catchment. Water level in the pond rises during the rising limb in the School Stream, peaking at or just after peak water level in the School Stream. The pond is, therefore, providing effective flood storage and attenuating the flood peak. A pipe drains Kingsnoad Pond to a set level in under 24 hours, thereby storing water during high flows, while ensuring that there is available capacity should 2 rainfall events occur in close succession. The pond created 2,400 m³ of storage and was designed to last 30 years (Cook and Byers, 2021).

The implementation of 5 water storage areas within the Glenderamackin catchment effectively decreased peak flows during small to medium-sized events within their respective sub-catchments (Row End – 0.15 km², Fieldside – 0.64 km², Storms Farm – 0.04 km², Askew Rigg – 0.42 km² and Lofshaw – 0.99 km²), attenuating 1.1% of the highest discharge of the River Glenderamackin at Threlkeld observed during the monitoring period (71 m^3/sec). Overall, the findings indicate that these ponds continued to fill and consequently reduced downstream stream flow at the peak of the events. However, the rate of filling progressively decreased during the events, especially in cases of multi-peaked events (Pearson, 2023a).

Small ponds have inherent limitations when it comes to mitigating floods due to their modest storage capacity, which restricts their ability to capture and attenuate high flood events effectively. During one-year storm events, around 70% of farm ponds surveyed in Fairfax County, Virginia USA managed to achieve a peak reduction exceeding 78%, and for 2-year storm events, this figure reached 55%. However, for more severe 10-year storm events, the peak flow reduction provided by 70% of these ponds remained limited, at approximately 7% (Ibrahim and Amir-Faryar, 2018).

Monitoring of NFM measures in the Belford Burn catchment (5.7 km²) in northern England demonstrated that offline storage areas and RAFs are most effective at reducing local flood peaks for small flashy events (1 in 2-year events); whereas during observed longer duration events (1 in 12.5 year) the available storage is depleted before the arrival of the main flood peak (Nicholson and others, 2020).

A water storage area at Fieldside Farm on the floodplain of the River Naddle, Cumbria functions as designed and stores up to 6,500 m³ of water during high flow events. However, due to a small outflow pipe, the water storage area was overtopping in a 1 in 2-year flood event (West Cumbria Rivers Trust, 2021c).

Photographs taken in Bootle village, Cumbria at the peak of high flow events show that properties were not at risk of flooding. High intensity rainfall is also shown through rapid filling of the created water storage area in a timelapse video (West Cumbria Rivers Trust, 2021c).

Effect on flood flows, peaks and storage: modelled evidence

In the Salmons Brook catchment near Enfield (catchment context not provided), 46 offline ponds have been installed, providing a storage capacity of 46,000 m³. Permeable bunds, in contrast to leaky dams, offer advantages due to their larger storage capacity and controlled water release. Simulations suggest that if these 46 permeable bunds were in place during an October 2000 event, they could have reduced peak flow by up to 35% at Hadley Road Bridge. Downstream in the urban catchment at Clarendon Arch, the impact lessens to 5% due to inflows from other tributaries and urban run-off diluting the effects. Peak water level difference mapping highlights distinct storage and attenuation locations, including the bunds in the rural catchment and downstream in urban Bush Hill. This reduction resulted in a 10 cm lower peak flooded level within the Environment Agency flood zones, demonstrating the positive impact of permeable bunds in contrast to leaky dams on flood risk reduction in the catchment (Gilbert, 2021d).

Run-off attenuation features (RAFs): process understanding

A small watercourse in Waberthwaite, Cumbria (no catchment details provided) flowing through the centre of the farm holding overtops in flood events and the water runs down the track into farm buildings. A bund was designed to hold water within the field to benefit the landowner, with the leaky dam causing more water to spill out of the channel and into the bunded area, thereby reducing downstream flood risk (Pearson, 2023b).

Run-off attenuation features (RAFs): observed evidence

A study monitoring the performance of a bund in Dovenby Beck, a small agricultural catchment (2.5 km²) in West Cumbria demonstrated that a water storage area filled and drained in high magnitude events (above one in one year) as designed, and that it likely reduces flood risk downstream by taking a significant volume of water (1,143 m³ to the bund crest) off the peak discharge (West Cumbria Rivers Trust, 2023).

Monitoring data from interventions in Littlestock Brook, West Oxfordshire, Littlestock Brook catchment (16 km²) demonstrated successful peak discharge reduction of (14.2 to 55.2%) during storm events, with over 40% storage capacity retained. The largest reductions occurred in intense rainfall events, notably a 55.2% reduction during the 23 December 2020 event. This event followed wet conditions, and the storage also reduced a subsequent peak by 19.1%. Drainage after the first peak, however, reduced the effect on the second peak. The event exhibited the highest sensitivity to travel time, indicating that slower travel times and drainage enhance peak attenuation. This event also showcased the effectiveness of flood storage areas (FSA) interventions amid wet conditions. Slower travel time from FSAs to the outlet further reduced flood peaks, but results varied due to event variability in conditions, intensity and duration (Robotham and others, 2022).

Comparison of 2 ditches that feed into the Furze Brook in Devon (no details on catchment context provided) revealed that the concentrated presence of leaky dams and an attenuation pond on the right ditch versus the comparative absence of interventions on the left ditch meant that a left versus right ditch pseudo-control comparison could be made. Analysis of the right ditch on the Furze Brook revealed that the estimated effect of the NFM interventions was statistically significant for peak rainfall events, results from the right ditch indicated a reduction in peak stage from 0.095 m to 0.075 m (21%) (Puttock, Brown, and others, 2021).

A study investigated the implementation of 2 protective bunds on Corney Fell in West Cumbria. These bunds were designed to function in 1 in 30 and 1 in 50-year events and were analysed in response to 2 significant rainfall events with return periods of 45 and 83 years, which had the potential to endanger nearby properties with flooding. Findings also revealed that during intense rainfall, water infiltrated the depressions both from surface run-off and field drains. Notably, the field drains had been obstructed within the designated water storage areas. When the amount of water entering these depressions surpassed the capacity of the drainage pipes within the bunds, the water storage areas filled to capacity. To mitigate this in future, larger 300 mm pipes situated near the upper part of each bund were installed to facilitate flow once the feature neared its full capacity. Additionally, a lowered reinforced overspill channel was constructed along the sides of the bunds to guide the overflow when the water storage areas reached maximum capacity. The study underscored that the effectiveness of the bunds was more pronounced during shorter-duration or less intense rainfall events (West Cumbria Rivers Trust, 2021d).

A large bund was constructed at the lower end of a field near Flimby, Cumbria to capture and temporarily hold surface run-off during storms, preventing flooding of farm buildings and properties. Flimby is a small catchment (4.5 km²). An existing drain connects to Cat Gill, serving as an outlet for the stored water. An adjustable manhole cover was added to control water storage, and kested hedgerows (hedgerows on small embankments) were restored to further slow and retain run-off. The bund effectively reduces flood risk by temporarily storing surface water when the culvert drain is overwhelmed during heavy rainfall. It has the capacity to store over 200 m³ of water, and better utilisation could alleviate flooding in the village by reducing water discharge through connected culverts. Continued management and monitoring are recommended to avoid excessive water storage which might hinder grazing and to assess the response to more significant flood events (Chadwick, 2021).

The effectiveness of bunds installed on Corney Fell, West Cumbria was assessed under 2 storm conditions. On 21 May 2021, 89 mm of rain fell at Corney Fell within 24 hours. This event had a return period of 45 years (FEH, 2013 rainfall modelling). On 27 to 28 October 2021, 82 mm of rain fell within 24 hours and 114.6 mm in 48 hours. This event had a return period of 83 years. The results from these events suggest that for storm events of this magnitude and duration, the bunds effectively reduced downstream discharge by 0.1 m³/sec over the early stages of the events (approximately the first 10 hours). The long duration of these events meant the bunds were overwhelmed by the later stages of the storms. The bunds assessed were considered to be more effective in shorter duration or lower magnitude events (West Cumbria Rivers Trust, 2021d).

A case study of 2 bunds installed on Corney Fell found that for bund 1 there were a series of rainfall events causing the feature to store water 5 times over a period of 7 days. Between each period of heavy rainfall, the water storage feature drained down to base level. For the 3 events between 12 and 15 December 2021, the water storage area took between 5 hours 45 minutes and 7 hours 15 minutes to reach peak depth from base level and between 4 and 8 hours to drain back to base level. The timing of the peak depth within the feature corresponded to the peak depth of water in the stream at the downstream road bridge. For bund 2 during December 2021, the feature filled on 3 occasions. Unlike dam 1, it did not drain down between periods of heavy rainfall on 13 and 18 December 2021, but remained full for the duration of these rainfall events. The water storage area took 35 hours and 52 hours to drain down after reaching the level of the overflow pipe. The timing of the peak depth within the feature corresponded to the peak depth of water in the stream at the downstream road bridge (West Cumbria Rivers Trust, 2021d).

Water storage in the studied bund in Dovenby, Cumbria (Dovenby Beck catchment, 2.5 km²) responded to rainfall intensity, filling most rapidly during the highest intensity rainfall and draining when rainfall eased. The bund drained rapidly after intense rainfall, ensuring storage was available for successive periods of high intensity rainfall (West Cumbria Rivers Trust, 2023).

Analysing 2 rainfall events in the Flimby catchment (4.5 km²), Cumbria in detail showed that the water levels in the bund respond rapidly to rainfall; the catchment has a very flashy response to rainfall and a large proportion of rainfall becomes surface run-off. The magnitude of the response will depend on the antecedent conditions, saturation of the ground and both rainfall intensity and duration. The bund has the capacity to store 230 m^3 water before overspill. There was no property flooding during the analysis period, but the risk of flooding was high at one point and villagers were forced to use sandbags for protection. There was moderate rainfall, followed by intense rainfall after (peak intensity 3.4 mm in 5 minutes). The return period using ReFH2 was estimated as 1 in 2.4 years. Other factors influencing flood risk include canopy protection and tides coinciding with peak flow. The maximum storage achieved during all events analysed was around 5 m^3. As overwhelming of the culvert is a main mechanism for filling of the bund and flooding in the village, the intensity of rainfall is more relevant to flood risk than the overall volume of rain (Chadwick, 2021c).

A case study of 2 bunds on Corney Fell found that the bunds were taking ~3 to 4 % off the stream flow of the whole 1 km^2 catchment above a road bridge during the first flood peak. But that by the second peak, this had reduced to ~1 to 2 % and by the third peak both water storage areas were overtopping and not capturing any further water (West Cumbria Rivers Trust, 2021d).

In the Potwell Dyke catchment, Southwell, UK bunds in 2 neighbouring sub-catchments with clay loam, slowly permeable soils were modelled based on simulated real events (Wells, 2019). This showed that:

- in the Springfield Dumble sub-catchment (0.65 km^2), 4 bunds were constructed with around 600 to 900 m^3 capacity each, the cumulative storage behind these bunds reduced peak flow by 32.5 to 38.2 %
- in the Parklane Dumble sub-catchment (0.41 km^2), a bund with 322 m^3 capacity became active in storing water, but the impacts on peak flow were more limited, reducing peak discharge by 0.5% possibly because the bund was being bypassed by overland flow or could be due to spatial variance in rainfall between both sub-catchments
- each bund functions differently during rainfall events, so it is important that locations are selected appropriately based on flow paths to make sure that they are located where they can effectively store overland flow

Run-off attenuation features (RAFs): modelled evidence

Modelling of the Kent catchment (71 km^2) in Cumbria, UK show that RAFs designed with an intermediate residence time of around 10 hours would be more effective for a series of flood events such as those in the period November through December 2015. The percentage reduction in peak flows are similar to the 2 to 5% peak run-off reduction predicted by a JFlow model (for a 30-year event) for the upper Kent for most of the period of modelling, apart from Storm Desmond which shows less reduction, potentially because RAFs have not emptied. It also revealed that there is an ‘optimum’, intermediate retention for RAFs of about 10 hours where storage is more limited, but that longer drain-down times may be acceptable when opportunities are more widespread (Hankin and others, 2016).

Results from modelling the effectiveness of NFM measures on the Littlestock Brook (16 km^2), a tributary of the River Evenlode in Oxfordshire, also indicate that water accumulates in storage areas during the rising phase of a flood, but doesn't efficiently reduce peak floods, potentially hindering flood management. Woody dams and scrapes exacerbate this by diverting water prematurely. Solutions may include engineered structures like offtake systems, albeit deviating from natural flood management principles. Optimising NFM hinges on addressing flood hydrograph synchronisation. For instance, with 2 tributaries, holding back water in one while allowing the other to flow freely reduces downstream flooding, benefitting from staggered peak flow hydrographs. Synchronicity analysis employs simpler rainfall-run-off and flow routing models to track flood hydrograph movement within a catchment. This approach helps improve NFM effectiveness without deviating from its principles (HR Wallingford, 2020).

Razmand and others (2019) modelled the effects of a distributed storage system built with ponds located in the headwater catchments in the Clear Creek Watershed (270 km^2), Iowa using a GHOST model. The 65 ponds result in average peak flow reductions at all index points, under historic precipitation conditions, that range between 10% and 23%.

In the Braid Burn catchment (22.8 km^2) in Scotland, (Birkinshaw and Krivtsov, no date) used a Shetran model to show the effect of ponds in 8 measured and 2 designed events (1 in 100-year 1hour, and 1 in 100-year 6hour). For the 1 in 100-year 1hour event, the Blackford Pond reduced peak discharge by 0.51% and the Upper Ponds by 0.77%, while the Lower and Oxgangs Ponds increased the discharge by 0.26%. For the 10 measured events, the Upper Pond reduced peak flow in 7 out of 10 events, with an average reduction in peak flow of 0.34%, the Oxgangs Pond downstream reduced peak flow in 6 out of 10 events (average reduction 0.06%) and the Lower Pond increased the discharge in 9 of 10 events (average 0.16% increase). These results show that when considering flood risk, the location of a retention pond within a river catchment is important, and it can make the flooding worse at the outlet if it is located in the wrong place. This work suggests the pond should be located in the upper part of the catchment, although the ideal location will depend on the catchment’s shape and lag time.

A study modelled the impact of installing 1,549 storage bunds over the River Kent catchment (209 km^2) in Cumbria. Despite the large number of bunds (with a median individual storage volume of 240 m^3) in the simulation, it was shown that the effect of the distributed storage on 3 major hydrograph peaks in the November to December 2015 period (with return periods of 1 in 500, 5 and 2 years) at the catchment outlet was small, and much less than the uncertainty in those simulations surviving the limits of acceptability criteria. It was found to be more feasible to use bunds amounting to 10,000 m^3 to protect small areas of communities where the flooding source is as small as 1 km^2. This could be completed on one farmer's land but would need to simulate a gauged catchment to show where the overland flow naturally accumulates, and identify the contributory areas that flood clusters of homes and businesses in order to select the correct site (Beven and others, 2022).

Effect at different catchment scales

Modelling of the Eden catchment (223 km^2), Cumbria over a 30-year return period revealed that it may be 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 or sets of features (Metcalfe and others, 2018).

In the Glenderamackin catchment (no catchment size provided), water storage features were implemented. Although the features are insufficient to create a significant effect at the catchment scale, they do show some favourable pond-functioning characteristics and appear effective on the small streams on which they are installed for the events analysed (Pearson, 2023a).

As mentioned above, a study by (Beven and others, 2022) modelled the impact of installing 1,549 storage bunds over the River Kent catchment (209 km^2) in Cumbria. It found that, despite the large number of bunds (with a median individual storage volume of 240 m^3) in the simulation, it was shown that the effect of the distributed storage on 3 major hydrograph peaks in the November to December 2015 period (with return periods of 1 in 500, 5 and 2 years) at the catchment outlet was small, and much less than the uncertainty in those simulations surviving the limits of acceptability criteria. It was found to be more feasible to use bunds amounting to 10,000 m^3 to protect small areas of communities where the flooding source is as small as 1 km^2.

Scaling up results from several storms from Wells' (2019) study on the Potwell Dyke (5.7 km^2) Southwell, a lesser impact in peak discharge reduction percentage occurred when scaling up from the smaller sub-catchment scale to the larger catchment scale of the Potwell Dyke (5.7 km^2). A bund on the Springfield Dumble (0.65 km^2) reduced peak flow by 32.5 to 38.2 %, but when calculated for the overall reduction on the full Potwell Dyke catchment was only 1.7 to 1.9 %.

Effect in different watercourse typologies

A series of papers (Aghajani and others, 2023d; Aghajani and others, 2023b; Aghajani and others, 2023c) investigated the effect of NBS on water resources in a chalk catchment in Norwich to understand where NBS might be implemented, using MODFLOW. Surface RAFs (sRAFs) and channel RAFs (cRAFs) here are designed to be similar to infiltration basins, which return the run-off to the ground.

In the Bure catchment (no catchment size given), sRAFs and cRAFs were modelled. The effect of these on groundwater flow was approximately the sum of the individual impacts, so they work in combination. Increased numbers of RAFs showed a linear increase in recharge of 1 to 3% with 25 to 100% possible cRAFs, and 1 to 5% recharge increase with 25 to 100% possible sRAFs.

In the Cam catchment (928 km^2), cRAFs were more effective than sRAFs in storing run-off. Boundary cRAFs alone give a 6% increase in recharge, compared to 7% of all cRAFs, meaning the majority of the effect can be obtained from Boundary cRAFs on their own.

In the Wensum catchment (no catchment size given), modelled RAF scenarios showed a consistent trend of reducing high flows, and then increasing lower flows. sRAFs had a slightly greater impact on groundwater flows than cRAFs.

Effect on sedimentation and geomorphology: process understanding

A study, synthesising evidence from across Western Europe, noted that for mitigation measures the emphasis should shift from individual fields to connected systems. In areas where off-site impacts are of concern, the emphasis should be on how run-off and sediment transfer systems are connected, rather than on rates of erosion alone. This study also argued that field observation and monitoring are crucial in understanding connectivity in arable landscapes (Boardman and others, 2019).

A study of ponds in Littlestock Brook *(*16km²), within the River Evenlode catchment (430 km²), West Oxfordshire revealed that ponds retained dissolved nitrate by 29%, soluble reactive phosphorus (P) by 5% and suspended solids during baseflows. During small to moderate storm events, some ponds were also able to reduce peak concentrations and loads of suspended solids and phosphorus. However, during large magnitude events, resuspension of deposited sediment resulted in net loss. Net losses of sediment and P can occur during higher magnitude storm events, with this risk likely to increase as pond storage capacity reduces. The ponds were seen to be most advantageous for capturing silt and sand-sized material during smaller to medium events, typically experienced during winter. The size and morphology of a water body influences trapping efficiency. Design of online ponds with a ~1:1 width-to-length ratio is less effective at mitigating total phosphorus loading (Robotham and others, 2021).

Effect on sedimentation and geomorphology: observed evidence

Between August 2019 and March 2020, the ponds within the Littlestock Brook sub-catchment (16 km²) that lie within the Evenlode catchment (430 km²) accumulated 0.306 t ha^{-1} sediment from the 30 ha contributing area. During this period, total sediment accumulations in ponds were estimated to equal 7.6% of the suspended flux leaving the 340 ha catchment downstream (Robotham and others, 2021).

Research on flood storage areas (FSAs) and pond features within the Littlestock Brook sub-catchment (16 km²) found that sediments deposited within FSA and pond features were significantly enriched in total phosphorus (TP), with an average concentration 1.5 times greater than the surface soil in contributing areas. It was also observed that, on average, the sediment was composed of 86% silt and clay particles and that enrichment of clay was typically higher in the offline features. The opposite trend was observed for sand content. In terms of organic carbon enrichment, there were no apparent differences between the offline and on-line features (Robotham and others, 2022).

The same study looking at FSAs and pond features in the Littlestock Brook sub-catchment (16 km²) found that FSAs offered multiple benefits, notably trapping sediment during larger storm events when linked to the stream via spillways. They captured approximately 15% of sub-catchment sediment yield within 2 to 3 years of construction, also representing 10% of

TP and 8% of particulate organic carbon yields. Sediment accumulation rates varied between features, but this didn't seem to hinder their primary water storage function, requiring maintenance roughly every decade. The accumulated sediment, mostly fine and nutrient-enriched, holds potential value for agricultural reuse (Robotham and others, 2022).

A study demonstrated that the presence of farm ponds in Fairfax County, Virginia, USA provided significant erosion protection for the downstream receiving channel through reducing the peak flows for the most frequent events (1 and 2 years) (Ibrahim and Amir-Faryar, 2018).

Design life and effectiveness

In the case of 5 pond features in the Glenderamackin catchment, Cumbria (no further details provided), they tended to be overwhelmed by incoming water before reaching the peak flow during larger rainfall events. To address this issue, 2 main strategies were considered. First, increasing the storage capacity per catchment area, which would allow the ponds to continue filling for a longer duration, accommodating more water during significant events. Second, enlarging the outflow pipes. Smaller pipes lead to faster pond filling, capturing mainly rising limb water, and slow drainage, making it difficult to regain capacity for multi-peaked or closely spaced rainfall events. For smaller capacity ponds relative to catchment size, larger outflow pipes are crucial to prevent premature filling before the storm's peak. This approach was demonstrated successfully by the upgrade to 150 mm outflow pipes at Row End and Lofshaw, improving their performance and reducing the risk of overtopping, especially in smaller rainfall events (Pearson, 2023a).

A study looking at FSAs and pond features in the Littlestock Brook sub-catchment (16 km^2) found that most FSAs retained their storage capacity well, with average annual losses during the 2 to 3-year post-construction period ranging from 0.01% to 12.9%. To ensure these features maintain their ability to fill and drain effectively during and after events, it was pointed out as crucial for their outlets to stay above the accumulated sediment level, preventing siltation in drains. When assessing remaining storage capacity up to the drain height, accumulated sediment volumes had a more substantial impact. Potential storage for water and sediment was most reduced in online features, with 3 features predicted to fill beyond their outlet drain heights within 10 years (annual reduction in maximum storage capacity was 12.9%, 10.23% and 4.22%) (Robotham and others, 2022).

Modelling of the Eden headwaters (223 km^2), a large rural catchment in Cumbria showed that the combined impact of many 'leaky' attenuation features of approximately 8 million m^3 of storage on the hillslope could have significantly attenuated the flood peak. For Storm Desmond, with a residence time of one hour, the attenuation features resulted in a likelihood-weighted median reduction in peak flow of 1.7%. When residence time is increased to 10 hours, a likelihood-weighted median reduction in peak flow of 5.7% was realised, and with a 100-hour residence time, a likelihood-weighted median reduction in peak flow of 1.9% was seen. Therefore, demonstrating that their effectiveness was contingent on how their drainage characteristics would allow them to recover capacity between events (Metcalfe and others, 2018).

Simulations underscored the crucial factors for enhancing NFM efficacy in addressing over-bank flows downstream from rivers. First and foremost, it was apparent that individual hillslope storage units must possess significantly larger capacities, approaching or ideally reaching the NFM threshold of 10,000 m^3. This substantial capacity is essential to ensure that these storage units are not easily overwhelmed during flood events, enabling them to effectively store and manage excess water. Furthermore, the simulations indicated that achieving a meaningful impact in NFM necessitates a considerable increase in cumulative flood storage per unit catchment storage. This enhancement would require approaching levels of 10,000 m^3 per km^2 or 2,100,000 m^3 for the 209 km^2 Kent catchment in Cumbria. These adjustments are integral to bolster NFM's capability in mitigating downstream flood occurrences and minimising their impact on affected areas (Beven and others, 2022).

Modelling of the effectiveness of NFM measures on the Littlestock Brook catchment (16 km^2), a tributary of the River Evenlode in Oxfordshire, demonstrated that the percentage of the design volume for flood storage areas that contributes to reducing flood risk ranged from 36% to 51% depending on event size, while the volume filled with stored water ranges from 51% to 94%. Comparing these, the effective volume constitutes approximately 70% of stored volume for a 10-year flood, declining to 54% for a 100-year flood accounting for climate change. In essence, an NFM flood storage area designed for flood reduction might achieve only 50% or less of its intended reduction in flood volume at the targeted site. While this analysis simplifies the dynamic nature of flooding, it serves as a guideline for designing NFM flood storage areas (HR Wallingford, 2020).

The bunds on Corney Fell were designed to effectively manage rainfall events with a return period ranging from 1 in 30 to 1 in 50 years. Monitoring demonstrated that they exhibited a notable capability to capture a substantial portion of the rainwater that initially entered the depression. This capture efficiency was most pronounced at the onset of the events but diminished as the water levels behind the bunds approached the larger outflow pipe. During the initial peak of the monitored events (1 in 45 and 1 in 83 AEP), the bunds successfully diverted approximately 3 to 4% of the total stream flow originating from the entire 1 km^2 catchment area located above the road bridge. However, as the events progressed to the second peak, their effectiveness reduced, capturing only about 1 to 2% of the flow. By the third peak, both water storage areas had reached their capacity, resulting in overtopping, and they were no longer able to retain any additional water (West Cumbria Rivers Trust, 2021d).

An investigation assessed a bund’s performance during higher magnitude events and quantified its downstream impact on flood risk. During the monitored event, the water storage area reached a maximum filling rate of 0.14 m^3/second, which translates to 0.2% of the flow in the River Glenderamackin at Threlkeld. These findings suggest that implementing a network of similar features throughout the Glenderamackin catchment could contribute significantly to reducing flood risk in Keswick. However, it's important to note that the water storage area appears to have limited additional capacity for storing water during events of larger magnitude, beyond what was observed in the monitoring period (AEP < 50%). Additionally, the slow drain-down rate of the feature limits its effectiveness in mitigating flood events, especially if successive rainfall events occur relatively quickly (West Cumbria Rivers Trust, 2021e).

Maintenance

A study looked at 2 contrasting pond sites in the sub-catchments of Halsewater (6.3 km^2) and Merriott (6 km^2) in the River Tone catchment (414 km^2), Somerset. It makes mention of the considerable ongoing maintenance required for optimal pond functioning. No further details provided (Lockwood and others, 2022).

A paper, looking at Littlestock Brook sub-catchment (16 km^2) makes the point that pond maintenance should be considered on a biennial basis and removed sediment should be reapplied to arable land as an organic-rich soil conditioner (Robotham and others, 2021).

4.5.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for air quality, climate regulation, amenity or soil derived from ponds, run-off attenuation features (RAFs) and bunds specifically.

Water resources

Modelling of the Cam, Bure, Test and Wensum catchments (no further catchment details provided) by (Aghajani and others, 2023d; Aghajani and others, 2023b; Aghajani and others, 2023a; Aghajani and others, 2023c) has revealed that where soils generate run-off but are sufficiently permeable to allow some recharge, storing water within surface RAFs increases infiltration, recharge and increases low flows in rivers. Modelling also indicated that as the RAFs were placed at the top of systems in individual flow pathways, the more that were installed across the landscape, the greater the effect they had. It should be noted that surface RAFs showed no effects in very permeable catchments (the Test), as there was limited run-off to capture and infiltrate into the ground.

Biodiversity

In the Evenlode catchment (2.2 km^2) in Oxfordshire, ponds and temporary ponds created 11.06 and 4.11 biodiversity net gain credits respectively. The creation of swales and ponds resulted in high quality habitats, but due to their discrete nature, they did not result in a large number of additional biodiversity net gain units (Miles and others, 2021).

Water quality

Retention ponds have the potential to provide many more co-benefits, including water quality enhancement through settling of water-borne sediment and biological degradation of pollutants. The degree to which these benefits are provided depend on the size of the pond, the geophysical context as well as the at-risk asset distribution downstream (Mulligan and others, 2023).

4.6 Run-off pathway management: agricultural landscape features

4.6.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of agricultural landscape features from an FCRM perspective and the scientific confidence in what we know.

Effect on flood flows, peaks and storage: process understanding

Hedges slow the flow by storing water behind the hedge and increasing infiltration (West Cumbria Rivers Trust, 2021b).

Hedgerows increase interception storage, and buffer infiltration-excess flow risk by enhancing infiltration and percolation of run-off. Hedgerow soils are less compacted at the surface and have lower bulk density at depth. This means they can absorb and store water during storms, reducing downstream flood risk (Holden and others, 2019).

In an observational study near Tadcaster, in well drained, loamy, calcareous brown soils, saturated hydraulic conductivity was notably higher under hedgerows, with a median value of 102 mm hr^{-1}. It took approximately one hour longer for the soil under hedgerows to reach its maximum moisture content after rainfall compared to adjacent arable land (median = 3 mm hr^{-1}) or pasture fields and margins (median = 27 mm hr^{-1}). Additionally, hedgerow soils exhibited a greater portion of flow through micropores and less through macropores when contrasted with other soil types. In contrast, pasture and margin soils predominantly featured macropore flow, accounting for over 85% of the total flow (Holden and others, 2019).

A study across north-western Europe showed that integrated buffer zones, a buffer zone combined with ponds where soil particles can be deposited and a planted subsurface flow infiltration zone (IBZ), can delay inflowing tile drainage and assist in storing surface run-off from adjacent fields. This is enhanced when the IBZ is optimised using an outlet flow control. The unsaturated soil downstream of the buffer can act as an additional buffer depending on water saturation and antecedent conditions. However, this needs to be better quantified (Zak and others, 2019).

Riparian buffer zones are a common strategy for improving water quality (Stutter and others, 2020). They are a multifaceted approach to improving water quality and fostering healthier aquatic ecosystems by employing various natural processes and vegetation interactions. By creating a physical barrier that slows the flow of overland run-off and promotes infiltration into the soil, riparian buffer zones effectively trap and retain pollutants before they can reach nearby watercourses. The mechanism behind this includes several important aspects:

- tree canopy interception: trees in the buffer zone intercept airborne spray drift of agrochemicals, reducing the amount reaching the watercourse

- surface run-off control: the tree roots and the soil within the buffer zone help control overland flow by allowing water to soak in, reducing the speed at which it reaches the watercourse
- slowing water flow: trees slow down the movement of water, facilitating infiltration and providing time for natural processes involving soil microbes and plants to process nutrients and contaminants
- nutrient uptake: vegetation in the buffer zone can take up and store nutrients, removing them from the water
- organic matter content: increasing the organic matter content in the soil helps natural processes that reduce pollutant levels
- altered bank profiles: changes in bank profiles can enhance the connection between the channel and the floodplain, leading to varying soil wetness levels and sediment trapping
- enhancing ecosystem interactions: promoting interactions between land and water ecosystems helps maintain the health of streams and the surrounding environment
- bank stabilisation: tree roots help stabilise the banks, preventing erosion and collapse

Effect on flood flows, peaks and storage: observed evidence

Hedges installed on the Rogerscale floodplain in Cockermouth acted as a leaky dam, with water levels during high flow events up to 36 cm higher upstream of the hedge than downstream. In all 5 recorded events, from data provided from water level loggers (HOBO U-20L), the peak depth downstream was between 41 and 51% lower than the peak depth upstream of the hedge. The volume of water stored behind the hedge was estimated to be 600 m^3. This volume was proportionate to the magnitude of the event and as the water depth was not close to the top of the hedge, it is expected that even more water could be helped back in higher magnitude events (West Cumbria Rivers Trust, 2021b).

Coates (2018) investigated the impact of hedgerows on soil hydrology and catchment response in the River Skell catchment (120 km^2) in Yorkshire. Saturated hydraulic conductivity was 98% higher under the hedge compared to 10 metres away. Improvements in soil organic matter (SOM) and reduced bulk density only extended 1 to 3 metres out from the hedgerow. The sheltering effect of the hedgerow caused up to 56% less rainfall reaching the ground on the leeward side, extending up to 2.5 metres from the hedgerow.

Interviews with farmers in the South Downs National Park showed that some felt that certain landscaping techniques (buffer strips or working across the field) would not offer enough protection from run-off from the full field or if the land was subject to large amounts of rain (Boardman and others, 2017).

A citizen science group, overseen by the Shropshire 'Slow the Flow' scheme, planted 1,225 metres of hedgerow on clay-loam soils in the Coalbrookdale catchment (1 km^2). In the wettest mid-winter months, soils in the middle of the hedge at 100- and 200-mm depth were as wet as soil upslope and downslope, so soil spiking and aeration may facilitate better infiltration of surface waters to these depths. It was hypothesised that hedges on these soils may have a greater ability to intercept rainwater when budding, but little impact in winter during dormancy. Therefore, the hedges laying on clay loam soils have little effect on overland flow unless water is infiltrating quickly (Severn Gorge Countryside Trust, 2021; Adams, no date).

A study in north-west France showed that sedimentation measures are efficient for catching coarser aggregates. Mean infiltration rates are about 400 mm/h for hedges and 35 mm/h for dead fascines (Richet and others, 2017).

Wild margins were found to generate considerably less overland flow than pastures, possibly due to increased drainage and/or evapotranspiration (Wallace and others, 2021).

In Storm Ciara, 98.2 mm of rainfall fell, which generated 37.63 mm (38.3% of rainfall), 2.45 mm (2.5% of rainfall) and 27.52 mm (28% of rainfall) of overland flow from a pasture plot and 2 wild margin plots, respectively.

In Storm Dennis, 67 mm of rainfall fell, which generated 31.68 mm (46.9% of rainfall) 11.21 mm (16.6% of rainfall) and 27.51 mm (40.7% of rainfall) of overland flow from a pasture plot and 2 wild margin plots, respectively.

Measurements of hydraulic conductivity in Bishopdale (38 km^2) suggested that riparian buffers (woody perennials) had statistically significant higher hydraulic conductivity compared to improved grassland for those buffers planted in 2012 and 2013. The difference in hydraulic conductivity between improved grassland and a riparian buffer planted in 2010 was not statistically significant, nor were the measures statistically significant between the different ages of riparian buffer (Kingsbury-Smith and others, 2023).

Effect on flood flows, peaks and storage: modelled evidence

A laboratory study (carried out with live specimens in glasshouses with sprinkler systems simulating rainfall) of the impact of hedge species by (Blanusa and Hadley, 2019) on rainfall run-off delay and reduction found that:

- while species with larger leaf areas usually retained more rainwater in the canopy, features like dense or horizontally spread branches, concave leaf shape, and the presence of structures like leaf hairs can enhance canopy capture regardless of leaf size
- the moisture content of the substrate at the time of rainfall, which is influenced by the plants' evapotranspiration rate, appears to be the pivotal factor explaining these effects

In Cumbria, a hedgerow wild margin and bordering pasture were compared over several storms. The hedge margins significantly reduced topsoil dry bulk density and increased porosity, and increased the topsoil median permeability by a factor of 22 to 27. Overland flow models and monitored Gerlack troughs show that hedges are slower to produce overland flow, requiring an equal or greater amount of saturation before overland flow generation occurs. Hedge margins consequently produced less overland flow volume, likely due to increased infiltration, percolation and/or evapotranspiration. Soil saturation models confirm that pastures saturate faster than hedge margins, with hedge margins having extremely variable precipitation dynamics compared to pastures that display more moderate and steady behaviour (Wallace and others, 2021).

Buffer strips were created in the Tarland sub-catchment of the River Dee. The catchment has a drainage area of 73 km^2. Riparian buffer strips were effective at field and catchment scale, but would be improved with complementary measures when located on a hillslope. This was influenced by the microtopography of vehicle tracks that diverted flow away from the buffer. Tree buffers have been found to provide more storage than grass buffers, but this was minor (<1%). This was only significant with 50-metre-wide buffers when compared with 10-metre wide buffers (Mason-McLean, 2020).

Artificial rainfall experiments in Cumbria confirm that pastures saturate faster than hedge margins. However, there is no evidence for this during major flood events (Wallace and others, 2021).

Modelled (SD-TOPMODEL) results in the Bishopdale catchment (38 km^2) Yorkshire Dales from Kingsbury-Smith and others (2023) showed that:

- riparian buffer strips show consistent effectiveness in reducing peak flow and time to peak once their trees transition from ‘young’ to ‘developing’ stages, and that the age of the trees doesn't influence these effects; the reduction in peak flow and delay in time to peak are attributed to enhanced hydraulic roughness, which attenuates upstream surface run-off
- for the 100-year event, developing, established woodland and mature woodland riparian buffer strips all decreased peak flow by 1%, while young buffer strips had no impact
- in the 10-year event, all riparian buffer strips reduced peak flow by 1%
- in the 100-year event, developing, established woodland and mature woodland riparian buffer strips reduced time to peak flow by 3% (15 minutes), whereas young buffer strips had no impact
- in the 10-year event, all riparian buffer strips, from young to mature, delayed time to peak by 3% (15 minutes)
- simulating the planting of hedgerows across the catchment did not lead to significant changes in peak flows compared to other modelled NFM interventions, while conversely, enhancing soil infiltration within the floodplain had a notably positive effect on both the timing and magnitude of peak flows within the catchment
- the implementation of all NFM interventions studied, including catchment-wide woodland planting, riparian buffer strips and hedgerows had a more substantial impact on a 10-year storm event compared to a 100-year storm event

A Soil and Water Assessment Tool (SWAT) model was used to study the effectiveness of riparian (grass and tree-based) buffer strips for peak flow reduction for the upper, middle and lower sub-catchments (25.3 km^2, 24.3 km^2 and 18.2 km^2, respectively) of the Tarland catchment of the River Dee, NE Scotland. Default parameters for SWAT were used in the absence of observed data. It found that for 10 m, 20 m, 30 m and 50m buffer widths, there was minimal distinction between vegetation types (grass versus deciduous trees) in terms of their impact when using SWAT model to assess their impact (Mason-McLean, 2020). It also found that:

- the average percentage reduction in peak flow (for events: QMED, 1 in 2-year, Q30, 1 in 5-year, Q10, 1 in 10-year) remained consistent across different spatial scales and vegetation types (grass versus trees)
- the most substantial reduction in peak flow was observed in the upper catchment area (25.3 km^2), with 9.2% to 9.8% reductions in peak flow with 10 m to 50 m wide riparian woodland buffers
- as the spatial scale increased, the reduction in peak flow became less pronounced in the middle (49.6 km^2), 7.3% for a 10 m buffer, 9.1% for a 50 m buffer and lower catchment areas (18.2 km^2) 7.5 for a 10 m buffer, 9.5% for a 50 m buffer
- it is worth noting that the reductions in peak flow were more uncertain in the upper catchment, but as the spatial scale increased, the uncertainty in peak reduction diminished

Modelling results in 3 sub-catchments of the Calder River (60, 19 and 5 km^2 in area) indicate that field boundaries and buffer zones have a positive impact in terms of reducing peak flows. When the boundaries are removed, the impact on peak flow is significant – an average increase of 4% to the peak flow for all events in all 3 sub-catchments. The level of pooling and reduction in terms of flow volumes for each wall is very low, but the combined effect over the whole catchment is significant. Model parameters were determined from local field data values and scientific literature (Willis and Klaar, 2021).

Effect at different catchment scales

Simulated rainfall results were obtained from Pays de Caux, Normandy, with flow rates at 61 litres per second. At catchment level, vegetative barriers are most effective when placed immediately downstream of erosion sources, across channels of concentrated run-off or immediately upstream of local assets at risk. A combination of these can be used to maximise efficiency (Richet and others, 2017).

A study in Devon concluded that the potential benefits of buffering rivers from their floodplains are shown to increase with catchment area, making the case for restoring unimproved grasslands on a larger scale than buffer strips (Ellis, 2021a).

Medium (250 to 800 m^2) integrated buffer zones were installed in north-western Europe (Denmark, Scotland and Sweden). The IBZ combined an aquatic area where suspended soil particles in drained water settle, and a planted infiltration zone. These drained less than 1% of each of the 11 catchments studied, but results cumulatively suggest that IBZ are more effective than standard buffer zones (Zak and others, 2019).

In a modelled study by Mason-McLean (2020) at catchment scale (>50 km^2), 10 m grass-based buffer strips were most effective for flood risk reduction and achieved a greater ratio of peak flow reduction (average 7.2%) to area of land required (2.1% of catchment). The greatest reduction in peak flow occurred in the upper catchment. As spatial scale increased, the reduction in peak flow decreased at the middle and lower catchment. Reductions in peak flow were more uncertain in the upper catchment, but as the spatial scale increased, the uncertainty in peak reduction diminished.

Effect in different watercourse typologies

A series of papers (Aghajani and others, 2023d; Aghajani and others, 2023c; Aghajani and others, 2023b) investigated the effect of NBS on water resources in a chalk catchment in Norwich to understand where NBS might be implemented, using MODFLOW. In the Bure and Wensum catchments (no catchment sizes given), soil improvement measures (including hedges and buffer strips) showed an increase in rainfall entering the groundwater system.

Effect on sedimentation and geomorphology: process understanding

Hedges trap sediment and slow the flow (West Cumbria Rivers Trust, 2021f).

Effect on sedimentation and geomorphology: observed evidence

Experiments conducted for a study in Flanders, Belgium, looking at the effectiveness of vegetative barriers used to buffer flows of water and sediment, showed that the barriers made of coconut-fibre bales performed markedly better than those of straw bales or wood chips (Manning's n values of 1.355, 1.049 and 2.231 s m-1/3 and a sediment deposition ratio of 19%, 38% and 64% for barriers made of straw bales, wood chips and coconut-fibre bales, respectively, during the first experiment). The study noted that some bales, especially coconut fibre, rapidly fill with sediment and, therefore, increase the risks of run-off bypassing or overtopping during subsequent events (Frankl and others, 2021).

The Yarrow Meadows Project in Chorley created buffer strips using brushwood ‘mattresses’, which were then built up with silt deposits. Following a large storm in September 2019, flooding brought high volumes of silt downstream which was deposited in the mattress, building the riverbank up overnight (Blackstock, 2020).

Design life and effectiveness

Hedges should become naturalised into the landscape and, therefore, not have a finite lifespan (West Cumbria Rivers Trust, 2021b).

The time needed for a hedge to reach full efficiency is comparable to the period over which a fascine (bundles of brushwood) can be efficient, so fascines can be used to fill the time gap while hedges establish (Richet and others, 2017).

3D buffer zones should be designed to include deep roots to promote soil biogeochemical processing, and should reshape the ground to enhance run-off capture and above ground vertical planting to facilitate canopy interception (Stutter and others, 2020).

A study assessing the multifunctionality of IBZ in north-western Europe (Denmark Scotland and Sweden) found that outlet flow controls can optimize IBZ for water storage (Zak and others, 2019).

Simulated rainfall results in NW France assessing vegetative barriers, found that fascine filling should be uniform over its length, width and height, and the bunches of stems must be untied and spread out. To achieve the highest densities, unbranched stems about 2.5 m long with diameters from 2 to 3 cm should be used and compressed with a mechanical digger (Richet and others, 2017).

2 or more buffer zones can be combined to add their individual benefits together and to overcome their individual limitations (Richet and others, 2017).

Effective functioning of riparian buffers relies on good soil and crop management in upslope fields to minimise water and pollutant transport to the buffer area. Buffer design should consider pollution pressure from adjacent fields, water quality in receiving environments, and specific ecological goals. The design must incorporate field, riparian and watercourse hydrology, including groundwater contributions. Buffer width is crucial and should be tailored locally. A 6 m buffer is a minimum for effective higher-scoring designs. A 10 m to 12 m (or wider where feasible) buffer is more suitable for stronger upslope pollution scenarios. For riparian buffers, planting fast-growing trees like poplar, willow, eucalyptus or alder should be considered. These trees should be managed for bioenergy, such as short rotation coppice/forestry, to balance economic interests while mitigating nutrient run-off (Stutter and others, 2020).

Maintenance requirements

For hedge establishment, the goal during the initial planting and subsequent maintenance phases should be to attain a density of 50 stems per linear metre as promptly as possible. During the initial decade of maintenance, pruning should be carried out cautiously, and minimised once the shrubs are strong enough. This will encourage the growth of new shoots and accelerate the stem count per linear meter. In the early years, effective weed control is particularly important. However, it is important to avoid using plastic protective sheeting, as this would hinder the emergence of new shoots (Richet and others, 2017).

Buffer strips, although unfertilised, sustain high biomass due to nutrient-rich run-off from adjacent fields. Regular access and inadvertent disturbances within buffers can strain their effectiveness. Compaction and erosion of buffer soils hinder pollutant retention. Buffer proximity to watercourses can lead to pollutant remobilisation. Solutions include fencing or tree planting to prevent disturbances (Stutter and others, 2020).

A study by (Frankl and others, 2021) of vegetative barriers in Flanders, Belgium argues that barriers need to be replaced every few years due to decomposition of organic material. It also states that barriers made of locally available materials are more sustainable.

Harvesting once a year is a practical and efficient management to combat phosphorus leaching from vegetative buffer strips. No increased benefit was observed when harvesting more than this, and this is discouraged to minimise the impact on biodiversity. As buffer strips prevent phosphorus from entering the water, careful management is needed over time to ensure that they do not become a source of phosphorus (Hille and others, 2019).

4.6.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for water resources, air quality, climate regulation, amenity or soil derived from agricultural landscape features specifically.

Biodiversity

Riparian tree buffer strips serve multiple purposes, including providing habitat and wildlife corridors, which were captured on field cameras on a study in the Tarland catchment in Scotland. They also offer the benefit of shading, which plays a crucial role in regulating stream temperatures and controlling Chl-a (chlorophyll-a) generation, especially during low-flow periods. By managing Chl-a concentrations in headwaters, these buffers help reduce the Chl-a biomass being transported downstream, where slower water velocities increase residence time and pose a risk of oxygen depletion (Mason-McLean, 2020).

Buffer strips play a crucial role in enhancing wildlife habitat and creating wildlife corridors. Woody riparian buffers have a significant impact on the channel's shape. The roots of these trees strengthen the banks, providing shelter, and contribute to the accumulation of deadwood, which forms large woody debris. This process increases structural diversity and has a positive effect on aquatic life within the ecosystem (Stutter and others, 2020).

Water quality

Hedgerows are highly 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).

4.7 Headwater drainage management: agricultural headwater management

4.7.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of headwater management from an FCRM perspective and the scientific confidence in what we know.

Effect on flood flows, peaks and storage: modelled evidence

Modelling estimated that the land use and land management NFM measures that have been implemented through the project will only reduce the flood peak on the Cheaton, Cogwell and Ridgemoor Brooks catchment (74 km²) in North Herefordshire by <1%, because only 1% of the catchment has had a measure implemented on it. A maximum of 8 to 11% for land use and 17 to 18% for land management flood peak reduction has also been modelled as possible, as uptake increases. Around 1 to 2% of this may come from flow pathway measures (Lewis and Hodges, 2021b).

Effect on flood flows, peaks and storage: process understanding

This study found that following the installation of ditches and pools in a wetland area northwest of Bickershaw in the Common Lane Brook sub-catchment, part of the River Glaze catchment, this created a new meandering channel reconnecting a watercourse previously held in a concrete line trapezoidal channel. The artificial channel prevented water from connecting with the surrounding grasslands to form a floodplain. Alongside this watercourse, work was carried out to connect previous agricultural drainage back to the landscape. While the past drainage was engineered to maintain drier conditions and the ditches were cut to enable water to flow off-site quickly, the grasslands have been used to absorb the water from heavy rainfall events (Champion, 2018).

Results from a field experiment on Migneint blanket bog, North Wales, in the Afon Ddu catchment (1.59 km^2) on the hillslope showed large reductions in discharge via blocked ditches, with water partly redirected into hillslope surface and subsurface flows and partly into remaining open ditches (Evans and others, 2018).

This study demonstrated that springtime monthly run-off/rainfall ratios in the studied peat grassland Flothers catchment (3 km^2) in northern England may reach 100%, representing a seasonal sponge effect which is eliminated from the forest catchment through the effects of ditches (Bathurst and others., 2018).

Effect on sedimentation and geomorphology

Findings from this study of 60 ditched road segments along 3 in-sloped forest haul roads in the Ridge and Valley region of Montgomery County, Virginia, USA suggest that grass seed with lime fertiliser and erosion control mat, grass seed with lime fertiliser, and completely rocked ditch best management process (BMP) treatments were highly effective at reducing erosion (an erosion control mat reduced erosion rates from 4.92 Mg $ha^{-1}y^{-1}$ to 0.824.92 Mg $ha^{-1}y^{-1}$), but that grass seed with lime fertiliser and erosion control mat was most effective since it provided immediate soil protection. However, grass seed with lime fertiliser and completely rocked BMP treatments reduced bare soil in ditches and provided long-term erosion control. Percentage bare soil values were significant predictors of ditch erosion rates and explained 58% of the total variation in erosion rates (Lang and others, 2017).

Maintenance requirements

Research by Lang and others (2017) in the Ridge and Valley physiographic region of Montgomery County, Virginia, USA showed that ditch maintenance was necessary to maintain drainage, but that it may result in increased erosion due to soil disturbance or removal of vegetative or other soil covers. It also noted that removing material within ditches loosens soil particles and makes them available for transport.

A study evaluated the surface peatland structure of 5 abandoned tracks (4 mesh tracks and one unsurfaced track), with varying past land uses, at an upland site in northern England. The study found that tracks, both meshed and unsurfaced, have long-term effects on peat function and recovery. 7 years post-abandonment, on all tracks, differential plant growth and peat formation essential to mire function was negatively impacted (nano-topography was simplified) compared to control areas. On unsurfaced tracks, the incidence of non-native/invasive species was higher. Frequency of previous usage was not a factor in this impact. The paper notes that this study was carried out on a site at a nature reserve, and so the recovery patterns of tracks at already disturbed or heavily managed sites may differ (Williams-Mounsey, Crowle, Grayson, Lindsay, and others, 2023).

A study at the same peatland site, but on a different track, a mesh track installed in 2013 and abandoned in 2015 was removed in 2020 to study the ecohydrological effects of removing and abandoning mesh tracks. 3 different management options were studied: track left in place, mown prior to track removal, and no preparation (mowing or cutting) prior to removal. The study found that abandoned tracks, whether removed or abandoned, increase non-bog and invasive plant species and impact species abundance. Areas of bare peat were increased and surficial surface was altered. Sward height was lower along the tracks, suggesting an edge effect. Nanotypes were simplified for all treatment options (Williams-Mounsey, Crowle, Grayson, and Holden, 2023). Both studies showed that where track installation is necessary, there must be a planned restoration intervention after track removal.

4.7.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for water resources, air quality, climate regulation, amenity, biodiversity, soil or water quality derived from headwater management specifically.

4.8 Headwater drainage management: headwater peatland restoration

4.8.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of headwater peatland restoration from an FCRM perspective and the scientific confidence in what we know.

Effect on flood flows, peaks and storage: process understanding

A study by Shuttleworth and others (2019) demonstrated that both revegetation and gully blocking delayed and reduced flood peaks across the 3 micro-catchments (control – 7,008 m², revegetation alone – 4,468 m², gully blocking alone – 7,096 m²) located on Kinder Scout in the southern Pennines, UK. This was primarily due to surface roughness reducing the flood wave speed, thereby thickening the overland flow (kinematic storage more important than static storage). Revegetation increases evapotranspiration during storms, not through increased interception. These 2 effects approximately offset one another, such that the overall impact of blocking on static storage capacity is negligible when compared to revegetation alone. Importantly though, for flood relevant storms, static storage plays only a secondary role to kinematic storage. In these storms, independent of intervention type, the main catchment change responsible for reducing peak discharge and delaying lag times is increased surface roughness through its impact on surface flow celerity.

This study of peatlands (Kinder Scout (84 ha), Bleaklow (26k m²), Rishworth Common (1,727 ha), Turley Holes (665 ha) and Black Hill (46 ha)) in the southern Pennines, UK found that revegetation led to an increased attenuation of storm flow, as well as increased lag time of 30 minutes and decreased peak storm discharge by 1.91 $Ls^{-1}ha^{-1}$, relative to control (Alderson and others, 2019).

Photos of a heather bale dam on Wessenden Moor, West Yorkshire (catchment details not provided) show the build-up of sediment and vegetation recovery. They blend into the landscape and form a shallow peat pan/gully head system (Moors for the Future, no date).

Results of a field study of sites within the Aclands and Spooner catchments on Bodmin Moor, Exmoor and Dartmoor (further catchment details not provided) show catchment rewetting may have caused a small increase in run-off connectivity for smaller rainfall events (<10 mm of rainfall), after restoration. However, for larger rainfall events (>10 mm of rainfall), that are more important for flooding and water treatment, this change does not lead to significantly increased peak or total run-off (Brazier and others, 2020)

A study set up and compared sphagnum propagule establishment and dense plug planting via 2 study sites on Kinder Scout in the southern Pennines. It found that based on sphagnum growth, over a period of 3 years and 3 months, the most successful propagule type is plugs, followed closely by clumps, then gel and lastly beads, which showed limited success. When both sphagnum coverage and cost is taken into account, the most successful propagule type is clumps, followed by gel, plugs and beads (Moors for the Future, 2018).

Effect on flood flows, peaks and storage: observed evidence

A study of 3 headwater micro-catchments in the Southern Pennines (UK) found that following revegetation there was a significant decrease in depth to the water table (a 9% reduction comparable to the control site) and an increase in the prevalence of hillslope overland flow production. There were no significant changes in storm run-off coefficient following either restoration treatment. Storm hydrographs following revegetation had significantly longer lag times (106% increase relative to the control), reduced peak flows (27% decrease relative to the control), and attenuated hydrograph shapes. With the addition of gully blocking, the effect is almost doubled. Lag times increased by a further

94% and peak flows reduced by an additional 24% relative to the control (Shuttleworth and others, 2019).

A study by Howson and others (2023) examined the function of a sample of 492 stone and timber gully blocks, 8 to 9 years after installation, on Kinder Edge, High Peak, Derbyshire, UK, which is within the Upper Derwent catchment (further catchment details not provided). This study found that, on average, vegetation covered 93% of gully floors and 90% of gully walls behind dams, as well as 45% of dam tops 8 to 9 years after restoration. It also found that sphagnum and Eriphorum were significantly more frequent on gully floors behind timber dams, whereas Calluna vulgaris (heather) was significantly more frequent on gully floors behind stone dams.

Effect on flood flows, peaks and storage: modelled evidence

A study by Gao and others (2017) looked at the effects of the below vegetation management measures on the upland catchment of Coverdale (84 km²) in the Yorkshire Dales National Park, UK. It modelled the impacts of different vegetation management measures under 2 different rainfall scenarios: 15 mm/hr and 30 mm/hr. The modelled measures were burning and revegetation.

The aim is to create mosaic vegetation of varying ages to promote habitats of game birds. They seek to burn vegetation cover quickly and avoid peat consumption. Burning leads to decreased surface roughness of 50% compared to the normal surface in the catchment, leading to faster overland flow and a lower water table, providing more storage capacity. Burn patches in the headwaters slightly raise the flow peaks under each storm event compared to baseline conditions. The peaks were increased by 3.2% (2.80 m³/s) and 2.3% (7.00 m³/s) under the 15 mm and 30 mm storm events, respectively, and there was not a large impact on flow peak timing. Impact on high flows is unclear, but burnt catchments seem to have deeper water tables and more consolidated peat than similar catchments without burning. This may reduce the occurrence of saturation excess overland flow and river flow peaks in moderate storms. However, in the heaviest storm events, the buffering influence could be limited. During large storms, the loss of vegetation cover would decrease surface roughness and, therefore, accelerate delivery and concentration of overland flow, increasing flow peaks.

Peat restoration includes drain blocking, gully blocking, bare peat stabilisation and vegetation restoration These influence the movement and concentration of overland flow and river flow peaks in flood events. Compared to drain blocking, several studies have shown that surface roughness increase resulting from vegetation restoration may have a greater impact on peak flows. Long-term river flow records in upland peat systems are lacking.

This modelling study, based on findings by Shuttleworth and others (2019) demonstrated that both revegetation and gully blocking delayed and reduced flood peaks across 3 micro-catchments (control – 7,008 m², revegetation alone – 4,468 m², gully blocking alone – 7,096 m²) located on Kinder Scout in the southern Pennines, UK. It also demonstrated that revegetation and gully blocking activities on Kinder Scout motivated by, and designed for, moorland restoration can provide significant additional catchment surface storage (static and kinematic storage), which helps to reduce peak discharge and increases lag times, independent of storm size. An interventions impact on 'static storage' (interception, ponding and evapotranspiration) becomes important for smaller storms. Although interventions always increase lag times, they can be less effective in reducing peak magnitude when maximum rainfall intensity is sustained for durations longer than mean catchment delay. Regardless of the duration of peak rainfall intensity, lag time was always increased (Goudarzi and others, 2021).

A modelled study in Coverdale studied the relative roles of stocking density, prescribed burning and peatland revegetation in flood flows across an upland catchment system where large, connected areas of land are under each of these management interventions. For the bare soil revegetation scenarios, the peak time was not delayed. Riparian vegetation change to sphagnum produced much lower flow peaks and strongly delayed the hydrograph peak under both rainfall events. Modelling results showed that the intensive management scenario raised river flow peaks by 86.3% and 59.2%, respectively under 15 mm and 30 mm storm events compared to the baseline scenario, and the peaks were 7-time steps (0.1 hours) and 3-time steps earlier. The flow peaks for the conservation scenario decreased by 12.1% and 10.8%, and the peaks were both 3-time steps later for the 2 events compared to the baseline scenario (Gao and others, 2017).

Effect at different catchment scales

The significant changes in hydrology observed after restoration interventions across the 3 headwater micro-catchments on the Kinder Plateau in the southern Pennines, UK (no further catchment details provided) examined in this study demonstrate a decrease in the risk of flooding at the headwater level following restoration. Alterations in headwater conditions were anticipated to ripple downstream, potentially leading to a reduction in flood risk within the broader catchment area. The extent to which downstream flood risk is diminished hinges on 2 critical factors. Firstly, the size of the restoration effort in relation to the catchment's dimensions, as well as the strategic placement of restoration projects within the landscape. Secondly, the topography of the catchment and its sub-catchments, along with the associated synchronisation effects on hydrographs, which contribute to the overall hydrology of the wider catchment. Assessing these scale-dependent effects and quantifying the advantages of restoration in terms of downstream flood risk reduction is challenging when using monitoring approaches. Complexity also arises from the multitude of influences on flow patterns in broader catchments, as well as the presence of confounding factors, making it hard to isolate the specific impacts of restoration within storm-flow data sets. Additionally, identifying suitable control systems at the larger catchment scale is challenging. The study also notes that the benefits of restoration in terms of reducing flood risk at larger catchment scales can be quantified through the application of hydrological models (Shuttleworth and others, 2019).

Effect in different watercourse typologies

This study of the establishment of sphagnum on Kinder Scout, southern Pennines (no further catchment details provided) found that topography (hagg top versus undulating ground) had a dramatic effect on the growth of sphagnum plugs, suggesting that moisture from precipitation and cloud cover is sufficient for sphagnum to survive and grow slowly, but much faster growth is observed when sphagnum is located in areas with a higher water table and better protection from desiccation (Moors for the Future, 2018).

The Trout Beck catchment in the Yorkshire Dales, covering 11 km^2, is dominated by shallow water tables and widespread saturation-excess overland flow response. Modelled results (SD-TOPMODEL) for 1 in 10 return period floods indicated that alterations in land cover from Eriophorium to sphagnum within riparian zones and on gentle slopes had a more pronounced impact on peak river flows compared to changes in other areas of the watershed. These effects varied under different rainfall intensities and patterns. As rainfall intensity increased, the relative change in flood peaks due to land cover changes in these sensitive zones diminished, but the actual alterations in flow peaks grew more substantial. To promote vegetation restoration in upland peat catchments, the most effective strategy is to establish robust buffer strips along waterways. Particular attention should be given to treating flatter areas and addressing any bare patches. In these cases, more comprehensive treatment gives better results, but a minimum 10% areal treatment is still worthwhile (Gao and others, 2018).

Effect on sedimentation and geomorphology: process understanding

This study on Kinder Scout in the southern Pennines (no further catchment details provided) found that restoration via establishment of vegetation cover and the consequential development of surface roughness were important factors in rapidly reducing particulate carbon loss (0.37 grams per week of particulate organic carbon loss before restoration compared to 0.05 grams per week after restoration) and attenuating stormflow (3.71 $Ls^{-1}ha^{-1}$ before restoration compared to 1.51 $Ls^{-1}ha^{-1}$ after restoration) (Alderson and others, 2019).

Effect on sedimentation and geomorphology: modelled evidence

Analysis of 3 micro-catchments (control – (7,008 m^2), revegetation alone – (4,468 m^2) and gully blocking alone – (7,096 m^2)) on Kinder Scout in the southern Pennines shows that the percentage reduction in peak discharge from micro-catchments can vary widely (5% to 90%), but that this may be due to rainfall characteristics. If so, the interventions studied will be least effective in reducing micro-catchment peak discharge for long-duration, ‘frontal’ rainfall, and more effective for shorter ‘convectional’ rainfall. The study also noted that regardless of the duration of peak rainfall intensity, lag times were always considerably increased following revegetation and gully blocking interventions (minimum 10 minutes for revegetated areas and 30 minutes for revegetated and gully blocked areas). Therefore, even in the longest frontal rainstorms, these increased lag times for upland headwater sub-catchments could be used to attenuate the downstream flood wave. However, the study notes that when alterations are primarily to flood wave timing rather than magnitude, it is possible that interventions synchronise sub-catchments rather than the reverse. To avoid this, catchment-scale modelling was noted as useful in testing different spatial patterns of NFM interventions and their impact on flood risk throughout a river network (Goudarzi and others, 2021).

Design life and effectiveness

Heather bale dams (which can also be made of coir logs) are semi-permeable gully and grip blocks that can be used both to slow the flow of water downstream and to trap sediment that would otherwise be lost from the moor. Sediment accumulates, raising the bed of the gully, which can then be recolonised by vegetation such as cotton grass or sphagnum moss (possibly artificially aided, for example, through plug planting or seeding). This process is helped by the heather bales slowing the flow of water. However, it should be noted that supply of heather may be limited, and installation requires enough substrate in which to key in the bales (MoorLIFE2020, no date).

Heather brash can be used to halt the erosion of bare peat in the short term while the propagules established (Moors for the Future, no date).

4.8.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for water resources, air quality, amenity, biodiversity, soil or water quality derived from headwater peatland management specifically.

Climate regulation

One study found that upland peat restoration can reduce then remove carbon from the atmosphere. It costs around £10 to £100 per tonne of CO_2 equivalent and can sequestrate 2 to 20 tCO_2e/ha/year. The carbon abatement potential nationally was deemed to be very high, and the technology is ready to create benefits (Beechener and others, 2021).

4.9 Headwater drainage management: grip and gully blocking

4.9.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of grip and gully blocking from an FCRM perspective and the scientific confidence in what we know.

Effect on flood flows, peaks and storage: process understanding

Results of a field study of sites within the Aclands and Spooner catchments on Bodmin Moor, Exmoor and Dartmoor (further catchment details not provided) found that regarding changes in gully run-off, it is important to note that the changes reflected both increased temporary storage in the peat soil/surface pools, as well as a switch to diffuse surface flow dominating storm run-off, after restoration. This does not mean that less water is leaving the moorland, but that it now leaves via multiple run-off pathways and much more slowly (Brazier and others, 2020).

This study monitored 6 natural and 6 artificial pools on the Cross Lochs peatland in Flow Country, northern Scotland. It found that the depth-below-peat-surface values were on average 15 cm. The study, therefore, concluded that creating larger pool areas in peatland restoration schemes may be beneficial in reducing downstream flood risk for some storms. It noted that these benefits may not be fully realised on occasions when the pools are already 'full', which is more likely in winter months when evaporation rates are low. The study noted that artificial pool levels fell at a significantly faster rate immediately following rainfall events than water levels in natural pools, resulting in a higher 'turnover' of water. Pools overflowed by a median of 9 and 54 times the pool volume per year for natural and artificial pools, respectively (Holden and others, 2018).

Gully blocking reduces the flow of peat sediment along erosion channels, reducing the loss of peat downstream and aiding the recovery of a characteristically high water table, helping to rewet degraded areas and reduce flooding downstream (Moors for the Future, 2018).

Stone dams are permeable gully blocks constructed from piles of stone, airlifted into place using underslung hoppers or dumpy bags and re-profiled by hand. Due to their porous nature, they do not trap water immediately (but will do once the pores fill with sediment). Instead, they slow its flow downstream, while trapping sediment from the water, which builds up upstream of the dams. This raises the bottom of the gullies by deepening the soil; this has been noted as especially useful in places where no soil currently exists. Once stabilised, plug plants or seed can be used to revegetate the gully bottoms; often, they will revegetate naturally with cotton grasses. Alternatively, another series of dams can be installed to raise the gully base still further (Moors for the Future, 2020).

A study into the effects of ditch blocking on blanket peat, on the Migneint plateau in the Upper Conwy catchment, North Wales (no catchment details provided) found that ditch blocking had a limited effect on the water table, as over time, the peat surrounding the ditch had effectively ‘self-rewetted’ and returned to a new stable state, with the peat surface again close to the water table. This finding helps to explain why the study showed no change, or only small changes, in water table depth following ditch blocking on blanket peat; the water table is still near to the peat surface, and blocking the ditch has relatively little effect as there is little dry peat to rewet (Williamson and others, 2017).

A study looking into an infield trial of ditch blocking on blanket peat, on the Migneint plateau in the Upper Conwy catchment, North Wales (no further catchment details provided), found that ditch damming and reprofiling led to an initial 5-fold reduction in discharge. However, it also found that there was a gradual change over time in ditch flow regime in subsequent years, with the overall volume of water leaving the dammed and reprofiled ditches increasing per unit of rainfall to around twice that which occurred in the first years after blocking. This reinforces the need for longer term monitoring to understand the impacts of peatland restoration. This study also found that while ditch blocking had an immediate effect on ditch flows, analysis demonstrated that there has been a long-term change in the hydrology of the system in the years following ditch blocking. The study also provided evidence that the system had become ‘leakier’ since initial restoration works, with a greater volume of water per mm of rainfall flowing down the ditch or former ditch channels in the form of slow seepage and baseflow, rather than high flow peaks (Holden and others, 2017).

A study examining the effectiveness of restoring afforested blanket bog looked at 6 combinations: damming or not damming plough furrows, with leaving the trees alive, felling and leaving them on the ground, or felling and removing them on blanket peatland across Halsary and Braehour Forests in Caithness, northern Scotland (no further catchment details provided), found that damming drains and plough furrows can help to raise the water table (Anderson and Peace, 2017).

This study conducted in the Upper North Grain catchment (0.49 km²) on the southern flank of the Bleaklow plateau in the Peak District National Park, northern England analysed the effect of blocking natural soil pipes to assess the impact on streamflow. Pipe flow was impeded in half of the pipe outlets in one stream, either by inserting a plug-like structure in the pipe-end or by inserting a vertical screen at the pipe outlet. Blocking pipe outlets did not completely prevent all pipe flow. Both trialled blocking methods either led to new pipe outlets appearing or seepage occurring around blocks within 90 days of blocking. Discharge from 4 individual pipe outlets was monitored for 17 months before blocking and contributed 11.3% of streamflow. Pipe outlets on streambanks with headward retreat produced significantly larger peak flows and storm contributions to streamflow compared to pipe outlets that issued onto straight streambank sections. The researchers found a distinctive distance-decay effect of the water table around pipe outlets, with deeper water tables around pipe outlets that issued onto straight streambanks sections. Ultimately, the study found no direct impact of pipe blocking on streamflow (Regensburg and others, 2021).

This study monitored 6 natural and 6 artificial pools on the Cross Lochs peatland in Flow Country, northern Scotland. It found that peat pipes did not play a large role in the functioning of the pools examined in the study. The study noted that further work is required to establish whether the hydrological function of pipe-connected pools is different from those disconnected from peatland pipe networks (Holden and others, 2018).

Effect on flood flows, peaks and storage: observed evidence

Restoration of degraded peatland in Dartmoor National Park, south-west England (no further catchment details provided) caused previously connected peat pans (flat areas of bare peatland) to be isolated by peat blocks, which physically obstructed branching flow pathways, enabling the accumulation of surface water. Restoration led to a statistically significant reduction in peak flow, by 0.0131 m³/s per unit of rainfall measured using a vented submersible pressure transducer. Mean water table level also rose within the peat pans from 3 mm below the surface to 64 mm above the surface following restoration. This occurred as peat blocks filled in gaps between adjacent haggs, creating a continuous but permeable barrier within which pools could form (Gatis and others, 2023).

In the same study, restoration of degraded peatland in Dartmoor National Park, south-west England (no further catchment details provided) appears to have visually influenced overland pathways and the storage of water within the peat and in surface pools, leading to reductions in rising limb gradient and peak flow, and to an increase in hydrological residence time within the catchment. The lag time between the start of a rainfall event and peak discharge also decreased (by 33.3% and 49%, respectively), aligning with the suggestion that restoration decreases water storage capacity within the peat between rainfall events. The implications of reduced lag times on the NFM potential of peatland restoration, particularly during wetter months and sequential rainfall events, warrants further investigation (Gatis and others, 2023).

A study by Howson and others (2023) examined the function of a sample of 492 stone and timber gully blocks, 8 to 9 years after installation, on Kinder Edge, High Peak, Derbyshire, UK, which is within the Upper Derwent catchment (further catchment details not provided). This study found that there was 1,361 m^3 of potential static storage space behind the 492 dams surveyed. It also found that 56% of stone and 87% of timber dams were pooling, that ~50% of static storage remained behind dams 8 to 9 years after restoration once the sediment supply largely ceases.

This study conducted in the Upper North Grain catchment (0.49 km^2) on the southern flank of the Bleaklow plateau in the Peak District National Park, northern England found that the statistical response variable showed the overall effects of pipe outlet blocking on stream responses was small for total storm run-off (68% to 66.5% for control and treatment respectively, peak discharge (7.7 Ls^{-1} and 6.7 Ls^{-1} for control and treatment, respectively) and for peak lag (1.6 hours to 1.7 hours for control and treatment, respectively) (Regensburg and others, 2021).

Effect on flood flows, peaks and storage: modelled evidence

A pilot modelling study of 4 sites (Saddleworth, Snailsden, Kinder and Bradfield – all locations within the southern Pennines special area of conservation (SAC), northern England), conducted by Newcastle University in collaboration with Moors For the Future Partnership developed a methodology to identify and prioritise 100,000 gully block locations that could restore the hydrological regime towards that of an active blanket bog, with a view to moving the vegetative community towards a favourable condition (Milledge and others, 2020).

Output block locations were expected to be suitable for:

- applications where changes in water table or bog pool area resulting from blocks are the hydrological property of interest
- large-scale application, such as prioritising regions of the SAC, informing selection of sites and areas for restoration
- small-scale application, such as prioritising areas within a site or suggesting specific block locations
- improving the accuracy of future projects for estimation during the bidding process

The study notes that the output block locations are not suitable to inform NFM without additional analysis. The methodology optimises block locations to maximise average water table rise and pond area in a particular location. It does not account for flow interactions between blocks and, therefore, cannot provide any indication of the impact of blocks on gully discharge. As a result, it cannot be used as a ranking of flood management potential of the blocks (Milledge and others, 2020).

Effect at different catchment scales

Results of a field study of sites within the Aclands and Spooner catchments on Bodmin Moor, Exmoor and Dartmoor (further catchment details not provided) found that the restoration response within the smaller Aclands catchment was less pronounced. In the smaller catchments: for large rainfall events, total event quick flow and peak event discharge were not significantly different. For smaller rainfall events, total and peak discharge were significantly higher following restoration (Brazier and others, 2020).

Modelling of 3 micro-catchments (control – (7,008 m²), revegetation alone – (4,468 m²) and gully blocking alone – (7,096 m²)) on Kinder Scout in the southern Pennines shows that both revegetation and gully blocking delay and reduce flood peaks. This is primarily due to surface roughness reducing the flood wave speed, thereby thickening the overland flow (kinematic storage more important than static storage). The impact of gully blocking in increasing kinematic storage is very significant and comparable to that of revegetation alone. Gully blocking extends the evapotranspirative losses to the inter-storm period through increasing the static storage capacity, but also reduces catchment average evapotranspiration rates. These 2 effects approximately offset one another, such that the overall impact of blocking on static storage capacity is negligible when compared to revegetation alone. Importantly though, for flood relevant storms, static storage plays only a secondary role to kinematic storage. In these storms, independent of intervention type, the main catchment change responsible for reducing peak discharge and delaying lag times is increased surface roughness through its impact on surface flow celerity (Goudarzi and others, 2021).

Effect on sedimentation and geomorphology: process understanding

Ongoing monitoring of gully blocking on Kinder Scout (no further catchment details provided) since 2011 has shown that 95% of gully blocks surveyed in the winter of 2014 to 2015 were holding either water, sediment, or both. Monitoring has also shown that 94% of gully blocks were vegetated or beginning to show signs of revegetation (MoorLIFE2020, no date).

Results of a field study of sites within the Aclands and Spooner catchments on Bodmin Moor, Exmoor and Dartmoor (further catchment details not provided) found that for the Spooner catchment, there was an observed notable improvement in hydrological behaviour during rainfall and run-off events with similar contributing rainfall. Specifically, following restoration, there was a significant reduction in both the total discharge and peak event discharge. For smaller rainfall events (those with less than 10 mm of rainfall), the study observed a remarkable 32% decrease in total event discharge and a 29% decrease in peak event discharge, with a high level of statistical significance. For larger rainfall run-off events, while the effect was still noticeable, it was less statistically significant. This suggested that the restoration efforts had a more pronounced impact on reducing peak and total event discharge for smaller events. On average, following restoration, total discharge decreased by an impressive 32%, and peak event discharge decreased by an average of 21%. Furthermore, following restoration, the study observed a substantial reduction of approximately 66% in run-off production through the gully. Simultaneously, there was an increase in channel storage, defined as pooled water within the gully, with an average rise of 32 cm. These findings collectively highlight the positive outcomes of the peatland restoration efforts, particularly in mitigating run-off and enhancing water storage within the gully (Brazier and others, 2020).

This paper noted that blocking gullies blocked the flow of peat sediment along erosion channels (no further details provided), which restored the high water table and helped to rewet degraded areas. This provided sphagnum moss better conditions to grow and preserve the peat (Moors for the Future, 2018).

Analysis of 3 micro-catchments (control – (7,008 m²), revegetation alone – (4,468 m²) and gully blocking alone – (7,096. m²)) on Kinder Scout in the southern Pennines noted that most cobble stone dams were clogged up with sediments. However, the precise state of (im)permeability of the cobble dams during the study periods is unknown. As such, although it seems less likely that including such process in our model would have considerably altered our static and/or kinematic storage estimates, it cannot be said with confidence (Goudarzi and others, 2021).

This paper noted that gully blocks block sediment upstream of the dam, raising the bed of the gully, which is then recolonised by vegetation (MoorLIFE2020, no date).

This paper noted that pores in stones in gully blocks fill with sediment which raises the bottom of the gullies by deepening the soil (Moors for the Future, 2020).

Effect on sedimentation and geomorphology: observed evidence

This paper observed that on Kinder Scout (no further catchment details provided), in systems that have been both gully blocked and revegetated, the amount of carbon particles (mostly peat) in the water have been reduced by 42% (MoorLIFE2020, no date).

This study on Kinder Scout in the southern Pennines (no further catchment details provided) noted that particulate organic carbon (POC) declined by 90% in 2 years following restoration across the study sites in the southern Pennines (UK). Data was collected through the monitoring of sediment traps (Alderson and others, 2019).

This study of the restoration of degraded peatland in Dartmoor National Park, south-west England (no further catchment details provided) demonstrated a non-statistically significant impact on dissolved organic carbon for sample hydrological events. Data was collected through water sampling using automatic pump samplers, filtered samples were analysed by UV spectrometry for dissolved organic carbon. However, it should be noted that the project operated over a course of 4 years, and ecohydrological processes driving peatland communities and carbon accumulation run on decadal to centennial timescales (Gatis and others, 2023).

A study by Howson and others (2023) examined the function of a sample of 492 stone and timber gully blocks, 8 to 9 years after installation, on Kinder Edge, High Peak, Derbyshire, UK, which is within the Upper Derwent catchment (further catchment details not provided). This study found that there was no significant difference in sediment depth for the different gully blocking techniques between the first year and 8 to 9 years after restoration, and that deeper gullies with steeper channels and wall slopes accumulated more sediment.

Design life and effectiveness

Robustness of different dam types used for grip and gully blocking after 7 years was evaluated using a qualitative RAG status (green being best, red worst). These statuses were:

- heather bale – green
- peat dam - amber
- plastic dam – amber
- stone dam – green
- timber dam - amber (MoorLIFE2020, no date)

This study conducted in the Upper North Grain catchment (0.49 km²) on the southern flank of the Bleaklow plateau in the Peak District National Park, northern England looked at 2 streams in a heavily degraded blanket peat bog. It noted that when pipes were active, pipes at head locations contributed more to streamflow compared to pipes at edge locations. Therefore, a primary focus should be on pipe outlets at head locations. Pipe blocking at the outlet had a measurable impact on the water table, but its extent was very localised. Water tables in gully edge zones showed a distance-decay effect, with significantly deeper water tables at edge locations compared to head locations, but a larger reach further away from the gully at head locations. A key recommendation of this study was that impeding pipeflow at pipe outlets would exacerbate pipe development in the gully edge zone and, therefore, it proposed that future pipe blocking efforts in peatlands prioritise increasing the residence time of pipe water by forming surface storage higher up the pipe network. Therefore, the study does not advocate blocking pipes at the pipe outlet as part of peatland restoration. Blocking pipes further upslope away from streambanks would generate a return flow, causing spill on the surface, before flowing through vegetative surfaces with lower velocity and, therefore, potentially reducing flood risk more than pipe outlet blocking (Regensburg and others, 2021).

This paper emphasises the advantages of using stone dams as a gully blocking technique (no catchment details provided). These dams are constructed using natural materials that blend seamlessly with the surroundings once they have collected silt and become vegetated. Importantly, no vehicular access is necessary to install them, as stones can be airlifted to any location and shaped using simple hand tools. This flexibility allows them to be used even in areas where gullies have eroded down to mineral soil, but this comes at a significant financial cost. Furthermore, once the sediment is trapped and consolidated within these dams, it becomes easy to cross the gullies on foot, enhancing their practicality and environmental compatibility (Moors for the Future, 2020).

This paper noted that gully blocking serves as an effective technique for capturing water and sediment, thereby impeding the flow of water and potentially elevating the water table (no catchment details provided). The height of these blocking structures is tailored to specific objectives. When the goal is to enhance water retention and restore peat wetness, ideally the block should align with the existing surface, although in practice this can be challenging to achieve. However, if the primary aim is to capture sediment, the block's height can be considerably lower. The determination of block height is also influenced by the scale of the gullies in question. In cases where gullies are deep and wide, a lower block may be a more suitable choice, aligning the structure with the unique characteristics of the landscape (MoorLIFE2020, no date).

In the Stroud Frome catchment (250 km²) in the southern Cotswolds, gulley stuffing using brash and small logs visibly reduced surface run-off in a steep-sided valley. This intervention was particularly effective in a steep catchment where wood extraction may be difficult, because it provides justification for woodland management activity in areas where this may not have previously been undertaken (Short and others, 2019).

A study by Howson and others (2023) examined the function of a sample of 492 stone and timber gully blocks, 8 to 9 years after installation on Kinder Edge, High Peak, Derbyshire, UK, which is within the Upper Derwent catchment (further catchment details not provided). This study found that only 2% of dams had failed after 8 to 9 years. 4 timber dams had been undercut and 5 stone dams had collapsed or been undercut. No timber dams had been breached due to timber decay.

4.9.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for water resources, air quality, amenity, biodiversity, soil or water quality derived from grip and gully blocking specifically.

Climate regulation

Grip and gully blocking to raise water table levels and rewet peatlands, whilst a popular method, has limited empirical data as to the carbon benefits. However, it is viewed as being a ‘no-regrets’ option, and that benefits could be realised over longer timeframes as the peatland ecosystem adapts to wetter conditions (Evans and others, 2018).

5 Coastal management

5.1 Saltmarsh and mudflat management/restoration

5.1.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of saltmarsh and mudflat management/restoration from an FCRM perspective and the scientific confidence in what we know.

Effect on wave attenuation/ flood flows: observed evidence

Paquier and others (2017) observed 2 storm events in 2015 at Chesapeake Bay, Virginia, USA. Across the 300 m transect, the marsh was found to attenuate waves, reduce current velocity, and attenuate high water levels.

A scheme incorporating the beneficial use of dredged sediment at Northey Island, Essex, UK found the largest current velocities and more high energy events occurred to the east of the island, indicating that the saltmarsh was attenuating wave energy from east to west. Furthermore, the highest bed velocity was found to reduce by 0.7 m/s due to the presence of saltmarsh. The elevation maintained by the saltmarsh meant that locally-generated waves within the saltmarsh were not able to develop sufficiently to present an erosion risk to the saltmarsh. The introduction of the creeks and the vegetation also created a hydraulic lag due to the additional friction exerted on the flow; however, the long-term influence of this on erosion risk requires further observation (National Trust and others, 2021).

Scirpus maritimus (Seaside Bulrush) on the Scheldt Estuary, Groot Buitenschoor, Belgium, (226 ha) and the Schor van Rilland, Netherlands (186 ha), aided in relative wave attenuation rates, ranging from 20 to 40% and reductions in wave height over the first 12 m of the marsh (Silinski and others, 2018).

Gillis and others (2022) conducted physical laboratory experiments and identified that unidirectional flow was reduced by 50% with the use of saltmarshes. After 2.5 m of saltmarsh, turbulent kinetic energy was reduced by 40% under wave-only conditions. This led to sediment deposition at the leading edge of the marsh between 1.5 and 2.5 m. For low-density vegetation under combined waves and currents, the flow speed reduction ranged from 20 to 24%, while for high-density vegetation it was 20 to 40%. The change in flow speed corresponded to greater sediment accumulation in high-density planting, which occurred closer to the leading edge. The largest increase in scale-dependent feedback was found between 0.5 and 2.5 m under all wave and current conditions.

Laboratory testing of submergent and emergent vegetation showed that average wave attenuation over vegetation was reduced by 10%/m in low frequencies, 9%/m in peak frequencies and 12%/m in high frequencies. The study reported that overall wave height was reduced by 70% over a 15.7 m long vegetated patch. When the vegetation height was equal to, or exceeded, the water depth, the % per m of wave dissipation was 40% greater in high frequencies. For submerged vegetation, high-frequency percentage dissipation was only 10% greater than for peak frequencies and, therefore, this created a change of spectral shape within the vegetation field. This suggests that vegetation preferentially dissipates energy at frequencies higher than the spectral peak for single- and double-peaked wave spectra (McKee Smith and Anderson Bryant, 2018).

Across saltmarshes (96.7 ha) in San Pablo Bay, San Francisco, Foster-Martinez and others (2018) observed greater wave attenuation when the vegetation was emergent than when the vegetation was submerged. This is because the drag force acts on the entire water column.

Effect on wave attenuation/ flood flows: modelled evidence

Taylor-Burns and others (2023) undertook Xbeach non-hydrostatic modelling, calibrated using marshes in San Pablo Bay, California, USA. Results showed that vegetation reduced wave runup by a median of 45 cm in the narrowest marshes and by a median of 30 cm in the areas with the lowest friction coefficients. The majority of wave energy dissipation occurred within the first 50 m of marsh vegetation. Furthermore, under storm conditions, vegetation was found to reduce wave runup by a median of 65 cm across a 50 m marsh.

Godfroy and others (2017) used 1D SWAN modelling at 2 locations prone to wave action in Galveston Bay, Texas, USA. From the methods tested, marsh vegetation was found to make the largest difference in wave heights at the output location for all return periods, with a reduction in wave height of 75%, 70%, 60%, and 52% for the 10, 50, 100 and 500-year return periods, respectively.

A study used a probabilistic model to quantify how constructed saltmarshes reduce flood risk in the long term (100 years), compared to dike heightening only. The study found that while constructing saltmarshes proves more economical compared to raising dikes, their impact on failure probabilities is constrained due to their reliance on sediment accretion in the intertidal zone. In the context of the examined case study, saltmarsh construction emerged as the more cost-effective option over dike heightening only when facing scenarios of small to moderate economic damage resulting from dike breaches (Vuik and others, 2019).

Using Xbeach modelling, Hewageegana and others (2022) found that the propagation distance of a storm surge increased with both amplitude and length. For example, the propagation distance for a surge amplitude of 1.0 m and 2.0 m over a saltmarsh with an initial channel width of 50 m and spacing of 300 m is 2.2 km and 3.8 km, respectively. Furthermore, the propagation distance for a surge duration of 2.1 hours and 2.8 hours over a saltmarsh with an initial channel width of 50 m and spacing of 300 m is 2.0 km and 2.2 km, respectively.

Effect on sedimentation and geomorphology: process understanding

Tognin and others (2021) measured sediment accumulation at 3 different saltmarsh sites in Venice, monthly or immediately after a storm surge. They found that under fair weather conditions sedimentation rates reached 20 g/m^2 per day. This largely comprised organic production by halophytes, representing up to 40% by weight of the sediment deposited in summer and early autumn. During storm surges, the organic contribution to overall soil accumulation decreased to around 10%. This suggested, especially in microtidal coastal wetlands, everyday tidal inundation may not provide the sediment necessary for marsh survival, and only storm surges can mobilise sand and silt from adjacent tidal flats and deliver them onto the saltmarsh surface. Furthermore, storm-driven contribution accounted for more than 70% of the annual total sediment accumulation on the marsh surface, even though just 25% of the observational period was storm dominated. Finally, the sedimentation rate increased exponentially with mean inundation depth, suggesting a non-linear effect of intense pulsing events.

2 intertidal schemes were introduced in the Scheldt Estuary (Belgium) (Oosterlee and others, 2020): Lippenhook, an 8 ha flood control area using a controlled reduced tide (CRT) (studied over 10 years) and Burchtse Weel, a 13 ha intertidal habitat using full tidal exchange (studied over 5 years). The CRT area can only drain once the water in the estuary is below the level of the outlet culvert, therefore, prolonging the hydroperiod. Depending on elevations, tidal water may remain in the tidal channels during spring low tide. The volume of water coming into the CRT area is determined by the dimensions of the inlet culvert. Silting up of the lower parts of the CRT leads to less frequent, less deep, and shorter flooding periods and subsequently lower sedimentation rates on sites with a lower topographic elevation. In contrast, sites that initially have higher topographic elevation will over time flood more frequently, deeper and longer, leading to increased sedimentation and erosion rates.

Where full tidal exchange is located lower in the tidal frame, water ingress will be more frequent, for longer periods and to greater water depths, resulting in high sedimentation rates for sites with initially low topographic elevation. Higher rates of sediment accumulation led to an increase in ground elevation, causing a reduction in tidal inundation and reduced sediment inflow. Sedimentation continues until there is an elevation equilibrium close to the mean high water spring level (Oosterlee and others, 2020).

Silliman and others (2019) conducted a 3-year saltmarsh plant removal study at field sites in Florida to understand the effects on lateral and vertical erosion at the saltmarsh edge. Lateral erosion rates were significantly higher in areas of vegetation removal (114.19 ± 9.42 cm) compared to those with vegetation (76.76 ± 8.91 cm). Lateral erosion rates were only found to increase when below ground biomass was lost, highlighting the importance of roots strengthening the soil compared to the stems reducing lateral erosion.

Baptist and others (2017) noted that the root systems of vegetation further stabilise the soil, reducing the potential for erosion in a case study in the Port of Harlingen, Netherlands.

Effect on sedimentation and geomorphology: observed evidence

Over the past 12 years, 14 small-scale living shoreline restoration projects have occurred in Mosquito Lagoon, Florida, USA. The rate of erosion before and after the restoration projects has reduced from -0.16 m/yr to 0.14 m/yr. Over the total restored living shoreline, the rate of change has reduced from -189.07 m^2/yr to +158.54 m^2/yr (McClenachan and others, 2020).

A study employed in situ real-time kinematic (RTK)-GPS surveys to measure the resilience, as indicated by the lateral shift in shore position, of 17 living shoreline sites both before and after the impact of a Category 1 hurricane event (Hurricane Florence, 2018). Significantly less lateral erosion following a storm event was experienced at living shorelines (saltmarsh with seaward breakwater) when compared to unprotected control, natural fringing saltmarshes (0.015 and −0.31 m $year^{-1}$, respectively). It is noted this reduced erosion should help preserve saltmarshes (Polk and others, 2022).

Schoutens and others (2022) excavated marsh monoliths from Phragmites australis (common reed) marshes in front of a dike along the Scheldt Estuary (Dutch-Belgian border area) and installed these in a 10 m long flume test section. 6 experimental runs were conducted under high flow velocities up to 1.75 m/s and water depth up to 0.35 m for 2 hours. The sediment bed remained stable after a cumulative 12-hour exposure, with erosion limited to “as little as a few millimetres”, indicating that the shear strength of the sediment was greater than the exerted shear stress force. The saltmarsh was, therefore, able to maintain a stable sediment bed.

A scheme at Steart Peninsula, Somerset (Pontee and Serato, 2019) included a (240 m) breach and the excavation of a creek system. After initial tidal waters entered the site and filled the creek system, the exchange of large volumes of water into and out of the site led to high velocities and significant erosion of the breach and former drainage channels. This led to the creation of a large ‘exit channel’ over the foreshore. 50% of erosion was observed in the first 15 days, 30% over the next 35 days, and 20% over the next 5 months. This constituted 88,900 m^3 of material over the first 61 days (including individual blocks of 2 to 5 m^3) and 31,100 m^3 of material over the next 151 days.

At the same scheme at Steart Peninsula, Somerset, Mossman and others (2022) undertook annual sediment cores and digital terrain model (DTM) measurements between 2014 and 2017. Within the site, elevation change varied from a net accretion of 2.2 m to a net erosion of 5.0 m, with 92% of DTM pixels experiencing net accretion and 7% experiencing net erosion. The overall mean sediment accumulation over the marshes was measured at 75 mm/yr.

2 intertidal schemes were introduced in the Scheldt Estuary (Belgium) (Oosterlee and others, 2020): Lippenhook, an 8 ha flood control area using a controlled reduced tide (CRT) (studied over 10 years) and Burchtse Weel, a 13 ha intertidal habitat using full tidal exchange (FTE) (studied over 5 years). The mean elevation of the total FTE area increased by 3.65 m, coinciding with 53% of the tidal frame and a net annual sediment accumulation rate of 5,441 m^3/ha/yr, whereas the mean elevation of the total CRT area

increased by 0.22 m, corresponding to 0.68% of the tidal frame and a net annual sediment accumulation rate of 212 m^3/ha/yr. However, the sediment within the FTE was less consolidated than the CRT.

The Medmerry managed realignment scheme (302 ha) in West Sussex, UK included a single breach through the shingle bank, 7 km of new defences extending 3 km inland, 4 drainage outlets with tidal gates enabling freshwater flow during low water, and reprofiled drainage channels known as rifes (Dale and others, 2018). Between November 2015 and October 2016, 1.7 cm of sediment accreted over the site. Suspended sediment concentrations (SSC) were typically 0.11 g/l in the breach area, indicating that under ambient conditions, sediment was successfully imported into and exported out of the site.

At the Medmerry managed realignment scheme, Sussex, high SSC events typically followed the tidal cycle. Bed elevation measurements indicated that around 5 mm of sediment was accreted following inundation on the flood tide. This peaked at high water and decreased sharply during the ebb tide. By the start of the succeeding flood tide, the bed elevation had fallen to a similar level to that of the previous tide. This process was heightened during Storm Eva, where the SSC at the breach increased by 0.19 g/l during the flood tide and continued to increase during the start of the ebb tide, only decreasing during the latter part of the outgoing tide. Bed elevation measurements suggested sediment accreted during the storm as well as during the tidal cycle the following day before eroding (Dale and others, 2018).

Two 25 m breaches were created in former levees, resulting in 60 ha of saltmarsh at Port Susan in the Stillaguamish River, Washington, USA (Nowacki and Grossman, 2020). Net sediment imports to the restoration area were 3.3 to 5.5 kt over the 15 months of data collection, corresponding to 2.6 to 4.3 kt/yr. Approximately 30% of the total sediment load was, however, attributed to a landslide. Storms were also found to increase sediment transport to the restoration area from the Stillaguamish River. For example, an increased sediment flux was observed during a December 2014 storm, where winds from the south-east peaked at >15 m/s, importing about 1 kt of sediment to the restoration area. At the restoration site, sediment fluxes were greatest at water levels above 2.5 m (the approximate elevation of the former levee).

A managed realignment scheme to create 66 ha of saltmarsh at Freiston Shore, Lincolnshire, UK involved 3 breaches into the old sea wall and the creation of an artificial creek (1,200 m). Attenuation rates were found to be higher over the natural saltmarsh in front of the managed realignment (0 to 101.0 cm km^{-1}). This was potentially due to the lack of natural species variation. Water blockage against the dikes/structures confining the marsh size was observed to cause high water level amplification for over half the measured tides. This occurs when the duration of the hydrodynamic forcing is long compared to the time it takes to fill the storage area. Therefore, size of the managed realignment site is important for the saltmarsh to reach its full attenuation capacity (Kiesel and others, 2019).

980 km of marsh terraces have been constructed over the past 30 years in Louisiana and Texas, USA to combat subsidence and sea level rise. 20 of these terrace fields were

analysed in detail between 2003 and 2017 using remote sensing. Results showed more predominant deposition (55%) than erosion (45%) in the marsh terraces. 70% of marsh terraces were consistently erosional or consistently depositional, while the remaining marsh terraces fluctuated between erosion and deposition. All depositional sites had a high density of adjacent or connecting channels, suggesting that accessible sediment sources promote deposition in marsh terraces (Osorio and others, 2020).

Dredging plays a vital socio-economic role, for example, to provide safe navigation for global shipping. This may take place through the following main methods:

- mechanical dredgers that use equipment to physically excavate sediment using mechanical force, for example, backhoe dredgers and grab dredgers
- hydraulic dredgers that use equipment to both excavate and transport dredged material using water, for example, trailing suction hopper dredgers and cutter suction dredgers
- hydrodynamic dredgers such as plough dredging and water injection dredging which raise material slightly above the seabed, either by mechanical means or by injecting water into the bed to create a fluidised layer, respectively

Dredging can have long-lasting impacts on the environment; for example, it can increase water turbidity through the formation of sediment plumes, remobilise contaminated sediments, and cause damage to marine spawning grounds. With the aim of offsetting some of these impacts where dredging cannot be avoided, there is a growing interest in applying this dredged sediment for beneficial use, in other words, using dredged material in a way that will benefit society and the natural environment, to offset some of the impacts. Disposal of sediment can take place through bottom placement, mechanical placement, hydraulic placement via pipeline, or hydraulic pumping via rainbowing. One valuable way to beneficially use dredge material is to physically protect or restore declining or lost habitats such as saltmarshes and mudflats (using fine sediments) or vegetated drift lines and oyster beds (using coarse sediments). It is worth noting that BUDS can support a number of coastal habitats depending on the sediments being dredged. The Restoring Estuarine and Coastal Habitats with Dredged Sediment Handbook (Manning and others, 2021) should be referred to for further understanding of BUDS.

Baptist and others (2017) reported on a ‘mud motor’ project in the Wadden Sea, Netherlands. Here, mud was dredged from the port of Harlingen and disposed of at a location where tidal flows could transport the material to a nearby intertidal area and saltmarsh, therefore, creating a ‘mud motor’. This took place during the storm season over an 8-month period (September to March) in 2 consecutive years. A sediment tracing experiment revealed 80% of the mud disposed of at the mud motor location reached the intertidal area where saltmarsh was desired.

The Isle of Wight Bay and Barren Island restoration projects in Chesapeake Bay, Virginia, USA used hydraulically pumped dredged material behind rubble mound breakwaters to create saltmarsh habitat, which was then planted with a variety of intertidal vegetation. This enabled saltmarsh to be established in the early stages of the project without being washed out in storm events. Overall, 1.86 ha of low marsh and 0.76 ha of high marsh was established at Isle of Wight Bay (Szimanski and others, 2019).

Swan Island in Chesapeake Bay, Maryland, USA was an uninhabited 25-acre island experiencing erosion rates of up to 2 m/yr. Nearby, the town of Ewell is only accessible by boat and highly dependent on navigation and, as such, the navigation channel gets dredged every 10 years. As part of this scheme, 46,000 m^3 of sediment was dredged and used to raise the low marsh on Swan Island by an average of 20 cm (Davis and others, 2022).

To create a marsh platform on Scofield Island, Louisiana, USA, 22 miles of pipeline was installed to convey sediment between the Mississippi River to Scofield Island, which has also been used for several further beneficial reuse projects. This used 1.3 mil m^3 of excavated sediment to create 206 ha of benefit area. As part of this project, settlement plates were installed within the marsh fill areas, which aim to provide a method of measuring long-term settlement and subsequent habitat creation (Dartez and others, 2020).

At Caminada Headland Beach, a 13.3-mile-long headland in Louisiana, USA, 2.8mil m^3 of sediment from borrow areas was used to provide habitat for nesting shorebirds. This used a cutterhead dredge and spider barge to load scow barges which were towed to 1 of 3 offshore pump-out areas. In some areas, a hopper dredge was used to excavate sediment from borrow areas and transport it directly to the offshore pump-out areas. It would then be transported via the submerged sediment pipeline to be pumped to the saltmarsh site (Dartez and others, 2020).

To accelerate sediment accumulation in West Bay, Louisiana, USA, 5 temporary earthen berms used as sediment retention enhancement devices (SREDs) were constructed over a 6-year period downstream of an artificial crevasse. These were orientated perpendicular to flow diversion and were formed from dredged sandy sediment. The SREDs diverted flow through and around the berm, reducing fetch, local scour and velocity. They provided protection and, therefore, allowed more time for suspended sediments to settle behind and adjacent to berms (McQueen and others, 2020).

Sediment dredged for navigational purposes on the Blackwater Estuary, Essex, UK was used to create saltmarsh habitat. This included raising the existing 4.5 ha of saltmarsh by up to 0.9 m. Sediment monitoring in 2018 found an additional 650 m^3 of material had naturally deposited following the 1,000 m^3 placement, while in 2019 another 850 m^3 had naturally deposited. Outside the area of intended saltmarsh, an additional 0.7 ha of new saltmarsh was created on the previously eroding bare mud at Delph Ditch (National Trust and others, 2021).

Design life and effectiveness

Bed velocity in the north-west of Northey Island, Essex was found to decrease with 30 to 50m of vegetated saltmarsh versus bare mudflat (0.1 m/s and 0.3 m/s, respectively), indicating that vegetation is more effective in dissipating wave attenuation when compared with non-vegetated areas (National Trust and others, 2021).

Lo and others (2017) used samples of Spartina spp. from 6 locations across 230 km of the Italian northern Adriatic coastline and undertook controlled experiments within wave mesocosms. Overall, the mean volume loss in vegetated cores was 16.26% for sandy cores and 7.11% for silty cores. In bare cores, volume loss was 84.37% in sandy cores and 23.44% in silty cores. Erosion was linked most significantly to the below-ground component of vegetation, while the effect of above-ground variables (above-ground biomass, stem density, shoot: root ratio) was marginal. This suggests sandy soils may require enhanced protection against wave exposure.

Generally, plants exposed to higher mean wave energy, for example, at the marsh edge, develop stress-avoidance plant traits compared to species growing more landward (Schoutens and others, 2020).

Stress-avoidance capacity of species has been observed in field studies conducted by Silinski and others (2018). They undertook field measurements at Groot Buitenschoor, Belgium, (226 ha) and the Schor van Rilland, Netherlands (186 ha) on the Scheldt Estuary (SW Netherlands) where Scirpus maritimus (seaside bulrush) vegetation is dominant. Exposed shoots were found to be more flexible, whereas shoots growing in more sheltered conditions were stiffer, suggesting a stress-avoidance strategy was assumed in exposed locations. There was also an increase in both shoot height and stem diameter between the marsh edge and the sheltered site. These variations were most evident over the first 8 m of the marsh.

The introduction of vegetation such as Phragmites australis (common reed) reduces plant biodiversity and may negatively change the marsh hydroperiod through the reduction of flood stage. This may also hinder access for nekton and the exchange of tidal materials (Weinstein and others, 2021).

In the Yangtze Estuary, Zhang and others (2022) observed that Phragmites australis (common reed, a tall and stiff Poaceae species) was more effective in reducing wave height than Scirpus mariqueter (club rush, a short and flexible Cyperaceae) due to its greater biomass and stem structure.

A study compared the characteristics of 2 pioneer tidal marsh species in the Elbe Estuary (Schoenoplectus tabernaemontani (softstem bulrush), which grows as a single stem without leaves, and Bolboschoenus maritimus (sea clubrush), which grows as a triangular stem with multiple leaves). The study found that the stems of S. tabernaemontani have lower flexural stiffness and less biomass when compared to B. maritimus. The findings showed that species with lower flexural stiffness and less biomass struggle to handle strong currents but can endure hydrodynamic forces. This creates zonation, with species at the marsh edge having these characteristics to withstand stress, while species with higher flexural stiffness and more biomass further inland better attenuate waves. To support wave-resistant species in areas of high stress, creating sheltered conditions or mimicking natural zonation during restoration or creation efforts is beneficial (Schoutens and others, 2020).

Schoutens and others (2021) studied Schoenoplectus tabernaemontani (softstem bulrush), which grows as a single stem without leaves, and Bolboschoenus maritimus (sea clubrush), which grows as a triangular stem with multiple leaves in a brackish part of the Elbe Estuary (Germany). Irrespective of site elevation, distance from the marsh edge and incoming wave height, wave height and flow velocities were lower in the B. maritimus areas than the *S.* tabernaemontani areas. *S.* tabernaemontani is more flexible, bending during waves and not reducing drag. B. maritimus, which allows for a greater reduction of drag due to the greater number of leaves. However, these are susceptible to breakage during high wave and current exposure.

Rupprecht and others (2017) studied wave interaction with Puccinellia maritima *(*common saltmarsh grass*)* and Elymus athericus (sea couch grass) (NW European saltmarsh species) within a 310 m long wave flume. Under high water levels (2 m) and long wave periods (4.1 s), orbital velocity reduced by 35% within the flexible, low-growing Puccinellia canopy. Contrastingly, in the more rigid, tall Elymus canopy, deflection and folding of stems occurred and there was no significant effect on orbital velocity. Under low water levels (1 m) and short-wave periods (2.9 s), Elymus reduced near-bed velocity more than Puccinellia. Under high orbital velocities (≥74 cm/s), flattening of the canopy and an increase of orbital velocity was observed for both Puccinellia and Elymus. Stem folding and breakage in Elymus was observed at a threshold orbital velocity of ≥ 42 cm/s, which coincided with a levelling-off in the marsh wave dissipation capacity. Puccinellia did, however, survive even extreme wave forces without physical damage. After the breakage of Elymus stems, turbulence around the stumps remaining on the marsh surface was noted to increase bed shear stress and erosion through local scour. The study, therefore, recommended wide species diversity to allow for differences in recovery and rates of dissipation.

Marsh monoliths were excavated from Phragmites australis (common reed) marshes in front of a dike along the Scheldt Estuary (Dutch-Belgian border area) and installed in flume experiments under varying velocities and water depths for 2 hours. 83% of the above ground P. australis stems did not break, suggesting a high capacity to withstand high flow velocities. Of these, 66.5% had a less than 25° bending angle at the end of all flume runs (Schoutens and others, 2022).

To explore the effect of salinity, Zhu and others (2019) studied 3 species dominant to lower marshes: Spartina anglica (common cordgrass) for saline areas, Scirpus maritimus (seaside bulrush) for brackish areas, and Phragmites australis (common reed) for freshwater areas. Increasing salinity tended to induce a shift from species with tall shoots and high flexural stiffness towards species with shorter and more flexible stems. Raised salinity levels in the low marsh can induce a shift from stiffer species such as Phragmites towards more flexible species such as the brackish marsh pioneer Scirpus and the salt-water pioneer Spartina.

Seedlings of pioneer species with contrasting biophysical traits were tested under storm conditions in laboratory experiments (Schoutens and others, 2021). Comparison between species showed:

- seedlings of Spartina anglica (common cordgrass) and Puccinellia maritima (common saltmarsh-grass) showed little damage
- schoenoplectus tabernaemontani (softstem bulrush) seedlings had more than a 57% chance of remaining upright
- the absence of leaves in *S.* tabernaemontani lowers their above ground biomass, which reduces the frontal area and the experienced drag
- bolboschoenus maritimus (sea clubrush) seedlings showed damage from wave exposure, with 26% of B. maritimus seedlings remaining upright

Schoutens and others (2021) concluded that all observed losses of B. maritimus and *S.* tabernaemontani shoots occurred mainly where the stem met the roots. Shoots started to become damaged at higher bending angles (> 18°), however, seedlings of B. maritimus had the greatest bending angles and the deepest scour holes, which resulted in partial uprooting due to the loss of anchoring strength from the roots. B. Maritimus and S. tabernaemontani are, therefore, more vulnerable to storm waves in the first growing season and should be considered in conjunction with other species when planting new saltmarsh vegetation (Schoutens and others, 2021).

To study the effects of inundation time, species studied included Elymus athericus (sea couch) for the high marsh, Suaeda maritima (herbaceous seepweed) and Aster tripolium (sea aster) for the low marsh, and Saliconia procumbens (glasswort) for the pioneer zone. All examined species showed seasonal variability in biomechanical properties, while the variation trend is species-specific. For instance, flexural strength of Spartina was highest in winter (December), whereas it was lowest for Scirpus in the same season (Zhu and others, 2019).

Schoutens and others (2019) studied wave attenuation over 50 m transects of saltmarsh in the Elbe Estuary (Germany) over a 17-month period. Wave heights were found to be attenuated up to 50% in summer and 10% in winter. Above ground biomass was lowest during winter months (<50 g/m^2), increased rapidly in May and peaked in August (700 to 900 g/m^2). No annual change to below ground biomass was observed. Wave attenuation capacity is, therefore, strongly reduced in winter; however, this is when incoming wave heights are at their highest during storm events which is when marsh-induced shoreline protection is most needed.

In the Yangtze Estuary, in the summer, 50 m of mature Scirpus mariqueter (club rush) provided more than 40% of wave attenuation, with Phragmites australis (common reed) contributing to the remainder. However, in the spring and winter, 100 m of Scirpus marsh was needed to achieve the same wave attenuation efficacy that 25 m of Phragmites could achieve (Zhang and others, 2022).

Ma and others (2023) undertook flume tests of flattened and standing Scirpus mariqueter (clubrush) collected from Nanhui in the Yangtze Estuary (China) to represent winter conditions of saltmarsh. The damping coefficient of waves in flattened vegetation was between 33.6% and 72.4% of that observed in standing vegetation of an equivalent length. Furthermore, as water depth increased, the wave orbital velocity decreased, yielding a smaller drag, and, therefore, reducing wave attenuation. As the water level rose, wave energy also moved upward, resulting in reduced wave energy due to interaction with the deeply submerged flattened vegetation. This was reflected in a reduction in the wave damping coefficient for flattened vegetation which reduced more than that for standing vegetation. The wave damping coefficient for standing vegetation dropped 16.7% from 0.066 /m to 0.056 /m, while flattened vegetation dropped 36.8% from 0.038 /m to 0.024 /m when the water depth increased by 20% from 0.5 m to 0.6 m.

In the Scheldt Estuary (Belgium/The Netherlands), changes in above ground biomass through the growing season resulted in a varied wave attenuation rate (Silinski and others, 2018).

In San Francisco Bay (Foster-Martinez and others, 2018) measurements were taken during summer and winter to examine seasonal fluctuations in wave attenuation due to changes in above ground biomass throughout the year. The study found that the drag coefficients calculated for S. foliosa and S. pacifica were similar. This would suggest that equal amounts of vegetation would lead to similar wave attenuation. However, s. pacifica has much denser biomass close to the bed and retains that biomass throughout winter, whereas s. foliosa dies back in the winter. The die-back results in larger waves in winter. The study found that attenuation was most pronounced at lower water depths when the vegetation was emergent, regardless of the season.

Marin-Diaz and others (2022) noted that although vegetated silty and sandy established saltmarshes in the Wadden Sea (Netherlands) have different sediment/soil properties, they were equally stable compared to bare tidal flats. Established marsh vegetation is, therefore, theorised to have a greater influence on foreshore stability.

Marshes with thinner cohesive and/or fine-grained top layers are more sensitive to lateral erosion than marshes with deep cohesive soils, independently of the adopted management practice. Compaction by large grazers did, however, lead to thinner fine-grained layers and lower elevation, potentially leading to more inundation under sea-level rise (Marin-Diaz and others, 2021).

Dartez and others (2020) noted that the composition of sediment was important when using dredged material for beneficial reuse. For example, in the SOBA (Scofield Offshore Borrow Area), Louisiana, USA strata of sandy, silty and clayey sediment with a mean grain size of 0.10 mm and a percentage of silt ranging from 18% to 43% was noted to be ideal sediment for marsh creation.

Amato and others (2022) planted small-scale (~10 m) plots of Juncus roemerianus (black needlerush) in 2 sites (33 m and 16 m in length) in the northern Gulf of Mexico that experienced significant wave energy. These were planted at 50% or 100% initial cover or unplanted. The experiment was, however, unsuccessful in securing growth and expansion of saltmarsh as wave energy was too high. Coir logs in different formations were consequently applied to attenuate waves, enabling greater saltmarsh expansion. This suggests that managed realignment in isolation may not be sufficient for the development of saltmarsh habitat, and that additional structures or interventions may also be needed to increase the probability of success.

Converse and others (2020) undertook laboratory experiments using rock, oyster shell and tree root wad sill structures at the toe of the saltmarsh and found that sills may enhance wave breaking over saltmarshes, as shown by the wave transmission in the table below. The reflection coefficient was lowest in all trials for the no-sill condition and largest for the rock sill; this was proportional to the size of the scour pocket on the seaward side of the structure. Under all wave conditions, the waves over the no-sill scenario broke further towards shore or at the shoreline, compared to the sills which generally broke at the sill. Scour is, therefore, more likely to occur to the saltmarsh under the no-sill scenario, whereas the sills can act sacrificially. The percentage reduction under varying conditions is shown in Table 1 below.

Table 1. Percentage wave reduction over varying hydrodynamic conditions and marsh sill types (Converse and others, 2020)

Sill type	Low water level + storm waves	Low water level + average waves	High water level + storm waves
No sill	40%	30%	0%
Oyster sill	80%	60%	20%
Rock sill	75%	65%	20%
Tree wad sill	63%	60%	10%

All structures also increased bedload transport on the seaward side of the sill under storm conditions (0.05 m^3/m/day for oyster and rock sills, 0.06 to 0.11 m^3/m/day for root wad sills), while also reducing bedload transport on the sill rear slope between -0.15 to -0.3 m^3/m/day under all conditions (Converse and others, 2020).

A study used a probabilistic model to quantify how constructed saltmarshes reduce flood risk in the long term (100 years), compared to dike heightening only. The study found that implementing artificial high zones and breakwaters on saltmarshes can significantly enhance the reliability of flood defences at relatively low costs. A foreshore featuring high zones proves even more cost-effective than dike heightening, particularly when constructed well above mean high water levels. However, without human interventions, such as breakwaters and high zones, saltmarshes lose their effectiveness due to sea level rise and the lack of natural sediment accretion. Periodic earthmoving from the pioneer zone to the high zone is an alternative for achieving sustained flood risk reduction. Sheltering structures like brushwood or bamboo dams promote sediment accretion, eventually yielding similar foreshore effects to instant construction via nourishment. Nevertheless, the ongoing maintenance expenses and delayed safety benefits associated with brushwood dams detract from their appeal as a flood risk reduction strategy (Vuik and others, 2019).

In Florida, USA, 2 designs of living breakwalls (using tree branches) with different porosities showed that for a porosity of 0.7 where branches were bundled, wave transmission rates varied between 9% and 70%, with an average of 53%, and for a porosity of 0.9 where branches were not bundled, wave transmission rates were mainly between 70% and 84%, with some reaching 100% transmission (Safak, Angelini and others, 2020).

Sediments gathered within living shorelines showed an increase in organic matter, silt and clay content compared to control treatments. Moreover, gabions — wire cages filled with seasoned oyster shells — resulted in successful establishment and robust reef development. However, optimal oyster growth occurred where gabions were positioned at lower intertidal elevations. Additionally, the saltmarsh cordgrass, shielded by the living shoreline structures, maintained stability or even advanced at a rate of approximately 1 m per year. Conversely, cordgrass in control treatments retreated at nearly double that rate, around 2 m per year (Safak, Norby and others, 2020).

Aranda and others (2022) studied 7 geomorphological diachronic maps of saltmarsh in the San Vicente de la Barquera estuary (northern Spain) between 1956 and 2017. They identified a 20% reduction in saltmarsh extent since 1956, with most significant losses from the lowest elevations of saltmarshes. The lost saltmarsh mainly turned into mudflats. The limit between saltmarsh and mudflat is generally found to be around 0.5 m above mean sea level (MSL). Relative sea level rise should, therefore, be considered when designing and creating new saltmarsh habitats.

A number of thin layer sediment placement projects were undertaken at the Seven Mile Island Living laboratory, New Jersey, USA, with instalments of sediment ranging between 750 m^3 and 37,500 m^3. Tedesco and Chasten (2019) found that applying sediment in instalments improved the structure of bird nesting habitats. This enabled a sacrificial berm to be created with sandier sediments for edge protection, while the unconfined marsh sediment placement strengthened nesting habitat for wading birds.

National Trust and others' (2021) use of dredged sediment for a beneficial reuse scheme at Northey Island, Essex noted erosion in the form of sediment loss during the winter period measured at 15 m^3 (approximately 0.5% of the total volume placed). Such losses were anticipated in the design; therefore, a greater volume of dredged sediment was initially deployed. Furthermore, starting works in the spring was recommended to maximise the opportunity for generating natural growth.

Chirol and others (2024) studied the evolution of creek networks across 10 managed realignment sites across the UK between 2 to 20 years post breach. They observed that creek systems initially exhibit less branching complexity compared to fully developed natural systems (with a maximum creek order of 2 to 4 compared to 3 to 5), and feature lower sinuosity and broader channels across all orders. Nevertheless, following 5 years of evolution, the branching complexity escalates to align with that of natural systems in later stages, while sinuosity generally rises across most creek orders. Additionally, the morphologies of managed realignment creek networks continue to be significantly shaped by the initial creek template, as illustrated by the presence of unnaturally straight creeks inherited from previous drainage ditches.

Rezek and others (2017) found that Spartina density, above ground biomass and below ground biomass were generally similar between restored and natural marshes in Nueces Bay, Texas, USA 4 to 5 years after restoration, suggesting that managed realignment schemes can effectively replicate natural saltmarshes.

Across a wider UK study on managed realignment evolution, Chirol and others (2024) noted that schemes at Abbotts Hall, Allfleet and Tollesbury, Essex started out predominantly at the elevation of a mudflat (below mean low water neap), and 8 to 12 years after breaching have not yet reached the elevation of a lower marsh (between mean low water neap and mean high water). However, areas that began at the elevation of a lower marsh (Paull Holme Strays [Yorkshire], Chowder Ness [Lincolnshire], Welwick [Yorkshire], and parts of Alkborough [Lincolnshire] and Freiston [Lincolnshire]) have risen to middle to upper marsh elevation levels (above mean high water) 6 to 9 years after breaching, suggesting pre-breach landscaping should be designed higher in the tidal frame.

Considering the unvegetated-vegetated ratio (UVVR), Castagno and others (2022) found that for low-intensity wave conditions, the average percentage decrease in wave energy ranged from 91.9% at 33% vegetated to 98.7% at 90% vegetated. For high-intensity wave conditions, average percentage decreases in wave energy ranged from 97.8% at 33% vegetated to 99.7% at 90% vegetated. Overall, an optimal vegetation coverage was considered to be 50%, where there was a 95% decrease in wave energy for the first 100 m of marsh for all morphology types.

Through the calibrated and validated hydrodynamic model in Delft3D-Flow for the managed realignment site of Freiston Shore, Lincolnshire, Kiesel (2021) found that vegetation is necessary for wave attenuation. In the 200-year tide event, wave attenuation was found to switch to wave amplification when vegetation was completely absent.

Mi and others (2022) found through numerical modelling of the Chongming Dongtan Shoal wetland on the Yangtze River, China that mudflats attenuated wave heights by 24% at the boundary, while marsh without vegetation reduced wave height by 50%, and saltmarsh with vegetation reduced wave height by 70%. Under varying storm conditions (50 to 5,000-year return levels), there was a larger contribution of wave dissipation from marsh morphology (65 to 78%) compared to the vegetation itself (22 to 35%).

In low elevation sites, tidal introduction results in high flooding frequencies, duration and water depths, creating bare mudflats or areas of open water rather than vegetated tidal marshes (Oosterlee and others, 2020).

Chirol and others (2024) note the importance of managed realignment size across a review of the evolution of creek networks as a result of managed realignment. This research revealed that the managed realignment creeks experiencing the most rapid changes are those primarily influenced by volumetric factors, such as the cross-sectional area of breaches and the volume of the creek. This is because erosive activities near the breach occur earlier than the deposition-driven processes responsible for creek expansion, owing to the heightened hydrodynamic energy in the breach zone, rendering that part of the site highly dynamic. For example, at Freiston, the breach area expanded by ~10 m^2/yr over 12 years after implementation, while at Steart, Somerset, UK, the breach cross-sectional area increased by ~71 m^2 /yr over 2 years. However, as most of the creek length and volume for a managed realignment is clustered around the breach area, the marshes are found to be left poorly drained.

Following the managed realignment scheme at Steart Marshes, Pontee and Serato (2019) noted the size of exit channels associated with managed realignment sites are likely to be proportional to the tidal prism of the site and inversely proportional to the number of breaches. Sites with larger tidal prisms are likely to be larger in size, have lower elevations, and experience higher tidal ranges. In macro- or hyper-tidal environments, if initial creek levels surpass natural equilibrium levels, it is probable for a step feature to recede into the site. The inclusion of man-made creeks in design may, therefore, encourage the erosion process. The extent of erosion in breach and exit channel areas depends on the difference between the ‘as constructed’ channel dimensions and the final equilibrium dimensions.

Castagno and others (2022) undertook SWAN (Simulating Waves Nearshore) modelling of different marsh morphologies, including the width of the leading edge of the saltmarsh. Under low-intensity wave conditions, a 40 m leading edge with ~85% vegetation cover was found to reduce wave energy by at least 80%. Under medium-intensity wave conditions, a 30 m leading edge at 50% vegetation cover was found to provide the same reduction. Under higher-intensity wave conditions, even thinner, leading edges at higher vegetation ratios provided more than 75% reduction in wave energy. A 10 m vegetated edge was reported to still provide >50% reduction in wave energy at low-intensity conditions and >80% reduction at high-intensity conditions.

Considering marsh morphology, Castagno and others (2022) also found that marshes with a leading mudflat performed better than channelled and ponded marshes and nearly as well as the fully vegetated scenarios. This is likely due to a combination of consistent vegetation, uninterrupted by major topographic features, and the general ability of the system to reduce wave heights and subsequent wave energy through increasing marsh platform elevation and decreasing water depth.

Kiesel and others (2022) used a calibrated hydrodynamic model in Delft3D-Flow for a managed realignment site in Freiston Shore, Lincolnshire to understand the influence of breach width. It was found that (when full vegetation coverage was assumed) the 10-year return event would require a breach width of >1,148 m to be attenuated, the 50-year event a width of >1,247 m, the 100-year event >1,277 m and the 200-year event requires at least

1,302 m. Furthermore, high water level attenuation rates were -4 cm km^{-1} for a 118 ha area with a 900 m managed realignment width, and an area of 145 ha and 1,100 m width, 2 cm km^{-1} for a 180 ha area and 1,320 m width, and 7 cm km^{-1} for a 205 ha area and 1,500 m width. At the open coast, larger managed realignment widths are, therefore, necessary for the most effective attenuation.

Jung and others (2019) modelled marsh terraces in Terrebonne Bay, Louisianna, in Delft3D. Terrace designs included a chevron (V-shape) with 100 m spacing, 200 m spacing, linear, box, and T-shape. Box style terraces were found to be the preferred design in terms of effectiveness; chevron and linear designs also were effective for perpendicular wind and wave direction. Deeper water depths between terraces increased sediment retention. Sediment type was found to be the most significant factor for determining terrace stability.

Cousins and others (2017) deployed stone-gabion and clay-filled terraces (7 of the 12 terraces were colonised by 12 species of plant, most commonly Salicornia sp*.,* reaching a maximum coverage of 85) as a soft engineering approach to repair damaged sea walls in estuarine embayments in Mersea Island and Tollesbury, Essex, UK. Over 22 months of monitoring, 7 of the 12 terraces found net deposition towards the sea wall and erosion towards the seaward edge of the terraces. There was net accretion across the terraces, the largest recorded being 12 cm. Elevation was found to be the most influential variable to saltmarsh recruitment where recruitment increased as terrace height approached the height of the existing marsh.

The levels between mean low and high water using a constant digital terrain model (DTM) are often used to calculate potential saltmarsh areas and their locations (Weinstein and others, 2021).

Effective computational modelling of managed realignment schemes must consist of a fluid portion, ideally using a 3-dimensional incompressible Navier–Stokes equation; sediment, modelled under Eulerian or Lagrangian frameworks; vegetation dynamics, often simplified as rigid cylinders, but with potential to be modelled considering flow–structure interaction to account for plant flexibility, as well as more complex geometries; and mass transport, able to be modelled using an advection–diffusion–reaction equation, with the appropriate boundary conditions. Although this process is time consuming and costly, without this, modelling can be oversimplified (Tinoco and others, 2020).

The numerical modelling of the Steart Marshes managed realignment scheme, using MIKE21, only considered the tidal exchange. However, monitoring of the project showed that freshwater drainage had a significant impact on the erosion of the existing creek network. Freshwater drainage, therefore, also needs to be considered within habitat creation models (Pontee and Serato, 2019).

McKee Smith and Anderson Bryant (2018) validated saltmarsh attenuation in Jamaica Bay, New York using a nearshore spectral wave model, STeady-state spectral WAVE (STWAVE).

Zhang and others (2020) designed a new drag coefficient formula to account for saltmarsh plant flexibility. This was validated in North Hangzhou Bay, China under combined macro-tidal and storm surge conditions. Although water depth was found to be the most dominant factor in the formula, the findings also suggest that vegetation flexibility needs to be accounted for within future saltmarsh models.

Similarly, Zhu and others (2019) used a stem bending strength coefficient which can feed into a stem breakage model to predict storm wave-induced vegetation loss. From this prediction, wave attenuation during extreme conditions could be calculated.

This formula was extended by Ma and others (2023) using wave flume tests of flattened and standing Scirpus mariqueter (clubrush) to validate an empirical formula for a wave attenuation indicator. This is thought to be able to be implemented into large-scale models such as SWAN, Xbeach, and TOMAWAC to evaluate the impact of vegetation on wave properties.

To understand wave attenuation and drag over vegetation, typically 2 calibration approaches have been established based on local wave height decaying by a reciprocal function (α) and an exponential function (k). Zhang and others (2021) undertook 99 laboratory experiments to confirm that both functions are applicable for submerged vegetation, however for emerged vegetation, k can lead to underestimated values of the drag coefficient (Cd).

A multivariate scaling relationship has been developed by Hewageegana and others (2022), which combines the effects of channel geometry and surge scales on water level attenuation by the saltmarsh.

Mi and others (2022) compared implicit (differentiating saltmarsh to its surroundings by a Mannings coefficient) and explicit (considering each plant individually), vegetation modelling of saltmarshes. The dissipated wave height was approximately 76% from the implicit vegetation modelling, and 84% from the explicit vegetation modelling, highlighting the differences in these techniques. However, explicit modelling was more computationally costly, taking 17 hours to run a model compared to 6 hours for the implicit model.

Maintenance

Marin-Diaz and others (2021) conducted soil core extractions from marshes varying in age, subjected to different grazing management practices (including cattle, hare/geese, and artificial mowing), and located at various elevations at Schiermonnikoog (Netherlands). Wave flume experiments revealed that the erosion resistance of the fine-grained layer was positively influenced by several factors:

- the presence of large grazers, which compacted the soil through trampling
- mowing activities that excluded soil-bioturbating species
- grazing by small grazers, which encouraged the growth of vegetation types with higher root density

Marin-Diaz and others (2021) suggest that large grazers, such as cows, can increase lateral erodibility at sites that are transitioned from coastal grazing marsh under managed realignment. The historic land use results in soil compaction, increased soil bulk density and root density due to trampling.

In coastal studies across Europe and the Americas, grazing decreased all measures of above ground plant material (height, cover, aboveground biomass, litter), which could limit the ability to reduce wave attenuation (Davidson and others, 2017).

5.1.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for water resources, air quality, soil or water quality derived from saltmarsh and mudflat management/restoration specifically.

Climate regulation

Davidson and others (2017) found that soil carbon increased with grazing in European coastal grazing marshes which are often converted to saltmarsh during managed realignment schemes.

MacDonald and others (2020) assessed carbon stocks and greenhouse gas fluxes at Hesketh Outmarsh West, Lancashire and Inner Forth, Clackmannanshire, Fife, and Stirling) to calculate the annual net benefits to climate change mitigation. The benefits were found to be greater in realigned marshes compared to natural marshes. The greatest component (over 98%) of the total carbon stock at the sites was found to be held in the soil.

The additional and enhanced saltmarshes at Northey Island, Essex, UK are estimated to generate 12 T of greenhouse gas flux moved from an erosive situation (potentially releasing carbon) to a depositional one (storing carbon). Through analysing total organic carbon (TOC) in sediment samples, this includes 7 T of carbon locked up within the saltmarsh over the lifetime of the project (National Trust and others, 2021).

Mossman and others (2022) monitored the carbon accumulation as a result of the 250 ha managed realignment scheme at the Steart Marshes, Somerset, UK. The sediment that accumulated across the Steart Marshes between October 2014 and September 2018 (average of 75 mm/yr), was found to have a high carbon content (4.4% total carbon, 2.2% total organic carbon). This resulted in an estimated carbon accumulation of 36.6 t/ha/yr total carbon (19.4 t/ha/yr total organic carbon). The calculated carbon emissions linked to the site's construction accounted for approximately 2 to 4% of the total carbon build-up observed throughout the study duration. This reinforces the notion that managed realignment initiatives in similar environments could yield substantial carbon sequestration advantages. It should, however, be noted that the sediments from the natural saltmarsh had significantly higher total carbon (4.72 ± 0.58%) than the newly accreting sediment on the restoration site (4.37 ± 0.50%).

Amenity

MacDonald and others (2020) noted that the annual number of car visits to Hesketh Outmarsh West (Lancashire) more than doubled from 2,158 to 4,949 after the creation of a managed realignment (MR) site.

The Geltinger Birk realignment scheme (northern Germany) saw an influx of visitors; 89% of first-time visitors and 71% of regular visitors came for walking, followed by biking and/or to watch wildlife. First-time visitors especially liked the landscape (40%), walking tracks (20%), wild horse and Galloway cattle herds (13%) and, to a lesser degree, the quietness and views. Regular visitors especially liked nature and landscape (59%), wildlife (11%), as well as walking and cycling tracks (11%). Overall, 80% of all visitors highlighted the outstanding nature experience (Schernewski, Bartel and others, 2018).

At Northey Island, Essex enhanced saltmarshes were measured to introduce 2,500 to 3,000 visitors annually, doubling during the Covid-19 pandemic. This was assisted by educational events and the annual 'castaway' event hosted on the island (National Trust and others, 2021).

The realigned embankments at the Geltinger Birk realignment scheme (northern Germany) provided 30 km of walking paths (Schernewski, Bartel and others, 2018).

2 km of walking paths and improvements to the existing walking paths were applied to the Markgrafenheide-Hütelmoor (Germany) restoration scheme (Schernewski, Schumacher and others, 2018).

The Lower Otter, Devon intertidal restoration included improvements to public footpaths (3.7 km public footpath raised/enhanced), a new footbridge at breach location, and opportunities for footpaths to be designed to be more disability friendly, supporting the South West Coast Path (Burgess-Gamble and others, 2023).

Szimanski and others (2019) noted the Isle of Wight Bay, USA restoration also included an accessible viewing platform.

Kurth and others (2022) found that educational programmes were introduced at San Francisco Bay wetland restoration.

Burgess-Gamble and others (2023) found that the Lower Otter, Devon intertidal restoration scheme reached adults and children through educational talks and site visits. This project also provided freely available educational packs, interactive materials and resources for students at all levels.

Rahman and others (2019) highlighted that a restoration project in Nova Scotia (Bay of Fundy) was used as a part of the climate adaptation training, working with government departments to develop softer skills, for example, planning and communication.

The Island of Ewell, Chesapeake Bay, Maryland is only accessible by boat and, therefore, highly dependent on navigation. As such, the channel gets dredged approximately every

10 years. This dredging could be combined with the restoration of Swan Island saltmarsh/ mudflats, providing benefits to the marshes as well as to the people on Ewell (Davis and others, 2022).

Routine maintenance dredging was carried out on the federal navigation channel in Louisiana; between 2011 and 2015, 28 x 10^6 m^3 of dredged sediment was used to create 6,526 ha of saltmarsh in West Bay, thereby providing benefits for both navigation and saltmarsh creation (McQueen and others, 2020).

Smith and others (2017) noted that managed realignment schemes provide an opportunity to create new setback defences, offering FCRM benefits where defences may be failing from both the defences and the habitat created. This has been evident on the Missouri River where flooding in 2011 resulted in infrastructure requiring repairs, rehabilitation or replacement. Restoring this infrastructure would provide protection to a 1:80-year event, whereas a setback defence would provide protection for a 1:125-year event. Similarly, the levee system in Hamilton City, California has a 45% chance of safely passing a 10% AEP event; the new setback system was able to improve the standard of protection to a 90% confidence level in passing a 1.3% AEP event.

Biodiversity

The Marconi offshore project (Port of Delfzijl, Netherlands) incorporated a large wetland area by guiding freshwater flow towards the estuary, encouraging an estuarine gradient, and allowing the implementation of fish passages (Baptist and others, 2017).

The tidal wetland restoration in San Francisco Bay, USA included 16 islands for nesting birds, 97 ha of shallow water habitat for shorebird foraging, and 52 ha of tidal wetlands, enabling a range of habitats (Kurth and others, 2022).

The Lower Otter (East Devon) saltmarsh restoration project included 2 raised bird islands using cut out creek network excavations (Burgess-Gamble and others, 2023).

The Barren Island saltmarsh restoration (Chesapeake Bay, USA) saw an increase in waterfowl populations to over 6,400 individuals in the following winter, post-restoration (Szimanski and others, 2019).

Following completion of the beneficial use of dredged sediment scheme at Northey Island, Essex, bird surveys conducted over a 32-month period recorded that the average number of species per survey increased from 0.5 to 2.83, while the average number of birds counted increased from 13.3 to 88 (National Trust and others, 2021).

5.2 Beach nourishment

5.2.1 Flood risk reduction evidence

This section sets out advances in our understanding since 2017 of the effectiveness of beach nourishment from an FCRM perspective and the scientific confidence in what we know.

Effect on wave attenuation: process understanding

Almarshed and others (2020) assessed multiple hybrid coastal structures and identified that when a rubble-mound structure or vertical wall is combined with a sand dune, during storm conditions the sand dune acts as a buffer and forms sediment deposits in the foreshore, which reduces the wave energy hitting the structure.

Ludka and others (2018) found that the 344,000 m^3 of sand nourishment used to protect low-lying homes at Imperial Bay, Southern California mitigated coastal flooding by wave overtopping but elevated the water table, inducing groundwater flooding.

Nordstrom and others (2018) studied the 2011 beach nourishment campaign at Fire Island in New York and found it was too high to be overtopped by waves. This resulted in the development of a prominent scarp in the foreshore as the beach had not yet achieved an equilibrium slope as late as 5 months after nourishment.

Effect on sedimentation and geomorphology: process understanding

A study completed on the sand engine in the Netherlands found that beach scarps (defined as near vertical seaward-facing sandy cliffs 2 to 3 m high) can form in areas of eroding coastlines where beach nourishment has been carried out. This has been linked to mildly erosive summer storm conditions, whereby erosion occurs without excessive overwash of the nourishment platform. This leads to further steepening of the upper beach profile and eventual beach scarp formation. This can restrict aeolian transport and dune formation (Van Bemmelen and others, 2020).

Prevention of beach scarps could be designed by predicting expected run-up and altering nourishment volumes to change platform height. High platform nourishments will promote the formation of beach scarps, and steep initial profiles increase the speed at which scarps form (Van Bemmelen and others, 2020).

Initial beach steepness influences the rate at which a beach scarp forms under erosive conditions, whereas platform height influences beach scarp height and the frequency of removal by hydrodynamic controls (overwash and/or inundation). By predicting the expected run-up elevation during storm conditions, the platform height could be designed to reduce the formation (and/or increase the destruction) of beach scarps (Van Bemmelen and others, 2020).

Profile nourishment involves the placement of sand in the nearshore waters with the expectation that sand will either reduce wave energy reaching the beach or naturally nourish the beach through onshore sediment transport (Elko and others, 2021).

A study of a large-scale nourishment project at Nags Head, North Carolina, USA found that all beaches experience profile adjustment, which is the response of the beach to changing wave heights and water levels. Beaches absorb and dissipate wave energy, with the universal response being a flattening of the profile as wave energy increases. A flatter profile provides a broader wet-sand beach over which wave energy is reduced (Kaczkowski and others, 2018).

Although nourishment may provide habitat space, it may 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).

The idea of large-scale nourishment is to deposit a significant amount of sand in one location. This material is then gradually redistributed across and along the shore by natural processes (for example, wind and waves). By making use of natural processes to redistribute the sand, this approach aims to reduce the disturbance of local ecosystems. Sandscaping, a method of beach nourishment, is the most cost-effective option for erosion protection that would also mitigate any negative impacts on the beaches and associated communities down drift (Vikolainen and others, 2017).

Placing sediment fill at the elevation of the natural storm berm allows for natural interaction between the beach and landward habitat. This reduces the likelihood for development of an erosional scarp in the beach and restricts the amount of sediment transported inland by wind (Nordstrom and others, 2018).

Under present conditions, sediment bypassing and maintenance dredging do not provide sufficient sediment to counteract local erosion. Adding fill material on the bayside to mimic artificial fans can deliver sediment alongshore in a way that replicates the erosional stage of the fans without replicating the natural depositional phase that would involve storm-wave overwash and be accompanied by loss of preexisting upland or marsh habitat (Nordstrom and others, 2018).

Beach nourishment creates a wider beach which provides an effective source for aeolian transport. Estuarine beaches are characterised by narrow widths with limited backshore development, so the potential for aeolian transport can greatly increase with only small amounts of sediment fill (Nordstrom and others, 2018).

Pagán and others (2018) focused on 3 gravel beaches in urban areas of the province of Alicante in the south-east of Spain. In 2002, Campello Beach was nourished with 470,000 m^3 of sand, Villajoyosa Beach was nourished with 90,400 m^3 of sand and Calpe Beach was nourished with 31,500 m^3 of sand. The nourishment of these 3 studied gravel beaches with sand caused part of the finer grained sediments to infiltrate between the coarser gravel grains, resulting in partial loss of the contributed material. Also, the change in median sediment size caused the formation of a new beach profile within the first few years.

Increases to estuary and bay water depth due to dredging can destabilise shorelines by modifying wave processes and redirecting swell energy to shorelines, and creating sediment sinks (Fellowes and others, 2021).

Dredging and land reclamation can lead to retreating and relict shorelines if new sediment sinks are created and if wave energy is redirected through dredged channels. Meanwhile, groynes and sand nourishment are measures that can be successful in creating quasi-stable shorelines if interventions consider the altered wave or sediment conditions within a modified estuary or bay (Fellowes and others, 2021).

Effect on sedimentation and geomorphology: observed evidence

Van Bemmelen and others (2020) completed 39 surveys at the sand engine in the Netherlands between August 2011 and January 2017 following 21.5 million m^3 of nourishment in 2011. They documented beach scarps in 18 of the 39 surveys, with heights estimated between 0.3 m and 1.3 m. Based on video observations, it was determined that the formation of these scarps took place between R2% and R15% wave run-up elevation, that is, the wave run-up in metres that 2% and 15% of waves exceed.

Beach nourishment projects are usually placed at slopes steeper than equilibrium due to the time lag between initial placement and profile adjustment.

Kaczkowski and others (2018) found an important feature of beach profile equilibration at both of their studied sites at Nags Head in North Carolina and Bridgehampton-Sagaponack in New York, where both exhibited significant natural dune growth after nourishment via aeolian transport. The extra volume and elevation in the dunes have provided a higher level of storm protection, and helped both sites avoid any major damage to oceanfront properties during hurricanes or severe winter (Kaczkowski and others, 2018).

Van Bemmelen and others (2020) studied the sand engine in The Netherlands and found that beach scarps are more likely on nourished sites with high platform elevations and steep initial beach slopes. Scarps are mostly present along the most seaward part of the nourishment and are generally not observed at the same location for long periods of time. The temporal variability reveals a cycle of formation, migration and destruction of beach scarps on scales of a season or smaller. The emergence of beach scarps coincides with spring and early summer periods (March to July). During winter months (November to February), while waves are typically more energetic, very few scarped sections are present.

There is a significant loss of surface coverage in the first years after nourishment, possibly due to sand infiltration between gravel spaces and the formation of the new profile (Pagán and others, 2018).

The accelerated particle weathering test was used to analyse Campello, Villajoyosa and Caple beaches in Alicante. It found that the beach with the highest proportion of quartz is the one that behaves worst in the accelerated particle weathering test. This could be due to the presence of dolomite which has a higher resistance (Pagán and others, 2018). Based on their study, Pagán and others (2018) found that gravel beaches have an advantage over sandy beaches due to the capacity of energy absorption, because of the infiltration of the waves between the gaps of the material.

Clipsham and others (2021) carried out analysis of the short-term response of the scheme during the first 6 months after nourishment and how this affected the long-term prediction. The main findings of the analysis were that there was seaward movement of sediment but no loss of sediment to deep water, enabling it to recover in summer. Large amounts of sediment were displaced from the upper beach to the foreshore as the beach moved to a more natural profile.

Although storms and dredging generally reduce beach widths, in Pittwater Estuary and Kamay in the Sydney metropolitan area in New South Wales, Fellowes and others (2021) found that repeated sand nourishment increased the net beach width by 12.9 m between 1943 and 2017 (approximately 0.17 m/year). However, this is not the case at all beaches, with one example in Kamay which had overall width reduced by 13.2 m (approx. 0.18 m/year).

The 'sand motor' in the Netherlands consisted of 21.5 million m^3 of sand extracted from 10 km offshore and deposited as a hook-shaped peninsular, 2 km wide, extending 1 km offshore and up to 5 m above mean sea level. In the first 4 years, the sand motor provided 1 million m^3 of sand to the southern coastline and 1.5 million m^3 to the northern coastline. The resulting feature is expected to exceed the initial design life of 20 years (Vouk and others, 2021).

Design life and effectiveness

Nordstrom and others (2018) suggest that sediment bypassing is effective when accretion rates updrift of structures are similar to erosion rates downdrift, the quantities bypassed are adjusted to these rates, and bypassing continues through time. At Sailors Haven in Great South Bay, New York, net movement is away from the nourished site, so bypassing does not appear to be a viable method.

The most important design parameters of the Dutch sand engine are the required volume and its anticipated design life. To limit the spatial extent of the sand engine and thereby ensure that the port remains undisturbed, the design life is set to one year. To account for the erosion expected in one year, the sand volume applied in the sand engine should be at least equal to the expected yearly undisturbed longshore sediment transport capacity (Van Der Spek and others, 2020).

Elko and others (2021) observed that in the US most federal beach nourishment programmes are now designed for a 50-year life cycle, with multiple, planned nourishment that address losses due to background erosion and episodic events.

A study site in Portonovo Bay along the Adriatic Coast had subtle changes in terms of polychaete abundance and community structure when compared to controls, possibly due to beach nourishment, although the role of other factors cannot be ruled out. The paper concludes that small-scale beach nourishments appear to be an eco-sustainable approach to contrast coastal erosion (Danovaro and others, 2018).

Clipsham and others (2021) looked at the functional life of the Bacton to Walcott defences and the estimated life of the nourishment in front of the terminal. Evidence showed that the performance of defences was not significantly sensitive to a change in timing and the volume of nourishment.

Kaczkowski and others (2018) found that at Nags Head in North Carolina, ~ 22% of the 3.5 million m^3 of total nourishment volume shifted into the foredune within the first 5 years. At Bridgehampton–Sagaponack in New York, ~ 12% of the 1.95 million m^3 of total nourishment volume shifted to the foredune within the first 3 years. The results of the composite profiles show the foredunes average 0.6 m taller and 12 m wider in 2016 than before nourishment. Average profiles also confirm the beach face shifted seaward by ~ 20 m, and the underwater portion had more volume in 2016 than in 2010.

Clipsham and others (2021) discussed how the uncertainties relating to future climate change were embedded into the design of the sandscaping scheme at Bacton in Norfolk. An appropriate allowance for sea level rise was included within the scheme's targets. Changes to wave angle, wave height and sediment loss offshore were tested to confirm the impact on the scheme's key performance indicators. The indicators looked at the functional life of the defences and the estimated life of the nourishment; this helped to confirm its viability and affordability in business case terms.

Maintenance

Van Der Spek and others (2020) studied the coast along west Africa; the paper discusses the maintenance of a harbour access channel in Lekki, Nigeria. A sandbar breakwater and sand engine should be constructed in an integrated way to preserve the alongshore sediment balance along the coastline. Due to its dynamic character, the sandbar's width and height should be monitored, especially in the first years after construction. A minimum required width at different levels has been defined as a critical limit for applying maintenance to ensure a sufficient body. Maintenance can then be performed relatively easily by placing or moving sand to the most critical locations by waterborne, but preferably by land, equipment. Sediment balance should be incorporated in a maintenance chain, whereby, for instance, before sand bypassing takes place, replenishment is performed by importing sand from elsewhere.

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).

Vikolainen and others (2017) have reviewed sandscaping as part of the 'Building with Nature' approach, which uses the principles of the sand engine in the Netherlands. As part of this, 19 potential locations for sandscaping were identified in England and Wales.

Vikolainen and others (2017) looked at the Bacton Gas Terminal coastal defence scheme in North Norfolk where the sandscaping solution would be fine-tuned through detailed design and environmental impact assessment; and could see somewhere in the order of 2 million m^3 of sediment with a functional life around 20 years implemented in the coming years.

5.2.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for water resources, air quality, climate regulation, soil or water quality derived from beach nourishment specifically.

Amenity

The arguments for beach nourishment are typically focused on the economic benefits of beaches. Economic activity, often driven by tourism-related expenditure, significantly increases in areas with nourished beaches (Porro and others, 2020).

Beach nourishment may offer a more flexible, no-regrets solution to erosion. A no-regrets solution provides benefits which exceed costs, regardless of the effects of climate change or sea level rise. If sea level rise-induced erosion is less than projected, nourishment still offers the benefits of sustaining visitor activity and maintaining recreational and cultural use of beaches (Porro and others, 2020).

Biodiversity

Following analysis of the short-term response of a beach nourishment scheme in Bacton, Norfolk, UK, similar analysis was carried out for the subsequent summer period to determine to what extent the beach has recovered. This included ornithological surveys during the 2019 and 2020 breeding season to record any species of bird breeding on the section of beach and cliff face where nourishment was carried out. The monitoring showed that sand martins, prevalent along this section of coast, returned and successfully bred following the scheme’s construction. The successful hatching of at least one brood of ring plover was also observed. Overall, it can be concluded that the scheme did not adversely impact the viability of bird breeding in the area (Clipsham and others, 2021).

During the first 4 years of monitoring of the sand engine in the Netherlands between 2011 and 2015, an additional 40 species of birds were regularly observed (Vouk and others, 2021).

5.3 Sand dune management

5.3.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of sand dune management from an FCRM perspective and the scientific confidence in what we know.

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 (NRW) 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 the 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.

Effect on wave attenuation: process understanding

Maximiliano-Cordova and others (2021) completed a field-based study on 3 beaches in Mexico which evaluated the effect of plant communities, beach and dune topography before and after a storm event. The study demonstrated that plant roots contribute to strengthening the cohesiveness of the sand dunes, while the above-ground plants slow wave uprush, and reduce wave overtopping and overwashing.

Fernández-Montblanc and others (2020) evaluated the effectiveness of dune system rehabilitation as a disaster risk reduction (DRR) measure under current and future sea level scenarios at a rapidly eroding coastline in Bellocchio, Italy. The design of the dune reconstruction and revegetation was performed according to the morpho-dynamics and ecosystem characteristics of the existing dune system. The findings suggest vegetated dune systems play an important role in favouring a positive or near equilibrium coastal sediment budget. They capture sediment during landward wind episodes, reducing sediment erosion during overwash and overtopping episodes under storm conditions.

Laporte-Fauret and others (2021) carried out an experiment on a 4 km stretch of coastal dunes in south-west France where experimental notches were excavated in the incipient foredune and established foredune. It was noted that during the past century, most of the European coastal foredunes have been stabilised by reprofiling, planting vegetation and fence installation and/or beach nourishment. The objective was to build stabilised dunes to buffer storm waves and surge, and to limit sand transport to the back of the dune, thereby protecting the area from flooding and/or sand burial.

Biel and others (2017) examined how invasive beach grass management affects 3 ecosystem services (coastal protection, western snowy plover conservation, and endemic foredune plant conservation) in the U.S. Pacific Northwest coastal dune ecosystem. The study noted that invasive beach grasses harm plover productivity yet build foredunes that reduce the risk of wave overwash and erosion. It also found that mechanical beach grass removal reduces invasive beach grass abundance and foredune height.

Maximiliano-Cordova and others (2019) researched the role of plants in conferring dune resistance in Mexico. Results showed that sand dunes helped to reduce the landward extent of erosion, the impact of waves (swash, collision, overwashing, and inundation), and the degree of damage to property by dissipating wave energy and reducing/preventing flooding.

Effect on wave attenuation: observed evidence

During the design of dune reconstruction and revegetation based on morph-dynamics and dune ecosystem function, Fernández-Montblanc and others (2020) noted that wave run-up is controlled by beach slope and wave characteristics. On dissipative and intermediate beaches under extreme storm conditions, the swash run-up and run-down of long-period waves becomes dominant, as the surf zone becomes saturated. This acts to control dune erosion, overwash and overtopping.

Jenks (2018) analyses the potential of sustainable achievements for immediate and extensive restoration of New Zealand's coastal dune ecosystem. He notes that new and gentle lower profile accretionary dune slopes are rapidly established soon after planting. These increasingly advance seaward from old degraded and eroding scarp faces, ensuring these improved dunes and beaches are consequently predisposed to effectively dissipate the swash energy of subsequent storm waves.

Jenks (2018) also demonstrated how a new beach berm and foredune were created as a result of planting halophyte coastal plants in Papamoa, New Zealand. This 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.

During an investigation into how invasive beach grasses affect ecosystem services on Pacific Northwest coastal dune ecosystems, Biel and others (2017) found that beach grass removal and elevated storm surge further increased the likelihood of overtopping.

Maximiliano-Cordova and others (2019) explored whether the functional richness of plant species helps to reduce wave erosion on embryonic coastal dunes in the Gulf of Mexico. The experimental design consisted of 8 conditions to which the artificial dunes were exposed, including:

- control
- no vegetation
- 1 single species
- 2 species
- 3 species

The findings support the theory that coastal dunes may attenuate and dissipate wave energy, fix sediments and mitigate erosion and subsidence.

Feagin and others (2019) conducted wave flume and field experiments to assess whether planting vegetation increases the protective capacity and reduces erosion of coastal dunes. The study found that dune plants primarily reduced erosion by attenuating wave swash and run-up bores with their stems and leaves, while their roots initially enhanced erosion through uprooting. During extreme events, waves might cease to be the predominant hydrodynamic force impacting dune survival. Instead, when the dune is completely submerged, buoyancy and changes in pore pressure among sand grains could assume greater significance. Furthermore, wave attenuation by the above ground portions of plants was found to be the primary mechanism through which erosion is reduced.

Konlechner and others (2019) examined the abundance of 6 early colonising dune-building species across 71 beach foredune sites in south-east Australia to predict the response of foredune plant communities to increased erosion. The study indicates that foredunes are valued due to their role in mitigating coastline erosion and flooding, and, in many regions, have been encouraged to form or been created as defences against coastal hazards.

Effect on wave attenuation: modelled evidence

Output results from the hydro-morphodynamic XBeach model show that the combination of dune reconstruction and revegetation provides the best solution to minimise the impacts of coastal erosion and flooding under current and future sea level scenarios (Fernández-Montblanc and others, 2020).

Effect on sedimentation and geomorphology: process understanding

Generally, beach vegetation, such as vines and grass cover, can assist in the accretion and stabilisation of sand at the top of the beach (Ellison, 2018).

Maximiliano-Cordova and others (2021) monitored the topography and vegetation at 3 beaches in Mexico before and after the impact of a single winter storm in September and November 2019. The study demonstrated that plant roots contribute to strengthening the cohesiveness of the sand, while the above-ground plant parts slow wave uprush and reduce wave overtopping and overwashing. This displaces the wave breaking point seawards and deaccelerates the undertow close to the shoreline.

Vegetated dune systems play an important role in favouring a positive or near equilibrium coastal sediment budget. Fernández-Montblanc and others (2020) assessed dune reconstruction and revegetation on a beach in Italy. The study suggested that dune systems capture sediment during landward wind episodes, which reduces sediment erosion during overwash and overtopping episodes under storm conditions.

After extreme storms, plants contribute to the beach recovery processes, as the vegetation traps the sediment transported by onshore wind and contributes to incipient dune formation (Fernández-Montblanc and others, 2020).

Jenks (2018) investigated the sustainable restoration achievements on a coastal dune ecosystem in New Zealand and noted that indigenous low stature herbaceous littoral species are tolerant to salt spray and sand inundation. These pioneer species possess naturally sparse growth that ensures effective non-turbulent deceleration of onshore wind velocity to a point where sand grains entrained by the wind become too heavy to remain suspended, and become deposited, often within the most critical seaward 5 to 10 m of the foredune zone.

Walker and Zinnert (2022) examined above and below ground traits of 4 dominant dune grasses on the Atlantic and Gulf Coasts of North America to document the potential for species-specific effects of dune growth, maintenance and erosion resistance. The findings demonstrate that species with greater below ground biomass reduce sediment loss under both wave and wind erosional regimes.

Feagin and others (2019) suggested that dune plants primarily reduce erosion by attenuating wave swash and run-up bores with their stems and leaves, while their roots initially enhanced erosion through uprooting. Furthermore, herbaceous non-grass species situated at the lower beach level, and most seaward zones were found to have the most efficient structures for erosion reduction. Macroalgal communities, seagrasses, halophytic reeds and terrestrial species have also been found to perform erosion protection by modifying near surface current velocity profiles.

Konlechner and others (2019) examined the abundance of 6 early colonising dune building species across 71 beach foredune sites in south-east Australia. The aim of this study was to predict the response of foredune plant communities to increased erosion. The findings suggested that foredunes are the direct result of the interaction between vegetation and aeolian processes, whereby the growth of dune building plants causes localised reduction of wind velocities and the deposition of sand. Burial was found to stimulate the growth of dune building plants, facilitating further sand deposition in a sequence of events that can culminate in foredune development. Foredune development principally depends on plant density, distribution, height and cover, as well as wind and sand transport.

D’Alessandro and others (2020) completed 2 pilot field studies along the Salento coast in southern Italy to test an innovative colloidal silica-based consolidation technique for coastal sand dunes restoration. The proposed colloidal silica-based technique aims to reduce the:

- near-surface wind effect
- impact of more frequent minor storms
- events that continue to erode the base of coastal dunes

Van Der Biest and others (2017) completed a study aiming to underpin the added value of dynamic versus fixed dunes. Dynamic dunes along erosive coasts were found to gradually lose the frontal dunes as a result of progressive erosion. Parts of the mobilised sand will be blown into the inner dunes, turning them into dynamic systems and allowing the dunes to migrate transgressively inland over time. If no space is available at the inner margin of the dunes (for example, due to the presence of properties and infrastructure), additional measures such as beach nourishment are needed to guarantee coastal safety.

A study from the Westhoek nature reserve (~340 ha) on the north-west coast of Belgium reported that water quality regulation and climate regulation are typically associated with well-developed dune soils (an accumulation of organic matter). Therefore, regulation is considered to be low in younger dune deposits along the shoreline, yet they become increasingly important as dunes develop and evolve (Van der Biest and others, 2017)

Laporte-Fauret and others (2021) completed an experiment on a 4 km stretch of coastal dunes in south-west France where experimental notches (EN) were excavated in the incipient foredune. 2 experimental notches were excavated in November 2018; one in the incipient foredune and the other in the established foredune. The excavation of the foredune notches affected sediment transport, promoting either vertical accretion or more landward sand deposition. The disturbance generated by these new sand deposits significantly affected vegetation diversity and composition, inducing an increase in species richness due to the colonisation of ruderal species.

The effects of the excavated notches were strongly dependent on location. Only the experimental notch within the established foredune promoted landward sand transport, while showing similar evolutionary characteristics to natural blowout. The experimental notch located in the incipient foredune was found to rapidly infill after excavation during the first winter storms (Laporte-Fauret and others, 2021).

Biel and others' (2017) investigation on invasive beach grass management notes that regions with shallow-sloping nearshore environments and wide beaches (dissipative beaches) provide greater area for wave energy dissipation to occur than regions with moderate- to steep-sloped nearshore environments and narrow beaches (intermediate, and reflective beaches).

Pinna and others (2017) described the conservation and restoration of habitat at a site in the provinces of Cagliari, Matera and Caserta (Sardinia). The study demonstrated that sand-trapping fences are considered one of the most important interventions affecting the morphology and vegetation on sandy coasts. The fences trap the wind-blown sand and increase the likelihood that plant species outweigh the stressors from the wind, aeolian sand transport and salt spray. Coir mesh made of coconut husk and cane structures for sand capping were positioned in all study areas; these measures enabled stabilisation of sand particles and protected seedlings.

Effect on sedimentation and geomorphology: observed evidence

Maximiliano-Cordova and others (2021) completed a field-based study along 3 beaches on the coast of Veracruz (Mexico) which evaluated the effect of plant communities, beach and dune topography before and after a storm event. The effect on plant communities was evaluated in terms of diversity and cover. The role of plants in conferring against erosion was then examined to assess the impact on geomorphology. The results showed that:

- patterns of erosion depended on the local geomorphological attributes and pre-existing conditions, beaches with higher dunes are less likely to be eroded and overwashed than those that are flatter; wider beaches with more gentle slopes and shorter incipient dunes were more erodible
- the impact of a winter storm on the plant communities was most often observed on inland plant species; plant cover and diversity would decrease after the impact of the storm and species dominance would change, but dune building plants were tolerant to the storm and increased their plant cover, demonstrating an ability to tolerate harsh storm conditions

- the protective role of plant-cover and species richness was site dependent and was only noted where erosion was less intense; this coincided with high dune areas and narrower beaches

Van Der Biest and others (2017) examined 5 different ecosystem services in a case study in Belgium with the aim of underpinning the added value of dynamic versus fixed dunes. They describe that when sand is deposited, shoots rapidly grow through it and the new sediment is bound by the root network. Vegetation of fixed dunes is not adapted to large amounts of sand burial and will die off. Woody vegetation is also more prone to erosion and damage as stems are less flexible, meaning that they are unable to adjust their form during high winds, unlike dune-binding grasses.

Jenks (2018) noted that increasingly natural processes are being observed as a result of a significant number of restoration schemes in New Zealand. The study data shows that the beach water table was higher in front of the marram dunes compared to the native plant dunes, meaning water drains more easily into the beach sand adjacent to dunes dominated by native plants. This favourable attribute enhances upper beach face accretion. The beach profiles showed that the beach was higher and wider in front of the native plant dunes. This study also investigated the role of natural nutrient inputs by beach-cast seaweed. It found that its consistent storm-related occurrence and subsequent decomposition adjacent to, or on, exposed foredunes provides important nutrients that naturally boost plant growth on temperate-zone beaches, a natural ecosystem continuum. This habit consequently led to increased trapping and accretion of sand.

Konlechner and others (2019) examined 6 early colonising dune building species in south-east Australia. Species-specific differences in the ability to mitigate coastal erosion have also been identified. Changes to coastal processes have been identified even when the original vegetation is replaced by a functionally similar species. These changes in dune morphology were due to slight differences in congener morphology (for example, the extent of lateral spreading growth) and their respective responses to burial. Differences in lateral growth rates have also been linked to variation in alongshore dune shape. Such studies suggest that even relatively subtle species-specific differences can have significant implications for coastal landscapes.

Ellison (2018) outlined how ecosystem-based adaptation can be used to integrate biodiversity conservation and ecosystem services. This study discusses the use of dune rehabilitation techniques on narrow Pacific Island beaches. The study suggests that ecosystem-based adaptations such as defining access pathways and natural recovery of trampled vegetation, combined with community engagement foster the reduction of erosional impact caused by human activities. It will also increase the resilience of beaches to climate change variability and provide alternative soft-engineering approaches that are both low cost and can be effectively applied and managed by local communities.

Pinna and others (2017) investigated the restoration used at priority habitats in Sardinia. Restoration was promoted by sowing native germplasm (seeds from local, native species) and ensuring the eradication of invasive plants.

Hilgendorf and others (2022) monitored a recently restored foredune in the Humboldt Bay National Wildlife Refuge (California, USA) biannually between 2015 and 2021 to characterise the impacts of dynamic restoration on foredune form and resilience. This research included 2 control plots (native and invasive) and 3 restored, revegetated plots with different types of native species. The restored and natively vegetated foredune plots exhibited enhanced foredune resiliency, compared to foredunes that were invasively vegetated. Dune ramp rebuilding, following scarping, was quicker along natively vegetated foredunes (1.5 years), compared to along the invasive foredune plot (3.5 years). This is likely driven by enhanced sediment connectivity in the lower-density, natively vegetated plots.

D’Alessandro and others (2020) made preliminary observations of 2 pilot field studies in southern Italy. They set up an intervention consisting of different operational phases irrigation, perforation, and injection.

1. **Irrigation phase** mineral colloidal silica-based grout was sprayed on the exposed dune face.
2. **Injection phase** a fill valve was used for the injection of the mineral colloidal silica-based grout inside the dune.
3. **Perforation phase** a tube was temporarily inserted vertically by hand to a depth of 0.5 m within a mesh 0.3 x 0.3 m.

The results of D’Alessandro and others (2020) show that mineral colloidal silica increases the mechanical strength of non-cohesive dune sediments allowing for the reduction in the volume of dune erosion and dune scarp retreat rate. Visual observations of the dune before and after the intervention identified an improvement in vegetation growth and an average deposit from 0.1 to 0.3 m of sand on the exposed dune face.

Fernández-Montblanc and others (2020) investigated the role of dune vegetation in controlling storm impact at an eroding coastline in Bellochino, Italy. Several factors affecting dune system reduction were identified, such as land use changes driven by services linked to tourism and recreational development; the presence of invasive species causing ecosystem and geomorphological changes; and human and natural causes behind the reduction of sediment supply in coastal areas.

Ellison (2018) outlined how ecosystem-based adaptation can be used to integrate biodiversity conservation and ecosystem services relating to dune rehabitation techniques on Pacific Island beaches. The study suggests that ecosystem-based adaptations (for example, clearly defined pathways, natural recovery of trampled vegetation and community engagement) results in a reduction of erosional impact caused by human activities. It also increases resilience to climate change and provides low cost, soft-engineered approaches that can be effectively applied by local communities.

Conery and others (2020) collected high resolution terrestrial LiDAR of dune morphological evolution along 100 m of open coast at Nags Head, North Carolina, USA. The results of the study showed managed dunes grew 1.7 times faster than the unmanaged dune, due to greater sediment supply and enhanced sediment capture through fencing and planting.

Effect on sedimentation and geomorphology: modelled evidence

Mendoza and others (2017) undertook wave flume experiments consisting of a horizontal berm and narrow dune. This was used to validate a numerical model using CSHORE. Both sets of modelling found that the presence of dune vegetation did not significantly modify the beach profile dynamics or the dune erosion regime; its role was only retarding the erosion, by slightly attenuating hydrodynamics.

Design life and effectiveness

D'Alessandro and others (2020) demonstrated that a silica-based consolidation method used on dunes has the capacity to mitigate the erosion process globally associated with natural and human forcing (population and development growth, rising sea level and increasing vulnerability to more frequent and intense wind/wave storms).

Eichmanns and others (2021) investigated sand trapping fences as a nature-based solution for coastal protection in Germany. The study identifies that the extent of expected storm surges differs strongly based on location. A severe storm surge is achieved in the German Baltic Sea at a water level of 1.5 m above the mean water level, whereas a water level of 2.5 m above mean high water constitutes a severe storm surge. Due to the differences in storm surge magnitude, the coastal protection strategies differ among various localities, including different uses of sand trapping fences. The fences vary in terms of their characteristics (for example, height, porosity and relative position on the beach).

Winters and others (2020) developed a high resolution robust unmanned aerial vehicle (UAV) based monitoring strategy to observe dune construction and evolution. The field-based investigation was located along the Cardiff Living Shoreline project in northern San Diego, California. The study suggests that a buried cobble berm toe may provide additional erosion protection and stability to the dune, and even as sand erodes, the berm could potentially migrate landward and continue providing protection. The cobble and rock create large void spaces, which enhance infiltration processes, limit erosion and potentially stabilise the dune toe and sand covering. The 'soft' portion of the structure (vegetation, sand) provides protective benefits (reducing flow velocities, minimising transport) and adapts to coastal forcing, while the hard structure provides a traditional protective measure. This, therefore, confirms that mitigation options often work most effectively with a combination of measures.

Mendoza and others (2017) aimed to improve the understanding of the behaviour or nature-based coastal defences by analysing the morphodynamic response of a dune-beach system with vegetation to storms. The 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 retarding erosive processes by slightly attenuating hydrodynamics.

Maintenance

Carro and others (2018) investigated the potential for beach and sand dune ecosystem-based adaptation (EbA) strategies to cope with extreme events and sea-level rise at Kiyú on the Uruguayan coast.

They implemented several management approaches and summarised the benefits of each option in terms of ease of implementation. Monitoring measures were implemented as a means of informing management decisions, including the provision of maintenance. The measures included:

- sand captor fencing for dune recovery - easy to implement; low cost; rapid results
- signposting - easy to implement, low cost
- monitoring - easy to implement; low cost; allows cross-comparison

5.3.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for water resources, air quality, climate regulation, soil or water quality derived from sand dune management specifically.

Amenity

Carro and others (2018) demonstrated a case study of ecosystem-based adaptation measures to increase coastal system resilience to extreme weather events at Kiyu (Uruguay). The study notes that ecosystem-based adaptation measures can have benefits to environmental and human issues, including:

- increased resilience and preservation of sandy ecosystems
- stakeholder engagement
- protection of bluffs
    - traffic security
    - improvements in beach quality and accessibility
- environmental education and community ownership
- short-term management with early warnings of sand loss and community involvement

Biodiversity

Laporte-Fauret and others (2021) carried out an experiment in 2018 on a 4 km stretch on a coastal dune in south-west France where notches were excavated in the incipient foredune and established foredune. The study noted that coastal dunes provide a wealth of ecosystem services, including natural and efficient protection from eroding storms, limiting flood risk, pollutant filtration and provision of bird nesting sites.

Bolt and others (2019) described how the Kennedy Space Centre (Florida, USA) is located on a barrier island and is at a continued high risk of erosion and flooding due to climate change. The research focused on this case study to investigate the option of adaptive managed retreat to address shoreline erosion. A main finding from this study was that the use of dunes as a form of green infrastructure appears to be an effective strategy for the simultaneous protection of NASA assets and conservation of important wildlife habitat.

5.4 Reefs

5.4.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of reefs from an FCRM perspective and the scientific confidence in what we know. The original directory did not have a section on reefs and so the scientific papers are those published after 2017, while noting that there is substantial evidence before this period.

Effect on wave attenuation: observed evidence

Chowdhury and others (2019) studied the placement 0.6 m high oyster reefs on the eroding intertidal mudflat at Kutubdia Island (Bangladesh). As a result, waves were dissipated 95 to 100% by the reef at water levels less than 0.5 to 0.6 m. At water levels greater than 1 m, the smaller waves were not dissipated by the reef structures, however dissipation was observed for the larger waves (40 to 50 cm).

Marin-Diaz and others (2021) studied the installation of biodegradable artificial reefs along 630 m of tidal flats on the Dutch Wadden Sea. The structures attenuated on average 30% of wave height for water levels below 0.5 m, with a maximum wave height reduction of 60%.

Vien (2022) undertook a field study in a microtidal estuary on the Atlantic coast of Florida, to test configurations of oyster reef structures constructed from bagged oyster shells. This involved both continuous and gapped structures situated 3 m and 12 m from the edge of existing black mangrove vegetation. Structures further from the shore in deeper waters exhibited more variable and lower wave attenuation rates (-6% to 36%). Greater wave attenuation rates (30 to 70%) were observed at structure closer to the short and in shallower waters. This attenuation rate was also greater than that observed pre-placement (0 to 10%). Generally, attenuation rates decreased with increasing water depth and structures near the shore in shallow water provided greater wave energy attenuation.

Ma and others (2018) undertook flume testing as part of a study to install an artificial submerged reef in Beidaihe, China. The reef was found to cause more dissipation than reflection to attenuate the waves. It reflected more short period waves than long period waves, which were mainly dissipated by the reef, while the short period waves were largely transmitted. The dissipation effect of the reef increased with wave height and period as greater wave breaking occurred as the wave passed over the reef. After the reef, the wave crest became steeper and the wave trough flatter, causing a highly asymmetrical wave shape.

Effect on wave attenuation: modelled evidence

Godfroy and others (2017) utilised 1D SWAN modelling in Galveston Bay, Texas, USA at 2 locations subject to wave action. The study found that when positioned near the targeted zone for reducing wave heights, oyster reefs reduce wave height in shallow water.

Effect on sedimentation and geomorphology: observed evidence

Over the past 12 years, 89 oyster reef restoration projects have occurred in Mosquito Lagoon, Florida. The rate of erosion before and after the oyster reefs were installed has reduced from -0.03 m/yr to 0.06 m/yr. Over the total oyster restored shoreline, the rate of change has reduced from -106.89 m^2/yr to +182.02m^2/yr. Furthermore, before the oyster restoration, 50% of sites were eroding; since the oysters have been restored, 68% sites are now accreting (McClenachan and others, 2020).

Over a 10-year period, La Peyre and others (2022) studied experimental reefs implemented in 2009 in an estuarine lake in Louisiana, USA. At low wave exposure shorelines, the oyster reefs were found to reduce retreat from 1.6 ± 0.2 m/yr to 0.6 ± 0.1 m/yr. At medium wave exposure shorelines, the oyster reefs were found to make limited difference in retreat, reducing from 1.1 ± 0.07 m/yr to 1.1± 0.1 m/yr. As such, the oyster reefs were not considered to provide sufficient shoreline protection in this environment and would need to be implemented with another measure.

Chowdhury and others (2019) studied the placement of 0.6 m high oyster reefs on the eroding intertidal mudflat at Kutubdia Island (Bangladesh). As a result, 29 cm of clayey sediment accreted on the leeward side of the reef, enabling the seaward expansion of saltmarsh. This led to reduced erosion of 54% compared to the control sites. Overall, oyster reefs encouraged average accumulation of 0.11 m^3 of sediment/ m^2 of area. Marin-Diaz and others (2021) studied the installation of biodegradable artificial reefs along 630 m of tidal flats on the Dutch Wadden Sea. During the first measurement period, maximum accretion was 6 cm compared to 3 cm at the control plots. Overall, local sediment accretion of up to 11 cm was recorded. However, the effect did not expand beyond 10 m from the landward edge of the structures. Furthermore, up to 10 cm of scouring was observed on the seaward side of the reef. The nearshore sediment properties were also not affected by the presence of the artificial reefs.

Vien (2022) undertook a field study in a microtidal estuary on the Atlantic coast of Florida, assessing oyster reef continuous and gapped structures (constructed by bagged oyster shell); located 3 m and 12 m from the edge of existing black mangrove vegetation. Surveys showed within 3 years of reef formation, significant sediment deposits (418.5 m^3) accumulated between the reef and shoreline. Accumulation was 20% greater behind reef further from the shore than those nearer the shore. Little difference between gapped and continuous reef plots was noted. In terms of sediment composition, the organic matter content of shoreline sediment increased from 10.6 g/kg to 32.0 g/kg. Sediment closer to the shore coarsened after reef creation.

Observations from oyster reefs in the Dutch Scheldt Estuary found that shell content peaked at the marsh margin, suggesting that oyster reefs can provide natural reinforcement to saltmarshes (Fivash and others, 2021).

Design life and effectiveness

Wiberg and others (2019) assessed the effectiveness of wave attenuation by oyster reefs in shallow coastal bays. Generally, the 4 reefs studied decreased wave height. However, this was less (0 to 20%) for deeper water (1.0 to 1.5m) and greater (30 to 50%) for shallow water (0.5m to 1.0 m). The crest of all reefs assessed was (0.3 m and 0.5 m) below mean sea level.

Marin-Diaz and others (2021) installed biodegradable artificial reefs along 630 m of tidal flats on the Dutch Wadden Sea and observed that variability in attenuation increased when wind direction was parallel to the structure/foreshore.

Similarly, Morris and others (2021) found a critical threshold for intertidal oyster reef establishment at 50% inundation duration across 15 living shoreline sites in New Jersey, Virginia, Florida, Alabama, and Louisiana, USA. Living shorelines that spent less than half of the time inundated were not considered suitable habitat for oysters. However, they were effective at attenuating wave heights with a 68% reduction. In contrast, reefs that experienced > 50% inundation were considered suitable habitat for oysters, but wave attenuation was similar to the no reef scenario (~5% reduction in wave height). Within this study, wave attenuation was also found to be greater at natural reefs (84%) compared to restored oyster reefs (75%).

Hogan and Reidenbach (2022) monitored artificial oyster reefs along the eastern Shore of Virginia, USA, over a 4-year period. Oyster density was consistently lower on the second tier compared to the fourth tier of the oyster castle. Each castle block measured 30.5 cm by 30.5 cm. In years 1, 3, and 4, no wave attenuation was measured at the low elevation design. However, the high elevation design resulted in 13% attenuation in year 1, 21% attenuation in year 3, and 10% in year 4. These percentages represent an average across all wave conditions and water depths. Overall, design elevation had the biggest impact on wave attenuation, while the width of the reef (1 or 3 rows) had minimal effect.

Wave attenuation can be achieved not only by organisms such as oysters but by the bare artificial reefs they attach to. Hogan and Reidenbach (2022) collected data before the oyster spawning season ('year 1'), when any wave attenuation measures would be due to the bare oyster castle. The study found wave attenuation measured in year 1 was 5%, 14%, and 15%, respectively for shallow, intermediate and deep water. The wave attenuation increased to 40%, 25% and 13% for shallow, intermediate and deep water respectively in year 3 and 36%, 15% and 1% in year 4. This suggests biomass increased wave attenuation further in shallow water.

Colden and others (2017) found that in Virginia, USA patches of oysters >30 cm in height on an artificial reef supported greater oyster density, survival and complexity than those <30 cm.

La Peyre and others (2022) found that the intrusion of freshwater into oyster reef systems significantly affected the production of the reefs and consequently their ability to attenuate waves. This study was conducted in Louisiana, USA.

Dunlop and others (2017) set up flume tests comprising various configurations of oyster bags and sandbags. A single oyster bag followed by a sandbag offered the greatest stability for 1-tier structures; for 2-tier structures this increased to a single oyster bag combined with 2 sandbags. For 3-tier structures, symmetrical configurations were found to be the most stable, while asymmetrical structures were prone to rocking. Designs which were placed parallel to the wave action marginally enhanced resistance to displacement and provided increased stability against rocking.

The same study found 1- and 2-tier designs with the largest crest widths had the lowest wave transmission coefficients, ranging from 0.2 to 0.5. Furthermore, the combination of oyster bags and sandbags improved results due to the increased crest width. Structures of oyster bags on the seaward face measured the most significant decrease in wave transmission as well as the fewest reflections. For the 3-tier structure, the ‘all oyster’ bag structure, demonstrated the greatest reduction in transmitted wave height compared to the other configurations. Reduced crest heights lead to increased waved overtopping and, therefore, high transmitted waves (Dunlop and others, 2017).

Godfroy and others (2017) applied 1D SWAN modelling in Galveston Bay, Texas, USA to understand the impact of oyster reefs on wave action. The effect of oyster reefs varied with water depth, with a larger water column above the reef resulting in a smaller reduction in wave energy. If the oyster reef is far from the output location, its attenuation effect at the output is voided when compared to the original wave height propagation. In the study, when the reef was located in front of the output location, the reduction percentage increased from 9% to 64% under 10-year storm conditions. This indicates that a more nearshore reef is likely to be more effective.

Osorio-Cano and others (2019) identified that computational fluid dynamics (CFD) modelling is required to fully understand the roughness of reefs and the interactions with individual oysters. To overcome this for modelling of the biogenic reefs installed in Now Jade Resort, Mexico, the WAPOQP model (a 2D modified elliptic mild-slope equation model) contained an energy dissipation term to reproduce losses from wave breaking and bottom friction in place of using a roughness parameter.

Maintenance

In Louisiana, USA, La Peyre and others (2022) found oyster density decreased from that measured in 2009 to 2011 (>1,000 oysters/m^2) to that measured in 2019 to 2020 (<60 oysters/m^2). In 2019 to 2020, the density measured was <10% of density measured during 2009 to 2011. This was mainly due to fewer small (<75 mm) and new oysters in 2019 to 2020. The density of adult oysters remained similar between sample years. La Peyre and others (2022), therefore, determined regular monitoring is required to determine short and long-term responses to environmental variation.

5.4.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for water resources, air quality, climate regulation, amenity, soil or water quality derived from reefs specifically.

Biodiversity

Cobble berm reefs facilitate the recruitment of bivalves. For example, in Milwaukee Harbour, Wisconsin, USA cobble-sized stones were placed over limestone boulders creating a continuous network of caves. This resulted in increases of Hemimysis anomala, a shrimp-like crustacean, and rainbow smelt as well as the primary food source of nearshore game fishes such as young-of-the-year yellow perch, young-of-the-year largemouth bass and juvenile rock bass (Geisthardt and others, 2022).

Oyster reefs applied in a field study on the Atlantic coast of Florida, USA increased mean organic matter content of shoreline sediments from 10.6 g/kg to 32.0 g/kg (Vien, 2022).

5.5 Submerged aquatic vegetation (SAV) and kelp

5.5.1 Flood risk reduction evidence

This section sets out what we have learnt since 2017 about the effectiveness of submerged aquatic vegetation (SAV) and kelp from an FCRM perspective and the scientific confidence in what we know.

Effect on wave attenuation: observed evidence

Over a degraded seagrass meadow at Berre Point (France), Paquier and others (2019) observed varying positive wave attenuation rates: 0.018 m at the offshore non-vegetated section, 0.042 m at the meadow front section, 0.03 m at the in-meadow section, and 0.035 m at the meadow back edge. Notably, the most significant wave attenuation occurred at the front section of the meadow in all scenarios.

The flexibility of kelp allows individual macroalgae to move passively with the wave cycles; this minimises drag and the effectiveness of kelp at attenuating waves (Morris and others, 2019).

Effect on wave attenuation: modelled evidence

Wave energy dissipation rates for a 1D model of a suspended kelp canopy in southern Australia were 94% for 2 m of water depth. More attenuation was noted towards the outer edge of the canopy in shallower water depth. As water depth increased, the effect decreased (Bodycomb and others, 2023).

Unguendoli and others (2023) undertook Xbeach modelling of seagrass meadows at Bellocchio Beach Nature Reserve (Italy). Their study revealed an average attenuation of 32% at the storm peak and a maximum attenuation of 89% of incoming wave height.

Seagrass was also modelled to decrease maximum inundation depths by 37% and 58% respectively.

James and others (2021) applied Xbeach modelling to Baie de L'Embouchure in the Caribbean. The presence of a seagrass canopy was found to induce wave dissipation at a rate 4 times greater than that of the biogeomorphic landscape alone.

Chen and others (2022) also applied 1D Xbeach modelling to a Zostera marina (common eelgrass) meadow (50 cm in plant height and 1,000 plants/m^2 in density) and found that it was able to effectively attenuate infragravity waves, with a maximum reduction of 80.3% compared to the no seagrass case. Meanwhile, the maximum attenuation of the incident wave height was 54.5%. Under storm conditions, there was an overall reduction of 58% in wave height.

Sierra and others (2023) applied SWAN modelling to seagrass meadows on the Catalan coast (NW Mediterranean). Wave attenuation was found to be up to 10.5% on average over the meadow, with a maximum attenuation of 36.1%.

Godfroy and others (2017) used 1D SWAN modelling in Galveston Bay, Texas, USA at 2 locations that are susceptible to wave action. The study found that seagrass meadows provided a 14%, 11%, and 8% reduction in wave attenuation in the 10-, 50-, and 100-year return periods, respectively.

Effect on sedimentation and geomorphology: observed evidence

In the summer, the high shoot density and long leaf lengths in a seagrass meadow at Berre Point, France sheltered the meadow, enabling accretion in front of it. This process was evidenced by the grain-size distribution as the grain sizes were always finest in the back of the meadow. Furthermore, erosion was observed to be greatest when shoot density and leaf lengths were lowest (Paquier and others, 2019).

Effect on sedimentation and geomorphology: modelled evidence

Xbeach modelling of seagrass meadows at Bellocchio Beach Nature Reserve, Italy found that seagrass reduced erosion compared to the no seagrass case in all scenarios and was able to trap sand within the vegetation. Throughout the area, seagrass meadows reduced erosion volumes between 43% and 50% (Unguendoli and others, 2023).

Chen and others (2022) applied 1D Xbeach modelling to a seagrass meadow and found that beach erosion (the integrated sand erosion shoreward of the shoreline) was reduced from 200 m^3/m to 53 m^3/m. After a 1-week storm event was applied, beach erosion reduced by 17.5 m^3/m.

Design life and effectiveness

Morris and others (2019) found that within Port Phillip Bay, Australia, vegetation was found to be more effective at attenuating waves in shallow depths relative to the height of vegetation.

Bodycomb and others (2023) undertook 1D modelling of a suspended kelp canopy in southern Australia. This showed that wave attenuation decreased with depth from 94%, 81%, and 67% for depths of 2 m, 3 m, and 4 m, respectively.

Chen and others (2022) applied 1D Xbeach modelling to seagrass meadows. When the ‘seed planting’ technique was applied, it showed a slow growth rate for the first 10 days (5 cm shoot height) and a faster growth rate for the following 50 days (45 cm shoot growth). Mature seagrass of high leaf and shoot density provided the strongest wave attenuation and lowest beach erosion. This suggests a reduction in effectiveness during the initial seagrass growth stages. Furthermore, the study found that seagrass of the lowest leaf and most sparse shoot density provided the least protection to the coast; however, the beach erosion was still much less (72 m^3/m) than the one without seagrass (92 m^3/m).

Additionally, Chen and others (2022) found that during a simulated 1-week storm event, up to 42% of seagrass was buried by sand, reducing the current-vegetation interaction and the drag induced. SAVs may, therefore, need to be incorporated with secondary measures.

Sierra and others (2023) applied SWAN modelling to seagrass meadows on the Catalan coast (NW Mediterranean). The largest wave damping was found in water depths between 1 and 5 m and reduction only occurred when the submergence ratio was greater than 0.19. Furthermore, wave attenuation was found to be greatest with a denser seagrass canopy and a greater canopy height.

Zhu and others (2020) undertook physical modelling as well as theoretical modelling applied to the north-eastern US coast and found that compared to a dense SAV meadow in shallower water, suspended aquaculture farms, consisting of mussels and kelp, attenuated random waves more effectively.

James and others (2021) found denser seagrass meadows provided greater sediment and seabed stabilisation. Species with longer leaves had the greatest impact. The study was conducted on in-situ natural seagrass meadows in the Caribbean Sea. Grazing also impacted the level of stabilisation provided by the seagrass.

Maintenance

Pope (2019) found, as a result of the 1970’s low cost shore protection programme (USA), that using features such as rock or geotextile bags absorbs wave energy, while vegetation establishes behind it. Areas with thin sand cover over organic soil support healthy root growth and plant anchoring. Using larger plants leads to more successful planting.

Modelling

Nowacki and others (2017) used field observations to document wave-height reduction, wave-period transformation and wave-energy dissipation to inform and calibrate a spectral wave model of the study area at Chincoteague Bay, Maryland. The field observations and model results agreed when local wind forcing and vegetation-induced drag were included in the model, either explicitly as rigid vegetation elements or implicitly as large bed-roughness values.

5.5.2 Multiple benefits

Of the papers reviewed since 2017, none explicitly stated benefits for water resources, air quality, amenity, soil or water quality derived from submerged aquatic vegetation (SAV) and kelp specifically.

Climate regulation

Based on the greenhouse gas offsets achieved by a restored seagrass area in South Bay, Virginia, USA the forecast offset credits were expected to achieve $87,000 at $10 per million tonnes of carbon dioxide equivalent (MtCO2e-1), which is nearly 10% of the seagrass projects restoration cost (Oreska and others, 2020).

Biodiversity

Seagrass beds support global food security by providing nursery habitat for fish and creating expansive fishery habitat rich in fauna, which also provides trophic support to adjacent habitats and fisheries. UK seagrass beds have been found to support commercially important juvenile fish, such as plaice, pollock and herring (Unsworth and others, 2019).

6 References

ABBOTT, JULIAN, KAMARINAS, MEITZEN, FULLER, MCCOLL AND DYMOND, 2018. State-shifting at the edge of resilience: River suspended sediment responses to land use change and extreme storms. 305. Geomorphology. 49–60.

ACUÑA-ALONSO, NOVO, RODRÍGUEZ, VARANDAS AND ÁLVAREZ, 2022. Modelling and evaluation of land use changes through satellite images in a multifunctional catchment: Social, economic and environmental implications. 71. Ecological Informatics. 101777.

ADAMS, no date. Final Report of the Defra Funded ‘Shropshire Slow the Flow - Severn Tributaries’ Natural Flood Management Project. English Severn & Wye RFCC.

ADDY AND WILKINSON, 2019. Representing natural and artificial in-channel large wood in numerical hydraulic and hydrological models [Online]. 6 (6). WIREs Water. Available from: https://onlinelibrary.wiley.com/doi/10.1002. [Accessed: 28 April 2023].

ADDY AND WILKINSON, 2021. Embankment lowering and natural self-recovery improves river-floodplain hydro-geomorphic connectivity of a gravel bed river. 770. Science of The Total Environment. 144626.

AECOM AND THE NATURE CONSERVANCY, 2021. Promoting nature-based hazard mitigation through FEMA mitigation grants.

AGHAJANI, HOWLETT AND MCFADDEN, 2023a. Quantifying the Water Resources Impacts of Nature Based Solutions in the Test Catchment.

AGHAJANI, HOWLETT AND MCFADDEN, 2023b. Quantifying the Water Resources Impacts of Nature Based Solutions in the Cam Catchment. JBA, WSP.

AGHAJANI, HOWLETT AND MCFADDEN, 2023c. Quantifying the Water Resources Impacts of Nature Based Solutions in the Wensum Catchment.

AGHAJANI, HOWLETT AND MCFADDEN, 2023d. Quantifying the Water Resources Impacts of Nature Based Solutions in the Bure Catchment.

AGÓCSOVÁ, HÖGYEOVÁ, CHODASOVÁ, ONDREJIČKA, HUSÁR AND JAMEČNÝ, 2020. River Restoration as a Method Towards Harmonization of Natural Habitats in the Context of Ecological Corridors Preservation: A Case Study on the Hron River. 960 (2). IOP Conf. Ser.: Mater. Sci. Eng. 022058.

ÅHLÉN, THORSLUND, HAMBÄCK, DESTOUNI AND JARSJÖ, 2022. Wetland position in the landscape: Impact on water storage and flood buffering. 15 (7). Ecohydrology. e2458.

ALDERSON, EVANS, SHUTTLEWORTH, PILKINGTON, SPENCER, WALKER AND ALLOTT, 2019. Trajectories of ecosystem change in restored blanket peatlands. 665. Science of The Total Environment. 785–796.

ALMARSHED, FIGLUS, MILLER AND VERHAGEN, 2020. Innovative Coastal Risk Reduction through Hybrid Design: Combining Sand Cover and Structural Defenses. 36 (1). Journal of Coastal Research. 174

AMATO, ALBERTI, MARTIN, TEMPLE, SPARKS AND CEBRIAN, 2022. Do small-scale saltmarsh planting living shoreline projects enhance coastal functionality? A case study in the Northern Gulf of Mexico. 321. Journal of Environmental Management. 116025.

AMELI AND CREED, 2019. Does Wetland Location Matter When Managing Wetlands for Watershed-Scale Flood and Drought Resilience? 55 (3). J American Water Resource Assoc. 529–542.

ANDERSON AND PEACE, 2017. Ten-year results of a comparison of methods for restoring afforested blanket bog. 19. Mires & Peat.

ANTONARAKIS AND MILAN, 2020. Uncertainty in Parameterizing Floodplain Forest Friction for Natural Flood Management, Using Remote Sensing. 12 (11). Remote Sensing. 1799.

ARANDA, PERALTA, MONTES, GRACIA, FIVASH, BOUMA AND VAN DER WAL, 2022. Salt marsh fragmentation in a mesotidal estuary: Implications for medium to long-term management [Online]. 846 (157410). Science of The Total Environment. Available from: https://linkinghub.elsevier.com. [Accessed: 10 May 2023].

AUSTER, BARR AND BRAZIER, 2020. Wildlife tourism in reintroduction projects: Exploring social and economic benefits of beaver in local settings. 58. Journal for Nature Conservation. 125920.

BAIR, SEGURA AND LORION, 2019. Quantifying Restoration Success of Wood Introductions to Increase Coho Salmon Winter Habitat [Online]. Physical: Geomorphology (including all aspects of fluvial, coastal, aeolian, hillslope and glacial geomorphology). Available from: https://esurf.copernicus.org. [Accessed: 8 June 2023].

BAPTIST, VAN EEKELEN, DANKERS, GRASMEIJER, VAN KESSEL AND VAN MAREN, 2017. Working with Nature in Wadden Sea Ports.

BARNES, BATHURST, LEWIS AND QUINN, 2023. Leaky dams augment afforestation to mitigate catchment scale flooding. 37 (6). Hydrological Processes. e14920.

BARNSLEY, 2021. Quantifying the benefits of natural flood management methods in groundwater-dominated river systems [Online]. University of Southampton. Available from: https://figshare.com.

BATHURST, BIRKINSHAW, JOHNSON, KENNY, NAPIER, RAVEN, ROBINSON AND STROUD, 2018. Runoff, flood peaks and proportional response in a combined nested and paired forest plantation/peat grassland catchment. 564. Journal of Hydrology. 916–927.

BATHURST, FAHEY, IROUMÉ AND JONES, 2020. Forests and floods: Using field evidence to reconcile analysis methods. 34 (15). Hydrological Processes. 3295–3310.

BEECHENER, CURTIS, FULFORD, MACMILLAN, MASON, MASSIE, SHEANE, SMITH, WARNER AND VENNIN, 2021. Achieving net zero: A review of the evidence behind potential carbon offsetting approaches [Online]. Environment Agency. Available from: https://assets.publishing.service.gov.uk.

BENTLEY AND COOMES, 2020. Partial river flow recovery with forest age is rare in the decades following establishment. 26 (3). Global Change Biology. 1458–1473.

BERDENI, TURNER, GRAYSON, LLANOS, HOLDEN, FIRBANK, LAPPAGE, HUNT, CHAPMAN, HODSON, HELGASON, WATT AND LEAKE, 2021. Soil quality regeneration by grass-clover leys in arable rotations compared to permanent grassland: Effects on wheat yield and resilience to drought and flooding. 212. Soil and Tillage Research. 105037.

BEVEN, PAGE, HANKIN, SMITH, KRETZSCHMAR, MINDHAM AND CHAPPELL, 2022. Deciding on fitness-for-purpose-of models and of natural flood management. 36 (11). Hydrological Processes. e14752.

BEZAK, KOVAČEVIĆ, JOHNEN, LEBAR, ZUPANC, VIDMAR AND RUSJAN, 2021. Exploring Options for Flood Risk Management with Special Focus on Retention Reservoirs. 13 (18). Sustainability. 10099.

BICKLEY, HELMS, ISENBERG, FEMINELLA, ROBERTS AND GRIFFITHS, 2021. Lack of long-term effect of coarse woody debris dam restoration on ecosystem functioning and water quality in Coastal Plain streams. 40 (4). Freshwater Science. 593–607.

BIEL, HACKER, RUGGIERO, COHN AND SEABLOOM, 2017. Coastal protection and conservation on sandy beaches and dunes: context-dependent tradeoffs in ecosystem service supply [Online]. 8 (4). Ecosphere. Available from: https://onlinelibrary.wiley.com/doi/10.1002. [Accessed: 10 May 2023].

BIRKINSHAW AND KRIVTSOV, no date. Evaluating the Effect of the Location and Design of Retention Ponds on Flooding in a Peri-Urban River Catchment [Online]. 11 (8). Land. Available from: www.mdpi.com.

BLACK, PESKETT, MACDONALD, YOUNG, SPRAY, BALL, THOMAS AND WERRITTY, 2021. Natural flood management, lag time and catchment scale: Results from an empirical nested catchment study [Online]. 14 (3). J Flood Risk Management. Available from: https://onlinelibrary.wiley.com/doi/10.1111. [Accessed: 28 April 2023]

BLACKSTOCK, 2020. Yarrow Meadows - Final Report. Environment Agency.

BLAEN, KURZ, DRUMMOND, KNAPP, MENDOZA-LERA, SCHMADEL, KLAAR, JÄGER, FOLEGOT, LEE-CULLIN, WARD, ZARNETSKE, DATRY, MILNER, LEWANDOWSKI, HANNAH AND KRAUSE, 2018. Woody debris is related to reach-scale hotspots of lowland stream ecosystem respiration under baseflow conditions. 11 (5). Ecohydrology. e1952.

BLAKE, TRILL, O'BRIEN, ROBOTHAM, SCARLETT, OLD AND RAMESHWARAN, 2022. LANDWISE field surveys: How land use and soil management affects soil properties, with implications for flood risk [Online]. Available from: https://nora.nerc.ac.uk.

BLANUSA AND HADLEY, 2019. Impact of plant choice on rainfall runoff delay and reduction by hedge species. 15 (4). Landscape Ecol Eng. 401–411.

BOARDMAN, BATEMAN AND SEYMOUR, 2017. Understanding the influence of farmer motivations on changes to soil erosion risk on sites of former serious erosion in the South Downs National Park, UK. 60. Land Use Policy. 298–312.

BOARDMAN, VANDAELE, EVANS AND FOSTER, 2019. Off-site impacts of soil erosion and runoff: Why connectivity is more important than erosion rates. 35 (2). Soil Use Manage. 245–256.

BODYCOMB, POMEROY AND MORRIS, 2023. Kelp Aquaculture as a Nature-Based Solution for Coastal Protection: Wave Attenuation by Suspended Canopies. 11 (9). JMSE. 1822.

BOKHOVE, KELMANSON AND KENT, 2018. On using flood-excess volume to assess natural flood management, exemplified for extreme 2007 and 2015 floods in Yorkshire [Online]. Physical Sciences and Mathematics. Available from: https://eartharxiv.org. [Accessed: 21 August 2023].

BOLT, MERCADANTE, KOZUSKO, WEISS, HALL, PROVANCHA, CANCRO, FOSTER, STOLEN AND MARTIN, 2019. An Adaptive Managed Retreat Approach to Address Shoreline Erosion at the Kennedy Space Center, Florida. 37 (3). Ecological Rest. 171–181.

BOND, KIRKBY AND HOLDEN, 2021. Upland grassland management influences organo-mineral soil properties and their hydrological function [Online]. 14 (8). Ecohydrology. Available from: https://onlinelibrary.wiley.com/doi/10.1002. [Accessed: 30 June 2023]

BOND, KIRKBY, JOHNSTON, CROWLE AND HOLDEN, 2020. Seasonal vegetation and management influence overland flow velocity and roughness in upland grasslands. 34 (18). Hydrological Processes. 3777–3791.

BOND, WILLIS, JOHNSTON, CROWLE, KLAAR, KIRKBY AND HOLDEN, 2022. The influence of land management and seasonal changes in surface vegetation on flood mitigation in two UK upland catchments. 36 (12). Hydrological Processes. e14766.

BRADSHAW, 2023. Scientific monitoring suggests leaky dams are a success at Hardcastle Crags [Online]. Available from: https://slowtheflow.net.

BRAZIER, BENAUD, GATIS, LUSCOMBE, ANDERSON, BARROWCLOUGH, CARLESS, FREEMAN, GILLARD, GRAND-CLEMENT, HAND, MALONE, MCALEER AND SMITH, 2020. Mires on the Moors: Science and Evidence Report 2020.

BUECHEL, SLATER AND DADSON, 2022. Hydrological impact of widespread afforestation in Great Britain using a large ensemble of modelled scenarios. 3 (1). Commun Earth Environ. 6.

BURGESS-GAMBLE, MCINTYRE AND FOUQUE, 2023. Promoting Adaptation to Changing Coasts - a practical guide [Online]. Available from: www.pacco-interreg.com.

ENVIRONMENT AGENCY, 2017. Working with Natural Processes - Evidence Directory [Online]. Environment Agency. Available from: https://assets.publishing.service.gov.uk.

CARLING, LEYLAND, KLEINHANS, BESOZZI, DURANTON, TRIEU AND TESKE, 2020. Quantifying Fluid Retention Due to Natural Vegetation in a Forest Floodplain Analogue Using the Aggregated Dead Zone (ADZ) Dilution Approach [Online]. 56 (9). Water Resources Research. Available from: https://onlinelibrary.wiley.com/doi/10.1029. [Accessed: 10 May 2023].

CARRO, SEIJO, NAGY, LAGOS AND GUTIÉRREZ, 2018. Building capacity on ecosystem-based adaptation strategy to cope with extreme events and sea-level rise on the Uruguayan coast. 10 (4). IJCCSM. 504–522.

CASTAGNO, GANJU, BECK, BOWDEN AND SCYPHERS, 2022. How Much Marsh Restoration Is Enough to Deliver Wave Attenuation Coastal Protection Benefits? [Online]. Frontiers. 8. Front. Mar. Sci. Available from: www.frontiersin.org/articles/10.3389. [Accessed: 9 April 2024].

CHADWICK, 2021a. Flimby Natural Flood Management.

CHADWICK, 2021b. Buckbank Leaky Dams. West Cumbria Rivers Trust.

CHADWICK, 2021c. Natural Flood Management Performance Monitoring, Cat Gill Bund.

CHALISE, SINGH, WEGNER, KUMAR, PÉREZ-GUTIÉRREZ, OSBORNE, NLEYA, GUZMAN AND ROHILA, 2019. Cover Crops and Returning Residue Impact on Soil Organic Carbon, Bulk Density, Penetration Resistance, Water Retention, Infiltration, and Soybean Yield. 111 (1). Agronomy Journal. 99–108.

CHAMPION, 2018. Bickershaw Northern Wetland Enhancement, Slowing the Flow and Habitat Creation Completion report. The Wildlife Trust: Lancashire, Manchester, and North Merseyside.

CHAMPKIN, COPP, SAYER, CLILVERD, GEORGE, VILIZZI, GODARD, CLARKE AND WALKER, 2018. Responses of fishes and lampreys to the re-creation of meanders in a small English chalk stream. 34 (1). River Research and Applications. 34–43.

CHANDLER, STEVENS, BINLEY AND KEITH, 2018. Influence of tree species and forest land use on soil hydraulic conductivity and implications for surface runoff generation. 310. Geoderma. 120–127.

CHAPPELL, EVANS, HAMMOND, HANKIN, JOHNSTON AND ADEKANMBI, 2023. Illustrating the value of presenting NERC NFM programme findings as effective volumes at flood peaks, flood damages avoided and learning on soil as an NFM tool.

CHAPPELL, HANKIN, BIELBY AND TYCH, 2017. Quantifying flood mitigation benefits of tree planting and related interventions in Wasdale [Online]. Lancaster University. Available from: www.es.lancs.ac.uk. [Accessed: 12 September 2023].

CHEN, MULLER, GRABOWSKI AND DODD, 2022. Green Nourishment: An Innovative Nature-Based Solution for Coastal Erosion. 8. Front. Mar. Sci. 814589.

CHIROL, PONTEE, GALLOP, THOMPSON, KASSEM AND HAIGH, 2024. Creek systems in restored coastal wetlands: Morphological evolution and design implications. 921 (171067). Science of The Total Environment.

CHOWDHURY, WALLES, SHARIFUZZAMAN, SHAHADAT HOSSAIN, YSEBAERT AND SMAAL, 2019. Oyster breakwater reefs promote adjacent mudflat stability and salt marsh growth in a monsoon dominated subtropical coast. 9 (1). Sci Rep. 8549.

CLILVERD, H.M., THOMPSON, J.R., HEPPELL, C.M., SAYER, C.D. AND AXMACHER, J.C., 2013. River–floodplain hydrology of an embanked lowland Chalk river and initial response to embankment removal. Hydrological Sciences Journal-Journal Des Sciences Hydrologiques, 58 (3), 627-650.

CLILVERD, H., THOMPSON, J., HEPPELL, K., SAYER, C. AND AXMACHER, J., 2015. Removal of river embankments and the modelled effects on river–floodplain hydrodynamics. EGU General Assembly Conference Abstracts 2015, abstract 1297.

CLIPSHAM, FLIKWEERT, GOODLIFFE, COURTNELL, FLETCHER AND HESK, 2021. Bacton to Walcott sandscaping, UK: a softer approach to coastal management. 174 (5). Proceedings of the Institution of Civil Engineers - Civil Engineering. 49–56.

COLDEN, LATOUR AND LIPCIUS, 2017. Reef height drives threshold dynamics of restored oyster reefs. 582. Mar. Ecol. Prog. Ser. 1–13.

COLLINS, VERHOEF, MANSOUR, JACKSON, SHORT AND MACDONALD, 2023. Modelling the effectiveness of land-based natural flood management in a large, permeable catchment. 16 (2). J Flood Risk Management. e12896.

CONERY, BRODIE, SPORE AND WALSH, 2020. Terrestrial LiDAR monitoring of coastal foredune evolution in managed and unmanaged systems. 45 (4). Earth Surf. Process. Landforms. 877–892.

CONVERSE, WENGROVE AND LOMONACO, 2020. Observations of wave attenuation, scour, and subsurface pore pressures across three marsh restoration sill structures on a sandy bed. Shore & Beach. 14–30.

COOK, SNYDER, OSWALD AND PARADIS, 2020. Timber harvest and flood impacts on sediment yield in a postglacial, mixed-forest watershed, Maine, USA. 29. Anthropocene. 100232.

COOK AND BYERS, 2021. Case Study - School Stream - Medway NFM.

COOK AND BYERS, no date. Case Study - Alder Stream - Medway NFM.

COSGRAVE, 2017. Cleavelys Wet Woodland: City of Trees.

COUSINS, COUSINS, GARDINER AND UNDERWOOD, 2017. Factors influencing the initial establishment of salt marsh vegetation on engineered sea wall terraces in south east England. 142. Ocean & Coastal Management. 96–104.

DALE, BURGESS, NASH AND CUNDY, 2018. Hydrodynamics and sedimentary processes in the main drainage channel of a large open coast managed realignment site. 215. Estuarine, Coastal and Shelf Science. 100–111.

D'ALESSANDRO, TOMASICCHIO, FRANCONE, LEONE, FREGA, CHIAIA, SAPONIERI AND DAMIANI, 2020. Coastal sand dune restoration with an eco-friendly technique. 23 (4). Aquatic Ecosystem Health & Management. 417–426.

DANOVARO, NEPOTE, MARTIRE, CIOTTI, DE GRANDIS, CORINALDESI, CARUGATI, CERRANO, PICA, DI CAMILLO AND DELL'ANNO, 2018. Limited impact of beach nourishment on macrofaunal recruitment/settlement in a site of community interest in coastal area of the Adriatic Sea (Mediterranean Sea). 128. Marine Pollution Bulletin. 259–266.

DARTEZ, BORNE AND POFF, 2020. Turning a tragedy into large-scale barrier island restoration in Louisiana: A three-project case study. Shore & Beach. 58–64.

DARTMOOR NATIONAL PARK AND ENVIRONMENT AGENCY, 2021. Dartmoor Headwaters Natural Flood Management (NFM) Project Newsletter.

DAVIDSON, FOWLER, SKOV, DOERR, BEAUMONT AND GRIFFIN, 2017. Livestock grazing alters multiple ecosystem properties and services in salt marshes: a meta-analysis. 54 (5). J Appl Ecol. 1395–1405.

DAVIS, WHITFIELD, SZIMANSKI, GOLDEN, WHITBECK, GAILANI, HERMAN, TRITINGER, DILLON AND KING, 2022. A framework for evaluating island restoration performance: A case study from the Chesapeake Bay. 18 (1). Integr Envir Assess & Manag. 42–48.

DEANE, NORREY, COULTHARD, MCKENDRY AND DEAN, 2021. Riverine large woody debris introduced for natural flood management leads to rapid improvement in aquatic macroinvertebrate diversity. 163. Ecological Engineering. 106197.

DITTRICH, BALL, WREFORD, MORAN AND SPRAY, 2019. A cost-benefit analysis of afforestation as a climate change adaptation measure to reduce flood risk [Online]. 12 (4). J Flood Risk Management. Available from: https://onlinelibrary.wiley.com/doi/10.1111. [Accessed: 10 May 2023].

DIXON, SEAR AND NISLOW, 2019. A conceptual model of riparian forest restoration for natural flood management: Riparian Forest Restoration for NFM. 33 (3). Water and Environment Journal. 329–341.

DRAYER, SENA, BARTON AND ANDREWS, 2017. Long-Term Response of Stream and Riparian Restoration at Wilson Creek, Kentucky USA. 35 (3). Ecological Rest. 246–254.

DUNLOP, FELDER, GLAMORE, HOWE AND COGHLAN, 2017. Optimising Ecological and Engineering Values in Coastal Protection via Combined Oyster Shell and Sand Bag Designs.

EICHMANNS, LECHTHALER, ZANDER, PÉREZ, BLUM, THORENZ AND SCHÜTTRUMPF, 2021. Sand Trapping Fences as a Nature-Based Solution for Coastal Protection: An International Review with a Focus on Installations in Germany. 8 (12). Environments. 135.

ELKO, BRIGGS, BENEDET, ROBERTSON, THOMSON, WEBB AND GARVEY, 2021. A century of U.S. beach nourishment. 199. Ocean & Coastal Management. 105406.

ELLIS, 2021a. Understanding the capacity of unimproved grassland to deliver natural flood management. University of Exeter.

ELLIS, 2021b. How can Culm grassland help with natural flood management? Exeter University.

ELLIS, BRAZIER AND ANDERSON, 2020. Comparing fine-scale structural and hydrologic connectivity within unimproved and improved grassland [Online]. 14 (7). Available from: https://onlinelibrary.wiley.com/doi/10.1002.

ELLISON, 2018. Pacific Island Beaches [Online]. Springer International Publishing. 24. 679–700. Available from: http://link.springer.com/10.1007. [Accessed: 10 May 2023].

EVANS, PEACOCK, GREEN, HOLDEN, CHAPMAN, LEBRON, CALLAGHAN, GRAYSON AND BAIRD, 2018. The impact of ditch blocking on fluvial carbon export from a UK blanket bog. 32 (13). Hydrological Processes. 2141–2154.

FAHEY AND PAYNE, 2017. The Glendhu experimental catchment study, upland east Otago, New Zealand: 34 years of hydrological observations on the afforestation of tussock grasslands. 31 (16). Hydrol. Process. 2921–2934.

FAIRFAX AND WHITTLE, 2021. Smokey the beaver: Beaver-dammed riparian corridors stay green during wildfire throughout the western USA. 102 (1). Bulletin of the Ecological Society of America. 1–5.

FEAGIN, FURMAN, SALGADO, MARTINEZ, INNOCENTI, EUBANKS, FIGLUS, HUFF, SIGREN AND SILVA, 2019. The role of beach and sand dune vegetation in mediating wave run up erosion. 219. Estuarine, Coastal and Shelf Science. 97–106.

FELLOWES, VILA-CONCEJO, GALLOP, SCHOSBERG, DE STAERCKE AND LARGIER, 2021. Decadal shoreline erosion and recovery of beaches in modified and natural estuaries. 390. Geomorphology. 107884.

FERGUSON, 2020. The effects of upstream Natural Flood Management on urban surface drainage performance [Online]. Available from: www.repository.cam.ac.uk. [Accessed: 9 June 2023].

FERGUSON AND FENNER, 2020a. Evaluating the effectiveness of catchment-scale approaches in mitigating urban surface water flooding. 378 (2168). Phil. Trans. R. Soc. A. 20190203.

FERGUSON AND FENNER, 2020b. The impact of Natural Flood Management on the performance of surface drainage systems: A case study in the Calder Valley. 590. Journal of Hydrology. 125354.

FERNÁNDEZ-MONTBLANC, DUO AND CIAVOLA, 2020. Dune reconstruction and revegetation as a potential measure to decrease coastal erosion and flooding under extreme storm conditions. 188. Ocean & Coastal Management. 105075.

FOLLETT, SCHALKO AND NEPF, 2020. Momentum and Energy Predict the Backwater Rise Generated by a Large Wood Jam [Online]. 47 (17). Geophysical Research Letters. Available from: https://onlinelibrary.wiley.com/doi/10.1029. [Accessed: 28 April 2023].

FOLLETT, SCHALKO AND NEPF, 2021. Logjams With a Lower Gap: Backwater Rise and Flow Distribution Beneath and Through Logjam Predicted by Two-Box Momentum Balance [Online]. 48 (16). Geophysical Research Letters. Available from: https://onlinelibrary.wiley.com/doi/10.1029. [Accessed: 28 April 2023].

FOLLETT AND BEVEN, 2023. Leaky barrier retention times for Natural Flood Management interventions. Design tool to support modelling of leaky barriers [Online]. Available from: www.jbatrust.org.

FOLLETT AND HANKIN, 2022. Investigation of effect of logjam series for varying channel and barrier physical properties using a sparse input data 1D network model. 158. Environmental Modelling & Software. 105543.

FOLLETT, HANKIN AND CHAPPELL, 2023. Impact of engineered logjams in enhancing performance of full floodplain restorations [Online]. oral. Available from: https://meetingorganizer.copernicus.org. [Accessed: 28 November 2023].

FOSTER-MARTINEZ, LACY, FERNER AND VARIANO, 2018. Wave attenuation across a tidal marsh in San Francisco Bay. 136. Coastal Engineering. 26–40.

FRANKL, DE BOEVER, BODYN, BUYSENS, ROSSEEL, DEPREZ, BIELDERS, DÉGRE AND STOKES, 2021. Report on the effectiveness of vegetative barriers to regulate simulated fluxes of runoff and sediment in open agricultural landscapes (Flanders, Belgium). 32 (15). Land Degrad Dev. 4445–4449.

GAO, HOLDEN AND KIRKBY, 2017. Modelling impacts of agricultural practice on flood peaks in upland catchments: An application of the distributed TOPMODEL. 31 (23). Hydrological Processes. 4206–4216.

GAO, KIRKBY AND HOLDEN, 2018. The effect of interactions between rainfall patterns and land-cover change on flood peaks in upland peatlands. 567. Journal of Hydrology. 546–559.

GATIS, BENAUD, ANDERSON, ASHE, GRAND-CLEMENT, LUSCOMBE, PUTTOCK AND BRAZIER, 2023. Peatland restoration increases water storage and attenuates downstream stormflow but does not guarantee an immediate reversal of long-term ecohydrological degradation. 13 (1). Scientific Reports. 15865.

GEERTSEMA, TORFS, EEKHOUT, TEULING AND HOITINK, 2020. Wood-induced backwater effects in lowland streams. 36 (7). River Research and Applications. 1171–1182.

GEISTHARDT, SUEDEL AND JANSSEN, 2022. A Hemimysis-driven novel ecosystem at a modified rubble-mound breakwater: An Engineering With Nature® Demonstration Project. 18 (1). Integr Envir Assess & Manag. 49–62.

GEORGE AND TODD, no date. Small-scale NFM interventions in Essex Norfolk and Suffolk: Weybourne/Spring Beck, Norfolk.

GILBERT, 2021a. Salmons Brook Natural Flood Management Pilot: results and lessons. Thames21. [Accessed: 27 September 2023]

GILBERT, 2021b. The River Pinn Park Wood NFM Pilot: results and lessons.

GILBERT, 2021c. Woodland and river management in two headwater streams, NFM Pilot: results and lessons.

GILBERT, 2021d. Salmons Brook Natural Flood Management - appendices. Thames21.

GILLIS, MAZA, GARCIA-MARIBONA, LARA, SUZUKI, ARGEMI CIERCO, PAUL, FOLKARD AND BALKE, 2022. Living on the edge: How traits of ecosystem engineers drive bio-physical interactions at coastal wetland edges. 166. Advances in Water Resources. 104257.

GODFROY, VUIK, VAN BERCHUM AND JONKMAN, 2017. Quantifying Wave Attenuation by Nature-based Solutions in the Galveston Bay. TU Delft.

GORCZYCA, KRZEMIEŃ, SOBUCKI AND JARZYNA, 2018. Can beaver impact promote river renaturalization? The example of the Raba River, southern Poland. 615. Science of The Total Environment. 1048–1060.

GOUDARZI, MILLEDGE, HOLDEN, EVANS, ALLOTT, SHUTTLEWORTH, PILKINGTON, AND WALKER, 2021. Blanket Peat Restoration: Numerical Study of the Underlying Processes Delivering Natural Flood Management Benefits [Online]. 57 (4). Water Res. Available from: https://onlinelibrary.wiley.com/doi/10.1029. [Accessed: 28 April 2023].

GRAHAM, PUTTOCK, ELLIOTT, ANDERSON AND BRAZIER, 2022. Exploring the dynamics of flow attenuation at a beaver dam sequence. 36 (11). Hydrological Processes. e14735.

GROLL, 2017. The passive river restoration approach as an efficient tool to improve the hydromorphological diversity of rivers – Case study from two river restoration projects in the German lower mountain range. 293. Geomorphology. 69–83.

HAFEN, WHEATON, ROPER, BAILEY AND BOUWES, 2020. Influence of topographic, geomorphic, and hydrologic variables on beaver dam height and persistence in the intermountain western United States. 45 (11). Earth Surf Processes Landf. 2664–2674.

HAJDUKIEWICZ, WYŻGA, ZAWIEJSKA, AMIROWICZ, OGLĘCKI AND RADECKI-PAWLIK, 2017. Assessment of river hydromorphological quality for restoration purposes: an example of the application of RHQ method to a Polish Carpathian river. 65 (3). Acta Geophys. 423–440.

HANKIN, CRAIGEN, CHAPPELL, PAGE AND METCALFE, 2016. The Rivers Trust Life-IP Natural Course Project: Strategic Investigation of Natural Flood Management in Cumbria.

HANKIN, HEWITT, SANDER, DANIELI, FORMETTA, KAMILOVA, KRETZSCHMAR, KIRADJIEV, WONG, PEGLER AND LAMB, 2020. A risk-based network analysis of distributed in-stream leaky barriers for flood risk management. 20 (10). Nat. Hazards Earth Syst. Sci. 2567–2584.

HANKIN, PAGE, CHAPPELL, BEVEN, SMITH, KRETZSCHMAR AND LAMB, 2021. Using micro-catchment experiments for multi-local scale modelling of nature-based solutions [Online]. 35 (11). Hydrological Processes. Available from: https://onlinelibrary.wiley.com/doi/10.1002. [Accessed: 12 June 2023].

HANKIN, PAGE, MCSHANE, CHAPPELL, SPRAY, BLACK AND COMINS, 2021. How can we plan resilient systems of nature-based mitigation measures in larger catchments for flood risk reduction now and in the future? 13. Water Security. 100091.

HARVEY, HENSHAW, PARKER AND SAYER, 2018. Re-introduction of structurally complex wood jams promotes channel and habitat recovery from overwidening: Implications for river conservation. 28 (2). Aquatic Conservation: Marine and Freshwater Ecosystems. 395–407.

HERITAGE AND ENTWISTLE, 2020. Impacts of River Engineering on River Channel Behaviour: Implications for Managing Downstream Flood Risk. 12 (5). Water. 1355.

HERNÁNDEZ-MORCILLO, BURGESS, MIRCK, PANTERA AND PLIENINGER, 2018. Scanning agroforestry-based solutions for climate change mitigation and adaptation in Europe. 80. Environmental Science & Policy. 44–52.

HEWAGEEGANA, BILSKIE, WOODSON AND BLEDSOE, 2022. The effects of coastal marsh geometry and surge scales on water level attenuation. 185. Ecological Engineering. 106813.

HILGENDORF, WALKER, PICKART AND TURNER, 2022. Dynamic restoration and the impact of native versus invasive vegetation on coastal foredune morphodynamics, Lanphere Dunes, California, USA. 47 (13). Earth Surf Processes Landf. 3083–3099.

HILLE, GRAEBER, KRONVANG, RUBAEK, ONNEN, MOLINA-NAVARRO, BAATTRUP-PEDERSEN, HECKRATH AND STUTTER, 2019. Management Options to Reduce Phosphorus Leaching from Vegetated Buffer Strips. 48 (2). J. Environ. Qual. 322–329.

HINSHAW, WOHL, BURNETT AND WONDZELL, 2022. Development of a geomorphic monitoring strategy for stage 0 restoration in the South Fork McKenzie River, Oregon, USA. 47 (8). Earth Surf Processes Landf. 1937–1951.

HOGAN AND REIDENBACH, 2022. Quantifying Tradeoffs in Ecosystem Services Under Various Oyster Reef Restoration Designs. 45 (3). Estuaries and Coasts. 677–690.

HOLDEN, GRAYSON, BERDENI, BIRD, CHAPMAN, EDMONDSON, FIRBANK, HELGASON, HODSON, HUNT, JONES, LAPPAGE, MARSHALL-HARRIES, NELSON, PRENDERGAST-MILLER, SHAW, WADE AND LEAKE, 2019. The role of hedgerows in soil functioning within agricultural landscapes. 273. Agriculture, Ecosystems & Environment. 1–12.

HOLDEN, GREEN, BAIRD, GRAYSON, DOOLING, CHAPMAN, EVANS, PEACOCK AND SWINDLES, 2017. The impact of ditch blocking on the hydrological functioning of blanket peatlands. 31 (3). Hydrological Processes. 525–539.

HOLDEN, MOODY, EDWARD TURNER, MCKENZIE, BAIRD, BILLETT, CHAPMAN, DINSMORE, GRAYSON, ANDERSEN, GEE AND DOOLING, 2018. Water-level dynamics in natural and artificial pools in blanket peatlands. 32 (4). Hydrological Processes. 550–561.

HOWSON, EVANS, ALLOTT, SHUTTLEWORTH, JOHNSTON, REES, MILLEDGE, EDOKPA, LOCKYER, KAY, SPENCER, BROWN, GOUDARZI AND PILKINGTON, 2023. Peatland gully restoration with stone and timber dams (Kinder Plateau, UK). 195. Ecological Engineering. 107066.

HR WALLINGFORD, 2020. Littlestock Brook, Effectiveness of natural flood management measures.

HUANG, ZENG, ZHA AND YANG, 2022. Investigation of flow characteristics in open channel with leaky barriers. 613. Journal of Hydrology. 128328.

HUANG AND YANG, 2023. Impacts of Channel-Spanning Log Jams on Hyporheic Flow. 59 (11). Water Resources Research. e2023WR035217.

HUNT, FAIR AND ODLAND, 2018. Meadow Restoration Increases Baseflow and Groundwater Storage in the Sierra Nevada Mountains of California. 54 (5). J Am Water Resour Assoc. 1127–1136.

IACOB, BROWN AND ROWAN, 2017. Natural flood management, land use and climate change trade-offs: the case of Tarland catchment, Scotland. 62 (12). Hydrological Sciences Journal. 1931–1948.

IBRAHIM AND AMIR-FARYAR, 2018. Strategic Insights on the Role of Farm Ponds as Nonconventional Stormwater Management Facilities. 23 (6). J. Hydrol. Eng. 04018023.

IOANA-TOROIMAC, ZAHARIA, MOROȘANU, GRECU AND HACHEMI, 2022. Assessment of Restoration Effects in Riparian Wetlands using Satellite Imagery. Case Study on the Lower Danube River. 42 (4). Wetlands. 30.

ISMAIL, XU AND LIU, 2021. Flow and Scour around Idealized Porous Engineered Log Jam Structures. 147 (1). J. Hydraul. Eng. 04020089.

JACKSON AND WHITTINGHAM, 2021. Lyde Brook/Coalbrookdale: Natural Flood Management Assessment.

JAMES, LYNCH, HERMAN, VAN KATWIJK, VAN TUSSENBROEK, DIJKSTRA, VAN WESTEN, VAN DER BOOG, KLEES, PIETRZAK, SLOBBE AND BOUMA, 2021. Tropical Biogeomorphic Seagrass Landscapes for Coastal Protection: Persistence and Wave Attenuation During Major Storms Events. 24 (2). Ecosystems. 301–318.

JANES, GRABOWSKI, MANT, ALLEN, MORSE AND HAYNES, 2017. The Impacts of Natural Flood Management Approaches on In-Channel Sediment Quality: Natural Flood Management and Sediment Quality. 33 (1). River Res. Applic. 89–101.

JENKS, 2018. Restoring the natural functional capacity of coastal dune ecosystems: Utilising research records for New Zealand littoral refurbishment as a proxy for analogous global responses. 22 (4). J Coast Conserv. 623–665.

JUHÁSZ, KATONA, MOLNÁR, HAHN AND BIRÓ, 2020. A reintroduced ecosystem engineer species may exacerbate ongoing biological invasion: Selective foraging of the Eurasian beaver in floodplains. 24. Global Ecology and Conservation. e01383.

JUMAIN, IBRAHIM, ISMAIL, ENTALAI, MAKHTAR, RAHMAN AND ALIAS, 2018. Influence of riparian vegetation on flow resistance in mobile bed straight compound channels. 1049. J. Phys.: Conf. Ser. 012027.

JUMAIN, IBRAHIM, ISMAIL, JAMAL, RASHID, SALLEH, SHARIFF AND ZULKIFLI, 2021. Hydraulic and morphological patterns in a riparian vegetated sandy compound straight channel. 646 (1). IOP Conf. Ser.: Earth Environ. Sci. 012036.

JUNG, MOSS, DI LEONARDO, CARRUTHERS, DEMARCO, MATHEWS AND BRASHER, 2019. Modeling potential benefits of fragmented terrace restoration in Terrebonne Bay, Louisiana: wave attenuation, sediment process, and potential SAV habitat.

KACZKOWSKI, KANA, TRAYNUM AND VISSER, 2018. Beach-fill equilibration and dune growth at two large-scale nourishment sites. 68 (9). Ocean Dynamics. 1191–1206.

KARRAN, WESTBROOK AND BEDARD-HAUGHN, 2018. Beaver-mediated water table dynamics in a Rocky Mountain fen. 11 (2). Ecohydrology. e1923.

KEYS, GOVENOR, JONES, HESSION, HESTER AND SCOTT, 2018. Effects of large wood on floodplain connectivity in a headwater Mid-Atlantic stream. 118. Ecological Engineering. 134–142.

KIESEL AND OTHERS, 2022. Can Managed Realignment Buffer Extreme Surges? The Relationship Between Marsh Width, Vegetation Cover and Surge Attenuation. (45). Estuaries and Coasts. 345–362.

KIESEL, 2021. Tidal marsh restoration for flood risk mitigation: The effectiveness of managed realignment at Freiston Shore, Lincolnshire, UK.

KIESEL, SCHUERCH, MÖLLER, SPENCER AND VAFEIDIS, 2019. Attenuation of high water levels over restored saltmarshes can be limited. Insights from Freiston Shore, Lincolnshire, UK. 136. Ecological Engineering. 89–100.

KINGSBURY-SMITH, WILLIS, SMITH, BOISGONTIER, TURNER, HIRST, KIRKBY AND KLAAR, 2023. Evaluating the effectiveness of land use management as a natural flood management intervention in reducing the impact of flooding for an upland catchment. 37 (4). Hydrological Processes. e14863.

KITCH, PHILLIPS, PEUKERT, TAYLOR AND BLAKE, 2019. Understanding the geomorphic consequences of enhanced overland flow in mixed agricultural systems: sediment fingerprinting demonstrates the need for integrated upstream and downstream thinking. 19 (9). J Soils Sediments. 3319–3331.

KONLECHNER, KENNEDY, COUSENS AND WOODS, 2019. Patterns of early-colonising species on eroding to prograding coasts; implications for foredune plant communities on retreating coastlines. 327. Geomorphology. 404–416.

KOWALSKA, AFFEK, WOLSKI, REGULSKA, KRUCZKOWSKA, ZAWISKA, KOŁACZKOWSKA AND BARANOWSKI, 2021. Assessment of regulating ES potential of lowland riparian hardwood forests in Poland. 120. Ecological Indicators. 106834.

KÜHNEL, GARCIA-FRANCO, WIESMEIER, BURMEISTER, HOBLEY, KIESE, DANNENMANN AND KÖGEL-KNABNER, 2019. Controlling factors of carbon dynamics in grassland soils of Bavaria between 1989 and 2016. 280. Agriculture, Ecosystems & Environment. 118–128.

KURDISTANI, PALERMO, PAGLIARA AND HASSANABADI, 2019. Log-frame deflectors scour morphology in curved channels [Online]. Available from: www.iahr.org.

KURTH, GREENFELD, SMITH, FIELDING, ABELLERA AND KING, 2022. Financing Natural Infrastructure: South Bay Salt Pond Restoration Project, California.

LA PEYRE, BUIE, ROSSI AND ROBERTS, 2022. Long-term assessments are critical to determining persistence and shoreline protection from oyster reef nature-based coastal defenses. 178. Ecological Engineering. 106603.

LANG, AUST, BOLDING, MCGUIRE AND SCHILLING, 2017. Forestry best management practices for erosion control in haul road ditches near stream crossings. 72 (6). Journal of Soil and Water Conservation. 607–618.

LAPORTE-FAURET, CASTELLE, MICHALET, MARIEU, BUJAN AND ROSEBERY, 2021. Morphological and ecological responses of a managed coastal sand dune to experimental notches. 782. Science of The Total Environment. 146813.

LAW, LEVANONI, FOSTER, ECKE AND WILLBY, 2019. Are beavers a solution to the freshwater biodiversity crisis? 25 (11). Diversity and Distributions. 1763–1772.

LEVI AND MCINTYRE, 2020. Ecosystem responses to channel restoration decline with stream size in urban river networks [Online]. 30 (5). Ecol Appl. Available from: https://onlinelibrary.wiley.com/doi/10.1002. [Accessed: 10 May 2023].

LEVINE AND MEYER, 2019. Beaver-generated disturbance extends beyond active dam sites to enhance stream morphodynamics and riparian plant recruitment. 9 (1). Sci Rep. 8124.

LEWIS AND HODGES, 2021a. River Wye and Lugg Natural Flood Management Project: Dulas Brook catchment.

LEWIS AND HODGES, 2021b. River Wye and Lugg Natural Flood Management Project: Cheaton, Cogwell and Ridgemoor Brooks catchment.

LIVERS AND WOHL, 2021. All Logjams Are Not Created Equal. 126 (8). JGR Earth Surface. e2021JF006076.

LO, VAN LEEUWEN, KLAAR, WOULDS AND SMITH, 2022. Geomorphic effects of natural flood management woody dams in upland streams. 38 (10). River Research & Apps. 1787–1802.

LO, BOUMA, VAN BELZEN, VAN COLEN AND AIROLDI, 2017. Interactive effects of vegetation and sediment properties on erosion of salt marshes in the Northern Adriatic Sea. 131. Marine Environmental Research. 32–42.

LOCKWOOD, 2022. Quantifying the efficacy of Natural Flood Management in agricultural headwater catchments. University of Bristol.

LOCKWOOD, FREER, MICHAELIDES, BRAZIER AND COXON, 2022. Assessing the efficacy of offline water storage ponds for natural flood management [Online]. 36 (6). Hydrological Processes. Available from: https://onlinelibrary.wiley.com/doi/10.1002. [Accessed: 28 April 2023].

LORENZ, 2021. Continuous riverine biodiversity changes in a 10-years-post-restoration-study—Impacts and pitfalls. 37 (2). River Res Applic. 270–282.

LUDKA, GUZA AND O'REILLY, 2018. Nourishment evolution and impacts at four southern California beaches: A sand volume analysis. 136. Coastal Engineering. 96–105.

MA AND OTHERS, 2018. Wave Attenuation Mechanism of the Artificial Reef in Beidaihe, China [Online]. Available from: https://onepetro.org.

MA, ZHU, PENG, XUE, ZHAO, LI, LIN, BOUMA, HOFLAND, DONG AND LI, 2023. Wave attenuation by flattened vegetation (Scirpus mariqueter). 10. Front. Mar. Sci. 1106070

MAASS AND SCHÜTTRUMPF, 2019. Reactivation of Floodplains in River Restorations: Long-Term Implications on the Mobility of Floodplain Sediment Deposits. 55 (10). Water Resources Research. 8178–8196.

MACDONALD, DE RUYCK, FIELD, BEDFORD AND BRADBURY, 2020. Benefits of coastal managed realignment for society: Evidence from ecosystem service assessments in two UK regions. 244. Estuarine, Coastal and Shelf Science. 105609.

MAJEED, 2023. Soar NFM Project Data Analysis (2022-2023).

MAJEROVA, NEILSON AND ROPER, 2020. Beaver dam influences on streamflow hydraulic properties and thermal regimes. 718. Science of The Total Environment. 134853.

MANNING, SCOTT AND LEEGWATER, 2021. Restoring Estuarine and Coastal Habitats with dredge sediment: A Handbook.

MARDEN AND SEYMOUR, 2022. Effectiveness of vegetative mitigation strategies in the restoration of fluvial and fluvio-mass movement gully complexes over 60 years, East Coast region, North Island, New Zealand [Online]. 52. NZJFS. Available from: https://nzjforestryscience.nz/index.php. [Accessed: 10 May 2023].

MARIN-DIAZ, FIVASH, NAUTA, TEMMINK, HIJNER, REIJERS, CRUIJSEN, DIDDEREN, HEUSINKVELD, PENNING, MALDONADO-GARCIA, VAN BELZEN, DE SMIT, CHRISTIANEN, VAN DER HEIDE, VAN DER WAL, OLFF, BOUMA AND GOVERS, 2021. On the use of large-scale biodegradable artificial reefs for intertidal foreshore stabilization. 170. Ecological Engineering. 106354.

MARIN-DIAZ, GOVERS, VAN DER WAL, OLFF AND BOUMA, 2021. How grazing management can maximize erosion resistance of salt marshes. 58 (7). Journal of Applied Ecology. 1533–1544.

MARIN-DIAZ, GOVERS, VAN DER WAL, OLFF AND BOUMA, 2022. The importance of marshes providing soil stabilization to resist fast-flow erosion in case of a dike breach [Online]. 32 (6). Ecological Applications. Available from: https://onlinelibrary.wiley.com/doi/10.1002. [Accessed: 10 May 2023].

MARTÍNEZ-FERNÁNDEZ, GONZÁLEZ, LÓPEZ-ALMANSA, GONZÁLEZ AND GARCÍA DE JALÓN, 2017. Dismantling artificial levees and channel revetments promotes channel widening and regeneration of riparian vegetation over long river segments. 108. Ecological Engineering. 132–142.

MASON-MCLEAN, 2020. Riparian buffer strips and their effectiveness as a natural flood management measure.

MATTERN, LUTGEN, SIENKIEWICZ, JIANG, KAN, PEIPOCH AND INAMDAR, 2020. Stream Restoration for Legacy Sediments at Gramies Run, Maryland: Early Lessons from Implementation, Water Quality Monitoring, and Soil Health. 12 (8). Water. 2164.

MAWDSLEY, CHAPPELL AND SWALLOW, 2017. Hydrological change on Tebay Common following fencing and tree planting: A preliminary dataset. Report in support of the Woodland Trust Upland Planting Research Programme. Lancaster University.

MAXIMILIANO-CORDOVA, MARTÍNEZ, SILVA, HESP, GUEVARA AND LANDGRAVE, 2021. Assessing the Impact of a Winter Storm on the Beach and Dune Systems and Erosion Mitigation by Plants. 8. Front. Mar. Sci. 734036.

MAXIMILIANO-CORDOVA, SALGADO, MARTÍNEZ, MENDOZA, SILVA, GUEVARA AND FEAGIN, 2019. Does the Functional Richness of Plants Reduce Wave Erosion on Embryo Coastal Dunes? 42 (7). Estuaries and Coasts. 1730–1741.

MCCLELLAND, PAUSTIAN AND SCHIPANSKI, 2021. Management of cover crops in temperate climates influences soil organic carbon stocks: a meta-analysis. 31 (3). Ecological Applications. e02278.

MCCLENACHAN, DONNELLY, SHAFFER, SACKS AND WALTERS, 2020. Does size matter? Quantifying the cumulative impact of small-scale living shoreline and oyster reef restoration projects on shoreline erosion. 28 (6). Restoration Ecology. 1365–1371.

MCKEE SMITH AND ANDERSON BRYANT, 2018. Engineering with Nature to Reduce Wave Energy in Wetlands.

MCKENNA, 2021. Rise Park Stream catchment, Hydraulic Modelling Report [Online]. Available from: https://jbagrp.sharepoint.com.

MCQUEEN, SUEDEL AND WILKENS, 2020. Restoring marsh habitat with beneficial use of dredged sediments from a riverine environment [Online]. Available from: \\SAL-RDC03\Live Data\2023\Projects\2023s0350 - EA - Update to the WwNP ED\2_Shared_Outgoing\IPSOS\Grey\SystematicReview\Grey Literature\USEPA\WEDA_Journal_Vol_18_No_1.pdf

MEDEL, STUBBLEFIELD AND SHEA, 2022. Sedimentation and erosion patterns within anabranching channels in a lowland river restoration project. 20 (3). International Journal of River Basin Management. 399–409.

MENDOZA, ODÉRIZ, MARTÍNEZ AND SILVA, 2017. Measurements and Modelling of Small Scale Processes of Vegetation Preventing Dune Erosion. 77. Journal of Coastal Research. 19–27.

MENG, ZHOU, SUN, DING AND CHONG, 2021. Hydraulic Characteristics of Emerged Rigid and Submerged Flexible Vegetations in the Riparian Zone. 13 (8). Water. 1057.

METCALFE, BEVEN, HANKIN AND LAMB, 2018. A new method, with application, for analysis of the impacts on flood risk of widely distributed enhanced hillslope storage. 22 (4). Hydrol. Earth Syst. Sci. 2589–2605.

MI, ZHANG, ZHU, VUIK, WEN, GAO AND BOUMA, 2022. Morphological wave attenuation of the nature-based flood defense: A case study from Chongming Dongtan Shoal, China. 831. Science of The Total Environment. 154813.

MILES, WINLOW, NEWALL AND BULCOCK, 2021. Evenlode NFM scheme, Multiple benefits assessment.

MILLEDGE, GOUDARZI AND DIXON, 2020. Water Environment Grant- Building Blocks: Hydrological Analysis to Prioritise Gully Block Locations Final Report.

MONGER, BOND, SPRACKLEN AND KIRKBY, 2022. Overland flow velocity and soil properties in established semi-natural woodland and wood pasture in an upland catchment [Online]. 36 (4). Hydrological Processes. Available from: https://onlinelibrary.wiley.com/doi/10.1002. [Accessed: 28 April 2023].

MONGER, SPRACKLEN, KIRKBY AND SCHOFIELD, 2022. The impact of semi-natural broadleaf woodland and pasture on soil properties and flood discharge [Online]. 36 (1). Hydrological Processes. Available from: https://onlinelibrary.wiley.com/doi/10.1002. [Accessed: 28 April 2023].

MOORE AND RUTHERFURD, 2017. Lack of maintenance is a major challenge for stream restoration projects. 33 (9). River Research and Applications. 1387–1399.

MOORLIFE2020, no date. Grip and Gully Blocking.

MOORS FOR THE FUTURE, 2018. Kinder Scout Sphagnum Trails 2018.

MOORS FOR THE FUTURE, 2020. Stone Dams.

MOORS FOR THE FUTURE, no date. Heather Bale Dams.

MORRIS, GRAHAM, KELVIN, GHISALBERTI AND SWEARER, 2019. Kelp beds as coastal protection: wave attenuation of Ecklonia radiata in a shallow coastal bay. Annals of Botany. mcz127.

MORRIS, LA PEYRE, WEBB, MARSHALL, BILKOVIC, CEBRIAN, MCCLENACHAN, KIBLER, WALTERS, BUSHEK, SPARKS, TEMPLE, MOODY, ANGSTADT, GOFF, BOSWELL, SACKS AND SWEARER, 2021. Large-scale variation in wave attenuation of oyster reef living shorelines and the influence of inundation duration [Online]. 31 (6). Ecological Applications. Available from: https://onlinelibrary.wiley.com/doi/10.1002. [Accessed: 10 May 2023].

MOSELEY, CONNOLLY, SING AND WATTS, 2018. Developing an indicator for the physical health benefits of recreation in woodlands. 31. Ecosystem Services. 420–432.

MOSSMAN, PONTEE, BORN, HILL, LAWRENCE, RAE, SCOTT, SERATO, SPARKES, SULLIVAN AND DUNK, 2022. Rapid carbon accumulation at a saltmarsh restored by managed realignment exceeded carbon emitted in direct site construction. 17 (11). PLoS ONE. e0259033.

MUHAWENIMANA, FOLLETT, MADDOCK AND WILSON, 2023. Field-based monitoring of instream leaky barrier backwater and storage during storm events. 622. Journal of Hydrology. 129744.

MÜLLER, FOLLETT, OURO AND WILSON, 2022. Influence of Channel-Spanning Engineered Logjam Structures on Channel Hydrodynamics [Online]. 58 (12). Water Resources Research. Available from: https://onlinelibrary.wiley.com/doi/10.1029. [Accessed: 10 May 2023].

MÜLLER, WILSON, OUROAND CABLE, 2021. Leaky barriers: leaky enough for fish to pass? 8 (3). R. Soc. open sci. rsos.201843, 201843.

MULLIGAN, VAN SOESBERGEN, DOUGLAS AND BURKE, 2023. Natural Flood Management in the Thames Basin: Building Evidence for What Will and Will Not Work. Springer.

MURPHY, HANLEY, ELLIS AND LUNT, 2021. Native woodland establishment improves soil hydrological functioning in UK upland pastoral catchments. 32 (2). Land Degrad Dev. 1034–1045.

MURPHY, HANLEY, ELLIS AND LUNT, 2022. Optimizing opportunities for oak woodland expansion into upland pastures [Online]. 3 (1). Ecol Sol and Evidence. Available from: https://onlinelibrary.wiley.com/doi/10.1002. [Accessed: 4 August 2023].

MURRAY, NEILSON AND BRAHNEY, 2021. Source or sink? Quantifying beaver pond influence on non-point source pollutant transport in the Intermountain West. 285. Journal of Environmental Management. 112127.

NATIONAL TRUST, DEFRA AND ENVIRONMENT AGENCY, 2021. Northey Island Saltmarsh Regeneration, Project Report - March 2021.

NATURAL RESOURCES WALES, 20/032024. Sands of LIFE [Online]. Available from: https://naturalresources.wales. [Accessed: 2 April 2024].

NEUMAYER, TESCHEMACHER, SCHLOEMER, ZAHNER AND RIEGER, 2020. Hydraulic Modeling of Beaver Dams and Evaluation of Their Impacts on Flood Events. 12 (1). Water. 300.

NICHOLSON, O’DONNELL, WILKINSON AND QUINN, 2020. The potential of runoff attenuation features as a Natural Flood Management approach [Online]. 13 (S1). J Flood Risk Management. Available from: https://onlinelibrary.wiley.com/doi/10.1111. [Accessed: 10 May 2023].

NOON, 2020. Wetland restoration design modifications to mitigate climate change impacts at Delaware Water Gap National Recreation Area: A case study report [Online]. 36 (1). Parks Stewardship Forum. Available from: https://escholarship.org. [Accessed: 10 May 2023].

NORBURY, PHILLIPS, MACDONALD, BROWN, BOOTHROYD, WILSON, QUINN AND SHAW, 2021. Quantifying the hydrological implications of pre- and post-installation willowed engineered log jams in the Pennine Uplands, NW England. 603. Journal of Hydrology. 126855.

NORBURY, SHAW AND JONES, 2019. Combining hydraulic modelling with partnership working: towards practical natural flood management. 172 (7). Proceedings of the Institution of Civil Engineers - Engineering Sustainability. 372–384.

NORDSTROM, JACKSON, RADER AND GARILAO, 2018. Protecting natural landforms and habitats by nourishing an eroding estuarine beach. 77 (19). Environ Earth Sci. 680.

NOWACKI, BEUDIN AND GANJU, 2017. Spectral wave dissipation by submerged aquatic vegetation in a back-barrier estuary. 62 (2). Limnology & Oceanography. 736–753.

NOWACKI AND GROSSMAN, 2020. Sediment transport in a restored, river-influenced Pacific Northwest estuary. 242. Estuarine, Coastal and Shelf Science. 106869.

OOSTERLEE, COX, TEMMERMAN AND MEIRE, 2020. Effects of tidal re-introduction design on sedimentation rates in previously embanked tidal marshes. 244. Estuarine, Coastal and Shelf Science. 106428.

ORESKA, MCGLATHERY, AOKI, BERGER, BERG AND MULLINS, 2020. The greenhouse gas offset potential from seagrass restoration. 10 (1). Sci Rep. 7325.

OSORIO, LINHOSS AND DASH, 2020. Evaluation of Marsh Terraces for Wetland Restoration: A Remote Sensing Approach. 12. Water. 336.

OSORIO-CANO, ALCÉRRECA-HUERTA, MARIÑO-TAPIA, OSORIO, ACEVEDO-RAMÍREZ, ENRIQUEZ, COSTA, PEREIRA, MENDOZA, ESCUDERO, ASTORGA-MOAR, LÓPEZ-GONZÁLEZ, APPENDINI, SILVA AND OUMERACI, 2019. Effects of Roughness Loss on Reef Hydrodynamics and Coastal Protection: Approaches in Latin America. 42 (7). Estuaries and Coasts. 1742–1760.

PAGÁN, LÓPEZ, LÓPEZ, TENZA-ABRIL AND ARAGONÉS, 2018. Study of the evolution of gravel beaches nourished with sand. 626. Science of The Total Environment. 87–95.

PAGE, CHAPPELL, BEVEN, HANKIN AND KRETZSCHMAR, 2020. Assessing the significance of wet-canopy evaporation from forests during extreme rainfall events for flood mitigation in mountainous regions of the United Kingdom. 34 (24). Hydrological Processes. 4740–4754.

PANG VALLEY FLOOD FORUM, 2021. Pang Valley Flood Forum - NFM Project - Final report.

PAQUIER, HADDAD, LAWLER AND FERREIRA, 2017. Quantification of the Attenuation of Storm Surge Components by a Coastal Wetland of the US Mid Atlantic. 40 (4). Estuaries and Coasts. 930–946.

PAQUIER, MEULÉ, ANTHONY, LARROUDÉ AND BERNARD, 2019. Wind-Induced Hydrodynamic Interactions with Aquatic Vegetation in a Fetch-Limited Setting: Implications for Coastal Sedimentation and Protection. 42 (3). Estuaries and Coasts. 688–707.

PAUSTIAN, COLLINS AND PAUL, 2019. Management Controls on Soil Carbon. CRC Press.

PEARSON, 2023a. Monitoring of Natural Flood Management water storage areas in the Glenderamackin catchment.

PEARSON, 2023b. Charlesground leaky barriers and bund [Online]. West Cumbria Rivers Trust. 2. Available from: https://thefloodhub.co.uk. [Accessed: 12 July 2023].

PEARSON, 2020. Modelling the interactions between geomorphological processes and Natural Flood Management. University of Leeds.

PESKETT, 2020. Catchment subsurface water storage, mixing and flowpaths: implications for land cover change as a natural flood management strategy. University of Edinburgh.

PESKETT, HEAL, MACDONALD, BLACK AND MCDONNELL, 2021. Tracers reveal limited influence of plantation forests on surface runoff in a UK natural flood management catchment. 36. Journal of Hydrology: Regional Studies. 100834.

PESKETT, HEAL, MACDONALD, BLACK AND MCDONNELL, 2023. Land cover influence on catchment scale subsurface water storage investigated by multiple methods: Implications for UK Natural Flood Management. 47. Journal of Hydrology: Regional Studies. 101398.

PESKETT, MACDONALD, HEAL, MCDONNELL, CHAMBERS, UHLEMANN, UPTON AND BLACK, 2020. The impact of across-slope forest strips on hillslope subsurface hydrological dynamics. 581. Journal of Hydrology. 124427.

PHILLIPS, MCBRIDE, PEUKERT, UGLOW AND JAMES, no date. Do Man-Made Leaky Woody Dams Work? [Online]. Available from: https://jbagrp.sharepoint.com.

PIERCE, ROSGEN, GEENEN AND ROSGEN, 2022. Wild trout and hydrologic response to restoration of incised streams with improved water use for ranching and fisheries [Online]. 13 (3). Ecosphere. Available from: https://onlinelibrary.wiley.com/doi/10.1002. [Accessed: 10 May 2023].

PINNA, BACCHETTA, ORRÙ, COGONI, SANNA AND FENU, 2017. Results of the Providune project: restoration of the “Coastal dunes with Juniperus spp.” priority habitat in Sardinia. (54(1)S1). Plant Sociology. 73–84.

PINTO, ING, BROWNING, DELBONI, WILSON, MARTYN AND HARVEY, 2019. Hydromorphological, hydraulic and ecological effects of restored wood: findings and reflections from an academic partnership approach. 33 (3). Water and Environment Journal. 353–365.

POLK, GITTMAN, SMITH AND EULIE, 2022. Coastal resilience surges as living shorelines reduce lateral erosion of salt marshes. 18 (1). Integr Envir Assess & Manag. 82–98.

PONTE, SONTI, PHILLIPS AND PAVAO-ZUCKERMAN, 2021. Transpiration rates of red maple (Acer rubrum L.) differ between management contexts in urban forests of Maryland, USA. 11 (1). Sci Rep. 22538.

PONTEE AND SERATO, 2019. Nearfield erosion at the steart marshes (UK) managed realignment scheme following opening. 172. Ocean & Coastal Management. 64–81.

POPE, 2019. Retrospective on the 1970’s “Low Cost Shore Protection” program. Shore & Beach. 3–12.

PORRO, KIM, SPIRANDELLI AND LOWRY, 2020. Evaluating erosion management strategies in Waikiki, Hawaii. 188. Ocean & Coastal Management. 105113.

POTIĆ, MIHAJLOVIĆ, ŠIMUNIĆ, ĆURČIĆ AND MILINČIĆ, 2022. Deforestation as a Cause of Increased Surface Runoff in the Catchment: Remote Sensing and SWAT Approach—A Case Study of Southern Serbia. 10. Front. Environ. Sci. 896404.

POWELL, LOMAS, LEKSMONO, ZITO, DURANEL, NISBET AND CLARK, 2021. Evaluating leaky barriers on the River Bourne - Interim report March 2021 [Online]. Available from: Evaluating leaky barriers on the River Bourne - Interim report March 2021.

PUGLIESE, CAROPPI, ZINGRAFF-HAMED, LUPP AND GERUNDO, 2022. Assessment of NBSs effectiveness for flood risk management: The Isar River case study. 71 (1). Journal of Water Supply: Research and Technology-Aqua. 42–61.

PUTTOCK, BROWN, GRAHAM AND BRAZIER, 2021. Ottery St Mary Natural Flood Management Project Monitoring Report 2021 – Preliminary Results [Online]. University of Exeter. Available from: https://catchmentbasedapproach.org. [Accessed: 27 September 2023].

PUTTOCK, GRAHAM, ASHE, LUSCOMBE AND BRAZIER, 2021. Beaver dams attenuate flow: A multi-site study [Online]. 35 (2). Hydrological Processes. Available from: https://onlinelibrary.wiley.com/doi/10.1002. [Accessed: 28 April 2023].

PUTTOCK, GRAHAM, CARLESS AND BRAZIER, 2018. Sediment and nutrient storage in a beaver engineered wetland: Sediment and Nutrient Storage in a Beaver Engineered Wetland. 43 (11). Earth Surf. Process. Landforms. 2358–2370.

PUTTOCK, GRAHAM, CUNLIFFE, ELLIOTT AND BRAZIER, 2017. Eurasian beaver activity increases water storage, attenuates flow and mitigates diffuse pollution from intensively-managed grasslands. 576. Science of The Total Environment. 430–443.

PYE, BLOTT AND GUTHRIE, 2017. Advice on Options for Sand Dune Management for Flood and Coastal Defence Volume 1: Main Report [Online]. Natural Resources Wales. Available from: https://naturalresources.wales. [Accessed: 2 April 2024].

RAHMAN, SHERREN AND VAN PROOSDIJ, 2019. Institutional Innovation for Nature-Based Coastal Adaptation: Lessons from Salt Marsh Restoration in Nova Scotia, Canada. 11 (23). Sustainability. 6735.

RAK AND STEINMAN, 2019. An Analysis of the Influence of Floodplain Landuse on the Flood Propagation [Online]. International Association for Hydro-Environment Engineering and Research. Available from: www.iahr.org.

RAYNIE, KHALIL, VILLARRUBIA AND HAYWOOD, 2020. Coastal monitoring and data management for restoration in Louisiana. Shore & Beach. 92–101.

RAZMAND, POLITANO, AMADA AND WEBER, 2019. A physically-based coupled hydrologic model for Clear Creek Watershed [Online]. Available from: www.iahr.org.

REGENSBURG, CHAPMAN, PILKINGTON, CHANDLER, EVANS AND HOLDEN, 2021. Effects of pipe outlet blocking on hydrological functioning in a degraded blanket peatland [Online]. 35 (3). Hydrological Processes. Available from: https://onlinelibrary.wiley.com/doi/10.1002. [Accessed: 12 June 2023].

REVELL, LASHFORD, RUBINATO AND BLACKETT, 2022. The Impact of Tree Planting on Infiltration Dependent on Tree Proximity and Maturity at a Clay Site in Warwickshire, England. 14 (6). Water. 892.

REZEK, LEBRETON, STERBA-BOATWRIGHT AND BESERES POLLACK, 2017. Ecological structure and function in a restored versus natural salt marsh. 12 (12). PLoS ONE. e0189871.

RICHARDS, MOGGRIDGE, WARREN AND MALTBY, 2020. Impacts of hydrological restoration on lowland river floodplain plant communities. 28 (3). Wetlands Ecol Manage. 403–417.

RICHET, OUVRY AND SAUNIER, 2017. The role of vegetative barriers such as fascines and dense shrub hedges in catchment management to reduce runoff and erosion effects:

Experimental evidence of efficiency, and conditions of use. 103. Ecological Engineering. 455–469.

RIQUIER, PIÉGAY, LAMOUROUX AND VAUDOR, 2017. Are restored side channels sustainable aquatic habitat features? Predicting the potential persistence of side channels as aquatic habitats based on their fine sedimentation dynamics. 295. Geomorphology. 507–528.

ROBERTSON AND MADDOCK, 2019. Assessing the effectiveness of Natural Flood Management (NFM) at Lower Hope Farms, Herefordshire.

ROBOTHAM, OLD, RAMESHWARAN, TRILL AND BISHOP, 2022. High-resolution time series of turbidity, suspended sediment concentration, total phosphorus concentration, and discharge in the Littlestock Brook, England, 2017-2021 [Online]. NERC EDS Environmental Information Data Centre. Available from: https://catalogue.ceh.ac.uk. [Accessed: 9 June 2023].

ROBOTHAM, OLD, RAMESHWARAN, SEAR, GASCA-TUCKER, BISHOP, OLD AND MCKNIGHT, 2021. Sediment and Nutrient Retention in Ponds on an Agricultural Stream: Evaluating Effectiveness for Diffuse Pollution Mitigation. 13 (12). Water. 1640.

ROGERS, 2017. Can Structure from Motion determine the efficacy of river re-meandering as a natural flood management measure? [Online]. Available from: http://rgdoi.net/10.13140. [Accessed: 21 August 2023].

RUPPRECHT, MÖLLER, PAUL, KUDELLA, SPENCER, VAN WESENBEECK, WOLTERS, JENSEN, BOUMA, MIRANDA-LANGE AND SCHIMMELS, 2017. Vegetation-wave interactions in salt marshes under storm surge conditions. 100. Ecological Engineering. 301–315.

SAFAK, ANGELINI, NORBY, DIX, RODDENBERRY, HERBERT, ASTROM AND SHEREMET, 2020. Wave transmission through living shoreline breakwalls. 211. Continental Shelf Research. 104268.

SAFAK, NORBY, DIX, GRIZZLE, SOUTHWELL, VEENSTRA, ACEVEDO, COOPER-KOLB, MASSEY, SHEREMET AND ANGELINI, 2020. Coupling breakwalls with oyster restoration structures enhances living shoreline performance along energetic shorelines. 158. Ecological Engineering. 106071.

SCHALKO, FOLLETT AND NEPF, 2023. Impact of Lateral Gap on Flow Distribution, Backwater Rise, and Turbulence Generated by a Logjam. 59 (10). Water Resources Research. e2023WR034689.

SCHALKO, SCHMOCKER, WEITBRECHT AND BOES, 2018. Backwater Rise due to Large Wood Accumulations. 144 (9). J. Hydraul. Eng. 04018056.

SCHALKO, WOHL AND NEPF, 2021. Flow and wake characteristics associated with large wood to inform river restoration. 11 (1). Sci Rep. 8644.

SCHERNEWSKI, BARTEL, KOBARG AND KARNAUSKAITE, 2018. Retrospective assessment of a managed coastal realignment and lagoon restoration measure: the Geltinger Birk, Germany. 22 (1). J Coast Conserv. 157–167.

SCHERNEWSKI, SCHUMACHER, WEISNER AND DONGES, 2018. A combined coastal protection, realignment and wetland restoration scheme in the southern Baltic: planning process, public information and participation. 22 (3). J Coast Conserv. 533–547.

SCHOUTENS, HEUNER, FUCHS, MINDEN, SCHULTE-OSTERMANN, BELLIARD, BOUMA AND TEMMERMAN, 2020. Nature-based shoreline protection by tidal marsh plants depends on trade-offs between avoidance and attenuation of hydrodynamic forces. 236. Estuarine, Coastal and Shelf Science. 106645.

SCHOUTENS, HEUNER, MINDEN, SCHULTE OSTERMANN, SILINSKI, BELLIARD AND TEMMERMAN, 2019. How effective are tidal marshes as nature-based shoreline protection throughout seasons? 64. Limnology and Oceanography. 1750–1762.

SCHOUTENS, REENTS, NOLTE, EVANS, PAUL, KUDELLA, BOUMA, MÖLLER AND TEMMERMAN, 2021. Survival of the thickest? Impacts of extreme wave-forcing on marsh seedlings are mediated by species morphology. 66 (7). Limnol Oceanogr. 2936–2951.

SCHOUTENS, STOORVOGEL, VAN DEN BERG, VAN DEN HOVEN, BOUMA, AARNINKHOF, HERMAN, VAN LOON-STEENSMA, MEIRE, SCHOELYNCK, PEETERS AND TEMMERMAN, 2022. Stability of a Tidal Marsh Under Very High Flow Velocities and Implications for Nature-Based Flood Defense. 9. Front. Mar. Sci. 920480.

SCHULZ-ZUNKEL, SEELE-DILBAT, ANLANGER, BABOROWSKI, BONDAR-KUNZE, BRAUNS, GAPINSKI, GRÜNDLING, HAAREN, HEIN, HENLE, JUNGE, KASPERIDUS, KOLL, KRETZ, RAST, SCHNAUDER, SCHOLZ, SCHRENNER, SENDEK, SPRÖSSIG, TAVARES, VIEWEG, TÜMPLING, WEITERE, WIRTH, WUNSCH AND DZIOCK, 2022. Effective restoration measures in river-floodplain ecosystems: Lessons learned from the ‘Wilde Mulde’ project. 107 (1–2). Internat Rev Hydrobiol. 9–21.

SCRIDEL, GROOM AND DOUGLAS, 2017. Native woodland creation is associated with increase in a Black Grouse Lyrurus tetrix population. 64 (1). Bird Study. 70–83.

SEAR, D., KITTS, D. AND MILLIGAN, C., 2006. New Forest LIFE-III monitoring report: the geomorphic and hydrological response of New Forest streams to river restoration. Southampton: University of Southampton.

SEAR, SPECK AND PEARS, 2023. Carbon storage in river and floodplain systems: A review of evidence to update and inform policy development for riverine Nature based solutions. [Online]. Available from: https://eprints.soton.ac.uk.

SEELE-DILBAT, KRETZ AND WIRTH, 2022. Vegetation of natural and stabilized riverbanks and early effects of removal of bank fixation. 107 (1–2). Internat Rev Hydrobiol. 88–99.

SEVERN GORGE COUNTRYSIDE TRUST, 2021. Learning about Lydebrook Citizen Science and Soil Science.

SHERRIFF, ROWAN, FENTON, JORDAN AND Ó HUALLACHÁIN, 2019. Influence of land management on soil erosion, connectivity, and sediment delivery in agricultural catchments: Closing the sediment budget. 30 (18). Land Degrad Dev. 2257–2271.

SHORT, CLARKE, CARNELLI, UTTLEY AND SMITH, 2019. Capturing the multiple benefits associated with nature-based solutions: Lessons from a natural flood management project in the Cotswolds, UK. 30 (3). Land Degrad Dev. 241–252.

SHRESTHA, FARRELLY, EGGLETON AND CHEN, 2017. Effects of conservation wetlands on stream habitat, water quality and fish communities in agricultural watersheds of the lower Mississippi River Basin. 107. Ecological Engineering. 99–109.

SHUTTLEWORTH, EVANS, PILKINGTON, SPENCER, WALKER, MILLEDGE AND ALLOTT, 2019. Restoration of blanket peat moorland delays stormflow from hillslopes and reduces peak discharge. 2. Journal of Hydrology X. 100006.

SIERRA, GRACIA, CASTELL, GARCÍA-LEÓN, MÖSSO AND LIN-YE, 2023. Potential of Transplanted Seagrass Meadows on Wave Attenuation in a Fetch-Limited Environment. 11 (6). JMSE. 1186.

SILINSKI, SCHOUTENS, PUIJALON, SCHOELYNCK, LUYCKX, TROCH, MEIRE AND TEMMERMAN, 2018. Coping with waves: Plasticity in tidal marsh plants as self-adapting coastal ecosystem engineers: Marsh plants as self-adapting ecosystem engineers. 63 (2). Limnol. Oceanogr. 799–815.

SILLIMAN, HE, ANGELINI, SMITH, KIRWAN, DALEO, RENZI, BUTLER, OSBORNE, NIFONG AND VAN DE KOPPEL, 2019. Field Experiments and Meta-analysis Reveal Wetland Vegetation as a Crucial Element in the Coastal Protection Paradigm. 29 (11). Current Biology. 1800-1806.e3.

SMITH, TETZLAFF, GELBRECHT, KLEINE AND SOULSBY, 2020. Riparian wetland rehabilitation and beaver re-colonization impacts on hydrological processes and water quality in a lowland agricultural catchment. 699. Science of The Total Environment. 134302.

SMITH, MINER, THEILING, BEHM AND NESTLER, 2017. Levee Setback: An innovative, cost-effective, and sustainable solution for improved flood risk management [Online]. Available from: \\SAL-RDC03\Live Data\2023\Projects\2023s0350 - EA - Update to the WwNP ED\2_Shared_Outgoing\IPSOS\Grey\SystematicReview\Grey Literature\Google Advanced\Levee-Setbacks-ERDC-EL-SR-17-3.pdf.

SOULSBY, BRAUN, SPRENGER, WEILER AND TETZLAFF, 2017. *I*nfluence of forest and shrub canopies on precipitation partitioning and isotopic signatures. 31 (24). Hydrological Processes. 4282–4296.

SOULSBY, DICK, SCHELIGA AND TETZLAFF, 2017. Taming the flood—How far can we go with trees? 31 (17). Hydrological Processes. 3122–3126.

SPRAY, BLACK, BROMLEY, CAITHNESS, DODD, MACDONALD, MARTINEZ ROMERO, MCDERMOTT, MOIR, QUINN AND REID, 2021. Eddleston Water 2021 Report. Scottish Government, Tweed Forum.

STUTTER, WILKINSON AND NISBET, 2020. 3D buffer strips: Designed to deliver more for the environment. Environment Agency.

SZIMANSKI, MCQUEEN AND SUEDEL, 2019. Realizing Multiple Benefits in U.S. Army Corps of Engineers (USACE) Baltimore District Dredging Projects through Application of Engineering with Nature® Principles.

TAYLOR AND CLARKE, 2021. Monitoring the impact of leaky barriers used for Natural Flood Management on three river reaches in the Stroud Forme and Twyver catchments, Gloucestershire, UK.

TAYLOR-BURNS, NEDERHOFF, LACY AND BARNARD, 2023. The influence of vegetated marshes on wave transformation in sheltered estuaries. 184. Coastal Engineering. 104346.

TEDESCO AND CHASTEN, 2019. Experiences with engineering with nature and thin-layer placement in New Jersey [Online]. Available from: \\SAL-RDC03\Live Data\2023\Projects\2023s0350 - EA - Update to the WwNP ED\2_Shared_Outgoing\IPSOS\Grey\SystematicReview\Grey Literature\Google Advanced\2019-AIWA.pdf.

THOMAS AND ABBOTT, 2018. Hedgerows reduce nitrate flux at hillslope and catchment scales via root uptake and secondary effects. 215. Journal of Contaminant Hydrology. 51–61.

THOMPSON, VEHKAOJA, PELLIKKA AND NUMMI, 2021. Ecosystem services provided by beavers Castor spp. 51 (1). Mammal Review. 25–39.

TINOCO, SAN JUAN AND MULLARNEY, 2020. Simplification bias: lessons from laboratory and field experiments on flow through aquatic vegetation. 45 (1). Earth Surf. Process. Landforms. 121–143.

TOGNIN, D’ALPAOS, MARANI AND CARNIELLO, 2021. Marsh resilience to sea-level rise reduced by storm-surge barriers in the Venice Lagoon. 14 (12). Nat. Geosci. 906–911.

UKCEH, 2021. The Sand Dune Managers Handbook. UKCEH.

UNGUENDOLI, BIOLCHI, AGUZZI, PILLAI, ALESSANDRI AND VALENTINI, 2023. A modeling application of integrated nature based solutions (NBS) for coastal erosion and flooding mitigation in the Emilia-Romagna coastline (Northeast Italy). 867. Science of The Total Environment. 161357.

UNSWORTH, NORDLUND AND CULLEN-UNSWORTH, 2019. Seagrass meadows support global fisheries production. 12 (1). CONSERVATION LETTERS. e12566.

VAN BEMMELEN, DE SCHIPPER, DARNALL AND AARNINKHOF, 2020. Beach scarp dynamics at nourished beaches [Online]. 160 (103725). Coastal Engineering. Available from: https://linkinghub.elsevier.com. [Accessed: 10 May 2023].

VAN DER BIEST, DE NOCKER, PROVOOST, BOEREMA, STAES AND MEIRE, 2017. Dune dynamics safeguard ecosystem services. 149. Ocean & Coastal Management. 148–158.

VAN DER SPEK, BIJL, VAN DE SANDE, POORTMAN, HEIJBOER AND BLIEK, 2020. Sandbar Breakwater: An Innovative Nature-Based Port Solution. 12 (5). Water. 1446.

VAN LEEUWEN, 2021. Natural flood management potential of leaky dams in upland catchments. University of Leeds.

VAN LEEUWEN, KLAAR, SMITH AND BROWN, 2024. Quantifying the natural flood management potential of leaky dams in upland catchments, Part II: Leaky dam impacts on flood peak magnitude. 628. Journal of Hydrology. 130449.

VANNOPPEN, DE BAETS, KEEBLE, DONG AND POESEN, 2017. How do root and soil characteristics affect the erosion-reducing potential of plant species? 109. Ecological Engineering. 186–195.

VERSCHOREN, SCHOELYNCK, COX, SCHOUTENS, TEMMERMAN AND MEIRE, 2017. Opposing effects of aquatic vegetation on hydraulic functioning and transport of dissolved and organic particulate matter in a lowland river: A field experiment. 105. Ecological Engineering. 221–230.

VIEN, 2022. Testing the Influence of Water Depth in Design of Created Oyster Reef for Living Shoreline Applications. University of Central Florida.

VIKOLAINEN, FLIKWEERT, BRESSERS AND LULOFS, 2017. Governance context for coastal innovations in England: The case of Sandscaping in North Norfolk. 145. Ocean & Coastal Management. 82–93.

VOUK, PILECHI, PROVAN AND MURPHY, 2021. Nature-Based Solutions for Coastal and Riverine Flood and Erosion Risk Management.

VUIK, BORSJE, WILLEMSEN AND JONKMAN, 2019. Salt marshes for flood risk reduction: Quantifying long-term effectiveness and life-cycle costs. 171. Ocean & Coastal Management. 96–110.

WADE, LAUTZ, KELLEHER, VIDON, DAVIS, BELTRAN AND PEARCE, 2020. Beaver dam analogues drive heterogeneous groundwater-surface water interactions. 34 (26). Hydrological Processes. 5340–5353.

WALKER AND ZINNERT, 2022. Whole plant traits of coastal dune vegetation and implications for interactions with dune dynamics [Online]. 13 (5). Ecosphere. Available from: https://onlinelibrary.wiley.com/doi/10.1002. [Accessed: 10 May 2023].

WALLACE AND CHAPPELL, 2019. Blade Aeration Effects on Near-Surface Permeability and Overland Flow Likelihood on Two Stagnosol Pastures in Cumbria, UK. 48 (6). Journal of Environmental Quality. 1766–1774.

WALLACE AND CHAPPELL, 2020. A statistical comparison of spatio-temporal surface moisture patterns beneath a semi-natural grassland and permanent pasture: From drought to saturation. 34 (13). Hydrological Processes. 3000–3020.

WALLACE, MCSHANE, TYCH, KRETZSCHMAR, MCCANN AND CHAPPELL, 2021. The effect of hedgerow wild-margins on topsoil hydraulic properties, and overland-flow incidence, magnitude and water-quality. 35 (3). Hydrological Processes. e14098.

WALSH, JAKEMAN AND THOMPSON, 2020. Modelling headwater channel response and suspended sediment yield to in-channel large wood using the Caesar-Lisflood landscape evolution model. 363. Geomorphology. 107209.

WARNER, TZILIVAKIS, GREEN AND LEWIS, 2020. Establishing a field-based evidence base for the impact of agri-environment options on soil carbon and climate change mitigation – phase 1. Final Report. Work package number: ECM50416. Evidence Programme Reference number: RP04176. Natural England.

WEINSTEIN, GUO AND SANTASIERI, 2021. Protecting People and Property While Restoring Coastal Wetland Habitats. 44 (6). Estuaries and Coasts. 1710–1721.

WELLS, 2019. Natural flood management: assessing the barriers to wider implementation. Nottingham Trent University.

WELSH, VIDON AND MCMILLAN, 2020. Stream and floodplain restoration impacts riparian zone hydrology of agricultural streams. 192 (2). Environ Monit Assess. 85.

WEST CUMBRIA RIVERS TRUST, 2021a. Natural Flood Management Performance and Monitoring - Matterdale leaky dams. West Cumbria Rivers Trust.

WEST CUMBRIA RIVERS TRUST, 2021b. Natural Flood Management Performance Monitoring - Rogerscale floodplain restoration. West Cumbria Rivers Trust.

WEST CUMBRIA RIVERS TRUST, 2021c. Natural Flood Management Performance Monitoring, Fieldside Farm water storage area.

WEST CUMBRIA RIVERS TRUST, 2021d. Natural Flood Management Performance Monitoring, Corney Fell water storage areas, Update November 2021.

WEST CUMBRIA RIVERS TRUST, 2021e. Natural Flood Management Performance Monitoring - Row End water storage area.

WEST CUMBRIA RIVERS TRUST, 2021f. Natural Flood Management Performance Monitoring - Threlkeld Hall bund [Online]. West Cumbria Rivers Trust. Available from: https://thefloodhub.co.uk.

WEST CUMBRIA RIVERS TRUST, 2023. Natural Flood Management Performance Monitoring Dovenby Bund.

WESTBROOK, RONNQUIST AND BEDARD-HAUGHN, 2020. Hydrological functioning of a beaver dam sequence and regional dam persistence during an extreme rainstorm. 34 (18). Hydrological Processes. 3726–3737.

WIBERG, TAUBE, FERGUSON, KREMER AND REIDENBACH, 2019. Wave Attenuation by Oyster Reefs in Shallow Coastal Bays. 42 (2). Estuaries and Coasts. 331–347.

WIKAR, CIECHANOWSKI AND ZWOLICKI, 2023. The Positive Response of Small Terrestrial and Semi-Aquatic Mammals to Beaver Damming [Online]. SSRN. Available from: www.ssrn.com. [Accessed: 28 September 2023].

WILLBY, LAW, LEVANONI, FOSTER AND ECKE, 2018. Rewilding wetlands: beaver as agents of within-habitat heterogeneity and the responses of contrasting biota. 373 (1761). Phil. Trans. R. Soc. B. 20170444.

WILLIAMS, BANGEN, GILLIES, KRAMER, MOIR AND WHEATON, 2020. Let the river erode! Enabling lateral migration increases geomorphic unit diversity. 715. Science of The Total Environment. 136817.

WILLIAMS-MOUNSEY, CROWLE, GRAYSON AND HOLDEN, 2023. Removal of mesh track on an upland blanket peatland leads to changes in vegetation composition and structure. 339. Journal of Environmental Management. 117935.

WILLIAMS-MOUNSEY, CROWLE, GRAYSON, LINDSAY AND HOLDEN, 2023. Surface structure on abandoned upland blanket peatland tracks. 325. Journal of Environmental Management. 116561.

WILLIAMSON, ROWE, REED, RUFFINO, JONES, DOLAN, BUCKINGHAM, NORRIS, ASTBURY AND EVANS, 2017. Historical peat loss explains limited short-term response of drained blanket bogs to rewetting. 188. Journal of Environmental Management. 278–286.

WILLIS AND KLAAR, 2021. NFM Calderdale: Summary Modelling Report 1.0. iCASP(NERC). 40.

WINTERS, LESLIE, SLOANE AND GALLIEN, 2020. Observations and Preliminary Vulnerability Assessment of a Hybrid Dune-Based Living Shoreline. 8 (11). JMSE. 920.

WOHL AND ISKIN, 2022. The Transience of Channel-Spanning Logjams in Mountain Streams. 58 (5). Water Resources Research. e2021WR031556.

WOHL AND SCAMARDO, 2021. The resilience of logjams to floods [Online]. 35 (1). Hydrological Processes. Available from: https://onlinelibrary.wiley.com/doi/10.1002. [Accessed: 10 May 2023].

WREN, BARNES, KITCHEN, NUTT, COLLETTE, MARIANNE, ROSS, TIMBRELL, DOWN, JANES, ROBINS, CHARLOTTE, TAYLOR AND TURNER, 2022. The natural flood management manual, C802, CIRIA [Online]. CIRIA. Available from: www.ciria.org. [Accessed: 14 December 2022].

XIAO, ROBINSON AND O'CONNOR, 2022. Woodland's role in natural flood management: Evidence from catchment studies in Britain and Ireland. 813. Science of The Total Environment. 151877.

YU, CHEN, ZHOU, AGATHOKLEOUS, LI, LIU, WU, ZHOU, XUE, CHEN, YAN, LIU, SHI AND ZHAO, 2022. Natural forest growth and human induced ecosystem disturbance influence water yield in forests. 3 (1). Commun Earth Environ. 148.

ZABRET AND ŠRAJ, 2019. Rainfall Interception by Urban Trees and Their Impact on Potential Surface Runoff. 47 (8). Clean – Soil, Air, Water. 1800327.

ZAK, STUTTER, JENSEN, EGEMOSE, CARSTENSEN, AUDET, STRAND, FEUERBACH, HOFFMANN, CHRISTEN, HILLE, KNUDSEN, STOCKAN, WATSON, HECKRATH AND KRONVANG, 2019. An Assessment of the Multifunctionality of Integrated Buffer Zones in Northwestern Europe. 48 (2). J. Environ. Qual. 362–375.

ZHANG, WANG, GUO, LIAN AND CHEN, 2019. Increase and Spatial Variation in Soil Infiltration Rates Associated with Fibrous and Tap Tree Roots. 11 (8). Water. 1700.

ZHANG, GE, LI, TAN, ZHOU, LI, XIE AND DAI, 2022. The role of seasonal vegetation properties in determining the wave attenuation capacity of coastal marshes: Implications for building natural defenses. 175. Ecological Engineering. 106494.

ZHANG, LIN, GONG, LI AND CHEN, 2020. Wave Attenuation by Spartina alterniflora under Macro-Tidal and Storm Surge Conditions. 40 (6). Wetlands. 2151–2162.

ZHANG, HUANG, TAN, CHEN AND CHENG, 2021. A study on the drag coefficient in wave attenuation by vegetation [Online]. Coasts and Estuaries/Theory development. Available from: https://hess.copernicus.org. [Accessed: 10 May 2023].

ZHU, HUGUENARD, ZOU, FREDRIKSSON AND XIE, 2020. Aquaculture farms as nature-based coastal protection: Random wave attenuation by suspended and submerged canopies. 160. Coastal Engineering. 103737.

ZHU, YANG AND BOUMA, 2019. Biomechanical properties of marsh vegetation in space and time: effects of salinity, inundation and seasonality. Annals of Botany. mcz063.