Nature-based Solutions Water Resources Handbook

Report version 1, July 2025

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We operate at the place where environmental change has its greatest impact on people's lives. We reduce the risks to people and properties from flooding; make sure there is enough water for people and wildlife; protect and improve air, land and water quality and apply the environmental standards within which industry can operate.

Acting to reduce climate change and helping people and wildlife adapt to its consequences are at the heart of all that we do.

We cannot do this alone. We work closely with a wide range of partners including government, business, local authorities, other agencies, civil society groups and the communities we serve.

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Contents

List of Figures

List of Tables

Nature-based Solutions for Water Resources Handbook

Part 1

Main Chapters

1 Introduction

The Environment Agency has commissioned a handbook to outline how Nature-based Solutions (NBS) can be used for water resources benefits. The target audience of this handbook is managers and practitioners in the environmental and water management sectors, but it is intended also to be accessible to a wider audience of interested stakeholders.

At its heart, Nature-based Solutions for Water Resources (NBS4WR) is about improving the resilience of the water environment through the use of ecosystem services. The methods discussed in this handbook focus on three main elements:

- How NBS4WR can improve groundwater resources
- How NBS4WR can improve low flows in rivers
- How NBS4WR can improve resilience to drought in the land and water environments

Table 1-1 outlines the chapters of the handbook and broadly what these chapters cover. Part 1 of the handbook contains the four core chapters. Part 2 of the handbook contains 6 chapters included as standalone appendices, which deal with more specialised topics.

Table 1-1: Content of this report

Part 1 Chapter	Content
Section 1 - Introduction	Introduction to the concept of NBS4WR.
Section 2 – Suite of Nature-based Measures	This section provides a broad overview of the types of measures that could be implemented.
Section 3 – Other Workstreams Supported by NBS4WR	This section looks at how NBS4WR could be integrated within wider schemes and projects, and available funding.
Section 4 – Planning Nature-based Landscapes	This section sets out a holistic framework for designing landscapes with NBS.

Part 2 Chapter	Content
Section 5 – Appendix. Literature Review	This section provides a literature review of existing studies looking at the whole range of NBS4WR measures. Grey literature will be utilised including recently delivered Environment Agency modelling work.
Section 6 – Appendix. Conceptual Models for NBS Features	This section provides a series of case studies to understand what measures might work in different contexts. It concludes by drawing together broad lessons on where in the landscape NBS4WR is most effectively implemented.
Section 7 – Appendix. Mapping of NBS for Water Resource Benefits	This section reviews: • Mapping specific to water resources • Other types of mapping

Part 2 Chapter	Content
	• Available data that can be used where specific mapping products are not available
Section 8 – Appendix. Modelling to Quantify Water Resources Impacts of NBS Features	This section considers: • What modelling techniques are appropriate for modelling NBS4WR • A series of case studies • Broad findings on the potential benefits of widespread NBS4WR adoption
Section 9 – Appendix. Monitoring of NBS Features	A guide is presented outlining how to measure different parts of the water cycle and different styles of NBS4WR, including linkages to land use changes, surface water flow changes and groundwater modelling.
Section 10 – Appendix. Construction of NBS Features	This section provides a checklist of elements required to bring schemes to fruition, including consideration of permitting and CDM (Construction, Design, Management) requirements.

1.1 What are Nature-based Solutions?

Nature-based Solutions (NBS) can be defined as:

> “Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted and systemic interventions.” (Nature-based solutions - EU Commission)

NBS can play an important role in ‘limiting the impacts of climate change, while simultaneously improving biodiversity and providing a range of other social and economic benefits (Environment Agency, 2022).’

NBS foster more integrated and sustainable solutions and can play an important role in the protection, restoration, and management of natural and semi-natural ecosystems (Understanding the value and limits of nature-based solutions to climate change and other global challenges). The restoration of these ecosystems will help:

- Enhance biodiversity
- Build resilience to climate change
- Capture carbon
- Provide flood risk management benefits
- Regulate microclimate
- Improve resilience of the agricultural and fisheries industries
- Improve water quality
- Protect water resources

Once established they often provide cost-effective benefits, with minimal maintenance compared to traditional engineered measures.

The importance of NBS is recognised internationally with guidance on their implementation being provided by the IUCN (IUCN Global Standard for Nature-based Solutions), World Bank (Implementing Nature Based Flood Protection: Principles and Implementation Guidance – World Bank), United States Army Corps of Engineers (International Guidelines on Natural and Nature-Based Features for Flood Risk Management) and the Environment Agency. Adopting a nature-based solutions approach addresses not only the climate and biodiversity crises but also achieves some of the United Nation’s sustainable development goals (Transforming our world: the 2030 Agenda for Sustainable Development).

1.1.1 Nature-Based Solutions and scale of benefits

Different types of NBS operate on different spatial and temporal scales. Some NBS categories may have the potential for implementation across a range of different settings, whereas others may be more spatially constrained. Similarly, certain NBS measures may be more fast-acting than others. It is important to appreciate these differences when considering options for NBS implementation.

1.1.2 Soil and land management NBS

Table 1-2 describes the different sorts of soil and land management NBS which could be delivered and the types of water resources benefits which they have the potential to provide.

Table 1-2: Soil and land management NBS and their water resources benefits

NBS Name	NBS Description	Main outcomes for water resources

Soil and land management

Photo: [WWNP Evidence Directory]
	Includes a variety of different measures such as:
	• Soil aeration and subsoiling
	• Arable systems:
	  ○ Conservation tillage
	  ○ Early sowing winter crops and cover crops
	  ○ Crop rotation
		• Improved soil health and structure
		• Increased surface roughness
		• Capture runoff on the surface
		• Allow infiltration and recharge

Change in land use cover

Photo: [WWNP Evidence Directory]
	Includes a variety of different measures such as:
	• Grassland systems:
	  ○ Altering stocking density
	  ○ Changes to vegetation cover
	• Agricultural landscape features:
	  ○ Planting of hedgerows
	  ○ Inclusion of buffer strips
		• Reduced evaporation & transpiration
		• Reduced interception of rainfall
		• Reduced irrigation demands
		• Improved soil health structure
		• Increased surface roughness
		• Capture runoff on the surface
		• Allow infiltration and recharge

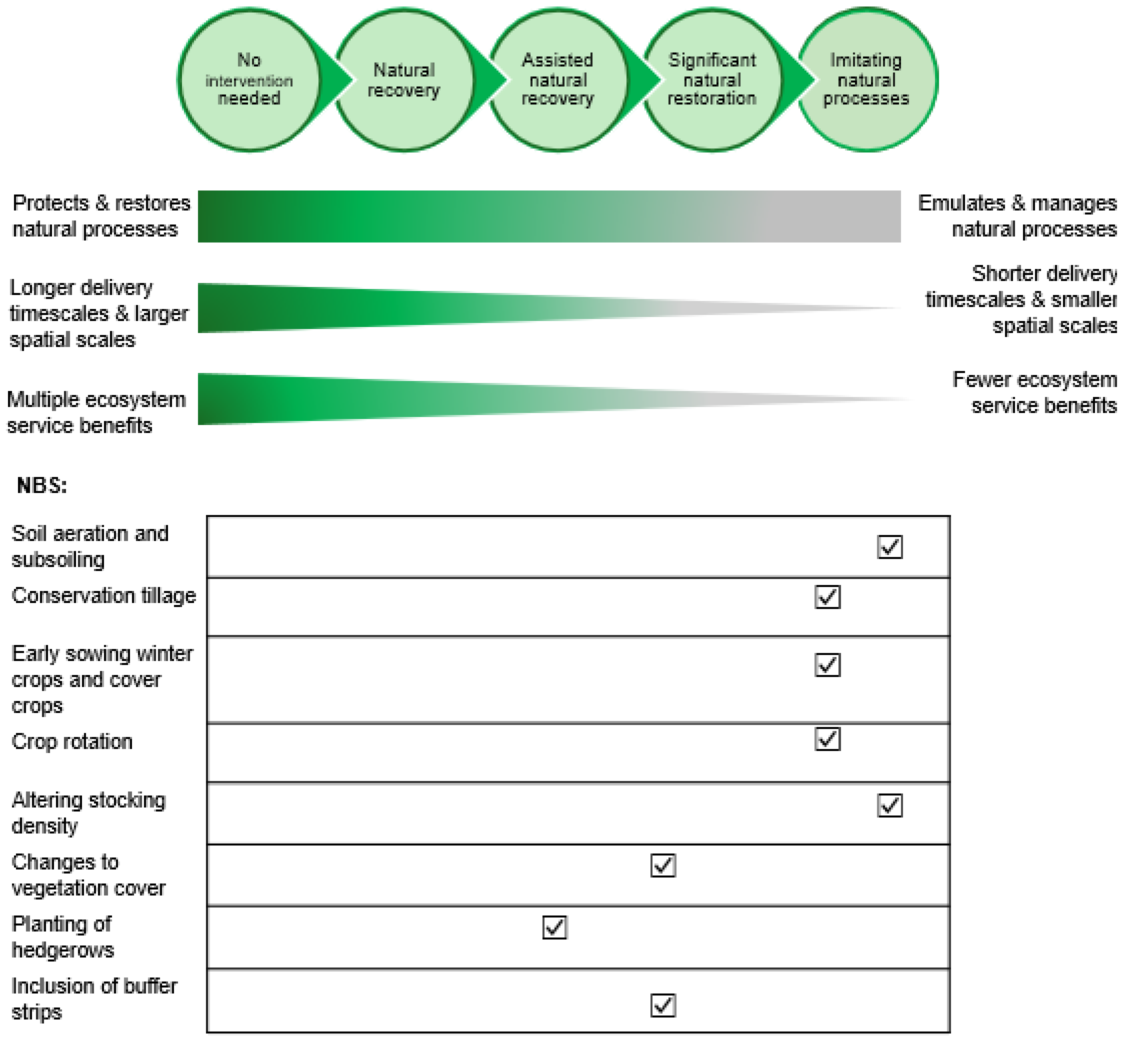
Soil and land management interventions can in theory be applied on most agricultural land, and as such there is the potential for them to be upscaled and delivered nationally, depending on willingness of farmers to change land management activities and their access to farming incentives.

These sorts of NBS are seeking to assist natural recovery and reverse the impacts of past farming practices through restoring or imitating natural processes.

These different types of intervention take different timescales to be effective. Whilst these sorts of measures are fast to implement, it will take time for many of them to become effective.

	Scale
Potential scale of deployment	These measures could potentially be deployed on any farmland in England, indicating a potentially extensive scale of deployment.
How quickly do they become effective?	0-5 years. Some of the measures will become effective faster than others. Restoring hedgerows and soil structure will take longer than, say, installing buffer strips or changing planting practices.
Scale of benefits achievable	These NBS have the potential to deliver a wide range of benefits alongside water resources.

Figure 1-1: Soil and land management NBS and scale of impact/delivery



1.1.3 River and floodplain NBS

Table 1-3 describes the different sorts of river and floodplain NBS which could be delivered and the types of water resources benefits which they have the potential to provide.

Table 1-3: River floodplain NBS and their water resources benefits

NBS Name	NBS Description	Main outcomes for water resources
Floodplain restoration  **Photo:** WWNP Evidence Directory	Floodplain restoration aims to restore the hydrological connection between rivers and floodplains so that floodwaters inundate the floodplains and store water during times of high flows. This can involve removing flood embankments and other barriers to floodplain connectivity.	• Increased surface roughness • Capture runoff on the surface • Allow infiltration and recharge • Raise the riverbed • Improve floodplain connectivity • Store water on floodplain
River restoration  **Photo:** WWNP Evidence Directory	River restoration restores hydraulic and sediment transport processes directly or indirectly by reinstating the physical form of a channel. This may help a river adjust towards a more natural form. River restoration can take many forms from assisted natural recovery to more engineered solutions (e.g. de-culverting).	• Increased surface roughness • Raise the riverbed • Improve floodplain connectivity
Wetland and reedbeds  **Photo: Suffolk Wildlife Trust**	Wetlands are areas of land where water is either permanently or seasonally present, supporting plant and animal life adapted to these conditions. Reedbeds, a specific type of wetland, are characterized by dense stands of common reed (*Phragmites australis*).	• Increased surface roughness • Capture runoff on the surface • Allow infiltration and recharge • Store water on floodplain

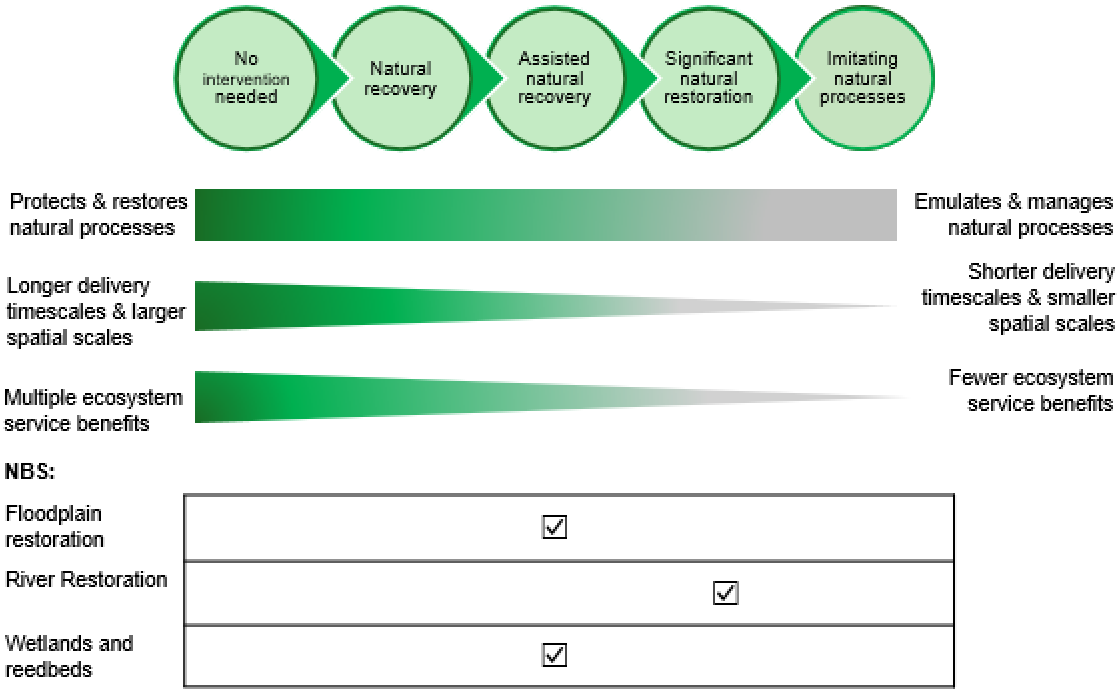
As can be seen in Figure 1-2, river, floodplain and wetland restoration seeks to assist the natural recovery of ecosystems. Depending upon the location in which they are delivered they can be designed to work with natural processes or can be more engineered to fit into more constrained environments. They are typically delivered over medium timescales, though these habitats can take longer time periods to be restored once constructed.

Clearly the restoration of rivers and floodplains is constrained geographically to river corridors and floodplains. They can be costly to implement depending on the scale of restoration and the types of restoration techniques used.

Scale	
Potential scale of deployment	River and floodplain restoration has the potential to be delivered across many rivers and streams as our river systems in England are highly modified.

How quickly do they become effective?	0-5 years.
Scale of benefits achievable	High. River floodplain restoration delivers a high number of multiple benefits alongside water resources.

Figure 1-2: River and floodplain NBS and scale of impact/delivery



1.1.4 Runoff and overland flow NBS

Table 1-4 describes the different sorts of runoff attenuation and overland flow NBS which could be delivered and the types of water resources benefits which they have the potential to provide.

Table 1-4: Runoff and overland flow NBS and their water resources benefits

NBS Name	NBS Description	Main outcomes for water resources
Peatland Restoration  **Photo:** WWNP Evidence Directory	Peatland restoration involves rewetting degraded areas via measures such as grip blocking which involves blocking eroding gullies to help re-wet the habitat by raising the water table. Peatland restoration can also involve re-planting peat species such as sphagnum moss.	• Increased surface roughness • Capture runoff on the surface • Allow infiltration and recharge
Runoff pathway management	Runoff pathway management measures capture water generated by overland flow and store it temporarily using bunds,	• Capture runoff on the surface • Allow infiltration and recharge

NBS Name	NBS Description	Main outcomes for water resources
 **Photo:** WWNP Evidence Directory	ponds, swales or other offline storage features.	
Infiltrations basins/Sustainable Drainage Systems  **Photo**: **United Utilities**	Infiltration basins, a key component of Sustainable Drainage Systems, are vegetated depressions designed to temporarily store stormwater runoff and allow it to infiltrate into the ground. They are typically dry, except during and immediately after rainfall.	• Capture runoff on the surface • Allow infiltration and recharge

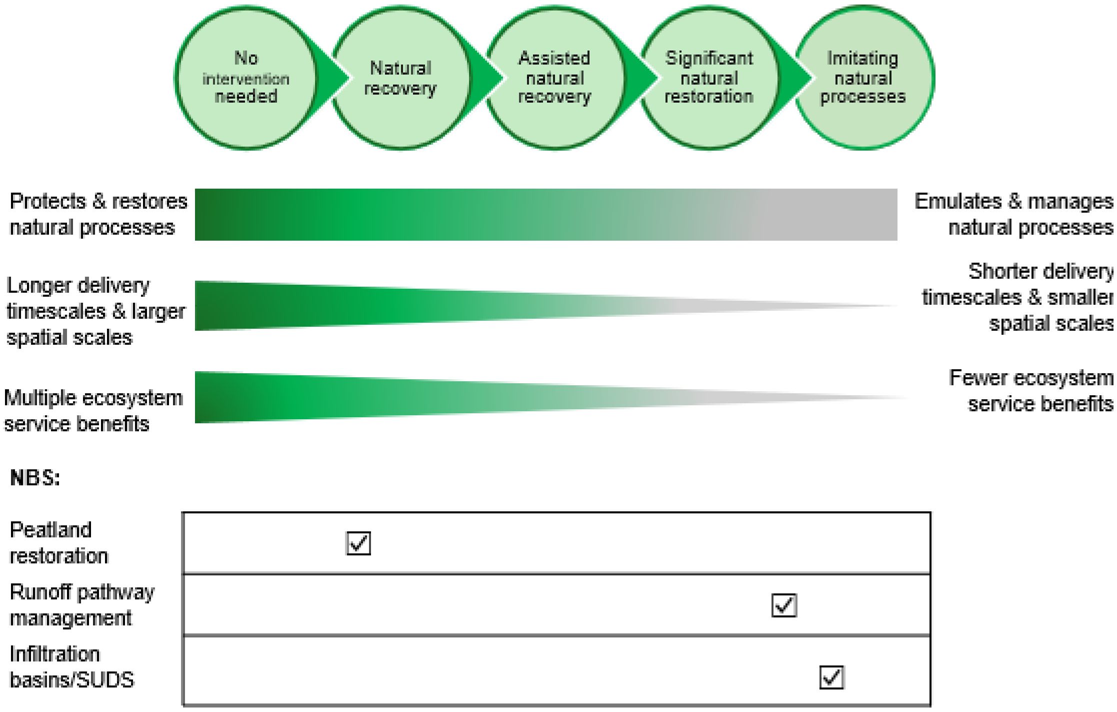
As can be seen in Figure 1-3, peatland restoration contributes to the restoration of natural processes, whereas runoff attenuation features and SuDS are more manmade and as such they initially mimic natural processes.

Peatland restoration facilitates the natural recovery of lost ecosystems and therefore is delivered over longer timescales, whereas runoff attenuation features and SuDS are fast to implement and take a shorter timeframe to become effective.

Peatland restoration is restricted to locations where this habitat is currently or was present in the past; its potential for restoration is therefore more spatially constrained. Whereas runoff attenuation features and SuDS are suitable in many locations, they are also fast and cheap to implement and are hence often favoured by landowners and NGOs, making their delivery faster than the scale-up of some NBS.

	Scale
Potential scale of deployment	Peatland restoration can only occur in specific locations, so its scale of deployment is more limited. Whereas runoff attenuation features and SuDS can be deployed in most places.
How quickly do they become effective?	0-2 years. Peatland habitat restores itself quickly once measures are introduced, and runoff attenuation/SuDS features are almost immediately effective.
Scale of benefits achievable	• High. Peatland restoration delivers a wide range of ecosystem service benefits. • Medium. SuDS and runoff attenuation features deliver a medium level of ecosystem service benefits, though it largely depends on their design.

Figure 1-3: Runoff and overland flow NBS and scale of impact/delivery



1.1.5 In-channel NBS

Table 1-5 describes the different sorts of in-channel NBS which could be delivered and the types of water resources benefits which they have the potential to provide.

Table 1-5: In-channel NBS and their water resources benefits

NBS Name	NBS Description	Main outcomes for water resources
Leaky barriers  **Photo:** WWNP Evidence Directory	Leaky barriers consist of pieces of wood that accumulate naturally in river channels as well as on riverbanks and floodplains. Structures can also be engineered by humans to restore rivers and floodplains to slow and store flood water.	• Allow infiltration and recharge • Raise the riverbed • Improve floodplain connectivity
Beaver dams  **Photo: Southampton University**	Beavers are ecosystem engineers because they have the ability to modify ecosystems. Beaver dams extend beyond channels, creating durable berm-like structures which can hold back water and create wetland-type features.	• Increased surface roughness • Allow infiltration and recharge • Capture runoff on the surface • Raise the riverbed • Improve floodplain connectivity • Store water on floodplain

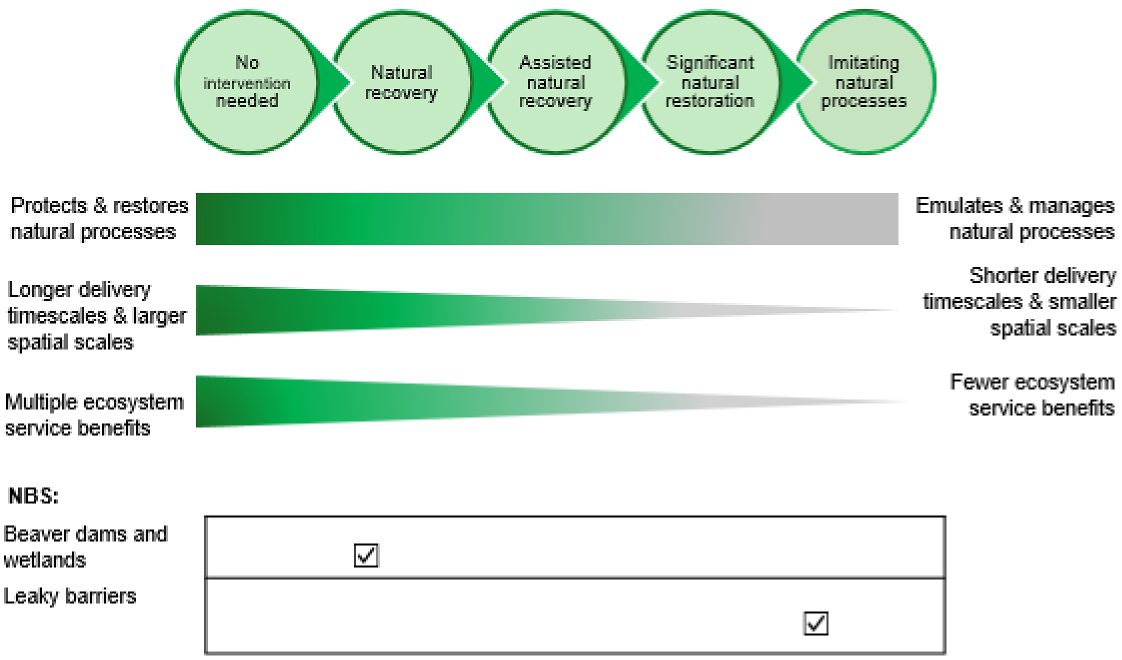
As can be seen in Figure 1-4, beaver dams contribute to the restoration of natural processes, whereas leaky dams are more manmade and as such they initially mimic natural processes, though in the long term they may help restore natural processes, reconnecting rivers to floodplains.

Beaver dams facilitate the natural recovery of lost ecosystems and therefore are delivered over longer timescales, whereas leaky dams are fast to implement and take a shorter timeframe to become effective.

The reintroduction of beavers may be spatially constrained to catchments where the local community accepts them, and so therefore, the scale at which this NBS can be implemented may be more limited than other NBS. By contrast, leaky dams are fast and cheap to implement and are hence often favoured by landowners and NGOs, making their delivery faster than the scale-up of some NBS.

	Scale
Potential scale of deployment	Leaky barriers have the potential to be delivered across many rivers and streams. Whereas the reintroduction of beaver will only be suitable in certain locations
How quickly do they become effective?	0-5 years
Scale of benefits achievable	• High. Beaver dams deliver a wide range of ecosystem service benefits alongside water resource benefits • Medium. Leaky barriers can deliver a wide range of ecosystem service benefits but it depends on their design.

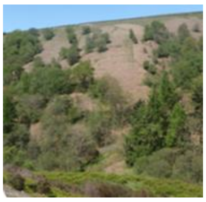
Figure 1-4: In-channel NBS and scale of impact/delivery



1.1.6 Woodland NBS

Table 1-6 describes the different sorts of woodland NBS which could be delivered and the types of water resources benefits which they have the potential to provide.

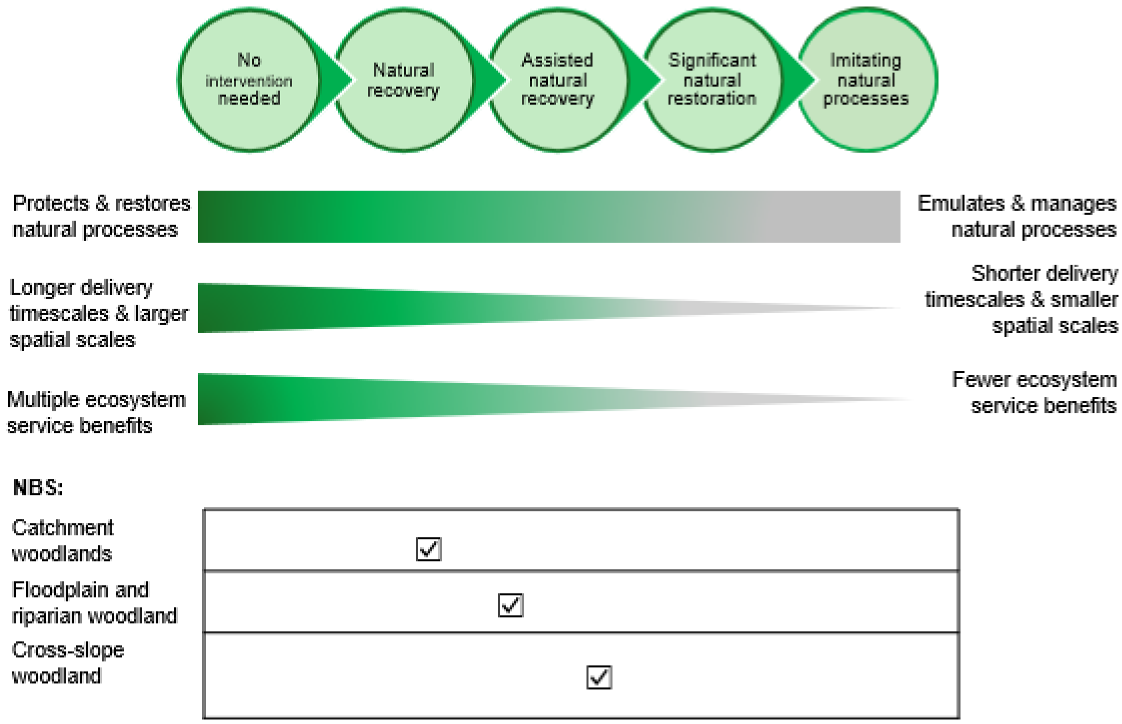
Table 1-6: Woodland NBS and their water resources benefits

NBS Name	NBS Description	Main outcomes for water resources
Catchment woodland  **Photo:** [WWNP Evidence Directory]	Catchment woodland is defined as the total area of all woodland within a catchment. It combines general woodland cover of all types and species, including plantations, plus specific forms where present, such as cross-slope, riparian and floodplain woodland.	• Reduced irrigation demands • Improved soil health structure • Increased surface roughness
Floodplain and riparian woodlands  **Photo:** [WWNP Evidence Directory]	Floodplain and riparian woodland include woodland lying within the fluvial floodplain and within the riparian corridor. It is subject to an intermittent, regular planned or natural flooding regime. It typically comprises broadleaved woodland and can range from productive woodland on drier, intermittently flooded, areas to unmanaged, native wet woodland in wetter areas.	• Reduced irrigation demands • Improved soil health structure • Increased surface roughness
Cross-slope woodland  **Photo:** [WWNP Evidence Directory]	Cross-slope woodland involves the placement of smaller areas or typically belts of woodland across hill slopes. It can comprise all woodland types and species.	• Reduced irrigation demands • Increased surface roughness • Capture runoff on the surface • Allow infiltration and recharge

As can be seen in Figure 1-5, woodland NBS can deliver the restoration of natural processes or assist in natural recovery. Woodland can take time to develop so have longer delivery timescales and take longer to become effective. The location in which woodlands are planted is important as in some locations they may have negative water resource benefits.

	Scale
Potential scale of deployment	Constrained to locations where farmland can be converted to woodland. Need to avoid locations that will facilitate negative impacts on water resources.
How quickly do they become effective?	10-20 years
Scale of benefits achievable	High. Woodlands deliver a wide range of ecosystem service benefits alongside water resource benefits.

Figure 1-5: Woodland NBS and scale of impact/delivery



1.2 The Nature-based Solutions spectrum

NBS falls on a continuum (Figure 1-6) which includes:

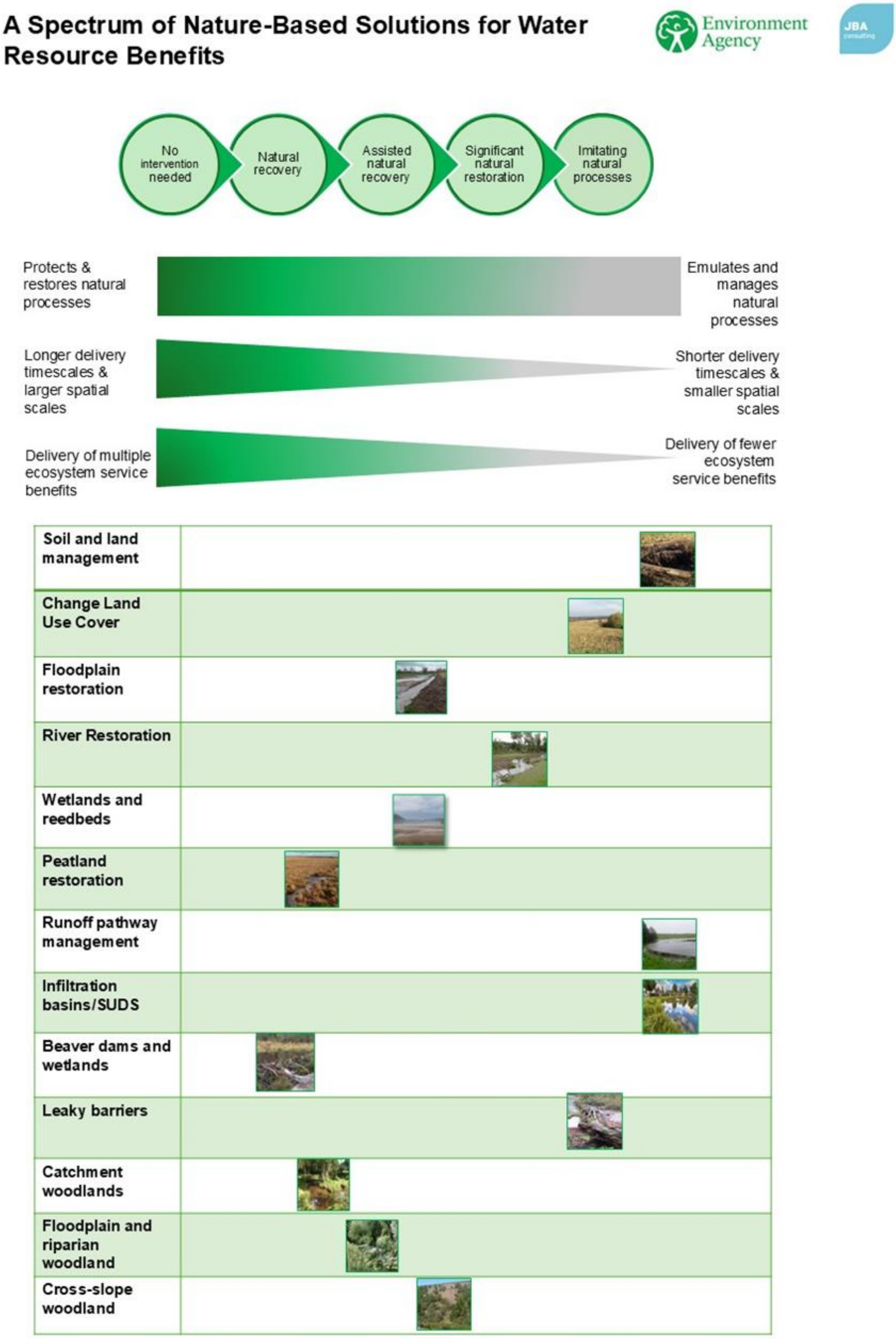
- Protecting existing services
- Natural recovery
- Assisted recovery
- Significant natural restoration
- Imitating natural features

At one end of the continuum, NBS seeks to protect and utilise existing ecosystem services or restore and rehabilitate degraded natural processes. At the other end of the continuum, NBS manage the development of new services emulating natural processes.

Typically, the NBS which fall on the left-hand side of the continuum are delivered over longer time scales, larger spatial scales and help achieve multiple benefits. They involve the use of more passive approaches such as removing pressure(s) or using measures that work with natural processes to assist the natural recovery of habitats.

The NBS on the right-hand side of the continuum are typically delivered faster over smaller spatial scales, but they achieve fewer multiple benefits. They typically involve actively intervening in the natural environment by installing measures that emulate or manage natural processes, requiring active management. The NBS which fall in the middle of the continuum often achieve a sweet spot, balancing a wide range of ecosystem service benefits whilst still providing a range of benefits.

The NBS included in this report have been plotted on this continuum. They all have valuable roles to play individually or in combination across the enabling works area. The next chapter describes how NBS can be deployed to work with the water cycle to encourage water storage and infiltration.



Note: Photos taken from Environment Agency (2017) Working with Natural Processes Evidence Directory

Figure 1-6: The Spectrum of Nature-based Solutions

2 Suite of Nature-based measures

2.1 Introduction

The suite of measures that can be implemented for NBS4WR can achieve a wide range of environmental aims and co-benefits such as flood management, improved water quality, and habitat creation. This section provides a broad overview of the types of NBS4WR measures that could be implemented. The measures introduced in this section, such as soil improvements and runoff attenuation features (RAFs), will therefore be familiar to those implementing Natural Flood Management (NFM). However, to maximise water resource benefits their design and implementation may differ.

2.2 Water cycle and NBS

There are three main aims of NBS4WR:

- Improving groundwater resources
- Improving low flows in rivers
- Improving resilience to drought in the land and water environments

This section describes key features of the water cycle and then sets out the main aspects of the water cycle that can be modified to achieve these aims.

2.2.1 Water cycle part 1 - partitioning of rainfall

When rain hits the ground there are several pathways that it can take. Quinn (2012) identifies three zones, illustrated in Figure 2-1:

- Zone 1 – Surface: Here the soil properties and soil moisture status affect the split of rainfall between runoff and infiltration
- Zone 2 – Above the regional water table: Here water either passes to the water table or is taken up by plants and lost through evapotranspiration
- Zone 3 – Beneath the regional water table: The amount of water that reaches this zone is a function of the management of Zones 1 and 2

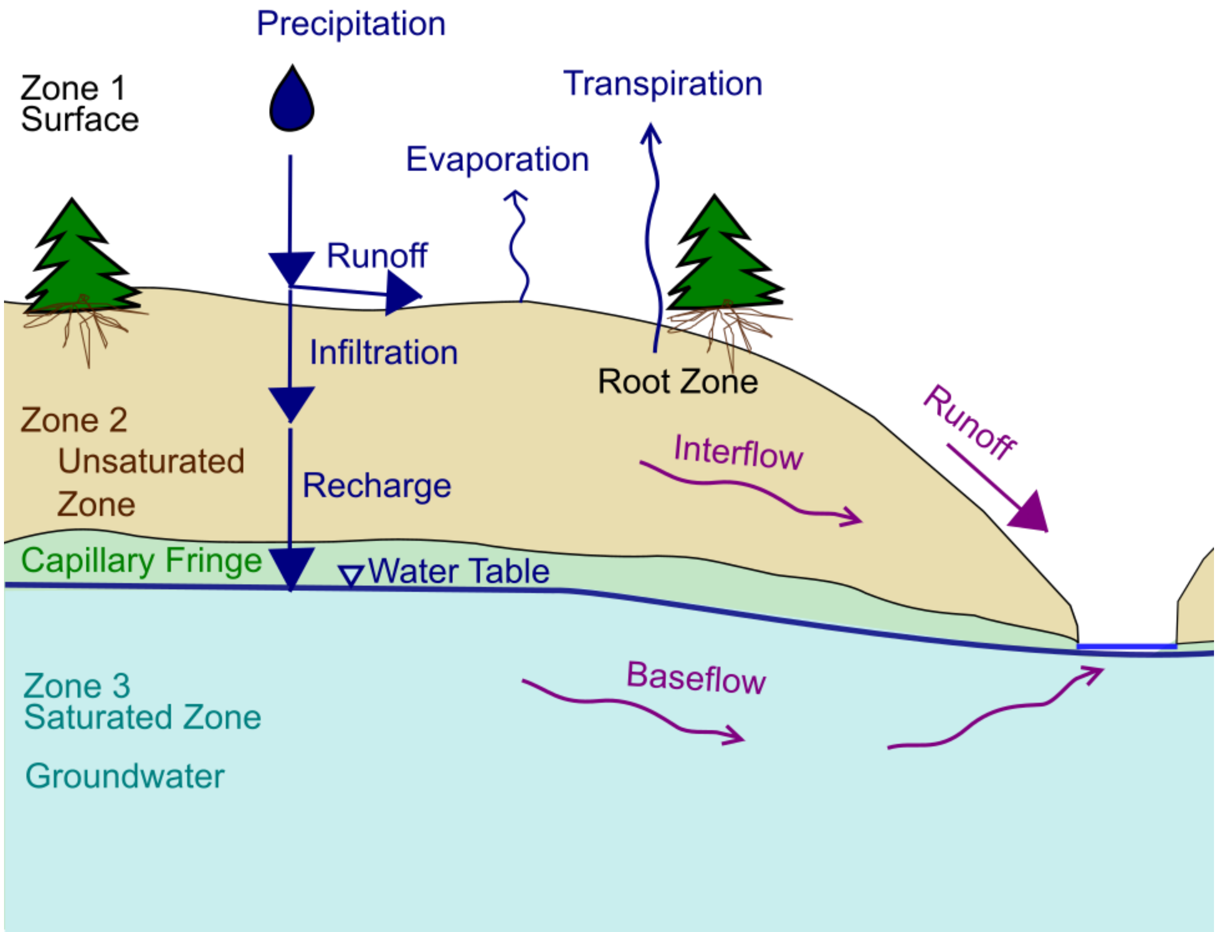


Figure 2-1: Partition between the unsaturated and saturated zones for groundwater and flow pathways

2.2.2 Water cycle part 2 - river flows

Flows in rivers are usually divided into two elements: baseflow and quickflow:

1. **Quickflow**, as the name suggests, consists of flows that quickly arrive at the river, so will be predominantly formed of runoff and interflow, which is water that passes through the shallow ground. On a hydrograph, quickflow will appear as a rise and fall in water levels following rainfall, as shown in Figure 2-2.
2. However, water can take a range of flow pathways before entering a river, as illustrated in Figure 2-1, and some of these take longer than others. **Baseflows** are broadly equivalent to groundwater input into a river and take a longer time to respond to a rainfall event as water travels through the ground. In dry periods, it is baseflow, and thus groundwater flow, that allows rivers to continue to flow. Cessation of baseflow can result in ephemeral/intermittent streams running dry.

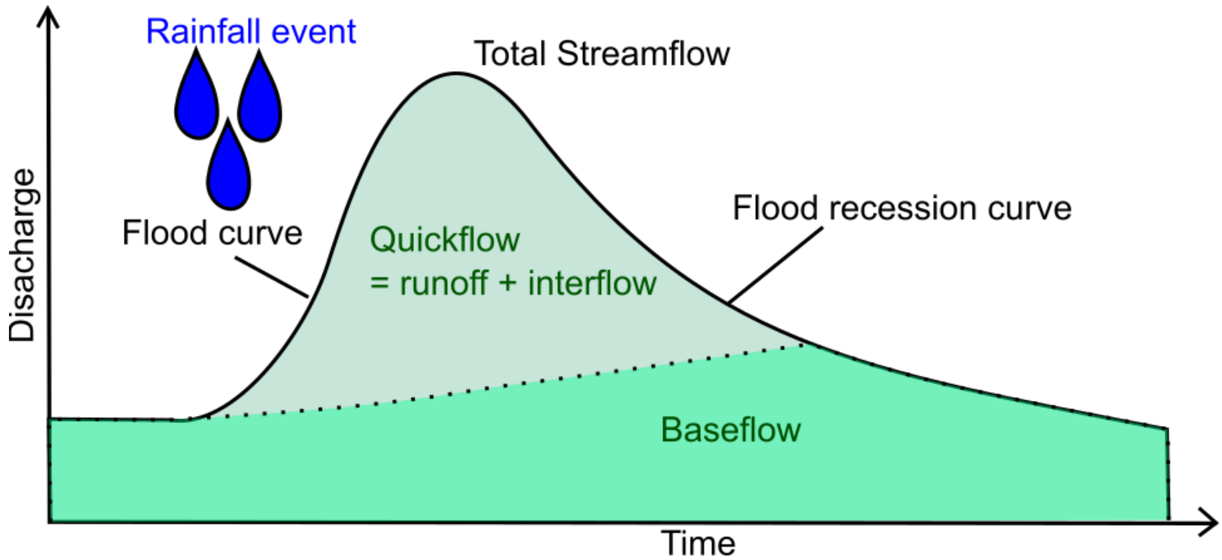


Figure 2-2: Baseflow-quickflow separation

The size and depth of a river also controls the amount of baseflow from groundwater and the height of the water table in the surrounding area. Figure 2-3 shows how an incised channel can suppress the water table, resulting in less storage of water beneath ground.

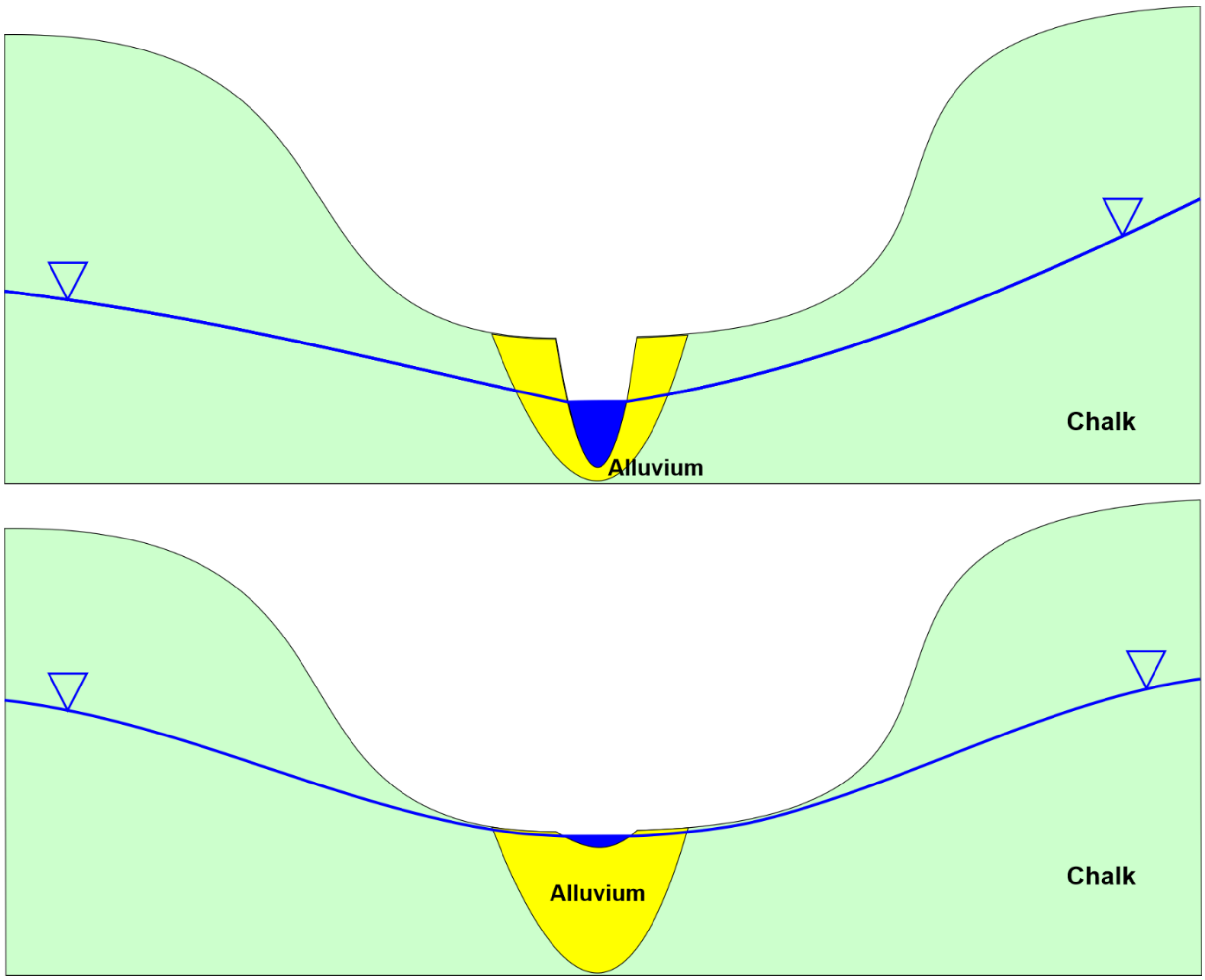


Figure 2-3: River depth and storage

2.2.3 Water cycle part 3 – intervention locations

NBS4WR can have the greatest impact when focused on the shallow groundwater zones of the water cycle. There are four interventions within this zone which can improve groundwater resources and low river flows:

- Water Usage – changing to land uses that reduce irrigation demands or lower evapotranspirational losses
- Runoff Infiltration Split – reducing rapid runoff and moving water into slower pathways through the soil and underlying geology
- Runoff Capture and Infiltration – slowing runoff that is generated and allowing it to infiltrate to ground
- Floodplain and River Restoration – modifying floodplains to store more water, and restore rivers to be more resilient to low flow periods

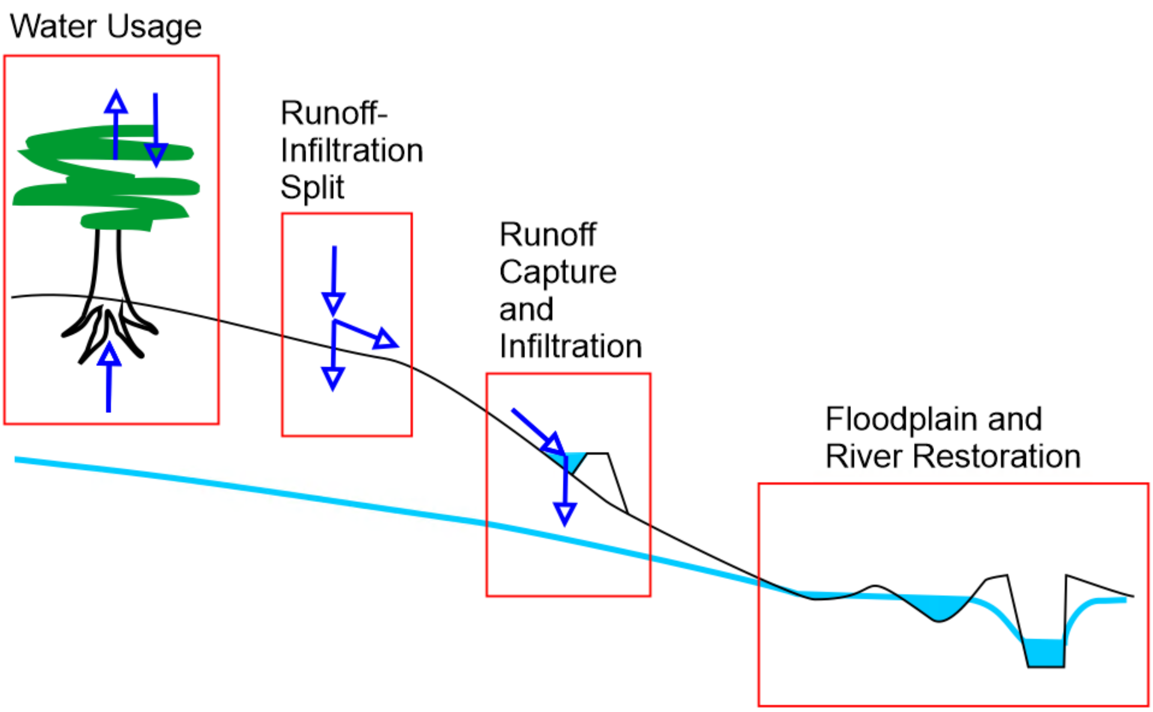


Figure 2-4: Water cycle NBS4WR topics

2.3 NBS4WR generic conceptual model

Figure 2-5 summaries the water cycle processes that can be affected by NBS4WR interventions and shows their locations in the catchment. Figure 2-6 illustrates some example intervention types.

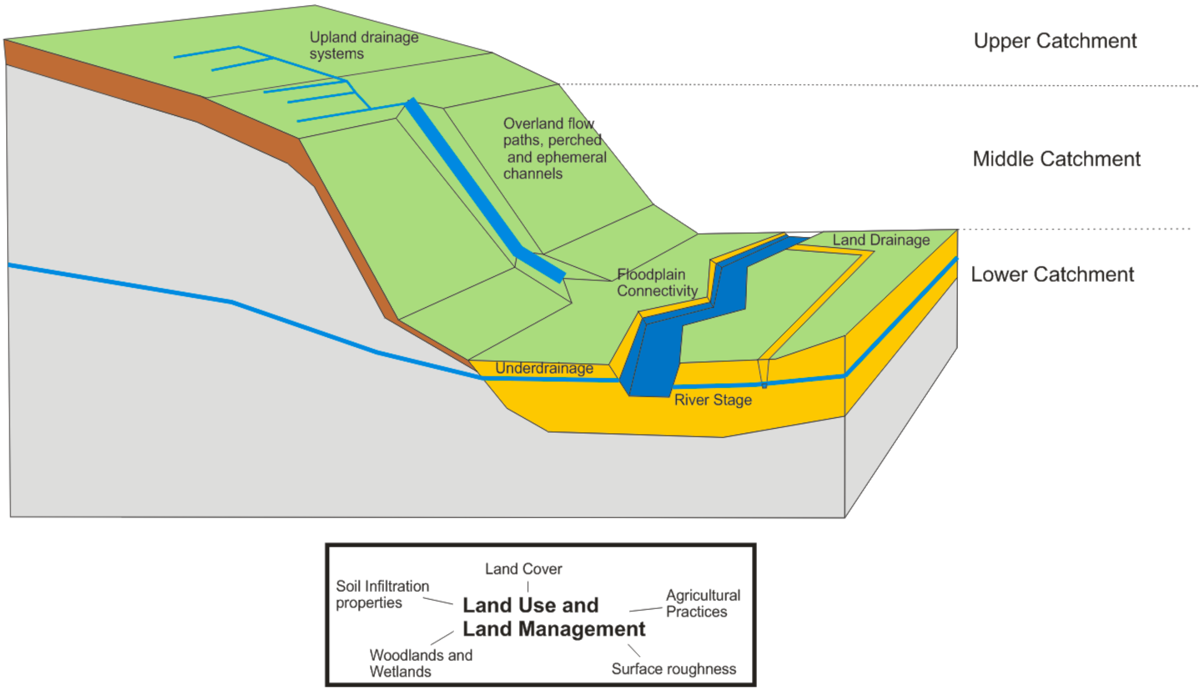


Figure 2-5: Generic catchment sub-divisions and locations of key processes

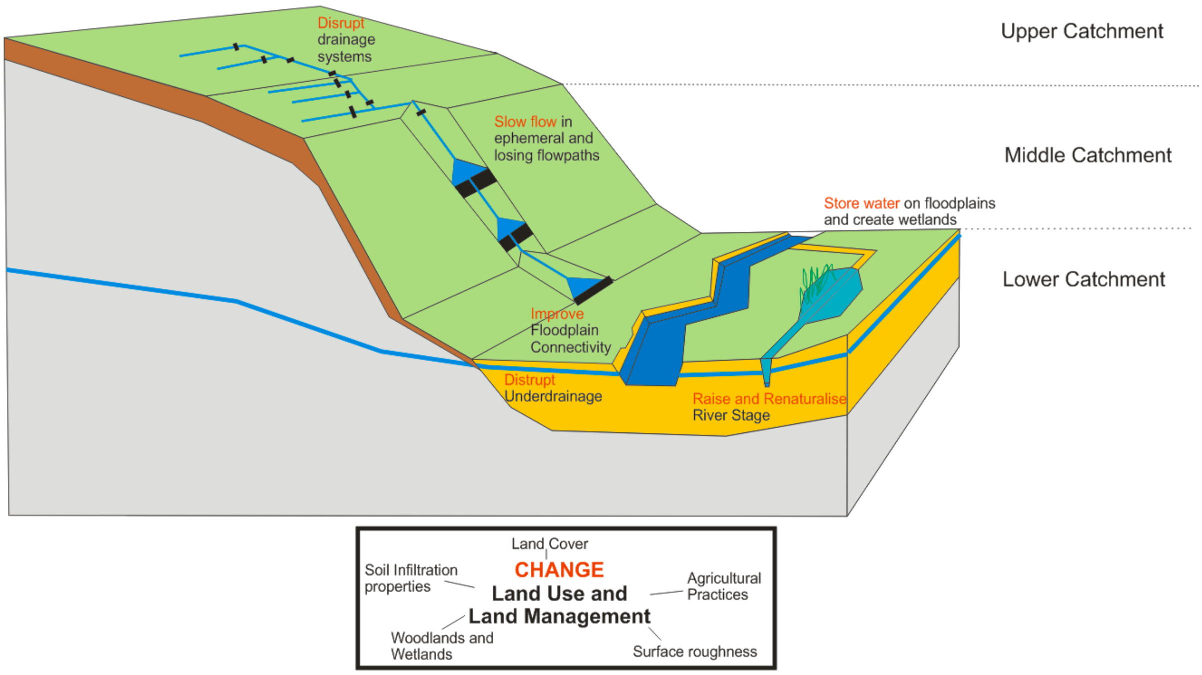


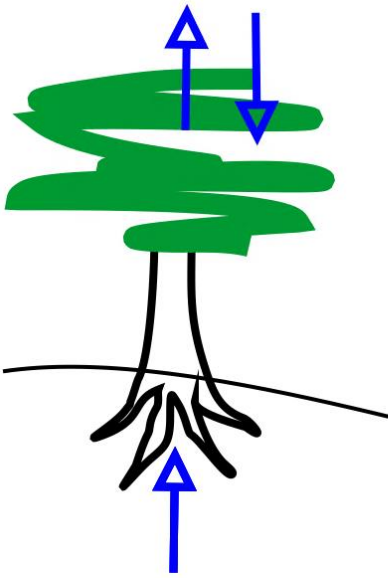
Figure 2-6: Catchment sub-divisions and generic intervention types

2.4 NBS4WR interventions

2.4.1 Water usage

Changes to the water cycle
Water Usage interventions can:

- Reduce evaporation and transpiration
- Reduce interception of rainfall
- Reduce irrigation demands



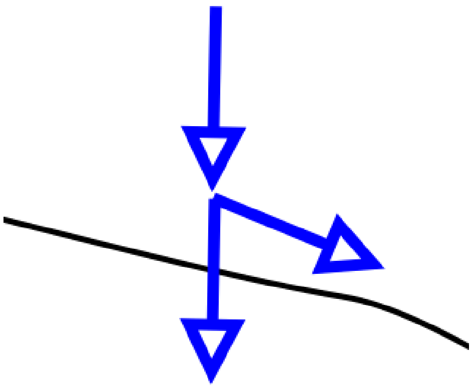
Available techniques
The following techniques might be implemented:

1. Chose crops that have lower evaporation rates and need less irrigation
2. Replace dense conifer plantations with more open deciduous woodland pasture
3. Intelligent use of cover crops to improve soil infiltration properties

2.4.2 Runoff infiltration split

Changes to the water cycle
Runoff Infiltration Split interventions could do the following:

- Improve soil structure to allow more infiltration
- Increase surface roughness to slow runoff at source, such as by using buffer strips
- Maintaining healthy chemical and biological soil properties



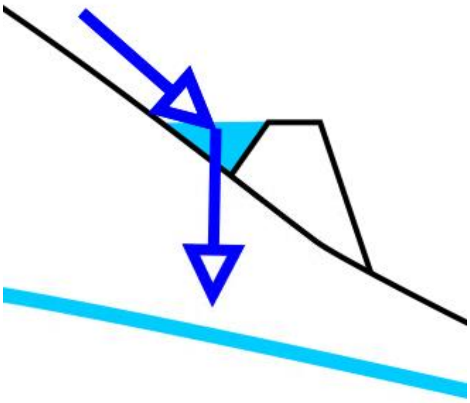
Available techniques
The following techniques might be implemented:

1. Adoption of sustainable soil management practices, with the aim or increasing organic content, reducing compaction and using limited tillage approaches
2. Change land use cover in areas susceptible to erosion, including consideration of the use of cover crops
3. Maintaining well-established habitats that have favourable effects on water resources
4. Woodland creation
5. Buffer strips

2.4.3 Runoff capture and infiltration

Changes to the water cycle
Runoff Capture and Infiltration interventions could do the following:

- Capture runoff on the surface and allow it to infiltrate into the ground



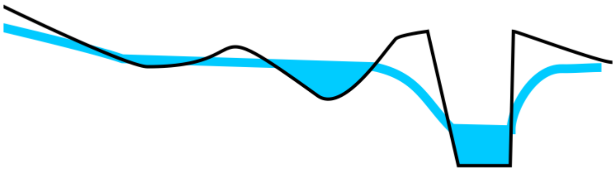
Available techniques
The following techniques might be implemented:

1. Runoff Attenuation Features
2. Infiltration basins, temporary storage ponds, earth bunds, field corner storage, swales and scrapes
3. Cross-slope interventions such as hedgerow planting, field boundary interventions
4. Headwater management

2.4.4 Floodplain and river restoration

Changes to the water cycle
Floodplain and River Restoration could do the following:

- Raising the bed of a river, so it has less impact on the local water table
- Improving floodplain connectivity – allowing floodwaters to be stored on the floodplain
- Creating wetlands in the lower catchment, increasing the storage of water on the floodplain



Available techniques
The following techniques might be implemented:

1. River-floodplain reconnection
2. Increased water storage on the floodplain
3. Wetland creation

2.5 Summary

Table 2-1 provides a summary of a range of different Nature-based Solutions illustrating the types of water resource benefits that they can provide. The table gives an indication of the number of water resource benefits different NBS have the potential to deliver. The greater the number of ticks in the table, the more natural capital benefits are delivered. Some NBS will have the potential to be delivered over a larger scale than others.

For example, in theory, soil, land management and land cover measures could be delivered over a larger area, so therefore they have the potential to have the greatest impact. By contrast, more spatially-constrained measures such as floodplain restoration have less potential to be delivered at scale, so they may have fewer water resource benefits. However, these assumptions are not supported by detailed scientific study. It is recommended that this gap in scientific knowledge is filled to better understand which suites of NBS have the greatest impact on water resources and at what scale they need to be delivered to have an impact.

Table 2-1: The water resource impacts of Nature-Based Solutions (based on expert opinion)

NBS Intervention	Water usage			Runoff attenuation split		Runoff capture and infiltration		Floodplain and river restoration		
	Reduced evaporation & transpiration	Reduced interception of rainfall	Reduced irrigation demands	Improved soil health structure	Increased surface roughness	Capture runoff on the surface	Allow infiltration and recharge	Raise the riverbed	Improve floodplain connectivity	Store water on floodplain
Soil & land management				☑	☑	☑	☑			
Change land use cover	☑	☑	☑	☑	☑	☑	☑			
Floodplain restoration					☑	☑	☑	☑	☑	☑
River restoration					☑			☑	☑	
Wetlands & reedbeds					☑	☑	☑			☑
Peatland restoration					☑	☑	☑			
Runoff pathway management						☑	☑			
Infiltration basins/SuDS						☑	☑			
Beaver dams & wetlands					☑	☑	☑	☑	☑	☑
Leaky barriers							☑	☑	☑	
Catchment woodlands			☑	☑	☑					
Floodplain & riparian woodland			☑	☑	☑					
Cross-slope woodland			☑		☑	☑	☑			

3 Other objectives supported by NBS4WR

NBS4WR frequently have multiple social, environmental, and economic co-benefits that can support the achievement of a range of environmental objectives. This section considers how NBS4WR can be integrated into Nature-based Solutions (NBS) projects with wider benefits beyond water resources, along with broader policy drivers and potential funding opportunities for NBS implementation.

3.1 Impacts of NBS4WR for other objectives

The crossover of NBS4WR with habitat creation, improved water quality, and natural flood management is considered in this section.

3.1.1 NBS4WR and habitat creation

The table below outlines the implications for water resources of a range of habitat creation schemes presented throughout the handbook.

Table 3-1: Habitats creation and NBS4WR implications

Broad Habitat Creation Type	WR Outcome	Discussion	Section Reference
Scrapes and ephemeral waterbodies	Net benefit (positive)	These can be designed to act like infiltration basins and runoff attenuation features, capturing water when it is in excess.	5.3.1
Arable to pasture	Net benefit (positive)	Converting arable agriculture to pasture can have water resource benefits, if replacing water hungry crops, although this depends on crop type.	5.1.1
Soil structure	Net benefit (positive)	Healthy soils can support invertebrate populations while improving water retention, drainage and increasing infiltration.	5.2.1
Improved pasture to extensive grassland	Mixed response (neutral)	Moving from improved pasture to extensive grassland may increase the roughness of the ground surface, improving infiltration. However, the deep root systems of established grasslands may increase the removal of water during dry conditions. Limited research was found for the variation within grassland types.	5.1.1
Wetland creation	Mixed response (neutral)	The literature review suggests that the effect of wetland creation is variable. Increased storage of water in wetlands can aid water resources, but there will be increased evaporation, which can lead to greater water losses, particularly in wetlands fed directly by rivers in the summer.	5.4.2

Woodland	Conflict of outcomes (negative)	The water resource benefits of replacing arable land with woodland is complex and is affected by climate and geology. In many cases dense coniferous woodland will have a higher water demand, but less dense woodland pastures may result in limited changes to the water budget.	5.1.4

In addition to the direct benefits on habitats offered by a broad range of NBS, these ecological benefits can in turn have favourable impacts on water resources. Many NBS interventions will improve the resilience of wetland and aquatic habitats to droughts and low flow conditions. In doing so, these habitats will become less sensitive to the impacts of abstractions for water resources. For a given system, this can therefore change the abstraction sensitivity band for the Environmental Flow Indicator (EFI), support an alternative flow constraint, or make the use of drought permits more acceptable. Hence, water resources may indirectly benefit in this way from enhanced habitats associated with NBS.

3.1.2 NBS4WR and water quality

Water that is stored in the soil, ground, or held on floodplains/wetlands by NBS measures, can deposit silt and undergo physical and biological filtration, removing sediments, heavy metals, and nutrients. This can protect groundwater from contamination, reduce turbidity in downstream water and reduce siltation of storage systems or water treatment, reducing the need for additional treatment.

The table below outlines the implications of the NBS4WR suite of measures for water quality.

Table 3-2: NBS4WR and water quality implications

NBS4WR intervention	WR Outcome	Discussion	Section Reference
Cover crops to bare soils	Conflict of outcomes (negative)	Changing from cover crops to bare soils can reduce evapotranspiration losses, improving infiltration and recharge. However, the loss of cover crops can negatively affect water quality, as they can limit nitrate leaching into aquifers and reduce soil erosion.	5.1.2
Improved soil health	Net benefit (positive)	Improving soil structure can reduce erosion and increase infiltration capacity and improve water quality by removing pollutants from surface water.	5.2.1
Woodland Planting	Mixed response (neutral)	Woodlands can significantly improve water quality, as they stabilise soils and reduce sediment and nutrient pollution. They can also reduce landslides and mudflows.	5.1.4

		However, their impact on groundwater recharge can be mixed and is frequently negative.	
Runoff attenuation features	Net benefit (positive)	Can slow flows, increasing recharge to depth, while reducing erosion and limiting the movement of diffuse pollutants.	5.3.1
Infiltration basins	Net benefit (positive)	Can significantly increase recharge to the saturated zone, while improving water quality and reducing nutrient and sediment load.	5.3.2
Floodplain connectivity	Mixed response (neutral)	Increased storage in the floodplain can reduce the movement of pollutants, improving water quality and sediment deposition. Floodplain inundation can store water offline during flood events, slowly releasing water to increase groundwater resources. However, the raising of riverbeds can raise groundwater levels, increasing evaporative losses. The response appears to be highly specific to each location.	5.4.1
Wetland Restoration	Mixed response (neutral)	Wetlands store water in the landscape, which can significantly improve water quality, particularly from diffuse pollutants. They allow increased settling of particulates and filtration of pathogens, nitrates and phosphates. Reuse of filtered nutrients can help to support plant and animal diversity. The literature review suggests that the effect of wetland creation for NBS4WR is variable. Increased storage of water in wetlands can aid water resources by slowly releasing retained waters during drought. However, there will be increased evaporation, which can lead to greater water losses, particularly in wetlands fed directly by rivers in the summer. The response appears to be highly specific to each location.	5.4.2

3.1.3 NBS4WR and natural flood management

NBS4WR measures can slow runoff and increase infiltration, reducing the impact of flooding. Holding water on floodplains and in wetlands increases storage capacity and reduces flood peaks and flow velocities, whilst increasing the replenishment of groundwater resources.

The table below outlines the implications of the NBS4WR suite of measures for natural flood management.

Table 3-3: Natural flood management and NBS4WR implications

NBS4WR intervention	WR Outcome	Discussion	Section Reference
Woodland management	Mixed response (neutral)	Woodland planting can stabilise slopes and reduce flood risk by slowing runoff velocity, reducing peak flows. However, in many cases woodland will have a higher water demand than other land use covers, reducing water resources. Less dense woodland pastures may result in limited changes to the water budget, and at the large and long-term scale there may be water resource benefits from increased woodland planting.	5.1.2
Soil health	Net benefit (positive)	Improved soil structure can reduce runoff, both reducing flood peaks and potentially increasing infiltration and recharge.	5.2.1
Runoff attenuation features	Mixed response (neutral)	Runoff attenuation features can slow the flow of water to rivers, reducing flood peaks, and increasing recharge. However, to maximise infiltration, runoff attenuation features would be designed to fill during average rainfall events. These would not have the capacity for attenuating greater than average flows during flood events.	5.3.1
Infiltration basins	Net benefit (positive)	Infiltration basins can significantly increase recharge, reducing overland runoff during heavy rainfall.	5.3.2
Floodplain connectivity	Mixed response (neutral)	Floodplain inundation can store water offline during flood events reducing flood peaks while slowly releasing water to increase water resources. However, the raising of riverbeds can raise groundwater levels increasing evaporative losses. The response appears to be highly specific to each location.	5.4.1
Wetland restoration	Mixed response (neutral)	Wetlands can slow runoff and store water offline during flood events, decreasing flood volumes. Wetlands can increase groundwater recharge; However, they can also increase evaporation, leading to water loss. In some cases, this can result in overall negative water resource	5.4.2

		impacts. The response appears to be highly specific to each location. Additionally, some kinds of floodplain wetlands can increase peak floods. The impact is therefore highly variable depending on wetland type and location in the catchment.	

There are, of course, a broad array of additional overlapping opportunities beyond these three objectives. For example:

- Improving runoff-infiltration splits through the installation of infiltration basins in urban areas can have social benefits
- Wetland restoration can improve air quality and help temperature regulation
- Improved soil health can benefit food security and carbon sequestration
- The introduction of beavers can improve floodplain connectivity alongside biodiversity gains

Encouraging the consideration of water resources during the design of NBS schemes can increase the overall benefits of the scheme and ensure that water resource improvement opportunities are not overlooked.

3.2 Conflicts with other objectives

The main targets of NBS4WR are:

- Improving groundwater resources
- Improving low flows in rivers
- Improving resilience to drought in the land and water environments

As highlighted in the above tables, the suite of measures identified for NBS4WR may sometimes be in conflict with other environmental objectives. If improving the quantity of infiltration and the recharge of groundwater was the sole objective, the following suite of measures might be adopted:

- Land use cover would be chosen based on the lowest evapotranspiration losses. In many areas this might mean limiting woodland cover, losing woodland habitats, and choosing crops such that fields are left with minimal cover during the late summer months, negatively affecting water quality.
- Runoff attenuation features would be designed to maximise infiltration, meaning that they would be filled by typical rainfall events. This would limit their effectiveness in attenuating flood flows.
- Some wetland and river restoration schemes would not be encouraged where they resulted in reduced low flows downstream.

However, a singular focus on water resources may fail to realise a healthier, more resilient river system. Consider, for example, a river system where riparian woodlands increase water losses by evapotranspiration, beavers contribute to floodplain connectivity and raise groundwater levels, and infiltration is reduced due to cover cropping. Such a system may receive reduced volumes of water during low flows but may be healthier overall and more resilient to the reduction in low flows.

One corollary to the above is that re-naturalised landscapes may not always be associated with increased low flows. Due to current land management practices, modern rivers may have higher flows than they did historically. To a certain extent, modern systems may have adapted to the increased flows and may not be revertible to historic conditions.

Overall, NBS interventions should weigh up the overall benefits to the water environment against evidence of any adverse effects on water availability in low-flow conditions, factoring in the local context of any scheme. Implementation should consider the net impacts and the relative importance of any conflicting objectives.

3.3 Building NBS4WR into a range of projects

There is a great deal of overlap in the suite of NBS4WR measures with other NBS practices and habitat creation programmes. Suitable adjustments to the programmes implemented under Environmental Land Management (ELM) schemes, Water Industry National Environment Programme (WINEP), or Local Nature Recovery Strategies (LNRS) could be made to encourage projects to maximise NBS4WR benefits while achieving their other aims.

3.3.1 Policy drivers

There are a wide range of UK and EU policy drivers which support the use of NBS:

- United Kingdom:
    - 25 Year Environment Plan. This plan aims to improve the natural environment within a generation, emphasising the use of NBS to enhance biodiversity, reduce flood risks, and improve air and water quality.
    - Environment Act 2021. This legislation sets legally binding targets for air quality, water, biodiversity, and waste reduction, promoting NBS as a means to achieve these goals.
    - Agricultural Transition Plan. This plan supports farmers in transitioning to sustainable practices, including the use of NBS. It emphasises the "Public Money for Public Goods" approach, rewarding farmers for environmental stewardship.
    - Biodiversity Net Gain. A policy requiring new developments to deliver an overall increase in biodiversity, often through NBS like green roofs, urban forests, and wetlands.
    - Draft Land-use Framework. The framework aims to provide a strategic and holistic approach to land use in England, addressing challenges such as climate change, biodiversity loss, and food security. It emphasises the importance of integrating NBS to enhance sustainability, climate resilience, and the restoration of nature.
    - Environment Improvement Plan. The EIP outlines strategies to enhance the natural environment, improve biodiversity, and tackle climate change. NBS are highlighted as key approaches to achieve these goals by leveraging natural processes to address environmental challenges.
    - Plan for Water. This comprehensive strategy aims to improve water quality, enhance water management, and ensure sustainable water resources. NBS are highlighted as effective approaches to achieve these goals.

- 30 by 30 on Land in England. As the impacts of climate change grow, the 30 by 30 approach supports NBS delivery to ensure that our natural environment is resilient and able to adapt to the impacts of climate change.

- European Union:
    - European Green Deal. This comprehensive plan aims to make Europe climate-neutral by 2050, with NBS playing a key role in carbon sequestration, climate adaptation, and biodiversity conservation.
    - EU Biodiversity Strategy for 2030. This strategy focuses on protecting and restoring nature, with targets for expanding protected areas and restoring degraded ecosystems using NBS.

3.3.2 Potential funding sources

At the time of writing, there are a wide range of potential funding sources available to fund NBS delivery (see Table 3-4). These funding sources range from:

- Government funding to deliver environmental outcomes
- Research council and European funding to deliver research projects
- Private sector funding to achieve environmental outcomes (e.g. net zero, biodiversity net gain and nutrient neutrality)
- Regulatory fines and water company funding sources

Table 3-4: Potential NBS funding sources

Potential funding source	Summary
Biodiversity Net Gain (BNG)	There is potential to fund NBS by offering up BNG units to developers and using the funds to deliver restoration.
Carbon / Net Zero (NZ)	As of 2021, the Woodland Carbon Code and the Peatland Code are the only two offset schemes accredited by the UK Environmental Agency. More offset schemes may be added in the future and guidance from the agency can be used to identify the best carbon credits.
Environment Land Management (ELM)	Environmental Land Management (ELM) schemes are the mechanisms for implementing the new policy in England. The schemes will pay land managers and farmers for providing environmental goods and services alongside food production. They include: Sustainable Farming Incentive, Countryside Stewardship, and Landscape Recovery.
European Funding	Post-Brexit the only EU funding available to the UK is Horizon Research and Innovation funding which has a climate change focus. This could be a potential avenue for funding innovative ideas which require scientific study and data collections. This could be especially relevant to the more innovative NBS options (e.g. hybrid reefs).
Flood Defence Grant in Aid (FDGiA)	FDGiA is the main source of funding that the Environment Agency uses to fund compensatory habitat. The fund is quite constrained because it is required by all Environment Agency areas teams across England. Unlocking FDGiA also requires the provision of Partnership Funding from other partner organisations.

Potential funding source	Summary
Green Finance Brokerage	Green financing brokerage services are being developed for organisations looking to purchase nature credits. There may be an opportunity to partner with them to offer NBS credits locally to help fund the delivery of NBS.
Green infrastructure framework	The Green Infrastructure Framework is a commitment in the Government's 25 Year Environment Plan. It supports the greening of our towns and cities and connections with the surrounding landscape as part of the Nature Recovery Network.
Local Nature Recovery (LNRS)	Local Nature Recovery Strategies in England are a new approach to restoring and protecting nature. They are part of a nationwide move to create space for nature to thrive. Local Nature Recovery Strategies will create a national Nature Recovery Network (NRN). They are a requirement of the Environment Act 2021.
Nature for Climate Fund	The £640 million Nature for Climate Fund – to create, restore and manage woodland and peatland, triple afforestation rates across England, and restore 35,000 hectares of peatland by 2025.
Nature Recovery Networks (NRN)	The Nature Recovery Network is a growing national network of wildlife-rich places, stretching from our cities to countryside, mountains to coast. The government is providing a range of funding streams, policies and delivery levers to support nature recovery, which local nature recovery strategies will be able to help target.
Nutrient Neutrality	There is potential to fund NBS by offering up nutrient neutrality credits to developers.
Regulatory fines	Money from fines handed out to water companies will be re-invested in schemes that benefit the natural environment. The funding from these fines will be administered by NGOs in the delivery of NBS.
Species Recovery Programme	The Species Recovery Programme Capital Grant Scheme is funded and delivered by Natural England as part of its long-running Species Recovery Programme. It focuses resources on projects that address the needs of Priority, Threatened or Near Threatened species.
Species Survival Funds	The Species Survival Fund supports projects which "tackle habitat loss, safeguard our fragile ecosystems, and create and restore nature-rich landscapes". It has been targeted to deliver against the Government's legally binding target to stop the decline in species abundance in England by 2030.
UK Research Institutes (UKRI)	UKRI may have science and research funding opportunities which could support future studies or long-term monitoring associated with NBS.
Water Industry National Environment Programme (WINEP)	WINEP is the programme of work that water companies in England are required to undertake to fulfil their obligations arising from environmental legislation and UK government policy. It includes projects such as NBS which are funded and delivered to improve the environment to deliver legal drivers such as WFD.
Water companies	Funding schemes offered by water companies may offer opportunities for NBS implementation projects.

4 Planning Nature-based Landscapes

4.1 Introduction

It is important to take a strategic approach when implementing NBS at scale within catchments, using a holistic framework to plan the future state of the landscape. This is likely to draw upon the expertise of many different practitioners at various stages in the process, together with valuable inputs from communities, landowners and regulators, whose contributions are essential to the success of schemes. Planners should not overlook the fact that they are designing a landscape as a whole, which requires an understanding of that landscape in its multiple aspects. To this end, we propose the concept of Nature-based Landscapes (NBL) as a counterpart to the Nature-based Solutions concept. Such Nature-based Landscapes centre natural processes to harness optimal environmental benefits.

Every landscape is unique, offering a different set of challenges, constraints and opportunities for NBS implementation. NBS can have benefits for multiple stakeholders within a landscape, but ownership, authority, regulations, and stakeholders may vary within and between catchments. A suite of NBS measures optimised for a given catchment may be ill-suited to the next catchment, sometimes despite superficial similarities. Differing geological, geographical and hydrological contexts require unique blends of NBS to optimise the benefits that can be realised, both in terms of water resources and other aspects of natural capital. Actualising NBL involves utilising these unique contexts to deliver tailored suites of interventions.

When evaluating the potential for implementing NBS in a catchment, assessors should not lose sight of the added value of existing good practices in an area. Recognition of these existing management practices is an important aspect of such assessments and any further NBS interventions should be designed to accentuate the positive outcomes of these practices. In other words, the value in sustaining what is already good should not be overlooked.

Within this chapter, some general principles underpinning landscape planning for NBS are set out, drawing upon material from the appendices within this handbook. These principles are based on experience in the environmental sector, noting that the widespread rollout of NBS for water resources is still in its infancy. Recent efforts have been concentrated in certain parts of the country, and so there are clear gaps in knowledge outside of these areas.

4.2 General principles

4.2.1 Suite of measures

Designing NBS for a landscape should prioritise the use of a wide suite of measures working in tandem to deliver water resources benefits. These measures should relate to different parts of the water cycle, reiterated in Figure 4-1, in pursuit of increasing aquifer recharge to augment groundwater resources and boost low flows in rivers.

The locations of NBS measures within the catchment should be carefully considered, ideally alongside supporting data from mapping and modelling assessments. Geology places strong physical constraints on the effectiveness of different types of NBS measures, so an understanding of hydrogeological processes is central to deciding where to place NBS in the landscape. Measures which seek to modify the runoff-infiltration split of the substrate or to promote runoff capture and infiltration are particularly sensitive to the permeability of the underlying geological deposits.

Once water reaches the more low-lying portions of the catchment, opportunities for it to be diverted into aquifers become more limited. Thus, although NBS measures which involve floodplain and river restoration can offer a range of benefits, enhancements to water resources are not chiefly among them.

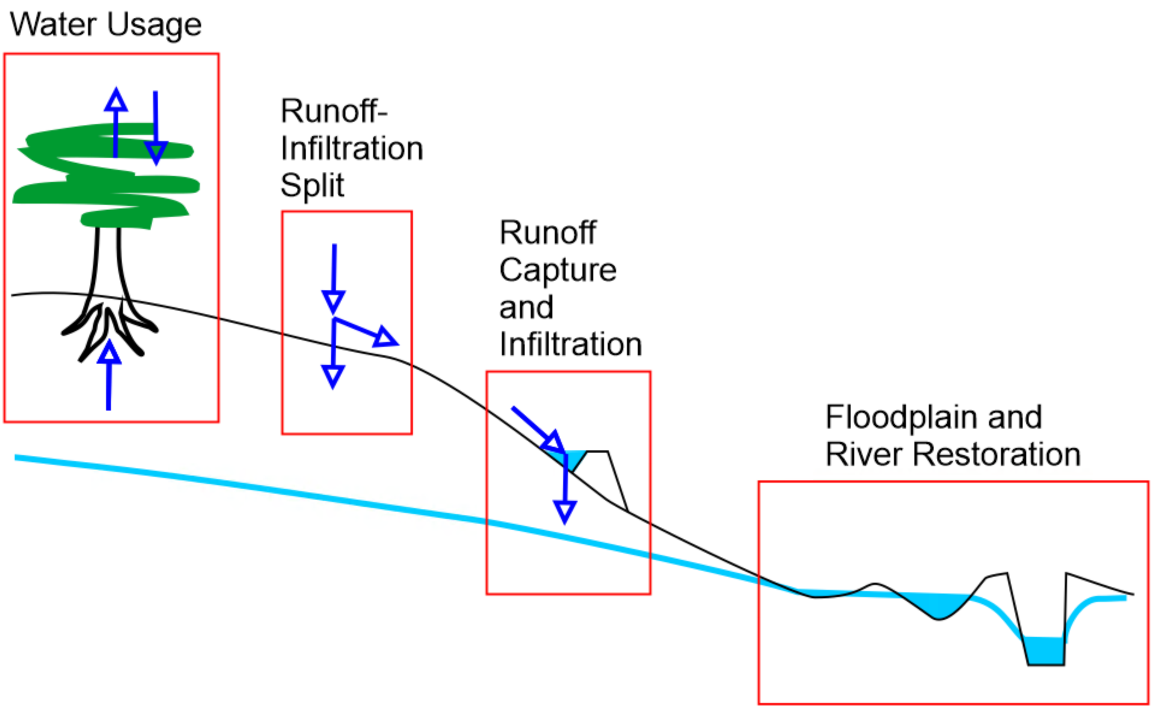


Figure 4-1: Categories of measures from the NBS4WR 'toolkit'

A process understanding of individual NBS features can be used to inform their designs and develop options for monitoring their effectiveness within the landscape. To exemplify this, a schematic diagram of a generic RAF is shown in Figure 4-2, which illustrates how monitoring of stream flows can be carried out to assess the effectiveness of the feature in boosting recharge. Rigorous monitoring is important for demonstrating project successes and to inform programmes of maintenance.

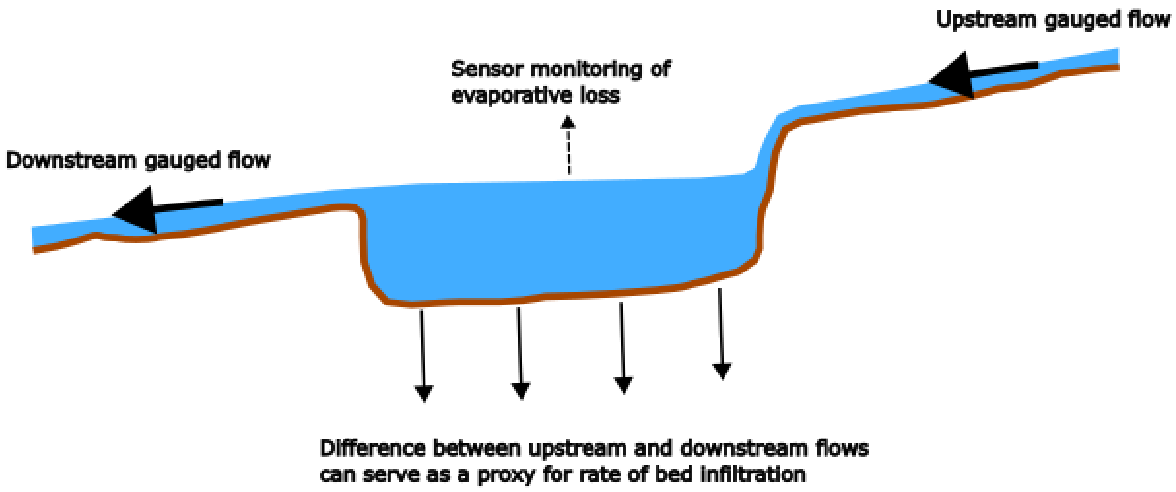


Figure 4-2: Cross section of a RAF, illustrating how flow gauging can be used to estimate the infiltration rate to groundwater

4.2.2 Spatial scale

Questions of spatial scale arise when rolling out NBS across a landscape. As there must be a physical upper limit on the extent to which recharge can be increased to a given aquifer, the intensive deployment of NBS must yield diminishing returns beyond a certain point. However, for most practical implementation options, regional groundwater modelling studies (which have typically focused on catchments with existing pressures on groundwater resources) have concluded that this upper limit is typically far out of sight. That is, increasing the scale on which NBS measures are implemented does not compromise their effectiveness. This contrasts with principles in Natural Flood Management, whereby the flood-mitigating effects of upland interventions can become attenuated with increasing catchment size.

4.2.3 Co-benefits and trade-offs

It is inevitable that the implementation of NBS4WR schemes will have wider environmental impacts beyond enhancing water resources. Although a given scheme may be primarily funded and designed to deliver water resources benefits, a myopic focus on water resources alone should be avoided.

The wider environmental benefits of NBS4WR are multiple and every effort should be made to maximise these positive externalities. Often, NBS4WR features can be optimised to deliver these co-benefits with relatively modest modifications, which are not to the detriment of water resources objectives. Identifying these synergistic relationships and exploiting them when designing and constructing suites of NBS is key to maximising natural capital gains.

Figure 4-3: Visualising opportunities for multiple benefits of NBS

However, designing NBS measures specifically for water resources benefits may conflict with other environmental objectives; elements of a design that are optimal for water resources may not be optimal for delivering other benefits. Managing these trade-offs is an inherent part of planning a landscape. Planners must remain cognisant of competing aims and be able to balance different factors when making decisions.

4.2.4 Integrating NBS with water infrastructure

NBS can protect water resources, increase ecosystem resilience and enhance environments. However, NBS measures may provide services at a less predictable rate than specially built infrastructure, and any system will have a limited capacity. For example, the implementation of NBS4WR may reduce the incidence of low flows during most summers, but drought storage may be required to maintain supplies during exceptionally dry years and meet regulatory requirements.

To gain the full benefit of NBS for water resources, they may need to be integrated with infrastructure developments such as seasonal water storage or water delivery networks. Protecting and enhancing existing nature-based water services can increase the efficiency of water infrastructure, prolong its lifespan, and reduce the need for expensive infrastructural alternatives that are required due to degrading natural services. Integrating NBS into infrastructure planning and investment may reduce costs, provide new livelihood and recreation opportunities, and increase the sustainability of water management systems.

Integrated systems may also be more resilient to climate change, by providing multiple mechanisms to achieve a joint aim.

4.3 Creation vs restoration vs maintenance of NBS

This handbook focuses on NBS which work with natural processes. These NBS are designed to emulate and manage natural processes. However, the majority of benefits accrued from the landscape are from systems and processes that already exist. Maintaining and preserving existing systems should be the priority of any water resource management program. For example, protecting the excellent soil structure and health of a historic meadow acts on the same part of the water cycle as enhancing the degraded soil structure of an arable field, with minimal impact, and supports a wide range of co-benefits.

The figure below shows that NBS fall on a spectrum.

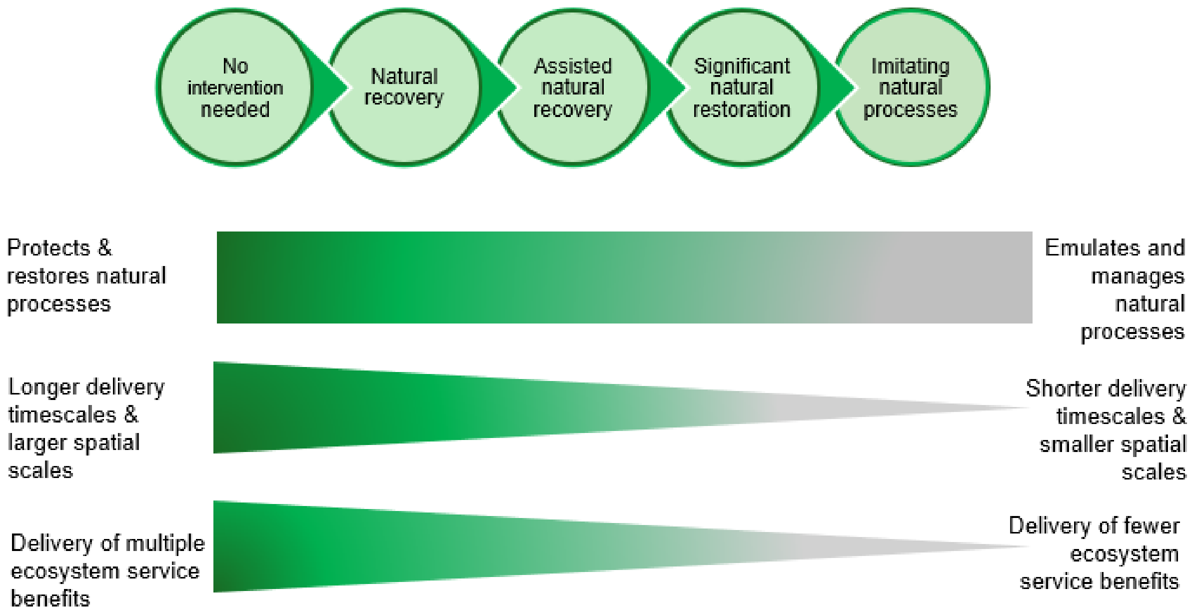


Figure 4-4: The Spectrum of Nature-based Solutions

An example along the spectrum can be found by considering improving soil health and infiltration basins. Both may aim to lead to less runoff and more recharge to ground. Improving soil health will focus on protecting and restoring natural processes, whereas the infiltration basin could be considered as managing a natural process. Both have their place, and in fact schemes that look to manage natural processes may be able to enhance the benefits accrued beyond just protection and restoration. However, if there is a choice between restoring soil health or installing an infiltration basin (whilst keeping a degraded system upstream to maintain a supply of runoff to the basin), restoring and maintain the existing environmental function provided by improved soil health improves the system, prevents further degradation, and provides other ecological, social, and water quality co-benefits at lower cost. The choice becomes even clearer if it is between maintaining and protecting an area of excellent soil health and allowing it to degrade and replacing its infiltration function with an infiltration basin.

4.4 Useful references

There are a wide range of other existing references available which support the delivery of NBS to provide water resources benefits (see Table 4-1).

Table 4-1 Nature-based Solutions Water Resource references

Organisation	Title	Available at:
Environment Agency, 2017a.	Working with natural processes: Evidence Directory.	https://assets.publishing.service.gov.uk/media/6036c5468fa8f5480a5386e9/Working_with_natural_processes_evidence_directory.pdf
Environment Agency, 2017b.	Working with natural processes: Using the evidence base to make the case for Natural Flood Management, Chapter 3 Hydrogeological and geological guidance for NFM.	https://assets.publishing.service.gov.uk/media/6036c7f9d3bf7f0aaa2a45fa/Working_with_natural_processes_using_the_evidence_base.pdf
Environment Agency, 2020.	Water Resource Benefits of Working with Natural Processes: Final Report. Environment Agency, 2021a. Counting the cost of flooding.	https://www.gov.uk/government/news/counting-the-costs-of-flooding
Environment Agency, 2023.	Nature-based Solutions to Water Management and Their Impact on Water Quality: A Scoping Review. Internal Report ENVWLB00568/R.	
Environment Agency, 2024a.	Exploring the use of resilience concepts in catchment management. Bristol: Environment Agency.	https://assets.publishing.service.gov.uk/media/65faafbe703c42001a58f01f/Exploring_the_use_of_resilience_concepts_in_catchment_management_-_report.pdf
Environment Agency, 2024b.	Improving river habitats to support wildlife during high and low flows.	https://www.gov.uk/government/publications/improving-river-habitats-to-support-wildlife-during-high-and-low-flows
Environment Agency,	Multiple benefits of nature-based solutions:	https://assets.publishing.service.gov.uk/media

Organisation	Title	Available at:
2025a.	an evidence synthesis.	/67ab5f525d27cee6cccec485/Multiple_benefits_of_nature-based_solutions_-_report.pdf
Environment Agency, 2025b.	Working with natural processes: Evidence directory update. FRS21232/MR.	https://assets.publishing.service.gov.uk/media/67c6e14c68a61757838d2265/FRS21232_Research_report.pdf
Nature Conservancy, 2024.	Nature-Based Solutions for Drought Resilience.	https://www.nature.org/content/dam/tnc/nature/en/documents/COP16-UNCCD_DroughtBrief.pdf
UN Environment-DHI, UN Environment and IUCN, 2018.	Nature-Based Solutions for Water Management: A Primer.	https://www.unepdhi.org/wp-content/uploads/sites/2/2020/05/WEB_UNEP-DHI_NBS-PRIMER-2018-2.pdf
Water Resources East, 2025.	Intervention level best-practice guidance on monitoring of nature-based solutions.	https://wre.org.uk/intervention-level-best-practice-guidance-on-monitoring-of-nature-based-solutions/

4.5 Uncertainties and further work

There is a considerable amount of work that has been done to date to understand NBS in the context of improving water resources. In this handbook, we have sought to present what we consider to be the most important aspects of this work, but the handbook is not intended to be an exhaustive resource. There are a number of avenues for further work that could be used to refine best practices for delivering NBS:

- Some regions of the country have been the subject of more detailed work to date (e.g. East Anglia). Further work could be done across other parts of the UK to gain an understanding of geographical variability.
- Gaps in scientific knowledge could be the focus of future research.
- Synthesis of lessons learned and best practice from experts rolling out novel or innovative schemes.
- Monitoring techniques may increasingly be able to harness new and emerging technologies, including artificial intelligence.
- Working more closely with other NBS workstreams to understand how best to optimise outcomes, secure funding, and publicise success stories.

Further discussion of the gaps in the evidence base can be found in the Environment Agency's evidence synthesis for the Chief Scientist's Group (Multiple benefits of nature-based solutions: an evidence synthesis. Chief Scientist’s Group report. Environment Agency (2025)).

Nature-based Solutions for Water Resources Handbook

Part 2

Appendices

5 Appendix. Literature review

There are multiple parts of the water cycle, and locations within catchments, where Nature-based Solutions for Water Resources could be implemented, as discussed in chapter 2. This chapter provides a literature review of the key NBS4WR proposals, namely:

- Changes in water usage
    - Crop choice – evapotranspiration rates and reduced irrigation demands
    - Using bare soils or cover crops
    - Changes to woodland management

- Changes in infiltration and runoff splits
    - Improving soil structure
    - Changes in surface roughness

- Capturing runoff and changes in infiltration
    - Runoff attenuation features
    - Purpose-built infiltration basins
    - Cross-slope interventions

- Changing floodplains and river restoration
    - River-floodplain connectivity
    - Wetland restoration
    - Upland and lowland peat restoration

Frequently, the primary focus of many of the sources used in the literature review is not NBS4WR. For example, work on infiltration basins has focused on their effectiveness in dealing with runoff rather than their effects on aquifer recharge, but this review aims to identify some key inferences for NBS4WR. Because of the wide-ranging scope of NBS4WR, and the limited literature that solely focuses on it, this review is not comprehensive or exhaustive but aims to illustrate key issues, common themes, and general principles.

Methodology

A systematic review of the literature was undertaken by conducting journal searches using key search terms. This was supplemented with materials provided by the project steering group. Evidence was taken from UK-based research preferentially. In the absence of UK-based evidence, research from other countries was used.

5.1 Water usage and land use change

Spatial variations in land use, or human interventions to land use, can have a significant effect on water uptake by altering evaporation, transpiration losses, irrigation demands, and rainfall interception. These can lead to changes in groundwater resources and stream flow. This chapter reviews literature on three land cover management practices:

1. Changing to crops that have lower evaporation rates and water demand
2. Adding cover crops compared to bare soil
3. Changes in woodland management

5.1.1 Crop choice, evapotranspiration rates, and water demand

Evapotranspiration comprises soil and plant surface evaporation and the water usage by a crop for growing and cooling, taken up by its rooting system from the soil root zone (Al-Kaisi, 2000). This will vary from species to species, with soil type, and throughout the year. Agriculture is responsible for around 70% of water abstractions globally (UN Environment-DHI, 2018), therefore changing to lower water demand crops can have a significant benefit for water resources.

Change in crop type can significantly influence annual evapotranspiration rates. Studies have also evaluated how intentional crop changes affect evapotranspiration and stream flow. Holder et al. (2019 - USA) observed that converting grassland to *Miscanthus* increased recharge by 40%, whereas Short Rotation Coppice raised evapotranspiration rates and reduced water yield. However, these changes had a limited (but potentially significant) net effect on stream flow (±5%).

Zhang and Schilling (2005 - USA) reported that between 1940 and 2003, stream flow in the Mississippi increased by 31–41%. This was considered to be due to more precipitation being routed as baseflow rather than storm flow, attributed to replacing perennial vegetation with seasonal row crops like soybeans. Reduced evapotranspiration and increased recharge may thus have resulted in higher baseflow and stream flow (Zhang and Schilling, 2006).

Qi et al. (2011 - USA) compared modified crop management with conventional crops and found that modified crop management produced higher evapotranspiration rates but similar drainage, reducing surface runoff and likely decreasing stream flow.

Groundwater modelling studies further support this. JBA Consulting (2023 - UK) modelled the impact of converting arable land to horticultural crops —characterised by shallower root structures and intermittent growing seasons—in the River Wensum, River Cam, and River Bure catchments. The model results indicated that this would lead to an 11% increase in interflow, an 8% rise in baseflow, and a 5% increase in rapid runoff. It was found that river flows increased at all exceedance levels, with up to 14% increase in average flow (at Q35-Q45).

Specific crop transitions also influenced recharge: converting beet fields to potatoes increased recharge by 8 mm/year, while horticultural crops such as strawberries, apple trees, and linseed added an additional 7 mm/year. Cropping regimes that promote earlier recharge initiation (e.g., August) and lower water demand during winter provided optimal conditions for groundwater recharge, suggesting potential strategies for crop planning to maximise recharge.

Seasonal changes in evaporation rates at different crop growth stages can also impact the seasonal pressures on water resources. Evaporation rates are highest after rainfall and irrigation, and will decrease as the crop canopy grows, covering wet soil and increasing the proportion of transpiration relative to evaporation (Al-Kaisi and Broner, 2014 – USA). The critical growth stages will also differ between crops, changing the timing of water usage. For example, the highest water usage by corn occurs in July and August while water intense bloom occurs later for soybean crops, even though the total water usage is roughly the same (Al-Kaisi, 2000 – USA). Therefore, one crop may have a greater pressure on water resources if it aligns with local periods of drought (Al-Kaisi, 2000 - USA). Zhang and Schilling (2006) attributed the substantial impact of soybean production on Mississippi Valley stream flow over 40 years to the crop's lower water demand and associated soil conservation practices.

Reduction in water demand due to lower evapotranspiration or shorter crop seasons can reduce the irrigation requirements for abstraction of water, reducing the impact on low flows and increasing resilience to drought (JBA Consulting, 2023 – UK). This is a critical consideration in regions with limited water resources or during drought conditions.

Catchment character can play a large role determining the impact of these factors. A detailed study by Peskett et al. (2023 - UK) explored the interaction between land use changes and catchment characteristics in upland Scotland using isotopic and geochemical measurements. The study found that local soil, geology, and topography strongly influence catchment hydrology, often overshadowing the effects of land use changes. This underscores the importance of comprehensive hydrological assessments before proposing land use changes, as underlying physical characteristics may play a dominant role in shaping catchment water storage and flow dynamics.

O'Connell et al. (2004) also underscores the importance of local geology and temporal factors. Their study observed seasonal differences in soil moisture beneath arable crops during the growing season compared to grassland, but no significant differences in annual soil moisture in a chalk catchment. This highlights the need to consider site-specific conditions when evaluating the effects of crop selection on water resources.

In summary, crop selection can influence water resources due to variations in evapotranspiration, total water demand, and seasonal water demand due to critical growing seasons of different crops. It should also be noted that catchment characteristics (soil, geology, topography) have been found to have a greater effect on catchment hydrology than land use changes.

Key findings:

- There are large variations in evapotranspiration between crops and between crop management regimes.
- Converting to crops with lower water demands can increase infiltration rates, soil water storage and recharge. This can translate to increases in river flows, but the effect is less pronounced.
- Water demands change seasonally. Crops with a critical growing season outside of drier seasons have reduced irrigation demands and could optimise water resources.
- Catchment characteristics (soil, geology, topography) can influence the impact of crop changes, emphasising the need for site-specific advice/catchment management approaches.

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5.1.2 Cover crops compared to bare soil

Cover crops are commonly recommended as part of land management practices to stabilise soils between seasonal or annual crop cycles. They are also proposed as NBS to reduce surface runoff and enhance soil health, discussed in section 5.2.1.

Most studies found that cover crops increase evapotranspiration, reduce soil moisture, and decrease groundwater recharge compared to bare soils (Meyer et al., 2019 - global; Qi et al., 2011 - USA; Blanchy et al., 2023 - Europe). The extent to which drainage and groundwater recharge are reduced varies, with no main determining factor found as to why based on meta-analyses of multiple studies (Meyer et al., 2019 - global).

The impact is less pronounced in permeable catchments. For example, Meyer et al. (2019) and O'Connell et al. (2004 - UK) observed minimal differences in soil moisture under arable crops and grassland in a chalk catchment. O'Connell et al. (2004) concluded that land use management had no measurable effect on aquifer decline in such contexts.

While bare soils optimise recharge, they negatively affect water quality. Wang et al. (2021 - global), in a meta-analysis of 121 studies, found that cover crops could be integrated into Nature-based Solutions for water resource management. Though cover crops reduce soil water storage and rainfall retention compared to bare soils, they showed no adverse effects on crop yields. Additionally, they decreased evapotranspiration by 6.2% and improved crop water use efficiency (the ratio of plant biomass to water loss by transpiration) by 5%.

Despite reduced groundwater recharge, cover crops offer recognised benefits relative to bare soils. Blanchy et al. (2023 - Europe), synthesising 161 studies, noted that 'continuous living cover' enhances carbon sequestration, stimulates biological activity, and improves soil aggregation and enhances bio-porosity. These improvements promote infiltration and reduce surface runoff. Additionally, cover crops significantly improve water quality by limiting nitrate leaching into aquifers and reducing soil erosion.

Key findings:

- Cover crops typically increase evapotranspiration, reducing soil moisture and groundwater recharge compared to bare soil.
- In permeable catchments, the impact of cover crops on soil moisture relative to bare soils is less pronounced.
- However, cover crops offer other recognised benefits relative to bare soils, improving soil health, which can increase infiltration, and reducing damage during rainfall and runoff, improving water quality by reducing nitrate leaching and soil erosion.

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5.1.3 Changes in woodland management

Woodland planting is a widely adopted Nature-based Solution due to its ecological and habitat creation benefits. It is also employed to stabilise slopes and reduce flood risk as part of Natural Flood Management (NFM) strategies. Trees and forest soils can regulate water flows, storing water and slowly releasing it. The role of woodlands in attenuating surface runoff flows by slowing the velocity of runoff and reducing peak flows has been widely studied within a flood risk and ecological context (see Pearson et al, 2025).

However, the specific impact of afforestation for water resources, appears to be highly variable and often negative, depending on cover, species, and density. This was reviewed as part of an assessment of the multiple benefits of Nature-based Solutions (Chapter 2.3.2, 2025). This review considered the effect of woodland on water resources. Although in the short term it appears that woodlands, particularly conifers have net negative impacts for water resources, broadleaf woodlands can have long-term benefits (Broadmeadow & Nisbet, 2024).

Forest and forest crops generally have a high water demand. Fahey and Payne (2017 – New Zealand) monitored forestry plantations over 22 years and observed a 26% reduction in low flows and 33% reduction in annual water yields in forested plantations relative to unforested catchments. Similarly, a long-term monitoring study in Northern England found a 250-300mm annual streamflow reduction following the development of mature spruce forest over grassland (Birkinshaw et al., 2014 - UK). Fennell et al (2023 - UK) modelled changes in low flows in an upland Scottish catchment from tree planting and assessed the impact on local whisky production. The study found that tree planting led to reduced recharge, decreasing low flows and increasing the number of days of low flows by 11-25 days relative to the baseline, impacting production at the distillery.

Collins et al. (2023 - UK) highlights the negative impact that land-based natural flood management interventions may pose for water resources in groundwater-dominated catchments. Modelling the upper Thames catchment, the paper found that both tree planting and sustainable agriculture scenarios led to decreased low flows due to greater evapotranspiration. Broadscale planting of spruce had the greatest negative impact, due to high evaporative losses throughout the year, leading to lower recharge and a 39% reduction in Q95 flows, increasing drought intensity by 134% despite benefits for flood reduction. This highlights the importance of weighing up reduced low flows and recharge when considering flood risk management projects in permeable groundwater-dominated catchments.

The type of woodland significantly influences water resources, with variations in rooting depth, density, and water uptake. Coniferous plantations generally have higher interception rates and greater water loss compared to deciduous woodlands (Robinson et al., 2003 - Europe; O'Connell et al., 2004). Dunn et al. (1995 - UK) documented evapotranspiration rates for various land covers in the Tyne catchment (Table 5-1), finding that evergreen woodland had over twice the annual evapotranspiration rate of felled woodland (bare soil). Areas of dense evergreen woodland could therefore be expected to limit the contribution of rainfall to river flow.

Table 5-1: Total annual rainfall and evapotranspiration in the Tyne Basin (Dunn 1995)

Land Cover	1985-1989 Average (mm)
Rainfall	*752*
Arable	554
Bracken	411
Conurbations	438
Deciduous	633
Evergreen	766
Felled	338
Grass	475
Heather	473

Calder et al. (2002 - UK) quantified recharge under different woodland types, estimating oak woodland recharge at 17% of rainfall, compared to 6–8% for Corsican pine. Archer et al. (2012 - UK) investigated the impact of different land use types in the Scottish borders and found that old mixed forests (500-180 years) had five to six times greater infiltration capacity than grassland, although soil moisture depletion rates may be greater and rewetting slower in the woodland (Green et al., 2006 - UK).

Despite these challenges, there is evidence that woodlands can have long-term water resource benefits. Woodland planting has been shown to enhance soil hydrology over time. Murphy et al. (2020 - UK) demonstrated that woodland planting improves soil structure, reducing compaction, increasing macro-porosity, and doubling saturated hydraulic conductivity over 15 years. These changes enhance infiltration and reduce surface runoff, aligning with Monger et al.'s (2022) findings and suggesting that woodland planting could support long-term water resource improvement through soil recovery. Most reforestation studies consider short monitoring periods, which may not cover the timespan of soil restoration, and detect any long-term water resources benefits.

Additionally, the effect of woodland planting on water resources and stream flow varies depending on the scale of implementation. While large-scale planting, such as industrial forestry, is water-intensive, small-scale planting may have minimal impacts on water resources. Collins et al. (2023) found negligible impacts on stream flow (0.2–2.6% peak flow reduction) from realistic small-scale tree planting scenarios in permeable catchments, however broad-scale planting scenarios reduced Q95 flow by 39%, negatively impacting water resources.

Furthermore, local catchment properties can have a more significant influence on water resource availability than land cover. In upland areas, soil hydraulic properties, geology, and topography have been shown to exert a greater influence on catchment storage potential and spatial variability than woodland cover (Peskett et al., 2021 - UK).

Another complexity is added by the impact of forests on atmospheric moisture vapour availability due to evapotranspiration from forests. Ellison et al (2012 - global) emphasises the importance of considering the impact of land use changes at multiple scales. They infer that while trees can decrease recharge at the scale of small catchments through high demand, they can increase the supply of precipitation and water availability, raising the recharge potential at a regional and global scale.

Overall, careful targeting and a thorough understanding of catchment characteristics are therefore essential before implementing or excluding woodland planting as a strategy for water resource management.

Key findings:

- Woodland planting can increase water demand due to the high evapotranspiration rates of trees relative to other land use types. This can reduce groundwater recharge and stream flows.
- The impact varies with species, density, and woodland type. Coniferous woodlands are generally more water intensive that deciduous woodlands.
- The impact of tree planting on water resources is scale dependent, with small-scale plantation having limited effects on streamflow.
- The complex impacts of woodlands demonstrates that not all Nature-based Solutions always benefit water resources.
- Woodland planting improves soil hydrological function over time (compared to pasture), storing water in soil and root systems, and slowly releasing it through seepage. So, expansion of woodlands may enhance water resources in the long term via soil recovery.
- Forests can intensify the hydrological cycle increasing the supply of precipitation leading to long-term increases in recharge.
- Understanding local geology, soil properties and topography is crucial for optimising woodland planting for water resource management.

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5.2 Runoff infiltration split

Improvements in soil health and increased surface roughness at the point that rainfall lands can reduce runoff generation and improve infiltration into the saturated zone, leading to increased aquifer recharge. This chapter reviews literature on two practices:

1. Improving soil structure
2. Changes in surface roughness

5.2.1 Soil structure

Soil structure refers to the arrangement and organisation of particles in the soil which determines the pore spaces in the soil. Soil structure is influenced by factors such as climate, biological activity, and soil management practices (Hillel, 2003). There is a large body of literature indicating that soil structure is an important control on infiltration capacity, generally directed at flood benefits from sustainable farming practices. Palmer et al. (2013 - UK) note that nearly 40% of soils in south-west England are structurally degraded, leading to increased runoff and decreased winter recharge to aquifers, with the greatest degradation and runoff from maize, where soils are frequently bare and compacted.

Soil structure can be improved by measures which reduce compaction and/or increase soil organic matter such as low or zero till systems, crop rotation, cover crops and mulching. Although cover crops have higher evaporation rates than bare soils (section 5.1.2), their role in improving soil structure provides infiltration benefits that may balance the increased evapotranspiration.

Improving soil structure can increase runoff infiltration as the pore structure of healthy soil retains a greater volume of water in dry weather, and coarse-textured soils help rapid percolation to the aquifer. Wallace and Chappell (2019 - UK) observed a 7.5 times increase in permeability (K_{fs}) due to blade aeration. Basset et al. (2023 - global) review the range of experimental and theoretical literature on this topic, and emphasise that soil amendments, crop management, and reductions in tillage significantly correlate with infiltration into soils.

Griffiths et al. (2018 – UK, Netherlands) present evidence that infiltration rates are significantly higher in fields with non-inversion tilling than conventional tilling. However, the paper highlights the challenges of monitoring the impacts of soil improvements on infiltration in the field. The paper suggests that earthworm abundance can be used as a proxy for infiltration rates, as earthworm burrows can increase soil infiltration rates significantly in untilled soils.

Additionally, the outcomes of tillage method for infiltration rates are not always the same and may vary with soil type and slopes. Lipiec et al. (2006) observed 61% lower infiltration under no-till agriculture than conventional tilling.

Pastoral farming can also impact soil structure and infiltration rates. Dunne et al. (2010 - Kenya) observed the impact of different cattle stocking densities on infiltration on rangelands in Kenya and found reduced infiltration in some circumstances due to trampling. This is supported by a meta-analysis by Basche and DeLonge (2019) which found that livestock systems were more likely to contribute to an overall decline in infiltration rates through soils by approximately -21.3% (with a confidence interval of -50.3-7.9%, based on 24 English language studies). Conversely, hydraulic conductivity from deteriorated soils can naturally recover to 10-15cm from the exclusion of animals, through burrowing by macro-invertebrates (Drewry et al., 2006 – NZ).

Although sustainable farming and improved soils can be encouraged by increased standardisation of soil monitoring and clear communication to farmers, this may not be appropriate in all settings. Subsurface geology must be accounted for; Delin et al. (2000 - USA) investigated the impact of microtopography and soils on recharge in maize agricultural fields in Minnesota but found that fine-grained laminations in the unsaturated zone retarded the flow path of surface water to groundwater, reducing recharge rates. Palmer et al. (2013) observed limited soil degradation on chalk and limestone areas, and the impact of soil enhancements for recharge is likely to be negligible on low-permeability clay soils.

Model studies indicate the relationship between improved soil infiltration and baseflow. Packman et al (2004 - UK), discusses how the Flood Estimation Handbook (FEH) rainfall-runoff model and Flood and Agriculture Risk Matrix (FARM) can be used to evaluate the impact of land use and soil management on baseflow. These modelling techniques can be a useful guide to understand the potential effects of interventions. Holman et al. (2011 - UK) modelled the effect of soil management on catchment baseflow. They ran a large array of models over thirty years for a range of variables reflecting catchments in England and Wales. The study suggests that 10% increases in baseflow index can be achieved with reasonable improvements in soil structure in some catchments. Changes were more limited in southern and northern England highlighting the importance of soil type, superficial geology, land cover, and climate on the potential to achieve baseflow increases.

In summary, healthy soil with intact soil structure can increase infiltration. Basche and DeLonge (2019) state from their meta-analysis that practices promoting ground cover and continuous roots, both of which improve soil structure, were most effective at increasing infiltration rates. However, the impact can vary based on local soil and geology.

Key findings:

- Maintaining healthy soil structure can increase infiltration.
- Non-inversion tilling and the sustainable management of livestock can improve soil structure.
- However, the impact will vary depending on underlying soils and geology: in saturated soils, or those with low-permeability, soil improvements may not increase infiltration.
- Modelling can be a useful for assessing the potential effect of soil improvements for different geologies and catchments.

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5.2.2 Increasing surface roughness

Although increases in surface roughness, through changes in soil roughness, buffer strips, and increased microtopography, can slow and reduce runoff, there is limited literature addressing the connection between roughness and infiltration. However, the study by Zhao et al (2013 - China) found empirically that soils with rough surface textures had increased infiltration capacity compared to smooth soils, on cultivated slopes in China, suggesting that improved microtopography and textured soils may have the potential for greater recharge.

Cole et al. (2020) reviewed the environmental impacts on buffer strips and noted increased infiltration and water retention where wooded buffer strips increased soils permeability due to their deep roots. This was also reflected in a report by Stutter et al., (2020 - UK) which showed that riparian buffers create a physical barrier which slows overland flow and increases infiltration to the soil which has the overall effect of trapping and retaining pollutants before they reach watercourses. Both studies showed that buffer strips increase infiltration to the soils, but there were no specific monitored changes to groundwater levels and water resources.

Lu et al. (2024 - China) modelled the impact of microtopography in agricultural regions on surface-groundwater interactions. The study found that microtopography has a significant effect on response times of groundwater, slowing the rate of infiltration but increasing the range of response times, and should not be neglected in models.

Wetland and peatland restorations also lead to increased surface roughness. The impact of this is discussed in section 5.4.2. The review found no reported studies in the following areas that would have been of particular interest:

- Comparisons between roughness and recharge on arable land versus grasslands
- Comparison within grassland types, especially between intensive and extensively grazing, and the impact of improvement measures
- Comparison of different methods of increasing roughness, such as leys, buffer strips, stubble, and microtopography

Key findings:

- Increased surface roughness can attenuate runoff, increasing infiltration and recharge. However, the range of field studies available on this is limited.

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5.3 Runoff attenuation features and infiltration basins

Runoff attenuation features are landscape features designed to create a temporary flow storage, slowing the flow of surface runoff, and facilitating infiltration. These include swales, ponds, bunds, and barriers across flow paths designed to store water and slowly release over time. Often the primary aim of these features is for Natural Flood Management. Infiltration basins direct surface water into groundwater. This chapter reviews literature on three practises:

1. Runoff attenuation features
2. Purpose-built infiltration basins
3. Cross-slope interventions

5.3.1 Runoff attenuation features

The use of leaky dams to improve baseflows and recharge aquifers, has historically been widely used in drier areas, (Standen et al., 2020 – global). Hut et al (2008 - Kenya) highlight examples of structures used to maintain water supplies in a range of areas and presents a model to evaluate the impact of sand groundwater dams on groundwater levels in Kenya.

Runoff attenuation features that store water in times of high flows, such as offline ponds, can also be used to supply additional irrigation during periods of lower flows, helping to improve low flows in rivers and increase resilience to drought (Camnasio and Becciu, 2010 - Italy). Although irrigation construction is beyond the scope of Nature-based Solutions, it is worth considering in the holistic assessment of any project.

Norbury et al. (2021 – UK) monitored changes in baseflow before and after RAF installation in the Pennine Uplands. These installations took the form of log jam leaky barriers, which are cost effective to install. The study observes both significant reductions in peak flows during flood events alongside 27% increased baseflow during dry periods. They summarised that ponding due to RAFs slows groundwater velocities, increasing storage during dry periods, while also allowing greater infiltration of surface water. This observation underlines the potential for RAFs to increase resilience of rivers to droughts, at least over short river stretches.

The first large-scale monitored use of RAFs in the UK was undertaken at Belford, Northumberland, with a focus on flood prevention (Nicholson et al., 2020 - UK). The project involved the construction of storage ponds and leaky barriers composed of bunds, vegetation, and woody debris. Nicholson et al. (2020 - UK) measured 12% reductions in the size of peak flows during small flashy storm events, evidencing that the RAFs provide a low impact and ecologically beneficial means of protection for properties at lower cost than traditional flood defences in this small catchment.

Although the focus of study by Nicholson et al., (2020 - UK) at Belford was on flood prevention, it can be inferred from the study that the drop in runoff may be linked to increased infiltration and groundwater recharge. However, the study highlights that infiltration at depths greater than 60cm is very limited, with the active hydrological zone in the Belford catchment restricted to the top metre of the subsurface. Wilkinson et al. (2010 - UK) present evidence that the RAFs applied in 2007 and 2008 reduced flooding during heavy rainfall in September 2008 by storing runoff for 8 hours. It may therefore be that RAFs are delaying the movement of runoff into the river over short periods, spreading out the volume of flow but not aiding infiltration; this could benefit from further field research in this catchment.

A study by the James Hutton Institute at Elm Sike, Scotland, also highlights the importance of site parameters, design, and placement for the efficacy of RAFs (Addy and Wilkinson, 2017). They found minimal evidence of impacts on low flows from leaky barriers after three years of monitoring, suggesting that the potential for water resource benefits from Runoff

Attenuation Features is limited in steep confined streams. It can be inferred from the study that it is likely that sites with lower gradients and wider floodplains, with RAFs placed along flow pathways, have greater potential for off-channel water storage.

Modelling can be used to understand the potential of RAFs in different catchments. Fennell et al. (2022 – UK) modelled the impact of nature-based runoff attenuation features on low flows in a Scottish catchment. They modelled the impact of the size and location of RAFs and found that the installed scheme led to a 0.1% increase in recharge and 4% increase in baseflow, alongside small increases in low flows and reduced high flows. Modelled RAFs were found to be most effective when distributed across a wide area, and on well-draining soils.

In a 1km upland catchment feeding the Glenlivet distillery, Fennell et al (2023 – UK) modelled a 3% increase in in Q95 with RAFs positioned through the catchment. This was associated with a 25% decrease in the number of low-flow days and halving of the mean number of 7-day consecutive low-flow periods when the distillery may be unable to function, making the installation of RAFs cost effective, particularly when combined with modelling to optimise the location of RAFs.

JBA and WSP have explored the impact of runoff attenuation features in regional models (WSP & JBA, 2023 - UK). A range of RAFs were investigated: surface RAFs at field level, catchment RAFs further down the drainage network, and RAFs at the boundary of Chalk and till deposits. Simple spreadsheet models, alongside 4R and MODFLOW modelling (see section 8) have been applied to investigate the impact of size, type, density, and location of RAFs, particularly across catchments in East Anglia. In general, modelling indicated that increasing the number of runoff attenuation features led to increased baseflows and larger low flows. Superficial geology played a significant factor in the scale of response, with the greatest modelled impact at the boundary between till and Chalk deposits.

However, benefits for low flows may not last during extended periods of drought. Meinen (2022 - Australia) investigated the impact of leaky weirs in Australia. The weirs increased recharge but also increased discharge. Although this led to increased stream flow at the start of the dry season, the rest of the dry season experienced lower discharge flows compared to pre-installation values, suggesting that runoff attenuation features may not deliver lasting benefits when drought is extended.

Although pilot studies and modelling appear to support the potential of RAFs, Quinn et al. (2022 - global) reviews the evidence basis for RAF interventions and emphasises the complex evidence required to prove the effectiveness of RAFs at lowering runoff rates and maintaining recharge. So far, there is a lack of large-scale projects that can empirically demonstrate recharge changes downstream of RAFs in large catchments, or the connection between the residence time of water in RAFs and groundwater flows.

Modelling can be helpful to understand the impact of RAFs on water resources, and underlies the current NFM evidence base, but is not yet supported by long-term observations. The Stroud Valley NFM Project should provide valuable insights to address these unknowns. Over 430 nature-based measures have been installed in the Stroud Valley, including a case study site at Cranham involving 10 leaky log dams at a cost of £280 per structure and 9 earth bunds costing £305 per bund. A long-term monitoring plan has been designed to assess the impact on low flows, groundwater recharge and soil moisture content, Van Biervliet (2022 – UK), which will help provide insights into RAFs and water resources in a larger catchment.

Quinn et al. (2022) argue that overall evidence seems to support the benefits of RAF interventions, particularly leaky barriers, for slowing flows, initiating recharge to depths over longer periods. These approaches seem applicable at both local scales and at large scales across a catchment, particularly when alongside other NBS methods such as peatland restoration, managed floodplains, and afforestation. Additionally, RAFs provide a wider range of benefits including flood attenuation, ecological benefits, reduced erosion, and limiting the movement of diffuse pollutants and sediments, increasing overall landscape resilience.

Key findings:

- RAFs store water and slowly release it, allowing greater infiltration and recharge. They have been shown to increase baseflow and reduce the severity of low flows in downstream rivers and streams in small catchments.
- RAFs also have a range of other benefits, including reducing peak flows at lower cost and impact than traditional flood defences, improving water quality, and supporting habitats.
- Modelling studies can be used to optimise the design and placement of RAFs at local and regional scales.
- However, there is insufficient empirical evidence to fully understand the impact of RAFs on groundwater and residence times in larger catchments.

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5.3.2 Infiltration basins

There is a large field of monitoring studies on the impact of stormwater infiltration basins for mitigating flood risks in urban areas and recharging aquifers. Urban NBS measures include permeable pavements, retention ponds, integrating reedbeds into storm and grey water drainage system, and green roof water harvesting, designed to remove water from the surface to ground, and improve water quality. They can also improve community wellbeing, cool urban areas and help green the local environment (Jarvie et al., 2017 - UK).

Masetti et al. (2015 - Italy) discuss the recharge dynamics of a large (16ha) storm water infiltration basin in Northern Italy above sands and gravels, monitored with a four-year field study and numerical model. They reported that groundwater levels can respond in minutes to recharge from the infiltration basins, with recharge up to fifty times natural levels. However, the study highlights that infiltration basins must be actively maintained to prevent clogging, otherwise recharge can become significantly reduced. Appleyard et al. (1993 - Australia) monitored urban and industrial stormwater infiltration basins in Perth, Australia. Groundwater recharged from the basins within minutes of rain events, with notable salinity reductions and increases in dissolved oxygen downgradient of the SuDS (sustainable drainage systems) basins. Although concentrations of toxic metals and nutrients were found to be low around the basin, the study noted the accumulation of lead and plastics within basins, again highlighting the requirement for long-term maintenance.

Lebon et al. (2023 - France) quantitatively studied the impact of stormwater infiltration basins on unsaturated zone chemistry and microbiology. The study observed increased dissolved organic carbon leading to increased microbial biomass in regions of rapid transit from surface to groundwater, while nitrates decreased due to dilution where recharge was rapid. Additionally, regions with a thinner unsaturated zone saw greater changes in phosphate. Although this handbook mostly considers the physical properties of groundwater – recharge, baseflow, infiltration, runoff etc – understanding the influence of nature-based interventions on groundwater chemistry and biology is important.

Mathematical models can be used to understand potential groundwater recharge from infiltration trenches and basins, and the impact of spatial arrangement of basins. For example, Chahar et al. (2012 - France) present a numerical solution to quantify the movement of stormwater through SuDS infiltration trenches. Choat et al. (2020) model flow dynamics in the unsaturated zone, suggesting that on short timescales the movement of water from infiltration to recharge and baseflow is controlled by partitioning between the unsaturated and saturated zone. Choat et al. (2020) also suggest that a distributed arrangement of discrete infiltration basins, results in greater storage in the unsaturated zone and reduced baseflow, compared to a clustered arrangement of basins. Therefore, clustering infiltration measures could lead to the greatest increase in groundwater recharge, although this is sensitive to the permeability and geology of the subsurface.

Key findings:

- Infiltration basins can significantly increase recharge of the saturated zone, with clustered arrangement more effective than distributed arrangements.
- They can also improve surface water quality, reducing nutrient and sediment loading.
- Infiltration basins require long term maintenance and may impact groundwater chemistry.

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5.3.3 Cross-slope interventions

The role of cross-slope woodlands at attenuating surface runoff, with mixed impacts for water resources, has been discussed in section 5.1.3.

Hedgerows can also be used in a similar manner as runoff attenuation features, slowing surface flows by obstruction. However, there is limited quantitative field data on the impact of hedgerows for groundwater resources. Blanusa and Hadley (2019 - UK) experimentally studied the influence of different hedgerow species on runoff and demonstrate that common hedgerow species can significantly reduce the volume of rainfall runoff. Significantly higher permeability (K_{fs}) values have also been observed under hedgerows than arable land (Holden, 2019), which would facilitate recharge. Wallace et al. (2021 - UK) present empirical data on reduction in overland flow incidence in plots with hedge margins compared to pasture, due to higher infiltration and soil saturation levels, but does not address the split between infiltration and evapotranspiration.

Ghazavi et al (2008 - France) highlight the significant impact of hedgerows on hydrological dynamics, reducing recharge seasonally. Hedgerows increased water uptake from the unsaturated zone in late summer, reducing summer recharge and drying soils. This can act as a barrier preventing lateral subsurface flow. The study observes that the influence of slope hedgerows on soil water extends across the area of rooting, up to 9m upslope. The loss of leaves in winter reduced rain interception and evaporative demand so recharge increased during winter due to reduced root water uptake, and the influence of the hedgerows was insignificant, but it took longer to rewet soils where root density was highest.

Vegetative barrier buffer zones also have been shown to increase vertical infiltration rates at a local scale with 10x greater infiltration in fascines (brushwood stick bundles) with high biological activity than those without (Richet et al., 2017 - France)

Key findings:

- Hedgerows and woodland planted on catchment slopes can act to attenuate surface runoff but may reduce summer recharge due to evaporative demand. However, the range of field studies available on this is limited.

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5.4 Floodplain, wetland, and peatland restoration

Field and model scenarios highlight the range of benefits for water resources that can be achieved by peatland and floodplain wetland restoration and increased connectivity between rivers and floodplains. This chapter reviews literature on three practises:

1. River-floodplain connectivity
2. Wetland restoration
3. Lowland peat restoration

5.4.1 Floodplain connectivity

Increased river to floodplain connectivity can increase the frequency of floodplain inundation, storing water offline across a wider area, and slowing the release of water from the floodplain during drought events. Through the expansion of canalisation, riverbank modifications, and urban development, up to 90% of Europe and North America's riparian floodplains are 'functionally extinct', with severe consequences for freshwater biodiversity (Tockner et al, 2002). Channelisation also increases flow velocities, with negative downstream consequences for low flows and floods (Heritage and Entwistle, 2020 – UK).

Liu et al. (2023 - UK) highlights the trade-offs between water quality and water availability from different NFM measures, suggesting an optimisation framework to balance different management objectives. The study models urban and rural water management in Norfolk and found that water availability is likely to be optimised by a combination of runoff attenuation features with floodplain restoration, with the benefits increasing with the scale of implementation.

Clilverd et al. (2016 - UK) highlight that 40% of river length in England and Wales has been severely modified with a large loss in river-floodplain connectivity. The study found that increasing river and floodplain connectivity by removing embankments increased subsurface groundwater storage, and improved river drainage of the River Glaven, North Norfolk, alongside ecological benefits. Regular flooding along marginal areas increased groundwater recharge and water table levels, while aiding the development of riparian habitats through nutrient delivery. The removal of embankments also allowed the drainage of groundwater and surface water back into the river, increasing stream flow during periods of low flows.

The interaction of rivers and floodplains is complex, and these benefits will not be achieved in all locations or under all meteorological conditions. Clilverd et al. (2016 – UK) highlights the value of a modelling methodology to quantify the impact of restoration and plan suitable restoration sites. Burt et al. (2002 - UK) conducted a numerical simulation of hillslope, floodplain and channel interactions for the River Severn, Shropshire, looking at the reversal of flows towards the hillslopes during flood events. This reduces the input of water from hillslopes to the riparian zones but depends on certain antecedent runoff and rainfall conditions.

Beaver reintroductions can increase the connectivity of floodplains and rivers, and can increase surface water storage by forming ponds. The release of these surface pools can help maintain flows during dry periods, increasing drought resilience (Brazier et al., 2020 - Europe). Raising water levels in the floodplain can therefore increase groundwater recharge. However, raised water tables also experience greater rates of water loss by evaporation. This balance appears to be in favour of improved groundwater resources: a study by Smith et al. (2020 – Germany) found a 5% increase in groundwater recharge in a river following riparian wetland restoration aided by beaver colonisation.

While river-floodplain connectivity can reduce flood peak flows downstream and improve floodplain biodiversity, the storage of water on the floodplain does not necessarily lead to increased infiltration and stream flow. The underlying geology must also facilitate recharge.

Acreman et al. (2003 - UK) model the impact of channel geometry on floods in the River Cherwell, Oxfordshire, and find that renaturalising river channels within the floodplain can reduce flood peaks and increase floodplain inundation, storing water on the floodplains. However, as the catchment is underlain by very impermeable clays, the impact of this intervention would have a negligible effect on groundwater resources.

Key findings:

- Increasing storage within floodplains can reduce high flows during flood events and maintain baseflow during periods of low flows.
- The creation of small ponds on the floodplain, particularly through beaver activity, has been shown to increase baseflow.
- However, the potential for improved groundwater resources depends on geology and the hydrological structure of the floodplain.
- Modelling floodplain hydrology can guide restoration of floodplain-river connectivity under different meteorological and groundwater conditions, ensuring sufficient water resource benefits.
- Floodplains also offer a range of co-benefits such as the settlement of nutrient rich sediments, improving water quality, and fertilising agricultural land. They have high biodiversity.

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5.4.2 Wetland restoration and creation

Wetlands provide a range of ecological benefits and there has been growing interest in the use of floodplain wetlands for flood alleviation and improvement of water resources. Over the twentieth century wetland coverage declined by 64-71%, losing valuable ecosystem services (Davidson, 2014).

In a literature review of non-floodplain wetlands, Lane et al. (2018 - US) considered the flow regulatory services of North American non-floodplain wetlands, highlighting that they can increase groundwater recharge, and store water to maintain baseflows and reduce flood peaks.

Demissie and Khan (1993 - USA) monitored stream flow in catchments with a variety of wetland coverage in Illinois. They observed that a one percent increase in wetland area led to an average 8% increase in low flows (Q95), while decreasing flood volumes. The wetlands increased the resistance to flow, slowing the input to streams, gradually releasing water from offline surface pools to groundwater and stream channels. However, the range of results spanned +22% to -5% changes in Q95, highlighting variation between wetland catchments due to differences in soils and geology.

Wetlands have rough surfaces compared to other land uses, with hollows and hummocks forming microtopography. Frei et al (2010 - Germany) modelled the impact of wetland microtopography on infiltration. They found that the surface depressions buffered the input of rainfall into recharge, leading to subsurface flow throughout the year except during severe storms, while a flat surface experienced flashy response to rainfall events, with greater runoff.

Wu et al. (2020 – China) used a hydrological model to assess the impact of wetlands on watershed hydrology, within the Upper Nenjiang River Basin in Northeast China. The study highlights the significant role of wetlands in attenuating quickflow and supporting baseflow, by slowing surface runoff, with a stronger regulation impact during the summer season, mitigating droughts. The model also suggests that increasing wetland areas enhances their cumulative effect on flow regulation.

Modelling the impact of wetlands for drought mitigation, Wu (2023 – China/Canada), found that wetlands can shorten and reduce the severity of droughts impacts, accelerating recovery and reducing the probability of hydrological droughts by approximately 18% in both a Chinese and a Canadian basin. However, in some situations, wetlands can exacerbate droughts effects, when water has been lost from wetlands by evapotranspiration. It can be inferred from this that the internal properties of soil vegetation and hydrology, as well as external controls by the basin hydrology, precipitation, anthropogenic influences, and climate, all can alter the wetland's impact on hydrological droughts. Furthermore, interventions to buffer wetlands against drought, such as changing the network of dykes to retain elevated water levels, can be effective for improving their NBS function.

Bullock and Acreman (2003 - global), emphasise that the hydrological role of wetlands is far from simple and varies with location and hydrological type. While floodplain wetlands often provide benefits for flood control, recharge and baseflow, in 47/71 studies – particularly headwater wetlands along river margins – wetlands have been shown to increase floods and reduce low flows. Wetlands also have large evaporative losses compared to other land types, so can reduce downstream flows during dry periods. Finally, many wetlands have insignificant interactions with groundwater as they lie on impermeable deposits, so have no recharge impact.

In summary, wetlands do not offer universal benefits for water resources. The location of the wetland in the catchment and its geology must be considered. Protecting and restoring wetlands in the upper catchment can play a significant role in attenuating surface runoff during heavy rainfall, increasing baseflow, and mitigating droughts, alongside ecological benefits.

Key findings:

- Restoring wetlands on lowland floodplains can improve groundwater recharge and reduce surface runoff.
- Wetlands store water in the landscape and can reduce the intensity and length of the effects of drought events.
- Wetlands also provide multiple other benefits including biodiversity gains, as well as taking up excess nutrients, filtering out sediments, and improving water quality.
- However, wetlands are also associated with increased evapotranspiration, and in some locations can reduce low flows, highlighting the variable impact on water resources dependent on location and geology.

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5.4.3 Upland and lowland peatland restoration

Peatland refers to carbon-rich wetlands where waterlogged conditions prevent plant material from fully decomposing, forming soils of partially decayed material which builds up slowly over time. Peatlands are dominated by mosses, sedges and shrubs (UKCEH). In the UK, upland peatlands, often called blanket bogs, are large areas of peat found in the uplands fed primarily by rainfall. Lowland peat can be split into lowland peat and fens. Both are found in flat lowland areas, but lowland peat is primarily rainfall fed, and fens are by groundwater, river water, and rainfall.

Restoration of upland peatlands by blocking drainage has been a major focus of natural flood management. Restoring lowland peatland on floodplains can raise water levels and increase surface roughness, reducing surface runoff (Goudarzi et al., 2024 – UK). In the same study, sphagnum moss was identified as a key peatland species which can deliver significant flood reduction benefits due to its unique properties (it can hold twenty times its weight in water).

However, although increased surface roughness on the surface of peatland can slow the movement of water towards rivers, this does not necessarily lead to increased recharge and baseflow. Holden (2002 - UK) highlights that there is little vertical percolation through peat deeper than 10cm in upland blanket peat, so they generally do little to maintain baseflow. The roughness and retention of peatlands therefore makes them important sinks for water but limits the transmission of water into downstream rivers or aquifers.

Gatis et al. (2023 - UK) also observed no increase in baseflow over four years of monitoring, following the blocking of peat gulleys and raising of water tables in peat in Dartmoor National Park.

In lowland peatland, which is more directly connected to the water table, the water resource response to peatland restoration can be complex. Ahmad et al. (2021) observed that rewetting and restoring fenland maintains high water tables, allowing peat accumulation and improving ecosystem functions. The study found increased evapotranspiration in restored fenland compared to the degraded fen, particularly in dry months, reducing groundwater levels due to elevated water levels and taller vegetation.

JBA (North Somerset Council, 2024 - UK) discussed the impact of methods of peatland restoration on water resources. Restoration requires the raising of water tables, often with a demand for irrigation at the start of projects. Although subsurface irrigation increases the stability of the water table across a wider area of peat, where peat is irrigated from the river the water demand can be as high as 3000m^3/ha, affecting water resources across a wider area. Peatland restoration schemes that rely on storing excess winter rainfall through surface water retention can improve peat conditions and stabilise water levels without reducing water levels elsewhere.

Key findings:

- Restoring upland peatlands can reduce surface runoff. This can maintain elevated water tables.
- The impact on groundwater resources of lowland peatland is often complex and generally is not associated with increased baseflow in rivers. With impermeable soils it may be neutral, but increased evapotranspiration may reduce infiltration to groundwater.
- Restoration of lowland peatland projects should consider the impact on groundwater resources from irrigation and utilise surface water retention over irrigation.

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6 Appendix. Conceptual models for NBS features

6.1 Introduction

Since 2019, the Environment Agency has commissioned a range of studies across England to identify how NBS4WR can be implemented in different landscapes. Works have been done across numerous different catchments. Much of the work has focused on how NBS4WR implementation may vary in Chalk catchments, and extensive modelling studies have been conducted on three Chalk catchments: the Wensum, Cam, and Test. This chapter consists of five parts:

1. An initial discussion on how geology affects the water cycle and the implementation of NBS4WR
2. Presentation of three conceptual models covering the Chalk
3. A discussion and comparison of the findings of studies on the three Chalk catchments
4. Presentation of conceptualisations on two other geology types
5. Conclusions

6.1.1 Value of conceptual models

A hydrogeological conceptual model is a simplified representation of a groundwater system, summarising the understanding of its geological and hydrological framework, including aquifer characteristics, flow paths, and boundary conditions, used for predicting and understanding groundwater behaviour (Brassington, F.C. and Younger, P.L. 2010. A proposed framework for hydrogeological conceptual modelling. Water and Environment Journal 24: 261-273).

The development of conceptual models is based on the available geological and hydrological information, which are observed data, such as water levels, borehole information and tracer concentrations, but often also includes a component of soft knowledge, such as geological insight or expert interpretation.

Conceptual models are valuable resources for understanding and communicating interactions between water and the environment. By simplifying processes in a catchment, we can highlight the dominant controls on groundwater resources. This can support interpretation of how any changes within the catchment system may impact other parts of the water cycle. Visualisation is also a useful tool for communication, aiding understanding of the catchment scale processes for a wider audience.

Conceptual models can help refine the list of potential NBS benefits, by highlighting catchments and locations with limited potential benefits, reducing wasted study effort. The particular features of interest in an NBS4WR conceptualisation are the pathways rainfall can be partitioned into, the split between baseflow and quickflow, and the geological structure at different locations which may affect the water cycle and NBS4WR implementation.

6.2 Geology and the water cycle

Between catchments, the splits in the water budget can differ widely. The variation between catchments should be taken into account in our approach to NBS4WR implementation.

Geology influences catchment hydrology. Figure 6-1 shows the variations of Baseflow Index (BFI) between catchments of different geologies. BFI reflects the proportion of a river's flow that comes from groundwater. In chalky upland streams, the proportion of river flows derived from groundwater can be up to 98%, whereas in low-permeability catchments, that proportion can be as low as 15%. NBS4WR implementation should respond to how different elements of the water cycle vary between catchments.

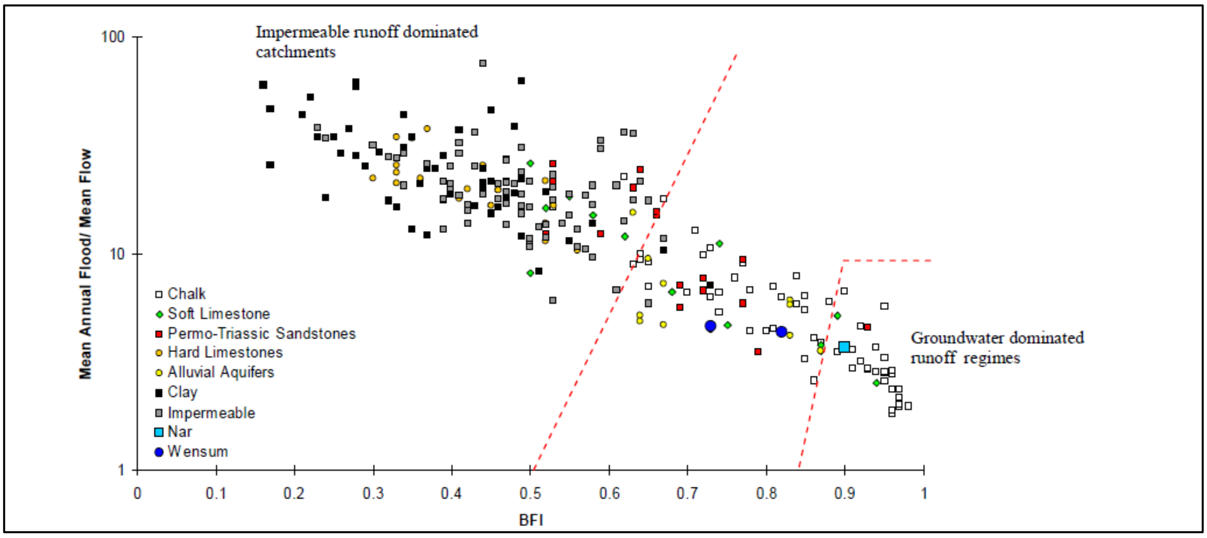


Figure 6-1: BFI between catchments of different geologies (Sear, D. A., P. D. Armitage, and F. H. Dawson. 1999. Groundwater dominated rivers. Hydrological Processes 13 (3): 255-276)

6.3 Three Chalk conceptualisations

This section presents the findings from case studies in the Cam, Test, and Wensum catchments. Figure 6-2 illustrates the locations of the three case study catchments within a hydrogeological map of the UK.

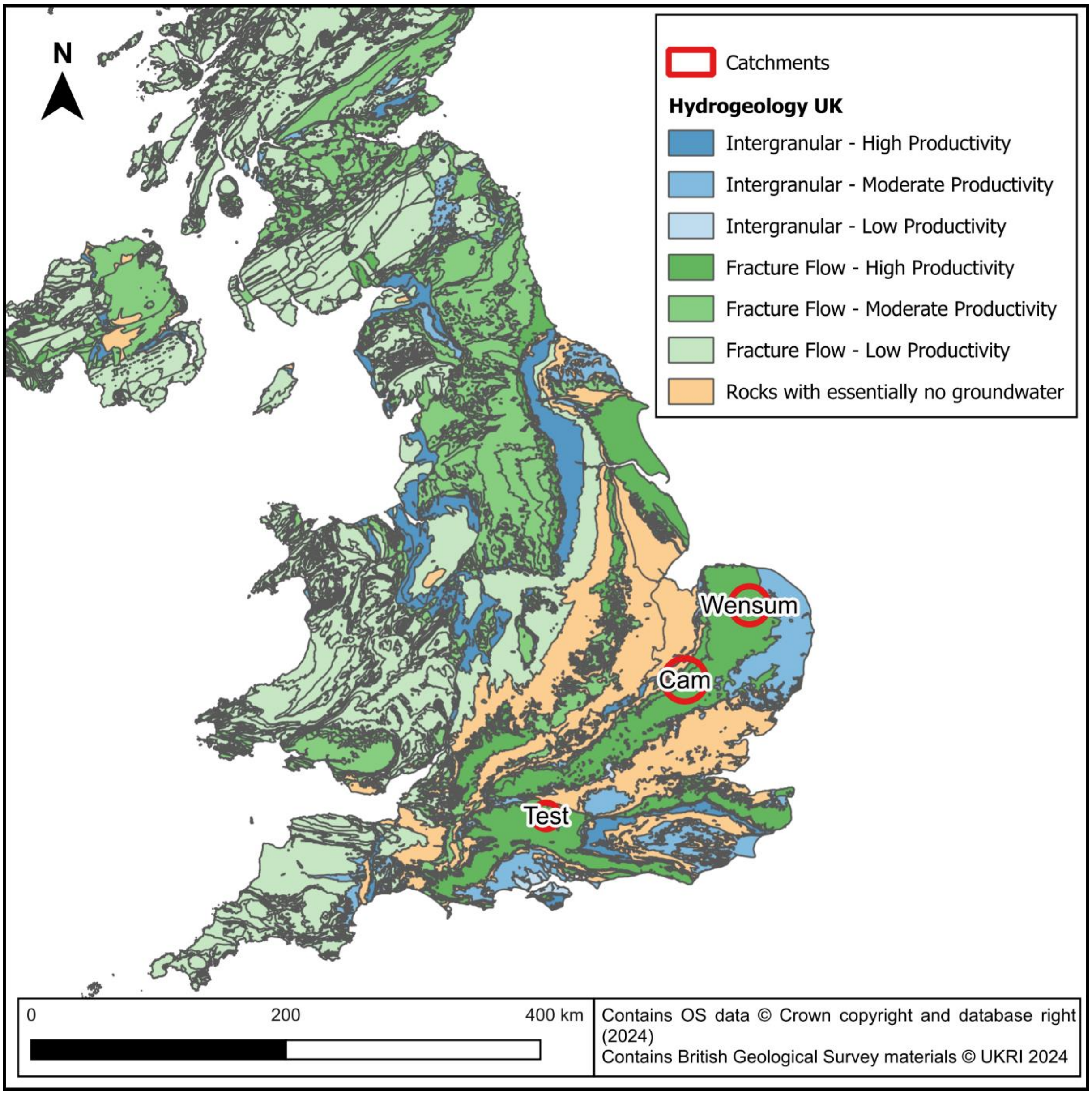


Figure 6-2: Locations of Chalk catchment case studies

Table 6-1 shows the proportion of rainfall, evapotranspiration, runoff, infiltration, and baseflow (groundwater input to river flows) in these three chalk case study catchments, namely the Cam, Test and Wensum catchments. This table shows that even within chalk catchments the water cycle can be very different and the approach to NBS4WR should reflect this.

Table 6-1: Water balance (mm/year) across catchments

	Cam	Test	Wensum
Rainfall	419	915	624
Actual evapotranspiration	314	496	420
Runoff	18	113	32
Interflow	17	7	45
Recharge	76	386	136
Baseflow	47	45	114
Baseflow Index (BFI) range (%)	42 - 94	92 - 94	51 - 75

6.3.1 Upper Cam

Introduction

The topography and geology underlying the Upper Cam's catchment, including superficial and bedrock units, are shown in Figure 6-3.

The Cam catchment is dominated by higher ground in the south and slopes north and north-westwards towards Cambridge and the River Ouse. The terrain falls from approximately 100mAOD in the south to -1.5mAOD in the north. In the east of the catchment, around the source of the Granta and River Kennett, elevations remain high at approximately 100mAOD.

Upland areas are dominated by low-permeability glacial till, covering most of the south and east of the catchment, the rises west of Cambridge, and around Ely towards the downstream extent of the catchment.

Glaciofluvial sediments can be found in a pocket in the upper area of the catchment, and along some of the valley floors south of Cambridge. The valley edges throughout the catchment consist of glaciofluvial sand and gravel deposits as well as river terrace deposits. These also occur as outcrops in the valleys and along tributaries of the Cam, Granta and Kennett rivers. The north of the catchment has limited superficial deposits with mostly peat present and outcropping clay bedrock.

The bedrock across the catchment is oldest in the north and becomes younger towards the southern boundary. The sequence dips slightly south-east.

Chalk bedrock underlies most of the area and outcrops across the eastern and central parts of the catchment, south of Cambridge.

Cambridge sits on the mudstone and marl of the Gault Formation, which extends northeast along the Cam to its confluence with the Great Ouse.

The north of the catchment, above the Cam's confluence with the Ouse, is underlain by an area of the undifferentiated clay units: the West Walton, Ampthill Clay and Kimmeridge Clay Formations, with pockets of Lower Greensand Group.

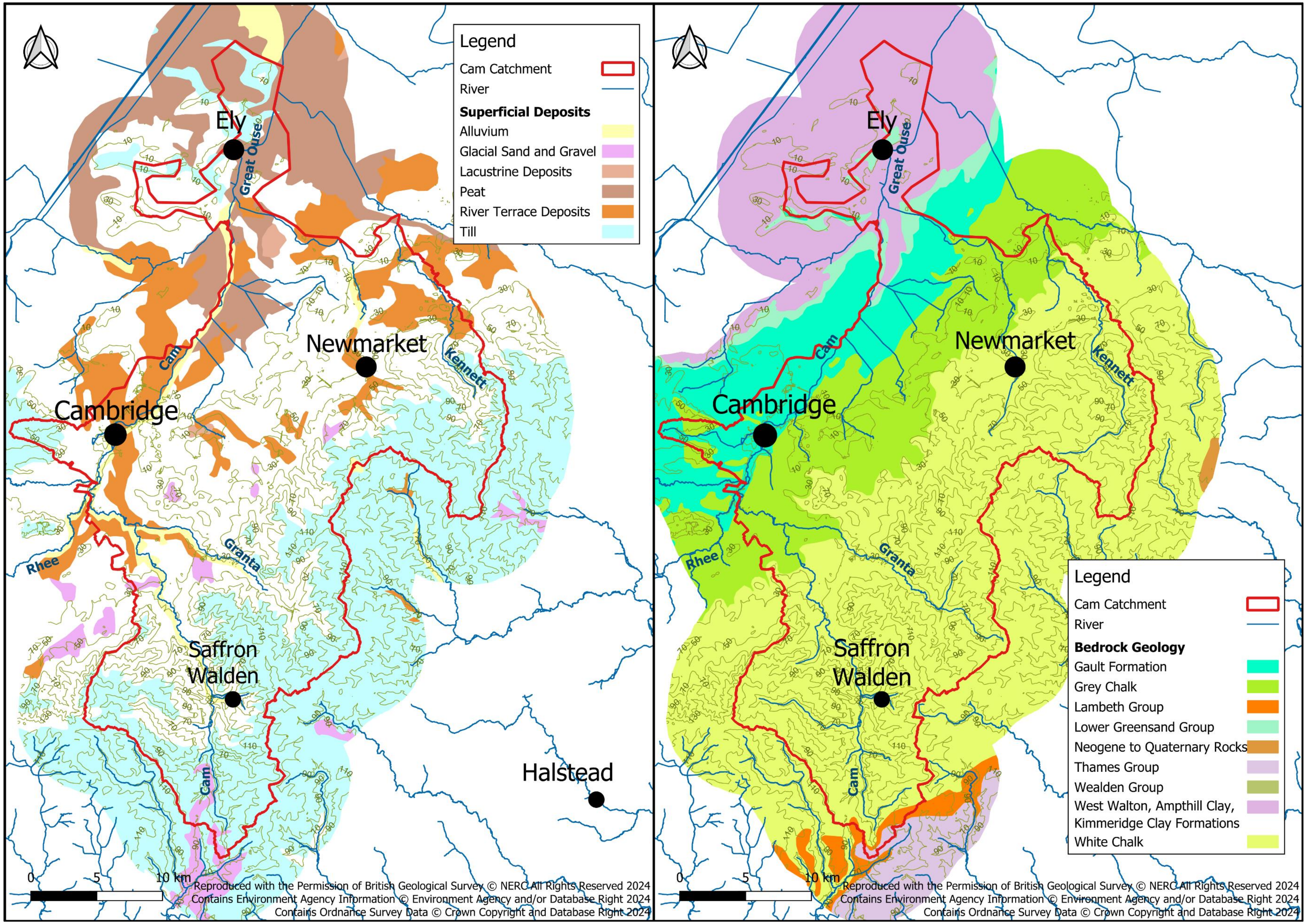


Figure 6-3: Topography, superficial deposits and bedrock units within the Cam catchment

Conceptual model

A hydrogeological conceptual model is a description of how a hydrogeological system is believed to behave. It describes how water enters an aquifer system, flows through the system and leaves the aquifer system. The conceptual model for the Cam catchment is shown in Figure 6-4. It focuses on the elements that could be affected by NBS and therefore has a focus on the shallow system. It has the following features:

- Topography – the catchment is covered by three distinct topographical zones:
    - The hilltop area in the east of the catchment at around 100mAOD (1)
    - The intermediate Chalk slopes (2)
    - The low-lying edge of the fens (3)
- Geology and hydrogeology:
    - The majority of the area is underlain by Chalk which forms a Principal Aquifer (4)
    - Across the lowland areas, the area is underlain mainly by unproductive clay strata (5)
    - Along the valley floors, the superficial deposits transition downstream, from a narrow band of alluvium to a wider valley filled with high-permeability river terrace deposits, progressing to peat as the valleys widen and flatten into the fens (6)
    - The superficial deposits of the fens are generally underlain by low-permeability bedrock. On the eastern edge, there is some interaction with the Chalk, with seepages faces on the edge of the peat/alluvium (7)
- Streams and rivers – there are seven main hydrogeological/hydrological settings for streams and rivers in the area:
    - Drainage network on the low-permeability till that removes runoff from the area (8)
    - Streams/drains that run from the edge of the till across the higher ground of Chalk, and lose water to the ground, even in high water table conditions (9)
    - Baseflow-fed streams that rise on the Chalk (10)
    - Reaches of streams/river on Chalk in the valley floor that are usually gaining but lose water to ground in dry conditions (11)
    - Permanently gaining Chalk river reaches, sufficiently low down the system that they always receive water from the water table (12)
    - Lowland rivers passing through peat and clay (13)
    - Lowland drainage systems (14)

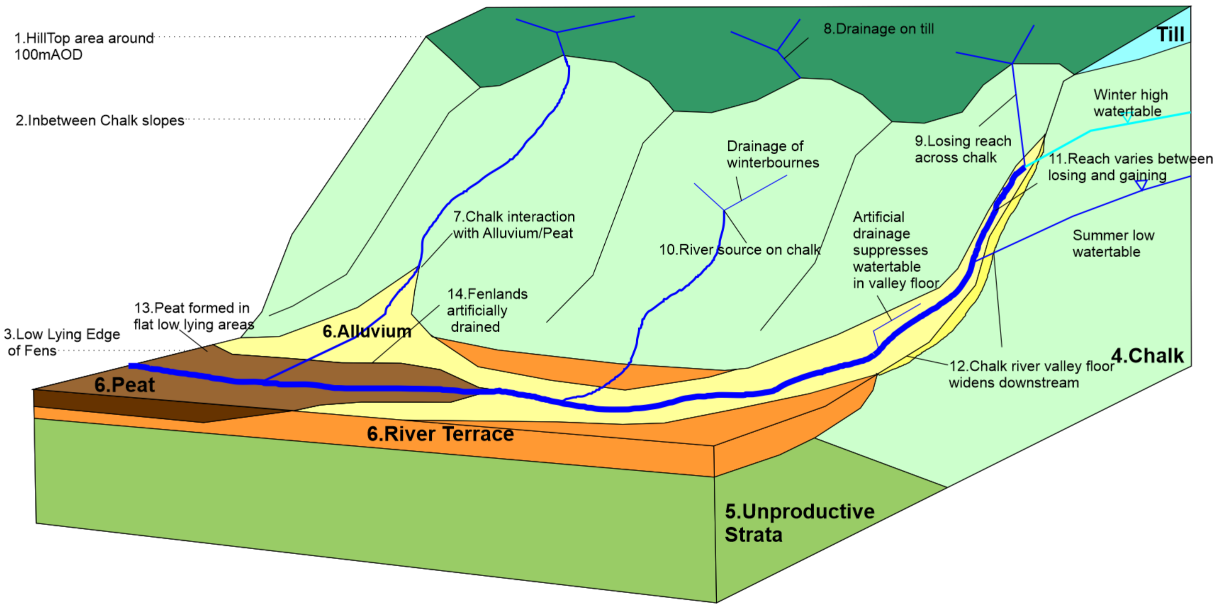


Figure 6-4: Schematic conceptual model of the Cam catchment, JBA Cam report

Catchment specific interventions

Due to the varying nature of the geology within the Cam catchment, including high-permeability bedrock catchments covered by patchy low-permeability drift (high runoff next to a high-recharge area), a wide suite of NBS interventions can be implemented across the Cam catchment which promote infiltration and limit runoff generation. It should be noted however that the presence of putty Chalk at the top of the Chalk may limit infiltration potential in places.

The long list of NBS options can be simplified into the categories: soil improvement, land use change, runoff attenuation features, and floodplain and river restoration.

Figure 6-5 provides a summary of intervention types that are specific to the hydrogeological controls of the Cam catchment. This identifies several distinct settings:

1. Improving infiltration on the till soils that dominate the plateau, by adding slowly draining surface water runoff attenuation features. This includes soil management techniques and roughness strips within fields. Surface water storage features for farm usage could also be located in this area. If the runoff from here is slowed down, then there will be more scope for infiltration of peak flows once they arrive at the Chalk outcrop
2. Runoff attenuation features on Chalk deposits on the edge of the till. These will enable enhanced runoff recharge of Chalk downstream of the outcrop edge. The higher in the catchment that recharge occurs, the longer the pathway through the subsurface and the greater the baseflow benefit for low flows
3. On the Chalk outcrop, taking land out of arable production that needs spray irrigation and reversion to Chalk grassland could reduce the overall losses/water uses from the catchment
4. Improving resilience of streams to low groundwater levels in the Chalk by re-naturalising the channel and storing more water within the valley floors through riparian restoration

5. Improving floodplain connectivity through the mid-catchment. Mapping identifies lots of reaches where connectivity could be improved, with increased storage of water in these areas
6. Changing management practices in the fenland areas to allow water levels to be maintained at a higher level, increasing the storage in the system. This would have the potential to further support baseflows in drought conditions

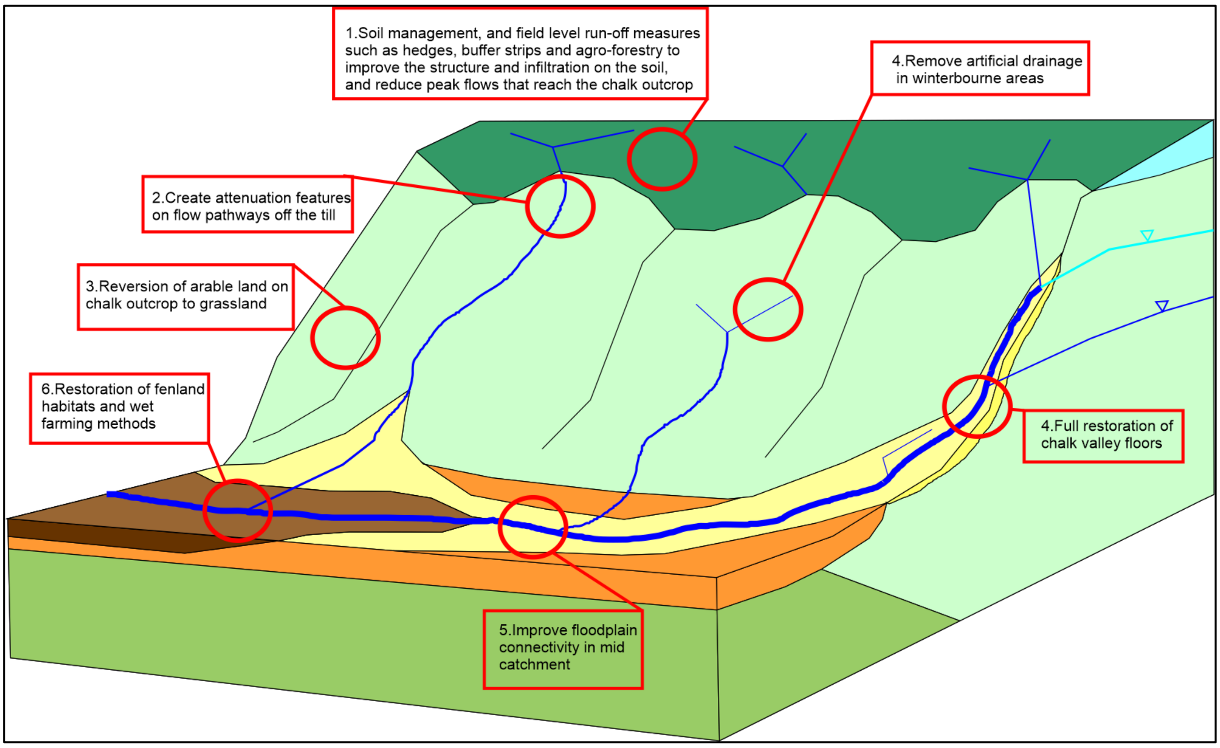


Figure 6-5: Cam catchment interventions, JBA Cam report

The NBS elements that are specific to the upper chalk catchments are shown in more detail in Figure 6-6.

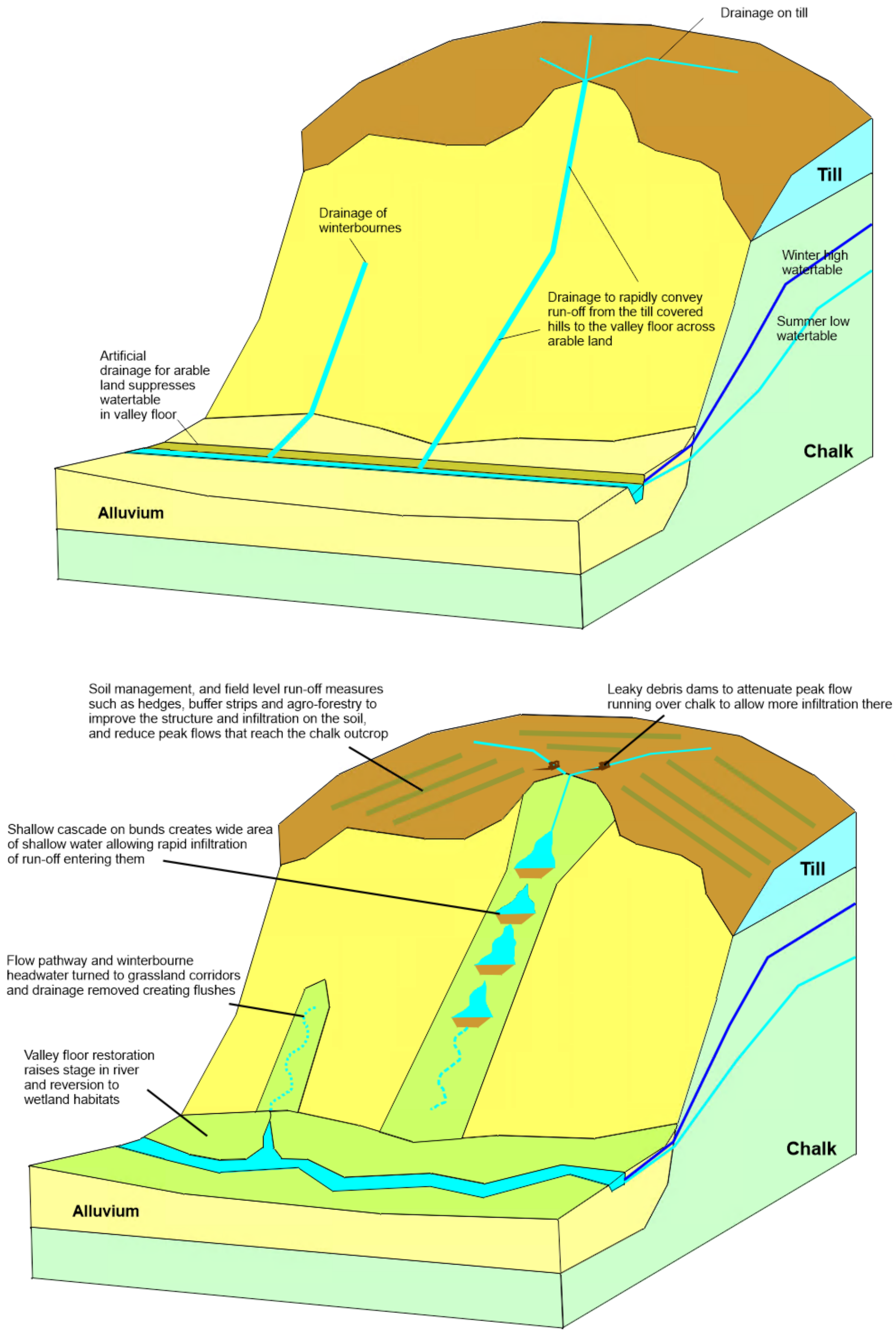


Figure 6-6: Upper Chalk catchment interventions (existing situation above, intervention scenario below), JBA Cam report

6.3.2 Upper Test

Introduction

The topography and geology underlying the Upper Test catchment, including superficial and bedrock units of the area, are shown in Figure 6-7.

The Bourne Rivulet forms the western part of the catchment and flows towards the south-east. It is surrounded by a horseshoe of relatively steep-sloping hills with elevations of up to 300mAOD. The Bourne Rivulet emerges into the lower part of the catchment at an elevation of 90mAOD and flows to its confluence with the River Test.

The north-eastern part of the catchment comprises the Upper River Test catchment, where elevations are lower (maximum of 220mAOD), and the hills slope gently towards the south-west. Similarly, the River Test emerges in the centre of the catchment and drains towards its outlet, just upstream of the Bourne Rivulet confluence.

The Middle Test catchment comprises the relatively small area draining into the Test as the river flows towards the south-west with only a 10m drop in elevation.

The catchment continues south and has a similar topography, covering the Dever, Anton and Wallop Brook around Andover.

The superficial geology varies across the area but is limited in extent. Clay-with-Flints mostly occurs on areas of high elevation, with additional patchy exposure throughout the catchment. Alluvial bands occur along the stream valley floors. A broader band of alluvium is seen in the wider Test valley. River terrace deposits outcrop at the edge of the valley floor in the upper and middle Test catchment.

The valley floor of the Test can be split into two areas: upstream and downstream of the confluence with the Bourne Rivulet. The lower reach is mapped as fen peat in the published soil mapping.

Above the Bourne Rivulet confluence, the valley floor is narrower and dominated by sand, gravel, and alluvium deposits, with less peat.

Much of the wider area is free of drift, but there are some areas of Clay-with-Flints around the north, south and east, river terrace deposits around the main River Test, and alluvium deposits within the main Test valley.

The youngest outcropping bedrock unit in the catchment is the Lambeth Group which has a limited exposure, with an unconformity at its base. The majority of the catchment is covered by the White Chalk Subgroup which frequently outcrops.

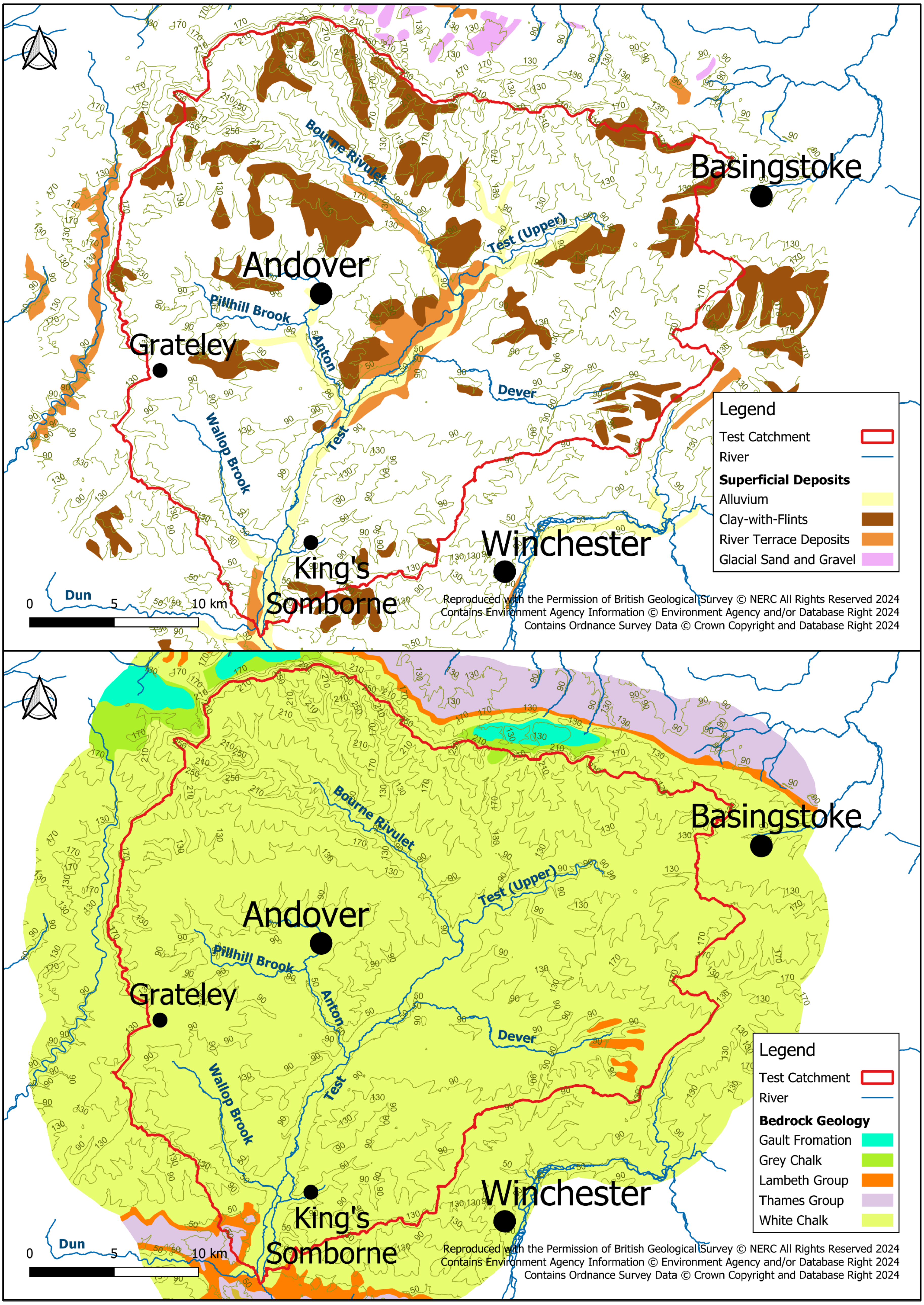


Figure 6-7: Topography, superficial deposits and bedrock units within the Test catchment

Conceptual model

The conceptual model for the Test catchment is shown in the Figure 6-8. It has the following features:

- Topography:
    - The Upper Test and Bourne Rivulet both have relatively narrow valley floors which widen beneath their confluence
    - The highest ground is in the north-west and is split by a series of narrow dry valleys
- Chalk:
    - The whole area is underlain by Chalk which acts as a Principal Aquifer
    - The transmissivity of the Chalk is highly variable, with the highest transmissivity underlying the valley floors and some dry valleys
- Clay-with-Flints:
    - Clay-with-Flints lies on top of the hills
    - It is moderately permeable and little to no runoff from it is observed
    - Some interflow is observed to discharge at the edge of the deposits
    - Dolines (sinkholes) within Clay-with-Flints areas form localised zones of rapid infiltration
- Valley floor:
    - The deposits of the valley floors differ upstream and downstream of the main confluence
    - Upstream of the confluence the Test and Bourne Rivulet, valleys are narrow with 0.5-2m of silty alluvium underlain by 1.5-5m of gravel
    - Downstream of the confluence, the valley is wider. It is underlain by circa 5m of gravel overlain by 0.5-4m of alluvium and peats
- Surface water-groundwater interactions:
    - The pattern of surface-groundwater interaction reflects and is controlled by the distribution of sediment within the valleys
    - Where peat deposits are found, downstream of the main confluence, the river is in an area of gaining baseflow even in dry conditions
    - The superficial deposits are relatively thin compared to the Chalk and so have a limited role at the groundwater-surface water interface
    - The Bourne Rivulet and Upper Test suffer more from low flows, as in dry periods these can be losing reaches/partly dry, or groundwater flow bypasses them to discharge directly to the lower part of the Test

- Infiltration patterns:
    - Infiltration on the Chalk is rapid and there is very limited runoff from it
    - The Clay-with-Flints has limited impact on slowing infiltration. Runoff infiltration from the Clay-with-Flints onto the Chalk is very limited
    - Runoff and surface water flooding of dry valleys may occur in extreme events

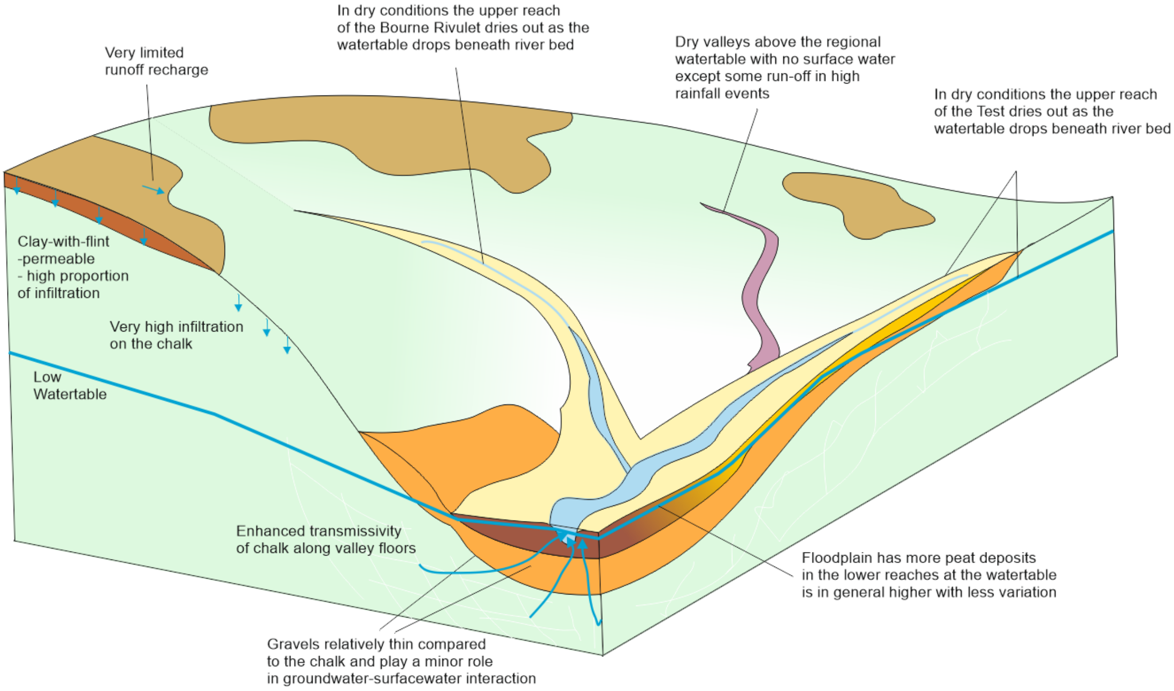


Figure 6-8: Schematic conceptual model of the Test catchment

Catchment specific interventions

There is already a very high rate of infiltration and limited runoff on the Chalk and the Clay-with-Flints deposits. Surface water flood mapping suggests that in extreme events, dry valleys above the regional Chalk water table can form flow paths, which rapidly transport runoff to the main valley floors. Runoff is not seen in a typical year but is seen in extreme events. This means that there is little scope for reducing runoff generation or capturing runoff as there is so little to begin with.

Outside of modifying runoff, there are two main ways the landscape could be modified to improve water resources:

- Changing land cover to reduce evapotranspiration and the need for consumptive abstractions
- Floodplain restoration to increase the amount of groundwater stored within the superficial deposits of the floodplain

If land is converted from arable farming for biodiversity gain, grassland and beech woodland are two likely options. Calder (2002) summarises the finding of a study at Blackwood, near Micheldever Station, immediately bordering the south-east corner of the area of interest:

> A new study was commissioned, this time involving full instrumentation of both the beech woodland and grass at the two original field sites in Hampshire – Black Wood and Bridgets Farm (Roberts et al., 2001). The principal conclusions of this second investigation are: that there is no significant difference in the seasonal reduction in water content of the soil under beech woodland and grass; that evaporation from grass over a 12-month period from March 1999 was 106% that from the beech woodland, i.e. 36 mm higher; and that drainage under beech was greater than that under grass by 34 mm over a 12 month period and by 90 mm over an 18 month period, i.e. a flux 111-114% of that under grass. The results of this new study “give very strong support to the previous work… which concluded that, compared to grassland, afforestation with beech woodland has little impact on recharge to Chalk groundwater” (Roberts et al., 2001).

Roberts et al. (2001) draw attention to the likely impact of soil type, suggesting that in shallow soils over Chalk (as at Black Wood and Bridgets Farm) there is a significant upward flux from the micro-porous bedrock into the soil (where the roots are confined) that helps satisfy evaporative demand throughout summer in most years, even under grass.

Based on this study, in most years there may be little difference between the water demands of grassland and beech woodland, due to the thick capillary fringe of the Chalk which readily allows water to be accessed. Only in very dry years do the shallow root systems of grassland lead to lower evapotranspirative losses compared to beech woodland. This observation is specific to large beech woodlands on Chalk. In most other situations, woodlands have greater losses, including wet woodland on floodplains where trees like willow and poplar have high water demands (Creating and managing riparian woodland, UK Forestry Standard Practice Guide).

Overall, this very high-permeability catchment has little opportunity to change the functioning of the water cycle. There is little runoff to capture, and the differences between the water budgets of many of the land use types are limited.

The options identified above are summarised in the conceptual model showing the locations of potential interventions in Figure 6-9. Some of these interventions, such as woodland planting, although marginal in terms of water resources benefits, may contribute a range of other benefits such as to water quality (via reducing diffuse pollutant loads).

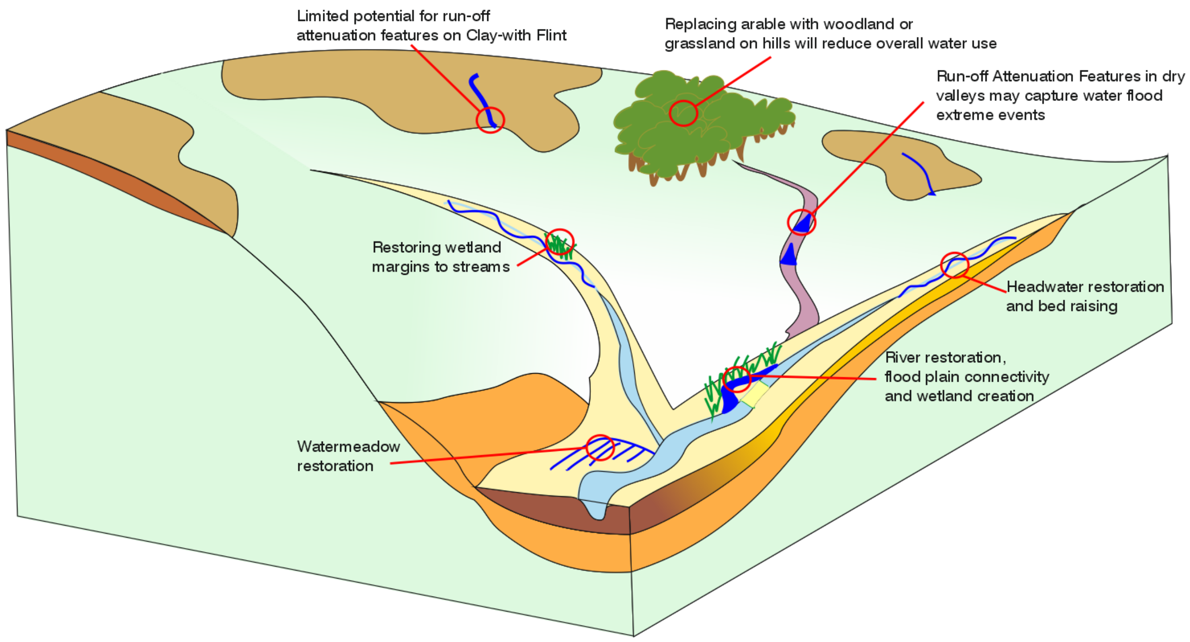


Figure 6-9: Test catchment interventions

6.3.3 Wensum

Introduction

The topography and geology underlying the Wensum catchment, Norfolk, including superficial and bedrock units of the area, are shown in Figure 6-10.

The Wensum catchment begins with the Tutt in the west at around 80mAOD and slopes eastwards to its lowest in the Wensum floodplain at around 10mAOD, with the river flowing generally eastward. The Wensum catchment includes several tributaries, including the River Blackwater, Wendling Beck, and the Tud. Downstream of the Wensum's confluence with the Tud, the Wensum enters the River Yare, south-east of Norwich city centre.

The majority of the catchment is underlain by till deposits with low to moderate permeabilities. The superficial deposits across the catchment can be split into the following areas:

1. South of the catchment

   The south area of the catchment is dominated by low-permeability Lowestoft Till which can be found at higher elevations in the lower catchment. Throughout the valley floors, alluvium deposits can be found along river courses with river terraces on the valley sides. Glacial sands and gravels can be found scattered throughout the catchment overlying till in many areas.

2. North and centre of the catchment

   The high ground of the north and centre of Wensum Catchment is overlain by Sheringham Cliffs Formation, predominantly the clay, silt, sand, and gravel members (moderate-permeability till). Glaciofluvial deposits are outcropping along the edge of the valley floor and are found along the main channel of the Wensum and partially along its confluence with Wendling Beck.

3. East of the catchment

   Around the Wensum's confluence with the River Yare, the glacial sands and gravels outcrop along the valley sides surrounding the alluvium along the valley floor.

The White Chalk Subgroup underlies the whole area, dipping gently. There are only small areas of Chalk outcropping due to the erosion of drift deposits in river valleys, for example in the west and east of the Wensum River valley. The Crag Group overlies the Chalk in two locations on the eastern fringes of the catchment. The Crag Group infills depressions in the eroded Chalk surface and varies in composition from sand to gravels.

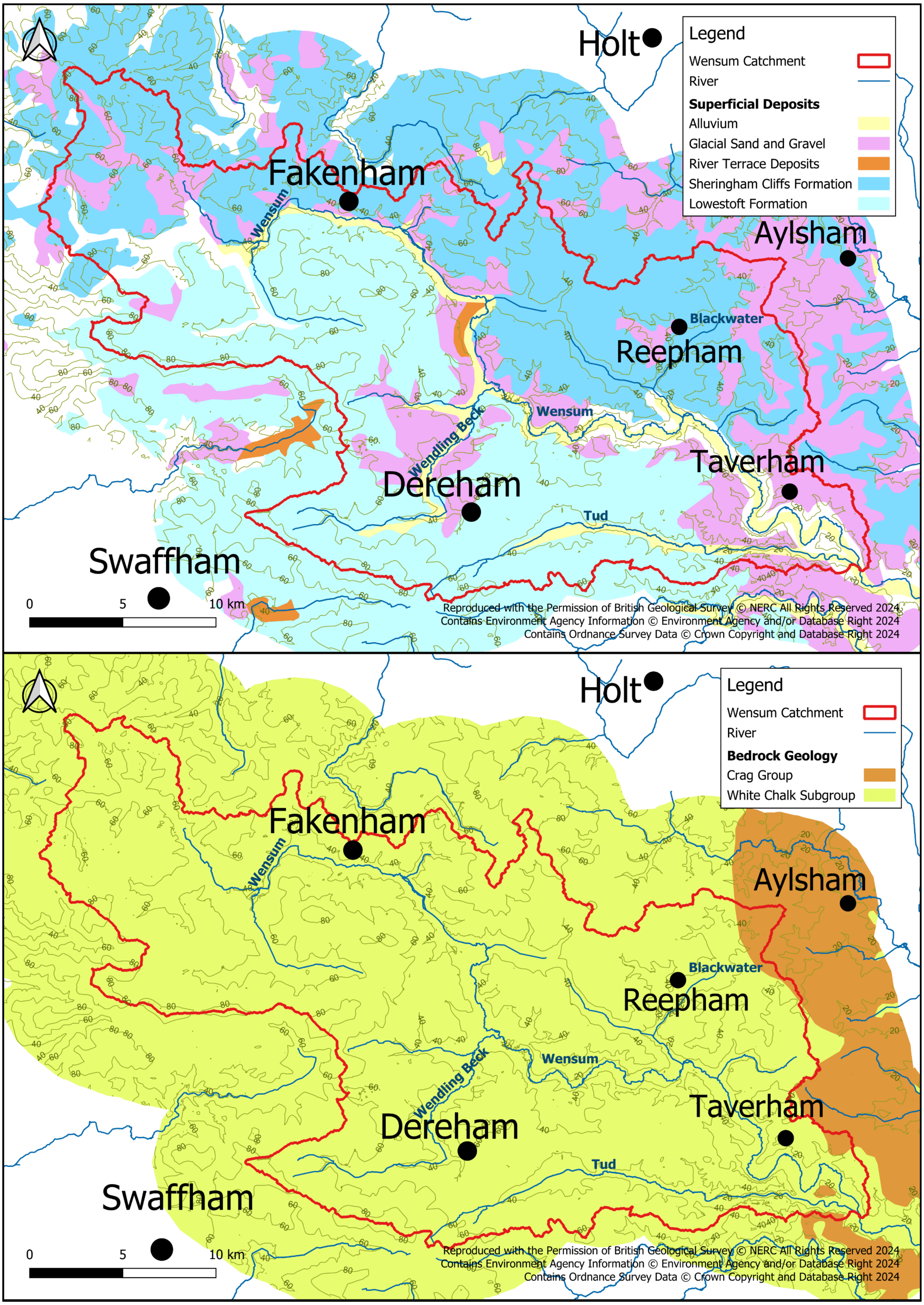


Figure 6-10: Topography, superficial deposits and bedrock units within the Wensum catchment

Conceptual model

The Wensum Catchment conceptual model is shown in Figure 6-11. It focuses on the elements that could be affected by NBS and therefore has a focus on the shallow groundwater system. It has the following features:

- Topography:
  - The west is occupied by a series of hills at around 80mAOD with narrow valleys
  - The east and downstream end is occupied by ground at around 10mAOD and a wide floodplain
- Geology and hydrogeology:
  - The whole area is underlain by Chalk which forms a Principal Aquifer
  - The overlying Crag Group is limited to the far east of the catchment
- The superficial deposits are complex:
  - North of the Wensum, the hills are covered by moderately permeable till deposits (Sheringham Cliffs Formation)
  - South of the Wensum, the hills are covered by low-permeability till deposits (Lowestoft Formation)
  - There are two sets of high-permeability glaciofluvial deposits in the area:
    - An upper layer sitting on top of the till covering patches of the hillside and the valley in the east
    - A lower layer sitting under the till and resting on the Chalk
  - Recharge to the underlying Chalk aquifer is controlled by the thickness and permeability of the till. It is lowest where there are thick, low-permeability till deposits (Lowestoft Formation)
- Water table:
  - The Wensum is impounded by a series of weirs. This raises the water table within the valley floor
  - In wet winters much of the low-lying moderately permeable till (Sheringham Cliffs Formation) area has a water table close to the surface. Underdrainage in fields is active during this period
  - The low-permeability till (Lowestoft Till) area is generally elevated with narrower valleys, so the areas of winter saturation are limited to the valley floors

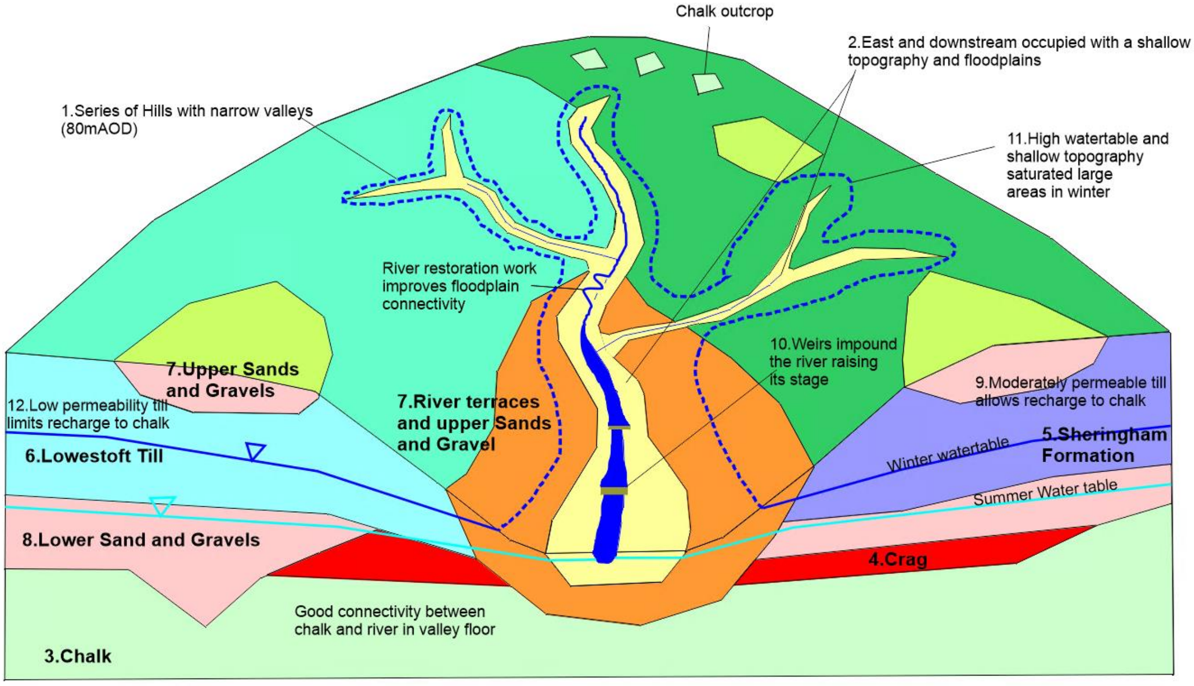


Figure 6-11: Conceptual model

Catchment specific interventions

Due to the varying nature of the geology within the Wensum catchment, including moderate and lower permeability aquifers, a number of types of NBS can be considered in different parts of the catchment which promote infiltration and limit runoff generation. The long list of NBS options can be simplified into the categories: soil improvement, land use change, runoff attenuation features, and floodplain and river restoration.

Figure 6-12 provides a summary of intervention types that are specific to the area's hydrogeological setting. The work identified three main settings:

- Hillsides - this covers both the low-permeability Lowestoft Till Formation and the moderately permeable Sheringham Cliffs Formation:
    - Improving infiltration on the till soils: this mainly focuses on soil management techniques including cover crops and roughness strips within fields
    - 'Catchment' RAFs on hillslopes capturing runoff from Lowestoft Till to divert this into high-permeability sand and gravel deposits
- In the valley floor - package of work that allows the river to be maintained closer to bank-full for longer periods and for the valley floor to be saturated for longer including:
    - River restoration
    - Conversion of land such as arable land back to wetland where appropriate
    - Weir removal should be accompanied by bed raising to ensure groundwater levels do not drop
- Saturated valley margins:
    - Reversion to grassland and removal of drainage including underdrainage in areas of seasonal saturation. This would allow areas that are naturally seasonally waterlogged to hold their water for longer

- Improved soil management techniques such as cover crops, and non-inversion tillage to improve soil structure and infiltration. This can be accompanied by wider measures such as buffer strips set as right angles to the slope to capture runoff
- Runoff attenuation features (RAFs) to store water on the land and capture runoff

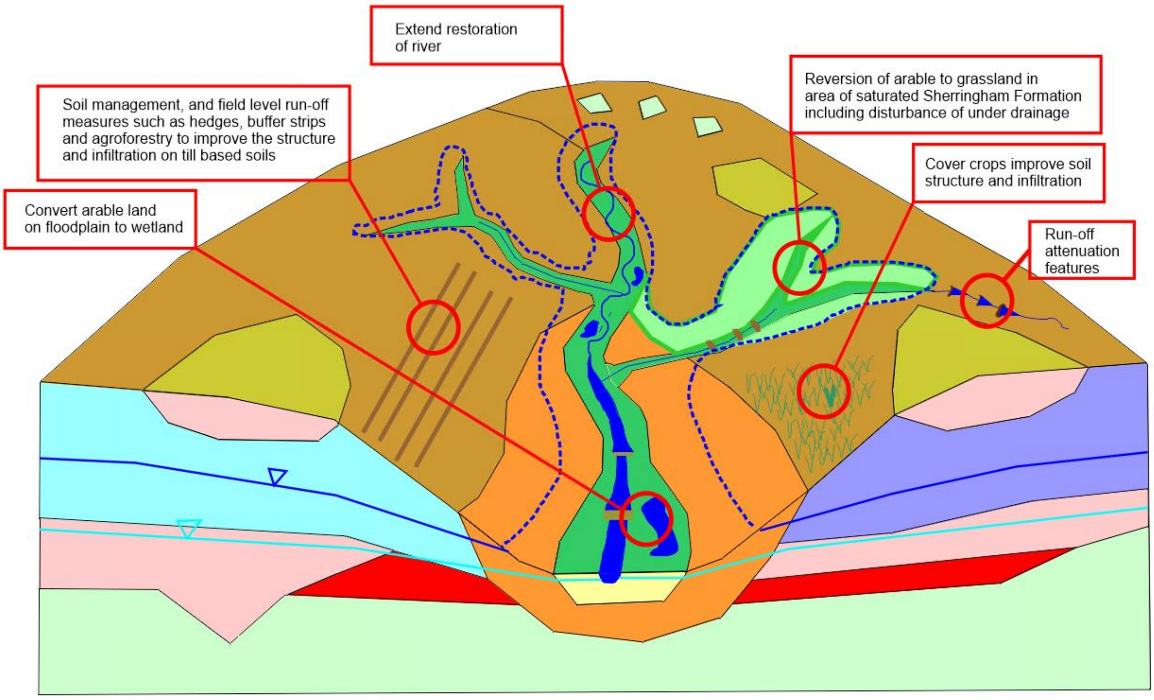


Figure 6-12: Wensum catchment interventions

Figure 6-13 presents an example of how land underlain by moderately permeable drift like the Sheringham Cliffs Formation (that naturally would be ephemerally saturated but has been converted to arable land through drainage) could be reconfigured. This involves removing the drainage from the naturally waterlogged valley floor and reconfiguring the underdrainage to discharge to the edge of this area. The valley floor (or part of the valley floor) would then form a seasonally waterlogged overland flow path that would slowly release the store of groundwater within it to the river during dry periods. This can be combined with other land management practices to slow runoff and increase infiltration on the surrounding hills.

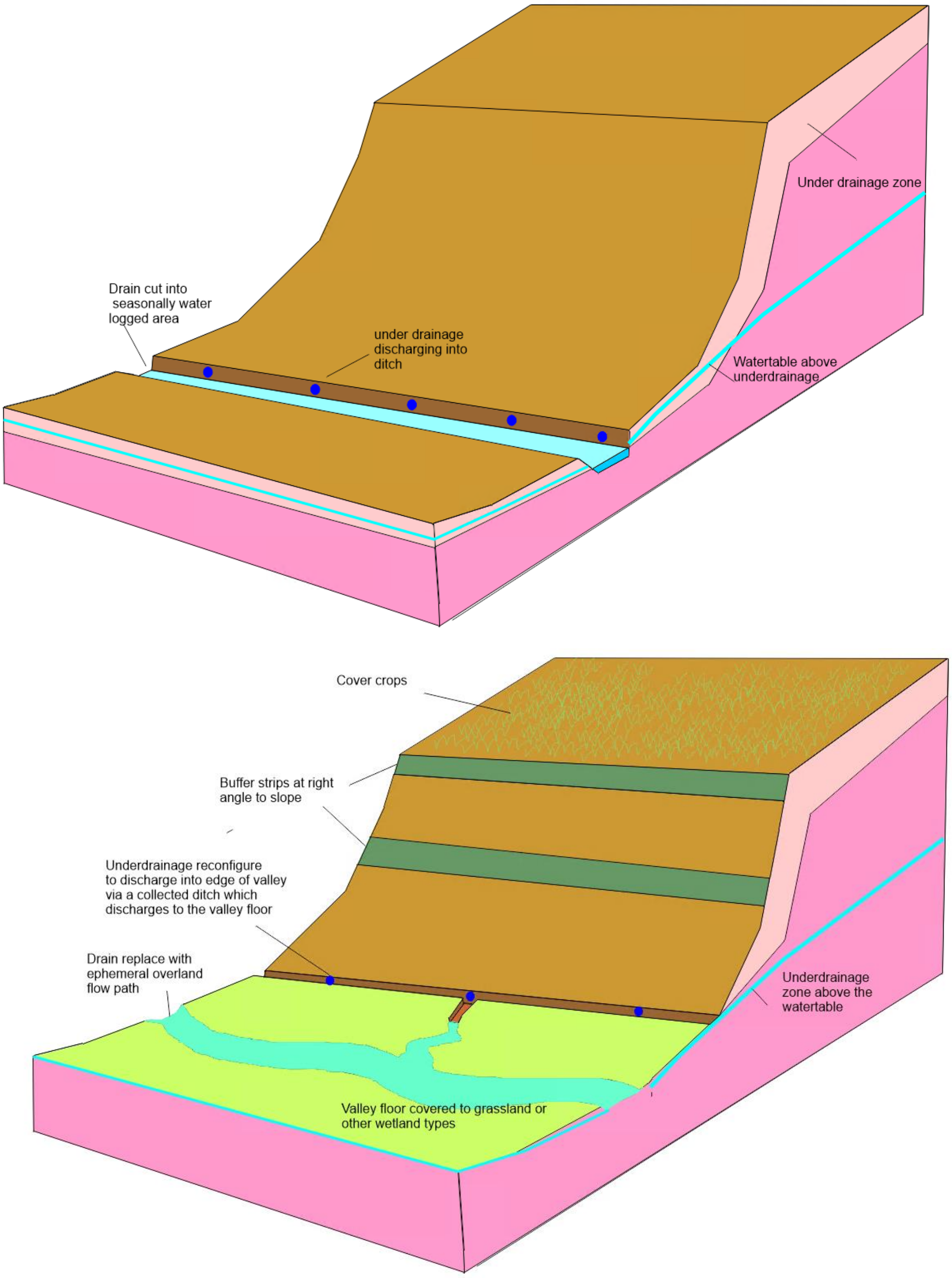


Figure 6-13: Drainage and land practices reconfiguration on naturally ephemerally waterlogged areas

6.4 Comparison between Chalk catchments

6.4.1 Overview

The conceptualisations above show that the NBS4WR options within the three Chalk catchments fall into the following broad categories:

- Water Usage (Land Use Change)
- Runoff Infiltration Split (Soil Improvement)
- Runoff Capture and Infiltration (Runoff Attenuation Features)
- Floodplain and River Restoration (Restoration)

Groundwater Modelling using regional groundwater models of different scenarios of NBS interventions has been done for the three catchments. Chapter 8 provides a description of the modelling that was undertaken.

This section presents some of these results and compares the results between the three catchments. Table 6-2 gives a summary of the names of the modelling scenarios and the broad categories that they fall into.

Table 6-2: Choices of NBS scenarios

Category	Description	NBS Scenario
Water Usage (Land Use Change)	Conversion of arable land use to pasture and horticulture	- Arable to Pasture - Arable to Horticulture
Runoff Infiltration Split (Soil Improvement)	Reduction of rapid runoff by improving soil health	50% Runoff Factor
Runoff Attenuation Features	A range of RAFs were modelled from within-field RAFs, to ones located on drains, to ones more akin to infiltration basins	RAF (various)
Floodplain and River Restoration	Raising water levels to store more water within the floodplain in alluvial aquifers	River Restoration

NBS categories and model results of the three case study catchments are discussed in the following sections.

6.4.2 Water usage

The Water Usage suite of measures is perhaps the least sensitive to the underlying geology. In considering how to improve water resources by using this suite of measures, it is important to identify land uses which have lower evapotranspiration rates or lower water usage (be this from rainfall or irrigation).

Choices of modelled Water Usage NBS measures in the three case study catchments include:

- Conversion of arable land use to pasture
- Conversion of arable land use to horticulture

Horticulture is a land use type in the regional groundwater models that represents a low water usage mix of crops (such as strawberries) compared to arable and so was used to assess the impacts of changing crop types. The table below shows the evapotranspiration rate in the three case study catchments. It also shows the percentage change in the evapotranspiration rate from the baseline (no NBS measures) after implementation of NBS measures. Table 6-3 shows that the evapotranspiration rate in the Test catchment is generally higher than in the Wensum and Cam catchments.

Table 6-3: Actual evapotranspiration (mm/year) across case study catchments through Water Usage NBS modelling scenarios (percentage change from baseline in brackets)

Scenario	Cam	Test	Wensum
Baseline	314	495	420
Arable to Pasture	316 (+0.8%)	515 (+3.9%)	430 (+2.4%)
Arable to Horticulture	303 (-3.4%)	489 (-1.3%)	403 (-3.9%)

The evapotranspiration results show that conversion of arable land use to pasture resulted in an increase of 0.8% to 3.9% in evapotranspiration rates across the three catchments, with the maximum change in the Test catchment. The results also shows that the conversion of arable to horticulture land use reduces the evapotranspiration rate in all three catchments, with a maximum reduction of 3.9% in the Wensum catchment. The parameterisation of arable land use characteristics is based on an averaged crop mix, for which a representative set of values have been derived. In practice, the effects of crop rotation will influence rates of actual evapotranspiration between years.

Model results of recharge and BFI in Water Usage NBS scenarios and their changes from the baseline (no NBS interventions) are presented in Table 6-4 and Table 6-5.

Table 6-4: Recharge (mm/year) to groundwater across case study catchments through Water Usage NBS modelling scenarios (percentage change from baseline in brackets)

Scenario	Cam	Test	Wensum
Baseline	76	386	136
Arable to Pasture	74 (-3.2%)	367 (-5%)	129 (-4.9%)
Arable to Horticulture	84 (+10.4%)	393 (+1.7%)	147 (+7.9%)

Table 6-5: Baseflow Index (BFI) percentages across case study catchments through Water Usage NBS modelling scenarios (percentage change from baseline in brackets)

Scenario	Cam at Dernford	Test at Chilbolton	Wensum at Costessey Mill
Baseline	54.3	93.6	75.7
Arable to Pasture	53.8 (-0.9%)	93.3 (-0.3%)	76.2 (+0.6%)
Arable to Horticulture	54.8 (+0.9%)	93.8 (+0.2%)	75.9 (+0.2%)

Results show that conversion of arable land use to pasture results in reductions in recharge to groundwater in all three catchments, with a maximum reduction of 5% from the baseline in the Test catchment. Results also show that conversion of arable to horticulture land use results in more recharge compared to the baseline with a maximum increase of 10.4% in the Cam catchment. This is mainly due to higher evapotranspiration rates for pasture compared to the horticulture land use. A similar trend is also seen in Baseflow Index (with an exception in the Wensum catchment) with a maximum reduction of 0.9% in BFI from the baseline in the arable to pasture conversion scenario in the Cam catchment and a maximum increase of 0.9% in BFI from the baseline in the arable to horticulture conversion scenario in the Cam catchment. The arable to pasture conversion model results show an increase of 0.6% in Wensum catchment at the Costessey Mill assessment point.

Overall, changing water usage of land cover affects the amount of water in the system independent of geology. It should be noted that conversion to pasture can offer extensive biodiversity benefits, whereas conversion to horticulture may have certain disbenefits, with more extended periods of bare earth leading to greater soil erosion.

6.4.3 Runoff infiltration splits and runoff capture and infiltration

The Runoff Infiltration Splits and Runoff Capture and Infiltration NBS measures involve suites of measures to reduce and capture surface runoff and increase infiltration. This can be achieved through soil improvements and the installation of runoff attenuation features. The potential for reducing the amount of runoff and increasing infiltration through soil improvements or using runoff attenuation features (RAFs) is particularly sensitive to the underlying geology.

The greatest benefit from soil improvements can be seen within the low-permeability areas where the rapid runoff is greatest. The runoff attenuation features also work best where there are two elements:

- A low/moderate-permeability area where lots of runoff is generated
- A high-permeability area where water can be collected and infiltrated to ground

Choices of modelled Runoff Infiltration Split (Soil Improvement) and Runoff Capture and Infiltration NBS measures in the two case study catchments, including the Cam and Wensum catchments include:

- 50% Runoff Factor: a 50% reduction in rapid runoff by improving soil health

- Implementation of Runoff Attenuation Features of varying sizes and locations (see Table 6-2)

No soil improvement or RAF scenarios were developed for the Test catchment, as there is limited runoff on Chalk to be captured to increase recharge and so no places in the model could be found to implement RAFs.

The results in terms of groundwater recharge and BFI in Runoff Infiltration Splits and Runoff Capture and Infiltration NBS scenarios and their changes from the baseline (no NBS interventions) are presented in Table 6-6 and Table 6-7.

Table 6-6: Recharge (mm/year) to groundwater across case study catchments through Runoff Infiltration Splits and Runoff Capture and Infiltration NBS modelling scenarios (percentage change from baseline in brackets)

Scenarios	Cam	Wensum
Baseline	76.4	135.7
50% Runoff Factor	77.5 (+1.5%)	138.9 (+2.4%)
RAFs	80.0 (+4.7%) to 84.7 (+10.9%)	139.4 (+2.7%) to 153.0 (+12.8%)

Table 6-7: Baseflow Index (BFI) as percentages across case study catchments through Runoff Infiltration Splits and Runoff Capture and Infiltration NBS modelling scenarios (percentage change from baseline in brackets)

Scenario	Cam at Dernford (49% till)	Cam at Swaffham Bulbeck (12% till)	Wensum at Costessey Mill
Baseline	54.3	93.7	75.7
50% Runoff Factor	56.1 (+3.3%)	93.7 (0%)	78.4 (+3.6%)
RAFs	59.1 (+8.8%) to 65.8 (+21.2%)	93.7 (0%)	77.0 (+1.7%) to 82.5 (+9%)

Model results show that soil improvement and implementation of RAFs result in higher recharge and BFI in comparison to the baseline across the two catchments, with a maximum increase of 12.8% in recharge and 21.2% in BFI in the Wensum and Cam catchments respectively through implementation of RAFs. Soil improvement and reduction of runoff by 50% resulted in an approximate increase of 3% in both the Cam and Wensum catchments. However, in the areas with lower permeability till coverage in the Cam catchment, there is limited runoff and therefore, reduction of runoff by 50% does not show any betterment in BFI.

The BFI results show that the greatest benefit from soil improvements and implementation of RAFs can be seen within the low-permeability areas such as in the Wensum catchment and in areas within the Cam catchment with more coverage of low-permeability till, where the rapid runoff is greatest. The BFI results show no change through soil improvement or application of RAFs in high-permeability Chalk areas in the Cam catchment with limited low-permeability till coverage.

Overall, for runoff interventions, they are most effective in catchments where lots of runoff can be generated but the geology allows some infiltration to occur.

6.4.4 Floodplain and river restoration

The Floodplain and River Restoration NBS4WR measures involve actions that raise water levels to increase groundwater recharge and storage within the floodplain. This can be achieved by increasing riverbed levels and allowing more leakage from the stream to groundwater. Raising water levels, however, could result in a wider riparian or wetland zone and consequently higher evapotranspiration which in turn may reduce groundwater recharge.

The modelled Floodplain and River Restoration NBS Measures include raising water levels by increasing riverbed levels in the three case study catchments.

Model results of groundwater recharge and BFI for the River Restoration NBS scenario within the three catchments and the changes from the baseline (no NBS interventions) are presented in Table 6-8 and Table 6-9.

Table 6-8: Recharge (mm/year) to groundwater across case study catchments through the River Restoration NBS modelling scenario (percentage change from baseline in brackets)

Scenario	Cam	Test	Wensum
Baseline	76.4	386.4	135.7
River Restoration	76.3 (-0.1%)	386.1 (-0.1%)	135.7 (0%)

Table 6-9: Baseflow Index (BFI) as percentages across case study catchments through the River Restoration NBS modelling scenario (percentage change from baseline in brackets)

Scenario	Cam at Dernford	Test at Chilbolton	Wensum at Costessey Mill
Baseline	54.3%	93.6%	75.7%
River Restoration	53.8% (-0.9%)	93.5% (-0.1%)	75.6% (-0.1%)

Modelling Floodplain and River Restoration NBS scenarios shows that raising water levels does not make a significant change in groundwater recharge or BFI in the three catchments and is unlikely to provide a useful benefit to water resources in general. This may reflect the small proportion of catchments that are occupied by floodplains.

6.5 Non-Chalk case studies

This section presents two case studies within geologies other than Chalk, including the Wye, Herefordshire and Otter, Devon. Table 6-10 presents the aquifer systems and the relevant case studies. Conceptual models of the areas have been developed for each aquifer system, and the potential NBS measures across each catchment then assessed. The locations of the two case study areas are shown in Figure 6-14.

Table 6-10: Aquifer systems and NBS case studied in geologies other than Chalk

Aquifer System	Case Study Catchment
Low-permeability (mudstone) bedrock catchments covered by low and high-permeability drift	Wye
High-permeability (sandstone) bedrock adjacent to the low-permeability (mudstone) bedrock catchments with limited covering drift	Otter

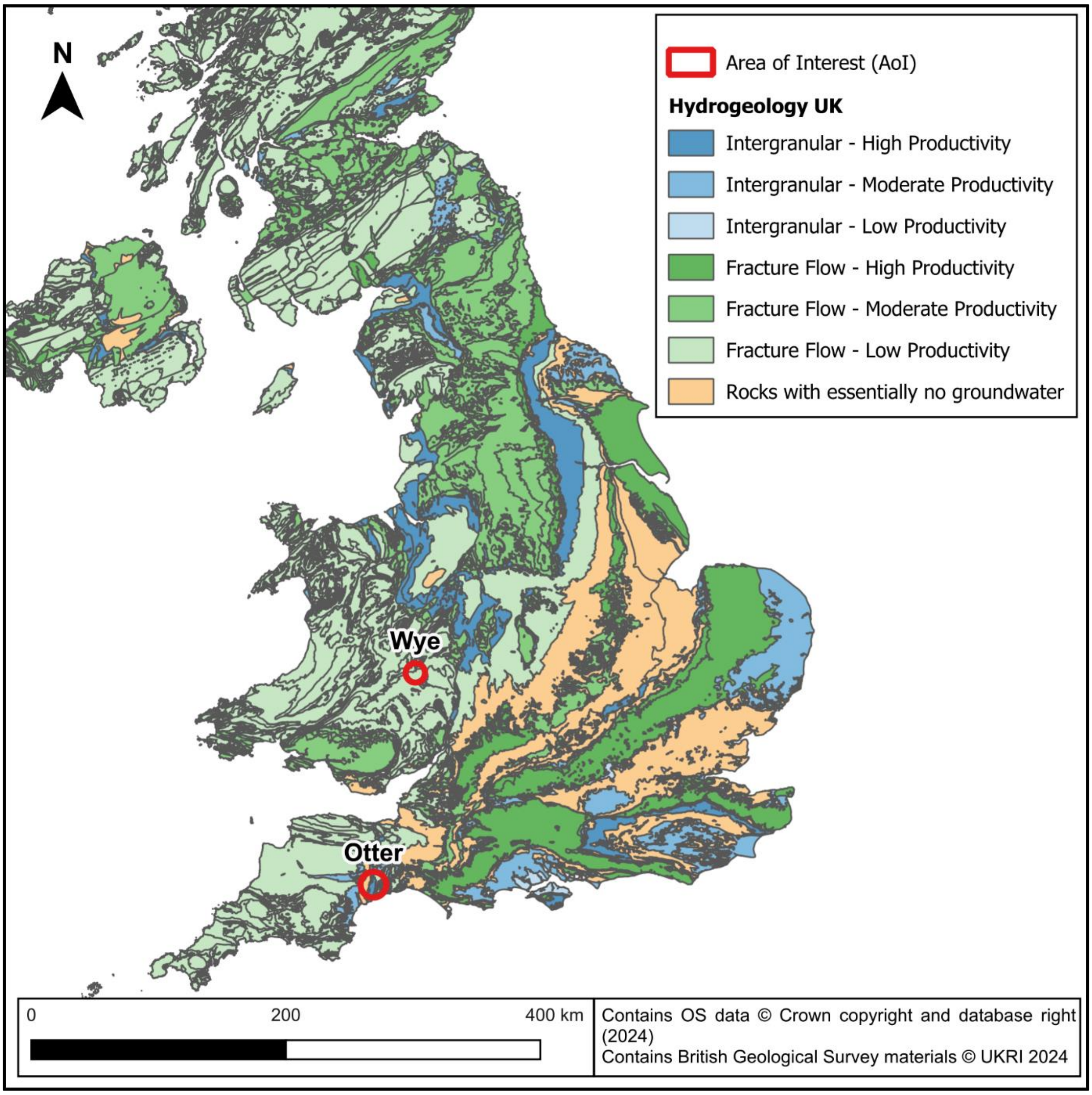


Figure 6-14: Locations of the Wye and Otter case studies

6.5.1 Conceptual model and NBS4WR potential area summary: Wye

This section summarises the key findings from the Wye Study Area The topography and geology underlying the Wye, including superficial and bedrock units, are shown in Figure 6-15.

The elevation is highest in the north-west of the Wye Study Area at approximately 280mAOD at its peak, decreasing towards the south-east (to approximately 65mAOD), following the path of the River Lugg.

Superficial alluvium, comprising clay, silt, sand and gravel, occurs along the valley of the River Lugg, in the centre of the Study Area, and along Ridgemoor Brook which runs north-south in the east of the Study Area. Glaciofluvial deposits outcrop along the edge of the Lugg valley and at the head of the Pinsley Brook valley.

Superficial till deposits occur throughout the Study Area in the higher areas and underlie the Lugg valley floor.

The eastern edge of the Wye Study Area is underlain by the St Maughan's Formation comprising clay-rich argillaceous strata with subordinate sandstones. The majority of the central part of the Wye Study Area is covered by the Silurian Raglan Mudstone Formation which comprises interbedded siltstones and mudstones. The western part of the Wye Study Area is underlain by the Whitcliffe Formation comprising siltstones and a series of smaller outcrops of older strata on the upper parts of the hill.

The structure of the bedrock is made up of a syncline, leading to the younger rocks outcropping in the low areas in the centre and east, with older rocks forming the hills in the north-west.

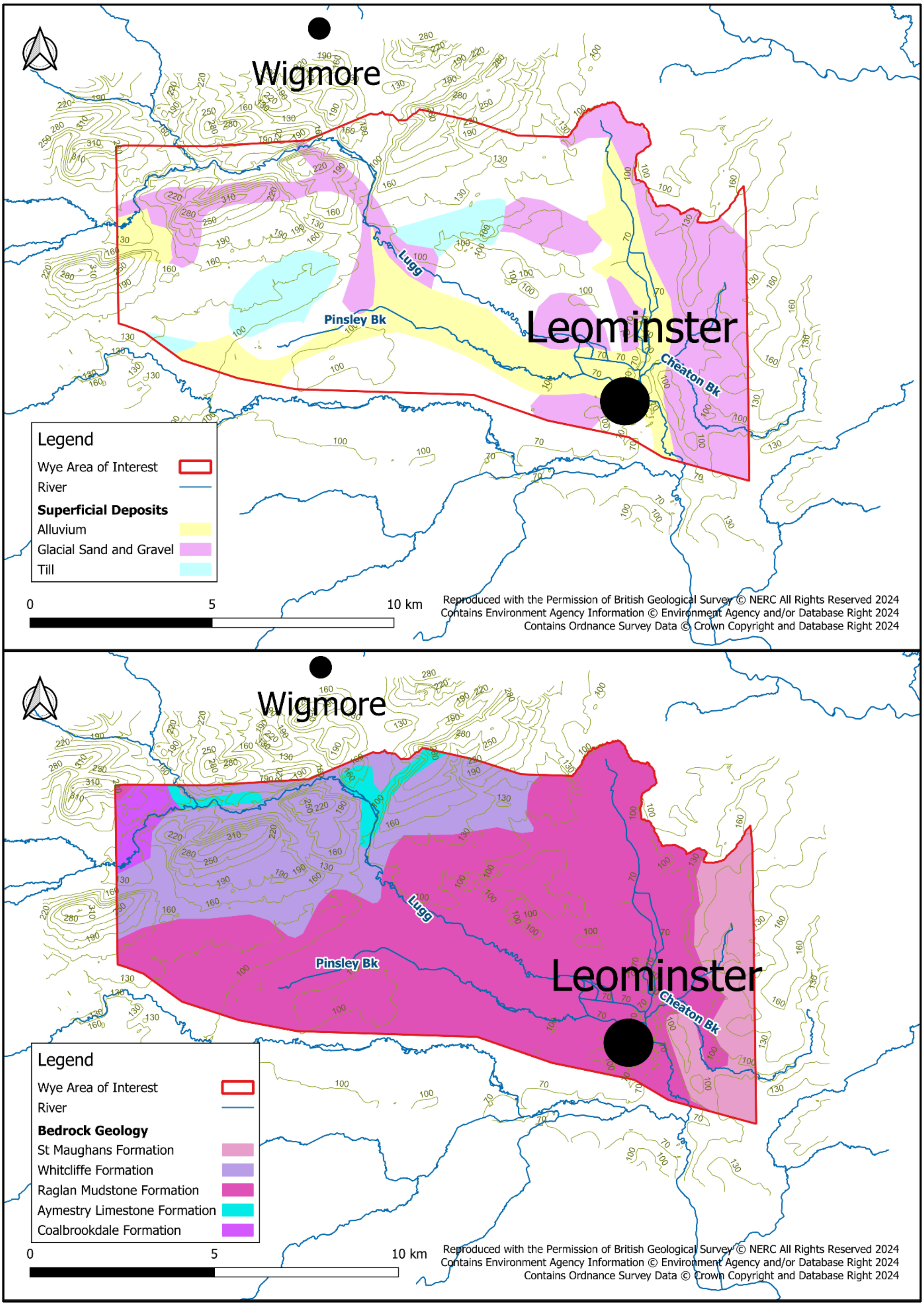
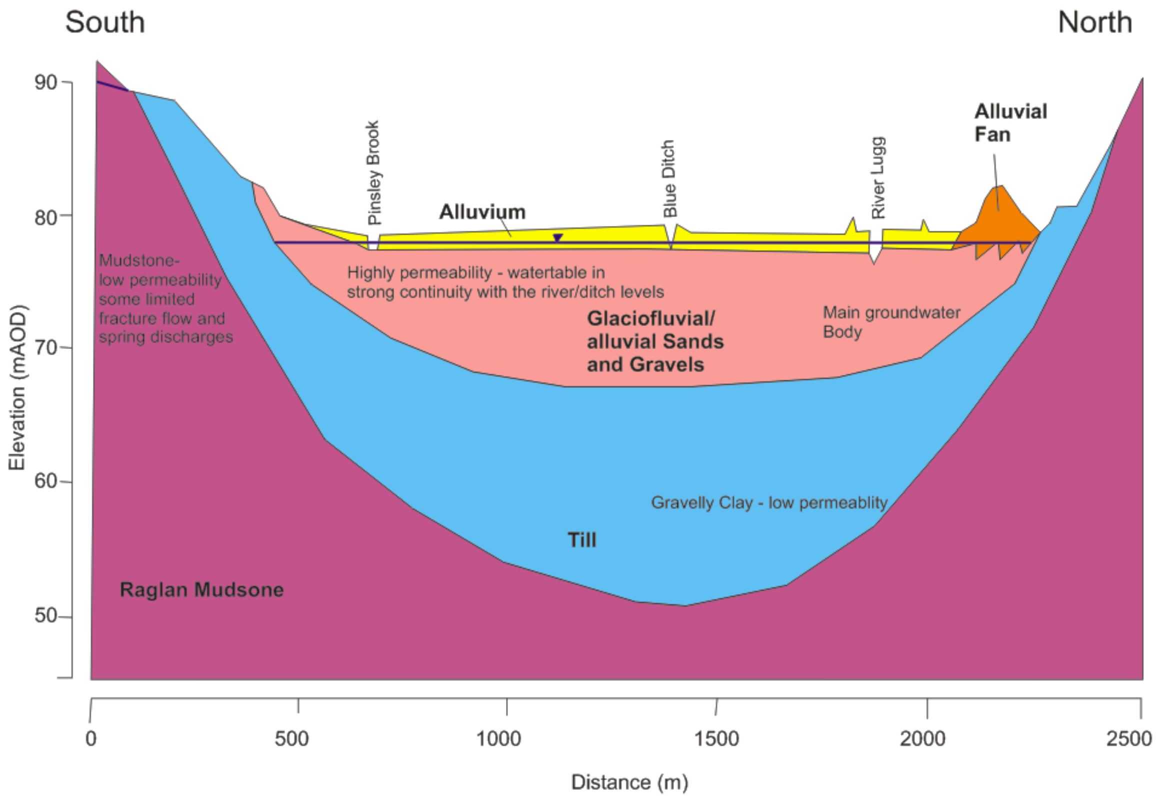


Figure 6-15: Topography, superficial deposits and bedrock units within the Wye Area of Interest

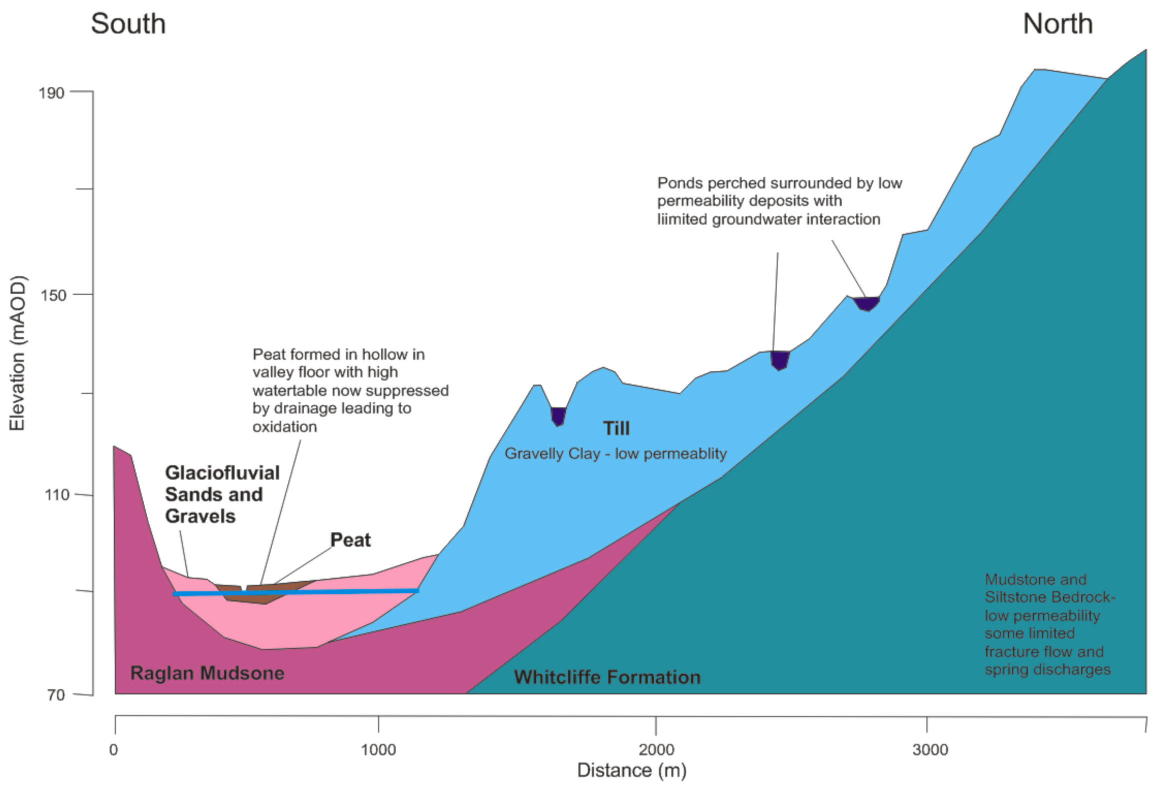
The hydrogeological conceptual model of the area is shown in two cross sections below (Figure 6-16). The first presents a cross section of the Lugg floodplain between Kingsland

and Eyton. The second is a line from the valley floor at Shobdon Marsh and through the uplands to the north. They show the following features:

- Bedrock geology and hydrogeology:
  - The area is underlain, in the main, by low-permeability mudstones and siltstones. There is some limited flow through fractures with spring discharges.
- Superficial geology and recharge:
  - Till covers parts of the hillside and underlies parts of the valley floors. Perched ponds and streams form in topographical hollows, with limited groundwater interaction.
  - Thick, high-permeability glaciofluvial sands and gravels underlie the main valley floors. These are dominated by intergranular groundwater flow.
- The height of the water table within them is controlled by the stage of the watercourses. The stages have been artificially influenced by weirs, drainage works and abstractions. A number of these weirs are now in the process of removal due to the benefits this may have on flood risk and biodiversity.
- When water is higher in the watercourse than the surrounding sands and gravels, the watercourses lose water.
- Peat is formed in a topographical hollow within the glaciofluvial deposits, which created an area with a high water table that allowed peat to accumulate. The straightening of Pinsley Brook will have lowered the water table in the area.



At Kingsland



At Shobdon Marsh

Figure 6-16: Wye/River Lugg Study Area conceptual models

A wide suite of NBS4WR interventions can be implemented across the catchment including land use and soil management practices which promote infiltration and limit runoff generation. The diagram below (Figure 6-17) however focuses on intervention types that are specific to the hydrogeological conditions of the Study Area. They cover options for the floor of the valley underlain by the alluvial aquifer and options for the surrounding hills.

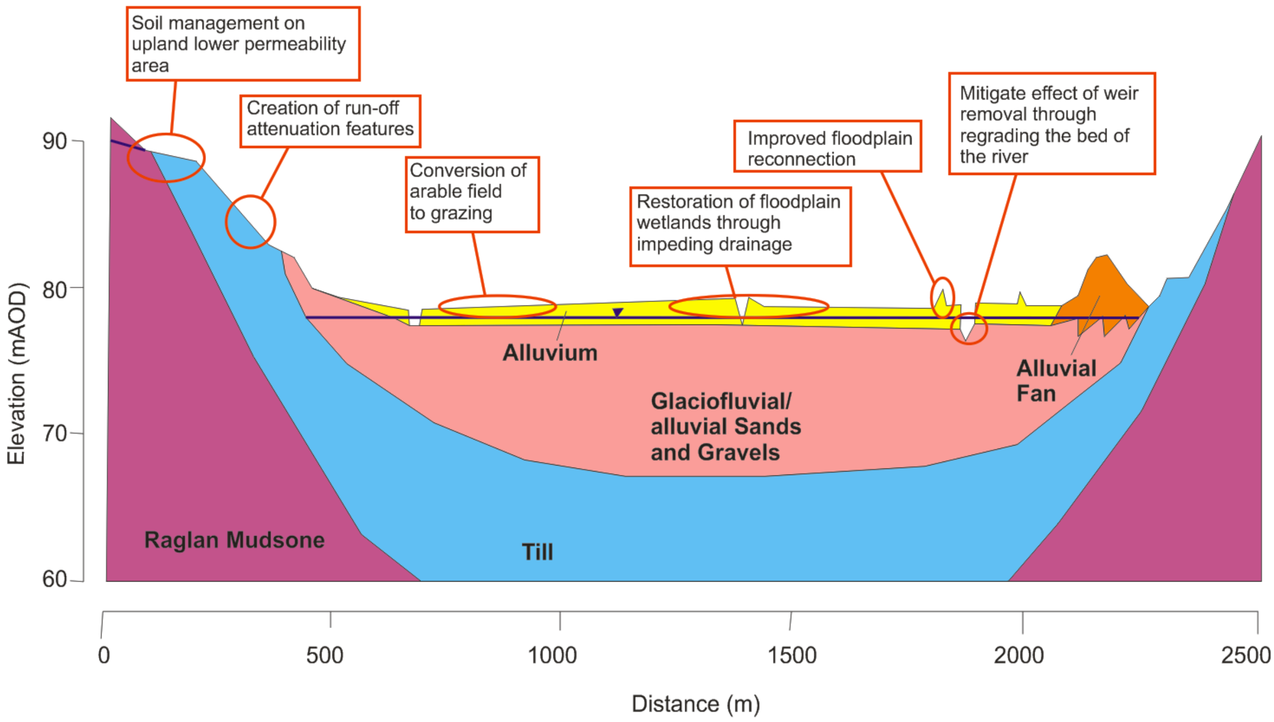


Figure 6-17: Wye/River Lugg Study Area conceptual model with NBS4WR measures

6.5.2 Conceptual model and NBS4WR potential area summary: Otter

This section summarises the key findings from the Otter Study Area. The topography and geology underlying the Otter Study Area, including superficial and bedrock units, are shown in Figure 6-18.

The eastern and northern borders of the Otter Study Area have the highest elevations at approximately 210mAOD and the western border has an elevation of approximately 100mAOD. Elevations are reduced towards the middle of the Otter Study Area and the River Otter at approximately 40mAOD, reaching a low of approximately 3mAOD in the south of the Otter Study Area.

Much of the Otter Study Area has no superficial deposits with bedrock exposed beneath the soils. Where superficial deposits are present these include:

- Clay-with-Flints: clay and sand with unworn cobbles of flint and chert – along the east of the Study Area, overlying the Upper Greensand, up to 30m thick. The Clay-with-Flints sediments formed by dissolution of the Chalk bedrock. It may contain solution collapse features and where thin may also be disrupted by roots. These features can provide some permeability. Runoff is likely to be localised, recharging the underlying and surrounding Upper Greensand aquifer.
- Alluvium: clay, silt, sand, peat and gravel – closely associated with the river valleys of the Otter (up to 500m wide), Tale and Sid.
- River terrace gravel: sand and gravel – along the valleys.

The solid geology dips slightly towards the east. From west to east the bedrock geology outcrops as follows:

- Interbedded units of sandstone and conglomerate of Triassic rocks including Chester (conglomerate) and Helsby Sandstone Formations
- Sidmouth Mudstone formation
- Gault and Upper Greensand Formation (sandstone)

Helsby Sandstone is the most prominent rock type, starting in the north-west near the River Tale and following the pathway of the River Otter to the south. To the east of this formation, the Sidmouth Mudstone Formation covers much of the north-east of the catchment extending down to Tipton St John.

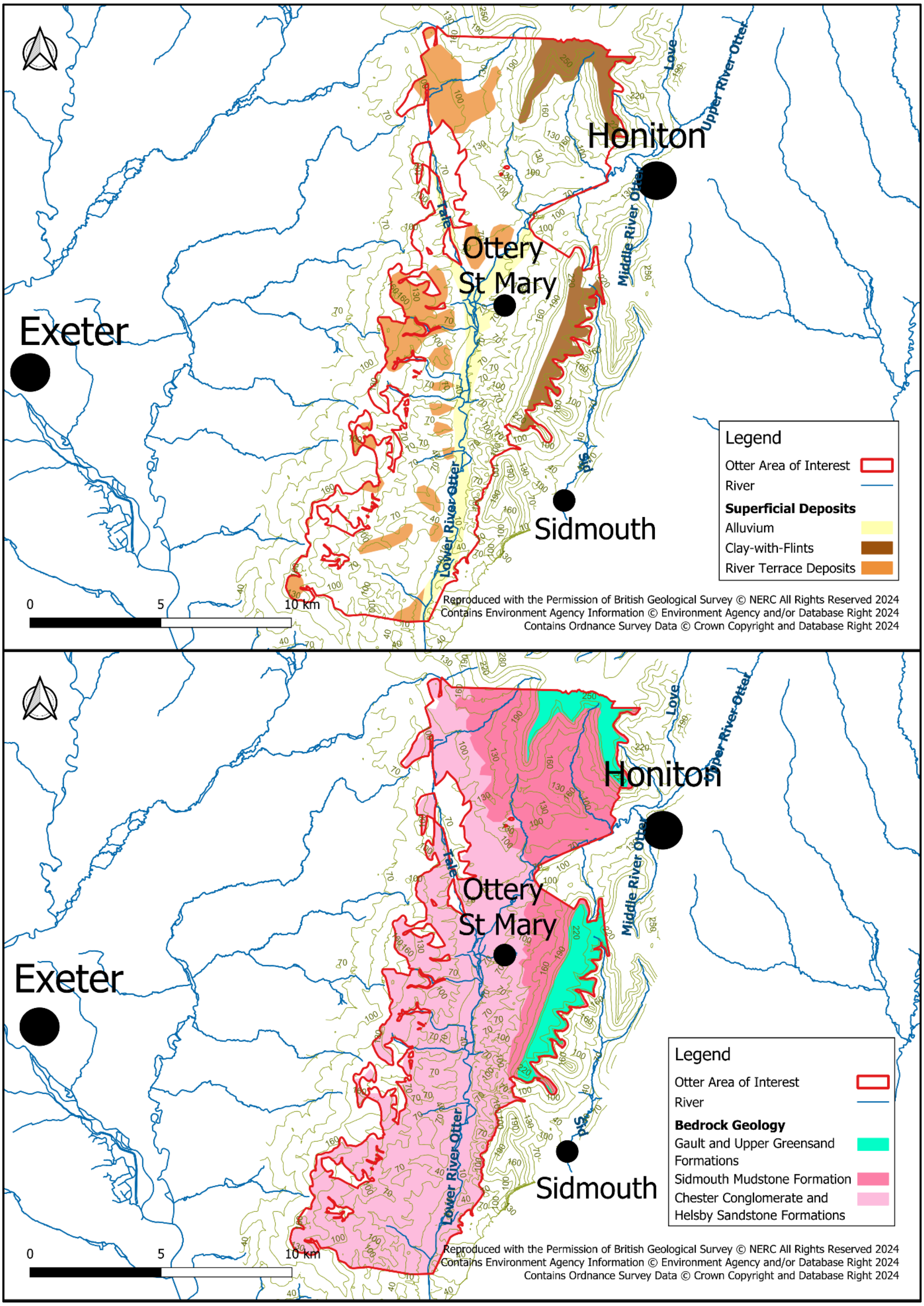


Figure 6-18: Topography, superficial deposits and bedrock units within the Otter Area of Interest

The hydrogeological conceptual model of the Otter Study Area is shown in Figure 6-19. It has the following features:

- Bedrock geology and hydrogeology:
    - The west of the Study Area along the edge of the Otter valley includes small outcrops of the Chester Formation which comprises a thin but highly permeable aquifer, cut by faults. The groundwater level is close to the surface and likely to be in connection with river terrace gravels. Enhanced recharge in this area may result in increased groundwater flow towards the main Helsby Sandstone in the Otter valley.
    - The main Otter valley is underlain by the Helsby Sandstone (Sherwood Sandstone) aquifer. The groundwater level is likely to be in connection with the River Otter but below the level of some of the more minor tributaries. This leaves the potential for leakage from the tributaries to contribute to groundwater recharge.
    - The Sidmouth Mudstone (Mercia Mudstone Group) has only limited potential for enhancing groundwater recharge. However, measures to increase recharge over the Sidmouth Mudstone may result in increased interflow within the soil and weathered upper margin of the mudstone. This interflow may flow horizontally to nearby surface waters or recharge the Helsby Sandstone in the Otter valley.
- Recharge:
    - Recharge through the clay caps on the Upper Greensand is likely to contribute to groundwater flow east away from the Otter valley.

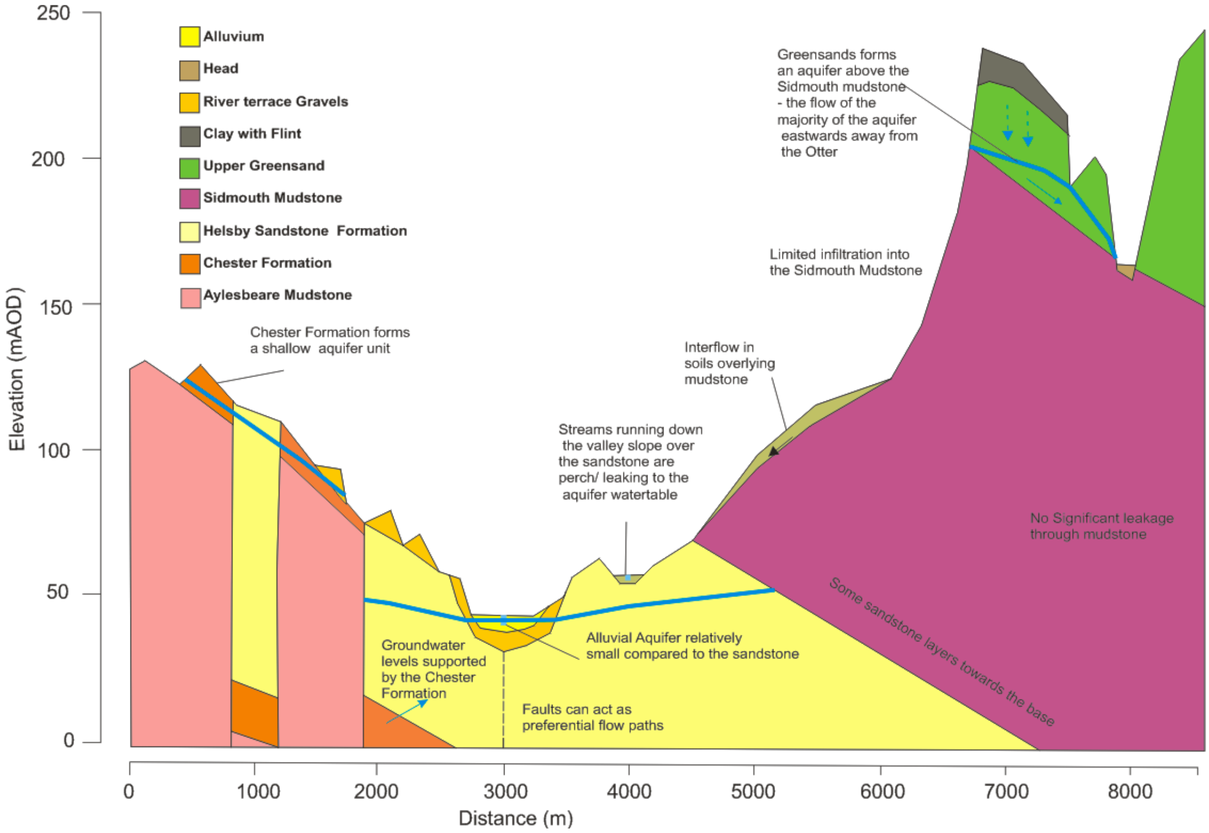


Figure 6-19: Otter Study Area conceptual model

A wide suite of NBS4WR interventions can be implemented across the catchment including land use and soil management practices which promote infiltration and limit runoff generation. The diagram below (Figure 6-20) however focuses on interventions that are specific to the hydrogeological conditions of the Study Area. Specific interventions relevant in the Study Area are:

- Slowing runoff pathways in the west over the thin Chester Formation bedrock to increase recharge. At times of high groundwater levels, the potential for recharge into the Chester Formation may be limited.
- There is likely to be scope for recharge to the margins of the Helsby Sandstone at the west and eastern margins of the Otter valley, as the groundwater level is lower. This recharge can be from slower runoff and also infiltration recharge from losing watercourses perched over the sandstone.
- Improving floodplain connectivity in the Otter valley. This will allow increased aquifer storage in the floodplain and associated alluvial aquifer.
- Slowing runoff in east of the Study Area will result in increased recharge through the clay caps and increased recharge to soils over the Sidmouth Mudstone. Recharge to the clay caps will benefit the Upper Greensand. Recharge over the Sidmouth Mudstone is likely to form interflow which will discharge slower to nearby surface waters and also have the potential to recharge the Helsby Sandstone.

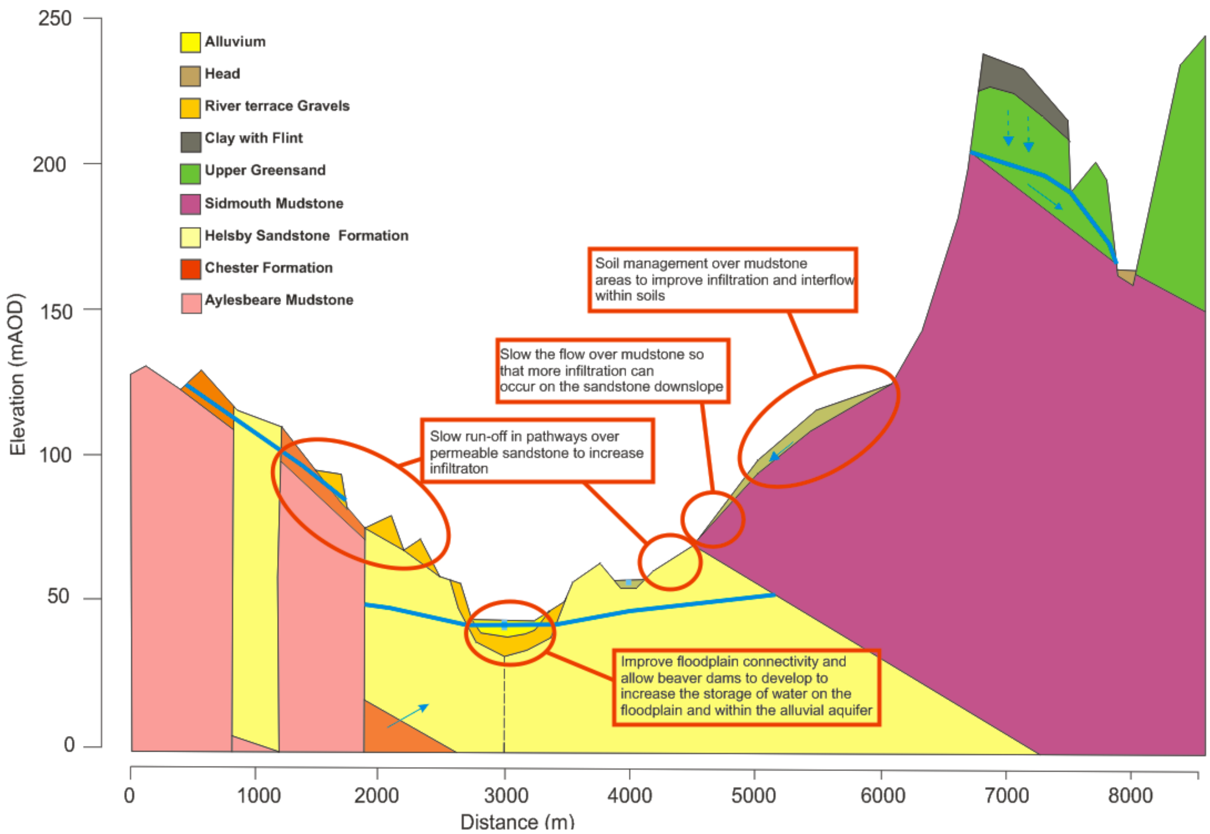


Figure 6-20: Otter conceptual model with NBS4WR measures

Modelling the implementation of combined NBS interventions including: 1) application of RAFs and 2) improving soil has been done on the Otter Study Area. The impacts of the NBS scenario have been assessed on groundwater and stream flows.

The results of the implementation of combined NBS measures on groundwater show a general steady increase in recharge and water table across the whole Otter Study Area which also results in long-term increases in groundwater storage. Figure 6-21 shows the changes in groundwater levels through the combined NBS measures scenario compared to the baseline (no NBS interventions). The largest changes occur away from the Otter valley floor. The river acts as a boundary, which dampens the range of groundwater movement, and the flat, low-lying topography of the valley floor means there is less unsaturated aquifer into which the water table can rise.

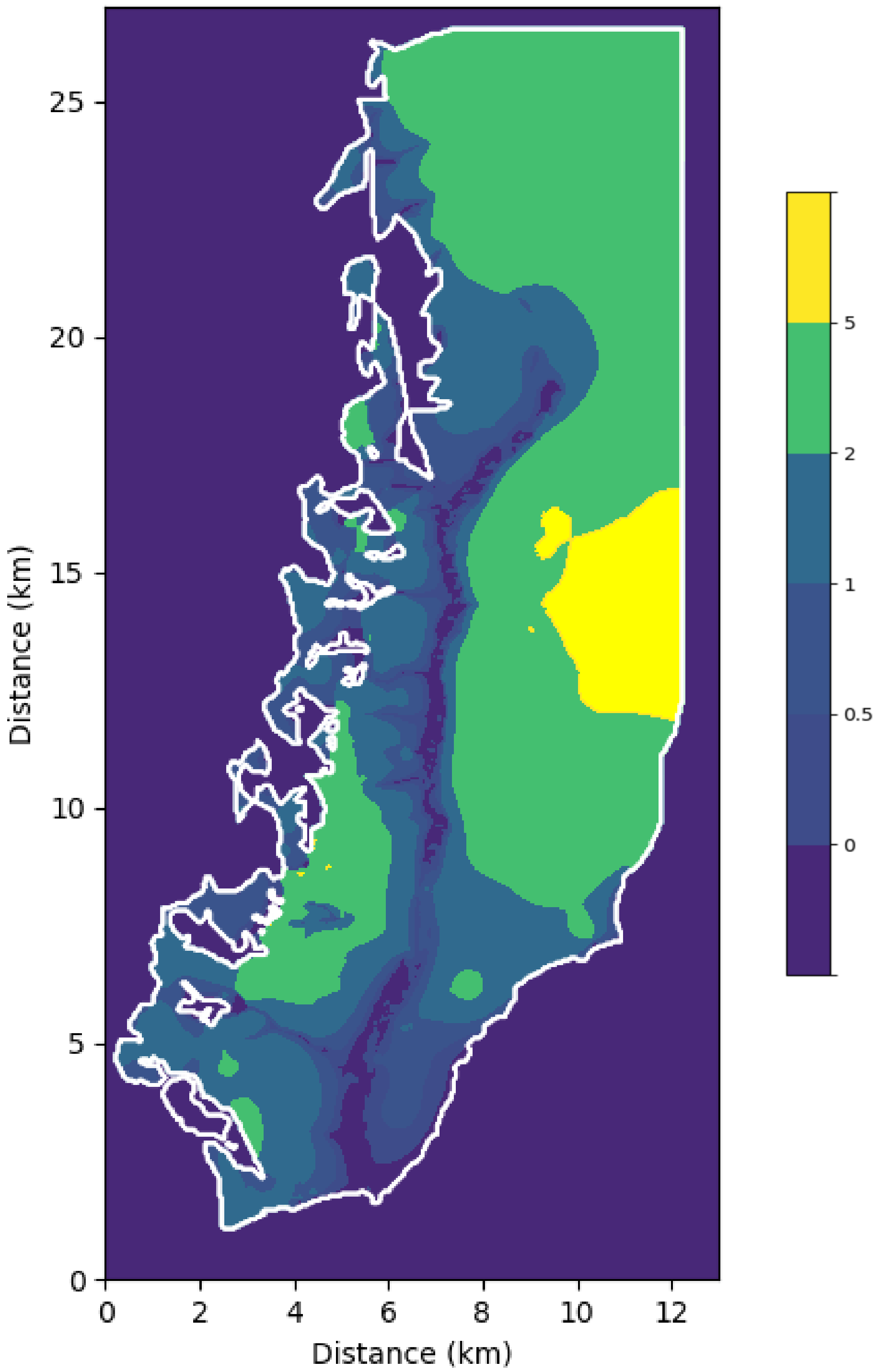


Figure 6-21: Change in groundwater level in metres with an NBS scenario compared to the baseline in an average year for a 100% uptake scenario

The results of the implementation of combined NBS measures on stream flows show increases in river levels and baseflow to the River Otter and its tributaries and a reduction in the amplitude of river level fluctuations. Figure 6-22 shows that the implementation of combined NBS measures results in a reduction in peak flows and increases the frequency of low flows, which means reduction in flood frequency and severity. The graph shows NBS scenario (ON Scenario) flows, Recent Actual model flows and Environmental Flow Indicator (EFI) flow trigger levels. For rivers in England, the Environment Agency uses the EFI to indicate where abstraction, or flow regulation, may start to have an undesirable impact on river habitats and species.

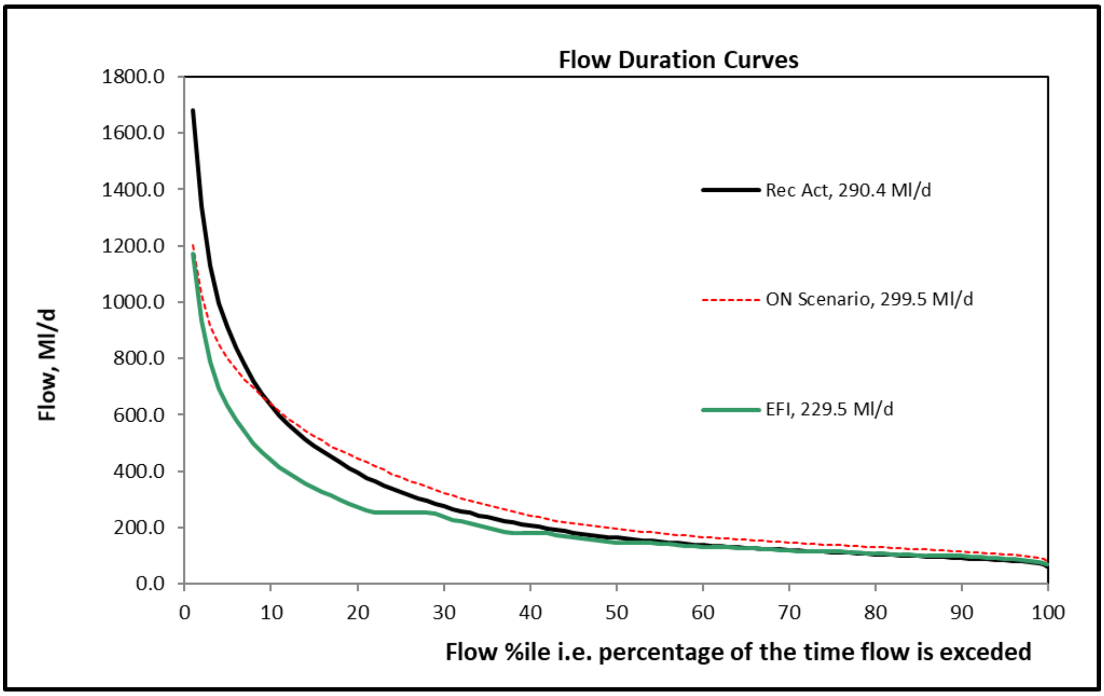


Figure 6-22: Flow duration curves of the River Otter at Otterton gauging station with implementation of combined NBS measures for a 100% uptake scenario

6.6 Summary

As discussed above, NBS measures are particularly sensitive to underlying geology and the aquifer system. The case studies showed the applicability of the potential NBS measures in each aquifer system. Table 6-11 presents the effectiveness of potential NBS measures across different aquifer systems. The effectiveness of measures is defined in terms of improvements to baseflows and recharge to aquifers.

Table 6-11: Modelled relative effectiveness of NBS measures in different aquifer systems

	NBS Measures	Alluvial Aquifers	High-permeability Bedrock Catchments	High-permeability Bedrock Catchments with Patchy Low-permeability Superficial Deposits	Moderate-permeability Catchments
Water Usage	Low Water Usage/ Evapotranspiration Crops	3	3	3	3
Water Usage	Conifer Plantation Replacement	3	3	3	3
Runoff Infiltration Split	Soil Improvement	1	0	2	2
Runoff Capture and Infiltration	RAFs	1	0	2	1
Runoff Capture and Infiltration	Boundary RAFs	2	0	3	1
Floodplain and River Restoration	Wetland Creation	1	1	1	1
Floodplain and River Restoration	River Restoration	3	2	2	2
3 = Most Effective 2 = Effective 1 = Possibly Effective 0 = Not suitable for this location					

7 Appendix. Mapping of NBS features for water resources benefits

7.1 Introduction

Catchment mapping can be used to identify priority locations where the implementation of NBS measures may be feasible and fruitful. Maps of NBS potential are thus important for strategic decision making in relation to delivering water resources benefits. Their usage extends to:

- Selecting the most suitable types of NBS for the catchment and its geology
- Estimating total land take of suites of NBS measures
- Identifying suitable trial locations for NBS implementation
- Relating NBS features to the geological properties of the subsurface
- Parameterising NBS scenarios in groundwater models (see the next chapter)
- Designing prioritised NBS schemes for water resources benefits and to achieve other environmental aims
- Identifying potential risks and disbenefits associated with NBS implementation to be eliminated or mitigated
- Visualising the *art of the possible* for wider stakeholder and public consultation or engagement

Different mapping methodologies may be used for spatial assessments of NBS, each tailored to the specific needs of the users and the nature of the proposed measures. The Environment Agency has produced maps of Working with Natural Processes (WWNP) potential across England, whilst they and their partner organisations have developed more refined, specialised mapping for certain parts of the country to meet set objectives. This chapter will set out in general terms how maps of NBS potential, typically to be viewed in a digital format, can be produced and used in the pursuit of realising benefits to water resources.

7.2 Mapping methodology

7.2.1 Tools

Digital maps of NBS potential can be developed using processes within a Geographical Information System (GIS) or using a computer programming language (e.g. Python). The resulting maps can then be viewed interactively within a GIS or uploaded to an interactive web-based interface.

The most common pieces of GIS software for generating, manipulating and viewing digital maps are QGIS and ArcGIS, though other GIS packages are available to use. QGIS is opensource software that is free to use, whilst ArcGIS is a licensed product available from Esri. The use of GIS for generating NBS mapping will ordinarily require some level of specialist experience, but viewing maps using a GIS is more readily accessible to the non-specialist.

The relative merits of GIS and programming techniques for generating NBS maps via spatial processing are outlined in Table 7-1, noting that these two approaches are not mutually exclusive.

Table 7-1: Strengths and weaknesses of GIS versus coding for generating NBS mapping

GIS mapping techniques	Scripted mapping techniques
Easy visualisation of intermediate outputs	More onerous visualisation of intermediate outputs
Less complexity for the user	More complexity for the user
More rigid functionality, albeit with a range of customisation options	Less rigid functionality and greater freedom to adapt methods
Greater manual input required, so less suited to bulk processing	More suited to bulk processing
Somewhat self-contained software environment	Possible for interfacing with other software

7.2.2 WWNP evidence base

The Environment Agency has undertaken national mapping of WWNP potential, which can form a useful basis for NBS4WR maps (WWNP being broadly synonymous with NBS). Whilst these WWNP potential maps are not specifically designed for NBS4WR purposes, and are instead intended to have more general applicability, there is overlap between generic WWNP measures and more specialised NBS4WR features. The layers that are available as part of the Environment Agency's WWNP evidence base include:

- WWNP Floodplain Reconnection Potential – areas with low flood risk but which are close to a watercourse, indicative of locations where the floodplain may be poorly connected and could provide potential for reconnection to promote enhanced groundwater recharge
- WWNP Floodplain Woodland Potential – areas with fluvial flood risk with potential opportunities for floodplain reconnection, wetland development and planting at low density for enhanced groundwater recharge
- WWNP Riparian Woodland Potential – areas within 50m of watercourses with the potential for river restoration and riparian planting for enhanced groundwater recharge
- WWNP Runoff Attenuation Features – small areas of water storage which could promote enhanced groundwater recharge
- WWNP Wider Catchment Woodland Potential – areas with slowly permeable soils with opportunities for improved land cover management and thus enhanced groundwater recharge

These layers were generated using multiple input datasets that relate to land usage, flooding, geology and hydrology. Their derivation is described in detail within the accompanying technical report (Mapping the potential for Working with Natural Processes - technical report. SC150005. Environment Agency, 2018) and the dataset is accompanied by a detailed user guide (Mapping User Guide. Accessed 24/03/25).

Users can visualise the Environment Agency's WWNP opportunity mapping layers using the web portal developed by JBA Trust (Environment Agency's WWNP opportunity mapping layers. Accessed 24/03/25 https://naturalprocesses.jbahosting.com/Map). Mapping is available for England and Wales alongside case studies of schemes. Example outputs from this publicly accessible portal are shown in Figure 7-1. Use of this dataset should be in conjunction with a hydrogeological conceptual model and potentially groundwater modelling to test for effectiveness in improving water resources.

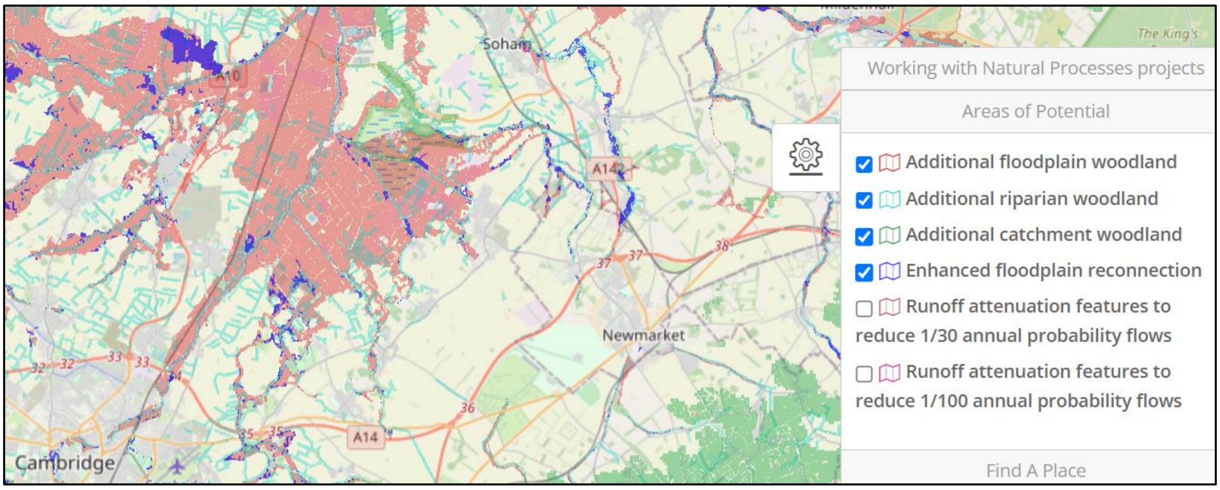


Figure 7-1: Example WWNP mapping from JBA Trust's interactive online portal

7.2.3 Converting the WWNP evidence base into NBS4WR mapping

As part of ongoing work, Water Resources East has commissioned a GIS product covering their area to understand the water resource potential of the features shown in the WWNP evidence base mapping. The following two subsections give details of the development of this product.

7.2.4 Establishing the extents of opportunity areas

Mapping methods for identifying NBS4WR potential can use the above WWNP layers as a basis for further spatial processing. By combining multiple datasets, areas of the catchment can be delineated according to the types of NBS measures that are likely to prove beneficial. An example output of this kind is shown in Figure 7-2, which shows opportunities in the lower catchment for floodplain reconnection. Using these methods, it is possible to identify prioritised areas of NBS potential for the following sorts of interventions:

- Stream, gully or ditch blocking/raising/reprofiling
- Infiltration basins/hollows
- Leaky dams
- Bunds
- Rewilding
- River restoration and renaturalisation
- Floodplain reconnection
- Riparian planting

- Wetland development or enhancement
- Soil improvements
- Pasture and grazing management
- Crop substitution, rotation and management
- Shelterbelts/buffer strips

Defined zones of the catchment can thus be generated in which grouped NBS intervention types could prove successful, pending further investigation as to their suitability.

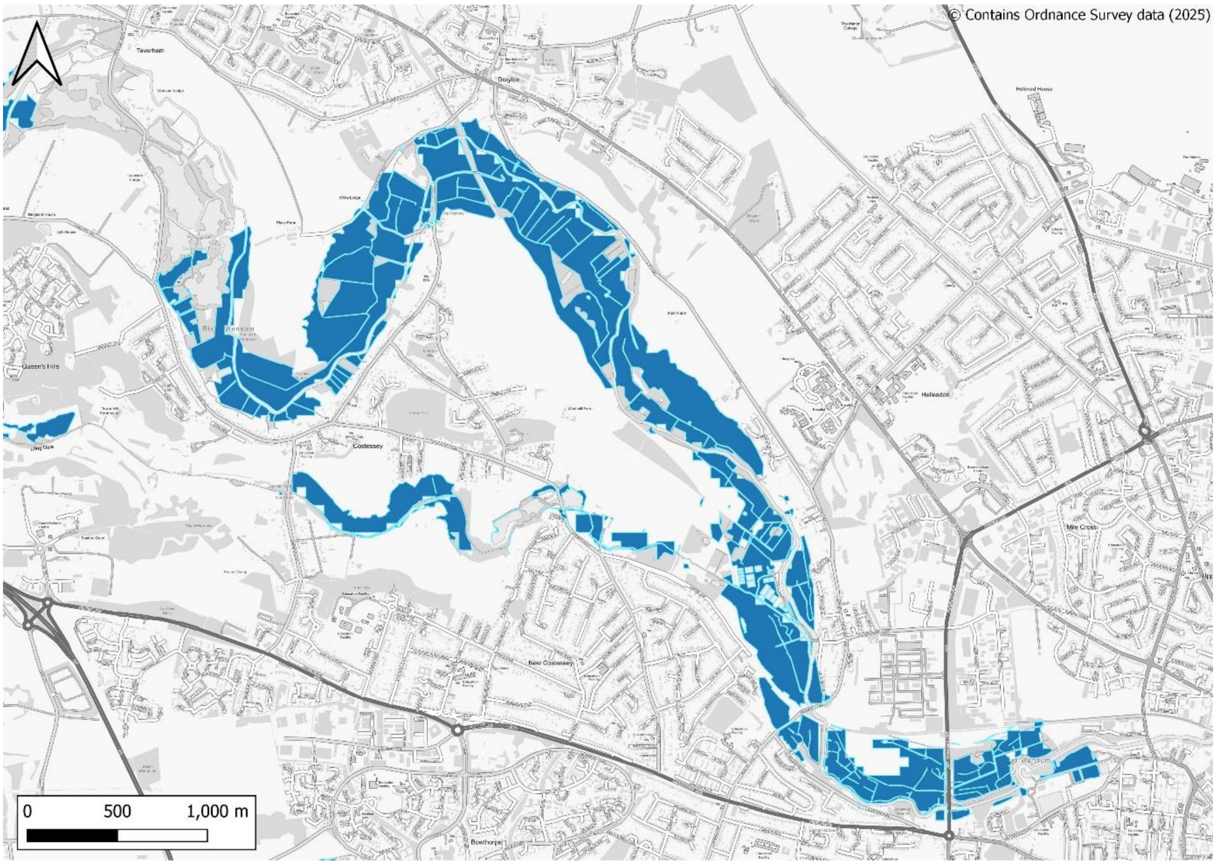


Figure 7-2: Example NBS potential mapping showing areas with NBS potential for floodplain reconnection in the lower catchment

7.2.5 Recharge potential attribution

Having established where in the landscape NBS measures could be introduced, the next stage is to determine their potential for facilitating increased recharge to aquifers. Mapping of recharge potential can be carried out with a semi-quantitative approach using geological and hydrological datasets, chief among these being the Environment Agency's Groundwater Vulnerability Map (Water Resource Benefits of Working with Natural Processes, JBA Consulting, 2021). Individual attributes are scored according to the extent to which they contribute to modifying infiltration, with the scores then weighted and combined to give an amalgamated scoring system for recharge potential. Categorised outputs for recharge potential are shown in Figure 7-3.

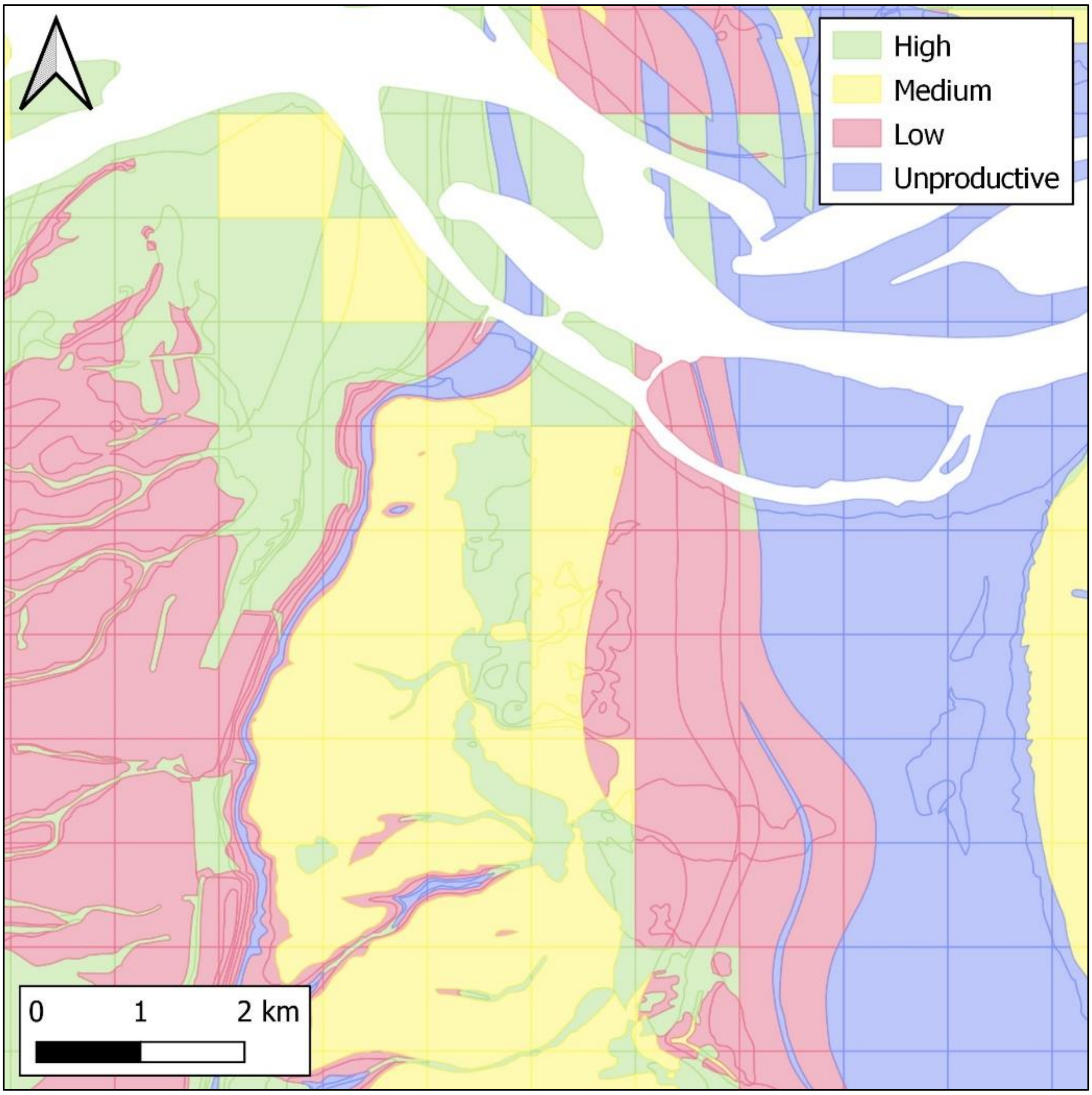


Figure 7-3: Example of recharge potential mapping derived from geological and hydrological data

By subsequently joining the locations with NBS potential to a layer estimating recharge capacity, areas can be prioritised for NBS that are both suitable for the implementation of measures and likely to deliver maximal water resources benefits. The process of mapping of NBS4WR features using layers of recharge potential in conjunction with those from the WWNP evidence base is illustrated schematically in Figure 7-4, showing the categories of the input data that are used for each.

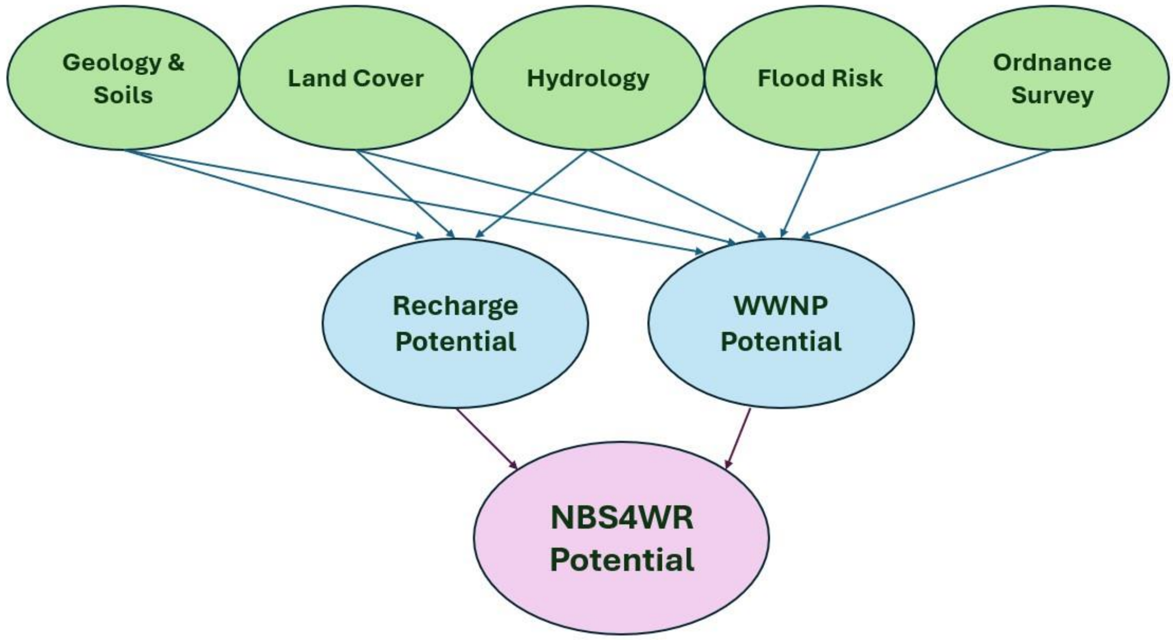


Figure 7-4: Example data inputs for NBS4WR potential mapping

7.2.6 Consultation areas

There are a range of existing maps available from the Environment Agency and other organisations (e.g. Natural England) that identify areas of England where there are known environmental sensitivities or that have heightened risks of geohazards. These datasets include the likes of Source Protection Zones (SPZs) for groundwater, landfill sites, areas of historic mining and pollution, landslide risks, and Groundwater Dependent Terrestrial Ecosystems (GWDTEs). Such areas may be outright unsuitable for certain types of NBS, or further investigative consultation may be required to understand how and where NBS can be implemented safely and effectively.

The Environment Agency has published national mapping of consultation areas tailored to NBS4WR. This can be viewed within an interactive online portal (Interactive Portal, Water Resources Recharge Potential & Consultation Mapping, accessed 24/03/25). Within the portal, these areas can be seen alongside mapping of recharge potential. Additionally, there is a wealth of useful information that is available from the Multi-Agency Geographic Information for the Countryside (MAGIC) map portal (Magic Maps. Accessed 24/03/25 https://magic.defra.gov.uk/home.htm).

An understanding of existing pressures on water resources can be used to target catchments for NBS interventions. The Environment Agency's Water Resource Availability and Reliability product classifies Water Environment (Water Framework Directive) catchments according to the availability of water resources within them and the pressures imposed on them by consumptive abstractions (Water Resource Availability and Abstraction Reliability Cycle 2, Accessed 24/03/25 https://www.data.gov.uk/dataset/b1f5c467-ed41-4e8f-89d7-f79a76645fd6/water-resource-availability-and-abstraction-reliability-cycle-21).

It may the case that an opportunity mapping exercise reveals that the implementation of NBS may not be viable in a particular area. For instance, this may be due to geological (e.g. extensive low-permeability material) or geographical factors (e.g. extensive urban land cover). Identifying such areas is important to avoid implementing ineffective NBS schemes.

7.3 Geological maps

This section considers situations where NBS4WR opportunity mapping is not readily available.

The geology of an area fundamentally affects whether NBS will be effective in delivering the intended water resources benefits, and the style of NBS measures best suited to doing so. Detailed geological maps of Britain have been developed by the British Geological Survey (BGS) and can be used in parallel with NBS opportunity mapping to aid decision making. At its most basic, this geological mapping describes the uppermost superficial and bedrock types present at a given location. However, a range of derivative products are available from the BGS, including maps with aquifer properties and ground stability. Among these, the BGS Groundwater Vulnerability Map can be used as a proxy for the recharge properties of the substrate. Areas with high groundwater vulnerability are vulnerable in part because they allow significant recharge. So, designers of NBS4WR features may wish to target these areas for this reason.

An alternative to groundwater vulnerability mapping is national soil mapping from Cranfield University, which is available from the Land Information System Soilscapes viewer online. For each Soilscapes Class there is a drainage description that ranges from Freely Draining to Impeded Drainage.

NBS opportunity maps can readily be overlain with geological maps to understand the interactions between individual NBS features and the underlying aquifers. This can be particularly illuminating where NBS opportunity areas straddle geological boundaries across which there is a contrast in permeability. In such instances, maps can be used to ascertain whether runoff from an area of low permeability can be captured near the interface, pooled and diverted to groundwater via infiltration within the more permeable area.

7.4 Limitations

For selecting individual sites for NBS implementation, broad-scale mapping can be a somewhat blunt instrument, so care should be taken to undertake further detailed mapping ahead of actualising any schemes on the ground. Detailed maps can be used to identify spatial and locational constraints, allowing shortlists of areas for implementation to be drawn up. Ultimately however, the accuracy of NBS maps on all scales is limited by the veracity of the data with which they are produced. Local knowledge is often essential in identifying exact locations for NBS implementation. Site investigation may also be required, especially when targeting features at the boundaries of different geologies. Mapping can therefore be used as a high-level tool to facilitate landowner and stakeholder engagement through which this local knowledge can be captured.

A fundamental limitation of two-dimensional maps is that variations in geology with depth are neglected. Vertical changes in permeability exert strong controls on recharge and shallow groundwater flow conditions. Geological cross sections, some examples of which were provided in the previous chapter, are valuable tools to be used alongside maps of NBS potential and can provide a fuller understanding of the system.

Whilst mapping can be advantageous for prioritising locations in a catchment suitable for NBS4WR implementation and identifying the types of measures that are feasible, maps alone do not provide quantitative assessments of the magnitude of the effects on water resources. Such assessments can instead be undertaken using recharge and groundwater models, which are the subject of the next chapter.

7.5 Summary

This chapter has provided an overview of:

- Usage of mapping to locate NBS4WR opportunities
- Methodologies for developing such mapping
- The relationship between opportunities maps of NBS potential and geological/soil mapping
- Limitations of broad-scale mapping exercises

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8 Appendix. Modelling to quantify water resources impacts of NBS features

8.1 Introduction

Quantifying the impacts of NBS is central to cost-benefit analyses of portfolios of such measures. Numerical and analytical modelling tools are available for the quantification of likely changes to water resources resulting from the implementation of NBS at a regional scale. The utility of such modelling lies in its ability to quantitatively predict:

- The scale of NBS implementation required to achieve desired water resources benefits
- The efficacy of specific NBS measures in different geological and hydrological contexts
- The spatial distribution of impacts on the water cycle throughout a catchment
- The timescales on which water resources benefits are likely to be realised, along with the seasonality of the associated effects

The Environment Agency and its partner organisations have explored the use of coupled recharge-groundwater models to simulate how different categories of NBS could offer water resources benefits across parts of England. This chapter focuses on modelling techniques which use these regional models.

8.2 Tools and techniques

The Environment Agency holds a suite of regional models that simulate coupled recharge and groundwater flow within major aquifers across England. Having been built and developed over recent decades, these numerical models are designed to support decision making in the strategic management of groundwater resources, being used by multiple external stakeholders at the discretion of the Environment Agency. The models combine a surficial hydrological model – one of either the 4R or SWAc codes (see the next paragraph) – with an underlying groundwater flow model constructed in MODFLOW. The use of these models involves first running 4R or SWAc to simulate surficial hydrological processes, before then using the resulting boundary conditions as inputs to MODFLOW.

4R and SWAc are modelling tools that have been developed specifically for regional water resources estimation in England, although both have applicability elsewhere. Both codes are similar in how they represent hydrological processes, but there are subtle differences between the two. 4R is proprietary software owned by WSP (Heathcote, J.A., Lewis, R.T., Soley, R.W.N., 2004. Rainfall routing to runoff and recharge for regional groundwater resource models. Engineering Geology and Hydrogeology, 37 (2): 113-130), whilst SWAc is opensource software developed by Groundwater Science (Black, A., Lagi, M., 2017. Surface Water Accounting Model, SWAc – linking surface flow and recharge processes to groundwater models. 15th meeting of the Groundwater Modellers' Forum).

MODFLOW is a numerical modelling tool that is used more widely in industry and academia for the simulation of groundwater flows in the subsurface (Documentation for the MODFLOW 6 Groundwater Flow Model, USGS. 2017). The exchange of water between aquifers and surface features (e.g. rivers) is also simulated within MODLFOW. MODFLOW is freely available from the United States Geological Survey (USGS) and solves the groundwater flow equation in three dimensions using a discretised approach on a grid. It has widespread usage, with applications beyond water resources estimation.

8.2.1 Spreadsheet recharge modelling

It is not always necessary to run a full regional simulation for an assessment of NBS implementation. A more rapid means of modelling NBS can be achieved using simplified spreadsheet tools. Such spreadsheet modelling can be used to approximate a single model cell or lumped catchment, and with high throughput, can be used to perform initial screenings of NBS options before taking forward selected options for testing using a full regional model.

'Simple' spreadsheet versions of both 4R and SWAc have been developed for NBS modelling. Both spreadsheet models emulate the processes simulated within the full, distributed versions of the respective codes, but are only able to do so for a single location at a time – be this a single model cell or a catchment represented using aggregate properties. Model parameters can be readily changed within individual cells in the spreadsheet to simulate changes due to NBS implementation, yielding effectively instantaneous results. This avoids the need to run a full simulation requiring hours of computational time, allowing parameter combinations to be bulk tested for initial screening assessments. Parameter combinations for specific NBS interventions can be optimised in this way, and certain options can be discounted on the grounds that they appear to offer limited water resources benefits. An example output tab from the 4R simple spreadsheet is shown in Figure 8-1. Please contact the authors of this report for copies of the simple spreadsheet versions of either 4R or SWAc.

	A	B	C	D	E	F	G
1	**Scenario summary:**	*Enter description of model scenario*					
2							
3		**Baseline**	**Scenario**		**cRAF parameters**		
4	**Soil-landuse:**	Loam Soil - Arable Landuse	Loam Soil - Arable Landuse		**Lumped catchment** area u/s of cRAF		1.42
5	**Shallow geology:**	Low K Till	Low K Till		Routed order of cell with cRAF		4
6					Routed runoff store release for each order		0.99
7	**sRAF parameters**				% of cells with nat runoff recharge		0.5
8	**Captured proportion of cell rapid runoff**		0.5		nat runoff recharge cell limit		1
9	**Aggregated open water area when spilling**		500		% of cells with sRAFs (step 6)		0
10	**Aggregated minimum water area before dry**		300		length		200
11	**Max aggregated spill water depth**		0.4		bot width		5
12	**Min fixed outflow**		1		top spill width		70
13	**Linear sRAF leaky outflow release factor**		0.1		Max spill depth		0.5
14	**sRAF extra bypass infiltration limit**		1		Floodplain cRAF Sy		1
15					cRAF leaky outflow release factor		0
16					cRAF extra runoff recharge limit		1
17							
18	**Annual average**						
19	**Parameter type**	**Parameter**	**Unit**	**Baseline**	**Scenario**	**Change**	**Change (%)**
20	General	Rainfall	mm/a	610.6	610.6	-	0.0%
21		AE	mm/a	400.8	401.0	0.2	0.0%
22		SMD	mm/d	47.3	47.3	-	0.0%
23		Runoff	mm/a	140.8	138.6	- 2.1	-1.5%
24		Recharge	mm/a	70.3	72.3	2.0	2.8%
25							

Figure 8-1: 4R simple spreadsheet – master outputs tab (source: WSP)

Currently the 'simple' spreadsheet requires a certain level of training before it can be used, but it could be adapted in future to be hosted on a website where simple parameters are inserted and results given. Such a development would allow practitioners to specify the size of individual features and quantify their benefits.

NBS modelling workflows can benefit from an initial stage involving simple spreadsheet modelling and a subsequent stage involving full regional modelling. This allows a range of NBS options to be preliminarily tested before tailored suites of implementation measures are shortlisted to be simulated more fully. Nonetheless, simple spreadsheet modelling can be usefully done as a standalone exercise, as can regional NBS modelling. Whilst they are often complementary, the relative merits of these two approaches are set out in Table 8-1.

Table 8-1: Strengths and weaknesses of simple spreadsheet modelling versus regional simulation

Simple spreadsheet	Full regional simulation
Rapid generation of results	Time-consuming computational exercise
Suitable for use by non-specialists	Requires specialist operation
Fast manipulation of model parameters	Parameterisation can be more complex
User-defined processes can be added	Coding of new processes requires specialist knowledge
Limited range of output formats	Wide-ranging outputs
Confined to a single location, with no spatial heterogeneity	Results available for an entire catchment
No simulation of groundwater and fluvial processes	Includes simulation of groundwater and river flows
Analytical model without stability issues	Potential stability issues with a numerical model
Limited usefulness of the results in relation to other impacts of NBS	Potential for the use of the results for the assessment of other effects of NBS in relation to water quality, flood risk etc.
Available to use without a licence	A data licence must be obtained in advance for use of the Environment Agency's regional models
Ease of file management, the model being contained within a single Excel document	Large number of input and output files can be required, some of which can have large data storage requirements for big models
No inbuilt audit trail for model results	Inbuilt audit trail in the form of output log files written out during simulations
No automated parameter checks are built in	Basic automated model checks are built in
Ease of communication of results with a lay audience	Some aspects of the modelling processes may prove a little cryptic to a wider audience of non-specialists
Could be adapted to be hosted on a web portal	Not particularly suitable for web hosting

8.2.2 Distributed recharge modelling

SWAc and 4R share a conceptual framework for modelling runoff and recharge processes, which is rooted in the approach for computing crop water requirements set out in the Food and Agriculture Organization's (FAO) Irrigation and Drainage Paper Number 56 (Crop evapotranspiration – Guidelines for computing crop water requirements – FAO Irrigation drainage paper 56. Food and Agriculture Organization of the United Nations, Rome, 1998). This approach calculates evapotranspiration from a soil moisture store based on the characteristics of the vegetation relative to a reference crop of grass. SWAc and 4R make these calculations on a daily timestep across a two-dimensional grid (which can be regular or irregular). They employ a system of water 'stores', each a well-defined component of the near-surface water cycle, between which water is transferred according to a user-defined set of parameters. These model parameters relate to the geological and hydrological properties distributed across the study area.

The full version of SWAc is written in the Python programming language and uses text-based input files. The full version of 4R is written in the Fortran programming language and uses text-based and Surfer grid input files. 4R and SWAc can produce input files for MODFLOW containing temporally and spatially varying boundary conditions relating to recharge, evaporation and stream flow.

For both SWAc and 4R, dedicated NBS modules have been developed as part of projects for the Environment Agency. The NBS modules allow for the representation of RAFs and other related features within recharge models. To do this, the code is modified to enable the capture and subsequent release of runoff using basin-like stores across the landscape. The properties of these features can be varied by the user across cells within the model, which include the dimensions of structures, their infiltration capacities, and rates of leakage from them.

8.2.3 Groundwater modelling

Whilst 4R or SWAc can be used in isolation to estimate recharge to aquifers, for a full understanding of the water resources benefits of NBS it is often necessary to couple a recharge simulation with a three-dimensional groundwater flow model. Although other solvers are available, MODFLOW is the software used for this within the Environment Agency's regional models.

Within the Environment Agency's regional models, an overlying 4R or SWAc recharge model is typically run independently to generate several boundary condition input files to MODFLOW. These input files can then be read directly by MODFLOW and include simulated recharge to groundwater, evapotranspiration demand from the water table, and flow within the stream network.

Multiple versions of MODFLOW are available from the USGS, each with different capabilities. Backwards compatibility is not available between major releases of MODFLOW, and there are significant differences in modelling approach between some versions. The Environment Agency's regional models do not all use the same version of MODFLOW; some make use of the more sophisticated functionality of more recent releases such as MODFLOW 6, whereas others still use older versions of MODFLOW for which customised extensions have been developed.

MODFLOW models can be viewed and manipulated using a graphical user interface (GUI) such as Groundwater Vistas, although many regional groundwater models are not currently equipped to be used in this way. Hence, programmatic approaches are likely to be needed to make changes to the baseline scenarios for NBS modelling. Similarly, the raw output files from MODFLOW are not human readable, so various postprocessing utilities must be run to generate comprehensible results. Example postprocessed outputs from a MODFLOW model are shown in Figure 8-2.

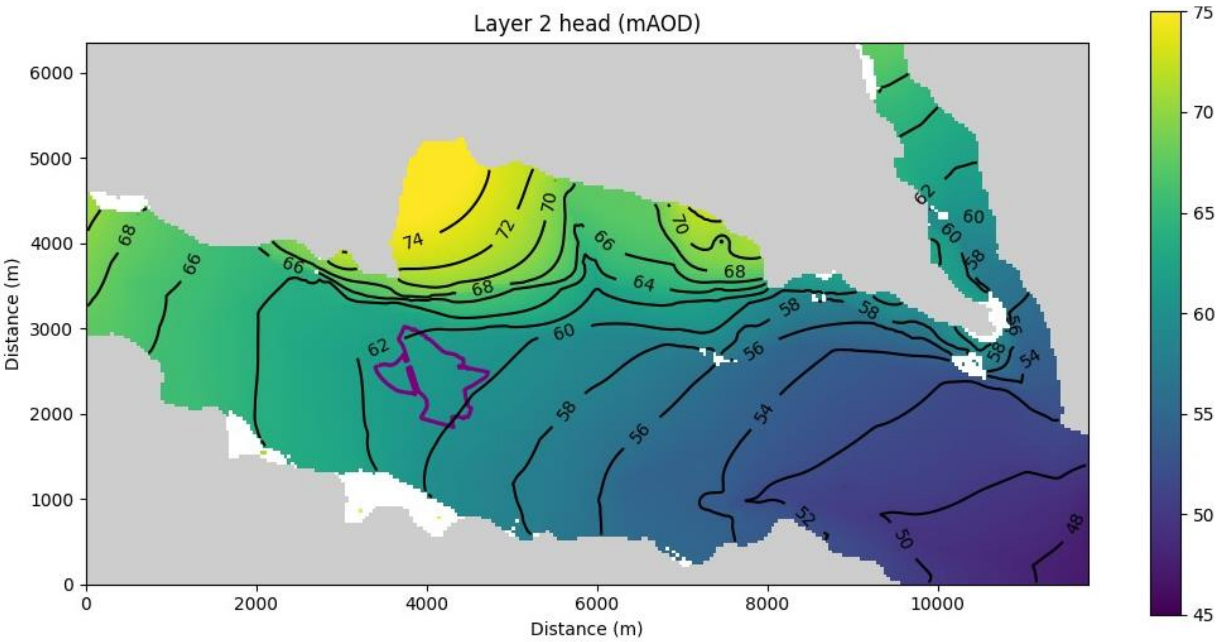

Figure 8-2: Example groundwater head outputs from a generic MODFLOW model

The results from MODFLOW that are likely to be of most use to practitioners relate to flows in the river network and fluxes of water to and from aquifers. Flow duration curves for strategic points on the river network can be generated by processing 4R/SWAc outputs in conjunction with those from MODFLOW, whilst water budget analyses (including estimates of occupied aquifer storage) can be constructed by running the Zone Budget postprocessing utility available from the USGS (A.W. Harbaugh, 1990. A computer program for calculating subregional water budgets using results from the U.S. Geological Survey Modular Three-Dimensional Finite- Difference Ground-Water Flow Model. USGS).

8.2.4 Structuring a modelling study

Experience has shown that there are benefits to structuring a NBS groundwater modelling study using a phased approach, from initial conceptualisation (see section 6 for examples) through to full regional modelling. A recommended approach is set out in broad terms below; this workflow can be modified according to the needs and scope of the study.

1. Conceptualisation phase – geological conceptual modelling of the catchment

   Develop a conceptual understanding of the hydrogeological processes within the study area. Begin to conceptualise what sorts of NBS measures might be feasible and beneficial for water resources within the catchment, which will be constrained by the geological properties of the rocks and superficial deposits present within it. Build a knowledge base of where the implementation of NBS in the catchment may be fruitful.

2. Scoping phase – simple spreadsheet modelling for a longlist of options

   Use simple quantitative approaches to test selected NBS options in hypothetical trial locations. Representative geological and hydrological properties can be assumed for this analysis. Simplified spreadsheet tools are available which can estimate changes to infiltration for defined NBS options. Take forward the more promising options for further testing using more sophisticated modelling tools.

3. Recharge modelling phase – Hydrological modelling to simulate recharge to groundwater

   Run either the full version of 4R or SWAc to quantify surficial hydrological processes across the catchment for shortlisted NBS options. Key processes being simulated will include rainfall, evapotranspiration, runoff, interflow, and infiltration. Outputs from the modelling can be used to estimate distributed recharge to groundwater within the study area. Boundary conditions for MODFLOW related to recharge to groundwater, evapotranspiration from the shallow water table, and flow in the stream network can be produced for subsequent groundwater flow modelling.

4. Groundwater modelling phase – Groundwater flow modelling to simulate regional water resources effects

   Using input files from the previous recharge modelling phase, carry out 3D groundwater flow modelling across the catchment using MODFLOW. This can be used to estimate aquifer storage and low flows in rivers over time, allowing benefits to water resources to be quantified. The binary file outputs from MODFLOW must be postprocessed to generate readable results, for which there are several postprocessing utilities available. Further detailed analysis/tabulation of the results and visualisation with maps and charts is then possible. Subsequent economic appraisal of NBS options can be conducted using various metrics.

8.3 Case studies

NBS modelling has been delivered for the Environment Agency and partner organisations using several of their regional models, namely:

- Northern East Anglia Chalk (NEAC) model in the East of England
- Cam and Beford Ouse (CBO) model in the East of England
- Test and Itchen (T&I) model in Hampshire
- Otter (OTR) model in Devon

The first three of the above models are examples of Chalk-dominated catchments (refer to section 6 for detailed discussion of results and trends), albeit each with different properties, whilst the latter contains the Otter Sandstone aquifer that is part of the Sherwood Sandstone Group. These models are built using 4R for recharge estimation (although it is SWAc in the case of the Otter model) and MODFLOW for groundwater simulation. The NEAC, CBO and Otter models use MODFLOW 96, whilst the Test and Itchen model has been upgraded to use MODFLOW 6 on an unstructured grid.

8.3.1 Catchment themes

Alongside other NBS measures, the installation of RAFs has been tested extensively using the NEAC, CBO and Otter models. The use of so-called ‘boundary RAFs’ has been demonstrated to be particularly effective in catchments that have low-permeability geological deposits in upland areas that give way to highly permeable geologies in low-lying portions of the catchment. These boundary RAFs can be constructed downstream of the interface between the two geology types, allowing high volumes of upland runoff to be captured and diverted into the ground where the infiltration capacity is significantly higher.

In the NEAC and CBO models, boundary RAFs on areas of Chalk immediately downstream of till deposits were shown via modelling to be capable of delivering sizeable water resources benefits for relatively minimal land take. However, this requires ground truthing with field trials, as areas of low-permeability putty Chalk may not be fully represented within models. In the Otter model, boundary RAFs downstream of mudstone bedrock were capable of significantly increasing recharge to the Otter Sandstone aquifer. Figure 8-3 visualises how groundwater levels in the Otter model for an average rainfall year could be raised for a combined NBS scenario involving RAFs and other measures. The effects of NBS measures on low flows in rivers can be assessed using flow duration curves, an example of which from the Otter model is provided in Figure 8-4.

In catchments with appreciable surface runoff, measures other than RAFs can be effective in promoting aquifer recharge via infiltration. Measures to improve soil health and structure can reduce rates of runoff and divert water to aquifers on suitable geologies. Soil improvements on areas of till in the NEAC and CBO models have been shown to be effective in boosting water resources.

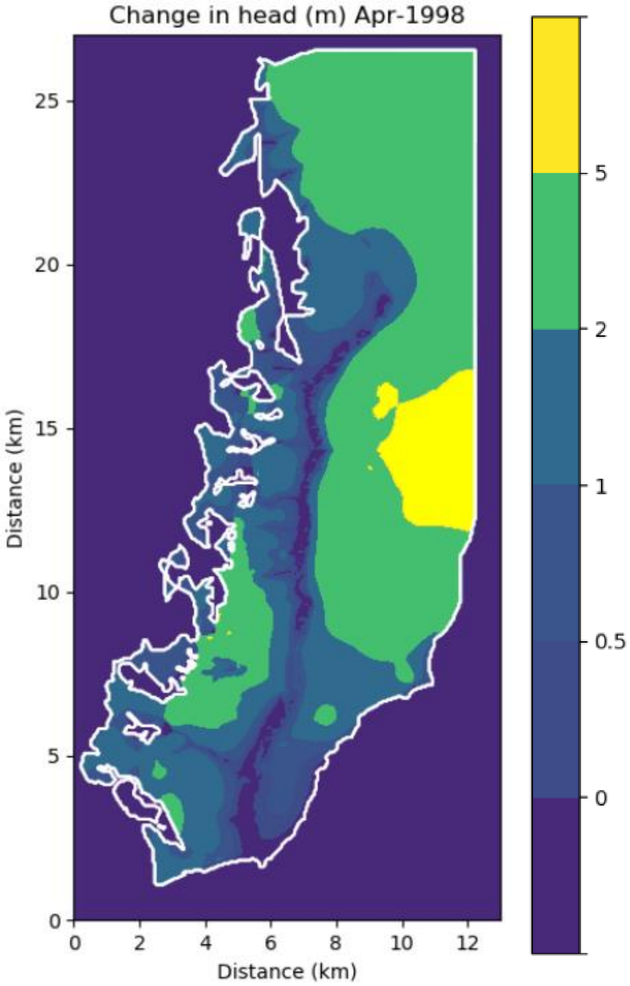

Figure 8-3: Modelled increases in groundwater level within the Otter Sandstone aquifer in an average year due to a combined NBS scenario with full uptake of potential measures

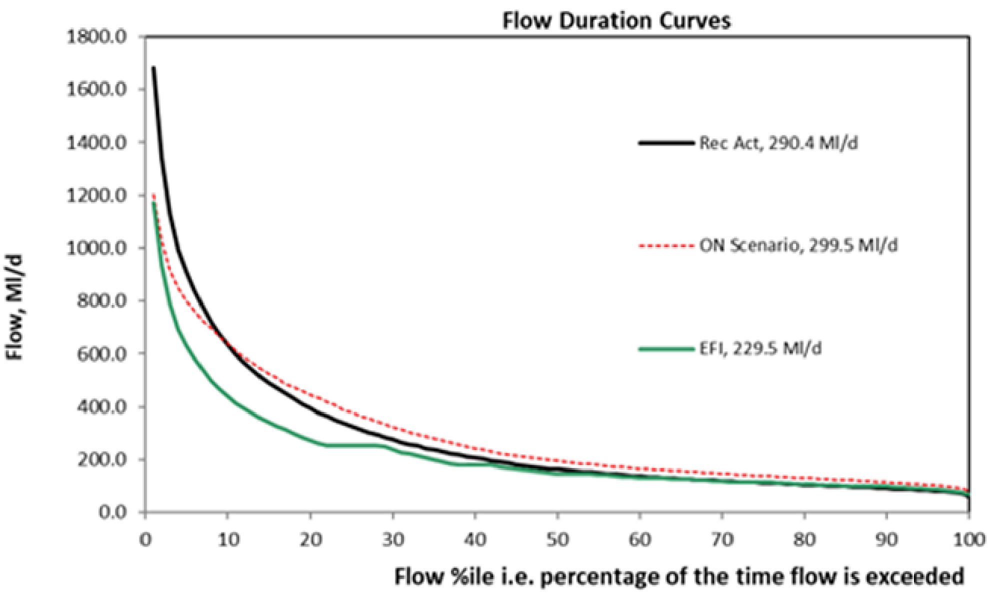

Figure 8-4: Flow duration curves for the River Otter for baseline ('Rec Act') and a combined NBS scenario ('ON Scenario') with full uptake of measures relative to the Environmental Flow Indicator (EFI)

For catchments such as the Test, which is underlain by a highly permeable geology throughout much of it, NBS measures seeking to capture or minimise runoff are of limited efficacy. This is because rates of recharge to groundwater are high and consequently there is little runoff available to be captured. Instead, NBS measures that change land use and reduce associated water demands can be substantially more effective in such catchments. These land use changes can offer benefits beyond water resources and have been shown with modelling to reduce diffuse pollution.

8.3.2 Secondary effects of NBS

The use of NBS modelling for assessing water resources benefits has identified other potential issues or opportunities that could arise through their implementation. Some of these effects can also be quantified through modelling.

The co-benefits of NBS4WR measures are multiple and wide ranging (see section 7). Models can be constructed to optimise the co-benefits associated with NBS4WR, for example in terms of enhancing water quality and reducing diffuse pollution loads within catchments, increasing carbon storage, or leading to reductions in flood risk.

Measures to enhance areas of wetland on the floodplain result in the elevation of the water table within riparian areas, potentially increasing rates of evapotranspiration from the shallow water table. Such an effect has been shown to deplete aquifer storage over time.

Modifications to the runoff regime within a catchment will inevitably have impacts on the dynamics of erosion and sedimentation within it. For example, the installation of RAFs can promote the capture of fine-grained sediments, leading to localised accumulation of material. Conversely, soil improvement measures can lead to retention of sediment locally and slow the erosion of sediment from fields. Related to this, many NBS features, from RAFs to wetland restoration, can have positive effects on nutrient cycling and water quality.

The intended raising of groundwater levels associated with NBS4WR brings water tables closer to ground surface in low-lying portions of the catchment and can consequently increase the risk of groundwater flooding. Whilst this may be largely confined to riparian areas which are already susceptible to frequent flooding from other sources, there is the possibility that property and infrastructure in other parts of the catchment could be put at increased flood risk during extreme events.

8.4 Limitations

Users of the Environment Agency’s regional models should bear in mind that whilst they are well-calibrated and capable of reproducing the behaviour of hydrogeological systems in detail, there are inherent limitations to the applicability and accuracy of the models. Being abstract representations of reality, they contain necessary simplifications due to scientific uncertainties and in the interest of computational efficiency. The regional models are limited by the availability of high-quality data with which they are parameterised and validated.

Some parameters in the Environment Agency’s regional models are more tightly constrained than others. Notably, there are significant uncertainties surrounding the parameterisation of evapotranspiration and canopy interception associated with trees. Many NBS schemes may consider tree planting as a means of delivering wider environmental benefits, but their representation in models may not always be ideal for the purposes of predicting the effects on water resources. Currently, canopy interception is not explicitly represented within regional models, and there are uncertainties related to feedback between interception and evapotranspiration processes. Instead, the representation of these effects is left to the crop coefficient, which amalgamates the multifaceted aspects of evapotranspiration into a seasonally varying multiplicative factor.

Certain processes are not fully represented within the Environment Agency's regional models due to the additional complexity required. As part of previous NBS modelling for the Environment Agency in East Anglia, the deactivation of spray irrigation abstractions has been simulated. However, the results of these simulations were suitably caveated because the representation of spray irrigation within the models is an approximate one. Whilst the abstraction of water for spray irrigation is modelled, the direct application of this water onto fields is not, other than by proxy via rainfall.

Another inherent limitation of models is one of spatiotemporal resolution. The Environment Agency's regional models are typically built on a relatively coarse grid and with monthly stress periods, limiting the scale at which the outputs can be interrogated. Whilst it is possible to use a finer grid spacing and a shorter timestep, doing so has significant computational overheads.

Whilst modelling can provide an informative, quantitative overview of the regional water resources effects of NBS, impacts of individual NBS features can be more difficult to model accurately. Regional models may struggle to replicate the behaviour of individual measures due to local specificities and variable conditions on the ground. As such, the direct monitoring of NBS sites can be a more illuminating exercise, which is discussed in the next chapter. Monitoring in this way can verify or refute the predictions of models, and monitored results can be used to refine the parameterisation of models.

8.5 Alternative methodologies

The use of the Environment Agency's regional groundwater models has been extensively tested for evaluating the effects of NBS implementation on water resources. This orthodoxy is well-founded given their extensive spatial coverage of key areas of England, the range of results available from them, and the methodological robustness of their usage. However, there are other modelling approaches that can be taken to carry out these assessments.

As one example of this, Clilverd et al. (Clilverd, H.M.; Thompson, J.R.; Heppell, C.D.; Sayer, C.D.; Axmacher, J.C.; 2016.Coupled Hydrological/Hydraulic Modelling of River Restoration Impacts and Floodplain Hydrodynamics. River Research and Applications, 32 (1927-1949)) have explored the use of MIKE-SHE/MIKE 11 modelling to simulate the groundwater impacts of river restoration to more naturalised conditions. They conducted hydrological modelling coupled with hydraulic modelling to simulate conditions within a wet meadow grassland habitat in Norfolk following river restoration, being able to demonstrate increased groundwater levels and aquifer storage. Peak flood flows were attenuated downstream with improved floodplain connectivity and enhanced biogeochemical cycling was inferred, offering potential water quality benefits.

Additionally, the modelling of water resources benefits from NBS need not explicitly include a simulation of groundwater. To illustrate this, hydrological modelling undertaken by Holman at al. (Holman, I.P.; Hess, T.M.; Rose, S.C.; 2011. A broad-scale assessment of the effect of improved soil management on catchment baseflow index. Hydrological Processes, 25 (2563-2572)) using the WaSim model was used to predict changes to baseflow index in rivers due to enhancements to soil structure across the subject catchments across England and Wales. WaSim is a water balance model which does not explicitly simulate groundwater processes, demonstrating that it is not always necessary to do this to model water resources benefits effectively.

8.6 Summary

This chapter has provided an overview of:

- Techniques for undertaking modelling to quantity water resources impacts of NBS
- Developing a modelling study for planning NBS4WR implementation
- Examples of projects which have used extensive groundwater modelling to assess NBS potential
- Limitations of numerical models in the context of simulating NBS scenarios

9 Appendix. Monitoring of NBS features

9.1 Introduction

Monitoring of NBS is an important but often overlooked activity which is necessary to:

- Demonstrate project success or failure
- Learn from mistakes
- Know when adaptive management is needed
- Fill known research gaps
- Inform funders, partners and local stakeholders about project outcomes
- Determine to what extent project objectives have been met

Monitoring and evaluation need to be both planned and budgeted for at the start of a project. If monitoring is not considered until after a project has been constructed, it may be too late to collect any useful data. Monitoring can also help to secure future funding and can help engage local communities.

There are some existing resources available to help project managers plan their monitoring, which include:

- The River Restoration Centre's (RRC) PRAGMO guidance (https://www.therrc.co.uk/monitoring-guidance)
- The Working with Natural Processes Evidence Directory, specifically Chapter 6 on monitoring and associated case study examples (https://www.gov.uk/flood-and-coastal-erosion-risk-management-research-reports/working-with-natural-processes-to-reduce-flood-risk)
- The catchment science field monitoring guide (https://catchmentbasedapproach.org/wp-content/uploads/2019/08/Atkins-Catchment-Science_Fieldscale-Monitoring-Handbook-2019.pdf)
- Low-cost environmental sensors for environmental research (https://eprints.lse.ac.uk/106639/1/0309133320956567.pdf)
- Norfolk Water Strategy Programme, best practice guidance: in-field monitoring of Nature-based Solutions for improved water management (https://wre.org.uk/wp-content/uploads/2025/05/BESTPR_2.pdf.pagespeed.ce.IKQ61tHk5c.pdf)

The RRC guidance includes a useful monitoring planner that can help project managers plan the monitoring needed for their projects. The chapter within the WWNP Evidence Directory also includes some useful decision trees to help define the extent of monitoring needed depending on project size and resources. It also explains key NBS research gaps that need to be filled through long-term monitoring.

This chapter covers:

- Developing a monitoring plan
- Different monitoring techniques
- Examples of monitoring
- Recording and evaluating monitoring data

9.2 Setting monitoring objectives

One of the first steps when developing a monitoring programme is to articulate the overall aim of the project, to describe what it is that you are trying to achieve. Defining clear objectives will help ensure that monitoring is cost-effective and aligned to the project's targets. It will also help to identify what baseline data and resources are required for monitoring.

Monitoring should primarily focus on demonstrating that project objectives have been achieved. Project objectives should be developed using the SMART approach set out in Table 9-1. The SMART approach to objective setting helps to articulate what it is you plan to monitor and how you intend to go about it. It also helps define timescales for delivery and potential funding needed to deliver the monitoring.

When monitoring approaches are developed in an ad hoc manner (in the absence of SMART objectives) there is a risk that money and time is wasted, collecting data which does not help to answer a specific question.

Table 9-1: Definition of smart objectives (source: adapted from RRC, 2017)

SMART	Objectives should:
Specific	Target a specific area of improvement or answer a specific need
Measurable	Be quantifiable, or at least allow for measurable progress
Attainable	Be realistic and based on a review of evidence of success by others
Realistic	Be based on available resources (money, people, time) and existing constraints
Time-bound	Have a deadline or defined end

9.3 Developing a monitoring plan

Once monitoring objectives are defined, a monitoring plan can be developed, following a suite of logical steps that help define whether a project has been a success and potentially unlock funding for future projects (adapted from RCC, 2017):

1. SMART project objective setting
2. Detailed monitoring plan
3. Effective monitoring
4. Project with demonstrable success
5. Results to help secure funding
6. Future funding and capacity increased

The RRC has a monitoring planner (RRC, 2014) which asks a series of questions which help to define a robust approach to monitoring:

- Why are you doing the project and what are the project's objectives?
- What is your monitoring objective / what are you trying to observe?
- How will you collect data and what assessment methods are you using?
- Do you have any access to pre-project baseline data?

- When are you collecting data?
    - Frequency of data collection
    - Duration of data collection
- Who is going to collect the monitoring data?
- Who is going to evaluate the monitoring data?
- How much will the monitoring and evaluation cost?
- How confident are you that the monitoring will show what you are trying to observe?
- How will your collected monitoring data be processed, analysed, validated and reported?

The amount of time needed to monitor an NBS measure will depend on how long it may take to become effective. Some NBS interventions will become effective almost immediately, whereas others will take longer. As such, it is important to ensure that monitoring is undertaken over suitable timescales to understand the effectiveness of a measure.

9.3.1 Spatial scale

Monitoring needs to be proportionate to the project's scale. For example, if one small localised NBS measure is being installed in a discrete location, then the level of monitoring needed would be much less than for a wide range of NBS measures being installed across a larger spatial scale.

For small-scale NBS projects, it may not be possible to fully understand its effect on groundwater. In this instance monitoring should focus on understanding how the measure works.

For larger-scale NBS projects where a range of measures are installed across a larger spatial scale, it will be important to develop an approach to monitoring that helps develop an understanding of the different measures' impacts on groundwater.

9.3.2 Targeted monitoring

It is important to prioritise monitoring activities and target monitoring activities that help achieve your SMART monitoring objectives. Monitoring is often hard to fund, so it is therefore useful to divide the activities into those that are deemed essential and those that are desirable. This could result in the development of alternative, lower-cost methods (e.g. fixed point photography) being sought to deliver the lower priority activities.

9.3.3 Collecting a baseline

Baseline monitoring is undertaken before NBS measures are installed. It helps to understand the environmental conditions of the site or catchment before construction. Having a robust baseline enables you to understand the effectiveness of the NBS measures, as it enables comparison of the study area before and after construction.

In an ideal situation, the catchment you are working in would have long-term baseline monitoring stations already in place, collecting data that enables you to detect environmental change following construction. This is rare; in most cases, pre-existing monitoring can be limited and may not be targeted at understanding the natural processes you are interested in. For example, the Environment Agency has a large network of gauging stations which collect useful datasets, however, these are typically located on the main river network and not on smaller ordinary watercourses.

If the existing baseline monitoring for a catchment is short term or patchy, this is likely to increase the uncertainty in the understanding of how effective the project has been and whether monitoring objectives have been met.

When developing the monitoring plan and associated SMART objectives, this should be informed by an understanding of:

- What monitoring equipment may already be present in the catchment
- What datasets already exist and are they available
- The duration of any previous or ongoing monitoring
- The quality of any existing data
- Which organisations within the catchment may hold or collect monitoring data
- Whether existing monitoring data is available and can be shared

Understanding what data already exists helps inform decisions related to the extent of monitoring that is needed. As a minimum, an adequate baseline dataset should capture a series of high and low flow events to understand how the catchment responds to both flood and drought conditions.

9.3.4 Extent of monitoring

Quantifying and demonstrating the effectiveness of NBS measures is challenging. It can be hard to demonstrate that an NBS measure or a suite of measures affects their ability to regulate high and low flows. In any catchment at any moment in time, multiple natural pressures are exerted upon the natural environment.

It can be difficult to understand whether the monitoring data shows a positive or negative response to the NBS measure(s) or whether the data you have collected shows a change because of some unknown activity or pressure elsewhere in the catchment.

This is not to say that monitoring is pointless, but it does demonstrate the importance of carefully developing a monitoring plan that enables change to be detected.

In developing a monitoring plan, it is important to think about the extent of monitoring that might be possible based on project timescales and budget. The list below summarises different scales of approach to monitoring. Detailed approaches to monitoring are clearly the gold standard; these are usually led by academic institutions and facilitate a long-term assessment of effectiveness compared against a baseline. Lighter touch approaches to monitoring alongside collecting monitoring data to inform modelling are more frequently used; they help you understand the effect of your interventions on water cycle processes or collect data that enables you to model the impacts of your interventions. Water Resources East’s best practice guidance contains helpful classifications of monitoring approaches into ‘gold standard’, ‘standard’ and ‘basic’ categories. In summary:

1. Detailed monitoring approaches:

    - Typically follows a Before, After, Control and Impact (BACI) approach to monitoring
    - Includes a long period of baseline data collection, either set up specifically for the project, or drawing on existing baseline data collection
    - May include a control site which can be compared against the site where NBS is being delivered to understand the effect of measures

- Includes a representative monitoring design approach which helps understand the effect of the NBS measures rather than collecting data about other catchment processes

2. Lighter touch monitoring approaches:
   - Focused locally, typically at a site level
   - Typically lacks a baseline or control site
   - Sometimes, the monitoring approach and associated network are installed after construction
   - Focused on understanding the effect of measure(s) on the water cycle
   - Aims to understand/describe how the measure:
     - Works during high and low flows
     - Affects natural processes

3. Monitoring for modelling:
   - Collects hydrological data (e.g. flow, soil moisture, hydraulic conductivity etc)
   - Collects field data to inform, parameterise, calibrate and validate a model
   - The model will be used to assess the effect of NBS measures under different flow regimes

9.4 Monitoring techniques

9.4.1 Overview of monitoring techniques

Once a monitoring plan is in place, the next step is to implement it and start collecting the necessary data.

It is important that the monitoring techniques selected help understand how the measures installed affect the flow of water across and through the landscape such as:

- Evaporation and transpiration
- Interception
- Infiltration
- Hydraulic roughness
- Flow (discharge)
- Storage

Table 9-2 provides and overview of different approaches to monitoring, which processes they collect data on and what instrumentation is used. These monitoring techniques are summarised in sections 7.4.2 to 7.4.12.

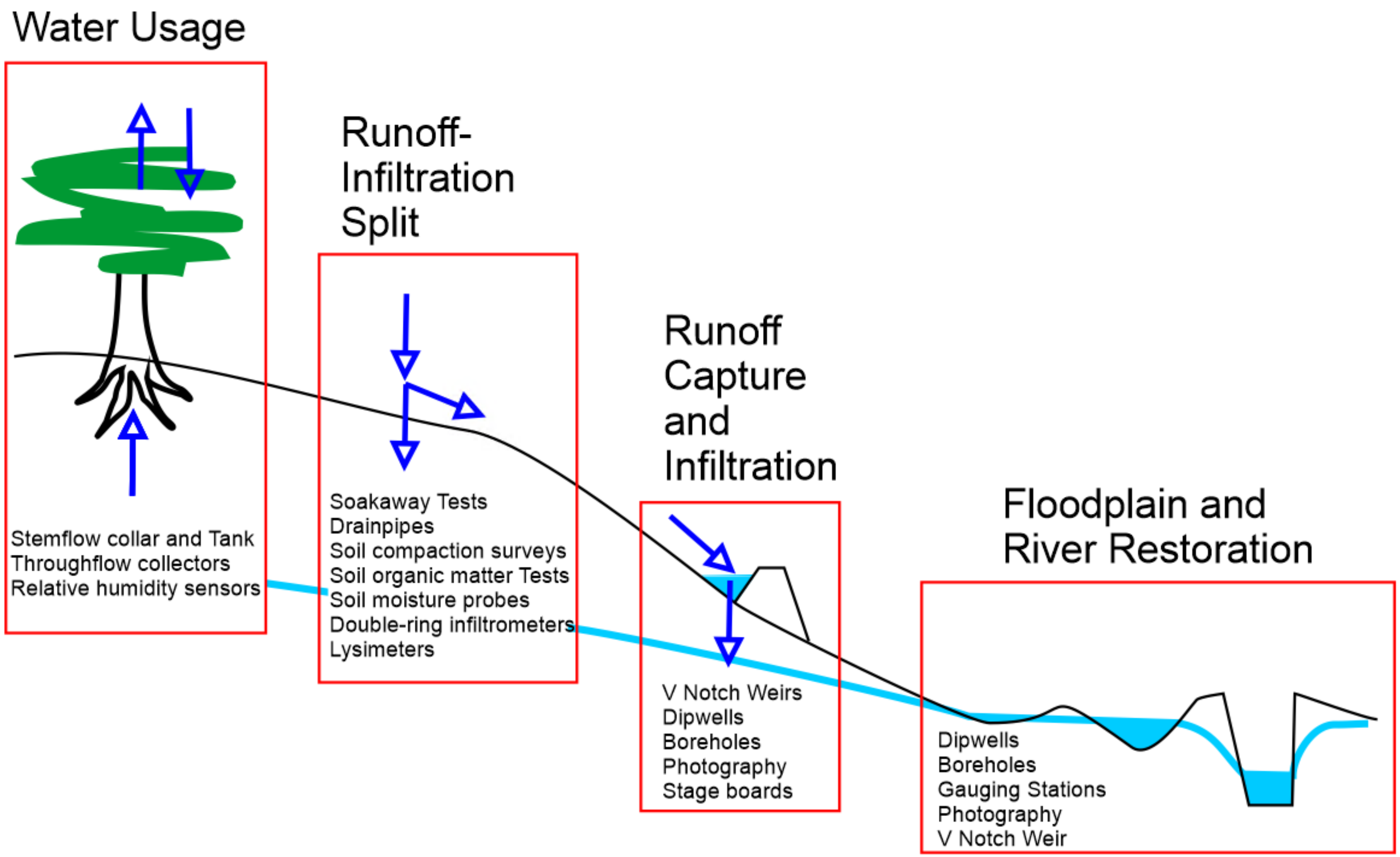

Figure 9-1: Monitoring techniques and water cycle NBS4WR topics

Table 9-2: Summary of potential monitoring techniques including costs (Please note: costs are indicative)

Monitoring approach	Processes being monitored	Instrumentation used	Approx. costs
Dipwells	Infiltration Baseflow	Dipwells and piezometers	£10 (Home-made with drainpipe)
			£150
Emerging technology	Can be used to monitor a wide range of natural processes	Autonomous sensors	Range of costs for different automated loggers (Low-cost electronic sensors for environmental research: Pitfalls and opportunities)
Flow/discharge assessment	Water flow/discharge Infiltration into the soil	V notch weirs at the intake and outtake of the site	£350 (plus water level monitoring equipment)
Groundwater boreholes	Groundwater levels Infiltration Recharge	Existing boreholes	Staff time only
Soil infiltration tests	Infiltration	Drainpipe and stopwatch Soakaway Tests	£10
Mapping site details	Location, scale and description of NBS measures	N/A	Staff time only
Photography and drone flyovers	Water interception and storage Flow routes	Fixed point photo posts	£10
		Drones	£500-10,000
		Timelapse photography	£400-2,500 (ALERT data is freely available)
Soil health and biology assessments	Infiltration Flow/runoff pathways	Soil compaction surveys	Staff time
		Soil organic matter assessments	Staff time to collect samples, £100 per sample for lab analysis
		Soil moisture probes	£300-1,500
		Double-ring infiltrometers	£200-£2,000

Monitoring approach	Processes being monitored	Instrumentation used	Approx. costs
		Automatic data logging weighing lysimeter	£3,000-230,000
		Field-scale weighing lysimeter	£250
		Lab analysis of samples	£100 per sample
Surface roughness assessment	Flow/runoff pathways	N/A (refer to lookup values in the literature based on empirical testing)	Staff time only
Water levels and storage volumes	Water levels (stage) Storage volumes	Stilling wells	£25
		Stage boards	£60
		Water level logger	£350
		Barometric logger	£300
Wet canopy evapotranspiration	Evaporation Transpiration Infiltration	Stemflow collar and tank	£50 (Pipe and Water butt)
		Throughfall collectors	£50
		Relative humidity sensors	£150-£1000
Geophysical surveys	Groundwater levels Groundwater flow pathways Subsurface hydrogeological properties	Ground penetrating radar Electromagnetic surveys Microgravity surveys Electrical resistivity tomography Seismic surveying (e.g. Tromino)	Highly variable, depending on the techniques used and the size, accessibility and nature of the site

9.4.2 Dipwells

	Details of monitoring approach
What are you monitoring?	Monitoring the elevation of the water table
What instrumentation are you using?	Dipwells
What processes are you trying to understand?	Groundwater levels, infiltration, baseflow
Description of monitoring approach	Dipwells are slotted tubes installed to a depth greater than the lowest known/anticipated water table. They can be used to monitor the elevation of the water-table at fixed points within a site.
Reference	• Hydrological monitoring protocol (Floodplain Meadow Partnership, 2023) • A review of techniques for monitoring the success of peatland restoration - NECR086A review of techniques for monitoring the success of peatland restoration - NECR086 (Natural England, 2011) • Guidelines for monitoring peatland restoration - TIN097 (Natural England, 2011) • MoorLIFE monitoring: water table (Moors for the Future)
Costs	• Dip wells or piezometers are available commercially prices vary from £45 – 150 each. • Dip wells can be constructed from waste water pipe, geotextile fabric and duct tape for under £10.

9.4.3 Emerging technology

	Details of monitoring approach
What are you monitoring?	Can be used to monitor wide range of variables
What instrumentation are you using?	Autonomous sensors
What processes are you trying to understand?	Can be used to monitor a wide range of natural processes
Description of monitoring approach	Autonomous sensors are an emerging technology which uses Artificial Intelligence and Machine Learning to undertake real-time monitoring. This approach would involve the placement of sensors throughout a catchment which would capture data and use this real-time information alongside satellite imagery to provide an overview of a catchment's health. This is an emerging area which as it develops could be applied on NBS schemes to help understand their performance and effectiveness.
Reference	• Developing deploying low cost distributed monitoring to evaluate NFM compressed (KCL, 2021) • Why using data and AI is key to effective river conservation (Sustainability Voices, 2024) • Field scale monitoring handbook (Atkins, 2021)

9.4.4 Flow/discharge assessment

	Details of monitoring approach
What are you monitoring?	Above-ground flow (discharge)
What instrumentation are you using?	V notch weirs or flumes at the intake and outtake of the site
What processes are you trying to understand?	Water flow/discharge, infiltration to the soil
Description of monitoring approach	To understand the effect of NBS interventions, it is first necessary to develop a baseline understanding of flow/discharge for a range of flow conditions across the catchment. This can be achieved by undertaking a desk-based assessment using model results, past catchment studies, and existing gauging stations. The catchment can be instrumented with flow/discharge data collection equipment in locations where interventions are planned. This enables baseline data to be collected prior to construction to compare the effects of NBS measures on flows before and after interventions are installed. V notch weirs could be installed at the location where the watercourse enters and leaves the site. If data is collected at both weirs, it is possible to understand water flow throughout the site and from this data infer how much water is being lost through processes such as infiltration or storage. Following construction, the monitoring equipment should be retained as long as is feasible/affordable to create an adequate monitoring dataset from which the effectiveness of the NBS measures on flow/discharge can be understood. A desk-based review of the monitoring data should be undertaken to provide a statistically robust analysis describing changes to river flow following the construction of NBS interventions (likely to involve hydrograph analysis). Scottish National Heritage has produced a guide which describes how to manage and monitor surface water levels and flows on fen sites.
Reference	• The Fen Management Handbook (Scottish National Heritage, 2011) • A review of techniques for monitoring the success of peatland restoration - NECR086 (Natural England, 2011) • Guidelines for monitoring peatland restoration - TIN097 (Natural England, 2011)

9.4.5 Groundwater boreholes

	Details of monitoring approach
What are you monitoring?	Groundwater levels to understand effect on water table
What instrumentation are you using?	Existing boreholes
What processes are you trying to understand?	Groundwater levels, infiltration, recharge
Description of monitoring approach	Where NBS interventions are located close to groundwater level monitoring boreholes with suitable long-term records, changes in groundwater levels could be monitored. The Environment Agency has produced a guide which describes how to monitor groundwater levels and flows on wetland sites. A statistically robust analysis would need to be undertaken describing changes to groundwater level records before and after construction of NBS interventions (likely to involve hydrograph analysis) in tandem with the development of a strong conceptual understanding of the system. This will need to be undertaken on long-term groundwater level records to ascertain if groundwater levels and recharge have been influenced by the installation of NBS measures and additional storage within the catchment. It is likely to involve a lag time assessment and the analysis and interpretation of groundwater levels during pre- and post-NBS installation periods.
Reference	• The Fen Management Handbook (Scottish National Heritage, 2011) • Hydrological assessment and monitoring of wetlands (Low et al., 2016)

9.4.6 Soil infiltration tests

	Details of monitoring approach
What are you monitoring?	The rate of infiltration of water into the ground/soil
What instrumentation are you using?	Drainpipe and stopwatch
What processes are you trying to understand?	Infiltration
Description of monitoring approach	The BRE365 infiltration test approach can be used to understand the rate of infiltration of water into the subsurface. This approach is typically used to inform the design of soakaways but can also be used to assess potential infiltration rates. This approach can be easily performed by digging a hole, installing a short section of drainpipe, filling it with water and then timing the rate at which the water is absorbed into the soil.
Reference	• BRE Digest 365 Soakaway design - Designing Buildings (BRE, 2020) • Water infiltration test (AHDB, 2018) • Soil Structure and Infiltration (AHDB, 2018)

9.4.7 Mapping site details

	Details of monitoring approach
What are you monitoring?	Location, scale and description of NBS measures

Description of monitoring approach	On any project which is being monitored, it is important to capture on a map sufficient information to describe the site, its location, and the measures being installed. This should include but not be limited to:
	• Location of the site(s), including a red line boundary and grid references
	• Description of the type(s) of NBS intervention installed/planted
	• Extent/scale of NBS intervention(s) installed/planted using metrics such as:
	  o Length of river affected
	  o Area of land affected
	  o Amount of water storage provided

9.4.8 Photography and drone flyovers

	Details of monitoring approach
What are you monitoring?	The function of NBS measures to understand the flow and storage of water
What instrumentation are you using?	Fixed point photos, drone flyovers, timelapse photography
What processes are you trying to understand?	Water interception and storage, flow routes
Description of monitoring approach	Fixed point photography, timelapse cameras and drone footage are useful tools for understanding how NBS measures intercept and/or store water. Fixed point photography posts can be set up in advance so that all photos taken at the sites are taken from the same vantage point, which enables the site's evolution to be compared over time. Fixed point photography should be undertaken during times of high flow to show visually how the measures are working (e.g. intercepting flow and storing water). Timelapse cameras can be inexpensive and easy to set up and capture data with minimal intervention, except to retrieve memory cards to download data. Drone footage is particularly useful because it can be used to capture and map water flow routes and flood outlines. Drone flights can be set to cover the same routes, this is useful for collecting repeatable and comparable datasets, enabling different flow events to be captured repeatably over time.
Reference	• Fixed point photography (RRC and Esmee Fairbairn Foundation, No date)

9.4.9 Soil health assessment

	Details of monitoring approach
What are you monitoring?	Soil health
What instrumentation are you using?	• Soil compaction surveys • Soil organic matter assessments • Soil moisture probes • Double-ring infiltrometers • Lysimeters
What processes are you trying to understand?	Infiltration, flow/runoff pathways
Description of monitoring approach	To understand how NBS measures which improve soil management affect water infiltration and storage, it is necessary to collect baseline data to understand how the soil's structure has changed over time, and from this, a change in infiltration and storage can be inferred. Improvements/changes to the soil can then be used to model the effects of land use change to understand its impact on groundwater: • Photos and observations during and after rain at the field scale, showing off-site impacts linked to accelerated runoff • Organic matter content as an indicator of soil health and water holding capacity, including worm counts • Soil moisture data from probes before and after installation of NBS interventions • Simple soil pit examination – three per field in representative areas of the site (not in the margins or heavily trafficked areas) • Soil compaction assessment before and after land use/land management change using soil pits and standard NSRI methodology • Soil infiltration measures using double-ring infiltrometers, lysimeters or runoff plots • Runoff plots and lysimeters should provide either runoff in volume and or a soil potential rating for that field
Reference	• Assessing soil health using an integrated approach (AHDB, No date)

9.4.10 Surface roughness assessments

	Details of monitoring approach
What are you monitoring?	Monitoring changes in surface roughness to understand how it slows the flow of water
What instrumentation are you using?	N/A (refer to lookup values in the literature based on empirical testing)
What processes are you trying to understand?	Flow/runoff pathways
Description of monitoring approach	The hydraulic roughness of an area of land will change due to the installation of NBS interventions. Understanding any changes in manning's '*n*' roughness coefficients will enable NBS interventions to be modelled to understand their effect on the flow, storage and infiltration of water across the landscape. To monitor changes in roughness, it will be necessary to understand the roughness of the site pre-construction so that the intervention can be modelled before and after construction using different roughness coefficients.

9.4.11 Water levels and storage volumes

	Details of monitoring approach
What are you monitoring?	Flood levels (stage), storage volumes
What instrumentation are you using?	Stage boards Gauging stations Photography
What processes are you trying to understand?	Water levels (stage), storage volumes
Description of monitoring approach	Installing a stage board within an NBS feature can help to establish water depths and flow paths. These water level/stage measurements can be correlated with measurements of rainfall intensity and river stage to compare the filling of the storage feature with peak discharge in the river. This will help understand flood levels and storage volumes during periods of high and low flow. Fixed point photography and drone flyovers are useful for capturing flood outlines, from which we can infer flood storage capacity of NBS features.
Reference	• Chapter 6. Research Gaps and Monitoring. In: Working with Natural Processes Evidence Directory (Burgess-Gamble et al., 2017)

9.4.12 Wet canopy evaporation

	Details of monitoring approach
What are you monitoring?	Monitoring tree canopies to understand the effect on evaporation, transpiration and infiltration
What instrumentation are you using?	Stemflow collar and tank Throughfall collectors Relative humidity sensors
What processes are you trying to understand?	Evaporation, transpiration, infiltration
Description of monitoring approach	NERC's QNFM project developed a methodology for monitoring the impacts of woodland planting on evaporation, creating a monitoring approach which collects data on gross rainfall (the rainfall that is received by the canopy) and net rainfall (the rainfall that reaches the ground). The difference between gross and net rainfall enables wet canopy evaporation to be calculated.
Reference	• A review of techniques for monitoring the success of peatland restoration - NECR086 (Natural England, 2011) • Guidelines for monitoring peatland restoration - TIN097 (Natural England, 2011) • The significance of wet canopy evaporation (Page et al, 2022)

9.4.13 Geophysical surveys

	Details of monitoring approach
What are you monitoring?	Geophysical surveys can be used to map the water table and monitor changes in groundwater levels over time, particularly in areas where groundwater is a critical water resource or where groundwater flooding is a concern.
What instrumentation are you using?	Ground penetrating radar (GPR) Electromagnetic surveys Microgravity surveys Electrical resistivity tomography (ERT) Seismic surveying (e.g. Tromino)
What processes are you trying to understand?	Groundwater levels Groundwater flow pathways Subsurface hydrogeological properties
Description of monitoring approach	Geophysical surveys offer non-invasive methods to monitor water resources by analysing subsurface properties. Common techniques include: ERT, which measures resistance to electrical current to identify water ingress; GPR, using radar waves to detect subsurface features like voids; and seismic surveys, which analyse wave propagation to map subsurface layers. Electromagnetic methods, including Ground Conductivity, are also used to assess moisture content. These techniques help in mapping groundwater, detecting leaks, and understanding hydrological processes.
Reference	Eddleston: Geophysical surveying | British Geological Survey (BGS) Application of Geophysical Methods for Hydrogeology Shallow geophysics - British Geological Survey

9.5 Examples of monitoring

9.5.1 Overview of monitoring case studies

This section provides some examples of different approaches to monitoring. Table 9-3 provides an overview of different approaches to monitoring used on the different case study sites and it summarises which processes they collect data on and what instrumentation is used. These monitoring examples are summarised in sections 9.5.2 to 9.5.7.

Table 9-3. Summary of potential monitoring techniques

Project name	Processes being monitored	Instrumentation used
Bishopdale NFM project (Yorkshire)	Infiltration, soil moisture	Soil moisture monitoring unit
Culm grasslands project (Devon)	Infiltration	Dipwell, rain gauge, soil samples (assessed for moisture content and bulk density)
Holnicote Estate (Somerset)	Water flow, water storage, infiltration, geomorphological evolution of the site	River sensors, drones, sediment transport monitoring, ecological surveys
Blairfindy catchment (Scottish Highlands)	Infiltration, groundwater recharge, soil water content	Weather stations, stage data recorder, End-member Mixing Analysis
Mires on the Moors (Devon and Somerset)	Changes to the water table, water quality, biodiversity	Water level monitoring, water quality monitoring, rain gauge, dipwells
Stroud Valleys (Gloucestershire)	Hydrograph attenuation, groundwater recharge	Doppler flow meter, soil moisture probes, piezometers, stilling wells

9.5.2 Bishopdale NFM project (Yorkshire)

The Bishopdale NFM project focused on reducing flood peak and the time it takes for water to be transferred throughout the catchment by using natural flood management techniques. It included tree planting, storage of water in offline ponds and scrapes and improvements to soil health. Yorkshire Dales Rivers Trust implemented a range of monitoring approaches. Dales Land Net implemented the soil monitoring described below.

	Details of monitoring approach
What are you monitoring?	Soil moisture and soil temperature, performance of NBS measures
What instrumentation are you using?	Soil moisture monitoring unit
What processes are you trying to understand?	Infiltration, soil moisture
Description of monitoring approach	Dales Land Net has developed a soil moisture monitoring unit that transmits real-time data about how wet the soil is in a specific location, measuring the soil from the surface down to a depth of 50cm. These readings are transmitted to the server using Internet of Things (IoT) technology that allows the unit to run for several years on only 3 AA batteries and a small solar panel. The sensor in the soil is divided into 4 zones which may each have differing levels of moisture due to the soil layer composition. The sensor also provides temperature readings from 6 depths.
Reference	• Low Cost IoT Soil Moisture Monitors (Dales Land Net) • Monitoring a Yorkshire Dales River Trust NFM Project in Bishopdale (Dales Land Net)

9.5.3 Culm Grasslands project (Devon)

The Culm Grassland Natural Flood Management project was led by Devon Wildlife Trust with the Environment Agency, Exeter University and other partners.

This rare habitat, a type of purple moor-grass and rush pasture particular to north Devon, is important for wildlife, but it also has real potential to hold water, filter pollution and retain carbon.

This project restored 468ha of this habitat and undertook extensive monitoring to understand the impacts of the restoration.

	Details of monitoring approach
What are you monitoring?	Water table, soil condition
What instrumentation are you using?	Dipwells, rain gauge, soil samples (assessed for moisture content and bulk density)
What processes are you trying to understand?	Infiltration
Description of monitoring approach	The aim of this objective was to understand soil conditions and water table response to rainfall in Culm grassland compared to improved grassland. The monitoring undertaken at each field plot of 30m by 50m included: • Five soil samples were taken to 0.15m depth, making a total of 45 samples. Each sample was divided into the organic layer of soil (O horizon) and the A horizon. Each sample was then processed in a laboratory to assess soil moisture and compaction • At each field plot, five dipwells were installed to 0.5m depth, with a data logger recording water table depth at 15-minute intervals • A rain gauge was also installed at each site for accurate rainfall measurements also at 15-minute intervals The results of fieldwork indicate that Culm grassland holds more water that improved grassland and has the ability to release the water more slowly into the catchment.
Reference	• Culm grassland reports (Devon Wildlife Trust)

9.5.4 Holnicote Estate (Somerset)

The National Trust ran a three-year project on their Holnicote Estate in Somerset to reconnect a section of a river to its floodplain to create a new and instantly different waterscape using the innovative 'Stage 0' river restoration technique. The project was monitored to understand its impacts on water resources, water quality, habitat and geomorphology.

	Details of monitoring approach
What are you monitoring?	Water storage, water quality, habitat change
What instrumentation are you using?	River sensors, drones, sediment transport monitoring, ecological surveys
What processes are you trying to understand?	Water flow, water storage, infiltration, geomorphological evolution of the site
Description of monitoring approach	The monitoring found that ground water levels rose dramatically across the site, in some places by over 1m. This allowed the site to act as a large sponge or filter in the river catchment, helping to store winter flood water, reducing flood risk downstream and releasing cleaner water more slowly in the drier months to help alleviate drought conditions. Monitoring has revealed a water table increase of up to 1m across the site, resulting in a big increase in water storage and helping to improve conditions for migratory fish and reduce the impacts of agricultural pollution.
Reference	• Stage 0 one year on, Somerset (National Trust, 2024)

9.5.5 Blairfindy catchment (Scottish Highlands)

RAFs (mainly leaky barriers) were installed by a distillery to intercept flow pathways and create temporary storage. The purpose of this was to increase infiltration and groundwater recharge to provide resilience to drought conditions. The site was monitored to understand the effectiveness of measures.

Details of monitoring approach	
What are you monitoring?	Whether NBS measures facilitate groundwater recharge.
What instrumentation are you using?	Weather stations, stage data recorder, End-member Mixing Analysis
What processes are you trying to understand?	Infiltration, groundwater recharge, soil water content
Description of monitoring approach	Monitoring data was combined with modelling and showed that RAFs: • Increase recharge • Increase groundwater contribution to streamflow and low flows • Reduce high and mean flows The results suggested that RAFs could help mitigate the impacts of low flows through periods of drought. It was found that distributing multiple features across the site was more effective than having one large RAF.
Reference	• Assessing the role of location and scale of Nature Based Solutions for the enhancement of low flows (Fennell et al, 2022)

9.5.6 Mires on the Moor (Devon and Somerset)

South West Water’s Upstream Thinking Programme restored 2480ha of peatland across Exmoor and Dartmoor. Monitoring was key to this investment programme to understand the impacts of restoration measures on water resources, water quality and biodiversity.

	Details of monitoring approach
What are you monitoring?	The effect of moorland restoration measures on water resources, water quality and biodiversity
What instrumentation are you using?	Water level monitoring, water quality monitoring, rain gauge, dipwells
What processes are you trying to understand?	Changes to the water table
Description of monitoring approach	At Exmoor a network of dip wells was installed in proximity to restored drainage ditches to understand water table depth below the surface. On Dartmoor the monitoring approach measured spatial patterns of water table depth and runoff from a single gully. Water tables were measured as the depth of water below the ground surface using a network of dipwells. In relation to water level monitoring the research found that: • In the driest areas of the shallow peats, water tables rose by as much as 4cm after restoration • But overall, water tables were seen to remain statistically similar post-restoration In deeper peats, restoration increased the permanent deep water storage in the soil by 7.3cm and increased average water tables by 2.45cm.
Reference	• Mires on the Moors project report by University of Exeter - Issuu 2020, Exeter

9.5.7 Stroud Valleys (Gloucestershire)

The Stroud Valleys NFM Project, led by Stroud District Council, involved the implementation of measures throughout the catchment of the River Frome in Gloucestershire. Monitoring of the scheme was undertaken in partnership with the University of Gloucestershire, the Wildfowl and Wetlands Trust, Gloucestershire Wildlife Trust and the Environment Agency to understand the impacts of the measures, particularly in terms of reducing flood risk within the catchment and increasing recharge to groundwater.

	Details of monitoring approach
What are you monitoring?	The effects of NFM measures in terms of attenuating flood flows within rivers and increasing recharge to groundwater
What instrumentation are you using?	Doppler flow meter, soil moisture probes, piezometers, stilling wells
What processes are you trying to understand?	Hydrograph attenuation, groundwater recharge
Description of monitoring approach	Monitoring of discharge upstream and downstream of intervention sites demonstrated the effects on flood hydrographs, revealing that peak flows were significantly attenuated following the installation of measures. A network of soil moisture probes and piezometers intersecting the water table were deployed in the vicinity of newly installed earthen retention bunds. Data from these instruments, in combination with meteorological data, were used to quantify groundwater recharge rates. In doing so, the impacts of the measures in terms of increasing infiltration could be assessed.
Reference	• Stroud Valleys Natural Flood Management Project (Stroud District Council)

9.6 Recording and evaluating monitoring data

9.6.1 Collecting and recording monitoring data

When developing your monitoring plan, it is vital at the outset to consider:

- How much data will be collected?
- How will the data be collected?
- How frequently will the data be collected?
- How will the data be recorded?
- Who will collect the data?

These questions are important because they help you understand the quantity of data you will need to analyse, what format this data will be provided in and any data processing that might be needed to interpret the data.

In addition, if multiple projects are being delivered throughout a catchment, they should collect and record data consistently to enable comparability between sites. Consistency of approach can save time later. For example, simply ensuring data is collected using the same metrics can save time later, as data from one site is then immediately comparable with another site without the need for additional processing.

9.6.2 Interpreting and evaluating monitoring data

As monitoring starts to yield results, the data will need to be analysed and interpreted to understand and communicate the study's findings. At this stage it is necessary to discuss the results with a range of disciplines to develop an agreed understanding of the results.

Artificial Intelligence and Machine Learning approaches can be used to interpret and evaluate monitoring data. These novel approaches have been used in analysing and identifying patterns in large monitoring datasets. It is therefore potentially applicable in the field of NBS4WR.

At this stage, it is important to allow the data to ‘do the talking’; this means explaining what the data shows, including all caveats and limitations.

It can be tempting to infer a positive result. However, it is vital to be scientifically objective about the study's findings, as this enables project-level learning and improved scientific understanding.

The results of monitoring need to be understood by a wide range of stakeholders, so consideration of how to describe the results using plain English is key.

9.7 Summary

This chapter has provided an overview of:

- Developing a monitoring plan
- Different monitoring techniques
- Examples of monitoring
- Recording and evaluating monitoring data

10 Appendix. Designing, constructing and maintaining NBS

10.1 Introduction

The design and construction phase of NBS projects is highly iterative, as it involves engagement with a wide range of different stakeholders to:

- Understand the catchment
- Find the best locations in a catchment for NBS delivery
- Find willing landowners keen to support NBS delivery on their land
- Appraise and select the right NBS for a specific location
- Design NBS measures which will work within the constraints of a specific site

The project design and delivery phase of a project will rely on the involvement of a wide range of different disciplines which will be key in helping to understand the opportunities and constraints associated with a specific site. This chapter covers a series of steps needed to design, construct and maintain NBS measures, these are set out in in the list below:

- Step 1. Understand the site
    - Undertake a desk-based assessment

- Step 2. Talk to people
    - Visit the site
    - Talk to landowners
    - Engage stakeholders

- Step 3. Develop a design
    - Develop and appraise options
    - Select a preferred option
    - Design the NBS
    - Apply the CDM regulations

- Step 4. Assess the impacts
    - Biodiversity net gain
    - Flood risk assessment
    - Habitat regulation assessment
    - Water Framework Directive assessment

- Step 5. Get permission
    - Flood risk activity permits
    - Ordinary watercourse consents
    - Natural England assent
    - Protected species licences
    - Planning permission

- Step 6. Built it

- Step 7. Maintain it
    - Develop a monitoring plan
    - Maintain and adapt it

10.2 Step 1. Understand the site

For NBS measures to be effective, it is important to initially spend time understanding your catchment so that the NBS can be installed in the right locations to maximise their benefits. This will help you select the right suite of measures for the right location(s).

10.2.1 Desk-based assessments

To help select the right site, it is advised to spend some time initially reviewing existing opensource mapped data to help give you a good overview of the catchment. Chapter 7 provides an overview of useful mapping resources you could access when trying to understand your site. A few of the key opensource datasets are summarised in Table 10-1. The desk-based assessment should include but not be limited to an assessment of opportunities and constraints across a range of disciplines. This should include but not be limited to:

- **Constraints:**
    - Risk of flooding and risk of drought
    - Ecological designations, presence/absence of specific species, assessment of non-native invasive species
    - Heritage assets which may constrain NBS
    - Presence of engineered infrastructure, public rights of way, utilities and services which may constrain construction
    - Presence of unexploded ordnance
    - Accessibility for construction machinery
    - Existing funding schemes in place may place constraints on what can and cannot be installed in a particular area

- **Opportunities:**
    - Policy drivers which support NBS delivery
    - Opportunity mapping to support or target specific forms of NBS

- Funding opportunities which support NBS delivery
- Presence of existing stakeholder and landowner networks within the catchment

Table 10-1: Summary of key opensource opportunity maps

Name of data source	Summary	Hyperlink
Environment Agency Working With Natural Processes Opportunity maps	Gives a high-level overview of the sorts of NBS which might be viable in a catchment. It includes: woodland planting, floodplain restoration and Runoff Attenuation Features.	Mapping Potential for WWNP - Online Maps (full functionality) - Overview
Forestry Commission's England Woodland Creation Offer maps	The Forestry Commission have developed a series of sensitivity maps to indicate whether there is likely to be potential to establish new woodland on land parcels or where there may be sensitivities that would prevent tree planting or woodland creation.	A guide to Forestry Commission's sensitivity maps for woodland creation - GOV.UK
Local Nature Recovery Strategies (LNRS)	Local Authorities across England are currently developing LNRSs, which will have maps and biodiversity prioritised for each county.	Local nature recovery strategies - GOV.UK
Natural England MAGIC maps	Enables you to understand what habitats are present in the catchment and any designations that you need to be aware of.	Magic Map Application
Wildfowl and Wetland Trust wetland creation potential maps	WWT has used national data to create Wetland Potential Maps, highlighting extensive areas across the UK that would benefit from wetland creation or restoration.	WWT Wetland Potential Data | WWT Wetland Data Explorer
ALERT (Agricultural Land Environmental Risk and Opportunity Tool)	The Farming Advice Service hosts a mapping tool created by the Environment Agency on behalf of Catchment Sensitive Farming to help farmers and local advisers analyse the landscape and reduce pollution from agriculture.	Catchment Sensitive Farming | ALERT
Regional NBS opportunity mapping from Water Resources East	NBS opportunity maps developed for Water Resources East by JBA, identified priority locations of different categories of interventions.	East of England NbS Planning Hub | Rivers Trust

10.3 Step 2. Talk to people

Opportunity maps will give you an indication of key locations where NBS will be beneficial. However, because these opensource datasets are produced nationally, they can be quite coarse and, in some cases, may not be locally accurate. It is, therefore, vital to not only look at maps but also to identify which organisations are already working in the same catchment. Talking with local actors such as non-governmental organisations (NGOs), public sector bodies and water companies will help you understand the catchment better. This will help you map out who is working where, and whether there are partnerships or funding opportunities you can tap into. Understanding the local context may also enable you to identify more locally specific datasets, which you can use alongside national opportunity maps to better identify key locations for NBS delivery. For example, local biological records are often an invaluable source of locally specific data.

10.3.1 Landowner, land manager, and farmer buy-in

Once more specific locations for NBS delivery have been identified through local discussions and engagement, a key next step is to find landowners, land managers and farmers who may be willing to allow NBS to be delivered on their land. In the absence of willing landowners, NBS delivery will not be possible.

Third-party intermediaries (e.g. NGOs and land agents) who already have existing relationships with local landowners/land managers/farmers can help identify and engage landowners who may be willing to have NBS delivered on their land. Alternatively, you may already have a good relationship with the landowner/land manager/farmer in which case the engagement could be delivered in-house. In addition to this, Catchment Sensitive Farming Advisors can provide free, confidential advice and training to help farmers produce food in a way that protects their local water, air and soil environments.

Once you have identified willing landowners it will be important to meet with them, share the objectives of the NBS project, and describe the high-level findings from the initial desk-based review. It should be noted that this phase of a project can take time, and the landowner may wish to see outline designs before committing to proceed. In some cases, a landowner may need to obtain permission from their board to proceed. In other cases, a land manager or farmer is interested in collaborating with the delivery of NBS, but the landowner is not, which can prevent the project from proceeding.

10.3.2 Visit the site

Undertaking a site walkover with the landowner will allow you to capture on a map their knowledge of how the site functions in high and low flows, drawing overland flow routes and areas where water naturally ponds. The site walkover will also help develop an understanding of:

- Areas of land where the landowner would or would not be amenable to NBS
- The sorts of NBS interventions which would or would not be acceptable to them

Conducting the site walkover with heritage, ecological, engineering, hydrogeological and geomorphological specialists is recommended because these disciplines will help identify potential opportunities and constraints relating to NBS delivery. In some cases, sites may be ruled out as unsuitable based on the findings of these surveys. This will enable you to build on the opportunities and constraints developed during the desk- based assessment.

For the project's duration, the site will need to be visited multiple times. Therefore, it is recommended that an approach to accessing the site be agreed upon with the landowner to ensure visits are undertaken at a convenient time. It may also be necessary to flag the fact that if the site becomes known as an NBS showcase they may receive multiple future requests to host visitors.

10.3.3 Stakeholder engagement

Engaging stakeholders in NBS delivery for water resources benefits can be more complicated than engagement for flood purposes. This is because when NBS are being developed for water resource purposes, they are restoring natural processes which are not necessarily tangible, such as infiltration, evaporation, restoration of low flows and aquifer recharge.

Physical models (“Ant farm” groundwater aquifer physical model. | Download Scientific Diagram) can be usefully developed to help explain groundwater processes and show the effect of different NBS. The Aquifer Partnership has developed an animation that explains how groundwater-fed catchments function (https://youtu.be/gRY7TYBx-is).

10.4 Step 3. Undertake surveys

Once a desk-based assessment has been undertaken, the site has been visited, and landowners have been engaged with, a series of surveys will be necessary to help identify opportunities and constraints that inform the design process.

Surveys will include but not be limited to:

- Ecology (including invasive non-native species)
- Geomorphology
- Geophysical and ground investigations
- Heritage and archaeology
- Landscape assessments
- Reservoir inspections
- Topography
- Unexploded ordnance
- Utilities

Depending upon the nature of the project it may be also necessary to undertake additional baseline surveys to understand how the site evolves over time. For example, soil cores may be needed to establish how much carbon the site currently captures, creating a carbon baseline which can be revisited post-restoration to enable a comparison.

The surveys will act as the foundation for developing the designs and will create a baseline for any long-term monitoring plans. They can also be shared with the landowner to help develop good working relationships.

10.5 Step 4. Develop a design

The institute of Civil Engineers (ICE) has developed a toolkit which describes the lifecycle of a construction project (ice-infrastructure-lifecycle-guidance-toolkit.pdf).

The Royal Institute of British Architects (RIBA) has also developed guidance which describes the different steps in the design and construction of building projects (RIBA Plan of Work). The guidance includes a useful plan of work template which organises the process of briefing, designing, delivering, maintaining, operating and using a building into eight stages.

10.5.1 Construction Design and Management (CDM) regulations

(The Construction (Design and Management) Regulations 2015 - HSE, Managing health and safety in construction. Construction (Design and Management) Regulations 2015. Guidance on regulations L153)

The CDM Regulations (CDM) helps to identify the roles and responsibilities of people involved in the design and construction phases of projects. The CDM aims to uphold health and safety in the construction industry.

The CDM regulations apply to the design and construction of NBS measures. The CDM Regulations defines the specific roles (CDM 2015 designer duties - Designing Buildings) performed by different individuals as part of the design and construction of projects. The roles include:

- Clients
- Designers
- Principal designers
- Principal contractors
- Contractors
- Workers

Each of these roles has responsibilities for producing different documentation to ensure that their project complies with the regulations. It is important that these roles are defined on any project.

The ICE's manual of health and safety in construction should be referred to throughout the project's development (9780727760104pre_pi-xx.indd). This manual provides a useful summary of the different roles and responsibilities of a construction project.

CDM does not just apply to the designer and contractor; the client must also be trained and certified as a CDM client. The client is also responsible for providing the Principal Designer and Principal Contractor with a letter of appointment.

10.5.2 Appraising and selecting the preferred option

The information collated during the desk-based assessment and site walkover can be used to develop a longlist of all potential NBS options that may be feasible. Once a longlist is developed it is recommended that each of the options are appraised to help define objectives, examine options and weigh up the costs, benefits, risks and uncertainties of the different options.

The options appraisal process must be collaborative and undertaken in partnership with the landowner and other relevant stakeholders. An options appraisal meeting should allow all the different stakeholders to assess and vote for a preferred option.

The outcomes of the options appraisal will be the development of a preferred option, which will include either a single NBS measure or a suite of measures.

10.5.3 Designing the NBS

Principal designers must plan, manage, monitor and coordinate health and safety in the pre-construction phase. To achieve this, they must take account of relevant information (e.g. existing health and safety files) that might affect design work carried out both before and after the construction phase has started (Principal designers: roles and responsibilities - HSE).

Designing an NBS scheme will typically follow a series of steps, developing a high-level concept design and refining it as more information becomes available to develop an outline and then finally a detailed design. The NBS designer will need to develop a design buildability statement, this is a statement which demonstrates that buildability has been evaluated and may include: methodology, feasibility, managing health and safety and environmental risks.

Most existing guidance on designing NFM measures is associated with designing features which slow or store water for flood benefits. When designing these measures for water resources benefits, there are different design considerations to be mindful of (see Figure 10-1).

Figure 10-1. Considerations for designing NBS to provide water resource benefits

Name	Change to the water cycle	Design considerations
Water usage	• Reduce evaporation and transpiration • Reduce interception of rainfall • Reduce irrigation demands	NBS in this category include planting crops and trees (deciduous woodland pasture) that reduce irrigation needs and have lower evapotranspiration rates. The layout of tree planting regimes can also be planned in such a way that it helps capture and augment water resources.
Runoff infiltration split	• Improve soil health to allow more infiltration • Increase surface roughness to slow runoff at source	NBS that fall under this category include crops that help improve soil health and increase surface roughness to slow runoff. Planting crops across slopes can help to capture and store water. Sustainable forms of agriculture can also help improve surface roughness. Intelligent management of livestock can reduce soil compaction and retain good soil structure. These measures need to be planned to encourage infiltration specifically.
Runoff capture and infiltration	• Capture runoff on the surface and allow it to infiltrate into the ground	NBS that fall under this category include measures which capture and store water (e.g. runoff attenuation features, infiltration basins and cross-slope planting). The location of these measures needs to be planned to not only intercept flow but also to encourage groundwater recharge. They need to be designed to function during 'typical' rainfall events to enable rapid infiltration. This may mean that these features are smaller in size but greater in number than those designed for flood risk purposes. Engineering input will be required for implementation.
Floodplain and river restoration	• Raising the bed of a river, so it has less impact on the local water table • Improving floodplain connectivity – allowing floodwaters to be stored on the floodplain • Creating wetlands on the floodplain, increasing the storage of water on the floodplain	NBS in this category aim to restore the connection between rivers and their floodplain, restoring wetland and floodplain habitat. Designing these NBS for water resources rather than flood purposes is different. Whilst it is important to reconnect the river to the floodplain the project will need to be designed to not impact the local water table. This means the design will need to focus potentially on bed raising and storing water on the floodplain. This can involve infilling and narrowing a channel to raise the bed of the river, which will in turn will encourage water to be stored on the floodplain. Engineering input will be required for implementation.

10.5.4 Designer risk assessment (DRA)

The CDM regulations require that a design risk assessment (DRA) is created to identify the hazards and evaluate the risks that may arise from the design. Depending on the hazard, the designer shall implement appropriate controls to either remove or mitigate the risk. By defining the risks, the DRA can also help the designer to have conversations with their client about risks and liabilities, which will help determine who will be responsible for owning and accepting liability for any outstanding risks.

10.5.5 Pre-construction information (PCI)

Pre-construction information is legally required under the CDM regulations. It involves collecting, collating, and communicating relevant health and safety information before construction work begins. The aim of PCI is to "ensure that all parties involved in any project understand the risks and hazards associated with the work, enabling them to take steps to protect themselves and others" (What Is Pre-Construction Information? | CHAS). PCI includes but is not limited to:

- Plans and Specifications
- Environmental Assessments
- Health and Safety Assessments

Following the PCI's provision to the client, a Construction Phase Plan (CPP) should also be provided for their approval.

The client is responsible for completing an F10 form which notifies the Health and Safety Executive of a notifiable construction project.

10.5.6 Hazards and constraints plan

A hazards and constraints plan will need to be developed for the site. Considerations include, but are not limited to:

- Location of services, infrastructure (e.g. roads, rail, flood defences etc) and public rights of way
- Unexploded ordnance (UXO) risk
- Accessibility for machinery
- Waste management
- Consenting requirements
- Presence of protected species/habitats and invasive non-native species presence
- Future maintenance needs

10.6 Step 5. Assess its impact

10.6.1 Biodiversity net gain assessments (BNG)

(Understanding biodiversity net gain - GOV.UK)

BNG is an approach to development. It makes sure that habitats for wildlife are left in a measurably better state than they were before the development. BNG could be relevant to the delivery of an NBS project in two ways:

- Landowners/managers may be able to sell biodiversity units to developers to enable habitat creation on their land (Meet your BNG requirements: steps to take for land managers - GOV.UK). BNG could help to fund NBS.
- If the NBS project needs to apply for planning permission, then as part of this submission a BNG assessment may be needed if the site is over 1ha in size.

10.6.2 Flood risk assessments (FRA)

As part of the development of the NBS design it is likely that flood modelling will be needed to ensure the proposal does not increase the risk of flooding. This will also form an important part of the Flood Risk Activity Permit which will likely need to be accompanied by a Flood Risk Assessment to ensure the NBS does not have an adverse impact (Flood risk activity risk assessment for your environmental permits - GOV.UK).

10.6.3 Habitat regulation assessments (HRA)

(Habitats regulations assessments: protecting a European site - GOV.UK)

The Conservation of Habitats and Species Regulations 2017 as amended (known as the Habitats Regulations) provides protection to the species and habitats present on sites designated as Special Protection Areas (SPA) and Special Areas of Conservation (SAC). If your NBS proposal is on or in close proximity to an SPA and/or SAC you will need to carry out an assessment under the Habitats Regulations, this will establish if your project proposal could significantly harm the designated features of a European site. Input from an ecologist will likely be needed to help determine the impact of your proposal on European-designated sites. Natural England's MAGIC mapping system can be used to determine whether your site is designated or not (Magic Map Application). It is important to note that some ecological surveys must be undertaken in the Spring. This needs to be factored into any time plans so as to not hold up construction.

10.6.4 Water Framework Directive (WFD) assessments

The purpose of the WFD assessment is to assess the impact of a proposal on the water environment to determine its potential effect on the ecological status of a waterbody. If the proposal leads to a deterioration in ecological status, it is unlikely to be acceptable. To be acceptable from a WFD perspective, a proposal must lead to either no deterioration in ecological status or an improvement in ecological status. Guidance is available to help you undertake a WFD assessment for fluvial/terrestrial (Water Framework Directive risk assessment) and intertidal/coastal (Water Framework Directive assessment: estuarine and coastal waters - GOV.UK) environments. WFD assessments are usually required as part of a FRAP and planning consent.

10.7 Step 6. Get permissions

As part of any proposal to design and construct NBS measures it is vital to be aware of which permits, consents, licences and assessments are needed to deliver the works. This section summarises some of the main permits, licences and assessments which may be needed.

At the project's outset, discussing and agreeing on a full list of all necessary permits and licences with relevant regulators is vital to ensure the proposed NBS scheme fully complies with the law.

10.7.1 Flood risk activity permits (FRAPs)

(Flood risk activities: environmental permits - GOV.UK)

FRAPs are needed for proposed works:

- On or near a main river
- On or near a flood defence structure
- In a floodplain
- On or near a sea defence

The purpose of the FRAP is to ensure that the proposed works do not increase the risk of flooding or negatively impact existing flood risk management infrastructure. If your project is being delivered on a main river, you will likely need to apply for permission to undertake the works. Guidance is available to help you determine if your works:

- Are exempt and do not need a FRAP (Excluded flood risk activities - GOV.UK)
- Are covered by a standard rules permit (Flood risk activities: environmental permits - GOV.UK)
- Require a bespoke permit (Flood risk activities: environmental permits - GOV.UK)

Depending upon the scale of the project, flood modelling may need to accompany the FRAP to demonstrate that the proposal does not increase the risk of flooding. Your FRAP may also need to be accompanied by other assessments such as Water Framework Directive Assessments and Habitat Regulation Assessments (see below) (Flood risk activity risk assessment for your environmental permits - GOV.UK).

10.7.2 Ordinary watercourse consents

Ordinary watercourse consents, also known as Land Drainage Consents (LDCs) are needed for works affecting the flow of ordinary watercourses. These consents need to be submitted either to the Lead Local Flood Authority (LLFA) or the Internal Drainage Board (IDBs), depending upon which organisation is responsible for the ordinary watercourse you are working on. If you are working on an ordinary watercourse, it is important to determine which flood risk management authority you will need to apply for consent to (Internal Drainage Boards - Association of Drainage Authorities, Find your local council - GOV.UK), and to be aware that ordinary watercourse consents have a two-month determination period. Ordinary Watercourse consents will need to be supported by information such as site location plan, designs and associated survey results.

10.7.3 Natural England assent

(Sites of special scientific interest: managing your land - GOV.UK)

Natural England Assent may be needed for proposed works on a Site of Special Scientific Intertest (SSSI). Each SSSI has a list of activities, known as ‘operations’, which need Natural England’s Assent. If your proposed project is on a SSSI it is recommended that you contact Natural England to discuss the proposal and agree whether assent is needed. Even with

Natural England's consent, it may be necessary to obtain other permits and licences discussed in this chapter.

10.7.4 Protected species licences

(Wildlife licences: when you need to apply - GOV.UK)

Depending upon the species present on your site your site you may need to apply for protected species licences if you plan to disturb/remove wildlife or damage habitats. Employing an ecologist to undertake a site walkover to help establish which protected species may be present will help establish which licences may be needed as part of the works; they will also be able to help develop an ecological calendar to help establish the best time of the year to undertake the works to reduce the likelihood of impacting species.

10.7.5 Planning permission

(Before submitting an application - GOV.UK)

It is recommended to obtain pre-application advice from your relevant local authority to determine if planning permission is needed. NBS schemes, particularly those that involve earthworks, may require planning permission. In some instances, NBS may be classified as agricultural developments and so may be exempt, but as a precaution it is best to contact your local authority and seeks their advice at the project's outset.

If planning permission is required, many of the assessments undertaken in Step 5 will form part of the planning application processes, as these will be required to demonstrate that the potential impacts of the NBS have been fully assessed and mitigated where necessary. Other assessments or surveys may also be needed, and a sufficient budget should be set aside to ensure that these can be delivered to support the planning application.

10.7.6 Utilities permission

Permission may also be needed to build near different types of utilities. It is, therefore, important to identify any utilities present on the site and ensure that any necessary permissions are obtained.

10.8 Step 7. Build it

The CDM regulations states that principal contractor must plan, manage, monitor and coordinate health and safety during the construction phase of a project involving, or likely to involve, more than one contractor. The contractor is responsible for planning, managing and monitoring all work carried out by themselves and their workers. The HSE's (Health and Safety Executive) guidance on planning construction work describes how to comply with CDM regulations during the construction phase (Planning for construction work - HSE).

The principal contractor should meet with the NBS designer to enable the handover of all relevant design information and the PCI. This provides the opportunity for the designer to take the contractor through the designs, the DRA, PCI and relevant drawings. Prior to construction, the contractor will need to develop documents such as but not limited to:

- Working method statements
- Risk assessments
- Biosecurity procedures
- Environmental/site management plans

The contractor will be responsible for health and safety during the construction phase of the project and will need ensure all construction staff are fit for work, appropriately trained, hold correct permits and have access to appropriate PPE (personal protective equipment). It is important to note that the construction phase can officially start as early as the ground investigation and ecological surveys.

The contractor will need to ensure they understand the ecological calendar for their site so that construction is undertaken at a time when it does not disturb or negatively impact protected species. Having an ecological clerk of works on site at all times can help mitigate the potential negative impacts of construction on plants and animals.

Another key decision will be whether to develop the scheme under traditional contracts in which a designer and a contractor are appointed separately, or under a design and build contract where one organisation delivers the entire scheme. Many smaller NBS4WR features may suit the design and build contract process, especially if lots of small schemes are to be delivered at scale.

The landowner and farmers must be involved in the construction phase to ensure that the construction is undertaken at a suitable time and in a manner that is not overly disruptive to them. Prior to construction, it is recommended that the contractor holds a meeting with the landowner to agree to items such as:

- Programme and timing of works
- Site access/egress
- Storage areas for any materials/plant
- Contact details (day to day and emergency)
- Monitoring during construction
- Updates/progress meetings

In some cases, landowners may wish to enter into a legal agreement prior to construction.

10.9 Step 8. Monitoring and maintaining it

If NBS projects are designed to work with natural processes, this should reduce the need for long-term maintenance. Designing NBS to work with natural processes ensures they are designed to be adaptable and resilient to the impacts of both droughts and floods. Designing for floods and droughts may involve designing two different types of NBS. For example, a water quality feature which filters water before it flows into a storage area that provides benefits during high and low flows.

Maintenance and adaptive management should be included in an organisation's long-term funding plans. This will enable the development and implementation of a plan to inspect NBS features to assess their performance and implement measures to adapt them should they need to be repaired.

Maintenance and adaptive management are important because failure of an NBS measure could have unintended consequences such as increasing flood risk downstream. The Environment Agency has developed helpful guidance which describes how to minimise legal, financial and reputational risks associated with delivering NBS projects (337_18 Flood Risk Management - Minimising the Risks - Quick Guide).

Post-construction activities need to be considered as part of the requirements of the CDM regulations. This should include developing an approach to the inspection and maintenance of the NBS which can be undertaken safely. As with the construction phase of the project, the CDM regulations require that the inspection and maintenance activities shall only be undertaken by appropriately trained individuals.

10.9.1 Monitoring for maintenance

Developing a robust monitoring plan plays a key role in helping to understand whether maintenance or adaptive management of NBS measures will be needed.

Chapter 9 describes different monitoring techniques in detail. When developing a monitoring plan, it is important to build in the need to review and assess how the NBS measures are performing, whether they are working as designed, and whether any adaptations are needed. This reflective process enables learning and will enable NBS features to be designed differently in the future if needed.

Monitoring for maintenance need not be a complex process. It can involve:

- Site walkovers at regular intervals to inspect features
- Fixed point photography of NBS measures to understand their evolution over time

It is important to monitor NBS in times of high and low flows to understand how they perform in different conditions.

10.9.2 Maintenance and adaptive management

The results of monitoring will help to determine whether NBS measures require maintenance to fix a problem or adaptive management to adapt the design to take account of unexpected changes needed. Maintenance needs will vary from project to project, they might involve:

- Removing woody debris dams if they become dislodged
- Affixing NBS features (e.g. woody debris dams) to ensure they do not become dislodged in high flows
- Removing sediment from storage features to maintain their capacity
- Control and removal of encroaching scrub
- Replacing or removing tree guards

10.9.3 Decommissioning

The final stage in a construction project may involve a decommissioning phase, whereby steps are taken to handover responsibility for assets to a landowner. This stage can involve retrieval of monitoring equipment that no longer needs to be deployed or filling in boreholes that were constructed during an earlier phase of work. Importantly, this phase is likely to require engagement with the landowner to design and agree a long-term plan for any necessary maintenance works.

10.10 Summary

This chapter has provided a high-level summary of some of the key steps needed to design, construct and maintain an NBS project.