Multiple benefits of nature-based solutions: an evidence synthesis

Chief Scientist's Group report

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Dr Robert Bradburne
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Executive summary

Nature-based Solutions (NbS) are increasingly being used to address issues such as water pollution or flooding whilst providing other benefits to the environment and people. NbS include a wide range of actions and interventions that protect and help sustainably manage and restore ecosystems. Examples include land-use changes such as afforestation, river restoration techniques including floodplain reconnection, and sustainable agricultural practices like cover crops. Whilst NbS is a relatively new term, these types of actions and interventions are built on our understanding of fundamental hydrological, geomorphological and ecological principles. However, more evidence is needed about where NbS are most effective, what other benefits can be provided, as well as their potential for unintended consequences. Robust evidence and confidence about NbS effectiveness is most likely to help target application and encourage appropriate uptake.

This report includes a synthesis of available evidence of the effects of freshwater-related NbS on environmental outcomes in different types of English catchments. The findings were summarised in a matrix that includes the type of NbS, and the catchment type (for example upland or lowland). The matrix also includes assessments of confidence in the realisation of, rather than hypothesised outcomes for the different NbS and catchment types based on the quantity and quality of the evidence. Five case studies illustrate the use of NbS across England and highlight some of the challenges faced by practitioners in implementing them. Two-page summaries of the findings for each type of NbS are provided in the appendices, designed for easy sharing.

The synthesis covered 135 studies, largely from peer-reviewed scientific literature. The monitored or modelled effects of NbS were considered under the themes of hydrological extremes (flood and low flow management), water quality (nutrient/sediment management and physical/chemical/biological properties), and biodiversity and habitat. Each piece of evidence was categorised into one of 9 broad catchment types based on characteristics such as rainfall, geology and land-use generally representative of catchments in England. Most studies were based in England and could easily be assigned to one of the catchment types, however, where studies were not, contextual information was used to categorise studies into the most appropriate type.

The review indicated that generally NbS have multiple positive environmental effects, however there were also instances of conflicting evidence. Conflicting evidence may reflect the variable nature of NbS, particularly in how benefits, or disbenefits, may change over time, or be highly dependent on local context. In some cases the derived benefits of NbS can be temporary with the ecosystem reverting back to its prior state over time. In these cases, the realisation of benefits may be dependent, at least to some extent, on the management and maintenance of NbS. It was found that different NbS have varying degrees of need for maintenance, though to be sustainable in the long-term, it is recognised that NbS need to be sustained by natural catchment processes. The review highlighted specific catchment contexts where some NbS are likely to be less appropriate due to potential trade-offs and risks, for example, constructed wetlands on steep slopes where high run-off volumes could reduce pollutant removal efficiency.

The realisation of intended benefits can also be hampered by extreme weather and its effect on soils, vegetation, and river flows. In the face of climate change, NbS may need to be adapted to improve their resilience and remain effective under more extreme conditions. There have been increases in the number of NbS studies monitoring pre and post-intervention, with monitoring periods of the reviewed studies ranging from 1 month to 45 years. However, the median monitoring period was 3 years, highlighting a bias towards shorter monitoring periods in the evidence base. Longer-term monitoring can help to appraise outcomes and inform the adaptive management of NbS, for example, to determine if additional intervention is needed to produce a sufficient change in the environmental processes that will result in benefits. Furthermore, monitoring under more extreme hydroclimatic conditions in different catchments can provide insight into how and where the efficacy of NbS may change in future.

There were gaps in the evidence under all themes, most notably the effects of NbS on biodiversity and habitats. Empirical evidence of the benefits for enhancing environmental resilience to low flow conditions was also lacking. Whilst evidence of the flood risk benefits were abundant, there was a distinct lack of evidence relating to mitigation of groundwater flooding. Studies often measured the effect of NbS on environmental processes and properties, but the consequences of these changes for wider ecosystem services were mostly implied. Cross-cutting evidence gaps include the effects of NbS at larger (for example, whole catchment) scales, and the effect of multiple NbS used in combination. Additionally, there were gaps in knowledge of the limits to the effectiveness of NbS (for example, capacity limits for nutrient removal), and in terms of the needs of maintenance for NbS efficacy.

Upland areas with high rainfall, mainly western upland landscapes, were less well represented in the literature. The availability of evidence was highest for NbS in catchments with mixed agricultural areas and arable land on lighter soils. This is likely to be in part due to the proportionally large area occupied by these lowland catchment types in England. Constructed wetlands, afforestation, and beaver re-introduction and management were all well represented. Notable gaps include the effects of peatland restoration and assisted natural regeneration in lowland catchments. The quantity and quality of evidence was highly variable between different NbS, catchment types, and environmental themes. In many cases, evidence was limited, inconclusive or implied, highlighting a low level of confidence in their effectiveness.

The synthesis has drawn on evidence from a growing field of research and contributes towards a more holistic understanding of NbS. Whilst limited in places, the resulting matrix can be used by practitioners to help make informed decisions on the suitability of NbS to different catchments, including consideration of benefits and potential trade-offs and help target where appraisal is needed. In future, the matrix can be updated as further evidence becomes available, thereby providing greater confidence in the knowledge of what benefits NbS can provide and where.

1 Introduction

1.1 Catchment resilience and Nature-based Solutions

The concept of resilience is widely cited in environmental policy, plans, and strategies, often in reference to preparing for extreme events and climate change (Environment Agency, 2024). Resilience can be defined as the capacity of a system to absorb disturbance and continue to have essentially the same function, structure, identity and feedbacks (Walker and Salt, 2012). However, resilience has different meanings in different contexts; within this report resilience is viewed from a social-ecological perspective which considers humans as part of catchment systems. The resilience of catchments is recognised as an important component of the sustainable management of freshwater ecosystems and water resources (Adger et al., 2021; Beevers et al., 2021).

Nature-based Solutions (NbS) can be used to enhance the resilience of the water environment to pressures such as climate change (UNESCO, 2018; OECD, 2020). The International Union for Conservation of Nature (IUCN) define NbS as "*actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges (e.g. climate change, food and water security or natural disasters) effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits*" (Cohen-Shacham et al., 2016). Commonly used examples include afforestation and floodplain reconnection. The concept of NbS has been adopted widely in recent years. For example, Ofwat (the water services regulation authority) expect water companies to expand their use of NbS, and work with stakeholders to improve the water environment (Ofwat, 2024). Though it is important to recognise that NbS are not intended to be a substitute for conventional (e.g. engineered) solutions to societal challenges such as flooding. NbS should be seen as a set of additional tools to use alongside and complement a range of other actions and interventions (Seddon et al., 2020).

Funding from the Environmental Land Management schemes (ELMs) and Water Restoration fund will likely increase the application of NbS across catchments in England (Defra, 2023b, 2023c). A more widespread use of NbS presents opportunities to enable and maximise environmental benefits, but also raises concerns about potential trade-offs or unintended consequences as a result of unsuitable use (Sowińska-Świerkosz and García, 2021; Finch et al., 2023). There is an increasing evidence base on the effectiveness of NbS. Reviewing this will aid understanding of the multiple benefits and potential trade-offs of NbS, and how they can be best applied, individually or in combination, to increase catchment resilience.

This report provides an overview of the types of NbS that have been studied in temperate climates. Through reviewing the evidence base at a high level, we have assessed the scientific confidence in the effects of various NbS actions across different catchment types. However, it was beyond the scope of this project to undertake a full systematic review of all available evidence. Additionally, knowledge gaps have been identified to help inform future research into NbS. A matrix was developed to summarise the findings of this evidence synthesis. Fifteen short summaries detailing the findings of this review for each type of NbS are presented in the appendices (Section 7.3 NbS summaries). Several case studies illustrate the application of NbS and highlight some of the challenges faced by practitioners in implementing them.

1.2 Report structure

Section 2 Evidence synthesis contains the main findings from the literature reviewed in this study. This section is subdivided into 3 main catchment resilience themes: 2.3 Hydrological extremes, 2.4 Water quality, and 2.5 Biodiversity and habitat. Section 2.6 Other outcomes discusses additional effects of NbS e.g. on greenhouse gases.

Section 3 Applicability of NbS to English catchments discusses the NbS evidence in the context of different catchment types in England. The matrix summarising the evidence on NbS is presented.

Section 4 Case studies presents examples of the use and functioning of selected NbS.

Section 5 Discussion provides an overview of the findings from the evidence synthesis, the matrix, and the case studies.

Section 6 Conclusions gives a summary of the main findings from this study and provides recommendations for the application of its results to future implementation of NbS in England.

2 Evidence synthesis

2.1 Review approach

References were gathered from previous Environment Agency projects (e.g. literature reviews) that were relevant to NbS. These included:

- Working with natural processes to reduce flood risk - GOV.UK (www.gov.uk)
- Improving river habitats to support wildlife during low flows - GOV.UK (www.gov.uk)
- 'Water Resource Benefits of Working with Natural Processes' (Environment Agency, 2020)
- 'Nature-Based Solutions to Water Management and Their Impact on Water Quality: A Scoping Review' (Environment Agency, 2023)

'ResearchRabbit' (a web-based literature search tool; Cole and Boutet, 2023) was used to generate suggestions for additional references to include in this review. The full list of studies and extracted information is available for download as a Microsoft Excel spreadsheet alongside this report ('NbS Evidence and Matrices.xlsx'). It was beyond the scope of the project to carry out a full systematic review and quantitative meta-analysis of all available evidence and therefore this review only includes a selected number of additions identified by ResearchRabbit.

The review examined 135 studies (published journal articles and project reports) into the effects of NbS on hydrological extremes, water quality, and biodiversity and habitat. Studies that focussed on either one or a combination of these evidence themes were considered. The theme of hydrological extremes includes properties and processes relating to the mitigation and management of flood and low flow risk and impacts. The theme of water quality includes properties and processes relating to the mitigation, and management of chemical, physical and biological pollution of surface water, soil water and groundwater. The theme of biodiversity and habitat includes properties and processes relating to the enhancement and provision of wildlife and habitat in freshwater and riparian environments. Only English language studies published prior to 2024 were included in the review. Both original research articles and review articles were considered. The scope of the review was limited to freshwater-related NbS, in temperate climates with relevance to English catchments. A significant number of international studies on NbS in other climates (e.g. tropical or arid) were therefore excluded from the review. NbS in both urban and rural settings, and across a range of spatial scales were considered. Whilst this review considers the benefits of NbS for flood management, a more comprehensive, updated review of evidence on reducing flood risk by working with natural processes is recently available (Environment Agency, 2025).

Studies were categorised based on the type of NbS, the geographical location and catchment context (see section 3.1 Catchment Matcher Typology), the type of research methods used, and the outcome(s) being assessed. For studies which reported results from multiple catchments or different NbS types, separate entries of evidence were recorded; this resulted in a total of 187 lines of evidence. The reported effects (or absence of an effect) of NbS were recorded under categories of environmental properties (e.g. dissolved oxygen) and processes (e.g. infiltration). Hypothesised effects were also included but recorded as such to separate them from observed or statistically significant results. The findings of the evidence synthesis were presented in a matrix giving an indication of the current scientific confidence in different NbS types to generate outcomes in different catchment types. The level of confidence was determined based on the quantity and quality of the available evidence. See section 3.3 Matrix for further details on the matrix and the supporting evidence used.

2.2 Overview of the literature

Geographically, most of the evidence came from NbS in England (n=75), with some from Scotland (n=9), and Wales (n=4) and Northern Ireland (n=2). European countries including Germany (n=19) and Sweden (n=10) made up a large proportion of the other studies. Additionally, review studies generated evidence that was not specific to any country (n=19). Out of the studies that gave details on climate information for the study area, mean annual precipitation ranged from 550 to 1863 mm. Mean annual air temperature ranged from 6.2 to 14.4 °C. The examined studies were published between 1999 and 2023, with over half of them being published between 2018 and 2022. The research methods used to generate the evidence mostly focussed on monitoring and measuring effects (n=139). Less of the evidence reported was from numerical modelling (n=45) which examined the potential effects of NbS under hypothetical scenarios.

The NbS approaches identified from the literature were allocated into 17 different categories (Table 1 provides a summary of each category). There is a degree of overlap between the NbS categories, particularly where NbS are used in different contexts or for different primary purposes. Several categories are broadly related to river restoration, e.g. instream wood, and floodplain reconnection. Others are focussed on aspects of rural land management, e.g. sustainable soil management. The permeable pavements, green roofs, and bioretention systems/rain gardens categories are all Sustainable Drainage Systems (SuDS) which target urban settings. All of the NbS can be viewed as sitting on a spectrum that ranges from primarily natural to primarily engineered; this degree of ‘naturalness’ varies both between and within the NbS categories. Beaver re-introduction and management has been included, though it is recognised that beavers cannot always be used in the same ways as other NbS given that they are mobile and introduced populations will spread freely in the wild. Existing beaver enclosures provide data that contribute to the NbS evidence base, though in future if wild release is considered, NbS benefits and trade-offs can be factored into the location of re-introduction. From the reviewed evidence, the most frequently studied type of NbS were constructed wetlands (n=26), followed by afforestation and beaver re-introduction/management (n=18).

Table 1. Categories of NbS identified from the literature.

NbS Category	Description
Beaver re-introduction and management	The re-introduction and management of the once native Eurasian beaver (*Castor fiber*) can be considered as a NbS due to the significant role beavers play in modifying their environment as 'ecosystem engineers'. Studies in this category include evidence from beavers in enclosures and from established populations in the wild.
Afforestation	The planting of trees in the landscape in areas where there was no recent tree cover. For example, on floodplains, in riparian zones, or urban areas. Studies in this category include evidence on both deciduous and coniferous trees, and at different spatial scales.
Constructed wetlands	Constructed wetlands (CWs) are artificially created wetland features that are primarily used to treat polluted water (e.g. sewage effluent or agricultural run-off). They typically have an inflow and outflow, but are diverse in their design, ranging from more natural features to highly engineered systems.
Temporary water storage features	Temporary storage features typically use natural topography to hold back water in the landscape, primarily for the purpose of Natural Flood Management (NFM). Examples include Run-off Attenuation Features (RAFs) and swales that intercept flow pathways.
Riparian restoration	This category includes interventions aimed at restoring the riparian zone, including its vegetation and ecosystem functions. Examples include the removal of embankments or rip-rap (rock used to armour riverbanks), and restoration of natural riparian wetlands.
Buffer strips/zones	Buffer strips/zones are narrow vegetated areas of land primarily aimed at protecting watercourses from diffuse (non-point source) pollution. They are multifunctional and can also be implemented to provide shade, refuge, or act as movement corridors for wildlife. This category includes integrated buffer zones which also incorporate pond features for interception of water and pollutants.

NbS Category	Description
Hedgerows and vegetative barriers	Hedgerows are made up of living shrubs, and typically used as boundary lines for agricultural fields. Vegetative barriers are made up of natural materials (e.g. straw) and are used to mimic the barrier effect of hedgerows.
Instream wood	Instream wood includes the (re)introduction of woody material into watercourses. This ranges from engineered approaches (e.g. log jams that are fixed to riverbanks/beds), to passive strategies (e.g. letting trees naturally fall into streams).
Peatland restoration	This category includes the restoration of upland peatland habitats (e.g. blanket bog) and their ecosystem functions through techniques such as revegetation and gully (ditch) blocking to aid rewetting. This category did not consider lowland peat settings due to a lack of studies.
Instream substrate addition	This category includes the addition of geological material (e.g. gravel) into watercourses, typically to raise the streambed or modify benthic habitat.
Channel restoration	This category includes measures that aim to restore natural river channel form and functioning. Examples include re-meandering, and the removal of dams, impoundments, culverts or embankments.
Floodplain reconnection	Floodplain reconnection involves restoring the connectivity of rivers to their floodplains through removing/lowering levees or raising the riverbed to enable overbank flows.
Sustainable Drainage Systems - Permeable pavement	Permeable pavements are forms of urban surfaces that are used to capture rainfall or surface run-off and encourage infiltration.
Sustainable Drainage Systems - Green roofs	Green roofs are roofs of buildings that are covered with a waterproof membrane and vegetation grown on a layer of substrate.

NbS Category	Description
Sustainable Drainage Systems - Bioretention systems/rain gardens	Bioretention systems or rain gardens are landscaped depressions that are used to capture and treat stormwater from impervious surfaces in urban settings.
Sustainable soil management	This category includes a variety of techniques aimed at improving the health and functioning of soils (largely arable). Examples include cover crops, no till farming, and ley farming (e.g. herbal leys). Leys are typically mixtures of herb species, grasses, and/or legumes grown in rotation with arable crops.
Assisted natural regeneration	This category includes measures that enable the natural ecological succession of land (e.g. rewilding, fencing).

2.3 Hydrological extremes

2.3.1 Flood management

There is considerable interest in evidence of the flood mitigation effects of NbS due to the significant economic and social cost of flooding. Large flood events across England in 2015/16 were estimated to have cost the economy £1.6 billion (Environment Agency, 2021a). Building flood resilience and adapting to climate change are emphasised in the Environmental Improvement Plan, which states the government's intention to double the number of government-funded flood resilience projects using NbS (Defra, 2023a). The Environment Agency's long-term investment scenarios (LTIS) report notes that investments needed to manage future flood risk include widespread implementation of Natural Flood Management (NFM) (Environment Agency, 2019a). Recent investment in NFM interventions across the country has helped to generate evidence in this area. This new knowledge has been incorporated into an updated evidence directory which sets out the state of scientific evidence underpinning NFM (Environment Agency, 2025); please refer to this for a more comprehensive review of measures from a flood risk perspective.

The reviewed evidence identified a range of hydrological processes and properties that can be enhanced by NbS to generate flood risk management benefits:

- Run-off generation (reduced)
- Flow/flood water storage
- Conveyance
- Run-off attenuation

- Infiltration
- Interception
- Flow attenuation
- Lag time
- Flow pathway interception
- Evapotranspiration

Afforestation

Studies examining afforestation typically looked at the effects on streamflow, and in particular peak flows. Modelled evidence suggests that large areas of forest are needed to have an effect on high flow events. For example, Badjana et al. (2023) found that over 75 % of the study catchment area needed to be forested to have an effect on higher magnitude events, particularly for reducing flows at a large catchment scale. The location of afforestation within catchments influences streamflow extremes, however the impacts on extreme floods are not consistent (Buechel et al., 2022). Modelled scenarios of large-scale woodland planting in a permeable catchment resulted in small reductions in flow that ranged from 0.2 to 2.6 % depending on the tree species planted (Collins et al., 2023). Peskett et al. (2023) conclude that large-scale planting of trees is likely to have limited potential for reducing flood risk when considering the effects on infiltration and water storage in some upland catchment types. These studies highlight the importance of catchment characteristics in the generation of flood risk benefits from afforestation. Peskett et al. (2023) note that the role of geology and soils can play a more significant role in the catchment response to rainfall compared with the effects of trees. A recent review of forested land as a NFM intervention found that whilst the evidence base in the UK is sparse, it does indicate that carefully planned and managed woodland can help to mitigate flood risk (Cooper et al., 2021). Again, this emphasises the importance of location and context in determining the effectiveness of outcomes from catchment afforestation.

Several studies modelled the effects of afforestation specifically on floodplains. This included the broader effects of trees on flood hydrology (e.g. slowing overbank flows), as well as their effect on processes removing water from the land (e.g. evapotranspiration). Thomas and Nisbet (2007) found that floodplain woodland reduced flow velocity, created a backwater effect and resulted in increased flood storage of up to 71 %. This also increased the travel time by 140 minutes, thereby delaying the flood peak downstream of the woodland. Increasing the cover of floodplain woodland was found to increase certainty in the direction of the effect on peak flow (Dixon et al., 2016). However, the authors observed the highest magnitude reductions in peak flow when 22 to 47 % of the river channel network was forested compared to scenarios of >50 % cover. The scenarios also showed that forest age had an effect on the magnitude of peak flow reduction, with a mean reduction of 10 % after 25 years of forest growth. A long-term study monitoring a forest plantation found that water losses from evaporation increased over time as trees matured, with the proportion of interception loss increasing from 22 % (younger trees) to 32 % (mature trees) of the gross precipitation (Birkinshaw et al., 2014). The mature trees increased evapotranspiration from the study catchment by 58 % when compared with the sheep-grazed upland grassland prior to afforestation. These effects also translated into decreases in stream discharge as trees matured. A similar long-term study of plantation forestry found that afforestation reduced peak flows by 78 % for small events, but only 37 % for higher magnitude events (Fahey and Payne, 2017).

Evidence suggests that afforestation can also improve the water storage capacity of soils. For example, soil saturated hydraulic conductivity (K_{fs}) was found to be significantly higher in native woodland compared to grazed grassland (Archer et al., 2013). K_{fs} is a measure of the rate of water movement through saturated soil and is influenced by properties such as soil porosity. Another study observed a two-fold increase in K_{fs} within 15 years of the establishment of upland native woodland (Murphy et al., 2020). This was thought to be related to the effect of trees on soil organic matter and consequent enhancement of soil porosity. Infiltration rates were also found to be higher in woodlands, thereby reducing the risk of overland flow generation (Archer et al., 2013). Similarly beneficial hydrological effects have been observed as a result of urban tree planting, with a rapid evidence assessment finding consistent evidence of local-scale impacts such as reducing run-off, and increasing infiltration and evaporative losses (Baker et al., 2021).

Assisted natural regeneration

Overall, assisted natural regeneration was found to have positive implications for flood risk management, though evidence (particularly at larger scales) is still limited. Field experiments show that exclusion of sheep for 5 years can delay run-off response, reduce run-off by 48 % compared to grazed grassland, and thereby lead to reductions in peak flow (Marshall et al., 2014). The study also demonstrated that run-off could be reduced further by the planting of broadleaf trees. Modelled evidence supports these findings, with Bond et al. (2022) observing reductions in overland flow peaks of up to 42 % as a result of agricultural conservation land management scenarios compared to high intensity grazing. Results also showed delays in peak flow. Harvey and Henshaw (2023) suggest that rewilding at large scales could help to mitigate the impacts of flooding through modifying hydrological processes.

Beaver re-introduction and management

There is a growing body of evidence to suggest that the re-introduction of beavers can help to mitigate the effects of flooding downstream. Beavers have been shown to hold back water in the landscape through the creation of ponds and canals, thereby storing surface water and slowing flows (Correll et al., 2000; Puttock et al., 2017; Brazier et al., 2020). Storage of water and reductions in flow velocity have been shown to increase with the age of the beaver wetland system (Ecke et al., 2017).

Significant reductions in both the total discharge and peak flows during storm events has been observed following beaver re-introduction at multiple sites in the UK (Puttock et al., 2021). Mean peak flow reductions between the sites varied from 0.065 to 0.359 $m^3 s^{-1}$ per mm total event rainfall, with a Before-After Control-Impact (BACI) design at one site showing a 47 % reduction (0.66 to 0.35 $m^3 s^{-1}$). Two out of 4 beaver-impacted sites showed significant increases in lag time, and all sites saw a reduction in the flashiness of the hydrological response to rainfall. The effectiveness of flood attenuation may vary seasonally, with Puttock et al. (2021) finding that the effect was greater during the wet season.

Neumayer et al. (2020) modelled the effects of beaver dam cascades, finding local scale reductions of up to 13 % in peak discharge during storm events and increases in lag time of up to 2.75 hours in an arable catchment. Effectiveness was lower in larger magnitude (> 2-year return period) events. In contrast, results from a steep forested catchment showed almost no impact on flood event hydrology.

Recent evidence on the interactions of beavers with the natural and human environment (in relation to England) has been reviewed by Howe (2020). Published evidence post-2015 suggests that beavers can help to restore catchment water storage, and attenuate fluvial flood flows to reduce downstream flood risk.

Buffer strips/zones

A review of the ecosystem services provided by buffer strips found that wooded buffer strips typically have deep roots that provide strength and complexity to the soil matrix, thereby enhancing its porosity, permeability and water retention capacity (Cole et al., 2020). The review also found that the aboveground structural complexity of wooded buffers helps to slow overland flow velocity. Modelled evidence suggests that riparian buffers in combination with bund features can flatten storm event hydrographs and delay peak flows (Adams et al., 2018). The study found that a 10 % change in catchment land-use through the addition of riparian buffers and bunds on degraded soil was needed to enhance water storage by 2000 m^3 and produce a flood attenuation effect (Adams et al., 2018). The study did not determine the relative contribution of the buffer strips and the bunds to the flood attenuation effect.

Floodplain reconnection

Observed evidence on floodplain reconnection suggests that reversing the effects of engineering through embankment removal can enable overbank flows and improve flood storage (Clilverd et al., 2013). Modelling of floodplain reconnection found that peak flows could be reduced by between 10 to 15 %, and timing of the peak could be delayed by 3 hours (Acreman et al., 2003).

Hedgerows and vegetative barriers

Evidence on the effectiveness of hedgerows and vegetative barriers to mitigate flood risk largely focussed on local-scale benefits to soil and hillslope hydrology rather than effects on streamflow. A field study found that hedgerow margins saturate more slowly compared to grassland pasture and are therefore slower to produce overland flow (Wallace et al., 2021). This was thought to be as a result of hedgerows significantly reducing topsoil bulk density, increasing porosity and permeability by a factor of 22 to 27. Holden et al. (2019) report similar findings, with soil under hedgerows having significantly lower bulk density, compaction, and moisture, and a higher K_{fs} compared to arable soil. Vegetative barriers made of brushwood and shrub have been found to increase surface roughness and aid infiltration at a local scale (Richet et al., 2017).

Instream wood

Hydrological modelling of engineered logjams found strong variability in the direction of the effect on flood peak magnitude when logjams were spaced at intervals of 7 to 10 times the channel width, with changes of ± 6 % observed (Dixon et al., 2016). The authors concluded that logjams alone were not found to have predictable effects on flood risk, particularly at the 1 to 5 km reach scale. Monitoring of 5 × 1 m high willowed engineered log jams showed a mean reduction of 27 % in storm event peak discharge, however lag time was not significantly impacted (Norbury et al., 2021).

Peatland restoration

There is considerable evidence on the effectiveness of peatland restoration to reduce flood risk, most of which is derived from monitoring. Several studies using BACI designs demonstrated that gully blocking and revegetation of blanket bog can reduce peak stream discharge by up to 51 % and increase lag time by up to 267 % (Pilkington et al., 2015; Shuttleworth et al., 2019). The greatest effects were observed in catchments where a combination of revegetation and gully blocking was carried out, suggesting a synergistic interaction between these interventions. Evidence demonstrates the effects of ditch blocking on slowing flow through a catchment, with increased buffering between rainfall and stream discharge attenuating storm hydrographs and creating a more stable hydrological response (Wilson et al., 2010; Alderson et al., 2019). Ditch blocking typically reduces rapid drainage pathways and consequent discharge from ditches, but enhances transport via slower overland flow pathways through rough vegetation (Wilson et al., 2010; Evans et al., 2018). However, Gatis et al. (2023) found that whilst gully blocking with peat blocks significantly reduced peak flows by an average of 49 %, storm event lag times decreased by 33 % on average. This was thought to be potentially due to spatial changes in the generation of flow, with post-restoration flow primarily being generated close to the downstream monitoring site rather than further up in the catchment where the gully blocking attenuated flows. Modelled evidence suggests that peatland restoration can be moderately effective at smaller spatial scales, with revegetation of 12 % (1 km^2) of the catchment producing an average reduction in peak discharge of 5 % (Pilkington et al., 2015).

For further evidence on the use of peatland restoration for flood risk management, please see the IUCN-commissioned review on peatland catchments and NFM in the UK (Allott et al., 2019).

Sustainable Drainage Systems (SuDS)

Urban areas are at greater risk of surface water flooding due to the high cover of impermeable surfaces; SuDS therefore crucially aim to increase infiltration and reduce surface run-off. Bioretention systems and rain gardens designed to treat urban stormwater run-off have been shown to reduce run-off volume and peak flow by 40 to 97 % at a local scale (Ahiablame et al., 2012). These interventions have also been shown to increase lag time and provide significant flow storage (Dietz and Clausen, 2005). Similarly, a designed river corridor located on a rural-urban interface showed attenuation of flow within wetland areas (Cockburn et al., 2022).

A review of green roofs found that on average, 57 % of rainfall was retained and this translated into delays in peak run-off and discharge (Berndtsson, 2010). The reviewed evidence also suggested that green roofs were more effective during low magnitude rainfall events. A review by Ahiablame et al. (2012) found that green roofs retained between 20 and 100 % of rainfall, though rainfall volume and duration were noted as important factors determining effectiveness. Soil depth and vegetation type were also shown to influence the efficacy of water retention in green roofs.

Evidence suggests that permeable pavements can reduce runoff by between 50 and 93 % (Ahiablame et al., 2012). A 2-year study monitoring a permeable pavement found that run-off volume was significantly lower than asphalt pavement, even in large rainfall events (Fassman and Blackbourn, 2010). The authors concluded that the effects of the permeable pavement were comparable to the pre-development hydrology of the area, with the underdrain lag time and hydrograph duration being similar to a vegetated area.

Sustainable soil management

The evidence on the effectiveness of sustainable soil management to generate flood risk benefits varied considerably, partly due to encompassing multiple management techniques, but also as a result of the heterogeneous nature of soils. The techniques are typically aimed at reducing soil erosion but can also benefit flood risk management. A multi-year, multi-site monitoring study found that simple disruption of compacted tramlines significantly reduced run-off (by up to 97 %) to levels similar to those measured in areas without tramlines (in 4 out of 5 years) (Deasy et al., 2009). The study also examined the effects of minimum till agriculture which was reported to only be effective at reducing run-off in 1 out of 3 years when run-off volume was 31 % less than from a ploughed field. Quinton and Catt (2004) found that minimum till did not significantly reduce run-off from arable fields. Lipiec et al. (2006) found that no-till agriculture reduced soil porosity, with a cumulative infiltration 61 % lower compared to conventional tillage. These findings suggest that minimum or no-till farming does not produce reliable benefits for flood risk. Further research to test minimum and no-till approaches across different soil types and slopes may help increase understanding of when and where these techniques can be applied successfully.

Only one of the studies considered the effects of blade aeration, a technique whereby the vegetation and topsoil are mechanically sliced by rotating blades, helping to open up the soil surface. Wallace and Chappell (2019) found that blade aeration significantly increased soil K_{fs} by up to 7.5 times, which decreased the likelihood of infiltration excess overland flow. The authors stressed that the effects were site-specific, suggesting that blade aeration on slowly permeable topsoil overlying a permeable subsoil may produce the greatest flood-mitigation benefit.

Several studies looked at the effectiveness of contour cultivation, whereby arable fields are ploughed following the elevation contour lines. Quinton and Catt (2004) found contour cultivation to significantly reduce mean event run-off, with fields yielding 0.82 mm compared to 1.32 mm from fields cultivated up-and-downslope. Deasy et al. (2009) also observed significant reductions in run-off, though found that contour cultivation was only effective in 1 out of 2 years of monitoring. The combination of contour cultivation with minimum till was also reported to significantly reduce run-off (Quinton and Catt, 2004).

Experimental evidence from the monitoring of topsoil monoliths (vertical cross-sections) found that grass-clover leys enhanced soil health by reducing soil compaction, and improving infiltration rates, macropore flow and K_{fs} (Berdeni et al., 2021). The study also observed increased resilience of wheat crops (42 to 95 % greater yield) under flood conditions as a result of the leys. The effects of herbal ley crop rotations were modelled at a large catchment scale, though were not found to have a meaningful impact on flood risk in a permeable catchment, with a <1 % reduction in flow observed in events with return periods of >2 years (Collins et al., 2023).

Temporary water storage features

A wide range of studies focused on evaluating the flood mitigation benefits of temporary water storage features such as Run-off Attenuation Features (RAFs) and bunded ponds, with evidence from both monitoring and modelling. Roberts et al. (2023) reviewed different types of temporary storage areas, finding that their total volume is positively correlated with observed reductions in peak flow. Monitoring of 2 connected offline storage ponds found modest attenuation of peak flow, with reductions of up to 7 % across storm events (Lockwood et al., 2022). The same study found that 2 separate offline ponds located in a different sub-catchment were only able to provide up to 1.4 % reductions in peak flow. Attenuation was observed to be greatest when ponds were able to fill from both rainfall run-off and from overbank flow. Trill et al. (2022) report similar findings, showing greater peak flow attenuation during storms where offline ponds filled via overbank flows that were diverted out-of-channel by instream leaky woody barriers. The study reported peak flow reductions of between 14.2 and 55.2 % during storm events as a result of ~15700 m^3 of new storage distributed across a 3.4 km^2 catchment. Fennell et al. (2022) found that temporary storage on a smaller scale can also be effective, with 40 ~2 m^3 RAFs installed in ephemeral channels reducing high flows by 5 % in a 0.9 km^2 headwater catchment. Modelling also confirmed that distributing the RAFs over a larger area resulted in a greater flood attenuation effect.

RAFs located in the landscape have also been shown to effectively store water and help mitigate flooding. Wilkinson et al. (2010) reported noticeable attenuation effects on flood hydrographs and observed increases of 15-minutes to the travel time of flood peaks compared to events prior to the construction of 4 RAFs in the ~6 km^2 catchment. Modelling studies also confirm the effects of RAFs on flood hydrographs, with Adams et al. (2018) reporting that 8000 m^3 of additional catchment storage flattened hydrographs and delayed peaks. Nicholson et al. (2020) found that RAFs reduced downstream peak flow by >30 %, concluding that they are most suitable for reducing local flood peaks in small (1 in 2-year) flashy events. Wilkinson et al. (2010) also suggest that RAFs are likely to work best in low-order catchments. However, further modelling demonstrated that distributing a network of RAFs along a channel reach may be effective at reducing flooding from larger (1 in 12.5 to 1 in 100-year) events at a small (~10 km^2) catchment scale (Nicholson et al., 2020). The authors also note that RAFs may not be able to provide adequate flood attenuation in long duration events where storage is depleted prior to the main flood peak. The filling and draining of temporary storage features are important components of their design and functioning (Roberts et al., 2023). These should be carefully considered when designing NbS that are resilient to future extreme rainfall events that are becoming increasingly more likely to occur as a result of climate change (Christidis et al., 2021).

Temporary storage features have also been used with the primary aim of mitigating soil erosion and preventing the phenomenon of 'muddy floods' (Evrard et al., 2008). The Belgian study examined the efficacy of a grassed waterway and 3 earthen dams, finding that these interventions reduced the peak discharge per hectare by 69 %, buffered run-off, and thereby increased lag time by 75 % (Evrard et al., 2008).

2.3.2 Low flow management

NbS were also reported to have an impact on processes and properties that enhance water storage and availability in soils, ground and surface water, thereby potentially reducing the impact of low flows on the environment. For example, low flows affect the environment by concentrating pollutants in watercourses or by reducing continuity of river networks and thereby limiting movement of aquatic wildlife (Stubbington et al., 2024). Climate change will modify patterns of rainfall, streamflow and groundwater recharge, and is therefore likely to impact the frequency and magnitude of low flows (Watts et al., 2015; Kay et al., 2021; Lane and Kay, 2021). This section discusses evidence of how NbS can help to restore the natural hydrological functions of catchments that could mitigate the impacts of low flow extremes. NbS can encourage water to take slower pathways through a catchment, thereby changing how and when water is stored and released. It is important to note that the direct benefits of NbS for low flows can be difficult to measure, and in some cases are inferred. Studies frequently use modelling to estimate how sub-surface processes such as groundwater recharge are altered by different scenarios involving NbS.

The benefits for low flows were not as widely reported in comparison to flood risk benefits. The literature also highlighted potential trade-offs and negative impacts on water availability in low flows. The identified processes and properties include:

- Infiltration and percolation
- In-channel low flow enhancement/refuge
- Groundwater recharge
- Water table height (depth from surface to water table)

Afforestation

Multiple studies found that afforestation is capable of altering catchment water balances, reducing water yields by changing the proportion of run-off, infiltration, and evapotranspiration (Allen and Chapman, 2001; Fahey and Payne, 2017). Both monitored and modelled evidence suggests that afforestation can result in altered hydrological regimes. Fahey and Payne (2017) observed that over a 22-year monitoring period, low flows (Q95) were reduced by 26 % on average in a catchment with plantation forestry relative to a control catchment. The average annual water yield was also reduced by 33 % over the same period. Large-scale modelling found that afforestation consistently decreases median and low streamflow, with median flow reducing by 2.8±1 % per 10 % increase in catchment cover of broadleaf woodland (Buechel et al., 2022). Modelling of afforestation in a permeable catchment found that large-scale planting of spruce was estimated to reduce low flows by 39 % (Collins et al., 2023). Birkinshaw et al. (2014) report similar effects from long-term monitoring, with 90% catchment cover of mature spruce (39 years since planting) reducing low flows and decreasing annual streamflow by 250 to 300 mm compared to the previous grassland landcover. Over the same period, the run-off ratio was reduced from 66.7 % to 54.8 %. Decreased stream discharge during low flow conditions could reduce the resilience of ecological communities to drought events, with impacts on longitudinal connectivity and habitat availability being exacerbated during prolonged dry periods (Sarremejane et al., 2021; Yang et al., 2023; Stubbington et al., 2024). It is important to note that the effects of plantation forestry on hydrological processes and streamflow may differ from mature or broadleaf woodland. Differences in the effects are likely to be driven by factors such as tree species, root depth, planting density and management (Archer et al., 2013; Monger et al., 2022). Therefore, evidence from plantation forestry (e.g. non-native conifers) cannot be directly extrapolated to predict the effects of planting native deciduous trees on a catchment.

There is evidence to suggest that trees enhance infiltration of water into soils compared to other landcovers such as grassland (Archer et al., 2013; Baker et al., 2021). However, due to the higher water requirements of trees compared to other vegetation, the net effect of afforestation on soil moisture can be depletive. Over a 4-year monitoring period, Green et al. (2006) found that soil moisture depletion was greater underneath oak woodland compared to grassland. Furthermore, the seasonal rate of soil moisture recovery during winter rewetting period was found to be slower in the woodland. Processes leading to the recharge of groundwater (e.g. percolation) were also affected, with a review by Allen and Chapman (2001) concluding that afforestation can lead to an overall decrease in recharge and lowering of local water tables. Monitoring over 4 years found that groundwater recharge under oak woodland overlying a sandstone aquifer was potentially only 55 % of that observed under grassland (Green et al., 2006). Similarly, modelling of land-use change to forestry over borehole capture zones over a 20-year period resulted in an annual reduction of up to 45 % in groundwater recharge (Zhang and Hiscock, 2010). Groundwater resources represent a significant source of drinking water in England, with approximately a third of the public water supply coming from groundwater (British Geological Survey, 2019).

Van Meerveld and Seibert (2024) reviewed evidence of the effects of reforestation and afforestation on low flows, and the complex interactions between forests and precipitation, evapotranspiration, soil water, and streamflow. It was found that a conversion to forested land cover typically increases evapotranspiration, but decreases groundwater recharge and streamflow. However, the authors also found that forests have the potential to offset some of the increases in evapotranspiration through returning evaporated water as precipitation. Forest planting was found to have the potential to enhance streamflow during dry periods in areas where soil hydraulic properties are significantly altered. The findings of van Meerveld and Seibert's (2024) review demonstrates how the effects of afforestation on hydrology can be site-specific and strongly influenced by catchment characteristics including the underlying geology, and both forest and soil properties.

Assisted natural regeneration

Rewilding has been hypothesised to help mitigate the impacts of drought, though there is currently a lack of evidence due to its novelty and therefore high uncertainty on its effectiveness (Harvey and Henshaw, 2023). Experimental evidence from the exclusion of sheep on improved grassland found that soil hydraulic properties (e.g. infiltration rate) in ungrazed plots were less impacted by drought conditions compared with the grazed control plots (Marshall et al., 2014). The study also found that excluding sheep and planting broadleaf trees resulted in a median soil infiltration rate 67 times greater than the control. Further evidence on the effects of assisted natural regeneration is needed to better assess the potential benefits for low flow management. In particular, further monitoring is required to determine long-term effects on the recovery of degraded soils and how these effects might operate at larger spatial scales.

Beaver re-introduction and management

The re-introduction of beavers has been found to increase lateral connectivity between watercourses and their floodplains, as well as increasing surface water storage within ponds and canal networks (Brazier et al., 2020). In turn, these effects can locally raise water tables and contribute to groundwater recharge. A study monitoring the effects of riparian wetland rehabilitation and beaver re-colonisation found that groundwater recharge (estimated using a water balance model) increased from <5 % of the total rainfall to <10 % following restoration (Smith et al., 2020). This effect is not entirely attributable to beaver activity; however the authors note that the impact of the riparian rehabilitation (which included backwater creation and in-channel bunds) was greatly enhanced by the beaver population. In their review of beavers as ecosystem engineers, Brazier et al. (2020) found that the gradual release of water from beaver ponds can maintain flows during dry periods, thereby providing better low flow refuges, greater potential for recolonisation, and increasing ecological resilience to drought.

Buffer strips/zones

None of the reviewed studies directly examined the effects of buffer strips/zones on low flows, however Cole et al. (2020) found that deep roots in wooded buffer strips increase soil complexity, porosity and permeability which enhance infiltration and water retention.

Floodplain reconnection

Studies examining the impacts of floodplain reconnection tended not to concentrate on the potential low flow benefits. However, there was some evidence to suggest that reconnecting rivers to floodplains may enhance groundwater recharge. A BACI study found that median water tables were 0.037 to 0.089 m higher following the lowering of an embankment (Addy and Wilkinson, 2021). Clilverd et al. (2013) highlight how embankment removal can change hydraulic gradients, providing opportunities for bidirectional surface-subsurface flows, and thereby increasing hydrological complexity of the river-floodplain system.

Hedgerows and vegetative barriers

Hedgerow margins were found to have significant positive effects on soil properties including bulk density, porosity, and also permeability, which Wallace et al. (2021) found was 22 to 27 times greater than on adjacent pasture soil. Holden et al. (2019) observed significantly higher K_{fs} under hedgerows (median = 102 mm hr^{-1}) compared to arable land (median = 3 mm hr^{-1}). This suggests that hedgerows enable greater vertical movement of water through the soil and increase potential opportunity for groundwater recharge. Vegetative barriers on arable fields were found to increase infiltration at a local scale, though this was noted to be a relatively small effect in the context of the whole catchment (Richet et al., 2017).

Instream wood

Only one study considered how instream wood contributes to drought resilience. Norbury et al. (2021) found that willowed engineered log jams made up of timber and willow saplings were able to elevate baseflows by 27 % through slowing rapid run-off pathways and wetting the landscape, thereby enhancing resilience to dry conditions.

Peatland restoration

Evidence on peatland restoration largely comes from empirical studies monitoring using a BACI approach to enable greater confidence in the findings. Peatland restoration in uplands, typically through revegetation and ditch/gully blocking, has widely been found to raise water tables (Wilson et al., 2010; Pilkington et al., 2015; Alderson et al., 2019; Shuttleworth et al., 2019; Gatis et al., 2023). The retention of water within peat and in surface pools was also observed to increase following restoration (Wilson et al., 2010; Gatis et al., 2023). Peatland restoration measures are therefore likely to enhance the resilience of these ecosystems to drought. However, the effects of restoration measures on low flow conditions can be complex, with Gatis et al. (2023) finding that gully blocking with peat blocks did not increase baseflows within the 4 years of post-restoration monitoring despite raised water tables. Further study is needed to better understand long-term changes to hydrological regimes in restored peatland catchments, and the potential benefits for low flow management. This is particularly important in light of climate change, with studies suggesting that the extent of suitable bioclimatic conditions for the formation of blanket peatland across Great Britain is likely to decrease in future (Clark et al., 2010; Gallego-Sala et al., 2010).

Sustainable Drainage Systems (SuDS)

Within the reviewed literature there was little evidence on the ability of SuDS to enhance low flows and resilience to drought. A review of low impact development (LID) practices suggests that permeable pavement can be used for stormwater harvesting and as storage mechanisms for reuse by urban populations (Ahiablame et al., 2012). Veldkamp et al. (2022) conclude that permeable pavements are potentially effective climate adaptation measures to reduce drought impacts in urban settings, however their effectiveness depends on environmental factors as well as maintenance and management. For example, permeable pavements can require regular maintenance as a result of being susceptible to clogging from solid particles that accumulate over time and reduce infiltration (Veldkamp et al., 2022).

Sustainable soil management

Studies of sustainable soil management tend to concentrate on measurements of run-off, and therefore observed decreases in run-off can only be implicitly assumed to result in increased infiltration. Several studies directly measured the effects on soil hydraulic properties. Wallace and Chappell (2019) found that blade aeration of soils significantly increased K_{fs} by up to 7.5 times, thereby enhancing vertical movement of water through the soil profile. One study reported negative effects on soil porosity from no till agriculture, with infiltration being reduced by 61 % compared to conventional tillage (Lipiec et al., 2006).

Temporary water storage features

The examined studies on temporary water storage features focussed primarily on their effects on flood hydrology, with only one study investigating their effect on low flows. Hydrological modelling by Fennell et al. (2022) showed that the installation of 40 RAFs increased groundwater recharge by ~0.1 %, groundwater contribution to streamflow by ~4 %, and enhanced low flows by ~1 %. The authors noted that although a positive direction of change was evident, the values should be treated with caution due to the relatively small size of the effects and consideration of model uncertainties. Further empirical data on the effects of temporary water storage features would help to reduce uncertainties.

The implementation of NbS (including RAFs) for the enhancement of groundwater recharge in chalk-dominated catchments has been modelled as part of the Environment Agency’s work to quantify the water resources impacts of NbS and working with natural processes. For further information and project reports, please contact research@environment-agency.gov.uk.

2.4 Water quality

Issues relating to the water quality of freshwater environments are wide-ranging and can pose risks to wildlife, the provision of ecosystem services, and to human health. In this report, water quality is defined as the physical, chemical and biological characteristics of water that contribute to the health of aquatic ecosystems, and determine its suitability for use by humans. This includes surface water, soil water, and groundwater. The reviewed evidence identified a number of elements, processes and properties relating to water quality that can be impacted by NbS:

- pH
- Dissolved oxygen (DO)
- Water temperature
- Hyporheic exchange
- Sedimentation
- Faecal bacteria concentration in watercourses
- Cyanobacteria (blue-green algae)
- Chlorophyll-a concentrations
- Heavy metals
- Nitrogen (N) retention/removal
- Phosphorus (P) retention/removal
- Carbon (C) retention/storage

The following sections (2.4.1 and 2.4.2) discuss the effects of NbS on water quality under the broad headings of 'Nutrient and sediment management', and 'physico-chemical and biological properties'.

2.4.1 Nutrient and sediment management

Catchments in England experience considerable pressure from an excess of nutrients in waterbodies, with phosphorus (P) being the most common reason for waterbodies not achieving good ecological status (GES). Based on the 2019 Water Framework Directive (WFD) classifications, 55 % of river waterbodies and 73 % of lake waterbodies assessed for P fail to meet the standard for GES (Environment Agency, 2019b). Fine sediment is also a significant issue in streams and has been considered alongside nutrients within this section due to its ability to act as a vector for nutrients. Additionally, excess fine sediment in streams can physically degrade habitat and negatively impact benthic invertebrates (Wood, 1997).

The studies examined as part of this review found considerable scope for using NbS to manage nutrients more sustainably and help mitigate freshwater eutrophication. However, some studies also highlight the potential risks of NbS to exacerbate the effects of nutrient pollution.

<u>Afforestation</u>

A systematic review of urban tree planting found that at a plot-scale, woodland can reduce mean concentrations in runoff, soil, or groundwater by an average of 44.2 % for total nitrogen (TN) and 47 % for total phosphorus (TP) (Hutchins et al., 2023). The review found that increasing the area of tree cover in a catchment by 20 % can reduce mean concentrations of TN by 15.7 %, and TP by 12.6 %. Hutchins et al. (2023) suggest that in heavily urbanised settings, leaf litter falling on impervious surfaces can increase the risk of TP leaching to streams. The review also considered instream impacts, with high riparian woodland canopy cover being found to suppress stream channel biological uptake of nitrate. Allen and Chapman (2001) suggest that afforestation can impact groundwater quality by increasing nitrification (conversion of ammonia/ammonium to nitrate/nitrite), which in turn can lead to acidification and leaching of nitrate into the saturated zone.

Beaver re-introduction and management

The impact of beavers on water quality in lotic environments has been widely studied, with evidence coming from both primary research and several reviews and meta-analyses. Beavers are able to slow the flow of water through dam and pond creation, thereby enabling sediment deposition, and also raising local water tables which can impact biogeochemical cycling and nutrient fluxes in the riparian zone (Brazier et al., 2020). The evidence suggests that there is no definitive consensus on the effects of beavers on nutrient retention in river systems. Some studies report that beaver dams and ponds can significantly reduce downstream concentrations of biologically-available P, with reductions ranging from 49 to 80 % (Law et al., 2016; Puttock et al., 2017); annual TP loads have been observed to reduce by 21 % (Correll et al., 2000). A meta-analysis by Ecke et al. (2017) suggests that the retention potential of P increases with the age of beaver pond systems, with this age-dependent relationship being attributed to increased inputs of organic matter and changes in sediment properties over time. Young beaver ponds were largely a source of P, whereas old ponds were suggested to have potential to mitigate eutrophication. These findings may help to explain why Smith et al. (2020) only found limited evidence of water quality improvements (including TP concentrations) following beaver re-colonisation of a riparian wetland rehabilitation site.

Mixed effects are also reported for the effect of beavers on different forms of N in water. A 43 % reduction in average downstream growing season concentrations of nitrate (NO_3^-) (Law et al., 2016); a 35 % reduction in Total Oxidised N (TON; the sum of nitrate and nitrite) (Puttock et al., 2017); and an 18 % reduction in annual TN load (Correll et al., 2000) have all been observed. On the other hand, Ecke et al. (2017) and Smith et al. (2020) found that beaver dam and pond systems did not retain different forms of N or decrease their downstream concentrations. Correll et al. (2000) note that the biogeochemical effects of beaver ponds can be seasonal; the differences in observed nutrient retention between the studies may therefore be a result of high temporal variation.

Evidence also suggests that beaver re-introduction can have mixed effects on both sediment and carbon transport and storage in river systems. Puttock et al. (2017) reported 65 % reductions in downstream concentrations of suspended sediment (SS), and Correll et al. (2000) observed 27 % reductions in the annual load of SS. However, Law et al. (2016) found that SS concentrations increased downstream of a series of 10 beaver dams and interconnected pools. The same study also found that the beaver modifications resulted in a seven-fold increase in the retention of organic matter. Spyra et al. (2023) report similar findings in beaver ponds, noting that organic matter retention was higher compared to unmodified river reaches regardless of pond age. Correll et al. (2000) observed that a single beaver pond reduced the annual load of total organic carbon (TOC) by 28 %. Studies that monitored impacts on dissolved organic carbon (DOC) concentrations found significant increases downstream of beaver sites, between 50 and 175 % on average (Puttock et al., 2017; Smith et al., 2020). These findings suggest that beaver pond systems are more likely to enhance particulate storage of carbon, and act as a source of dissolved carbon. Overall, there is strong evidence that there are positive benefits effects on water-related ecosystem services including nutrient processing and fine sediment storage, which can benefit downstream water quality. However, the scope for benefits varies with the scale of influence of beaver activity in different environmental conditions. Please see Howe (2020) for further detail on the effects of beavers on nutrient and sediment management.

Buffer strips/zones

Different designs and configurations of buffer strips/zones were found to have varying benefits for nutrient management. Modelled evidence suggested that converting 10 % of the study catchment into riparian buffers could reduce TP concentration peaks during storm events by 5 to 10 % due to enhanced trapping of sediment and particulate P (Adams et al., 2018). Integrated Buffer Zones (IBZ) were found to act as both sources and sinks of Soluble Reactive P (SRP), with Zak et al. (2019) observing removal rates of between −0.3 and 5.0 mg P m^{-2} d^{-1}, equating to a monthly average removal efficiency of between −29 and 67 %. However, when considering TP, the observed removal rates were all positive (between 0.3 and 6.9 mg P m^{-2} d^{-1}), with monthly average removal efficiencies of between 18 and 52 %. The issue of dissolved P release was also highlighted by Cole et al. (2020), with wooded riparian buffer strips being a potential source of SRP where particulate P is remobilised to more soluble forms due to high concentrations of organic matter. This was suggested to lead to increases in transport of SRP via overland or sub-surface flows.

The reported effects of buffer strips/zones on N cycling were all positive for water quality. Cole et al. (2020) suggest that zoned riparian buffer strips which include a zone of native tree species can help to reduce nitrate leaching into groundwater. Reducing nitrate inputs to the sub-surface is beneficial in helping reduce water treatment costs, particularly where drinking water is derived from aquifers. Zak et al. (2019) observed that IBZ removed nitrate and TN at rates of 0.2 to 0.5, and 0.1 to 0.6 g N m^{-2} d^{-1} respectively, resulting in monthly average removal efficiencies of between 23 and 37 % for nitrate, and 8 and 38 % for TN. In forested buffer strips, denitrification (conversion of nitrate to N gas) is thought to be an important mechanism for nitrate removal, with high concentrations of organic matter increasing the activity of denitrifying microbes (Cole et al., 2020).

Reviewing different types of buffer strips, Cole et al. (2020) found that grassed, wooded, and zoned buffer strips can effectively prevent sediment loss into watercourses through the trapping of particles and stabilisation of river bank soils. Models predicted that wooded buffers would be more efficient at removing pollutants compared to grass buffers due to their higher structural complexity. Buffers with distinct zones of grass and trees were found to be more effective than buffers that incorporate both as a mixture (Cole et al., 2020).

Channel restoration

Channel restoration measures were generally found to be beneficial for nutrient management. Restored river reaches which had undergone re-meandering, alongside floodplain reconnection, addition of riparian vegetation and instream woody material were found to have increased capacity to retain particulate P in bed sediment compared with unrestored or highly modified reaches (Janes et al., 2017). The reconnection of a backwater channel was found to significantly enhance retention of TP and organic matter compared to a control reach (Addy and Wilkinson, 2019). Daylighting (culvert removal) of an urban stream resulted in enhanced nutrient removal, with the restored reach having net retentions of 226, 128, 38 % for phosphate, TN, and TP, respectively (Baho et al., 2021). One study observed no effect on fluvial carbon from the re-meandering and addition of gravel to 4 stream sites (Baattrup-Pedersen et al., 2022). The authors suggested that morphological improvements were less important than other abiotic and biotic factors in the cycling of organic C at the reach scale.

Constructed wetlands

There was a substantial amount of evidence on the efficacy of CWs and interconnected pond systems to mitigate nutrient pollution from different sources. The studies mostly reported positive effects on the retention of different forms of P, with mean reductions in phosphate concentrations downstream of interventions ranging from 29 to 63 % (Cooper et al., 2020; Robotham et al., 2021). Phosphate loads were shown to be reduced by 16 to 70 % (Kill et al., 2018; Cooper et al., 2020), whereas TP loads were reduced by 14 to 21 % (Johannesson et al., 2011; Kasak et al., 2018; Kill et al., 2018). Flow rates have been shown to play an important role in P removal efficiency, with higher flows reducing residence time and nutrient retention, and in some cases resulting in net releases of dissolved and particulate forms of P (Johannesson et al., 2011; Kill et al., 2018). Tolomio et al. (2019) highlight how early-autumn storms can also mobilise dissolved P from decomposed wetland litter. The studies also observed a seasonal influence on dissolved P removal, with efficiency doubling during summer when temperatures were highest and aquatic plant (macrophyte) cover was highest. Only one study did not observe any effect on downstream phosphate, with concentrations from an aerated vertical-flow CW treating sewage treatment work (STW) effluent showing no significant difference to the inflow (Stefanakis et al., 2019).

The evidence suggested that CWs vary considerably in their ability to manage N pollution. Two integrated CW (ICW) treating STW effluent were able to significantly reduce mean nitrate concentrations by ~30 to 60 %, and nitrate loading into the rivers by ~57 to 70 % (Cooper et al., 2020). Stefanakis et al. (2019) also reported notable reductions in nitrate-N concentrations in STW effluent treated by a CW, as well as reductions of ammonium to very low levels (mean ammonium removal efficiency of 89 %). A surface-flow CW treating diffuse agricultural pollution was found to be similarly effective with a mean TN removal efficiency of 90 % over 5 years of monitoring (Borin and Tocchetto, 2007). The authors observed that the main removal mechanisms were plant uptake, accumulation in the CW soil, and denitrification. Much lower removal efficiencies have been reported, with a connected set of 3 small online ponds reducing baseflow nitrate concentrations by 5 % on average (Robotham et al., 2021). Both Kasak et al*.* (2018) and Kill et al. (2018) observed that agricultural CWs increased mean downstream nitrate concentrations by ~30 %. This unintended consequence was thought to be due to the influence of nitrate-rich groundwater seepage from the intensively farmed arable catchment.

Unintended consequences have also been reported for C, with CWs increasing concentrations of total inorganic C by 10 % (Kill et al., 2018), and also acting as sources of DOC (Cooper et al., 2020). However, evidence suggests that overall C can be retained by CWs, with Kasak et al. (2018) observing a mean total C removal efficiency of 12 %, equating to a retention rate of 3300 kg C ha^{-1} yr^{-1}.

Evidence suggests that CWs are able to trap significant volumes of sediment and bound nutrients transported from their upstream drainage areas, thereby helping to reduce the impact of agricultural activity in headwaters on downstream ecosystems. Johannesson et al. (2015) monitored 7 CWs with different designs and ages, finding that sediment accumulation rates ranged from 13 to 108 t ha^{-1} yr^{-1}, and P accumulation rates from 11 to 175 kg ha^{-1} yr^{-1}. The authors observed that for very fine (clay) particles to settle out of suspension, larger CWs with higher retention times relative to the upstream catchment area were required. Despite this, small, edge-of-field wetlands designed to capture agricultural run-off have been shown to effectively trap and store sediment and bound P, N and C in 4 different catchments (Ockenden et al., 2014). However, there is evidence to suggest that without suitable maintenance small online pond features can also act as a source of sediment pollution as a result of the remobilisation of particles, particularly during high flow events (Barber and Quinn, 2012; Robotham et al., 2021, 2023).

Please see Johnes and Hussey (2024) for further detail on nutrient cycling in wetland systems.

Floodplain reconnection

The evidence base for the effects of floodplain reconnection on nutrient management is limited, however multiple studies hypothesise that removing or lowering embankments improves river water quality by regularly supplying nutrient-rich water and sediment to the floodplain for removal via plants and microbial activity (Clilverd et al., 2013; Addy and Wilkinson, 2021). Modelled evidence suggests that large-scale floodplain reconnection can increase nitrate removal via denitrification by 15 % (Tschikof et al., 2022).

Hedgerows and vegetative barriers

Hedgerows are likely to be beneficial for water quality, however there may also be associated trade-offs. Wallace et al. (2021) found that hedge-margins store significantly more nitrate (70 to 260 %) and loose sediment (540 to 3970 %) compared to pasture. Holden et al. (2019) found that mean nitrate and phosphate concentrations were higher under hedgerows compared to arable land, though the authors warn that there was still a risk of soil-bound nutrients being mobilised and polluting watercourses. Monitoring the effect of oak hedgerows on nitrate dynamics, Thomas and Abbott (2018) found that they reduced annual fluxes of nitrate by 26 to 63 % at a hillslope scale, with root uptake accounting for most of the reduction. The effect of hedgerows was smaller at a catchment scale, removing 1 to 10 % of the annual nitrate flux (Thomas and Abbott, 2018).

Vegetative barriers have been shown to effectively intercept diffuse agricultural pollution, with higher rates of sediment deposition for coconut-fibre barriers compared to straw and wood chip barriers (Frankl et al., 2021). It was noted that the barriers mainly retained larger (sand) particles rather than fine (clay) particles which resulted in an increased risk of run-off bypassing or overtopping the dense coconut-fibre barriers. Richet et al. (2017) found that brushwood and shrub barriers were able to capture coarser aggregates and were most efficient when placed immediately downstream of critical source areas of erosion.

Instream wood

There is limited evidence of the effects of instream wood additions on nutrients. Experimental evidence found that the presence of hazel wood fascines increased nitrate removal in microcosms with chalk stream sediment, but had no effect in those with limestone and sandstone sediment (Howard et al., 2023). Instream large woody material introduced for NFM purposes was not found to have any effects on stream nutrient chemistry (Deane et al., 2021).

Peatland restoration

Evidence of the effects of peatland restoration on water quality concentrate on fluvial C dynamics. Alderson et al. (2019) reported reductions in the losses of particulate C from multiple peatland sites revegetated with the lime-seed-fertiliser-mulch method and monitored using a BACI approach. However, extensive monitoring by Pilkington et al. (2015) and Evans *et al.* (2018) found that peatland gully blocking and revegetation both had no significant effect on DOC or Particulate Organic Carbon (POC) in ditch water, stream water, run-off, or pore water. Gully blocking using peat blocks was also observed to have no effect on DOC loads from a site during the first 4 years following restoration (Gatis et al., 2023).

Riparian restoration

Studies looking at the effects of riparian restoration on water quality largely focused on N cycling, though one study reported enhanced retention of TP and particulate C (Wilcock et al., 2012). A 3-year study monitoring the recovery of a 360 m long riparian wetland following the installation of fencing to exclude cattle found that on average the wetland retained 5±1 % of TN loads but had a negative retention for nitrate (−29±5 %) (Wilcock et al., 2012). The authors suggested that the wetland acted as a source of nitrate due to the predominantly aerobic conditions which prevented denitrification. Peter et al. (2012) found that restoration of riparian zones can enhance nitrate removal following flood events, observing reductions of >50 % in groundwater nitrate concentrations in a willow (*Salix viminalis*) zone. These nitrate reductions were ~20 % higher compared to a channelized (unrestored) reach, however reductions were not seen in sections of the riparian zone dominated by gravel or reed canary grass (*Phalaris arundinacea*). This demonstrates the high spatial variability in denitrification rates. Batson et al. (2012) also observed high spatial variability, measuring reductions of 57 % in surface water TN fluxes from flow-through river diversion wetlands. Whilst only 3.5 % of the flux was permanently removed via denitrification, it was noted that similar rates have been seen in both natural and created wetlands.

Sustainable Drainage Systems

A review of bioretention systems suggested that they can potentially reduce sediment and nutrient losses by up to 99 % (Ahiablame et al., 2012), however pollutant removal efficiency has been found to vary depending on the media used. LeFevre et al. (2015) suggest that using iron-enhanced sand (sand mixed with iron filings) in bioretention systems can effectively remove dissolved P from stormwater. Evidence indicates that the removal of different forms of N in such systems is less effective and more unreliable (LeFevre et al., 2015), with Dietz and Clausen (2005) observing poor treatment of nitrate and organic N in a rain garden. However, the study did find that concentrations of ammonia were significantly lower in the effluent compared to the influent.

Nutrient removal in green roofs has not been widely proven, however some studies suggest they can act as sources of nutrient pollution, especially when artificially fertilised (Ahiablame et al., 2012). In a review of evidence, Berndtsson (2010) found that run-off water quality from green roofs is highly variable and they risk releasing nutrients during rainfall events. A pilot study monitoring a constructed wet roof (a green roof combined with a constructed wetland) treating domestic wastewater found that it was able to remove 81 to 91 % of Total Suspended Solids (TSS), 99 % of ammonium, ~90 % of TN, and 86 to 97 % of TP (Zapater-Pereyra et al., 2016). However, the study also observed that nitrate increased significantly from negligible levels to between 14 and 17 mg/l.

Evidence on the effect of permeable pavements on nutrients was generally lacking, however, Ahiablame et al. (2012) report that average reductions in TSS and nutrients can range from 0 to 94 %. A study monitoring permeable pavement also observed that it was able to reduce suspended sediment loading (Legret and Colandini, 1999).

Sustainable soil management

Evidence on the effect of sustainable soil management practices on nutrient losses was mixed, with studies highlighting a considerable degree of temporal and spatial variability in their effectiveness. Tramline disruption was found to significantly reduce losses of SS and TP (by ~99 %) to levels similar to those measured in areas without tramlines in 4 out of 5 years of a field study on silty clay loam soil (Deasy et al., 2009). The study found that in a catchment with sandy soil, tramline disruption decreased by SS and TP losses by ~75 %. Effectiveness was found to vary depending on the antecedent weather conditions, with potential for greater losses of SS and TP from disrupted tramlines in dry years due to less soil compaction and an increased source of particles for transport during their establishment in autumn compared to during wetter years.

Contour cultivation had mixed results with Deasy et al. (2009) observing significant reductions in sediment and TP loss in 1 out of 2 years of monitoring. Quinton and Catt (2004) found that only when combined with minimum till, did contour cultivation significantly reduce soil loss in rainfall events when compared to up-and-downslope cultivation and standard tillage (Quinton and Catt, 2004). Evidence suggests that minimum till farming is not a consistently reliable intervention to reduce SS and TP losses from fields, with Deasy et al. (2009) only reporting effective reductions in 1 out of 3 years, and Quinton and Catt (2004) observing no significant reductions in soil loss.

Evidence on the use of cover crops and crop residues in the assessed literature was not extensive, however they have been found to protect soil surfaces from erosion and reduce losses of SS and TP (Dabney et al., 2001; Deasy et al., 2009).

One study modelled soil health improvements through maximising infiltration, finding that this increased the transport of SRP to streams on the receding limb of hydrographs due to enabling rapid sub-surface flow pathways (Adams et al., 2018). However, the study found a net reduction in TP loading as transport was reduced from surface run-off, with mean and maximum TP concentrations in events reduced by 4.7 and 6.4 % respectively. Additionally, the export of SS was reduced.

Temporary water storage features

Evidence on temporary water storage features is primarily focussed on their effectiveness at mitigating flood risk, however they show potential for trapping sediment and improving water quality (Wilkinson et al., 2010; Roberts et al., 2023). Several monitoring studies have demonstrated their ability to capture significant masses of sediment in agricultural catchments, both from overland flow and out of bank flood flows (Barber and Quinn, 2012; Robotham et al., 2023). A study monitoring 8 different offline flood storage ponds in the same catchment found that accumulation rates of sediment and TP were highly variable between ponds due to their location, design, and configuration (Robotham et al., 2023). The study also highlighted the trade-off between trapping sediment and maintaining flood storage capacity which was predicted to diminish after ~10 years. This was also demonstrated in the modelling of stormwater pond performance which found that they trapped up to 69 % of SS, however sedimentation led to a 24 % loss in pond volume over 32 years (Ahilan et al., 2019). Importantly, the study also highlighted the risk of extreme rainfall events flushing out accumulated sediment and leading to intense pulses of sediment loading downstream. Catchment modelling has also shown that changing 5 % of land-use to Run-off Attenuation Features (RAFs) can reduce TP loading during storm events by up to 8 % (Adams et al., 2018).

Other forms of temporary water storage features have been shown to be effective at mitigating diffuse pollution. For example, the construction of a grassed waterway and 3 earth dams reduced the SS yield from agricultural fields by 93 % (Evrard et al., 2008). A review of vegetated swales in urban areas suggested that they can retain between 14 and

98 % of nutrients and TSS (Ahiablame et al., 2012). Similarly, monitoring of a Stormwater Infiltration Basin (SIB) found that average concentrations of SS and TP were reduced by ~50 % (Birch et al., 2005). Whilst the study observed a mean removal efficiency of 65 % for Total Kjeldahl N (TKN; the sum of ammonia and organic N), there was an increase of ~250 % in nitrate and nitrite N from the effluent of the SIB.

2.4.2 Physico-chemical and biological properties

This section largely discusses the effects of NbS on the physical and chemical (physico-chemical) properties of water quality in the freshwater environment. An important example is water temperature which is recognised as a fundamental variable in controlling other water quality parameters such as dissolved oxygen (DO), as well as ecosystem services such as nutrient cycling (Hannah and Garner, 2015; Orr et al., 2015; Ficklin et al., 2023). This section also considers the effects of NbS on chemical pollutants such as heavy metals in freshwaters. This section also considers the effects of NbS on the biological properties of water quality that are a concern for human uses of water, e.g. for recreational activities such as bathing. These properties include faecal coliform bacteria and other microbial indicators of waterborne pathogens, as well as potentially harmful algae.

Afforestation

Afforestation of riparian headwaters can play an important role in controlling instream primary productivity through providing shade, thereby limiting undesirable consequences for downstream water quality (Hutchins et al., 2023). Riparian trees have been shown to significantly reduce water temperature, particularly maximum stream temperatures; for further evidence see Bowler et al. (2012).

Allen and Chapman (2001) highlighted the potential risk of acidification and nitrification of groundwater as a result of large-scale afforestation due to trees scavenging atmospheric pollutants. The authors emphasised the importance of location on the impacts, with catchment geology, and the proximity to industrial areas and prevailing wind direction all influencing the risk to groundwater quality.

Beaver re-introduction and management

Most of the reported negative effects of beavers on physico-chemical water quality were related to water temperature. The removal of large numbers of riparian trees by beaver activity combined with their impoundments slowing the flow of water increases exposure to sunlight and can result in warmer water temperatures (Correll et al., 2000; Ecke et al., 2017; Smith et al., 2020).The effect of ponding can also impact DO levels, with lower concentrations being observed in beaver impoundments compared to upstream and downstream.

It is important to acknowledge that the wider evidence base (e.g. studies in non-temperate catchments) has shown that, in some cases, beaver colonisation can buffer diel temperature extremes at a reach scale during the summer months (Weber et al., 2017).

Please see Howe (2020) for further evidence on the effects of beavers on water temperature that was beyond the scope of this review.

A meta-analysis found that beaver ponds can be a source of mercury (Ecke et al., 2017). This was thought to be as a result of increased availability of degradable C leading to the formation of methylmercury, a toxic compound. The study also demonstrated that despite beaver ponds releasing mercury, the release from artificial impoundments (e.g. hydroelectric dams) was found to be more than double this. Correll et al. (2000) observed that a single beaver pond reduced the annual dissolved silicate load by 32 %.

Buffer strips/zones

A review of buffer strips found that they had positive effects on stream water temperature through providing shade and thereby moderating diel fluctuations in water temperatures and creating more stable temperature regimes (Cole et al., 2020). It was also suggested that using buffer zones of native tree species could reduce the acidity of groundwater (Cole et al., 2020).

Channel restoration

Channel restoration activities including re-meandering can enhance pollutant retention (Janes et al., 2017). Restored channel reaches and those with less artificial modification showed greater retention of iron, barium, tin, and potassium. One of the factors contributing to this enhancement was the increased cover and density of marginal and riparian vegetation enabling deposition and storage in restored reaches. A study monitoring the creation of a river side-channel found that this restoration had no detectable effect on water temperature, pH, or DO (Pander et al., 2015).

Constructed wetlands

CWs have been shown to effectively capture heavy metals (Lenormand et al., 2022). Monitoring found that a vertical-flow CW with a fine sand substrate removed copper, zinc, and lead most effectively, whereas a horizontal-flow CW with a gravel substrate was most effective at capturing nickel. Setback outfall wetlands have also been found to enable the deposition and storage of sediment-bound pollutants (Janes et al., 2017).

Aerated vertical-flow CWs treating STW wastewater can improve effluent water quality by reducing the 5-day Biological Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), and water temperature (Stefanakis et al., 2019). Monitoring also showed effective removal of *E. coli* from wastewater, with final effluent from the CW fulfilling legal criteria for environmental discharge and reuse (Stefanakis et al., 2019).

Instream wood

A study monitoring the effect of introducing instream large woody material (Deane et al., 2021), and a microcosm study monitoring the biogeochemical effects of wood introduction (Howard et al., 2023) both observed no changes to either DO or pH. However, Howard et al. (2023) found that the introduction of streambed wood significantly increased microbial metabolic activity. (Howard et al., 2023)

Riparian restoration

Only one of the assessed studies on riparian restoration examined biological effects. Wilcock et al. (2012) found that a natural 360 m long wetland fenced from cattle retained an average of 65±9 % *E. coli* over 3 years of monitoring. (Wilcock et al., 2012)

Sustainable Drainage Systems

Bioretention systems have been found to reduce heavy metals in stormwater, with reported removal efficiencies of between 30 and 99 % (Ahiablame et al., 2012). A review conducted by LeFevre et al. (2015) supports this, with the authors suggesting that dissolved heavy metals are effectively removed via sorption (the physico-chemical attachment of one substance to another) when there is adequate organic content in the bioretention media. Bioretention systems can also remove bacteria from stormwater, retaining between 70 and 99 % of bacteria on average (Ahiablame et al., 2012).

Porous pavements have also been shown to reduce pollution from heavy metals including lead, cadmium, and zinc by between 20 and 99 % on average (Legret and Colandini, 1999; Ahiablame et al., 2012). Monitoring over 8 years showed that the infiltration of stormwater into porous asphalt did not cause unwanted contamination of particulate pollutants into the reservoir structure beneath (Legret and Colandini, 1999). However, it was suggested that heavy metals can rapidly accumulate in the top layer of permeable pavements, resulting in an increased risk of pollution during subsequent run-off events.

The effects of green roofs on physico-chemical water quality are mixed, with potential negative effects through the release of heavy metals in run-off (Ahiablame et al., 2012), but also potential to mitigate mild acid rain by increasing run-off pH (Berndtsson, 2010). A study monitoring a constructed wet roof treating domestic wastewater observed ~80 % reductions in COD, and 95 % in BOD (Zapater-Pereyra et al., 2016). Significant increases in DO were seen (from 0.2 to ~5.5 mg/l), whereas pH was not affected.

Temporary water storage features

Vegetated swales and a Stormwater Infiltration Basin (SIB) were both found to reduce concentrations of some heavy metals, retaining 68 % of copper, 93 % of lead, and 52 % of zinc (Birch et al., 2005; Ahiablame et al., 2012). However, Birch *et al.* (2005) did not observe positive effects on chromium, iron, manganese, or nickel, finding that in some cases substantially higher concentrations of these pollutants were measured in the SIB effluent.

The risks posed by temporary water storage features to biological water quality were not widely considered in the literature. Robotham et al. (2023) highlight how offline pond features can stimulate the growth of potentially harmful cyanobacterial (blue-green) algae due to creating suitable conditions of shallow, nutrient-rich standing water.

2.5 Biodiversity and habitat

The 'state of nature' report (Burns et al., 2023) highlights that agriculture and climate change are having the biggest impacts on wildlife in the UK. NbS may help to reduce the impacts of these pressures on freshwater biodiversity (Van Rees et al., 2023). This section presents evidence of the effects of NbS on aspects of biodiversity and habitat such as species abundance and community composition.

Identified processes, properties and features that were affected by NbS include:

- Aquatic plant (macrophyte) growth
- Plant communities
- Benthic algae (photosynthetic organisms growing on the river bed)
- Physical habitat heterogeneity (i.e. diversity of habitats and landforms)
- Terrestrial invertebrate communities (species diversity and abundance)
- Aquatic macroinvertebrate communities (species diversity, abundance, productivity, and functional diversity)
- Invasive non-native species
- Fish communities (species diversity and abundance)
- Habitat provision and refuge (from high/low temperatures or flows)
- Bird communities
- Amphibian communities
- Habitat connectivity
- Seed dispersal

<u>Beaver re-introduction and management</u>

There is a large breadth of evidence (both from primary research and review/meta-analysis studies) investigating the effects of beavers on biodiversity and habitat. On the whole, the reported effects are beneficial, largely due to beavers being able to enhance biodiversity through their physical effect on river channel and floodplain geomorphology and consequent increase in habitat heterogeneity (Stringer and Gaywood, 2016; Brazier et al., 2020). A meta-analysis found positive impacts on numerous taxa, including plants, aquatic and terrestrial invertebrates, fish, amphibians, birds, and also several species on conservation interest e.g. water voles (Stringer and Gaywood, 2016). Long-term monitoring has shown that beaver-modified habitat can host higher numbers of species of conservation concern, as well as increasing bird and bat species abundances (Orazi et al., 2022). However, Stringer and Gaywood (2016) suggested that reductions in flow velocity immediately upstream of beaver dams can create less suitable lotic habitat for species requiring faster flowing water. Conversely, beaver impoundments can benefit species that favour ponded conditions.

Multiple meta-reviews suggest that on the whole beavers are likely to have positive impacts on fish. However, these impacts on fish vary between species, and negative impacts were also reported. These include the impediment of fish movement due to dams, and the siltation of spawning habitat (Kemp et al., 2012; Ecke et al., 2017). Kemp et al.

(2012) suggest that movement of species such as roach (*Rutilus rutilus*), stickleback (*Gasterosteus aculeatus*) and brook lamprey (*Lampetra planeri*) can be impeded by dams, whereas eel (*Anguilla anguilla*) movement appears to be unaffected. Brazier et al. (2020), for example, warn that some beaver dams could, in some circumstances restrict or delay access to spawning habitat, for some fish, in the upper reaches of low gradient systems. In particular, Brazier et al. (2020) note the mixed evidence on Atlantic salmon (*Salmo salar*), an endangered species under the IUCN red list (Nunn et al., 2023). For example, studies show conflicting effects on the provision of salmon rearing habitat in beaver ponds, and the impact on salmon movement and range. Overall, impacts on fish were positive and included increases in landscape-scale species richness, the availability of habitat for rearing and overwintering, flow refuge, and food availability through increased invertebrate production. The authors also found that beaver ponds provided refuge for fish due to more stable temperature regimes compared to stream reaches.

The reported effects on macroinvertebrates were also largely positive, with beavers increasing landscape-scale (gamma) species richness by 28 % on average (Law et al., 2016; Ecke et al., 2017). A study monitoring 10 beaver dams and interconnected ponds observed lower local (alpha) macroinvertebrate diversity compared to unmodified streams, highlighting the importance of considering effects at multiple spatial scales (Law et al., 2016). Evidence suggests that beaver modifications to habitat can alter macroinvertebrate community composition. Spyra et al. (2023) observed that macroinvertebrate scrapers (invertebrates that graze on algae growing on substrate/plants) were more abundant in beaver ponds compared to unmodified river reaches. Furthermore, the percentage of Ephemeroptera, Plecoptera, Tricoptera (EPT) taxa increased at the site modified by beavers but decreased at the unmodified site. Changes in EPT taxa are commonly used as an indicator of stream health due to their sensitivity to water pollution. Other notable impacts include an increased resilience to drought for aquatic biota, with the gradual release of water from beaver ponds helping to maintain flow downstream during dry periods (Brazier et al., 2020). This can provide refuge for macroinvertebrates and enhances their ability to recolonise following drought conditions.

From the reviewed evidence, all studies indicated positive effects on both aquatic and terrestrial plants as a result of beavers. Brazier et al. (2020) suggest that aquatic plant recruitment, abundance and species diversity is benefitted by beavers extending wetland areas into the wider landscape. Long-term monitoring following beaver re-introduction showed that after 12 years mean plant species richness had increased by 46 %, and the cumulative number of species recorded increased by 148 % (Law et al., 2017). Law et al. (2016) also report 20-fold increases in macrophyte biomass from the creation of a system of 10 beaver dams and ponds.

Please see Howe (2020) and Hänfling et al. (2024) for further evidence on the effects of beaver re-introduction on freshwater biodiversity in Britain.

<u>Buffer strips/zones</u>

A review of vegetated buffer strips found that evidence on their effectiveness at increasing plant diversity is conflicting, with management playing an important role in the outcome

(Cole et al., 2020). Minimal management was suggested to lead to increased structural diversity of vegetation, which in turn can enhance habitat for terrestrial invertebrates including carabids (ground beetles) and insect pollinators. Tall vegetation in riparian buffers was associated with cooler water temperatures and positive impacts on aquatic macroinvertebrates. Furthermore, aquatic macroinvertebrates can benefit from increased organic inputs from wooded riparian buffer strips. It was also hypothesised that wooded riparian buffers strips could help decrease the susceptibility of streams to invasive non-native species due to higher levels of shading favouring native species. Monitoring of Integrated Buffer Zones (IBZ) found that they were able to support a diverse ecological community, including Eurasian skylark (a red-listed species with a declining population) (Zak et al., 2019). However, the study demonstrated negative impacts on carabids, with species richness and abundance being significantly lower in the IBZ than in adjacent grass margins. This indicates that the type of buffer is also likely to play a role in determining outcomes for biodiversity.

Channel restoration

There is considerable evidence on the effects of channel restoration measures on habitat and biodiversity, considering both short-term and longer-term changes. A review found that channel restoration had positive biotic effects in 42 % of the examined studies, whilst the majority of studies detected no significant effects (Griffith and McManus, 2020). The review also emphasised the importance of spatial scale in determining restoration outcomes. Local scale benefits such as increases in macrophyte abundance and species richness can be derived from the restoration of short reaches, whereas the restoration of secondary channels can benefit wider populations of fish and macroinvertebrates. The creation of side channels has been shown to increase habitat for juvenile fish, and also riparian-dwelling birds including sand martins (*Riparia riparia*) and little ringed plovers (*Charadrius dubius*) (Marga et al., 2022). However, low colonisation potential, non-permanent flow, and a lack of instream wood were found to limit development of the macroinvertebrates in a side channel along the lower Rhine river (Marga et al., 2022). Another large-scale restoration creating a side channel in the river Danube floodplain induced positive changes in habitat morphology and availability, with rapid colonisation occurring and 46 % of the source species pool being recorded only 2 months following restoration (Pander et al., 2015). Small-scale (~200 m) restoration to reconnect an old pre-modification river channel found that geomorphological changes occurred, but their impact on physical habitat diversity was limited within 3 years of monitoring (Addy and Wilkinson, 2019). On the other hand, the restoration of >18 km of river through reconnecting former oxbow lakes and channels was found to improve hydromorphological status and biotic indicators for macroinvertebrates, fish, and macrophytes (Lüderitz et al., 2011).

Recent literature suggests that restoration of river channels through the removal of artificial instream structures such as dams and weirs can enhance hydromorphology and ecological communities. England et al. (2021) used a BACI approach to monitor impoundment removal and channel narrowing, finding that macroinvertebrate taxonomic and functional richness both significantly increased following restoration. Dam removals have been found to benefit fish assemblages, particularly anadromous fish species (e.g.

salmon) that need free movement for their migration upstream to spawn (Griffith and McManus, 2020). However, in their review Griffith and McManus (2020) also highlight how dam removal has been shown to alter downstream water temperature regime, and consequently change fish assemblages. It is important to note that these effects are likely to be context-specific and dependent on factors such as the spatial configuration of the stream network around the dam, and therefore not widely applicable. The authors of the study also reported some potential adverse effects on less mobile fauna such as unionid mussels.

Evidence on the biotic effects of re-meandering river channels is largely positive, though the timescale for benefits to be realised appears to be variable. A 9-year BACI study found that re-meandering increased macroinvertebrate species richness in the 6 years following restoration, despite initial decreases after the re-meandering works (Lorenz, 2020). Following re-meandering, Pedersen et al. (2007) reported enhancements in physical habitat structure and diversity, including water depth, velocity and substratum. The monitoring also found that macroinvertebrates rapidly colonised restored reaches and increased community diversity to develop a more even distribution of taxa. This was also seen in the macrophyte community composition of restored river edge habitats which developed away from being dominated by reed sweet-grass (*Glyceria maxima*). Small-scale re-meandering (370 m) was reported to have mixed effects on fish, with the biomass and mean weight of brown trout (*Salmo trutta*) increasing following restoration, but the abundance of European eel (*Anguilla anguilla*) decreasing compared to the 160 m control reach (Champkin et al., 2018). The authors noted that the effects on brown trout may have been due to the increases in pool habitat availability and either potential immigration into the restored reach, enhanced fish growth due to favourable conditions, or the replacement of smaller individuals by larger fish. It should be noted that whilst European eel abundance decreased in the restored reach, decreases were also observed in the control reach of the BACI study, however here the pre/post restoration difference was not statistically significant. Kristensen et al. (2014) found that large-scale re-meandering of a river channel did not change instream habitats significantly after 10 years since the restoration despite the enhancement of erosional and depositional processes. The authors posited that the restoration of lost habitat features such as islands and oxbow lakes is likely to occur over a much longer timescale of >100 years.

A study monitoring the effects of daylighting (culvert removal) an urban stream found that communities of benthic algae and macroinvertebrates colonised the restored reach within 9 months of the restoration works. (Baho et al., 2021) Negative short-term effects of channel restoration on biota have also been observed, with 50 % of the most common macroinvertebrate taxa being negatively impacted following physical restoration of instream habitat (Funnell et al., 2020). These findings highlight the importance of timescale in the realisation of benefits from NbS that involve restoring a system back to a more natural state. Restoration outcomes for habitat and different biota may vary significantly between locations and over time.

Constructed wetlands

The reported effects of CWs on biodiversity and habitat were limited, though a study modelling potential habitat suitability suggested that CWs can improve habitat connectivity and amphibian species richness (Préau et al., 2022). Locating CWs near forest and cropland were most effective at improving connectivity by providing refuge and suitable breeding sites. Small online ponds within an arable landscape have been shown to create wetland habitat and increase plant and macroinvertebrate taxonomic richness at a local scale (Robotham et al., 2021).

Floodplain reconnection

From the gathered evidence, floodplain reconnection was found to largely benefit habitat and biodiversity by altering the hydrological dynamics and morphology of river-floodplain environments. An increased frequency of inundation of the floodplain and storage of water has been suggested to support a more natural hydrological regime and floodplain plant communities (Richards et al., 2020; Addy and Wilkinson, 2021). Monitoring of floodplain plant communities observed increases in the heterogeneity of hydrological conditions across the floodplain as well as significant differences in community composition following reconnection (Richards et al., 2020). Clilverd et al. (2013) suggest that a more favourable soil-water regime is likely to enhance floodplain plant diversity.

Restoration of ephemeral floodplain habitats can provide habitat for fish. Monitoring of floodplain reconnection alongside re-meandering, dead wood introduction and river bed lifting over 17 years found that fish species richness and abundance increased to 2 and 3.5 times higher than pre-restoration, respectively (Höckendorff et al., 2017). Though the authors note that interannual variability of the fish species richness and abundance remained high, demonstrating that even over longer timescales the ecological effects of river and floodplain restoration can be highly dynamic. A similar study observed minimal effects on macroinvertebrate, macrophyte and fish communities over 10 years of monitoring, however there was an increase in the proportion of rare macroinvertebrate taxa (Sinclair et al., 2022). It is not possible to conclude if the observed effects are a result of the floodplain reconnection or the other restoration measures.

Instream substrate addition

The effects of adding instream substrate to rivers to manipulate and enhance habitat are considerably mixed and vary in their longevity. Griffith and McManus (2020) suggest that macrophytes typically respond well to reach-scale restoration and increase in their cover and richness. The local abundance of fish and macroinvertebrates can increase if there are other nearby sources of new migrants. However, the authors noted that important instream habitat characteristics such as aquatic moss can be damaged by the use of heavy equipment and can take multiple years to recover.

A study monitoring and modelling the effects of riffle creation (through gravel addition) found that the created gravel bedforms displayed hydraulic functionality associated with natural pool-riffle sequences (Sear and Newson, 2004). Following restoration, the instream physical habitat was shown to be more diverse. These findings are supported by a more recent study monitoring the effects of sand addition to a lowland stream (dos Reis Oliveira et al., 2019). The authors observed initial negative impacts on the macroinvertebrate community downstream due to intense sediment transport and sedimentation, however the community recovered once an equilibrium was reached and the habitat became improved by increased substrate and flow heterogeneity.

There is, however, evidence to suggest that such changes are not always permanent, with several studies highlighting the temporary nature of benefits resulting from instream substrate addition. Bauer et al. (2018) observed temporary improvements to riparian plant communities following separate gravel and sand additions, with a decline to pre-restoration conditions following 4 years. The authors suggested that these stream systems exhibited ‘negative resilience’ to instream substrate additions with species compositions showing a tendency to shift back to their original state. Evidence of negative resilience to restoration measures was also seen by Pulg et al. (2013) from monitoring of gravel cleaning and addition in a chalk stream. These measures created suitable spawning habitat for brown trout, with egg survival staying high (>50 %) in the first 2 years following restoration, but then declining to <50 % after this due to siltation of gravels by fine sediments. Kennedy et al. (2014) found that both flow deflector addition and boulder addition did not improve salmon (*Salmo salar*) fry recruitment, but increased their mean biomass and the density of juveniles. Again, the effects of siltation were thought to have impacted the potential for the interventions to increase fry recruitment. Significant enhancements in physical habitat characteristics (e.g. substrate particle size, water depth, and flow velocity) were observed post-restoration, helping to provide additional rearing habitat for local surviving juveniles and individuals migrating downstream from spawning areas.

Instream wood

A relatively large number of studies considered the effects of instream wood on habitat, with the evidence overwhelmingly reporting positive effects. Anlanger et al. (2022) observed positive impacts after only 8 months since installation of large wood (LW), with an eight-fold increase in morphological diversity and 127 % increase in flow diversity. Other studies also report significant increases in the physical diversity and complexity of instream and marginal habitat (Harvey et al., 2018; Pinto et al., 2019; Al-Zankana et al., 2021; Lo et al., 2022). Monitoring of wood jam installation in a chalk stream showed that their introduction generated sediment deposition in the surrounding reach to begin the formation of complex vegetated marginal habitat (Harvey et al., 2018). The findings of Parker et al. (2017) also demonstrate how the re-introduction of LW influences local-scale (patch scale of <100 m^2 area of river, and reach scale of larger sections of river with similar characteristics) sediment dynamics and encourages the establishment of macrophyte communities. Pinto et al. (2019) found that LW re-introduction in urban and rural streams created greater flow diversity in restored reaches which had higher mesohabitat spatial diversity index scores compared to control reaches. However, BACI monitoring of instream woody dams showed that their effects could be short-lived, with some of the dams causing bank erosion, becoming displaced by high flows, and consequently losing most of their geomorphic functions (e.g., sediment storage and pool formation) (Lo et al., 2022).

Largely positive effects of instream wood were also reported for biodiversity. LW installation creates additional habitats used by fish (Anlanger et al., 2022), and increases populations of brown trout through providing refuges or nursery habitat for salmonid fish (Thompson et al., 2018). Schulz-Zunkel et al. (2022) observed significant positive effects on fish at a local-scale. LW was also found to benefit macroinvertebrates, increasing their diversity by 9 to 35 % (Thompson et al., 2018; Anlanger et al., 2022), and their population density, biomass, abundance and taxonomic richness (Al-Zankana et al., 2021; Deane et al., 2021). Both Pinto et al. (2019) and Schulz-Zunkel et al. (2022) did not observe any significant impacts on macroinvertebrate abundance and diversity, however Pinto et al. (2019) report that some macroinvertebrate species were found exclusively on the LW installations in an urbanised catchment.

Introducing wood to streams was effective in initiating positive ecological change at a local-scale, helping to stimulate ecosystem processes and change abiotic conditions towards a more natural state (Anlanger et al., 2022; Schulz-Zunkel et al., 2022). There is limited evidence reporting effects beyond a patch or reach scale, however Deane et al. (2021) suggest that large wood material can also have positive impacts on downstream biodiversity.

Peatland restoration

Literature on peatland restoration focussed less on its effect on habitat provision and biodiversity, however the limited evidence indicated positive impacts. BACI monitoring following ditch blocking and revegetation at multiple sites showed increases in the plant cover over bare peat of 88 %, with the number and cover of peatland indicator species also increasing (Pilkington et al., 2015; Alderson et al., 2019).

Riparian restoration

The effects of riparian restoration on habitat and biodiversity were largely positive, though effects were found to vary at different spatial scales. At a local scale, the removal of rip-rap was shown to have significant positive impacts on the riparian bird community, and also benefit riparian vegetation and carabid communities (Schulz-Zunkel et al., 2022). At the reach scale, the effects on fish were found to be variable, and no effects were detected for macroinvertebrates, dragonflies, riparian vegetation, and carabid beetles. The removal of embankments has been found to have positive impacts on some carabids, with Sprössig et al. (2022) observing an increase in the proportion of species of conservation concern soon after the restoration. A BACI study of rip-rap removal found increases in the spatiotemporal heterogeneity of riparian vegetation after 2 years, indicating a shift towards a more natural dynamic plant community (Seele-Dilbat et al., 2022). However, Bauer et al. (2018) suggest that the effects of rip-rap removal on riparian vegetation can be temporary, and they observed the plant community revert to a pre-restoration state after 4 years.

A review found that restoration of riparian zones had mostly (54 % of studies) positive effects on biota (Griffith and McManus, 2020). Findings suggested that restoring riparian vegetation can impact stream ecosystems through creating shade, consequently causing a shift from instream primary producers (algae and macrophytes) to organic inputs from riparian vegetation. Inputs of large woody material were suggested to benefit instream biota by increasing cover for fish and providing substrates for macroinvertebrates. However, the authors note that the success of riparian restoration can often depend on the hydrological conditions experienced following restoration interventions.

2.6 Other outcomes

This section provides a brief overview of some of the other outcomes identified in the literature that were beyond the scope of the review – this is not an exhaustive list.

2.6.1 Climate regulation

It is acknowledged that there is significant interest in the role of NbS in climate regulation through the capture (and release) of greenhouse gases (GHGs) such as carbon dioxide (CO_2) (Seddon et al., 2020). In the evidence synthesis (section 2.4.1), the retention and storage of particulate and dissolved C was considered as an element of water quality. Some of the assessed literature indicated potential trade-offs for GHGs resulting from NbS discussed in the synthesis. Examples include:

- Afforestation can enhance denitrification which results in losses of N to the atmosphere, mainly as nitrous oxide – a GHG with a relatively high global warming potential (Allen and Chapman, 2001).
- Beaver activity can modify carbon cycling over different timescales (Brazier et al., 2020). For example, beaver ponds can increase methane (CH_4) production, however the rate of production may slow down with increasing age of the pond system (Ecke et al., 2017). Methane is the second most important GHG in the UK after CO_2 (NAEI, 2022).
- The presence of instream wood in catchments with limestone geologies could increase fluxes of CO_2 to the atmosphere (Howard et al., 2023).
- Peatland restoration (gully blocking) has been shown to increase methane emissions from rewetted areas within the initial 4 years following restoration (Gatis et al., 2023). Methane emissions may change over time due to influences such as vegetation cover, species composition and potential recovery of ecohydrological function.

For further evidence on the capture and emissions of GHG from NbS in the context of wastewater treatment, please see the UKWIR (2024) report.

2.6.2 Social, cultural and economic

Some studies also acknowledged the social, cultural and economic benefits (and disbenefits) resulting from the implementation of NbS. Examples of these outcomes include:

- Floodplain restoration measures such as the setback of levees have been suggested to enhance the aesthetic quality of landscapes and opportunity for outdoor recreation (Serra-Llobet et al., 2022).
- The implementation of a multifunctional lateral reservoir across a river valley was suggested to increase opportunity for environmental education and awareness (Kiedrzyńska et al., 2021).
- Macrophyte management to periodically remove excessive growth of submerged aquatic vegetation was found to result in temporarily unsuitable conditions for fly fishing in downstream reaches due to high sediment concentrations and floating debris. However, in the longer-term, this management benefits fly fishing by encouraging prolonged macrophyte cover for fish and macroinvertebrates throughout the season (Old et al., 2014).
- NbS, including wetland and forest creation, have been shown to be cost-effective approaches to the mitigation of hazards and disaster risk reduction (Vicarelli et al., 2024).

The potential for wider societal benefits from the implementation of NbS are discussed by Almássy (2022) in a briefing on harnessing NbS for transformational societal change in the context of climate change. The identified benefits include:

- Health and well-being (e.g. through improved air quality)
- Social cohesion and justice (e.g. through providing opportunities for social interaction and involvement of marginalised groups)
- Inclusive and effective governance (e.g. through creating a sense of ownership through community involvement to ensure long-term maintenance and stewardship)
- Cultural and natural heritage preservation (e.g. through raising awareness of the importance of natural ecosystems and their safeguarding)
- Economic development and sustainable production/consumption (e.g. through creating opportunities for tourism)

2.6.3 Human health

The importance of the environment to human health is increasingly being recognised. Concepts such as ‘One Health’ consider the linkages between animals, plants, humans, and ecosystems to support multi-disciplinary approaches to address global challenges such as the emergence of infectious diseases (Mackenzie and Jeggo, 2019). NbS could play a role in generating positive outcomes for human health, whilst also presenting potential risks:

- Constructed wetlands and riparian restoration show potential for helping to mitigate the human-induced increase in the presence of antibiotics, anti-microbial resistance, and pathogens in aquatic ecosystems (Pastor-López et al., 2024). Restoring and enhancing the natural biodegradation capacity of rivers and wetlands can enable these systems to act as effective sinks for pollutants that may pose health risks.
- The creation and restoration of wetlands in England will extend the availability of aquatic habitat for insects such as mosquitoes which can act as vectors of disease (e.g. West Nile virus; Bakonyi and Haussig (2020)), and increase undesirable consequences for humans through nuisance biting and further spread of disease (Medlock and Vaux, 2015).

3 Applicability of NbS to English catchments

The available evidence is presented in a matrix that includes the degree of scientific confidence for different NbS to generate outcomes across different catchment types. This matrix (see Section 3.3) was also split into 3 smaller summary matrices for each of the outcomes:

- Hydrological extremes (low flow management / flood management)
- Water quality (nutrient and sediment management / physico-chemical and biological water quality)
- Biodiversity and habitat

3.1 Catchment Typology

The 'Catchment Matcher' typology was used to categorise each line of evidence according to the type of catchment which the NbS was situated in. This typology was developed using statistical analysis to cluster 3767 Water Bodies in England into 9 groups that are broadly representative of catchments in England (see Appendix 7.1 for the spatial distribution). Variables used in the cluster analysis included slope, rainfall and percentage cover of: heavy to medium soils, high and medium productive aquifers, arable land and urban area. Table 2 summarises the characteristics of the catchments in each cluster. Figure 1 shows how many Water Bodies in England are in each of the catchment types. This typology was deemed to be particularly suitable for applying to NbS because it was originally developed to inform the implementation of mitigation measures for agricultural pollution. The typology aimed to address the challenge of extrapolating evaluations of interventions to other catchment types, which is also a significant challenge for NbS. For further details on the catchment typology, please see Lovett et al. (2024).

Table 2. Catchment type descriptions.

Catchment type	Description
Type 1: Western upland landscapes	These catchments have the highest rainfall and steepest slopes. Soils are typically lighter and have few underlying productive aquifers. Land cover is largely semi-natural, with relatively little or limited extensive agriculture.
Type 2: Northern upland landscapes	These catchments have high rainfall, steep slopes, relatively cold temperatures, and extensive underlying cover of productive aquifers. Land cover is typically dominated by semi-natural areas, with some sheep farming.

Catchment type	Description
Type 3: Western livestock agriculture	These catchments have above average rainfall and relatively steep slopes. Productive aquifers are largely absent and land cover is mostly grassland used for grazing livestock.
Type 4: Grassland-based agriculture	These catchments have a climate and slopes similar to the national average, with soils tending to be heavier. Land cover is dominated by grassland with high livestock densities; arable farming is uncommon.
Type 5: Patchwork middle England	These catchments have the closest to the national average characteristics out of all the types. Land cover is relatively evenly mixed between grassland, urban, arable, and woodland.
Type 6: Urban-dominated areas	These catchments have the warmest temperature, and below average rainfall. It is primarily characterised by the dominance of urban land cover.
Type 7: Mixed agricultural areas	These catchments have below average rainfall and slopes. Soils are typically heavier. Land cover is mostly grassland and arable, with a relatively high proportion of cereal cultivation.
Type 8: Arable on lighter soils	These catchments have below average rainfall and slopes. Soils are largely lighter and typically underlain by highly productive aquifers. Land cover is mostly arable, with some grassland too.
Type 9: Cereals on heavier soils	These catchments have the flattest slopes and lowest rainfall. It is characterised by heavier soils and arable land dominated by cereal cultivation.

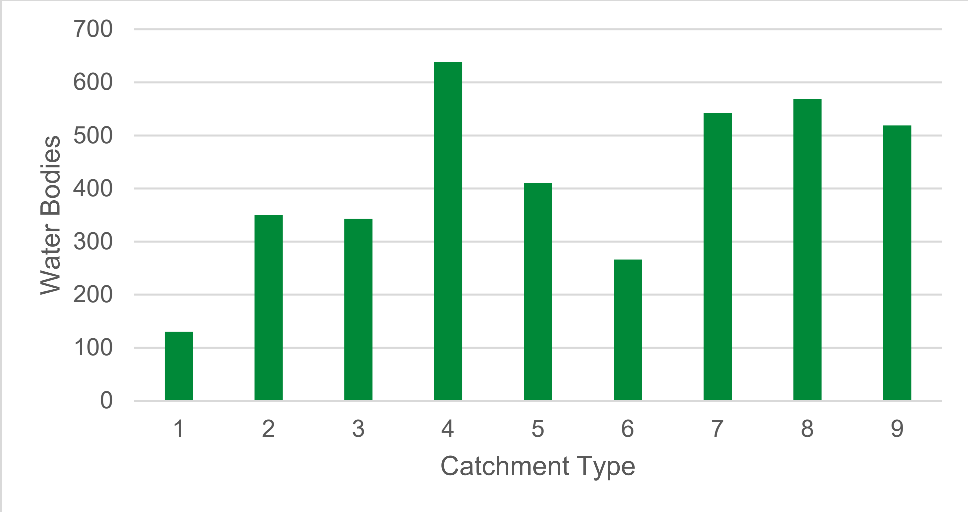

Figure 1. Number of Water Bodies in each catchment type.

Overall, there was fair coverage of evidence across the 9 catchment types for the 17 categories of NbS covered in the evidence synthesis. The availability of evidence was highest for NbS in Type 7 (Mixed agricultural areas) and Type 8 (Arable on lighter soils), but lowest for Type 1 (Western upland landscapes) and Type 3 (Western livestock agriculture) (Figure 2). Although evidence was limited for Types 1 and 3, this is to be expected given they cover a relatively small proportion of land in England.

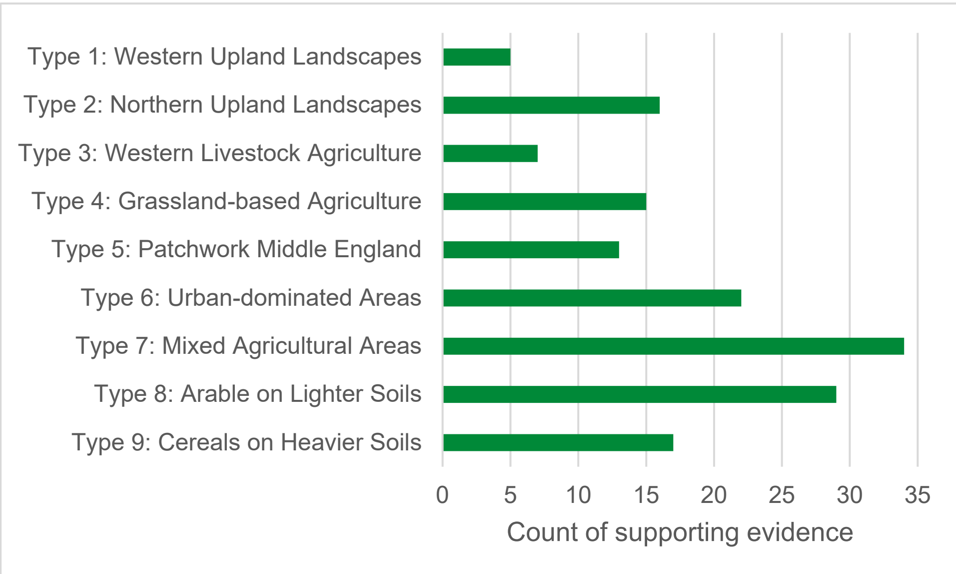

Figure 2. Total number of supporting pieces of evidence (for all NbS categories) in the evidence matrix for each catchment type.

3.2 Limitations

It is important to note that the matrix has some limitations that should be considered when drawing conclusions from it, or when using it as a tool to support decision-making.

Best efforts were made to gather the most relevant literature relating to NbS in the context of this project, however the review process was not systematic and the evidence reviewed is not exhaustive. This may also mean that not all specific types of NbS are included, particularly in the case of more novel NbS where the availability of published literature is limited.

Due to the complexities around beaver re-introduction and management in England, the matrix cannot be used for decision-making in the same way as other types of NbS, however it is useful in indicating potential environmental outcomes across different catchment types.

The Catchment Matcher typology is a broad-scale categorisation of catchment types and only one of many approaches that can potentially be used to create groups in which the effects of NbS can be assessed. It is acknowledged that all catchments are unique and not homogeneous in terms of their characteristics due to complexities within the landscape. Therefore, the matrix is only broadly indicative of where different NbS may result in benefits or disbenefits. It is not intended to identify where NbS can be located suitably at a local scale.

In addition, Catchment Matcher was developed specifically for England and it was therefore not possible to directly apply the typology to the NbS evidence in international catchment settings. Instead, contextual information from international studies was used to make an informed decision as to which catchment type was most suitable in each case.

3.3 Matrix

The main matrix comprises all 9 catchment types as rows, with each catchment type subdivided into the 5 outcomes, and categories of NbS listed as individual columns. Matrix cells are colour-coded in a ‘traffic light’ system according to the effects of the NbS reported in the evidence. The chosen colours were tested using a colour-blind simulator to ensure accessibility of the matrix.

- Green cells indicate that mostly positive effects are reported
- Amber cells indicate that mixed effects or contradictory evidence are reported
- Red-violet (purple) cells indicate that mostly negative effects are reported
- Blue cells indicate that no effects were observed/detected
- Grey cells indicate that no evidence is available

A letter in each cell of the matrix indicates the quantity and quality of the evidence relating to that combination of NbS, catchment type, and outcome. Blank cells indicate no evidence.

- ‘H’ (high) indicates that there are 2 or more studies with substantial evidence
- ‘M’ (medium) indicates that there is at least one study with evidence or multiple studies with some evidence

- ‘L’ (low) indicates that evidence is limited, inconclusive, or only modelled/hypothesised

Cells with evidence also contain evidence identification (ID) numbers which correspond to the studies considered within the synthesis. Some evidence ID numbers are appended with letters to indicate that they are separate lines of evidence but from the same study. All evidence ID numbers and their corresponding references are provided in Table 3.

Table 3. Evidence ID numbers and corresponding references used in the evidence synthesis.

Evidence ID	Reference	Evidence ID	Reference
1	Harvey and Henshaw, 2023	**2**	Roberts et al., 2023
3	Law et al., 2016	**4**	Anlanger et al., 2022
5	Fennell et al., 2022	**6**	Van Rees et al., 2023
7	Cooper et al., 2020	**8**	Badjana et al., 2023
9	Dadson et al., 2017	**10**	Puttock et al., 2021
11	Schulz-Zunkel et al., 2022	**12**	Marga et al., 2022
13	Dixon et al., 2016	**14**	Puttock et al., 2017
15	Correll et al., 2000	**16**	Wilkinson et al., 2010
17	Stringer and Gaywood, 2016	**18**	Marshall et al., 2014
19	Brazier et al., 2020	**20**	Kemp et al., 2012
21	Ecke et al., 2017	**22**	Golden and Hoghoogi, 2018
23	Seele-Dilbat et al., 2022	**24**	Sprössig et al., 2022
25	Kasak et al., 2018	**26**	Kill et al., 2018
27	Robotham et al., 2021	**28**	Robotham et al., 2023
29	Johannesson et al., 2015	**30**	Johannesson et al., 2011
31	Deasy et al., 2009	**32**	Wilcock et al., 2012
33	Ockenden et al., 2014	**34**	Batson et al., 2012
35	Borin and Tocchetto, 2007	**36**	Evrard et al., 2008
37	Quinton and Catt, 2004	**38**	Norbury et al., 2021
39	England et al., 2021	**40**	Addy and Wilkinson, 2021
41	Wallace and Chappell, 2019	**42**	Wallace et al., 2019
43	Cockburn et al., 2022	**44**	Baker et al., 2021
45	Hutchins et al., 2023	**46**	Cooper et al., 2021
47	Griffith and McManus, 2020	**48**	Ahiablame et al., 2012
49	Berndtsson, 2010	**50**	Pennino et al., 2016
51	Bhaskar et al., 2016	**52**	LeFevre et al., 2015
53	Adams et al., 2018	**54**	Sinclair et al., 2022
55	Orazi et al., 2022	**56**	Black et al., 2021
57	Trill et al., 2022	**58**	Tschikof et al., 2022
59	Préau et al., 2022	**60**	Tolomio et al., 2019
61	Hänel et al., 2022	**62**	Cole et al., 2020
63	Lenormand et al., 2022	**64**	Stefanakis et al., 2019
65	Birch et al., 2005	**66**	Dietz and Clausen, 2005
67	Zapater-Pereyra et al., 2016	**68**	Legret and Colandini, 1999
69	Fassman and Blackbourn, 2010	**70**	Lockwood et al., 2022
71	Acreman et al., 2003	**72**	Buechel et al., 2022

Evidence ID	Reference	Evidence ID	Reference
73	Allen and Chapman, 2001	**74**	Birkinshaw et al., 2014
75	Clilverd et al., 2013	**76**	Dabney et al., 2001
77	Green et al., 2006	**78**	Janes et al., 2017
79	Lavers et al., 2022	**80**	Law et al., 2017
81	Archer et al., 2013	**82**	Peskett et al., 2023
83	Lipiec et al., 2006	**84**	Neumayer et al., 2020
85	Nicholson et al., 2020	**86**	Peter et al., 2012
87	Pilkington et al., 2015	**88**	Shuttleworth et al., 2019
89	Thomas and Nisbet, 2007	**90**	Wilson et al., 2010
91	Zhang and Hiscock, 2010	**92**	Addy and Wilkinson, 2019
93	Al-Zankana et al., 2021	**94**	Baattrup-Pedersen et al., 2022
95	Old et al., 2014	**96**	Baho et al., 2021
97	Bauer et al., 2018	**98**	Funnell et al., 2020
99	Harvey et al., 2018	**100**	Höckendorff et al., 2017
101	Kennedy et al., 2014	**102**	Kristensen et al., 2014
103	Lüderitz et al., 2011	**104**	Reid et al., 2019
105	Pander et al., 2015	**106**	Parker et al., 2017
107	Pedersen et al., 2007	**108**	Pulg et al., 2013
109	Sear and Newson, 2004	**110**	Thomson et al., 2018
111	Spyra et al., 2023	**112**	Ahilan et al., 2019
113	Alderson et al., 2019	**114**	Despina et al., 2021
115	Howard et al., 2023	**116**	Bond et al., 2022
117	Champkin et al., 2018	**118**	Collins et al., 2023
119	Deane et al., 2021	**120**	Evans et al., 2018
121	Fahey and Payne, 2017	**122**	Frankl et al., 2021
123	Holden et al., 2019	**124**	Kiedrzyńska et al., 2021
125	Lo et al., 2022	**126**	Lorenz, 2020
127	Murphy et al., 2020	**128**	Barber and Quinn, 2012
129	Pinto et al., 2019	**130**	Richards et al., 2020
131	Richet et al., 2017	**132**	Smith et al., 2020
133	Thomas and Abbott, 2017	**134**	Zak et al., 2019
135	Gatis et al., 2023		

The full matrix and a key are given below. Matrices showing the separate outcome themes (hydrological extremes, water quality, biodiversity and habitat) are provided in the appendices (7.2 Evidence matrices). Microsoft Excel versions of the matrices are available in the spreadsheet provided alongside this report (‘NbS Evidence and Matrices.xlsx’).

Catchment Type	Beaver re-introduction	Afforestation	Constructed wetlands	Temporary water storage features	Riparian restoration	Buffer strips/zones	Hedgerows and vegetative barriers	Instream wood	Peatland restoration	Instream substrate addition	Channel restoration	Floodplain reconnection	Permeable pavement	Green roofs	Bioretention systems/rain gardens	Sustainable soil management	Assisted natural regeneration
Type 1: Western Upland Landscapes																	
Low flow management		L 127										M 40					
Flood management	L 84a	M 127										M 40					L 116a
Nutrient and sediment management												L 40					
Physico-chemical & biological water quality																	
Biodiversity & Habitat	M 55											L 40					
Type 2: Northern Upland Landscapes																	
Low flow management		H 74, 121		M 5				M 38	H 87, 88a, 90, 113								
Flood management		M 74, 121		M 5				M 38	H 87, 88a, 88b, 90, 113, 120								L 116b
Nutrient and sediment management	M 111				M 86			M 119	H 87, 113, 120								
Physico-chemical & biological water quality								M 119									
Biodiversity & Habitat	M 111							M 119, 125	M 87, 113								
Type 3: Western Livestock Agriculture																	
Low flow management									L 135								M 18a, 18b
Flood management	H 10a, 14			M 70a					M 135								M 18a, 18b
Nutrient and sediment management	M 14				M 32				L 135								
Physico-chemical & biological water quality					M 32												
Biodiversity & Habitat																	
Type 4: Grassland-based Agriculture																	
Low flow management		L 81					L 42									L 41	
Flood management	H 10b, 10c	H 81, 82, 89		M 53c, 70b		L 53b	M 42									M 41, 53a	
Nutrient and sediment management	M 3			L 53c		L 53b	M 42	M 115c								L 53a	
Physico-chemical & biological water quality								M 115c									
Biodiversity & Habitat	H 3, 80										M 98						
Type 5: Patchwork Middle England																	
Low flow management																	
Flood management																M 31b	
Nutrient and sediment management	M 15		M 64		M 34						L 92					M 31b	
Physico-chemical & biological water quality	L 15		M 64								L 105						
Biodiversity & Habitat					M 97a					M 97b, 97c, 101a, 101b	H 92, 105, 126	M 100					
Type 6: Urban-dominated Areas																	
Low flow management		L 44											L 48c, 69				
Flood management		M 8b, 44		L 48d, 112	L 43								H 48c, 69	H 48b, 49	H 48a, 66		
Nutrient and sediment management		M 45	M 78a	H 48d, 65, 112	L 43						H 78b, 96		H 48c, 68	H 48b, 49, 67	H 48a, 52, 66		
Physico-chemical & biological water quality			M 63a, 63b, 78a	H 48d, 65							M 78b		H 48c, 68	H 48b, 49, 67	H 48a, 52		
Biodiversity & Habitat					L 43			M 129a			M 78b, 96						

Catchment Type	Beaver re-introduction	Afforestation	Constructed wetlands	Temporary water storage features	Riparian restoration	Buffer strips/zones	Hedgerows and vegetative barriers	Instream wood	Peatland restoration	Instream substrate addition	Channel restoration	Floodplain reconnection	Permeable pavement	Green roofs	Bioretention systems/rain gardens	Sustainable soil management	Assisted natural regeneration
Type 7: Mixed Agricultural Areas																	
Low flow management	M 132	L 118b															
Flood management	M 132	L 118b		H 16, 57, 85								L 71				M 31a, 31c, 118a	
Nutrient and sediment management	M 132		H 27, 28a, 30, 33a, 60, 128b	M 16, 28b, 128a		H 134a, 134b	M 133	M 115a								M 31a, 31c	
Physico-chemical & biological water quality	M 132			L 28b				M 115a									
Biodiversity & Habitat			L 27		H 11b, 23, 24	M 134d, 134e		H 4, 11a, 93, 129b			M 103	M 54					
Type 8: Arable on Lighter Soils																	
Low flow management		M 77, 91					L 123, 131					L 75				L 114	
Flood management	H 10d, 84b	M 13b, 13c					M 123, 131	L 13a				L 75				H 37a, 37b, 37c, 114	
Nutrient and sediment management			H 7a, 7b, 35			M 134c	M 122, 123, 131				M 94	L 75				H 37a, 37b, 37c	
Physico-chemical & biological water quality											M 94						
Biodiversity & Habitat			L 59			L 134c		H 99, 106, 110		H 104, 108	H 94, 102, 107, 117	L 75					
Type 9: Cereals on Heavier Soils																	
Low flow management																M 83	
Flood management		L 8a		M 36												M 83	
Nutrient and sediment management			H 25, 26, 29a, 29b, 29c, 29d, 29e, 29f, 29g	M 36				M 115b									
Physico-chemical & biological water quality								M 115b									
Biodiversity & Habitat										M 109	M 12, 39	L 130					

Effects of NbS	
(green)	Mostly positive effects reported
(orange)	Mixed effects/contradictory evidence reported
(purple)	Mostly negative effects reported
(blue)	No effects observed/detected
(grey)	No evidence available

Quantity and quality of evidence	
H	2 or more studies with substantial evidence
M	At least 1 study with evidence or multiple studies with some evidence
L	Evidence is limited, inconclusive or only modelled/hypothesised

3.4 Evidence gaps

This section provides an overview of some of the gaps in information that were identified from the literature review and evidence matrix. The NbS summaries in the appendices include further details on evidence gaps specific to each of the NbS types reviewed.

The matrix highlights multiple areas that could benefit from further monitoring or assessments to address the existing gaps in the evidence base on NbS effectiveness in different catchment contexts. The most under-represented catchment type were those of western upland landscapes and areas of western livestock agriculture. In these catchment types, evidence of the effects of beaver re-introduction and assisted natural regeneration were most abundant. Conversely, NbS that are most applicable to agricultural land (e.g. sustainable soil management, and hedgerows and vegetative barriers) were not evidenced at all in upland catchments. On the whole, lowland catchments were well represented, with most evidence being generated in mixed agricultural areas, arable areas on lighter soils, and urban-dominated areas. However, the exception to this was catchments in areas of cereals on heavier soils, where evidence largely centred on constructed wetlands but was scarce across other NbS.

Evidence of the effects of peatland restoration were entirely generated from catchments in upland landscapes. Significant areas of degraded peat exist in lowland England, making this a notable evidence gap. The same was true for evidence of the effects of assisted natural regeneration which were low in number overall and exclusively in upland catchments. Conversely, evidence of the effects of constructed wetlands was absent from upland catchments.

Most of the reviewed studies generated evidence on the effects of NbS in relation to nutrient and sediment management, and flood risk management. However, there was a notable absence in evidence of the effectiveness of NbS to help mitigate flooding from groundwater sources. Fewer studies focussed on the effects of NbS on physico-chemical and biological water quality, and low flow management.

Whilst there was more evidence on biodiversity and habitat, this was limited to a smaller number of NbS. The matrix shows no evidence of biodiversity and habitat outcomes from the implementation of afforestation, temporary water storage features, hedgerows and vegetative barriers, SuDS, sustainable soil management, and assisted natural regeneration.

The review identified cross-cutting research gaps:

- Most available evidence is generated from small-scale studies e.g. where NbS have been piloted for research purposes. Modelling of NbS has allowed the likely effects to be upscaled, though empirical evidence at a catchment scale is still needed to validate the results of these studies.
- Studies typically do not evaluate the effects of NbS over longer time periods. The median monitoring period of studies that involved field monitoring or sampling

campaigns was 3 years (including any pre-intervention monitoring). Further evidence derived from long-term monitoring or studies that re-assess the effectiveness of interventions could inform how outcomes may change over time, and help to better understand the effect of maintenance (or lack of maintenance) on the realisation of benefits. Longer monitoring periods would also allow the seasonality of the effectiveness of NbS to be analysed. Seasonal variation in the benefits or disbenefits resulting from NbS are often overlooked in current studies.

- A limited number of studies assessed the effects of NbS in combination e.g. where 2 different sustainable soil management practices were applied to the same field, or where the cumulative effects of multiple NbS across a catchment were measured. Further evidence on the combined effects of NbS would illuminate their potential interactions (positive and negative) and enable more strategic implementation of NbS at a landscape scale.
- Current evidence does not always explicitly consider the influence of catchment context or location within a catchment on the outcomes of NbS. Further studies to separate these effects would improve knowledge on the role of catchment properties in determining the effectiveness of NbS.
- There is uncertainty over whether the measured benefits of NbS are still applicable under future climate conditions with more frequent extreme weather events and ecosystem disturbances. Research to stress test NbS under different scenarios could help to address this evidence gap.
- Few studies consider the limits of the effectiveness of NbS. For example, studies show that constructed wetlands can improve water quality, however their capacity limits for pollutant removal and overall longevity are not as well understood. There is a general acknowledgement that NbS aimed at managing flood risk are to be implemented alongside conventional solutions (e.g. grey infrastructure) rather than in place of them. However, evidence on the extent to which NbS remain effective compared to alternative solutions is limited.

4 Case studies

The following case studies provide recent examples of NbS projects implemented in England. Further examples of river restoration projects can be found on the River Restoration Centre website (RRC, 2014). Case studies focussed on working with natural processes to reduce flood risk (Environment Agency, 2021b) include 65 NbS projects focussed on the restoration of rivers and floodplains, woodland creation, run-off management, and coastal and estuarine management. For specific examples of NbS being used in the context of nutrient management, see the Natural England literature review on nature-based nutrient mitigation solutions (Lloyd et al., 2024).

Overview

Blean Woods is an extensive and ecologically important area of woodland in the headwaters of the Sarre Penn stream near Canterbury in the south-east of England (Figure 3). In recent years, the effects of climate change on the woodland have become more noticeable, with insects spawning earlier and the woodland floor drying out more than previously and at a faster rate. Reductions in wet micro-habitats have negatively impacted invertebrates and the woodland bird communities that feed on them.

Figure 2. Location of Blean Woods (green square).

During 2021 and 2022, the Royal Society for the Protection of Birds (RSPB) led a Green Recovery Challenge Fund (GRCF) project to re-wet Blean Woods using NbS, and thereby enhance its resilience to climate change. This included the addition of instream large woody material dams, gully blocking, and meander reconnection (Figure 4 and Figure 5). These interventions aimed to slow the flow of water through the woodland, increase floodplain connectivity, and retain more water within the landscape to create wetter soils.

Figure 3. In-stream woody material dams in Blean Woods. Image credit: Siôn Regan.

Observations

Early observations show that pools have formed behind the dams and the stream is once more flowing through the restored meanders. Despite receiving very little rainfall in the spring and summer of 2022, the stream continued to flow and provide suitable habitat for fish, amphibians, and invertebrates such as dragonflies. This was a particularly promising sign as in previous years the stream has been seen to dry out during summer.

These observations suggest that the interventions have helped to store more water and enhance the resilience of the woodland ecosystem to low flow conditions. Bird species such as lesser spotted woodpecker (*Dryobates minor*) and willow tit (*Poecile montanus*) have benefitted due to their preference for damp habitat. It is hoped that the NbS in Blean Woods will continue to generate resilience to the effects of climate change in future years.

Figure 4. Water being retained in the woodland as a result of the introduction of NbS. Image credit: Siôn Regan.

Monitoring

Annual breeding bird surveys carried out each spring will help to monitor the success of the interventions over time. Such monitoring could provide evidence to help fill knowledge gaps concerning biodiversity and habitat outcomes resulting from NbS in deciduous woodland settings with relatively dry climates.

2) Beaver re-introduction and management at Wallington

Overview

Wallington is a National Trust owned estate near Morpeth in the north-east of England (Figure 6). The estate includes over 5000 hectares of land, with some of this area draining into the Hart Burn, a tributary of the River Wansbeck.

Figure 5. Location of Wallington Estate (green square).

In July 2023, a family of 4 Eurasian beavers were released on a tributary of the Hart Burn. This is the third beaver re-introduction project undertaken by the National Trust as part of their efforts to renew and restore nature. It is hoped that the beavers will help to create a wildlife-rich wetland landscape. The beaver release is part of the ambitious [‘Wilder Wallington’ project] which addresses the challenge of long-term nature recovery at a landscape scale.

The beavers at Wallington were released into a 24 ha enclosure and are starting to have a significant impact on the habitat within this area. As ecosystem engineers, the beavers have constructed multiple dams in the stream, helping to create a more dynamic wetland ecosystem (Figure 7, Figure 8).

Figure 6. A beaver and one of the dam structures they have constructed in the enclosure at Wallington. Image credit: Krzysztof Dabrowski.

Monitoring

Monitoring at Wallington is being undertaken to understand the benefits of the beaver re-introduction for the wider environment. This includes the effects on water quality, flood risk management, and wetland plant communities. Newcastle University are monitoring habitat change over time by creating three-dimensional models of the beaver enclosure. Research is also being done by the Environment Agency to assess the effect of the beavers on white-clawed crayfish (*Austropotamobius pallipes*) populations living in the stream.

Figure 7. A beaver dam and pond on the Wallington estate holding back flow from the upstream catchment. Image credit: Krzysztof Dabrowski.

Maximising success

Since the re-introduction of beavers, several other measures have been implemented to assist the beavers adjust to their new habitat and thereby maximise the success of outcomes for the wider environment. For example, the planting of approximately 500 willow trees will provide a new food source for the beavers and increase shading of the watercourse.

Challenges and lessons learnt

Experiences over the first 10-months since the re-introduction of beavers have highlighted some of the challenges associated with the management of beavers. The Wansbeck catchment upstream of the enclosure is particularly flashy (hydrologically responsive) as a result of historic agricultural modification to drain the land. In combination with a notably wet winter, this exacerbated the effect of successive high flow events which caused significant damage to the newly established beaver dams. To increase resilience to future storm impacts, wooden stakes have been added to the dams to provide structural support. The National Trust also plan to implement grip-blocking (blocking of drains) in the catchment headwaters, with the aim of reducing the flashiness of the flow and increasing the likelihood of successful outcomes from the beavers.

3) Improving the sponge functioning of soils through regenerative farming

Overview

The Hendred Farm Partnership near Wantage in Oxfordshire use regenerative farming practices on their 800 ha arable farm growing crops such as wheat, barley, oats, beans, and oilseed rape. The farm is situated on silty clay loam soils over chalk of the Berkshire Downs (Figure 9).

Regenerative agriculture aims to produce food whilst also improving soil health. Examples of regenerative practices include the use of herbal leys, reduced traffic over fields, and minimum tillage farming.

Figure 8. Location of Hendred Farm Partnership (green square).

Poor management of agricultural soils can lead to degradation in soil health and reduced functioning of soils to deliver ecosystem services. For example, loss of soil structure can lead to capping of the soil surface, creating a less permeable top layer reducing infiltration of rainfall (Figure 10). Managing the farm using regenerative practices aims to put carbon back into the soil which in turn can provide other benefits for both the farm business and the environment.

Figure 9. Example of capped soil (top) and well-structured heavy soil (bottom).

Benefits

By minimising soil disturbance, keeping soil covered, maximising crop diversity, and minimising synthetic fertiliser use, the health of soils can be improved over time. These practices can improve soil structure, increase soil organic matter content, in turn benefitting the capacity of the soil to store water. Healthy soils (e.g. a well-structured soil; Figure 10) are less likely to generate overland flow during heavy or sustained rainfall, thereby helping to reduce flood risk.

Minimising soil disturbance helps to keep as much carbon in the soil as possible. Techniques like direct drilling (placing seeds directly into the soil after the previous crop without any cultivation) can help to reduce losses of carbon back into the atmosphere as CO_2.

Monitoring

Monitoring of the sustainable management practices at Hendred has been carried out through a number of research projects including the ASSIST programme, the LANDWISE NFM project, and the ongoing SpongeScapes project.

The LANDWISE project, led by the University of Reading, monitored soil properties across different land-uses, including innovative farming practices such as those being applied at Hendred (Figure 11). Fields with controlled traffic minimise soil compaction by having 80 % of the area free of heavy machinery. Measurements suggest that the soil in these fields are able to hold more water compared to conventionally farmed fields with the same soil type.

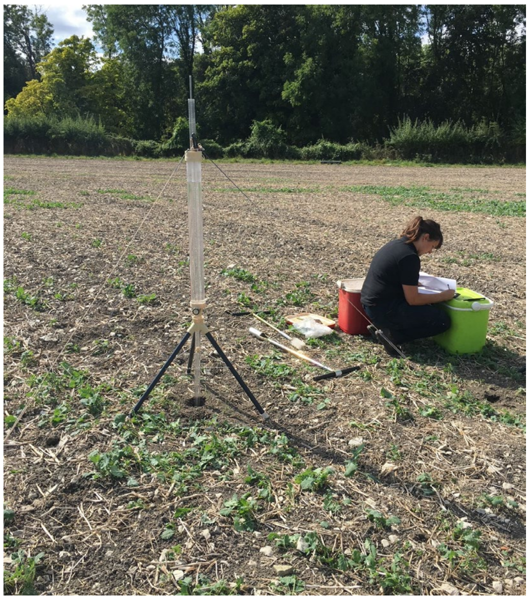

Figure 10. Measurements of soil hydraulic conductivity being taken on a controlled traffic field at Hendred Farm. Image credit: John Robotham.

4) Restoration of natural processes on the River Coquet

Overview

The Coquet is a dynamic upland river flowing through Northumberland (Figure 12). Part of the river flows adjacent to Caistron Lakes, upstream of the town of Rothbury. Caistron Lakes were created from gravel pits that were filled with water following gravel extraction. The Coquet has avulsed several times over the past decade. Avulsion is a natural process in which a new channel is formed and flow is diverted into it from the existing channel. This occurred most recently towards the end of 2022 when the river breached its right bank to flow into the lakes. An avulsion in 2021 that connected the river and lakes following a period of sustained heavy rainfall initially caused concern due to the potential for increased flood risk. The new course set by the river did not increase flood risk, and observations suggest that allowing the river to change its form naturally without intervention can generate multiple benefits.

Figure 11. Location of the River Coquet (green square).

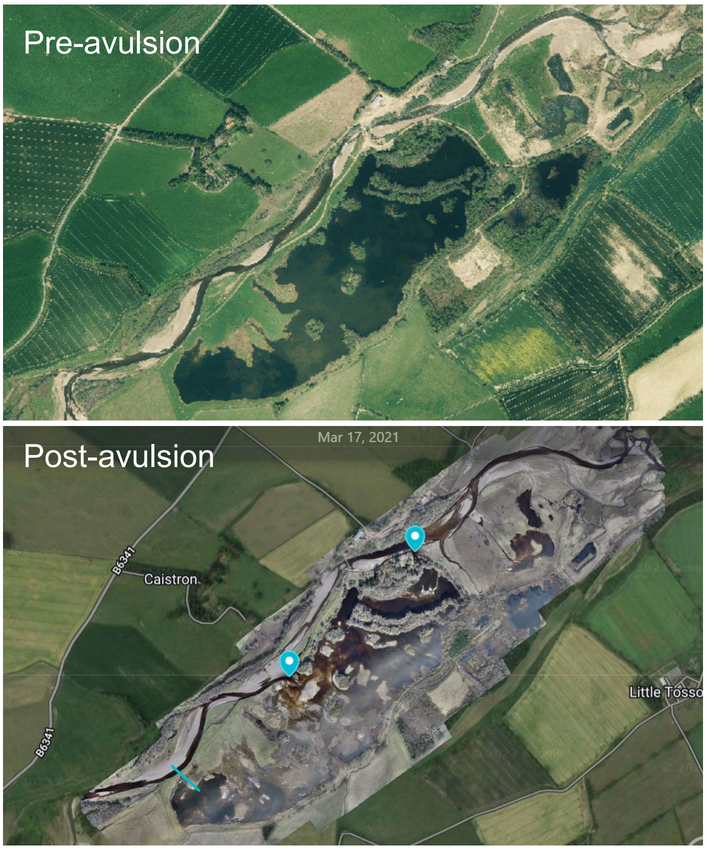

Figure 12. Pre and post-avulsion aerial imagery of the River Coquet and Caistron Lakes. Environment Agency drone images from March 2021 shows the area following the breach. Image credit: Google, ©2024 Airbus, CNES / Airbus, Getmapping plc, Infoterra Ltd & Bluesky, Landsat / Copernicus, Maxar Technologies, Map data ©2024.

Observations

The Coquet is a naturally wandering river with high energy that meanders and erodes through the landscape relatively rapidly to form new channels. Due to this, the Environment Agency and partners have been closely observing its geomorphology e.g. using drone imagery (Figure 13).

A large proportion of the river's flow now moves from the main channel into the lakes and surrounding area, which was estimated to hold between 100,000 and 500,000 m^3 of water. Observations suggest that the avulsion and consequent movement and deposition of sediment has also created areas of new habitat.

Monitoring

Environment Agency monitoring data from river level gauges located upstream (Alwinton) and downstream (Rothbury) of the avulsion have provided an indication of the potential effect on flood risk to the downstream community. Hydrographs comparing river levels pre and post avulsion suggest that the downstream peaks are reduced following avulsion (Figure 14), indicating that there may be additional flood storage capacity, though it may be limited to smaller storms. This could have an impact on slowing the flow and thereby increasing the travel time of flood water flowing downstream. Further monitoring and analysis are needed to determine the full extent of the benefits of the avulsion for flood risk mitigation. Impacts on fish were monitored upstream of Caistron. The results show that salmon numbers remained high and that upstream movement of migratory fish was not impacted.

Pre-avulsion

Post-avulsion

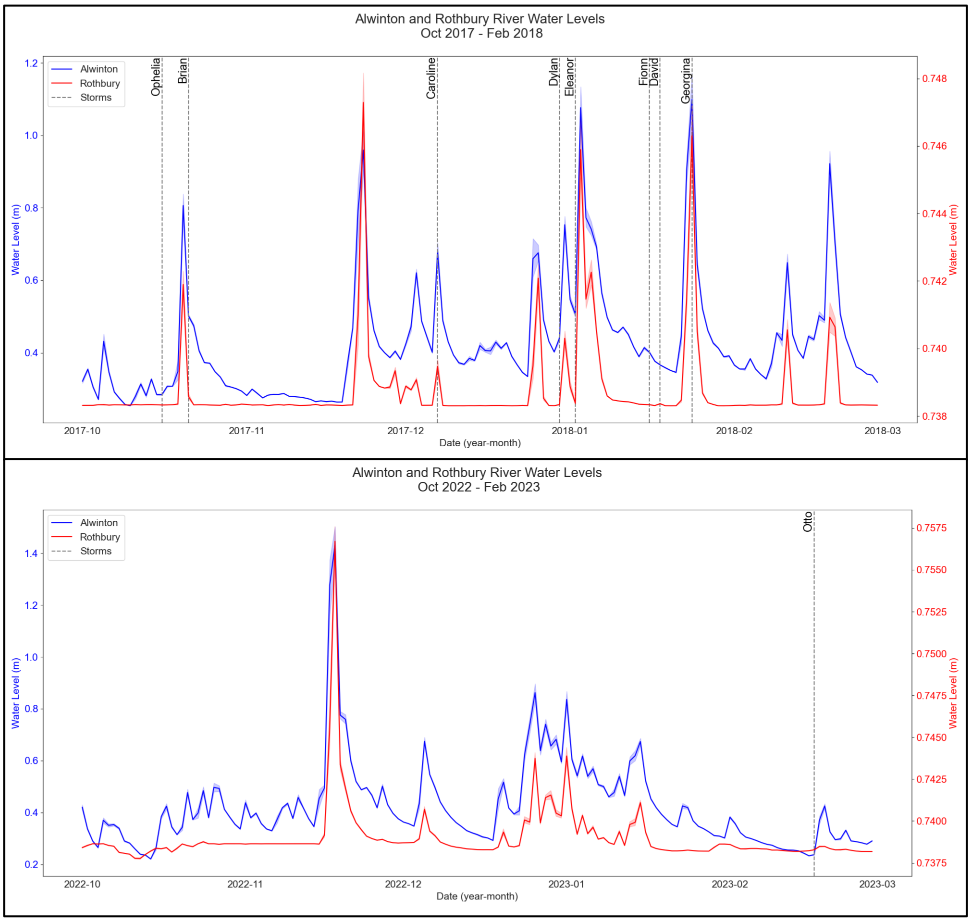

Figure 13. Hydrographs showing pre and post-avulsion water level (metres) on the River Coquet at Alwinton (blue) and Rothbury (red).

Challenges and lessons learnt

Managing a dynamic river system can prove challenging. In the case of the Coquet, the Environment Agency, partners and landowners worked to minimise the potential risks, and maximised benefits by letting natural processes take their course. The Coquet has status as a Site of Special Scientific Interest (SSSI) due to its catchment being relatively undisturbed and having high ecological and conservation value. Allowing natural processes such as avulsion to take place ensures that the river and its floodplain continue to provide good habitat for wildlife such as mayflies, stoneflies and caddisflies.

5) Sustainable grassland management trials in the White Peak

Overview

The Peak District National Park Authority were involved in developing ideas for the Environmental Land Management schemes. As part of this land management trials were carried out in the White Peak landscape, a limestone plateau located across parts of Derbyshire and Staffordshire (Figure 15).

The small-scale trials involved using herbal leys and species diverse grass margins around silage fields (Figure 16). Herbal leys are diverse mixtures of grasses, legumes and herbs that are sown into pasture. The aim of the grass margins was to create 3m strips of diverse tussocky grassland around fields and manage them with no nutrient inputs.

Figure 14. Location of the White Peak (green square).

Observations

Findings from the herbal ley trials show that the establishment of species can be very spatially variable despite the underlying soils being largely similar at the 5 trial farm sites. Despite this, all the herbal ley fields resulted in diverse pastures. The dominant species changed seasonally, with vetch occurring earlier and followed by red clover later in the season. All trial participants reported that cattle preferentially grazed on the herbal leys rather than on conventional ryegrass pasture. The success of the project meant that several of the participants decided to establish further areas of herbal ley beyond the trial.

Figure 15. A well-established tussocky margin at Bent Farm (left), and a herbal ley containing red clover at Lower Cumberland Farm (right). Image credit: Peak District National Park Authority and Natural England.

Benefits

Herbal leys have various potential benefits. They can improve soil health (e.g. soil structure and fertility), increase biodiversity, nutrient cycling (e.g. through nitrogen-fixing legumes), livestock health, weed suppression, water management (e.g. through deep roots improving soil water retention), and the climate resilience of pastures (Figure 17).

Tussocky grass margins are beneficial in providing structurally complex habitat and a source of nectar and pollen for invertebrates, as well as creating wildlife corridors for movement of species through agricultural landscapes. Margins also act as a buffer to help prevent the transport of pesticides, herbicides and nutrients in run-off to watercourses. Tussocky margins can also increase surface roughness and help to slow the flow of water overland, thereby contributing to reduced flood risk.

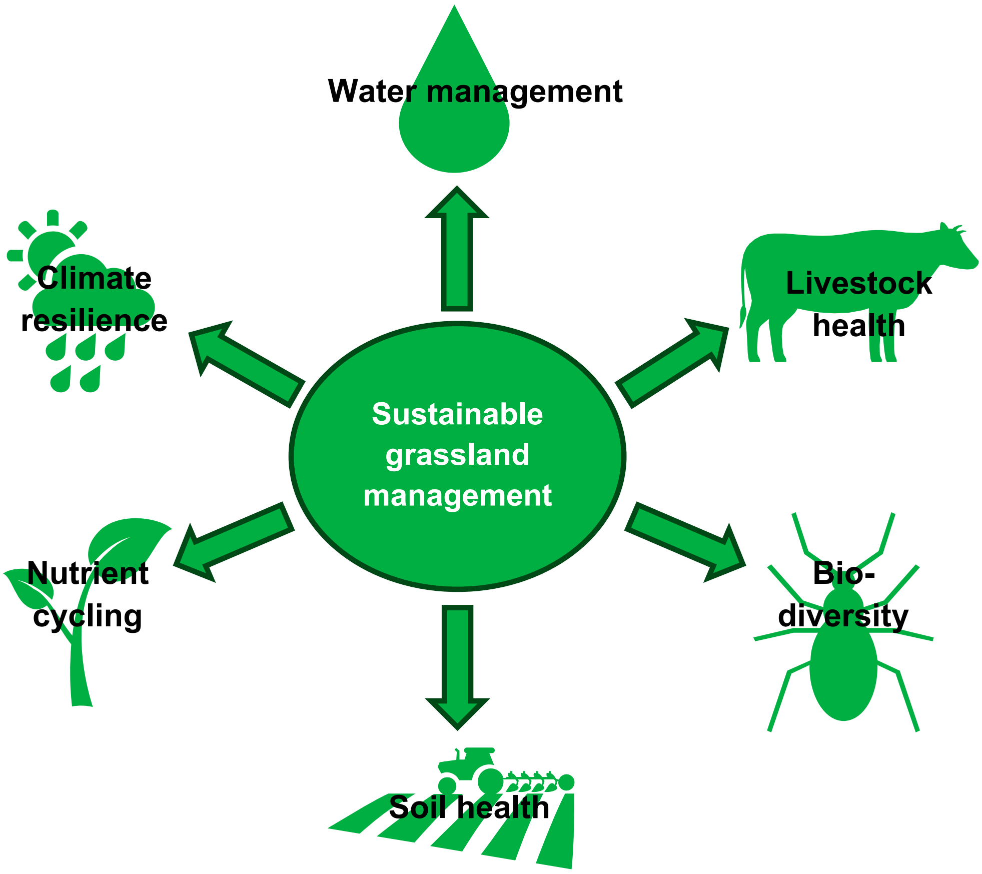

Figure 16. Potential benefits of sustainable grassland management.

Challenges and lessons learnt

The establishment of diverse margins and herbal leys can be challenging and success may be influenced by factors such as weather conditions. Direct sowing of seeds into fields (over-seeding) resulted in a poor establishment of legumes and herbs due to competition from the already existing grasses. Weed control was found to be crucial, including the controlled use of glyphosate. The trials showed that early grazing (5 to 6 weeks after germination) helped to encourage species to tiller (produce multiple stems) and root, as well as consolidating the soil. Potential risks to establishment include intense rainfall during winter causing soil erosion and surface capping, ultimately resulting in patchy cover of herbal ley species.

5 Discussion

5.1 Evidence overview

The evidence base for NbS has grown significantly over the past 2 decades, most notably since 2013. In recent years there has been increased interest in the study of the potential effects of NbS at larger scales.

Studies on constructed wetlands (CWs) made up the highest proportion of evidence out of the types of NbS that were considered in this review, though it is recognised that this may not be representative of the overall evidence base for NbS. In England there is a growing interest in the use of CWs to treat effluent discharged from sewage treatment works to improve river and lake water quality. Interest from both water companies and environmental non-governmental organisations (NGOs) is likely to have played a role in driving the growth in the evidence base on CWs. There is also a growing interest in using CWs to mitigate pollution from the agricultural sector which represents the other main source of water pollution in England. However, there was conflicting evidence of their effect on nutrient and sediment dynamics in mixed agricultural areas. Whilst having largely positive effects, studies demonstrated that CW design, size and configuration can all play significant roles in determining their effectiveness. Furthermore, some CWs were shown to be effective at removing specific pollutants whilst simultaneously releasing other pollutants, highlighting potential trade-offs for water quality. It is also worth noting that NbS, such as CWs, that are located on agricultural land are likely to have the associated socio-economic trade-off of reduced food production.

Afforestation was also well-studied, with evidence spanning 7 out of the 9 catchment types. The evidence on afforestation is largely positive, though several studies suggested it had negative impacts on the availability of water to support freshwater ecosystems at low flows, however this was typically when tree planting occurred intensively (e.g. afforestation of entire or large proportions of catchments). Locating trees suitably is crucial for maximising benefits and reducing potential trade-offs. Tree planting is one of the simplest types of NbS and is widely used in England, with drivers such as net zero targets, flood risk mitigation, and climate change adaptation. For example, the nationwide 'Keeping Rivers Cool' initiative seeks to increase the resilience of river ecosystems to warming water temperatures by using riparian shading. Such land-use change occurring across a large number of catchments is likely to generate further understanding of its effects. The evidence demonstrates the need to consider NbS holistically to help appropriately balance their costs and benefits.

Some of the least studied NbS in the review were sustainable soil management measures (e.g. herbal leys). It is likely that a more extensive evidence base on such agricultural practices from an agronomic and crop science perspective exists, however it is only recently that they are being studied more holistically for catchment management purposes. The Sustainable Farming Incentive (SFI) introduced as part of the recent Environmental Land Management (ELMs) includes payments for herbal leys and is therefore likely to increase their uptake. Whilst it is recommended to keep herbal leys for a minimum of 2 years, it is recognised that it may take up to 4 years or longer to establish enough root growth to see improvements in soil structure (Defra, 2024). This may also help to explain the lack in evidence of environmental benefits for sustainable soil management measures.

The review of evidence highlighted that the implementation of combinations of different NbS can have a synergistic effect. For example, carrying out gully blocking alongside blanket bog revegetation can improve hydrological functioning of upland peat catchments to greater effect (Shuttleworth et al., 2019). Natural flood management potential for flood water storage was shown to be much greater where combined interventions (leaky barriers alongside temporary storage areas) were in operation (Trill et al., 2022). Some sustainable soil management practices have also been shown to work more effectively in combination (Quinton and Catt, 2004).

The review also demonstrated that NbS that do not work with natural processes are less likely to be sustainable and only provide benefits in the short-term. For example, the addition of gravel to watercourses may need to be regularly repeated if there is no natural supply of coarse sediment from upstream to replenish it. Some NbS, including wetland features, require ongoing management (e.g. removal of vegetation) to maintain their efficiency. This highlights the importance of considering the maintenance requirements of NbS and how these requirements can be minimised by working with natural catchment processes. A holistic, catchment-based approach to the implementation of NbS is likely to result in better environmental outcomes in the long-term.

The evidence matrix demonstrates that appropriate spatial targeting of NbS is needed. Studies suggested that the implementation of NbS sometimes follows a ‘no regrets’ approach, however this can potentially lead to unintended consequences and resource wastage. For example, the evidence synthesis and matrix highlighted that the re-introduction of beavers in Type 1 catchments (Western upland landscapes) is unlikely to provide flood risk benefits. Neumayer et al. (2020) suggest that beavers can/should only be re-introduced into settings where they can establish suitable habitat (areas with floodplains) and therefore are unlikely to provide water resource benefits or flood mitigation in steeper, V-shaped river valleys with limited floodplains. Whilst the evidence matrix highlighted the ecological benefits of beaver re-introduction and management in Type 1, Type 2 (Northern Upland Landscapes), and Type 4 (Grassland-based Agriculture) catchments, Stringer and Gaywood (2016) note that beavers could cause a potential shift to younger growth in woodland age structure. In catchments with rare woodland habitat such as aspen woodland and Atlantic hazel woods, beaver activity could result in damage and decreased resilience of these ecosystems. This potential risk should be considered alongside the substantial range of positive benefits resulting from beaver re-introduction and management.

5.2 Evidence gaps

Considering the distribution of evidence across the catchment types, most NbS require further evidence in terms of their effectiveness in different settings. However, it should be acknowledged that some of these evidence gaps are unlikely to be filled because certain NbS are already deemed unsuitable for use in some catchments. For example, there was no evidence on the three types of Sustainable Drainage Systems (SuDS) outside of urban-dominated areas. The reviewed literature suggested that the effectiveness of SuDS such as green roofs are less likely to be determined by physical catchment characteristics, but mostly by factors including design and maintenance. As mentioned in the evidence overview, significant gaps on the effects of sustainable soil management measures such as ley farming remain, particularly in upland catchments. Another notable gap highlighted by the matrix was the evidence on peatland restoration in lowland catchments. Although the matrix did not categorise flood management benefits by different types of flooding (e.g. fluvial), the evidence focused entirely on flooding from rivers and surface water. There is therefore a clear gap in the evidence base on the effects of NbS on the mitigation of groundwater flooding.

In terms of the outcome themes that this review focussed on, the effects on biodiversity and habitat were the least studied for most types of NbS. Evidence on only 9 out of the 17 NbS types was assessed (7.2.3 Biodiversity and habitat matrix), with most of the evidence focussing on beaver re-introduction, channel restoration, instream wood, and floodplain reconnection. Studies highlighted how research on NbS is frequently focussed on one discipline e.g. flood mitigation, with potential biodiversity benefits often being assumed. Further interdisciplinary research on the effects of NbS such as temporary water storage features on biodiversity and habitat is needed to help bridge this disconnect in the evidence base.

When assigning studies to catchment types, it was not always clear which type they belonged to due to a lack of relevant information provided on catchment characteristics or location. This emphasises the importance of contextualising research on NbS to allow the wider application of the findings to be considered. In cases where exact geographical co-ordinates cannot be shared due to sensitivities with landowners, researchers should provide as much information on the study catchment as possible. Information on geology, soils, rainfall etc. helps to enable comparison and determine applicability of results to other catchments.

In addition to evidence reviews, knowledge gaps can also be identified through surveys and interviews with stakeholders and topic experts. This is likely to be particularly useful for understanding evidence gaps in novel NbS topics where monitoring data is limited or not available. This approach can also be used to identify priorities for NbS at an international scale. For example, Thorsøe et al. (2023) used a combination of interviews and a comprehensive review to assess the current state of knowledge and evidence gaps for sustainable soil management in Europe.

5.3 Building the evidence base

The case studies presented within this report are intended to highlight a small number of recent examples of NbS implemented in England. These examples demonstrate some of the challenges in the successful implementation of NbS projects, and in the generation of new evidence through monitoring. For example, the re-introduction of beavers on the Wallington estate has required further intervention to support the establishment of beaver dams in the face of extreme weather events. Monitoring is not only important for evaluating success and generating evidence, but also for informing adaptive management strategies. Monitoring data should be used to flag issues such as unintended consequences at an early stage to allow fixes to be implemented rapidly. Extending the current evidence base will require further monitoring and assessment of both existing and future NbS. Long-term studies on NbS such as rewilding and beaver re-introduction and management are providing evidence to inform how we might best use these approaches in future to help adapt to a changing climate. Such assessments will increase the overall body of evidence available for review, in turn increasing our confidence that the right NbS are being implemented in the right place. It is important to acknowledge that we can also learn from the wider evidence base on environmental processes and the functioning of natural systems; these can support our understanding of NbS and their applications.

The rollout of current and future changes to environmental policy presents new opportunities to grow the evidence base on NbS and help to produce better outcomes. The re-introduction of beavers into the wild in England is currently under consideration following a public consultation and extensive trials to gather evidence. In 2022, the government gave beavers ‘native species’ status and protection under Schedule 2 of the Conservation of Habitats and Species Regulations (2017). This means that it is now an offence to intentionally capture, injure, kill or disturb beavers, or damage and destroy their breeding sites or resting places without a wildlife management licence (Natural England, 2022). There is also a growing interest in their ability to help mitigate wildfires, with evidence from North America showing that beaver activity increases fire resistance of riparian zones (Fairfax and Whittle, 2020). Whilst wildfire does not currently present a high threat in England, it is likely that in future summers the risk of this natural hazard will increase due to climate change driving the likelihood of more extreme hot and dry conditions. Ecosystem engineering by beavers has also been shown to buffer water temperature extremes in rivers which present another increasing risk under climate change. Beavers could therefore play an increasingly important role in enhancing the future resistance of English catchments.

Opportunities to expand existing evidence around the effectiveness of NbS may come from the following initiatives:

Environmental Land Management schemes (ELMs) – These Defra schemes have been introduced to replace the European Union’s Common Agricultural Policy (CAP) in England following the UK leaving the EU. The new policy consists of 3 schemes that enable land managers to be paid for environmental and climate-related goods and services:

- Sustainable Farming Incentive (SFI) – This scheme pays farmers to adopt and maintain sustainable agricultural practices that protect and enhance the environment, and can support farm productivity. This includes NbS related to soil management (e.g. winter cover crops).

- Countryside Stewardship (CS) – This scheme pays for targeted actions that are related to specific habitats and features (e.g. woodland). The scheme is aimed at enhancing biodiversity, water quality, air quality, and using natural flood management to reduce flood risk. This includes NbS in and around watercourses (e.g. floodplain re-connection and large, complex riparian buffer strips).
- Landscape Recovery – This scheme pays for large-scale, long-term projects that involve land-use change to create and restore important habitats, and provide wider environmental benefits including adaptation to climate change. These projects are likely to encompass a wider range of NbS implemented across specific catchments.

Catchment Sensitive Farming (CSF) provides locally-informed advice to farmers, helping them to improve water and air quality, and reduce flood risk on agricultural land. CSF helps to raise awareness of NbS such as temporary water storage features and buffer strips.

The monitoring of interventions funded through initiatives such as ELMs could increase the NbS evidence base and help to address some of the knowledge gaps identified in this report. Monitoring can take many forms, covering a range of cost and resource requirements to suit different projects, spatial scales, and types of NbS. Monitoring designs that allow statistically reliable conclusions to be made (e.g. BACI design) are most beneficial. However, it is acknowledged that this approach is not always possible, particularly where time is limited, and therefore different approaches (e.g. substituting space for time) can potentially be useful. Increasingly, citizen science is being used to monitor the environment, with the potential to generate large volumes of data. Trade-offs between the quality and quantity of data and evidence can be balanced appropriately to suit the NbS in question. Importantly, when undertaking evaluations following NbS implementation, both positive and negative (or null) outcomes to interventions are valuable to report. Knowledge of where NbS did not work well can be used to help improve future targeting and likelihood of successful outcomes from NbS projects.

Large-scale research programmes such as the ongoing 'Nature Returns' partnership led by Natural England may provide new evidence about biodiversity benefits and climate regulation from NbS at a landscape scale (Morecroft et al., 2024). A main emphasis will be on the contribution of different habitats to carbon capture and storage, and how this relates to biodiversity, thereby supporting net zero and actions to improve biodiversity. Ongoing international research such as the European Union funded 'PONDERFUL' project which aims to understand how ponds can be used as NbS for climate change adaptation across Europe (Bartrons et al., 2024).

6 Conclusions

The evidence synthesis has demonstrated that NbS have significant potential to provide multiple benefits in different catchment types across England. Overall, the NbS discussed within this report offer more benefits for hydrological extremes, water quality, and biodiversity and habitat than disbenefits. The current evidence base was found to be contradictory or inconclusive in several places, most frequently in terms of the water quality outcomes of NbS. The availability and quality of evidence was highly variable between different NbS, catchment types, and environmental themes. In many cases, evidence was limited, inconclusive or implied, highlighting a low level of confidence in the ability of NbS to generate benefits in these circumstances. Evidence of the effects of constructed wetlands, afforestation, and beaver re-introduction were most abundant. In the case of constructed wetlands, this partly reflects a growing interest in the use of NbS by the water industry. The generation of evidence on the effects of beavers in England has been driven by the need for a clearer understanding of their impacts to enable society to learn, adapt and embed living alongside beavers in catchments in a way that maximises benefits and minimises risks. Buffer strips/zones were found to have relatively limited evidence despite having been commonly used in England for several decades. Future research on the effects of buffer strips/zones, particularly at larger scales (e.g. catchment scale), would help to quantify their multiple benefits and inform optimal application. Despite increases in monitoring of NbS and generation of evidence, there are still significant knowledge gaps that are likely to limit uptake of some potentially beneficial measures.

The evidence matrix shows how the applicability of different NbS is not uniform across different catchment types. Most evidence was generated from studies of NbS in lowland agricultural catchments, whereas western upland landscapes had the least evidence. There were also notable differences in the availability of evidence of the effects of different types of NbS between upland and lowland catchments. For example, evidence of the effects of peatland restoration was limited to upland catchments, whereas constructed wetlands were limited to lowland catchments. These results highlight the need for continued monitoring of NbS across environments with varying catchment characteristics to improve the state of knowledge and fill bridge research gaps in these areas. There have been increases in the number of NbS studies monitoring effects pre and post-intervention, however the median monitoring period of the reviewed studies was 3 years, highlighting a bias towards shorter monitoring periods in the evidence base. Longer-term monitoring will help to provide clarity on how the benefits and disbenefits of NbS may change over time. It should also be acknowledged that scientific studies on the underlying physical, chemical and biological principles of NbS can help to fill some of the identified evidence gaps.

The evidence synthesis, summaries and matrix presented here can guide catchment managers, land owners, developers, and farmers in selecting appropriate measures and consider the multiple benefits and any disbenefits. Considering the impacts of any NbS in the context of the catchment before implementation will help avoid unintended consequences. An awareness of potential trade-offs can be used to help balance the costs and benefits of different NbS. Ensuring that the use of NbS aligns with the wider priorities of the catchments that they sit within will help to maximise their benefits at a larger scale. It is acknowledged that NbS alone are not sufficient to completely mitigate the impacts of climate change, however they form an important part of the solution and the wider ambition to create resilient catchments and ecosystems.

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List of abbreviations

BACI	Before-After Control-Impact
BOD	Biological Oxygen Demand
C	Carbon
COD	Chemical Oxygen Demand
CSF	Catchment Sensitive Farming
CW	Constructed Wetland
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
ELM	Environmental Land Management
EPT	Ephemeroptera, Plecoptera, Tricoptera
GES	Good Ecological Status
GHG	Greenhouse gas
GRCF	Green Recovery Challenge Fund
IBZ	Integrated Buffer Zones
ICW	Integrated constructed wetland
IUCN	International Union for Conservation of Nature
K_{fs}	Field-saturated hydraulic conductivity
LID	Low impact development
LW	Large wood
NbS	Nature-based Solutions
NFM	Natural Flood Management
NGO	Non-governmental organisation
N	Nitrogen
P	Phosphorus
POC	Particulate Organic Carbon

Q95	Flow equalled or exceeded 95 % of the time
RAFs	Run-off Attenuation Features
RRC	River Restoration Centre
SFI	Sustainable Farming Incentive
SRP	Soluble Reactive Phosphorus
SS	Suspended Sediment
SIB	Stormwater Infiltration Basin
STW	Sewage treatment work
SuDS	Sustainable Drainage Systems
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TOC	Total Organic Carbon
TON	Total Oxidised Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
UKWIR	UK Water Industry Research
WFD	Water Framework Directive

Glossary

Aquifer	Permeable rock such as chalk or limestone that can store or transmit groundwater.
Denitrification	The process by which nitrate (dissolved in water) is ultimately converted to nitrogen gas. This is facilitated by microbes (denitrifying bacteria).
Nitrification	The biological conversion of ammonia or ammonium to nitrate or nitrite.
Run-off Attenuation Feature	Soft-engineered structures designed to intercept rainfall run-off and provide temporary storage of flood flow.
Run-off ratio	This ratio describes the proportion of rainfall that becomes run-off (overland flow).
Saturated hydraulic conductivity (K_{fs})	A measurement of the rate of water movement through saturated soil. Higher values indicate that water can flow through a soil more easily.
Soluble reactive phosphorus	A measure of the inorganic phosphorus that is dissolved in water. This represents biologically-available phosphorus and is also sometimes referred to as orthophosphate.
Total phosphorus	A combined measure of the dissolved and particulate phosphorus in a water sample.

7 Appendices

7.1 Catchment typology map

The WFD Water Bodies in England have been grouped into catchment types (Figure A.1).

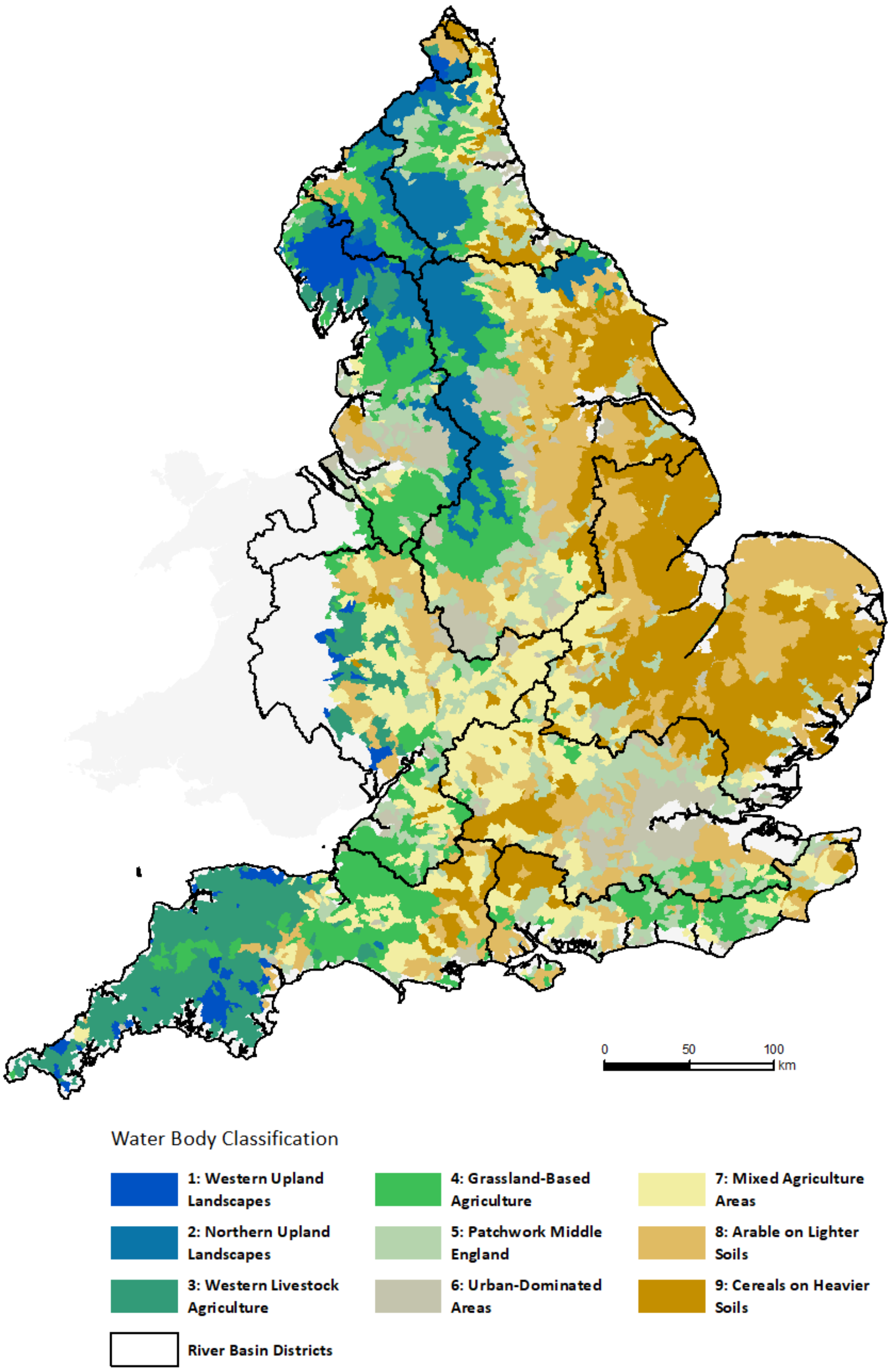


Figure A.1 Distribution of the 9 catchment types across WFD waterbodies in England. Black outlines show the boundaries of the 10 river basin districts in England. Map credit: unpublished internal Environment Agency product created by the University of East Anglia under commission from the Environment Agency (Lovett, 2024).

7.2 Evidence matrices

7.2.1 Hydrological extremes

Catchment Type	Beaver re-introduction	Afforestation	Temporary water storage features	Riparian restoration	Buffer strips/zones	Hedgerows & vegetative barriers	Instream wood	Peatland restoration	Floodplain reconnection	Permeable pavement	Green roofs	Bioretention systems/rain gardens	Sustainable soil management	Assisted natural regeneration
Type 1: Western Upland Landscapes														
Low flow management		L 127							M 40					
Flood management	L 84a	M 127							M 40					L 116a
Type 2: Northern Upland Landscapes														
Low flow management		H 74, 121	M 5				M 38	H 87, 88a, 90, 113						
Flood management		M 74, 121	M 5				M 38	H 87, 88a, 88b, 90, 113, 120						L 116b
Type 3: Western Livestock Agriculture														
Low flow management	H 10a, 14							L 135						M 18a, 18b
Flood management	H 10a, 14		M 70a					M 135						M 18a, 18b
Type 4: Grassland-based Agriculture														
Low flow management		L 81				L 42							L 41	
Flood management	H 10b, 10c	H 81, 82, 89	M 53c, 70b		L 53b	M 42							M 41, 53a	
Type 5: Patchwork Middle England														
Low flow management														
Flood management													M 31b	
Type 6: Urban-dominated Areas														
Low flow management		L 44								L 48c, 69				
Flood management		M 8b, 44	L 48d, 112	L 43						H 48c, 69	H 48b, 49	H 48a, 66		
Type 7: Mixed Agricultural Areas														
Low flow management	M 132	L 118b												
Flood management	M 132	L 118b	H 16, 57, 85						L 71				M 31a, 31c, 118a	
Type 8: Arable on Lighter Soils														
Low flow management		M 77, 91				L 123, 131			L 75				L 114	
Flood management	H 10d, 84b	M 13b, 13c				M 123, 131	L 13a		L 75				H 37a, 37b, 37c, 114	
Type 9: Cereals on Heavier Soils														
Low flow management													M 83	
Flood management		L 8a	M 36										M 83	

7.2.2 Water quality

Catchment Type	Beaver re-introduction	Afforestation	Constructed wetlands	Temporary water storage features	Riparian restoration	Buffer strips/zones	Hedgerows & vegetative barriers	Instream wood	Peatland restoration	Channel restoration	Floodplain reconnection	Permeable pavement	Green roofs	Bioretention systems/rain gardens	Sustainable soil management
Type 1: Western Upland Landscapes															
Nutrient and sediment management											L 40				
Physico-chemical & biological water quality															
Type 2: Northern Upland Landscapes															
Nutrient and sediment management	M 111				M 86			M 119	H 87, 113, 120						
Physico-chemical & biological water quality								M 119							
Type 3: Western Livestock Agriculture															
Nutrient and sediment management	M 14				M 32				L 135						
Physico-chemical & biological water quality					M 32										
Type 4: Grassland-based Agriculture															
Nutrient and sediment management	M 3			L 53c		L 53b	M 42	M 115c							L 53a
Physico-chemical & biological water quality								M 115c							
Type 5: Patchwork Middle England															
Nutrient and sediment management	M 15		M 64		M 34					L 92					M 31b
Physico-chemical & biological water quality	L 15		M 64							L 105					
Type 6: Urban-dominated Areas															
Nutrient and sediment management		M 45	M 78a	H 48d, 65, 112	L 43					H 78b, 96		H 48c, 68	H 48b, 49, 67	H 48a, 52, 66	
Physico-chemical & biological water quality			M 63a, 63b, 78a	H 48d, 65						M 78b		H 48c, 68	H 48b, 49, 67	H 48a, 52	
Type 7: Mixed Agricultural Areas															
Nutrient and sediment management	M 132		H 27, 28a, 30, 33a, 60, 128b	M 16, 28b, 128a		H 134a, 134b	M 133	M 115a							M 31a, 31c
Physico-chemical & biological water quality	M 132			L 28b				M 115a							
Type 8: Arable on Lighter Soils															
Nutrient and sediment management			H 7a, 7b, 35			M 134c	M 122, 123, 131			M 94	L 75				H 37a, 37b, 37c
Physico-chemical & biological water quality										M 94					
Type 9: Cereals on Heavier Soils															
Nutrient and sediment management			H 25, 26, 29a, 29b, 29c, 29d, 29e, 29f, 29g	M 36				M 115b							
Physico-chemical & biological water quality								M 115b							

7.2.3 Biodiversity and habitat

Catchment Type	Beaver re-introduction	Constructed wetlands	Riparian restoration	Buffer strips/zones	Instream wood	Peatland restoration	Instream substrate addition	Channel restoration	Floodplain reconnection
Type 1: Western Upland Landscapes									
Biodiversity & Habitat	M 55								L 40
Type 2: Northern Upland Landscapes									
Biodiversity & Habitat	M 111				M 119, 125	M 87, 113			
Type 3: Western Livestock Agriculture									
Biodiversity & Habitat									
Type 4: Grassland-based Agriculture									
Biodiversity & Habitat	H 3, 80							M 98	
Type 5: Patchwork Middle England									
Biodiversity & Habitat			M 97a				M 97b, 97c, 101a, 101b	H 92, 105, 126	M 100
Type 6: Urban-dominated Areas									
Biodiversity & Habitat			L 43		M 129a			M 78b, 96	
Type 7: Mixed Agricultural Areas									
Biodiversity & Habitat		L 27	H 11b, 23, 24	M 134d, 134e	H 4, 11a, 93, 129b			M 103	M 54
Type 8: Arable on Lighter Soils									
Biodiversity & Habitat		L 59		L 134c	H 99, 106, 110		H 104, 108	H 94, 102, 107, 117	L 75
Type 9: Cereals on Heavier Soils									
Biodiversity & Habitat							M 109	M 12, 39	L 130

7.2.4 Matrix keys

Effects of NbS	
	Mostly positive effects reported
	Mixed effects/contradictory evidence reported
	Mostly negative effects reported
	No effects observed/detected
	No evidence available

Quantity and quality of evidence	
H	2 or more studies with substantial evidence
M	At least 1 study with evidence or multiple studies with some evidence
L	Evidence is limited, inconclusive or only modelled/hypothesised

7.3 NbS summaries

7.3.1 Introduction

The aim of this project was to synthesise evidence on the effects of Nature-based Solutions (NbS) on natural processes and properties that contribute to catchment resilience. A wide range of NbS were identified from the literature and then grouped into 17 broad NbS types.

Evidence was considered under the themes of:

- Low flow management
- Flood management
- Nutrient and sediment management
- Physico-chemical and biological water quality
- Biodiversity and habitats

The reviewed evidence on each type of NbS was summarised into short (2-page) summaries to provide overviews of the different NbS and their potential effects in English catchments. The summaries are intended for use by catchment managers, catchment partnership groups, environmental non-governmental organisations (e.g. Rivers Trusts) land-owners, and farm managers. River/catchment restoration practitioners and researchers may also use these summaries to inform monitoring priorities for NbS projects.

Each summary includes:

- An introduction to the NbS type, and typical examples
- Examples of potential positive effects on environmental properties and processes resulting from implementation of the NbS (as identified in the evidence review)
- Examples of potential risks or trade-offs resulting from implementation of the NbS (as identified in the evidence review)
- Information on the current usage of the NbS in England, including drivers and mechanisms/support for implementation
- The spatial distribution of evidence on the NbS across English catchments
- An indication of where the NbS could be suitably located to maximise benefits and reduce the risk of trade-offs
- Best practice for monitoring and evaluation of the NbS, and suggestions of appropriate parameters to monitor
- Evidence gaps on the NbS type (as identified in the evidence review)

7.3.2 Types of NbS

NbS are diverse and can range from instream interventions to measures applied across whole catchments. It is also recognised that some NbS are referred to under different names. Table A.1 provides definitions of the broad NbS types discussed in this project, including the specific NbS (as identified in the literature) used to form the category. Please note that some of the summaries include multiple NbS categories.

Table A.1 Categories of NbS identified from the literature.

NbS Category	Description	Specific NbS
Beaver re-introduction and management	The re-introduction and management of the once native Eurasian beaver (*Castor fiber*) can be considered as a NbS due to the significant role beavers play in modifying their environment as 'ecosystem engineers'. Studies in this category include evidence from beavers in enclosures and from established populations in the wild.	Beaver re-introduction
		Beaver re-introduction and wetland rehabilitation
Afforestation	The planting of trees in the landscape in areas where there was no recent tree cover. For example, on floodplains, in riparian zones, or urban areas. Studies in this category include evidence on both deciduous and coniferous trees, and at different spatial scales.	Afforestation
		Urban tree planting
		Floodplain forest restoration
		Floodplain forest restoration and natural logjams
Constructed wetlands	Constructed wetlands (CWs) are artificially created wetland features that are primarily used to treat polluted water (e.g. sewage effluent or agricultural run-off). They typically have an inflow and outflow, but are diverse in their design, ranging from more natural features to highly engineered systems.	CWs
		Instream CWs
		Surface flow CWs
		Vertical flow CWs
		Horizontal flow CWs
		Integrated CWs
		Field wetlands

NbS Category	Description	Specific NbS
		Online ponds
Temporary water storage features	Temporary storage features typically use natural topography to hold back water in the landscape, primarily for the purpose of Natural Flood Management (NFM). Examples include Run-off Attenuation Features (RAFs) and swales that intercept flow pathways.	RAFs
		Temporary Storage Areas (TSAs)
		Grassed waterway and earthen dams
		Swales
		Stormwater pond
		Stormwater Infiltration Basin
Riparian restoration	This category includes interventions aimed at restoring the riparian zone, including its vegetation and ecosystem functions. Examples include the removal of embankments or rip-rap (rock used to armour riverbanks), and restoration of natural riparian wetlands.	Removal of rip-rap
		Riparian zone restoration
		River corridor rehabilitation
		Riparian wetlands
		Embankment removal
Buffer strips/zones	Buffer strips/zones are narrow vegetated areas of land primarily aimed at protecting watercourses from diffuse (non-point source) pollution. They are multifunctional and can also be implemented to provide shade, refuge, or act as movement corridors for wildlife. This category includes integrated buffer zones which also incorporate pond features for interception of water and pollutants.	Integrated Buffer Zones
		Riparian buffer strips
		Zoned buffer strips
		Wooded buffer strips

NbS Category	Description	Specific NbS
Hedgerows and vegetative barriers	Hedgerows are made up of living shrubs, and typically used as boundary lines for agricultural fields. Vegetative barriers are made up of natural materials (e.g. straw) and are used to mimic the barrier effect of hedgerows.	Hedgerows
		Vegetative barriers
Instream wood	Instream wood includes the (re)introduction of woody material into watercourses. This ranges from engineered approaches (e.g. log jams that are fixed to riverbanks/beds), to passive strategies (e.g. letting trees naturally fall into streams).	Willowed engineered log jams
		Large Wood (LW) installation
		Wood (re)introduction
		Engineered Logjams
Peatland restoration	This category includes the restoration of upland peatland habitats (e.g. blanket bog) and their ecosystem functions through techniques such as revegetation and gully (ditch) blocking to aid rewetting. This category did not consider lowland peat settings due to a lack of studies.	Blanket bog restoration (gully blocking and peat revegetation)
		Peatland restoration (ditch blocking)
		Blanket bog restoration (peat revegetation)
Instream substrate addition	This category includes the addition of geological material (e.g. gravel) into watercourses, typically to raise the streambed or modify benthic habitat.	Gravel addition
		Gravel addition and cleaning
		Boulder addition
		Flow deflectors
		Sand addition

NbS Category	Description	Specific NbS
		Instream habitat modification
Channel restoration	This category includes measures that aim to restore natural river channel form and functioning. Examples include re-meandering, and the removal of dams, impoundments, or culverts.	Channel restoration
		Side channel creation
		Impoundment removal and channel narrowing
		Dam removal
		Daylighting (culvert removal)
Floodplain reconnection	Floodplain reconnection involves restoring the connectivity of rivers to their floodplains through removing/lowering levees or raising the riverbed to facilitate overbank flows.	Floodplain reconnection
		Embankment lowering
		Levee removal
Sustainable Drainage Systems - Permeable pavement	Permeable pavements are forms of urban surfaces that are used to capture rainfall or surface run-off and encourage infiltration.	Permeable pavement
Sustainable Drainage Systems - Green roofs	Green roofs are roofs of buildings that are covered with a waterproof membrane and vegetation grown on a layer of substrate.	Green roof
		Constructed wet roof (Combined green roof and CW)
Sustainable Drainage	Bioretention systems or rain gardens are landscaped depressions that are used to	Bioretention system

NbS Category	Description	Specific NbS
Systems - Bioretention systems/rain gardens	capture and treat stormwater from impervious surfaces in urban settings.	Rain garden
Sustainable soil management	This category includes a variety of techniques aimed at improving the health and functioning of soils (largely arable). Examples include cover crops, no till farming and ley farming. Ley farming (e.g. herbal leys) is the practice of growing grass, legumes, or a mixture of herb species in rotation with arable crops.	Soil aeration
		Contour cultivation
		Cover crops
		No till
		Minimum till
		Minimum till and contour cultivation
		Minimum till and tramline disruption
		Minimum till, contour cultivation and vegetative field barrier
		Minimum till, tramline disruption and residue management
		Herbal ley
		Grass-clover ley
Assisted natural regeneration	This category includes measures that facilitate the natural ecological succession of land (e.g. rewilding, fencing).	Exclusion of sheep
		Exclusion of sheep and tree planting

NbS Category	Description	Specific NbS
		Agricultural conservation land management
		Rewilding

7.3.3 Summaries

The following pages contain the NbS summaries, with 2 pages per category of NbS.

Multiple benefits of Nature-based Solutions (NbS)

The re-introduction and management of the once native Eurasian beaver (*Castor fiber*) can significantly modify watercourses and the riparian zone due to beavers being 'ecosystem engineers'. Beavers can modify smaller (low-order) streams as a result of activities such as dam and canal building which can slow and change flows of water, creating ponds and wetlands. Beavers mainly forage on soft vegetation in spring/summer, and tree bark, shrubs and leaves in autumn/winter. This can include coppicing behaviour which can change vegetation canopy structure with wider consequences for the ecosystem.

Evidence from 18 studies suggests that beavers can affect the following environmental properties and processes:

Positive effects	Risks
↑ Flow attenuation and flood storage	↑ Longitudinal (up/downstream) connectivity
↑ Infiltration and evapotranspiration	↓ Mercury retention
↑ Sedimentation	↓ Dissolved oxygen
↑ Nutrient retention (C, N and P)	↑ Water temperature regime change
↑ Macrophyte (aquatic plant) growth/communities	↑ Chlorophyll concentration (algal growth)
↑ Physical habitat heterogeneity	
↑ Lateral connectivity with floodplain	
↑ Invertebrate diversity/productivity	
↑ Fish diversity/abundance	
↑ Riparian fauna (birds and amphibians)	
↑ Groundwater recharge	
↑ Low flow enhancement/refuge	
↑ Moderating water temperature extremes	

Image credit: Krzysztof Dabrowski, Environment Agency

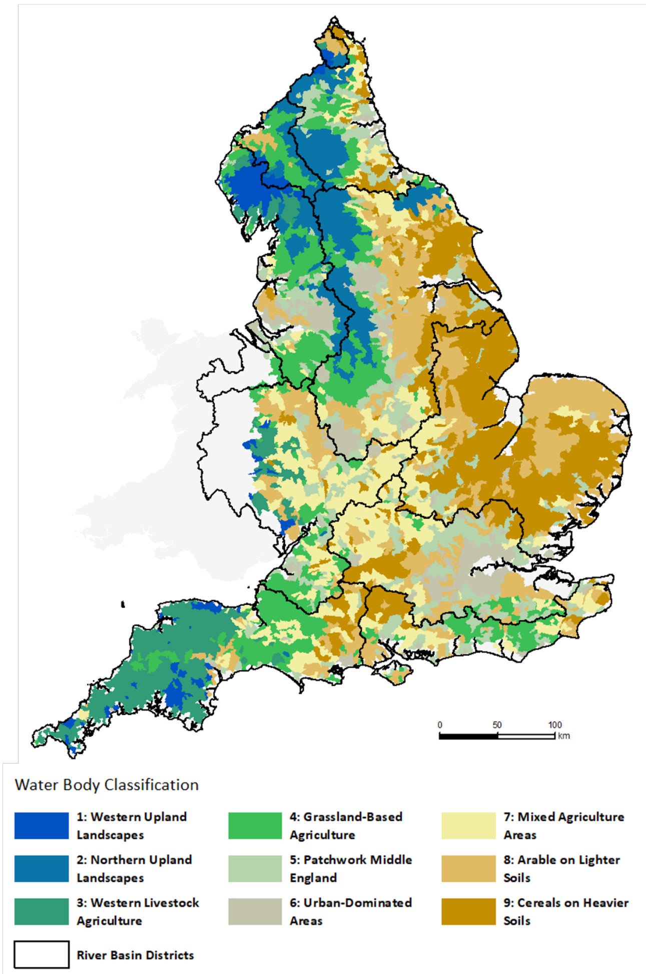
Eurasian beavers in England

A population of beavers in the River Otter catchment in Devon was monitored from 2015-2020. The evidence generated contributed towards decision-making on the wider re-introduction of beavers in England. There are also additional free-living populations elsewhere in England. Beavers have also been re-introduced in fenced enclosures including Spains Hall Estate in Essex, and the Wallington Estate in Northumberland. In 2022 Eurasian beaver received legal protection under the Conservation of Habitats and Species Regulations 2017. Natural England operate the licensing framework for the management of beavers in England.

Findings across English catchments

Evidence on the effects of beavers was derived from all catchment types except 6 and 8. The effects were mostly positive; however, evidence of potential negative water quality impacts was seen in Type 5 and 7 catchments. Mixed effects on nutrient and sediment management were reported for Type 4 catchments. No evidence was reviewed for Type 6 and 9 catchments, though it is recognised that beavers are present in these types.

Catchment Types



Catchment considerations

Benefits are most likely to be gained from beaver presence and re-introduction in:

- Low-order streams with relatively gentle gradients
- Areas where beavers will not result in conflicts with existing land-use or infrastructure

Challenges and risks are more likely to occur in:

- Areas with steep slopes e.g. V-shaped river valleys
- Areas with rare woodland habitat (e.g. aspen or Atlantic hazelwood) where beaver activity could shift tree population structure to younger growth
- Areas where fish spawning habitat is solely located in the upper reaches of the stream network and beaver dams could potentially limit up/downstream connectivity for fish passage

Monitoring and evaluation

The most effective approach for monitoring beaver re-introduction is a Before-After Control-Impact (BACI) study which compares changes to baseline and control data, allowing robust conclusions to be drawn. Monitoring of hydrology (e.g. water level and flow), water quality (e.g. nutrient concentrations), and biology (e.g. invertebrate species richness) up/downstream of beaver sites over time can help to evaluate effects.

Evidence gaps

The review of the 18 studies highlighted the following gaps in our knowledge on the effects of beavers:

- Benefits and trade-offs at larger spatial scales (e.g. catchment scale) and over longer timescales.
- Influence of beaver on long-term gaseous carbon fluxes and nutrient dynamics.
- Potential effects of beaver activity on vulnerable fish populations e.g. Atlantic salmon and lamprey.
- Potential effects on downstream communities and habitat refuges during extreme conditions e.g. drought.

For more information and evidence on beaver re-introduction and management, please see the Natural England review:
https://publications.naturalengland.org.uk/publication/5361572139761664 (Howe, 2020).

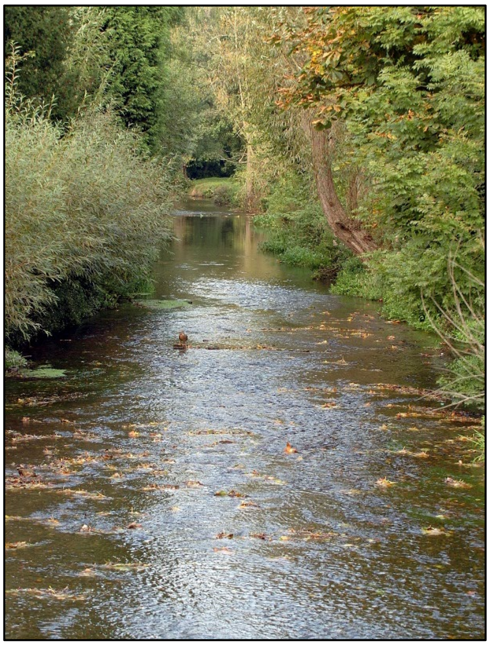
This summary has been produced from a review of evidence on the multiple benefits of NbS. Please refer to the published report for a full list of references to the reviewed studies, the matrix of evidence, and further information on the catchment types. Please note that this summary may not reflect all available evidence, but aims to provide a starting point to help inform the delivery and management of NbS to maximise benefits and minimise risks.

Multiple benefits of Nature-based Solutions (NbS)

Afforestation is the planting of trees in an area where there was no recent tree cover. It can take different forms, from large scale tree planting in the floodplain, or on slopes in catchment headwaters, to riparian tree planting along watercourses. The potential effects of afforestation can vary depending on factors such as the species planted, the age of trees, and extent of planting. At a large scale afforestation can significantly modify catchments by enhancing hydrological processes such as evapotranspiration, which can alter how much water is stored and moves through a catchment. At a smaller scale, the planting of trees can directly influence watercourses, for example through shading and moderation of water temperature.

Evidence from 18 studies suggests that afforestation can affect the following environmental properties and processes:

Positive effects	Risks
↑ Run-off generation	↑ Low flow habitat refuges
↑ Water temperature	↑ Groundwater recharge
↑ Flow attenuation and flood storage	↑ Groundwater pH
↑ Interception	↑ Potential overshading from riparian woodland could damage some habitat types (e.g. exposed riverine sediments)
↑ Infiltration	
↑ Evapotranspiration	
↑ Organic matter (carbon) storage	
↑ Nutrient retention/removal	
↑ Lag time	



Afforestation in England

Afforestation is one of the most commonly applied types of NbS. The rate of tree planting in England is currently increasing, with over 3000 hectares planted in 2022/23 – a 40% increase compared with 2021/22. Important drivers for this increase include net zero ambitions and the need to offset carbon emissions, as well as the use of trees as natural flood management interventions. The England Woodland

[Creation Offer] provides financial support to landowners, land managers, and public bodies for the creation of new woodland and delivery of multiple benefits, including water quality and Natural Flood Management. Please see the summary on ***riparian restoration*** for more information about tree planting in the riparian zone specifically (e.g. for [providing shade to help keep rivers cool and provide climate change adaptation]).

Findings across English catchments

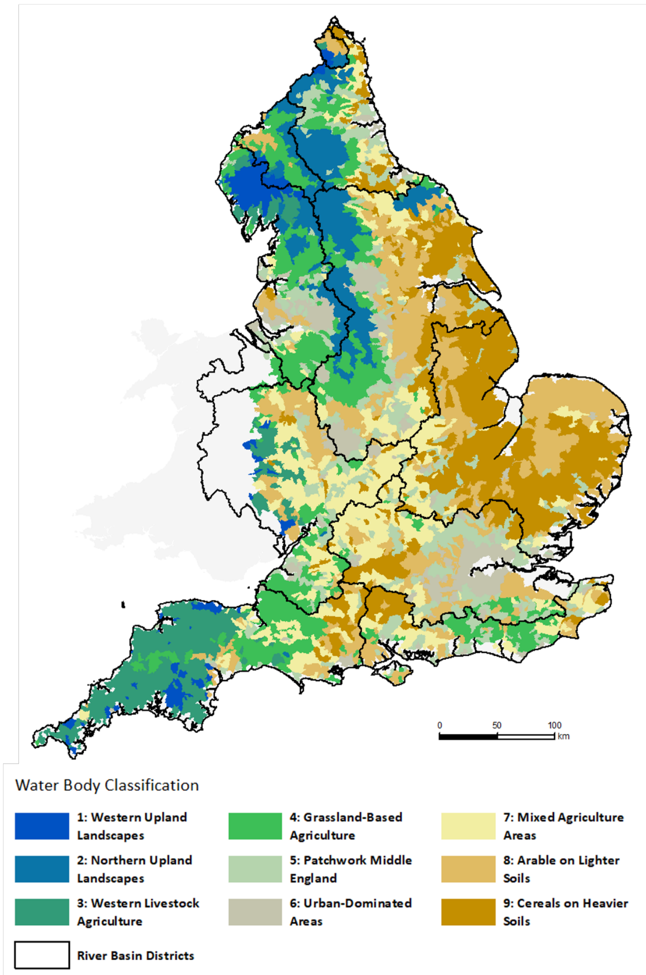
Evidence on the effects of afforestation was derived from all catchment types except Type 3 and 5. The effects were mostly positive; however evidence of potential trade-offs for low flows were found in Type 2, 7 and 8 catchments. Mixed effects on low flows were reported in Type 6 catchments. Trade-offs were influenced by factors including the scale/extent of afforestation, tree species, and catchment geology (e.g. permeability).

Catchment considerations

Benefits are more likely to be gained from afforestation in:

- Smaller catchments where less extensive planting is needed to achieve effects for natural flood management purposes
- Catchments suffering from soil erosion issues
- Riparian zones in headwaters and smaller rivers

Catchment Types



Trade-offs are more likely to occur in:

- Areas with a high proportion of permeable catchment geology (e.g. sandstone)
- Areas with existing high-value ecosystems such as unimproved grassland
- Riparian areas where rivers have habitats/species that may be damaged by overshading (e.g. exposed riverine sediment, and sunny lowland riverside rocks)

Monitoring and evaluation

The most effective approach for monitoring the effects of afforestation is a Before-After Control-Impact (BACI) study which compares changes to baseline and control data, allowing robust conclusions to be drawn. Monitoring of hydrological processes (e.g. infiltration and evapotranspiration), water quality (e.g. nutrient leaching) over time can provide evidence to evaluate environmental improvements and trade-offs.

Evidence gaps

The review highlighted the following gaps in our knowledge on the effects of afforestation:

- Observational evidence on large scale impacts to help upscale models more confidently.
- The effects of different configurations of tree planting (e.g. linear vs grouped)
- Evidence on the contribution of leaf litter to nutrient leaching in parkland and riparian environments
- Long-term evidence on groundwater recharge in afforested catchments under different climatic conditions
- The effects of acidification and nitrification processes in different forest soils and catchment geologies

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Multiple benefits of Nature-based Solutions (NbS)

Constructed Wetlands (CW), also known as treatment wetlands, are artificially created wetland features of varying sizes that are primarily used to treat polluted water (e.g. sewage effluent or agricultural run-off) by emulating natural wetlands. They are diverse in their design, ranging from instream CW that treat water continuously to highly engineered systems that have controlled inflows. Types of CW include subsurface flow or surface flow wetlands, and edge-of-field farm wetlands. CWs aim to use physical processes (e.g. settling out of particles) and biogeochemical processes (e.g. denitrification) to remove potential pollutants from inflowing water and thereby improve the outflowing water quality. The effects of CWs on the environment can vary depending on factors such as the vegetation composition/cover, the age of the wetland, and its size/surface area. Most CW also require maintenance (e.g. removal of accumulated sediment or vegetation) to ensure they continue to function effectively.

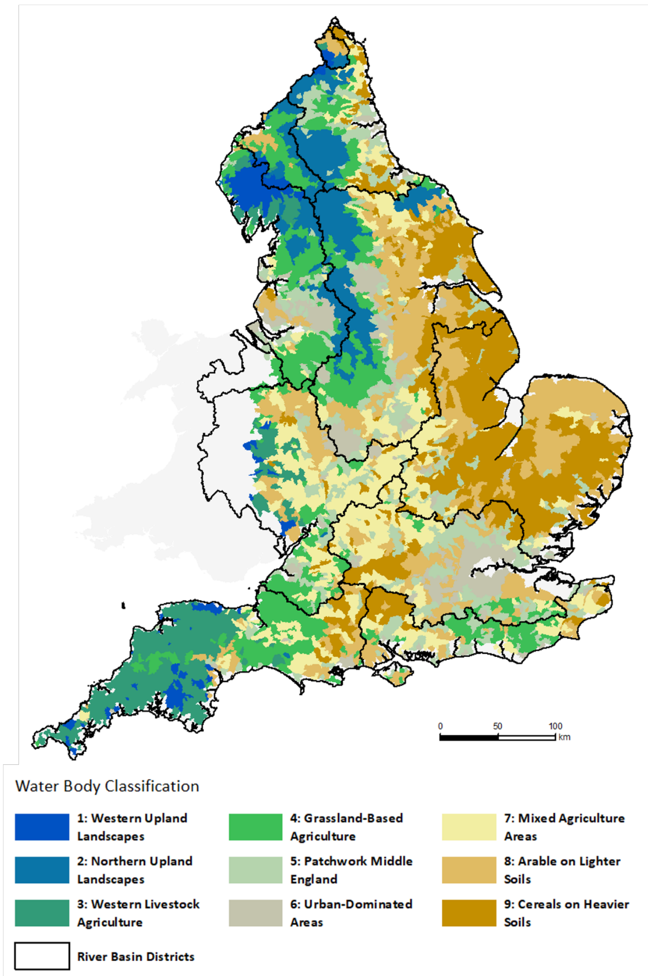
Evidence from 26 studies suggests that CWs can affect the following environmental properties/processes:

Positive effects	Risks
↑ Storage/retention of organic matter (carbon), fine sediment, phosphorus, and nitrogen (dependent on CW conditions and maintenance) ↑ Heavy metal retention/removal ↑ Faecal bacteria retention/removal ↑ Interception of overland flow pathways ↑ Habitat connectivity ↓ Water temperature	↓ Remobilisation and release of sediment and pollutants (e.g. nutrients) over time ↓ Interactions between CWs and shallow groundwater may increase risk of groundwater contamination or reduce pollutant treatment efficiency (in unlined CWs) ↓ Potential release of greenhouse gases ↓ Unlikely to meet numeric water quality permit limits (where used to treat sewage effluent)

Constructed Wetlands in England

Using CWs to treat water in England has grown since the 1980s and they have been used to treat domestic wastewater (sewage), as well as minewater, industrial effluent, landfill leachate, road run-off, and agricultural run-off. However, the use of CWs in England is currently not as widespread as in other European countries. Uptake of CWs is likely to increase with drivers such as the Habitats Regulations, Countryside Stewardship grants, and the trialling of NbS by water companies. CWs must comply with the relevant environmental regulations and effluent discharges must meet water quality standards. For example, nutrient treatment wetlands must meet conditions set out in the Environment Agency's regulatory position statement (RPS 260). This sets out conditions such as CW design and maintenance requirements. Where nutrient treatment wetlands are used as additional measures to treat wastewater, they must not result in deterioration of the water quality of final effluent.

Catchment Types



Findings across English catchments

Evidence on the effects of CWs was derived from catchments in Types 5-9. The effects were mostly positive, however some evidence on the effectiveness of CWs for sediment and nutrient management was contradictory in Type 7 catchments. Variability in the effectiveness of CWs is influenced by factors including hydrological conditions (e.g. flow), pollutant load, and underlying geology. The age of CWs can influence pollutant removal efficiency through changes such as vegetation structure. The extent and frequency of maintenance can also influence CW efficiency.

Catchment considerations

Benefits are more likely to be gained from CWs:

- In lowland areas (relatively gentle slopes)
- On naturally wet (agriculturally unproductive land)
- At a small, local scale, rather than treating large volumes (particularly for treating sewage effluent)

Trade-offs are more likely to occur in:

- Land with unsuitable topography e.g. steep hillside
- Areas with limited land availability
- Locations with very high pollutant loads
- Locations where significant on-going CW management is needed to maintain function

Monitoring and evaluation

The most effective approach for monitoring the effects of CWs is a Before-After Control-Impact (BACI) study which compares changes to baseline and control data, allowing robust conclusions to be drawn. Monitoring upstream and downstream (e.g. the inflow and outflow) of CWs can provide valuable information on the removal efficiency of pollutants over time. Water quality can be tested through taking water samples for laboratory analysis and/or use of in-situ sensors. Water quality parameters of interest will vary depending on the type of water being treated, but may include concentrations of nutrients, heavy metals, pesticides, faecal indicator organisms, and dissolved oxygen. Monitoring of flow (discharge) into/out of CWs alongside pollutant concentrations enables calculation of pollutant load retention. CWs used to treat sewage effluent should be monitored throughout their lifetime to ensure optimum treatment efficiency is maintained. Monitoring frequency should be high enough to capture seasonal differences in treatment efficiency. Higher monitoring frequencies provide greater certainty in CW efficiency.

Evidence gaps

The review highlighted the following gaps in our knowledge on the effects of CWs:

- The effect of CWs at larger spatial scales and the long-term fate of accumulated sediment and pollutants
- Influence of catchment characteristics, groundwater and flood regime on CW biogeochemistry/efficiency
- The efficiency of CWs to treat emerging pollutants e.g. pharmaceuticals, microplastics
- Case studies applicable to the UK climate, with appraisal of plant species & maintenance regime on treatment
- The extent to which CWs can help to achieve water quality permit limits

For guidance on CWs and their appropriate use, please see the government guidance on nutrient mitigation.

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Multiple benefits of Nature-based Solutions (NbS)

Temporary water storage features can hold back water in the landscape to slow the flow of water downstream, gradually releasing the stored water so that flood peaks are attenuated. Such features can also enhance hydrological processes such as infiltration. At a local scale, these features may also provide benefits for water quality through storage of sediment and associated pollutants. Temporary water storage features can take different forms, e.g. run-off attenuation features (RAFs) or offline ponds. The potential effects of temporary water storage features can vary depending on factors such as their size/volume, location, and configuration within the landscape.

Evidence from 12 studies suggests that temporary water storage features can affect the following environmental properties and processes:

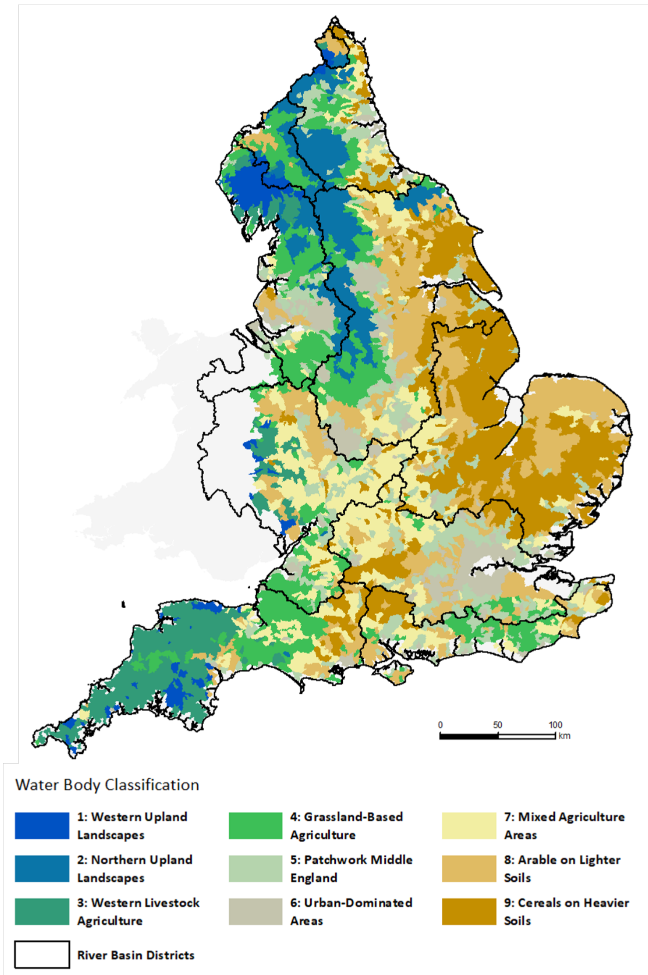
Positive effects	Risks
↑ Flow attenuation and flood storage ↑ Run-off attenuation ↑ Flow pathway interception ↑ Infiltration ↑ Groundwater recharge ↑ Lag time ↑ Lateral (floodplain) connectivity ↑ Organic matter/carbon storage ↑ Sediment and nutrient retention/removal	↑ Increased algal growth and potential for cyanobacterial (blue-green algae) blooms ↑ Leakage or failure of the feature ↑ Remobilisation of accumulated sediment and nutrients

Image credit: (left) Environment Agency; (right) © Terry Jacombs / Cox's meadow flood storage basin / CC BY-SA 2.0

Temporary water storage features in England

Temporary water storage features are increasingly being used in Natural Flood Management (NFM) schemes across England to help hold back water following heavy rainfall events, and also compensate for the increased urbanisation of catchments. Consent may be required for the construction of water storage features, as well as planning permission from the local planning authority depending on the size/volume. Relevant permits/consents may need to be obtained from the Environment Agency, local authority or internal drainage board.

Catchment Types



Findings across English catchments

Evidence on the effects of temporary water storage features was derived from catchments in Type 2, 3, 4, 6, 7 and 9. The effects were mostly positive; however evidence of potential trade-offs for physico-chemical and biological water quality was found in Type 7 catchments. Mixed effects on water quality were reported in Type 6 catchments. The effectiveness of storage features and their trade-offs were influenced by factors including design, and the hydrological conditions experienced.

Catchment considerations

Benefits are more likely to be gained from temporary water storage features in:

- Catchments with heavier soils and rapid run-off generation
- Areas where natural flow pathways can be intercepted
- Hydrologically responsive (flashy) headwater catchments

Trade-offs are more likely to occur in:

- Drainage areas where the volumes of overland flow generated are likely to regularly exceed the storage volumes of temporary storage features

Monitoring and evaluation

The most effective approach for monitoring the effects of temporary water storage features is through a Before-After Control-Impact (BACI) study which compares changes to baseline and control data, allowing robust conclusions to be drawn. Monitoring of hydrological processes (e.g. infiltration), water quality (e.g. nutrient concentrations) over time can provide evidence to evaluate environmental improvements and trade-offs.

Evidence gaps

The review highlighted the following knowledge gaps on the effects of temporary water storage features:

- Lack of empirical evidence on effectiveness at larger (>50 km^2) scales
- Longer term monitoring to understand effectiveness over time
- Interactions of storage features with soil properties and incorporation of these interactions in modelling
- Potential disbenefits of RAFs e.g. increased evaporation, changes to flow/sediment regimes
- Assessment of the ability of storage areas to remove emerging contaminants
- Implications of using RAFs in catchments with lighter soils and groundwater-dominated flow
- Research into maintenance of interventions required to maintain multiple benefits

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Multiple benefits of Nature-based Solutions (NbS)

Riparian restoration includes activities such as the removal of riverbank protection and embankments, and the creation of riparian strips and wetlands. Riparian restoration aims to create conditions that allow natural riverbank processes (e.g. colonisation by riparian vegetation) to take place. This can enhance processes such as erosion and deposition, which can result in changes to habitat availability and diversity. Riparian restoration may also help improve water quality and impact properties such as water temperature through shading.

Evidence from 9 studies suggests that riparian restoration can affect the following environmental properties and processes:

Positive effects	Risks
↑ Flow attenuation and flood storage ↑ Infiltration ↑ Organic matter (carbon) storage ↑ Sediment and nutrient retention/removal ↑ Establishment of plant communities ↑ Physical habitat diversity (e.g. flow diversity) ↑ Establishment of riparian invertebrate and bird communities ↑ Seed dispersal ↑ Hyporheic exchange ↓ Faecal bacteria	↑ Potential remobilisation of pollutants in riverbed sediments when carrying out restoration measures ↑ Potential increase in nitrate loads from riparian wetlands under aerobic conditions ↑ Potential overshading from riparian trees could damage some habitat types (e.g. exposed riverine sediment)

Riparian restoration in England

Drivers that will enable riparian restoration include the [Environmental Land Management (ELM) schemes](). For example, the Countryside Stewardship scheme provides payment for actions such as the management of riparian and water edge habitats. Previous riparian restoration in England has tended to be carried out at relatively small scales, however the Landscape Recovery scheme will help to deliver more ambitious, large-scale restoration projects over the longer-term. Recent efforts through the national ‘Keeping Rivers Cool’ initiative have also helped to restoring tree cover in riparian zones and provide shading to reduce instream temperatures. Please see the summary on ***afforestation*** for more information about tree planting as a Nature-based Solution.

Findings across English catchments

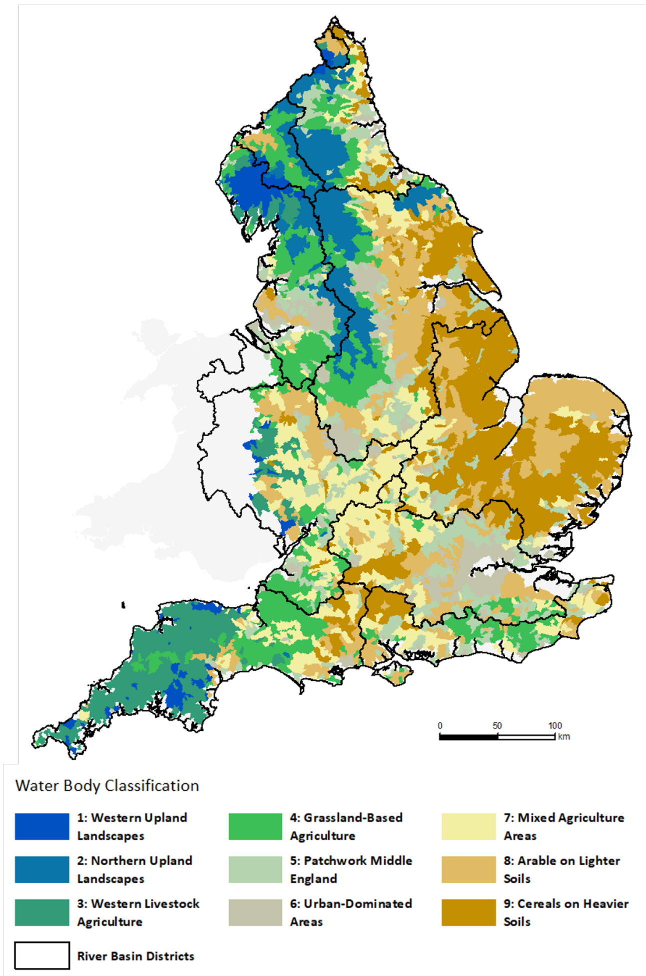
Evidence on the effects of riparian restoration was derived from catchments in Type 2, 3, 5, 6, and 7. The effects were mostly positive, however mixed effects on nutrient and sediment management were reported in Type 3 catchments. The effectiveness and success of interventions was influenced by factors including the spatial extent of the restoration, the hydrological conditions, and the available species pool.

Catchment considerations

Benefits are more likely to be gained from riparian restoration in:

- Catchments with well-connected river networks that allow movement of species for colonisation of restored reaches
- Agricultural areas where the absence of riparian vegetation is degrading water quality through diffuse pollution

Catchment Types



Trade-offs are more likely to occur in:

- Catchments with high densities of invasive non-native riparian species (e.g. Himalayan balsam) that may colonise restoration sites and outcompete the native target species
- Catchments with significant hydrological alterations where flow regimes may not be able to support establishment of riparian communities

Monitoring and evaluation

The most effective approach for monitoring the effects of riparian restoration is a Before-After Control-Impact (BACI) study which compares changes to baseline and control data, allowing robust conclusions to be drawn. Monitoring of geomorphological changes to riparian zones (e.g. flow and sediment diversity), water quality (e.g. nutrient concentrations), and biological communities (e.g. river invertebrate diversity) over time can provide evidence to evaluate environmental improvements and trade-offs.

Evidence gaps

The review highlighted the following gaps in our knowledge on the effects of riparian restoration:

- Risks surrounding contribution of riparian wetlands to greenhouse gas emissions
- Long-term monitoring of abiotic (e.g. water level) and biological indicators (e.g. species abundance/diversity) to evaluate restoration success over time (rather than just short-term benefits)
- Understanding of the influence of catchment/landscape context on restoration outcomes
- Holistic understanding of management actions following riparian restoration and consideration of the different interacting environmental processes needed to ensure the continuation of multiple benefits

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Multiple benefits of Nature-based Solutions (NbS)

Buffer strips/zones are narrow vegetated areas of land primarily aimed at protecting watercourses from diffuse (non-point source) pollution. They can be multifunctional, also providing shade, refuge, or acting as movement corridors for wildlife. They can enhance the roughness of the land surface to enhance hydrological processes such as run-off attenuation. Buffer strips/zones can take different forms, e.g. grassed, wooded, mixed, or 3-dimensional buffers (buffer strips that work above and below ground to tackle pollution pathways), or in some cases they are integrated with pond features for enhancing interception of water and pollutants to improve water quality. The potential effects of buffer strips/zones vary depending on factors such as the plant species composition, and the surrounding landscape.

Evidence from 9 studies suggests that buffer strips/zones can affect the following environmental properties/processes:

Positive effects

- ↑ Run-off attenuation
- ↑ Flow attenuation/storage
- ↑ Infiltration
- ↑ Sediment and organic matter/carbon storage
- ↑ Nitrogen retention/removal
- ↓ Water temperature
- ↑ Physical habitat diversity and connectivity
- ↑ Terrestrial and aquatic invertebrate diversity/abundance
- ↑ Bird and amphibian communities
- ↓ Invasive non-native species

Risks

- ↓ Macrophyte (aquatic plant) growth and diversity where shading is excessive
- ↓ Potential reduction in growth of Brown trout where excessive shading prevents streams from reaching optimum temperatures
- ↑ Potential for 'nutrient swapping' e.g. through remobilisation of particulate phosphorus to soluble forms in wooded buffer strips with higher organic matter content and microbial activity
- ↓ Potential for reduced crop yields due to land being taken out of production

Image credit: Environment Agency

Image credit: © Evrardo / Grassed waterway in Velm (Belgium)

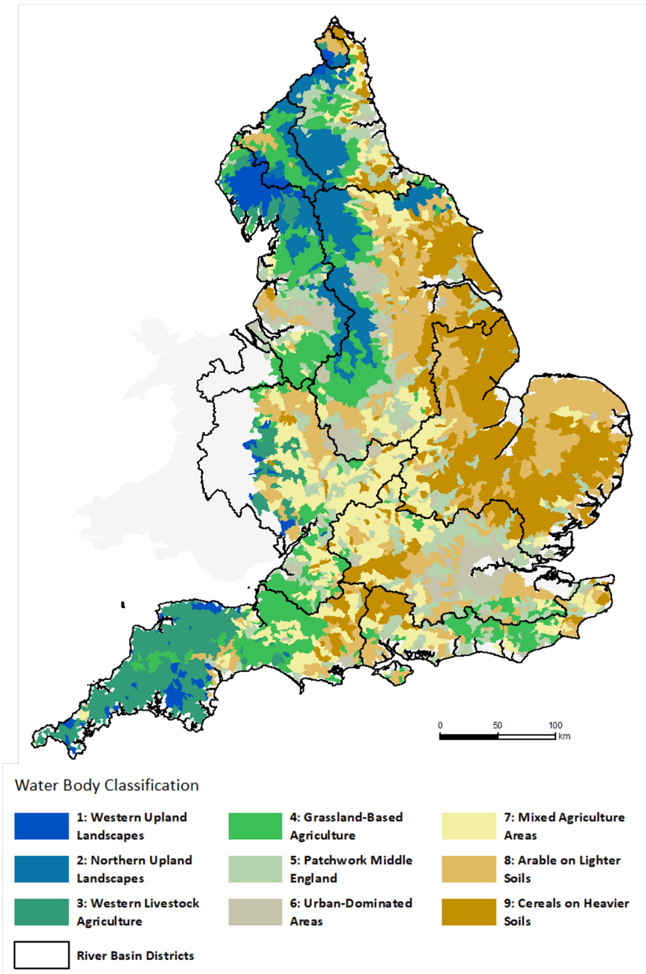
Buffer strips/zones in England

Buffer strips and zones are applied relatively widely across England, typically to protect water quality in watercourses running alongside arable fields or pasture used for grazing livestock. Going forwards, implementation of buffer strips/zones will be funded by the Environmental Land Management (ELM) schemes. The Sustainable Farming Incentive (SFI) provides payment for the establishment and maintenance of grass buffer strips on arable/horticultural land and improved grassland. Advice and support on implementation is provided by initiatives such as Catchment Sensitive Farming (CSF), run by Natural England and the Environment Agency.

Findings across English catchments

Evidence on the effects of buffer strips/zones was derived from Type 4, 7, and 8 catchments. The effects were mostly positive; however evidence of potential trade-offs for biodiversity and habitat was found in Type 8 catchments. Mixed effects on nutrient and sediment management were reported, also in Type 8 catchments. It should be acknowledged that trade-offs were influenced by factors including the age, width, and species composition of buffer strips.

Catchment Types



Catchment considerations

Benefits are more likely to be gained from buffer strips/zones in:

- Areas at higher risk from soil erosion
- Riparian zones adjacent to intensive agriculture
- Urbanised catchments with high volumes of road run-off and associated pollutants

Trade-offs are more likely to occur in:

- Areas with high agronomic value that would need to be taken out of production to implement buffers

Monitoring and evaluation

The most effective approach for monitoring the effects of buffer strips/zones is a Before-After Control-Impact (BACI) study which compares changes to baseline and control data, allowing robust conclusions to be drawn. Monitoring of hydrological processes (e.g. infiltration), water quality (e.g. nutrient concentrations), and biological communities (e.g.

abundance of insect pollinators) over time can provide evidence to evaluate environmental improvements and trade-offs.

Evidence gaps

The review highlighted the following gaps in our knowledge on the effects of buffer strips/zones:

- Understanding of the interactions between plant species in buffer strips, their stress responses, functional traits (characteristics such as root length), and their ability to retain/remove or mobilise pollutants.
- Understanding of the most effective management strategy for Integrated Buffer Zones.
- Decision support tools that include holistic cost-benefit analysis

For more evidence on buffer strips, please see the Defra-commissioned review on farm mitigation measures.

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Multiple benefits of Nature-based Solutions (NbS)

Hedgerows are made up of living shrubs, and typically used as boundary lines for agricultural fields. Vegetative barriers are made up of natural materials and are used to mimic the barrier effect of hedgerows. Barriers can be placed within fields to target critical flow pathways. Types of barriers include materials such as straw, wood chips, and coconut-fibre. Hedgerows and vegetative barriers can be used to enhance hydrological processes such as infiltration, and help to slow overland flow. Their potential effects can vary depending on factors such as the species composition of hedges, their location and configuration within the landscape, and the density of barriers.

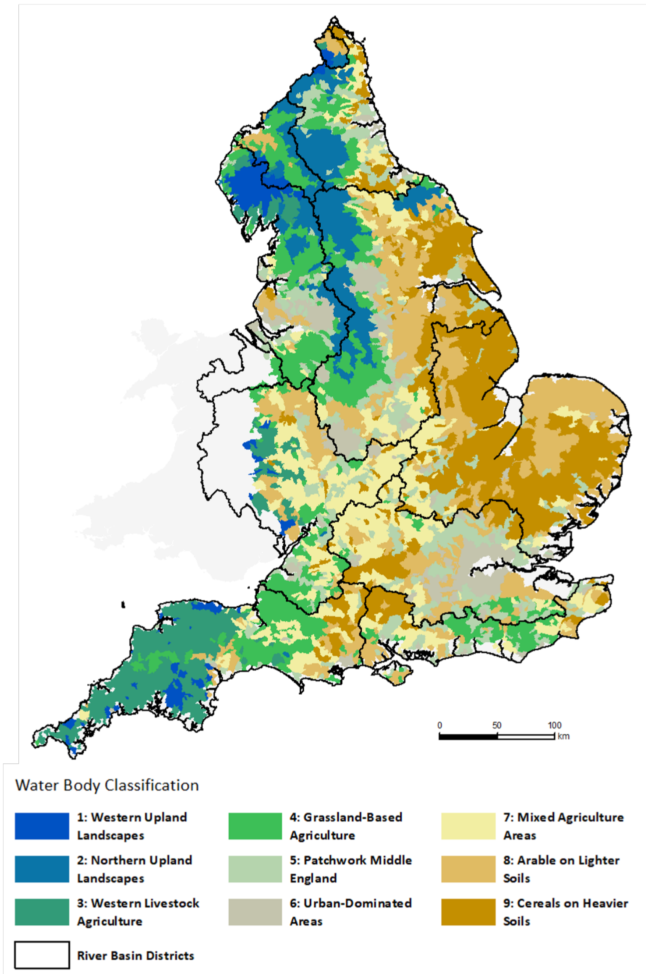
Evidence from 5 studies suggests that hedgerows and vegetative barriers can affect the following environmental properties/processes:

Positive effects	Risks
↓ Run-off generation ↑ Flow pathway interception ↑ Infiltration ↑ Evapotranspiration ↑ Flow/flood storage ↑ Organic matter/carbon storage ↑ Sediment retention/storage ↑ Nitrogen retention/removal	↑ Sediment accumulation within coconut-fibre barriers can increase the risk of run-off bypassing/overtopping barriers ↑ Potential of 'pollution swapping' from hedgerows capturing air pollution and transferring this into water pollution via the soil

Hedgerows and vegetative barriers in England

Hedgerows are commonly found across agricultural landscapes in England, however vegetative barriers are not typically used. The government's Environmental Improvement Plan sets out the target to create/restore 30,000 miles of hedgerows a year by 2037 and 45,000 miles of hedgerows a year by 2050. This aims to return hedgerow lengths in England to 10% above the 1984 peak. Environmental Land Management (ELM) schemes such as [Countryside Stewardship](https://www.gov.uk/government/collections/countryside-stewardship-get-paid-for-environmental-land-management) will incentivise farmers to deliver hedgerow planting and restoration.

Catchment Types



Findings across English catchments

Evidence on the effects of hedgerows and vegetative barriers was derived from Type 4, 7, and 8 catchments. The effects recorded were all positive, however no evidence on physico-chemical and biological water quality, and biodiversity and habitat. There may be potential benefits and trade-offs identified in evidence beyond that reviewed here.

Catchment considerations

Benefits are more likely to be gained from hedgerows and vegetative barriers in:

- Areas with high risk of soil erosion
- Fields with steep slopes
- Agricultural landscapes with fragmented habitats where hedgerows can act as wildlife corridors

Trade-offs are more likely to occur in:

- Areas with very high rates of pesticide application where drift of pesticides may negatively impact hedgerow species and potentially lead to ‘pollution swapping’

Monitoring and evaluation

The most effective approach for monitoring the effects of hedgerows and vegetative barriers is a Before-After Control-Impact (BACI) study which compares changes to baseline and control data, allowing robust conclusions to be drawn. Monitoring of hydrological processes (e.g. infiltration), water quality (e.g. suspended sediment concentrations in run-off) over time can provide evidence to evaluate environmental improvements and trade-offs.

Evidence gaps

The review highlighted the following gaps in our knowledge on the effects of hedgerows and vegetative barriers:

- Understanding of the potential for contaminant mobilisation from hedgerows/barriers under different rainfall conditions
- Understanding of if and when hedge margins act as sinks/sources of contaminants

- Effectiveness of hedges/barriers at attenuating run-off under more intense or prolonged rainfall
- Understanding of hedgerow impacts in different catchment contexts and topographic settings
- Understanding of the potential for hedges to enable ‘pollution swapping’ by capturing atmospheric pollutants and transferring them to water via run-off or groundwater flow emerging from hedgerow soils

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Multiple benefits of Nature-based Solutions (NbS)

The (re)introduction of woody material into watercourses includes both engineered approaches (e.g. logs/trees that are fixed to riverbanks/beds), and passive strategies (e.g. letting trees fall into streams). Instream wood can modify habitat and enhance river ecosystem processes. The potential effects of instream wood can vary depending on factors such as the size, density, and configuration of woody material.

Evidence from 15 studies suggests that instream wood can affect the following environmental properties/processes:

Positive effects

- ↓ Flow conveyance
- ↑ Run-off and flow attenuation
- ↑ Flow/flood storage
- ↑ Infiltration
- ↑ Nitrogen retention/removal (in chalk streams)
- ↑ Sediment retention/storage
- ↑ Aquatic plant communities
- ↑ Physical habitat and flow diversity
- ↑ River invertebrate diversity and abundance
- ↑ Microbial productivity and ecosystem respiration
- ↑ Fish abundance and diversity
- ↑ Groundwater recharge

Risks

- ↑ Presence of wood can increase fluxes of CO_2 (in streams with limestone beds)
- ↑ Potential displacement of woody leaky barriers due to bank erosion
- ↑ Potential remobilisation of pollutants in riverbed sediment through installation of instream wood
- ↑ Potential localised increases in streambed temperature variability (in lowland streams)

Image credit: (above) Environment Agency; (below) Siôn Regan

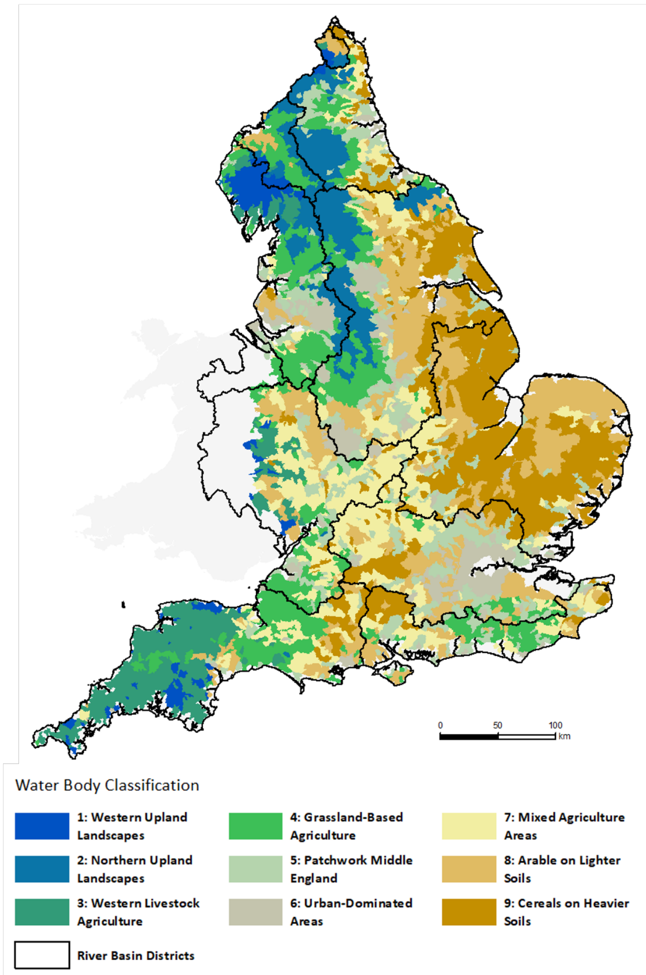
Instream wood in England

Instream wood is recognised as an important component of stream systems, with (re)introduction of wood commonly being used as a river restoration measure and increasingly for Natural Flood Management (NFM) purposes. Re(introducing) instream wood is part of the wider idea of ‘working with natural processes’ to manage river systems more sustainably. Defra and the Environment Agency’s £25 million [NFM programme]() will deliver 40 projects by 2027, many of which include the installation of instream wood to help reduce local flood risk and provide multiple benefits to the environment, nature, and society.

Findings across English catchments

Evidence on the effects of instream wood was derived from catchments in Type 2, 4, 6, 7, 8, and 9. The effects were mostly positive, however mixed effects on flood management were reported in Type 8 catchments. Instream wood was reported to have no effect on several aspects of water quality in Type 2, 4, 7, and 9 catchments.

Catchment Types



Catchment considerations

Benefits are more likely to be gained from instream wood in:

- Areas where land-use changes have removed natural sources of instream wood (e.g. agricultural catchments where instream habitats typically lack physical complexity)

Trade-offs are more likely to occur in:

- High energy watercourses where there is greater risk of leaky barrier displacement if significant bank erosion occurs
- Watercourses with culverts or screens downstream that could become blocked by dislodged instream wood (e.g. highly urbanised areas)

Monitoring and evaluation

The most effective approach for monitoring the effects of instream wood is a Before-After Control-Impact (BACI) study which compares changes to baseline and control data, allowing robust conclusions to be drawn. Monitoring of hydrological processes (e.g. infiltration and groundwater recharge), water quality (e.g. nutrient concentrations), and biological communities (e.g. river invertebrate diversity/abundance) over time can provide evidence to evaluate environmental improvements and trade-offs.

Evidence gaps

The review highlighted the following gaps in our knowledge on the effects of instream wood:

- Interdisciplinary understanding of hydraulic/geomorphic controls on habitat around large wood
- The combined effects of distributed woody leaky barriers with other NbS
- Longer-term assessments of wood reintroductions to determine the persistence of trajectories of change
- The influence of different types of wood jams, (e.g. naturally occurring wood), on fine sediment dynamics/transport in lowlands across varying discharges

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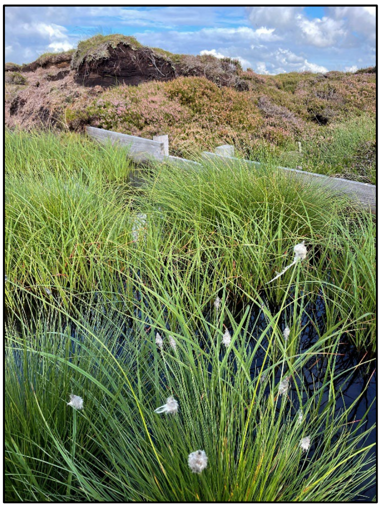
Multiple benefits of Nature-based Solutions (NbS)

Peatland restoration includes activities such as revegetation and blocking ditches (gullies) to aid rewetting of peatland habitats (e.g. blanket bog) and restore their ecosystem functions. These actions can help to restore the natural hydrological functioning of catchments through encouraging processes such as infiltration which can in turn help to slow the flow of water from headwaters. Restoration activities may also help improve water quality by preventing the organic peat soils from being eroded into watercourses. This also helps to lock up carbon and prevent the release of greenhouse gases into the atmosphere.

Evidence from 7 studies suggests that peatland restoration can affect the following environmental properties and processes:

Positive effects	Risks
↑ Flow attenuation ↑ Lag time ↑ Potential flood storage ↑ Raised water tables ↑ Groundwater recharge and drought resilience ↑ Organic matter/carbon storage ↑ Erosion protection ↓ Reduced rapid sub-surface flow pathways ↑ Lateral hydrological connectivity ↑ Plant communities	↑ Potential risks from increased run-off generation if not managed appropriately



Peatland restoration in England

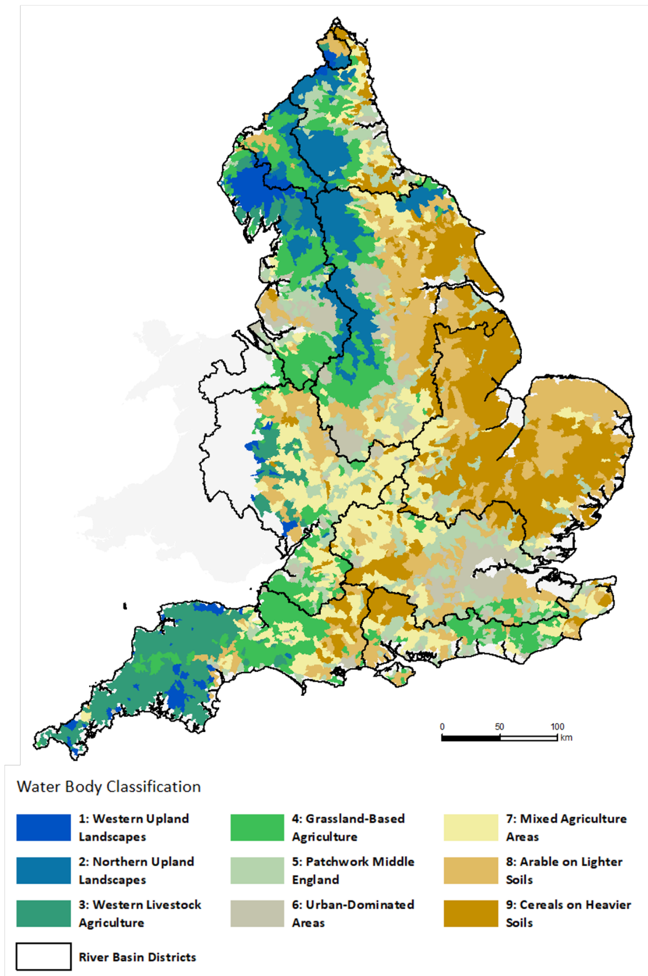
Peatland makes up a significant proportion of land area in England (approximately 10% of the UK). Partnership work has helped to restore some of our most degraded areas of upland peat. For example, the 'Moors for the Future' partnership has restored over 35km^2

of degraded peat across the Peak District and South Pennine moors. Drivers enabling peatland restoration include the UK's net zero targets given that degraded peatland acts as a significant source of carbon. The Environmental Land Management (ELM) schemes e.g. Countryside Stewardship incentivise actions such as moorland re-wetting, and will enable further restoration action to continue. Peatland restoration is also increasingly being used for Natural Flood Management through helping to 'slow the flow'.

Findings across English catchments

Evidence on the effects of peatland restoration was largely derived from catchments in Type 2, with the exception of one study in Type 3. This meant that all of the studies examined were focused on upland peat areas. The effects were mostly positive, however mixed effects on nutrient and sediment management, and low flows were reported in Type 2 and 3 catchments, respectively. The effectiveness of interventions was influenced by factors including the spatial extent of the restoration, and the length of time since restoration measures were implemented.

Catchment Types



Catchment considerations

Benefits are more likely to be gained from peatland restoration in:

- Catchments with highly degraded peatland that has a limited ability to store water
- Catchments where sources of drinking water are impacted by high levels of dissolved organic matter and associated issues (e.g. water colour)

Trade-offs are more likely to occur in:

- Peatland areas where water tables/levels are harder to maintain and manage following restoration activities

Monitoring and evaluation

The most effective approach for monitoring the effects of peatland restoration is a Before-After Control-Impact (BACI) study which compares changes to baseline and control data, allowing robust conclusions to be drawn. Monitoring of changes to peatland hydrology (e.g. infiltration, run-off, water table depth), water quality (e.g. concentrations of dissolved and particulate organic carbon), and biological communities (e.g. plant cover and species richness) over time can provide evidence to evaluate environmental improvements and trade-offs.

Evidence gaps

The review highlighted the following gaps in our knowledge on the effects of peatland restoration:

- The multiple benefits and trade-offs surrounding peatland restoration in lowland catchments
- More data to support holistic cost-benefit analysis of restoration activities in peatlands with varying degrees of degradation (particularly lightly degraded peatland sites)
- The effect of peatland landscape management on delivery of benefits following restoration
- Long-term trajectories of peatland subsurface hydrological and biogeochemical functioning following restoration
- Better spatial coverage of data/evidence from across different areas of peatland in England

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Multiple benefits of Nature-based Solutions (NbS)

The addition of substrate involves the (re)introduction of sediment into watercourses to modify instream habitats, raise the riverbed or replace lost sediment. This can range from addition of fine material (e.g. sand) to coarse gravels, or large boulders, or arrangements of rocky material into flow deflectors. Instream substrate addition can modify local flow patterns and thereby enhance river ecosystem processes and habitat diversity. The potential effects of instream substrate addition can vary depending on factors such as the river type, stream power, and flow regime.

Evidence from 15 studies suggests that instream substrate addition can affect the following environmental properties/processes:

Positive effects

- ↑ Aquatic plant growth
- ↑ Physical habitat and flow diversity
- ↑ River invertebrate diversity and abundance (e.g. species that prefer faster flowing habitat)
- ↑ Local abundance, density, and biomass of fish (particularly relatively mobile species e.g. brown trout)

Risks

- ↑ Potential initial decrease in river invertebrate diversity immediately following substrate addition
- ↑ Effects on fish abundance are not consistent for all species

Instream substrate addition in England

Instream substrate is an important component in naturally functioning river ecosystems. For example, clean (silt-free) gravels are needed for salmonid fish to spawn in. Human modifications such as dams and weirs have meant that some rivers no longer have a good supply of instream substrate, which has led to loss of suitable habitat. The addition of substrate is now commonly used as a river restoration measure to create habitat and shift rivers back towards a more natural state of functioning. Recent examples include an Environment Agency funded project with Trent Rivers Trust to reintroduce 220 tonnes of gravel to a 0.5km stretch of the River Mease.

Findings across English catchments

Evidence on the effects of instream substrate addition was derived from Type 5, 8 and 9 catchments. The effects were mostly positive; however instream substrate addition was reported to have no effect on biodiversity and habitat in Type 5 catchments.

Catchment considerations

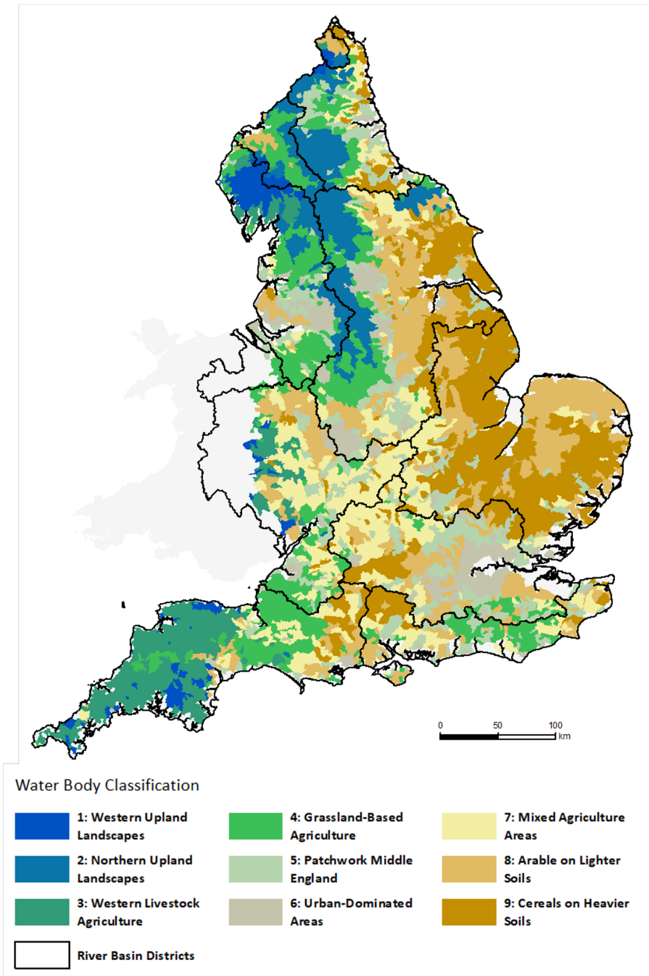
Benefits are more likely to be gained from instream substrate addition in:

- River reaches with a high level of connectivity to high quality habitat that can act as a source for colonisation of biota
- Streams with artificial modifications that have degraded the natural supply on instream substrate (e.g. incised channels)

Specifically for sand addition:

- Low gradient streams
- Stream stretches with patches of instream woody material to limit dispersion of sand
- Streams that have sufficient input of coarse organic matter from surrounding land

Catchment Types



Trade-offs are more likely to occur in:

- Watercourses with culverts or screens downstream that could become blocked/damaged by larger substrate (e.g. boulders) mobilised in very high flows

Monitoring and evaluation

The most effective approach for monitoring the effects of instream substrate addition is a Before-After Control-Impact (BACI) study which compares changes to baseline and control data (e.g. from a reference site), allowing robust conclusions to be drawn. Monitoring of river morphology and physical conditions (e.g. flow velocity), water quality (e.g. suspended sediment concentration), and biological communities (e.g. fish diversity and abundance) over time can provide evidence to evaluate environmental improvements and trade-offs.

Evidence gaps

The review highlighted the following gaps in our knowledge on the effects of instream substrate addition:

- Long-term monitoring of the effectiveness and longevity of instream additions and delivery of benefits

- Larger scale monitoring to gain evidence of the wider benefits of sand addition beyond instream habitat e.g. riparian zone reconnection, and stream valley rewetting
- Evidence of geomorphological and ecological effects of substrate addition across a broad range of channel gradients and substrate sizes.

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Multiple benefits of Nature-based Solutions (NbS)

Channel restoration includes activities such as the removal of dams, weirs, and culverts, the creation of side-channels and backwaters, or the re-establishment of former channel alignments. Channel restoration aims to restore the natural functions of rivers that have been lost through past management practices such as channel straightened or widening. Channel restoration can improve longitudinal connectivity and allow species to move more easily up/downstream. Restoration can also enhance instream processes such as erosion/deposition, which can result in changes to habitat availability and diversity.

Evidence from 15 studies suggests that channel restoration can affect the following environmental properties/processes:

Positive effects	Risks
↑ Organic matter/carbon storage ↑ Nutrient and heavy metal retention/removal ↑ Potential increase in emergent and submerged macrophyte (aquatic plant) cover and richness (from instream habitat modification) ↑ Colonisation of riparian plants ↑ Physical habitat and flow diversity ↑ Potential increase in macroinvertebrate and fish diversity/abundance ↑ Low flow refuge ↑ Longitudinal and lateral connectivity ↑ Changes to sediment regime	↑ Potential remobilisation of heavy metals accumulated in bed sediment in high flows ↑ Potential decrease in macrophyte cover (from re-meandering) ↑ Growth of benthic algae (from culvert removal) ↑ Potential colonisation of invasive non-native species ↓ Water temperature (from dam removal)

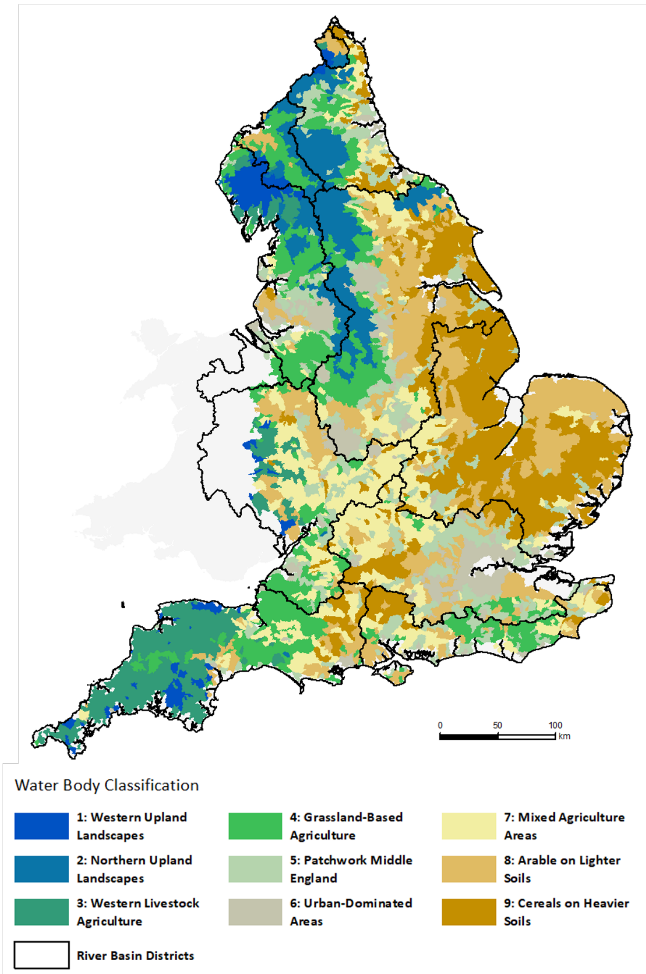
Channel restoration in England

An important driver that will enable channel restoration are the Environmental Land Management (ELM) schemes. For example, Countryside Stewardship option SW12 provides payments for restoration activity that allows watercourses to meander across floodplains. Additionally, the Landscape Recovery scheme will help to deliver more ambitious, large-scale restoration projects over the longer-term, including actions such as the removal of weirs and other obstructions to improve longitudinal (downstream-upstream) connectivity of habitats. Examples of channel restoration projects include re-meandering on the River Glaven in North Norfolk. For more information about river restoration approaches and schemes please contact the River Restoration Centre.

Findings across English catchments

Evidence on the effects of channel restoration was derived from catchment types 4, 5, 6, 7, 8 and 9. The effects were mostly positive, however mixed effects on biodiversity and habitat were reported in Type 4 and 8 catchments. Observations from catchments in Type 5 and 8 suggested that channel restoration had no effect on some aspects of water quality. It should be acknowledged that the effectiveness and success of interventions was influenced by factors including the scale of restoration and timescale over which it was monitored/evaluated.

Catchment Types



Catchment considerations

Benefits are more likely to be gained from channel restoration in:

- Catchments with migratory fish that would benefit from improved passage and access to upstream habitats and spawning grounds
- Catchments with fragmented habitats where populations are more susceptible to disturbances
- Catchments with artificially altered flow regimes

Trade-offs are more likely to occur in:

- Areas with high pressure from invasive non-native species (e.g. Himalayan balsam, signal crayfish) where restoration activities could increase the risk of spread

Monitoring and evaluation

The most effective approach for monitoring the effects of channel restoration is a Before-After Control-Impact (BACI) study which compares changes to baseline and control data, allowing robust conclusions to be drawn. Monitoring of geomorphological changes to channels (e.g. sediment movement and habit diversity), water quality (e.g. nutrient concentrations), and biological communities (e.g. fish diversity/abundance) over time can provide evidence to evaluate environmental improvements and trade-offs.

Evidence gaps

The review highlighted the following gaps in our knowledge on the effects of channel restoration:

- Long-term monitoring (>10 years) to better understand dynamics and trajectories of succession and species compositions following channel restoration activities
- Longevity/sustainability of channel restoration activities and their resilience to hydrological extremes
- Better characterisation of ecosystem functions in near-natural streams at different spatial and temporal scales (to help assess the success of restoration schemes)
- Understanding of benefits for flood risk management

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Multiple benefits of Nature-based Solutions (NbS)

Floodplain reconnection includes activities such as the removal or lowering of embankments or levees, and the lifting of riverbeds. Floodplain reconnection aims to enhance connectivity between the main river channel and its surrounding floodplain to encourage a more natural hydrological functioning of the system. This can help to create new and more diverse habitats. Floodplain reconnection can help improve water quality through the deposition of sediment and associated pollutants. Additional benefits include water storage and habitat refuge during periods of high flow.

Evidence from 7 studies suggests that floodplain reconnection can affect the following environmental properties/processes:

Positive effects	Risks
↑ Flood storage ↑ Flow attenuation ↑ Lag time ↑ Organic matter/carbon and sediment storage ↑ Nitrogen retention/removal ↑ Physical habitat diversity ↑ Macroinvertebrate diversity ↑ Fish abundance and diversity ↑ Low flow refuge ↑ Groundwater recharge ↑ Lateral connectivity	↑ Potential increase in delivery of nutrients to floodplain soils

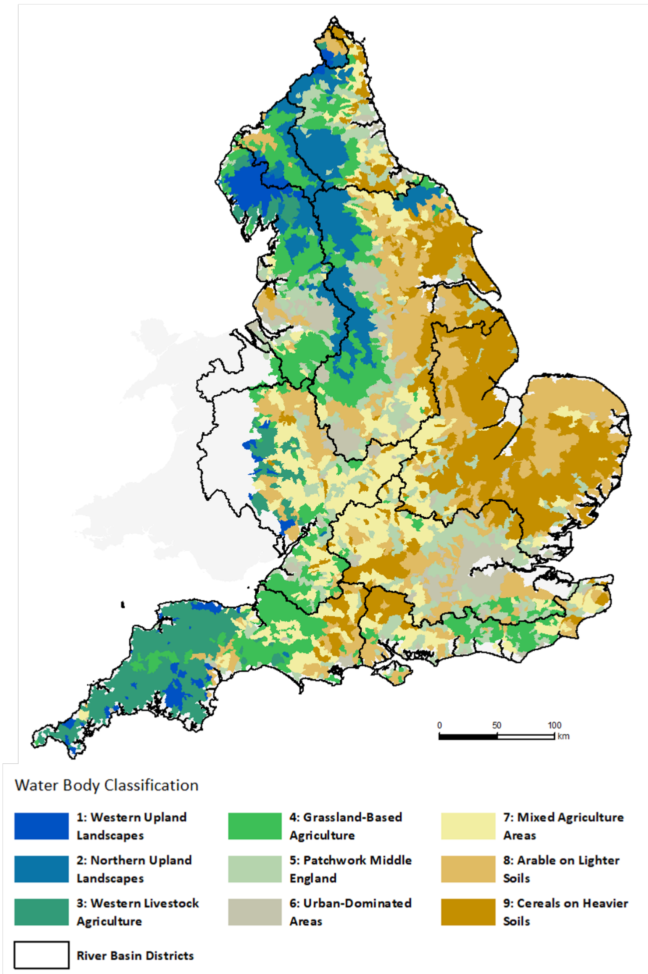
Floodplain reconnection in England

Drivers to enable floodplain reconnection include the Environmental Land Management (ELM) schemes. For example, the Landscape Recovery scheme is helping to deliver large-scale and long-term projects such as in the Evenlode catchment where over 1000 hectares of floodplain meadow will be restored. Additionally, government funding for Natural Flood Management schemes is helping to deliver enhanced water storage on floodplains. For more examples of floodplain reconnection schemes in England, see this Environment Agency report or contact the River Restoration Centre.

Findings across English catchments

Evidence on the effects of floodplain reconnection was derived from catchments in Types 1, 5, 7, 8, and 9. The observed effects were all positive, though the degree of success or effectiveness in the delivery of benefits varied. The effectiveness and success of interventions was influenced by factors such as the hydrological conditions experienced before and after floodplain reconnection.

Catchment Types



Catchment considerations

Benefits are more likely to be gained from floodplain reconnection in:

- Catchments with gentle slopes (low to moderate gradient streams) that typically have wider floodplains and slower flow velocities which can help to facilitate sediment deposition and habitat creation
- Catchments with evidence of historical floodplain disconnection

Trade-offs are more likely to occur in:

- Landscapes with a high density of development (e.g. housing or infrastructure) on the floodplain
- Catchments with contaminated soils (e.g. from industry) in the floodplain where increasing hydrological connectivity could risk mobilisation of pollutants

Monitoring and evaluation

The most effective approach for monitoring the effects of floodplain reconnection is a Before-After Control-Impact (BACI) study which compares changes to baseline and control data, allowing robust conclusions to be drawn. Monitoring of floodplain hydrology (e.g. frequency/duration of overbank flow into the floodplain), habitat and water quality (e.g. suspended sediment concentration), and biological communities (e.g. floodplain plant communities) over time can provide evidence to evaluate environmental improvements and trade-offs.

Evidence gaps

The review highlighted the following gaps in our knowledge on the effects of floodplain reconnection:

- Understanding of changes in water quality functions of floodplains and how these vary spatially following floodplain reconnection
- Understanding of long-term effects and quantification of changes to the delivery of wider ecosystem services
- Understanding of how floodplain reconnections respond to extreme flows (floods and droughts)

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Multiple benefits of Nature-based Solutions (NbS)

Sustainable Drainage Systems (SuDS) are features that aim to manage rainfall run-off by emulating natural drainage regimes. They are also referred to as a form of low impact development (LID). SuDS are primarily used to treat water in urban and suburban areas where there are higher risks of surface water flooding. SuDS are diverse in their design, including bioretention systems (swales, rain gardens), permeable pavements, and green roofs. SuDS are also used to treat pollution in run-off by harnessing physical processes (e.g. settling out of particles) and biogeochemical processes (e.g. denitrification) to remove pollutants and thereby improve water quality.

Evidence from 9 studies suggests that SuDS can affect the following environmental properties and processes:

Positive effects	Risks
↑ Flood storage ↑ Flow attenuation and lag time ↑ Run-off attenuation ↓ Run-off generation ↑ Interception, infiltration, and evapotranspiration ↑ Potential retention/removal of nutrients (N and P) ↑ Retention/removal of heavy metals ↑ Sediment storage ↑ Retention/removal of faecal bacteria ↑ Dissolved oxygen and pH	↑ Potential release of pollutants from green roofs and permeable pavements during intense rainfall events ↑ High level of variability in the removal efficiency of different pollutants and forms of nutrients

Image credit: (left) Environment Agency; (right) SuDS swale, Darwin Green © Hugh Venables CC-BY-SA/2.0

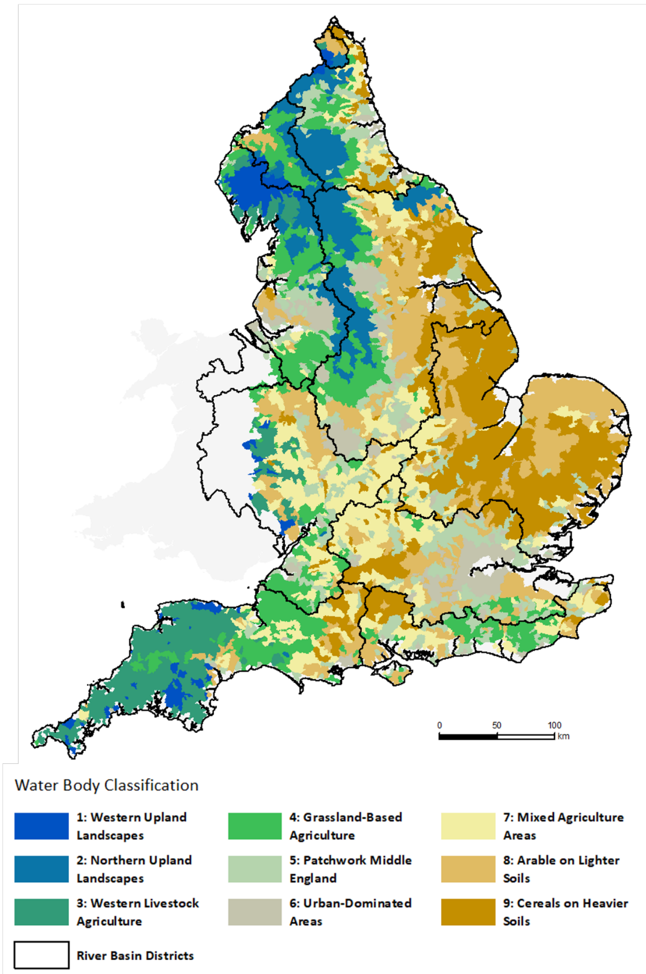
Sustainable Drainage Systems in England

SuDS are now commonly integrated into new developments in England to help offset the environmental impacts of changes in land-use. Green roofs are typically used in densely developed areas, helping to use space efficiently where land is costly. The uptake of SuDS is likely to increase with drivers such as Nutrient Neutrality. The Flood and Water Management Act (2010) contains standards required for the design, construction, maintenance and operation of SuDS in England. Examples of successful implementation of SuDS include swales and infiltration basins at Victoria Park Health Centre in Leicester. Case studies for different types of SuDS across the country can be found on the SusDrain website.

Findings across English catchments

Evidence on the effects of SuDS was derived from catchments in Type 6. The effects were mostly positive, however some evidence on the effectiveness of SuDS was contradictory for aspects of water quality. The variability in the effectiveness of SuDS is influenced by factors including hydrological conditions (e.g. run-off intensity), pollutant load, and design/configuration.

Catchment Types



Catchment considerations

Benefits are more likely to be gained from SuDS in:

- Areas with high proportions of impermeable surfaces and high risk of run-off
- Areas with combined sewer systems where SuDS can reduce volumes of rain/run-off entering sewers to help reduce the risk of overflows
- Areas that receive high and frequent rainfall

Trade-offs are more likely to occur in:

- Areas with highly variable/complex soil hydraulic properties that may lead to inconsistent infiltration rates (in bioretention systems or permeable pavement)
- Areas with high levels of contamination (e.g. industrial areas) where SuDS may fail to effectively remove dissolved pollutants
- Areas where SuDS cannot easily be maintained

Monitoring and evaluation

The most effective approach for monitoring the effects of SuDS is a Before-After Control-Impact (BACI) study which compares changes to baseline and control data, allowing robust conclusions to be drawn. Monitoring requirements will vary depending on the type of SuDS being used. Measuring infiltration rates and changes to run-off volumes will help to provide evidence of flood risk and low flow benefits. Water quality benefits can be tested by measuring pollutant concentrations in the run-off entering and leaving SuDS.

Evidence gaps

The review highlighted the following gaps in our knowledge on the effects of SuDS:

- The efficiency of SuDS to treat emerging pollutants e.g. pharmaceuticals, microplastics
- Evidence on the benefits of different SuDS designs for habitat creation and biodiversity
- Data for the long-term evaluation of SuDS over different spatial/temporal scales and climatic conditions
- Effects of combined SuDS performance at catchment/regional scales
- Potential use of SuDS (bioretention systems) to treat road salt in run-off from roads and urban areas
- Effects of vegetation type, location and density on pollutant removal efficiency in bioretention systems
- Understanding risks of long-term migration of metals within permeable pavement structures

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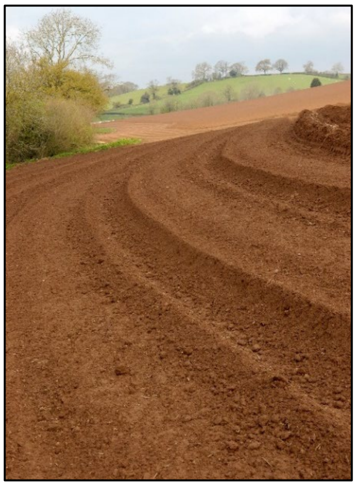
Multiple benefits of Nature-based Solutions (NbS)

Sustainable soil management encompasses various techniques through which the health and functioning of agricultural soils can be improved. For example, planting cover crops reduces the amount of time soil in fields is left bare and vulnerable to erosion. Techniques such as [minimum (or no) tillage farming] reduce soil disturbance and help to limit damage to soil structure. Tramline disruption is used to manage run-off by tilling compacted tramline soil with a tine. Ley farming is the practice of growing grass, legumes, or a mixture of herb species in rotation with arable crops. Overtime, these practices can enhance hydrological processes such as infiltration through reducing soil compaction, improving soil structure and boosting organic matter content. Sustainable soil management techniques help to improve resilience against extreme conditions such as drought. The potential effects of these techniques can vary depending on factors such as the soil type and wetness, underlying geology, and the land-use and management history.

Evidence from 12 studies suggests that sustainable soil management can affect the following environmental properties/processes:

Positive effects	Risks
↑ Infiltration ↑ Drought resilience ↑ Organic matter/carbon storage ↑ Phosphorus retention ↑ Nitrogen retention (from cover crops) ↑ Flow pathway interception ↓ Run-off generation ↓ Erosion	↑ Potential for tramline disruption to cause some soil erosion and loss of phosphorus during dry conditions where soil is very loose ↓ Potential reduction in infiltration on some soil types e.g. silt loam (from no till farming) ↑ Potential for 'pollution swapping' from particulate to soluble forms of phosphorus

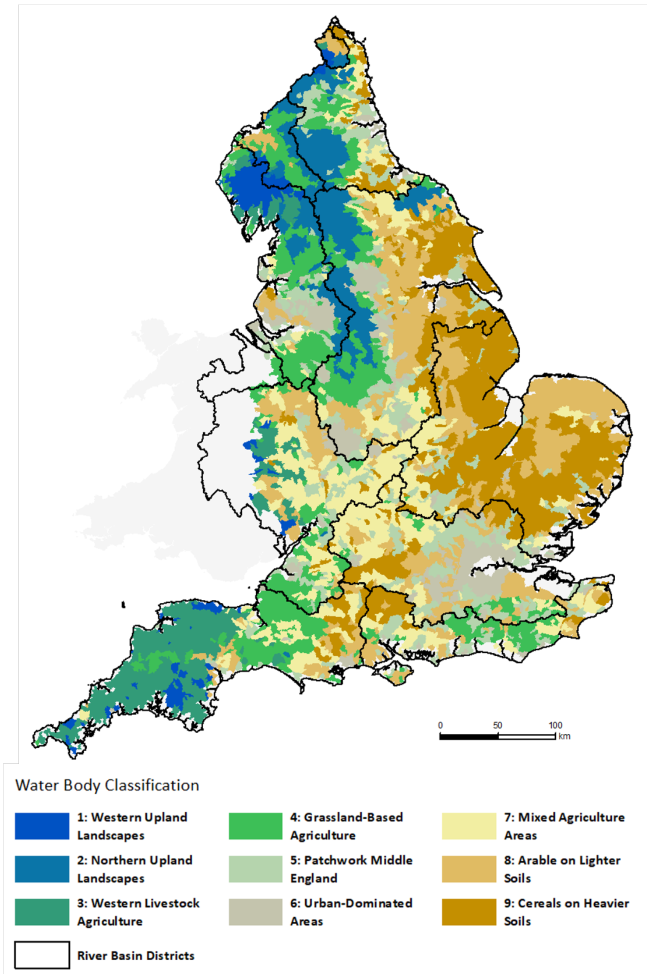


Sustainable soil management in England

Agricultural land has typically been managed to maximise productivity and crop yields; however this intensive approach has led to the degradation of soil health and knock-on impacts such as the pollution of watercourses from soil erosion. These environmental concerns have led to the uptake of sustainable approaches in farming that are regenerative and aim to improve soil health, and provide wider benefits such as climate regulation. In England, commonly applied measures in arable systems include the use of cover crops to limit losses of soil and nutrients during the wetter months. Important drivers for the future uptake of these measures include national net zero targets, but also the Environmental Land Management (ELM) schemes. The Sustainable Farming Incentive (SFI) provides payment for actions such as planting multi-species winter cover, establishing herbal leys, and using soil management plans. Please see Defra's statutory guidance on the 'farming rules for water' for further information on the management of soil and livestock, and the storage and application of fertilisers.

Findings across English catchments
Evidence on the effects of sustainable soil management techniques was derived from catchments in Type 4, 5, 7, 8 and 9. The effects were mostly positive, however one piece of evidence suggested potential negative impacts on flood and low flow management in Type 9 catchments. Mixed effects on nutrient and sediment management were reported in Type 8 catchments. The effectiveness of this category of NbS may be influenced by factors such as previous land management, the hydrological conditions experienced, and the time since they were implemented.

Catchment Types



Catchment considerations
Benefits are more likely to be gained from sustainable soil management in:

- Areas with high soil erosion risk or compaction-related issues
- Areas with high nitrate concentrations that can be improved through the use of cover crops

Trade-offs are more likely to occur in:

- Catchments with diverse or fragmented land-uses where soil management measures cannot be applied at a suitable scale
- Areas with soil types that are not well suited to the management technique/practice

Monitoring and evaluation
The most effective approach for monitoring the effects of sustainable soil management is a Before-After Control-Impact (BACI) study which compares changes to baseline and control data, allowing robust conclusions to be drawn. Monitoring of hydrological processes (e.g. infiltration, run-off generation), water quality (e.g. nutrient and pesticide concentrations in

run-off), and soil properties (e.g. organic matter content) over time can provide evidence to evaluate environmental improvements and trade-offs.

Evidence gaps

The review highlighted the following gaps in our knowledge on sustainable soil management:

- Understanding of the effectiveness of management measures under different soil types and slopes
- Improved understanding of the effects of minimum/no till on soil processes/properties and ecosystem services
- Potential for sustainable soil management practices to mitigate subsoil compaction
- Understanding the impact/effectiveness of combined soil and land management measures at a catchment scale

For more information on sustainable soil management please see the CaBA manual on 'Soils and Natural Flood Management', and the user guide on agricultural mitigation methods (Newell Price, 2011).

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Multiple benefits of Nature-based Solutions (NbS)

Assisted natural regeneration are interventions in the landscape that facilitate the natural ecological succession of land. This can involve large scale land-use change (e.g. rewilding) or allowing the natural recovery of patches of land within a landscape through measures such as fencing to prevent grazing in specific areas. Assisted natural regeneration is largely a passive NbS, however it can also involve active planting of trees or other vegetation. These interventions can enhance hydrological processes such as interception and evapotranspiration. The potential effects of assisted natural regeneration vary depending on factors such as the surrounding landscape/catchment, the previous land-use and management practices.

Evidence from 5 studies suggests that assisted natural regeneration can affect the following environmental properties/processes:

Positive effects	Risks
↑ Flood storage ↑ Flow attenuation and lag time ↑ Run-off attenuation ↑ Interception and infiltration ↑ Evapotranspiration ↓ Run-off generation	↑ High natural variability in soil properties could strongly influence effectiveness of assisted natural regeneration


Image credit: (left) Environment Agency; (right) © PeterEastern / Longhorn cattle free-ranging at Knepp Wildland / [CC BY-SA 4.0]

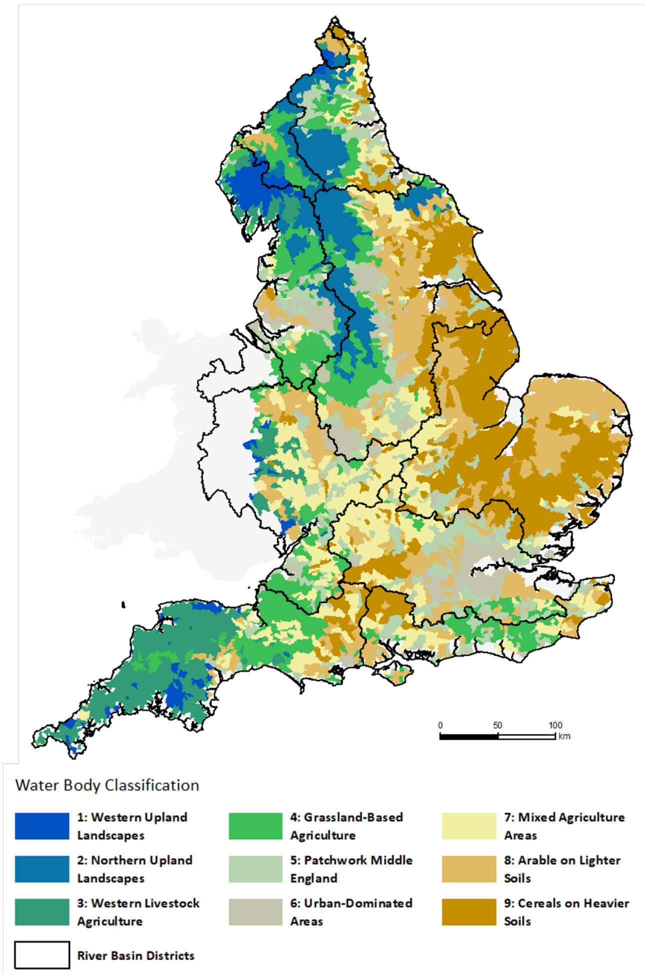
Assisted natural regeneration in England

Natural regeneration approaches have been gaining traction in England in recent years, however there is a lack of evidence of its benefits in the long-term. Assisted natural regeneration through measures such as fencing are more commonly applied, particularly in areas dominated by livestock farming. Drivers for the uptake of assisted natural regeneration include net zero targets, but also the Environmental Land Management (ELM) schemes. The Sustainable Farming Incentive (SFI) provides payment for actions including taking improved grassland field corners out of management. Countryside Stewardship Capital Grants can fund the construction of measures such as fencing. A successful example of assisted natural regeneration in England is the Knepp Castle Estate in Sussex where a former intensive dairy farm started undergoing rewilding in 2001. Natural succession has created a diverse range of habitats (e.g. water meadows, shrubland), and created refuge for species of important conservation value such as nightingales, and purple emperor butterflies.

Findings across English catchments

Evidence on the effects of assisted natural regeneration was derived from catchment types 1, 2 and 3, with observed and hypothesised effects all being positive. The success of assisted natural regeneration may be influenced by factors such as the availability of species to colonise from the surrounding landscape or soil seedbank.

Catchment Types



Catchment considerations

Benefits are more likely to be gained from assisted natural regeneration in:

- Areas where high livestock densities are recognised as a significant pressure on catchment soil health, water quality and ecosystems
- Catchments with artificially altered hydrology (e.g. from intensive agriculture) where natural processes can be restored

Trade-offs are more likely to occur in:

- Areas where pressure from non-native invasive species is high and assisted natural regeneration may increase risk of establishment
- Highly urbanised or densely populated areas

Monitoring and evaluation

The most effective approach for monitoring the effects of assisted natural regeneration is a Before-After Control-Impact (BACI) study which compares changes to baseline and control data, allowing robust conclusions to be drawn. Monitoring of hydrological processes (e.g. infiltration), water quality (e.g. in-stream nutrient concentrations), and biological communities (e.g. abundance/diversity of plants) over time can provide evidence to evaluate environmental improvements and trade-offs.

Evidence gaps

The review highlighted the following gaps in our knowledge on the effects of assisted natural regeneration:

- Understanding ecological trajectories following natural regeneration in different settings (including legacy effects from previous land-use)
- Better quantification of the hydrological and water quality effects on flood risk and low flow/drought mitigation at local and catchment scales
- Long-term effects of sheep removal combined with tree planting on the recovery of degraded soils under improved grassland land-use

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