NERC SCIENCE OF THE ENVIRONMENT

HR Wallingford
Working with water

Green approaches in river engineering

Supporting implementation of Green Infrastructure

Green approaches in river engineering

Supporting implementation of Green Infrastructure

This publication was produced under grant NE/N017560/1 which was awarded by the UK Natural Environment Research Council (NERC).

The team was led by HR Wallingford Ltd and comprised Environmental Policy Consulting, the River Restoration Centre, CIRIA, the University of Liverpool and the University of Nottingham.

Natural Resources Wales, the Environment Agency, the Welsh Local Government Association and Natural England were partners in this project.

Authors

Marta Roca (HR Wallingford), Manuela Escarameia (HR Wallingford), Olalla Gimeno (HR Wallingford), Lucas de Vilder (HR Wallingford), Jonathan Simm (HR Wallingford), Bruce Horton (Environmental Policy Consulting), Colin Thorne (University of Nottingham).

Contributors:

Janet Hooke (University of Liverpool), Martin Janes (River Restoration Centre), Marc Naura (River Restoration Centre),
Paul Weller (Environment Agency), Owen Tarrant (Environment Agency), Lydia Burgess-Gamble (Environment Agency),
Jenny Wheeldon (Natural England), Larissa Naylor (University of Glasgow), Hugh Kippen (University of Glasgow),
Helen Stevenson (HR Wallingford).

Acknowledgments:

Huw Alford (Natural Resources Wales), Martin Coombes (University of Oxford), Simon Cuming (Environment Agency),
Wyn Davies (Natural Resources Wales), Jean-Francois Dulong (Welsh Local Government Association), Heather Forbes (SEPA),
James Galsworthy (Natural Resources Wales), Victoria Greest (Natural Resources Wales),
David Holland (Salix River & Wetland Services Ltd), Rachel Hunt (Environment Agency), Adrian Jones (Natural Resources Wales),
Oly Lowe (Natural Resources Wales), Tim Martin (Greenfix), Fiona Moore (Land & Water Services Ltd),
James Neal (Natural Resources Wales), John Phillips (Environment Agency),
Lynn Puttock (Terraqua Environmental Services), Emma Thompson (Environment Agency), Dave Webb (Environment Agency).

The above have supported the project, provided references, case study information and/or photos to illustrate the measures.

Green approaches in river engineering
Supporting implementation of Green Infrastructure

This edition first published 2017

Registered office - HR Wallingford, Howbery Park, Wallingford, Oxfordshire OX10 8BA, United Kingdom

This document is available from:
CIRIA (www.ciria.org)
River Restoration Centre (www.therrc.co.uk)
HR Wallingford (www.hrwallingford.com)

978-1-898485-16-2

Contents

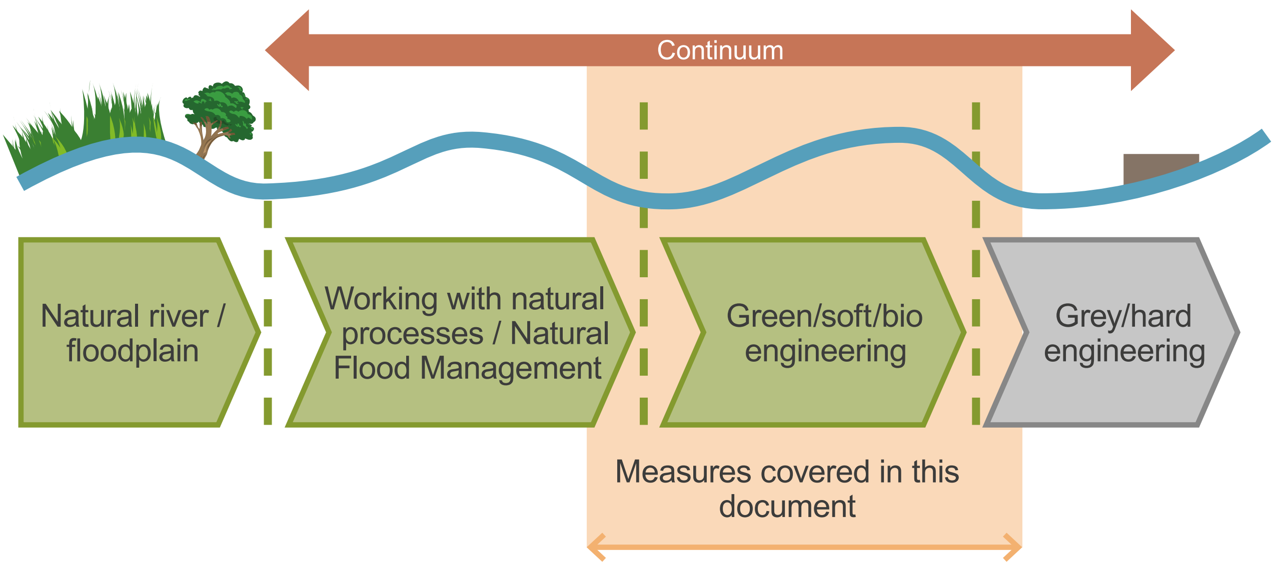
Chapter 1
Introduction

Working together with natural systems, which are powered by a diversity of life within them, provides a range of benefits to society, ranging from carbon storage, clean water and air to reduction of climate change impacts and protection against floods and other environmental hazards. This realisation has led to the concept of Green Infrastructure (GI): a network of natural and semi-natural features that intersperses and connects villages, towns and cities. Rivers are part of this green network, which has the potential to provide higher resilience and cost-effectiveness as well as more social and environmental benefits than conventional infrastructure.

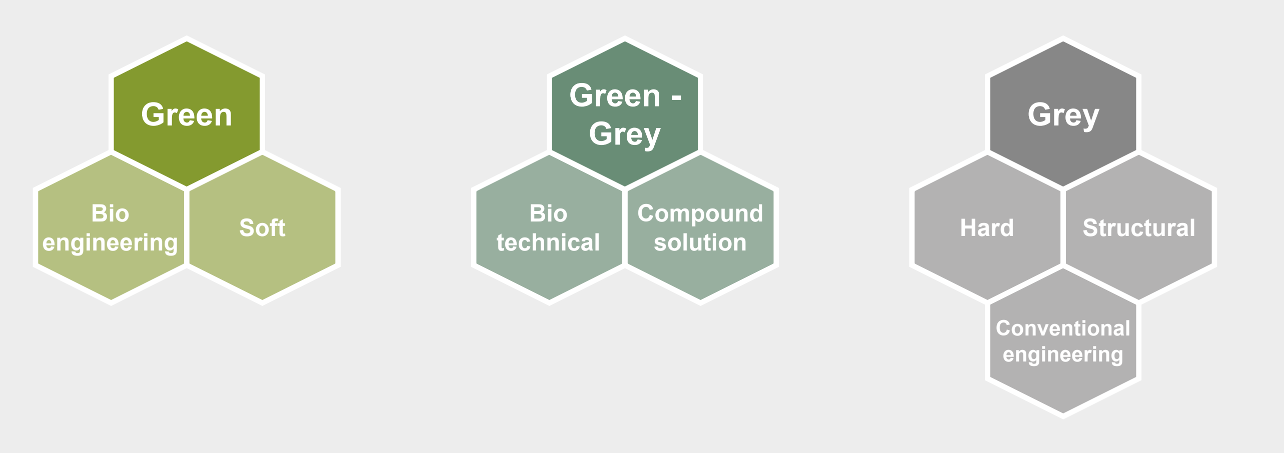
This document focuses on river engineering (which is concerned with river works) and therefore, we consider the river or watercourse as a natural or semi-natural corridor or infrastructure element. In this context, GI approaches are those that promote the conservation or restoration of the natural (green) character of our rivers. These approaches are fundamental to improving the water quality, morphology and ecosystems of rivers as well as contributing to an overall strategy to help people and communities adapt to the impacts of climate change.

There are, however, procedural and technical barriers that prevent or obstruct implementation of GI approaches as part of river engineering schemes. Examples include lack of evidence-based decision-making, risk aversion, resistance to innovation and the perception that GI has a higher risk of failure. The objective of this document is to contribute to overcoming some of these barriers by supporting asset managers, engineers, decision-makers and other end users such as regulators and planners in identifying critical success factors. These will permit selection and application of GI approaches for river engineering instead of more conventional engineering approaches, when and where appropriate.

Engineering approaches to be applied in the context of rivers form a continuum from “natural flood management”, which includes interventions such as management of woodlands and offline storage areas, to single-function methods, such as sheet piling and flood walls. This idea of continuum is presented in the figure which also highlights the type of measures considered in this document. They are mainly Green and Green-Grey measures although some Grey measures and techniques for “Working with Natural Processes” are also covered. Individual measures, and mainly Green measures, are rarely used in isolation, but are combined to provide a multi-functional, overall solution. For example, a combination of rock rolls at the toe of a bank and revegetation of the bank face above can be an effective, multi-benefit solution to a particular bank failure problem.



In this document we will use preferentially the terms Green, Green-Grey and Grey to describe the different measures presented but other terminology is also used in the literature as shown in the figure.



Due to lack of awareness, unsuccessful previous experience or other reasons, not least the difficulty of quantifying factors such as design life and risk of failure, river engineers and other end-users may tend to choose Grey (conventional engineering) solutions that do not contribute to the multiple co-benefits made possible by the creation of GI. This document builds on existing guidance and literature to provide strategic arguments as well as advanced, technical knowledge and clear evidence to promote the informed selection of Green or Green-Grey solutions in river engineering. The document summarises existing knowledge and information and is intentionally brief and focusing on the key points. Necessarily, it does not cover all potentially relevant details of available measures, data and solutions and therefore, it cannot be classified as a manual on GI approaches.

Descriptions of GI approaches presented in this document, covering both Green and Green-Grey measures, as well as associated river management techniques, are presented in Chapter 2. These are the main different types of measure that an asset manager, designer or other end-user may consider when appraising options for a river engineering intervention.

Chapter 3 presents strategic arguments and technical information to support the selection of GI approaches in the contexts of river engineering applications. The information is structured in the form of a decision support framework at two different levels: first, the Business Case, which provides arguments to support the decision to implement a GI approach, and second the Technical Support, which provides the technical information base from which to select an appropriate Green or Green-Grey measure or technique.

To support the technical information provided in Chapter 3 (and showcase the application of a range of GI approaches), a series of case studies is presented in Chapter 4. These case studies provide reliable evidence on key aspects of GI implementation, including constructability, engineering performance, environmental functions and social benefits. Links to other relevant case studies that are not reported in detail in this document are also provided.

This document has been produced as an output of investigations conducted under grant NE/N017560/1, which was awarded by the UK Natural Environment Research Council (NERC). The team was led by HR Wallingford and comprised Environmental Policy Consulting, the River Restoration Centre, CIRIA, the University of Liverpool and the University of Nottingham. Natural Resources Wales, the Environment Agency, the Welsh Local Government Association and Natural England were partners in this project. These partners provided most of the information reported in the case studies (Chapter 4). The project also benefited from close collaboration with a paired NERC grant (NE/N017404/1) led by the Universities of Glasgow and Oxford, which dealt with innovative measures to retro-fit GI techniques and measures to existing, grey infrastructure.

Chapter 2

GI approaches considered

Green Infrastructure approaches considered in this document employ:

- Green measures that use vegetative materials such as willow spiling, exclusively;
- Green-Grey measures that include non-vegetative, non-biodegradable components, such as artificial mattresses used to reinforce recently planted vegetation, to provide additional structural stability and/or erosion resistance to a Green measure;
- Grey measures such as rock rolls and geotextiles that are commonly used in combination with Green measures in situations where there is severe erosion/instability and high risk to people or assets;
- Associated river management techniques that contribute to creation of Green Infrastructure, such as meander restoration and bank regrading. For example, they help to recreate a more natural longitudinal profile and cross-sectional geometry, to restore longitudinal and floodplain connectivity, and to improve flow and sediment dynamics.

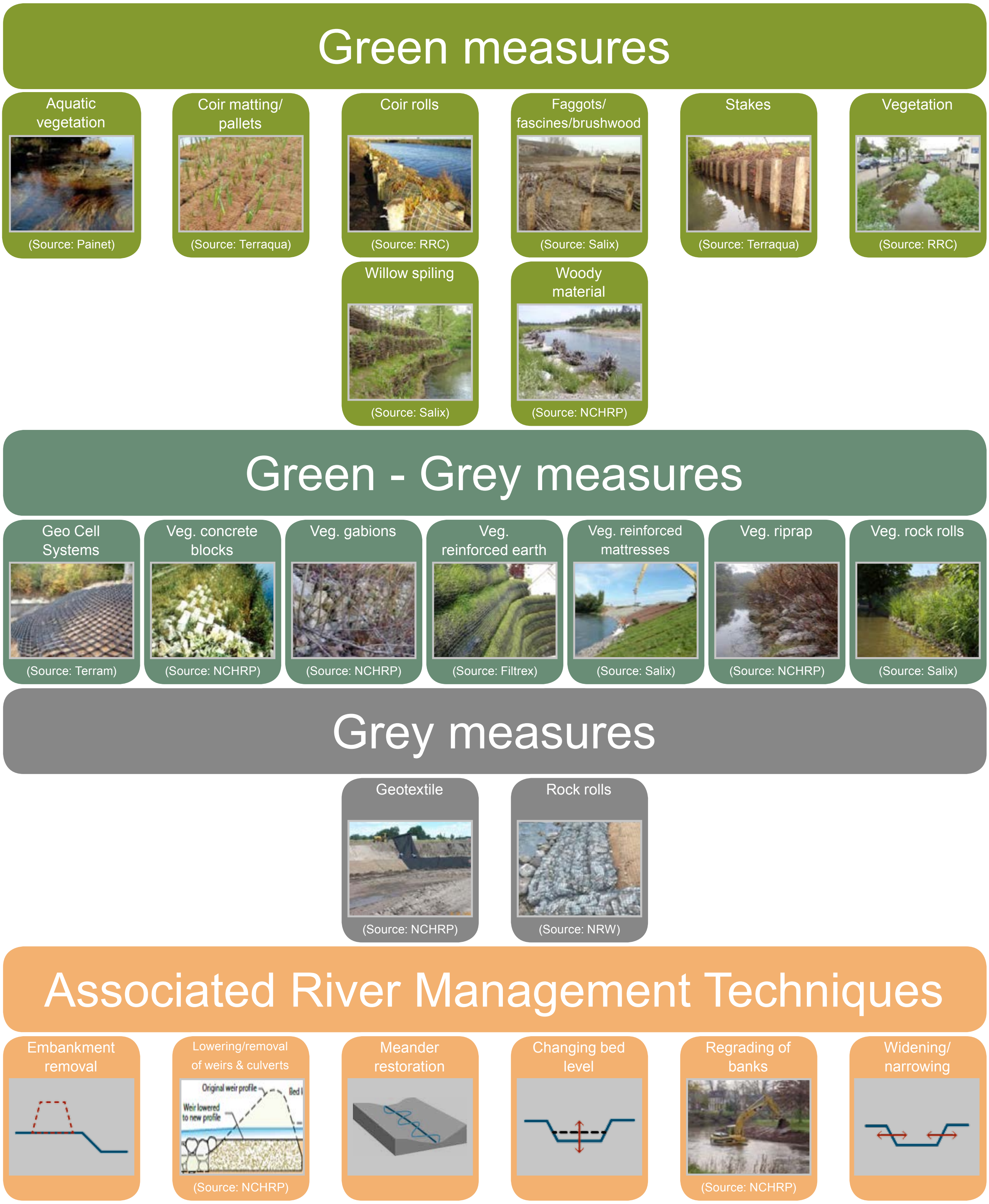
Green and Green-Grey measures are composed of selected materials or combinations of materials that may be installed in a new project or added to an existing project. The river management techniques are actions implemented in the river channel in conjunction with Green, Green-Grey or Grey measures appropriate to the situation.

Brief descriptions of each measure and technique are provided below. Where appropriate, basic guidance is provided concerning whether a measure is more suited for use on the bank face, at the bank toe or for both. The descriptions are not intended to be exhaustive and references are provided in Chapter 5 if the reader wishes to have more detail.

In practice, individual Green or Green-Grey measures are rarely used in isolation: they are usually just one component of a river engineering project. A good example of the use of measures in combination is provided by the Green measure "Stakes": stakes can be used with other woody material or coir rolls to provide enhanced protection at the toe of an embankment, with brushwood mattresses or coir matting installed to increase the stability of the bank as a whole. Similarly, most solutions are also likely to include an engineering action such as bank regrading. Examples of common solutions that employ various combinations of measures and techniques are also given in this chapter.

GI measures and techniques

This Section lists and briefly describes the types of GI measures and techniques considered in this booklet.



Green measures

Aquatic vegetation

Native plants well-adapted to living in-stream (i.e. in parts of the channel that are perennially inundated) can be used to protect the toe of river banks by locally retarding near boundary flow velocities and providing root reinforcement to the bed and lower bank (e.g. Iris and Sedge species).

Coir matting/pallets

Coir matting/pallets are biodegradable materials made from natural fibres that protect and stabilise the riverbank while allowing vegetation to grow through. Coir is the stiff fibre from the outside of coconuts. It can be woven and pressed into many shapes, including matting of various thicknesses. Biodegradable mats are often used to provide a rooting base in re-vegetation schemes, which promotes rapid re-establishment of live vegetation to stabilise an eroding bank.

Coir rolls

Coir rolls are sausage-shaped elements made of coir (coconut) fibre compressed into a roll and contained by an exterior mesh. They are used to protect the toe or the bank. Coir rolls need proper anchoring and are not recommended for areas with high near-bank velocities and/or intensely turbulent flow. These rolls are normally used in combination with live vegetation and stakes.

Faggots/fascines/brushwood

Faggots and fascines are bundles of untreated brushwood, bound together with biodegradable fibres and used to stabilise a river bank face and/or toe. The brushwood may be live and likely to root, such as willow, or dead, often hazel or chestnut. The bundles are usually set into shallow trenches on the river bank, parallel to the direction of flow. The bundles slow the near-bank flow and trap fluvial sediment (especially silt) and organic matter (including plant matter that may then root in situ).

Stakes

Live stakes may be used to reinforce the bank face, promote vegetation re-growth, and anchor other measures in place until they grow and take root sufficiently to become self-supporting. They can also be installed around the bank toe, in lines parallel to the flow, to protect the toe from scour. Stakes are usually cut from the stem or branches of appropriate willow types and are typically 0.5-1 m long. The portion of the stake below ground will take root and the exposed part will develop into either a tree or a bushy riparian plant, depending on the willow type selected and the manner in which bank vegetation is managed and maintained. Stakes are normally used in combination with other Green, Green-Grey or Grey measures and techniques.

Dead stakes, also called posts, are generally thicker and longer than live stakes and provide immediately effective bank reinforcement. In the long-term, live stakes will provide superior performance, provided that the resulting trees/shrubs are properly maintained. To prolong the effectiveness of posts, these are made of hardwood for increased durability. They should never be made from treated wood, however, as this contaminates the bank soil and, potentially, flow in the adjacent stream.

Vegetation

Vegetation established on bare soils helps to prevent surficial erosion by: shielding the bank surface from raindrop impact (splash erosion); increasing infiltration and slowing runoff draining down the bank (sheet, rill and gully erosion); retarding near bank flow velocities (fluvial erosion), and; anchoring the subsoil through root reinforcement. In addition, take up of soil water by healthy bank vegetation reduces the frequency of saturated conditions (note: most bank collapses are triggered by soil saturation) and generates negative pore water pressures that increase bank stability when the bank is unsaturated – which is most of the time. Vegetation, consisting mainly of grasses, herbaceous plants and shrubs, is almost always used in conjunction with other Green, Green-Grey or Grey measures and engineering techniques.

Willow spiling (also called woven stems, wattle fence or wall, willow hurdle, willow weave, willow plait)

Willow rods woven around stakes form a fence-like structure that is backfilled with soil to provide physical protection against erosion by fast-flowing water. The willow rods are live (although dead rods such as hazel can also be used), but stakes may be live or dead (i.e. posts). When installed within the channel, willow hurdles can be used to deflect flow away from a bank, albeit temporarily, and to promote near-bank deposition that might change the course of the stream. In this respect, they may be used as a river training technique, at least in small streams.

Woody material

Woody material sourced by felling trees can be used to deflect flows and promote sediment deposition at the toe of eroding banks. The wood may be installed in one or more of three forms: (1) whole trees or tree trunks placed parallel to the flow at the bank toe; (2) ‘root wads’, which consist of tree trunks with the roots still attached that are pushed into the bank (trunk first), leaving the roots exposed; (3) Engineered Log Jams (ELJs), which consist of large, expertly-designed, interlocked, wood structures kept in place by using some logs as vertically-driven piles. In these cases, the aim is to increase bank stability and shelter the bank surface while also substantially increasing bank roughness and, therefore, dissipating flow energy. Woody materials are also used as flow deflectors.

Green-Grey measures

Geo Cell Systems

Geo Cell Systems are three-dimensional earth-retaining structures that can be expanded and backfilled with material to stabilise the bank surface.

Vegetated concrete blocks

Vegetated concrete blocks are articulated block systems that can adapt to the irregularities of the bank topography. Vegetation in the form of live cuttings or grass plugs is inserted through openings in the blocks into the soil beneath them.

Vegetated gabions

Gabions are wire mesh baskets filled in situ with stone that can be used to stabilise the bank toe or piled up on top of each other to retain the bank at a steep angle. Woody vegetation is incorporated by inserting posts and poles through the basket during the filling and penetrating the underlying fill or intact soil. The space between the stone in the baskets may be filled with soil and seeded to promote vegetation growth within and between the baskets and the underlying fill or soil to improve the aesthetics.

Vegetated reinforced earth

Vegetated reinforced earth includes grasses or live cut branches intermixed with soil that is wrapped in a natural fabric or geotextile (the latter providing the geotechnical reinforcement). Vegetated reinforced earth may be used to protect the bank face.

Vegetated reinforced mattresses

Vegetated or turf reinforced mattresses are flexible mats that can be rolled out and fastened onto the bank slope. They can be be made of natural or synthetic materials. These mattresses are designed to resist fluvial shear stresses and turbulent forces of traction and uplift. The erosion resistance of planted grasses is greatly enhanced by the presence of such mattress. If all the materials comprising the reinforced mattress are biodegradable, this can be considered a Green measure.

Vegetated riprap

Vegetated riprap consists of layers of stone and/or boulders vegetated during construction using poles, brush-layering or live-staking. The measure increases the stability of the bank and/or toe while simultaneously establishing riparian growth within the rock revetment.

Vegetated rock rolls

Vegetated rock rolls consist of a net material filled with cobble-sized stones with established vegetation. These rolls are most often used to stabilise the toe of the bank, with other measures used higher up on the bank face.

Grey measures

Geotextile

Geotextiles are permeable textiles used in contact with soil to separate, filter, reinforce, protect, or drain and are made of synthetic materials. They have a longer life than biodegradable textiles and are normally used combined with other measures to protect the banks/toe.

Rock rolls

Rock rolls are made of synthetic polyethylene net material filled with stone. They are used to stabilise the toe of the slope. The generally small size of the stone promotes sediment deposition and allows vegetation to establish.

Associated river management techniques

Embankment removal

This measure involves the removal of flood embankments or the enlargement of set-back distances to provide more room for the river, especially during flood events, by reconnecting it to its floodplain and side channels. Lower mean flow velocities result from the increased space available for the river during periods of high flows but the risk of localised scour at the transition to the floodplain must be assessed.

Lowering/removal of weirs and culverts

Many existing weirs no longer provide benefits to society because they are not functional or have fallen into disrepair. Similarly, many culverts are under-sized with regard to increases in flood flows, sediment loads and debris volumes experienced due to climate change or land-use development in the catchment upstream. Hence, there is a need for obsolete weirs and culverts that have become liabilities rather than assets to be rehabilitated, modified or removed entirely to eliminate the costs of maintaining them, avoid the risks of blockage or failure of structures that are either under-designed, dilapidated or abandoned.

Meander restoration

Meandering is a form of slope adjustment with a sinuous channel path leading to a decrease in the channel gradient relative to the downstream slope of the watercourse. Meander planform and cross-sectional geometries depend on hydraulic and geomorphological parameters such as water depth, flow velocity and sediment transport. Meander restoration consists of reconstructing meandering channels that have been straightened or channelised in the past using Grey river engineering measures and techniques.

Changing bed levels

This technique consists of modifying the river bed elevation by dredging or refilling, creation of pools and ripples or protecting the surface to maintain bed levels. Restoring the bed elevation of an incised channel to reconnect the river to its floodplain is an effective and increasing popular technique in river restoration globally.

Regrading of banks (or re-profiling)

This technique involves excavating and/or back-filling a stream bank to an appropriate slope. This is often done in combination with other techniques including installation of bank and toe protection. When re-vegetating a tall bank to relatively steep angles (of the order of 1V:3H or higher) or a river cliff, creating a stepped profile is often a more appropriate approach than regrading.

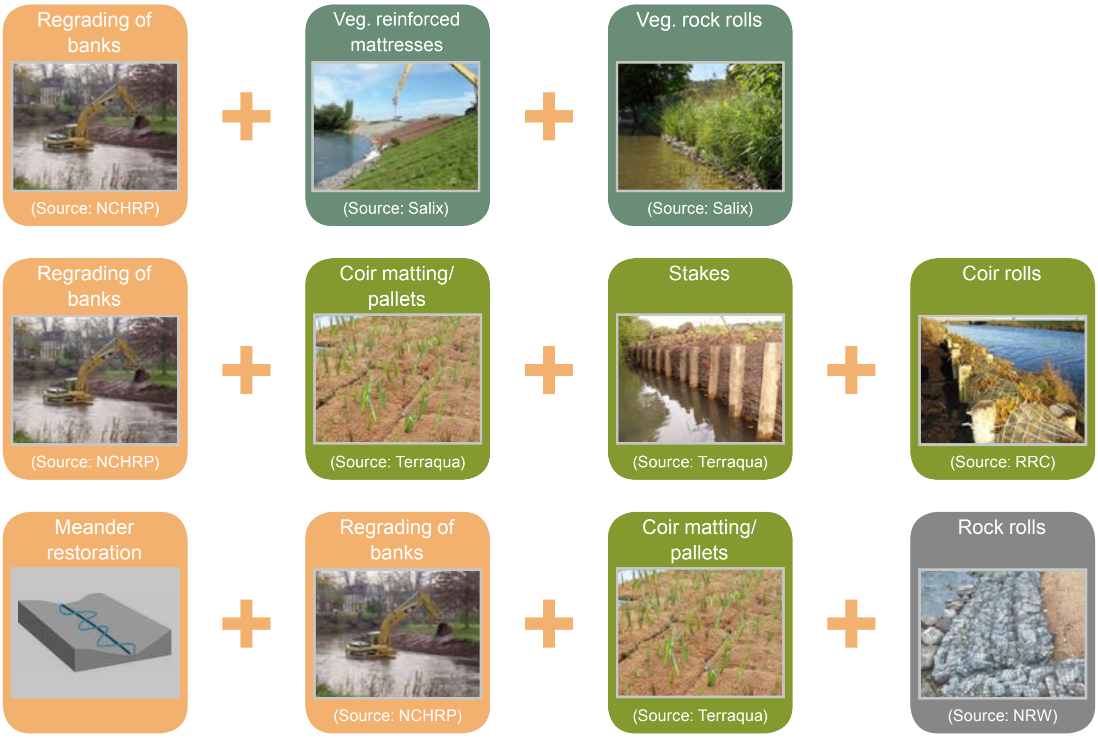
Widening/narrowing

This technique consists of modifying the channel width by means of dredging, re-profiling of the banks or applying in-stream structures to narrow the channel. Objectives of the measure can be to increase the conveyance capacity of the channel by widening it or locally increasing flow velocities to promote habitat diversity by narrowing it.

GI solutions

GI solutions are combinations of one or more measures or techniques. For example, in highly erodible bank material, it would not be sufficient to prevent erosion at the bank (should this be a problem), and some sort of toe protection would normally be required to prevent scour and undercutting. Other examples involve the modification of river shape or restoration of meanders to reduce flood risk.

The following are examples of some common solutions. The Case Studies presented in Chapter 4 show additional solutions with different combinations of measures.



Chapter 3

Decision-support framework

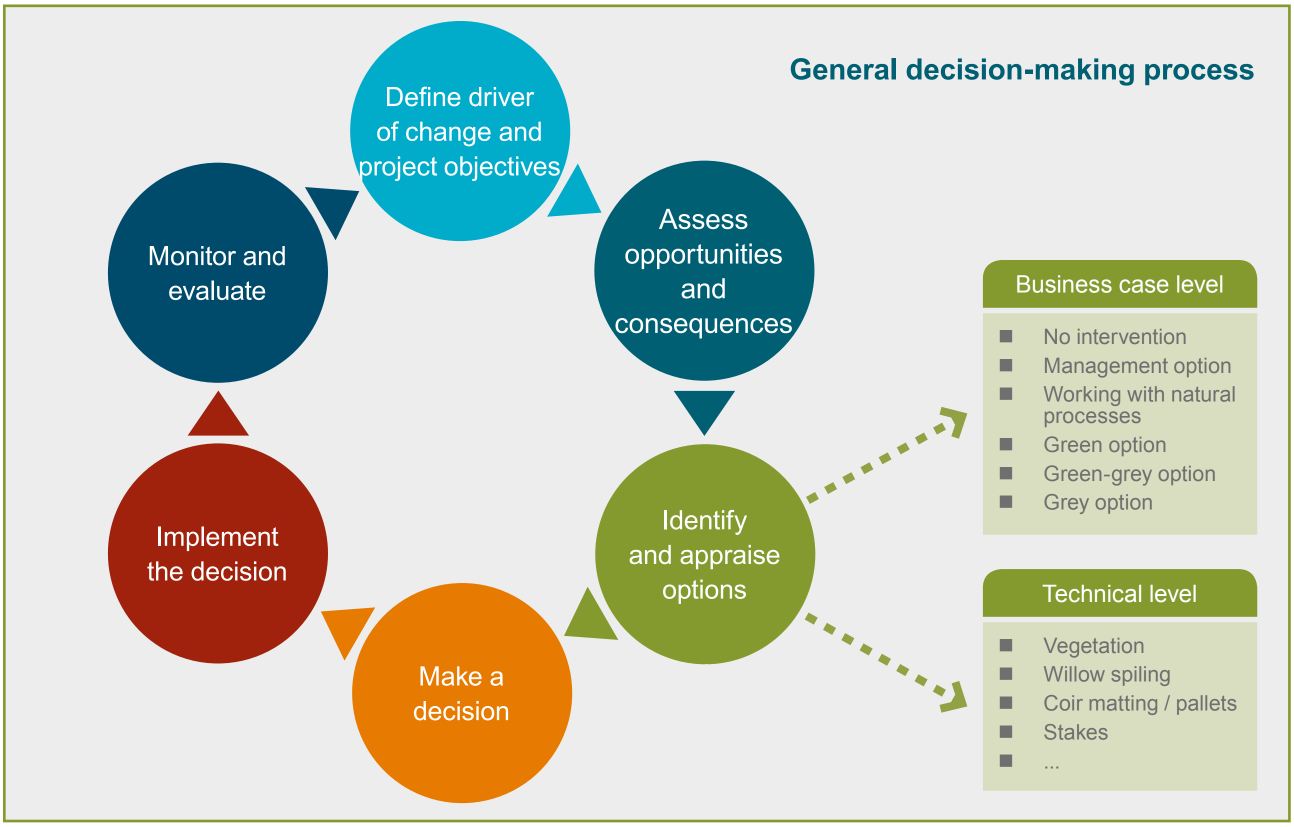
Overall view

A decision support framework covering the entire decision-making process is presented in the figure below. The framework is circular, allowing the decisions that have been implemented to be monitored, with their performance being appraised against the original objectives. The framework is flexible enough to allow general application in the context of a wide range of decisions. Two levels of decision are relevant to GI applications:

- the Business Case level, wherein the purpose is to determine whether an intervention is actually needed and identify the solutions likely to be applicable;
- the Technical level, wherein the purpose is to select and then design the preferred solution.

One of the main differences between the two levels when applying the decision-making cycle is the type of options identified and appraised: while at the Business Case level, the options considered are high level, at the Technical level, these are specific measures or solutions, as defined in Chapter 2. As the purpose of this document is to support consideration of GI approaches, other approaches such as grey measures or Working with Natural Processes are not appraised in detail in the Technical Options Appraisal.

The Business Case Framework presented in the next section provides the basis for ensuring that Green and Green-Grey options are included and properly assessed when considering alternative solutions at the high, Business Case level. If solutions that include Green or Green-Grey measures are selected for technical appraisal, the Technical Framework supports selection of the solution and provides further information that will help to make the selected intervention successful.



Define driver of change and project objectives

Understanding the drivers of change helps to define the best approach and reach the most appropriate solution. For river engineering problems, considerations at catchment scale, i.e. the wider geomorphological context, as well as the particularities at reach scale need to be considered.

Assess opportunities and consequences

The potential consequences of identified problems such as bank or bed erosion as well as the opportunities to improve the current conditions of the site or even the general catchment, should be assessed to help with the identification of measures and their prioritisation.

Identify and appraise options

A number of potential options should be considered and appraised in order to provide a robust basis upon which to make a decision.

Make a decision

Based upon the information provided by the previous step, a solution is selected that meets the objectives set up by the project.

Implement the decision

Depending on the decision-making context, implementing the preferred option may involve financial expenditure, ensuring stakeholder involvement or design of intervention.

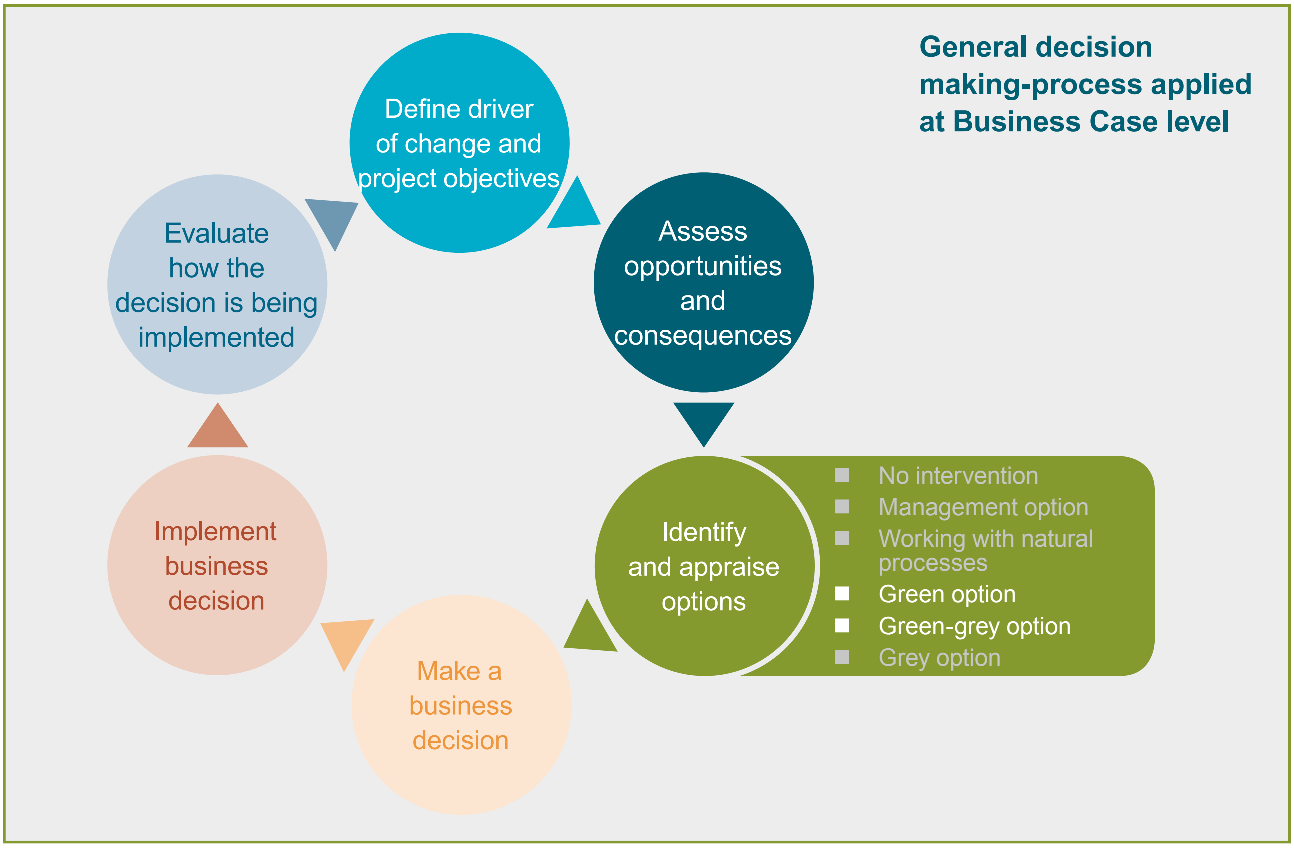
Monitor and evaluate

The impacts of the decision taken are monitored in order to appraise them against the original objectives of the project. The information should also be used to inform future decisions on maintenance and adaptive management.

Business Case framework

The purpose of the Business Case is to support the investment decision by setting out the basis for the project and helping to provide evidence that the project offers value for money. The Business Case framework presented here is based on the principles behind the Business Case forms of the Environment Agency but these principles are sufficiently general to allow wide application. The generalised decision cycle described above is further explained here, taking into account the type of decision made at this level.

Advice is provided here for the first three steps of the decision-making cycle. The information provided focuses on supporting the application of Green and Green-Grey measures (highlighted in the figure). The character of the second half of the decision-making cycle (Stages 4 to 6) is unique to the organisation making the decision, which may be a public or a private body, and hence it cannot be generalised for presentation here.



Decision-making stages

STAGE 1: Defining driver of change and project objectives

Understanding why an intervention is being considered, for example whether it is to solve a bank erosion problem or to reduce flooding, is the first step in identifying the best approach and selecting the most appropriate solution.

When GI approaches aim to change the river cross-section, it is necessary to understand the river morphology: how bed and banks may change over time, the type of sediment that is representative of the river bed and banks, etc. Therefore, the basin scale (the catchment context) should be considered, as well as the reach and site scales. For example, any approaches that will change the river cross-section or stabilise a retreating bank, may have an impact on fluvial processes (i.e. sediment transport) or channel morphology (i.e. planform evolution). Chapter 5 provides references to support geomorphological assessment of fluvial processes and landforms.

As a first step, it is useful to apply a river typology. This helps to characterise the past, current and likely future behaviour of the river. A simple river typology that may be used to initiate a geomorphological assessment is provided in the following box.

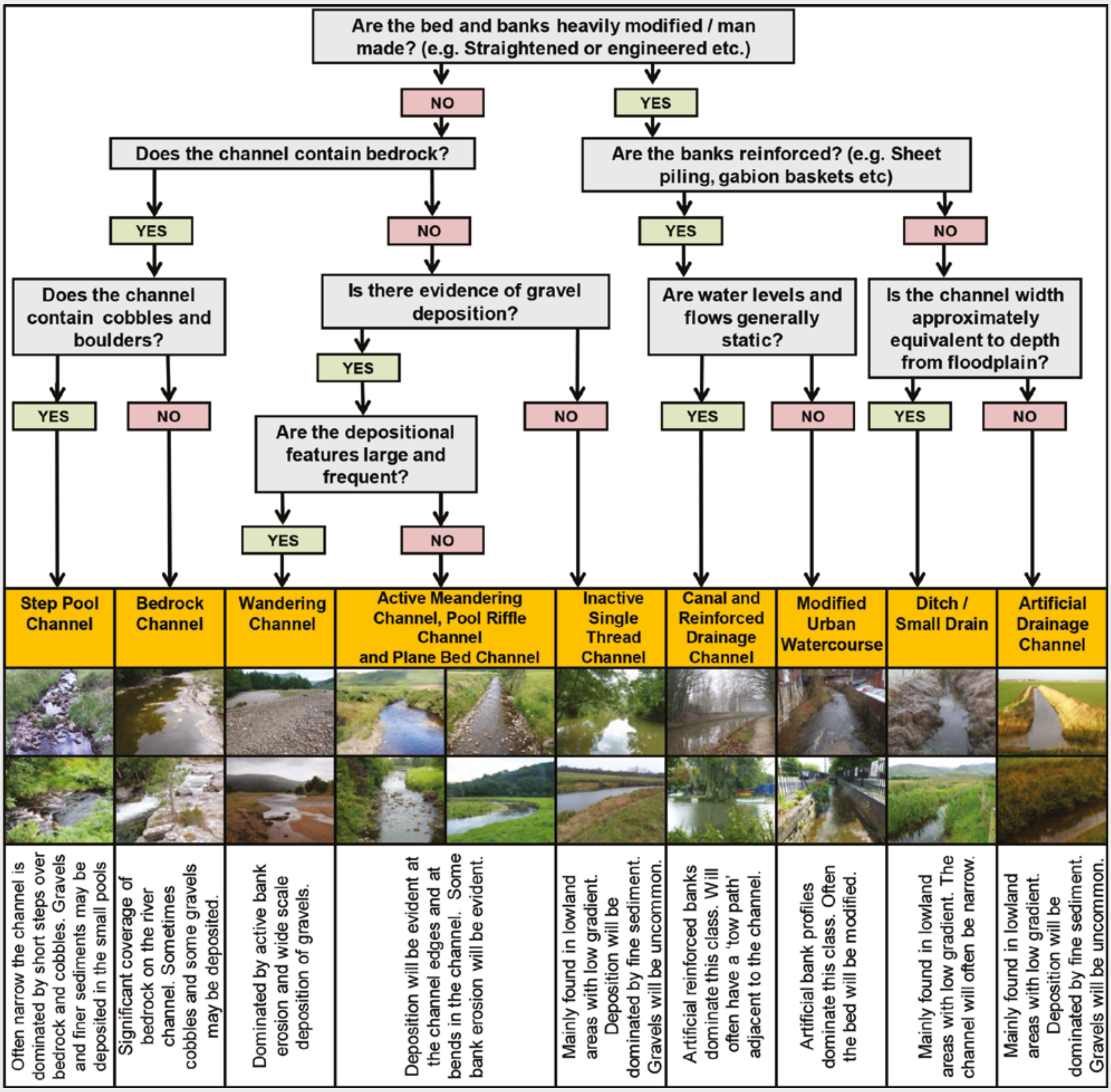
In the particular case of bank erosion, understanding whether the problem is caused by the activities of people or animals, or results from natural processes such as meander migration or general scour during flood events, or a combination of these, informs high level appraisal of alternative solutions. For example, if a bank erosion problem is caused by over-intensive use of the banks by people or farm animals (e.g. angling or uncontrolled grazing), “No intervention” is unlikely to be a good option. Problems caused by human or animal activities on the bank or within the river channel should be best addressed by managing the cause of the problem (people or animals) rather than its symptoms (bank retreat). Examples might employ restricting access to the affected bank using fencing.

In any decision-making process, the aim and objectives of the project must be clearly stated. In the context of this booklet, the aim will be to solve a particular bank erosion or flooding problem. It will often be the case that, at the location where the solution is required, failed or under-performing grey infrastructure will already be in place. If so, the initial assessment should identify options for replacing or rehabilitating the existing bank protection using green or green-grey measures suited to providing a more sustainable, long-term solution.

Understanding the type of river

The geomorphology of a river controls how it behaves naturally and how it is likely to respond to different engineering interventions. River or channel type is defined on the basis of the watercourse’s characteristics, specifically its hydrology, sedimentology and morphology. River typologies and classifications help river scientists and engineers to understand the relationships between fluvial forms and processes, which is the key to explaining the past and present behaviour of the river and causes of the current problem requiring treatment. Further, understanding the type of river being dealt with provides the basis on which to forecast how the river is likely to respond to a new engineering intervention. For these reasons, establishing the river type is an important step in selecting the preferred intervention option. For example, vegetation planted at the toe of an eroding bank in a wandering channel (see typology below) is liable to be undermined by local bed scour or buried by sediment deposition as the planform of the river changes through time. In wandering channels, it is therefore not only essential to use Green-Grey or Grey options at the toe, but also to select plant species that are able to tolerate sedimentation. In all situations, vegetation selected for planting as part of GI approaches on the banks should also be matched to the hydrological stream type (perennial, intermittent or ephemeral) and nature of variability in water surface elevations, in order to ensure that the species chosen has sufficient flood and drought tolerance to survive in the particular hydrological regime.

Here, a simple channel typology (commonly used in several references) is presented.



Source: Flowchart for identifying geomorphic watercourse type extracted from the Environment Agency guidance "Aquatic and riparian plant management: controls for vegetation in watercourses".

Detailed descriptions of each typology can be found in "Aquatic and riparian plant management: controls for vegetation in watercourses" or in the "Channel Management Handbook", both Environment Agency publications (references provided in Chapter 5). Here, only a very brief description of the expected behaviour of the river is provided.

Step-pool channel

Step-pool channels are often confined and lateral movement is restricted. Their high energy conditions enables them to transport gravel, pebbles and cobbles during high flows, but the boulders forming the steps themselves are rarely entrained; therefore, changes in bed elevation are likely limited most of the time. That said, rare but extreme flood events may radically alter both the morphology and elevation of the bed.

Bedrock channel

Bedrock dominated channels are stable and change very little over engineering timescales. Channel changes are confined to those associated with erosion and deposition of pockets of sediment in the lee of bed rock features and areas of slack water.

Wandering channel

Bank erosion can be significant where banks are weak and the floodplain is wide, resulting in channel planform switching between meandering and braided as the river migrates back and forth across the valley floor. Flow may be deflected around large, depositional bars (point, medial or diagonal in shape), resulting in accelerated bank erosion as the bars grow and migrate downstream. Wandering channels are sensitive to changes in the flow and/or sediment regimes as well as artificial alterations to the bed or banks. For example, artificially narrowing a wandering channel may lead to significant bed scour, bank instability and increased sediment mobilisation and delivery to reaches downstream.

Active meandering, Pool-Riffle and Plane bed channels

Channels of these types are also laterally mobile, though the extent and rate of shifting are generally lower than in wandering channels. Bed sediments are mobilised at high, in-bank flows and bank erosion can readily occur as well, especially on the falling limb of the flood, when positive pore water pressures may trigger failure in any poorly drained banks. In meandering channels, near-bank scour and high velocities characteristically focus bank retreat at the outer margins of bends, between the bend apex and exit. In straight and sinuous channels bank erosion is likely to be associated with the formation and growth of median and alternate bars. Woody debris, if present, naturally tends to stabilise bars in situ, trapping additional sediment and increasing bar heights, while accentuating local scour at the head and along the flanks of the bars in ways that can accelerate bank erosion.

Inactive single thread channel

These channels are associated with low energy rivers that are generally stable, although changes in the catchment leading to increased sediment input may lead to depositional instability. The banks are often cohesive, further restricting lateral movement.

Canal and reinforced drainage channel

Flows and levels are typically steady and uniform, meaning that very little channel change is expected. Instability may, however, result from changes in sediment input that result in net sedimentation.

Modified urban watercourse

Urban watercourses are generally stabilised using Grey measures although lack of maintenance can lead to instability, especially where sediment loads are high or vegetation is allowed to choke the channel. Urban streams can be characterised by high velocities, for example in reaches where the channel is concrete lined.

Ditch/small drain

These are generally stable systems, with low energy flows that are unable to entrain the bed or erode the banks. However, they have the potential for high rates of sedimentation and will become unstable unless frequently maintained.

Artificial drainage channel

Like ditches, these are generally stable systems, with low energy flows that are unable to entrain the bed or erode the banks. However, they have high potential for significant sedimentation and will become unstable where and when sediment inputs are high, unless dredged by their owner or the operating authority.

STAGE 2: Assessing opportunities and consequences

The main opportunities for implementing GI approaches derive from the additional benefits these approaches provide in relation to environmental, social and cultural aspects (or ecosystem services). The statutory framework in UK provides an excellent opportunity to support the case for implementation of GI approaches because it:

- advocates a sustainable management of the environment; for example Natural Resources Wales is under a duty to pursue sustainable management of natural resources;
- encourages more integrated approaches to tackling environmental, economic and societal issues, seeking solutions that deliver multiple benefits whilst increasing resilience;
- acknowledges that a healthy and resilient environment helps sustain people and economy;
- promotes good ecological status of watercourses.

Therefore, existing regulation and rules as the ones shown in the box below, setting the duties and responsibilities of public bodies such as the Environment Agency, Natural Resources Wales, Internal Drainage Boards, Lead Local Flood Authorities and Local Authorities, can be used to support the use of GI approaches.

In addition, there are several conservation designations that procure protection of particular areas for their special landscape and/or biodiversity importance and therefore, provide a strong case for using GI approaches to river engineering measures located in those areas. Examples of these conservation designations are: Areas of Outstanding Natural Beauty, Sites of Special Scientific Interest (SSSI), Special Areas of Conservation, Natura 2000 sites, etc. However, in many of these sites any actions are severely restricted.

There is also planning policy, for example at regional level through the Draft Regional Spatial Strategies, that requires local planning authorities to incorporate GI approaches into their own policies and plans. More information can be found in TCPA (2008).

Existing regulations

<table>
<tr><th>Flood risk management</th><th>Nature conservation</th><th>Ecological improvement</th><th>Others</th></tr>
<tr><td>Floods Directive 2007/ Flood risk regulations 2009
Flood and Water Management Act 2010
Water Resources Act 1991</td><td>Habitats Directive 1992
Wildlife in Countryside Act 1981
Countryside and Rights of Way (CROW) Act 2000
Natural Environmental and Rural Communities (NERC) Act 2006
Conservation of Habitats and species regulations 2010</td><td>Water Framework Directive 2000 / Water Environment (Water Framework Directive) (England and Wales) Regulations 2003</td><td>Well-being of Future Generations Act
Principles of Sustainable Development
National Planning Policy Framework</td></tr>
<tr><td colspan="2">Land Drainage Act 1991</td><td></td><td></td></tr>
</table>

The Water Framework Directive (Directive 2000/60/EC) is concerned with improving the ecology and water quality of water bodies, including rivers, watercourses, coastal waters, lakes and canals. The Directive requires the establishment of river basin districts and plans, which set out environmental objectives and when they should be achieved. The achievement of the environmental objectives depends upon the ecological status of the waterbody (high, good, moderate, poor or bad) or, in the case of heavily modified or artificial water bodies, upon its ecological potential.

There are strong links between the Water Framework and the Floods Directive, and GI approaches can satisfy the requirements of both.

The potential consequences of identified problems (e.g. bed or bank erosion) should be assessed to help with the identification of measures and their prioritisation.

The following table provides a list of areas where possible consequences of bed/bank erosion related problems should be considered. In a preliminary assessment they can be estimated as important, moderate or severe based on judgement of local conditions.

Consequences to	Description
Residential and non-residential properties	Through loss or damage to properties including gardens and allotments
Structures	Through loss or damage to bridges, weirs, sluices, locks, pumping stations, etc
Communications/ infrastructure	Through loss or damage to footpaths, roads, railways, navigation, etc
Agriculture	Through loss of forest, pasture, arable land
Bank and floodplain users	Through interference with ramblers, bathing, anglers, heritage, boating
Environment	By reducing aesthetic value, habitat diversity, water quality
Cultural/heritage sites	Through loss of invaluable assets and public amenities

STAGE 3: Identifying and appraising options

At the Business Case level, the options identified are the ones defined in the figure below. “No intervention” and “Management option” favour natural adjustment of the river and, where appropriate, these are the most sustainable and cost-efficient approaches.

No intervention

The “No intervention” option is a strategy that allows the natural adjustment of the watercourse and therefore, it is the most sustainable solution in many cases. This should always be applied when natural processes are likely to constitute a natural solution to the problem. This option is only possible if the river has the ability to adjust within a designated river corridor within which fluvial processes can operate. When this solution is selected, it is advisable to monitor the site subsequently, to detect whether any unexpected, adverse trends may develop. A ‘No intervention’ decision must be fully explained to stakeholders. For example, the owners of the land lost when a bankline is allowed to adjust naturally may otherwise feel that their land is being ‘sacrificed’ to the river.

Management option (non-engineering)

This strategy is based on addressing the causes of the problem particularly when they are related to the actions of people or animals. This option may be preferred because it involves changing the damaging behaviours of the perpetrators of the problem (the people or animals) rather than trying to protect the river from them, which imposes further, collateral damage on the ecosystem and natural environment. Generally, management solutions are much less costly than engineering ones. Management options may involve a wide variety of interventions including, for example, public education, working with communities, fencing, regulation of boat speeds, mooring restrictions, tree management or simply relocating the activities that are causing the problem.

Working with Natural Processes

Working with Natural Processes (or Natural Flood Management) is defined as ‘ taking action to manage fluvial and coastal flood erosion risk by protecting, restoring and emulating the natural regulating function of catchment, rivers, floodplains and coasts’ (extracted from EA, 2014a). Offline storage areas, river restoration, catchment and riparian woodlands are examples of this type of intervention.

Green and Green-Grey solutions

The Green and Green-Grey measures considered in this document are described in Chapter 2. They are combined to provide GI solutions.

Grey solutions

Grey measures use angular rock (riprap) and artificial materials such as concrete, steel and plastic to create surface protection and rigid structures to prevent bank retreat but offer few or no environmental, societal or cultural benefits or amenity.

Critical success factors

Options appraisal usually involves the assessment of the performance of alternative solutions. This hinges on whether the solution is able to meet the aim and fulfil all of the objectives for the project by addressing the causes rather than the symptoms, considering the consequences of taking no action, and assessing the risks, costs and benefits of implementing each of the candidate options. Familiarity with conventional approaches, reluctance to innovate or risk aversion may make decision makers reluctant to implement GI approaches. Conversely, decision makers who are forward thinking, early adopters of innovative approaches may be highly motivated to implement GI. Therefore, positive infrastructure performance, low costs and multiple benefits, together with decision maker motivation are the success factors necessary to delivery of GI solutions. These factors, and the risks associated with each of them, are described in the text below.

Motivation

There is evidence that many existing schemes incorporating green solutions were driven by highly motivated organisations or individuals. Given the current lack of regulation in this area, high motivation for considering the use of green options and to take the project to completion is often essential.

Despite the lack of legislation, green solutions are strongly encouraged by most funding bodies and therefore, they are likely to be considered more acceptable than conventional grey solutions as they support the achievement of policy objectives (as described in STAGE 2).

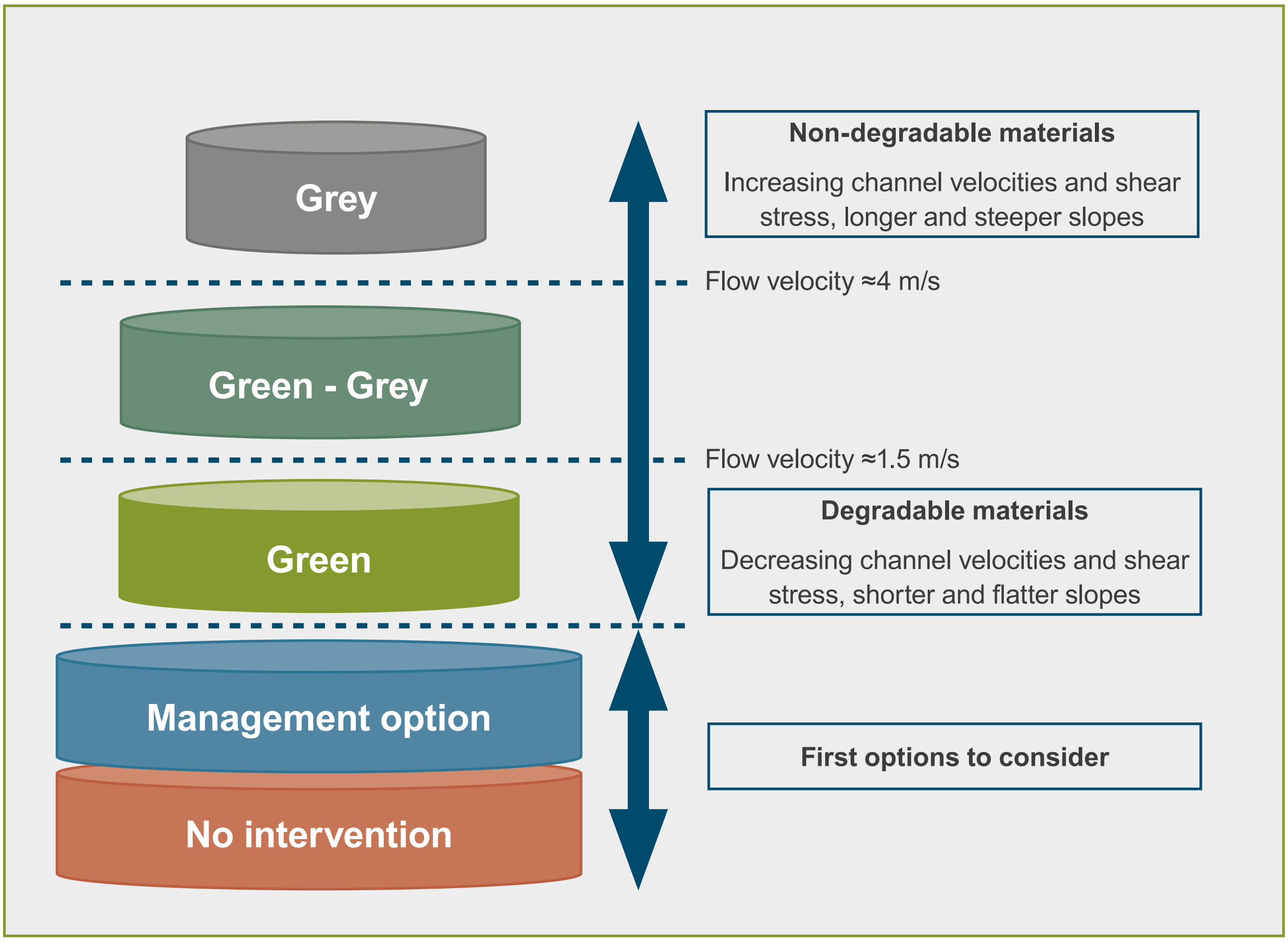
When implementing GI measures it is vital to engage with the stakeholders, communities, and individuals affected by the engineering work. Collaboration rather than consultation is required to overcome a general distrust of 'soft engineering' in both rural communities and urban neighbourhoods.

Engineering performance

As green measures have been traditionally assessed mainly for their environmental performance, it is fundamental for their credibility and uptake by designers that the engineering performance of these measures satisfies design specifications. Some of the strengths of GI approaches are:

- There is evidence that GI approaches are effective in protecting the bank and reducing flow speeds under a range of flow conditions
- They can be combined in existing schemes and with grey approaches
- Value and function may increase over time, including ecosystems benefits.

The following figure shows the likely applicability of the Green, Green-Grey and Grey options based on the river characteristics.



One important aspect when assessing engineering performance relates to maintenance. The need for maintenance and its perception as potentially "troublesome" is often a hindrance to the uptake of GI approaches. However, as Green and Green-Grey measures are living systems, it has to be recognised that some level of maintenance will be necessary (it is also noted that some level of maintenance is often required for Grey measures). If this aspect is neglected, it can have severe impact on the flow conveyance of the river and on the degree of protection offered.

Some of the strengths of GI approaches are:

- They are completely or partially self-sustained
- The general public can be involved in scheme maintenance when this does not require specialised skills.

As for all types of scheme, GI schemes require quality of construction and attention to detail (e.g. if live materials are being used these need to be kept under certain conditions to have a chance of establishing).

Benefits (or ecosystem services)

Apart from fulfilling the aim and objectives of the project which in the context of this booklet are related to river engineering interventions, there are a number of additional co-benefits (ecosystem services) that GI approaches create. These fall into the categories of economic, environmental, social and cultural benefits.

The main strengths of GI approaches are that they:

- improve wildlife and fish spawning habitats;
- contribute to improving water quality and biodiversity;
- help to establish or restore natural processes;
- integrate into the natural landscape better than grey solutions;
- improve the aesthetic and recreational values of the bank and river;
- are relatively new approaches that can be used as pilots to support future implementation and achieve a change in mindset;
- promote community engagement involving collaboration and cooperation;
- facilitate public participation in decision-making;
- can be used for education and research;
- contribute to improving people's well-being.

As example, the following table, adapted from USACE (2000) shows the additional environmental benefits provided by different types of measure.

	Green	Green-Grey		Grey	
	Vegetation	Vegetated reinforced soil	Turf reinforced mattresses	Riprap	Sheet piles
Wildlife access	Beneficial	Neutral to beneficial	Neutral to beneficial	Neutral to detrimental	Detrimental
Aquatic habitat complexity	Neutral to beneficial	Neutral to beneficial	Neutral	Neutral to beneficial	Detrimental
Vegetation habitat complexity	Beneficial	Neutral to beneficial	Neutral to beneficial	Neutral to detrimental	Detrimental
Shade, temperature	Neutral to beneficial	Neutral to beneficial	Neutral	Neutral to detrimental	Detrimental
Cover, refugia	Neutral to beneficial	Neutral to beneficial	Neutral to detrimental	Neutral to beneficial	Neutral to detrimental
Pollutant removal	Beneficial	Beneficial	Beneficial	Neutral to detrimental	Neutral to detrimental
Sediment capture	Beneficial	Beneficial	Neutral to beneficial	Neutral to beneficial	Neutral to detrimental

Key

Beneficial | Neutral to beneficial | Neutral | Neutral to detrimental | Detrimental

Definition of ecosystem services

These are the benefits that people derive from the natural environment. Examples of ecosystem services are those related to tangible physical goods such as food and wood, to the environment such as air quality and climate regulation or to cultural/social services such as recreation, health and wellbeing and public engagement with a site or asset. Compelling evidence of the way in which ecosystem services underpin our economy is detailed is several multi-disciplinary studies: Millennium Ecosystem Assessment (2005), the National Ecosystem Assessment (NEA), the Economics of the Environment and Biodiversity (TEEB) and the State of Natural Capital reports.

Costs

When compared with conventional solutions, GI approaches are often associated with lower capital costs and a wider range of benefits (as well as possibly higher maintenance costs). The quantification of all these costs can help build the case for GI measures on the basis of costs as well as environmental value. In general:

- GI approaches may be one with the lowest whole-life costs
- As GI measures provide multiple benefits, they can deliver greater benefits and be more cost-beneficial than grey solutions
- They can be financially supported by a wide range of public subsidies or other funding mechanisms.

As example, the following table summarises relative costs extracted from USACE (2000). More information on costs is provided under the Technical support framework.

Measure	Relative cost
Live stakes	Low
Live fascines	Moderate
Brush mattresses	Moderate
Vegetation	Low
Riprap	Moderate-High

Any consideration of the merits of different available options will inevitably be based, either implicitly or explicitly, on the costs of these options and how these costs compare to the benefits. Where a business case needs to be made, either internally or in consultation with partners, it is likely that a transparent assessment, which makes these costs and benefits explicit, will be required.

The key steps in any economic assessment are shown and described below. It is likely that specialist economic input will be required to ensure that these steps are applied in a robust and consistent way.

1. Define decision to be made → 2. Identify and set out baseline → 3. Set out options for assessment → 4. Describe and assess impacts of options → 5. Bring results together

1. Define decision to be made

If the decision is to be based on minimised costs alone, then a cost-effectiveness assessment is required. This should specify whether this is based on capital costs alone, or whole-life (capital, operation and other) costs and, if the latter, the timescales of the assessment. If benefits are also to be considered, a cost-benefit assessment is needed. The type and scope of benefits needs to be agreed (e.g. private benefits only, or public benefits as well). Other factors to consider here are the decision criteria to be used (e.g. net present value, benefit-cost ratio), distributional considerations (costs and benefits will fall on different parties in different locations and at different times), managing uncertainty and how non-monetary information is used.

2. Identify and set out baseline

Consideration of the baseline situation is important as it is against this that options should be assessed consistently so that a like-for-like comparison can be made. This should take account of both the existing situation and any drivers likely to impact on the project over its lifetime (e.g. growth, climate change).

3. Set out options for assessment

All feasible options should be clearly set out and described in relation to the baseline. In the context of this booklet the options to be included are 'No intervention', 'Management (non-engineering) option, Green, Green-Grey and Grey and, potentially, some combination of these options.

4. Describe and assess impacts of options

All key impacts on all stakeholders (including the general public), both positive and negative, likely to arise from the options should be considered consistently within a clear framework that minimises the risks of double counting and additionality (where impacts would have occurred anyway, regardless of the option being implemented). A staged, proportionate approach should be adopted, with impacts screened to identify those of relevance/significance for any given option. It should then move from a qualitative description and/or scoring of impacts to (where appropriate and supported by available evidence) quantitative assessment and finally monetary valuation. Valuation should be undertaken with care, based on appropriate techniques and good practice, and with appropriate economic support.

5. Bring results together

This involves aggregating and presenting costs and benefits across relevant impact categories, geographical areas, impacted communities and over time. As such, it needs to consider appropriate timescales, discount rates and any other key parameters. The costs and benefits of different options should be compared consistently so that the most favourable option can be recommended. Costs and benefits can be presented in different ways (e.g. benefits can be displayed in a benefits wheel).

Uncertainty should be explicitly addressed. For example, costs and benefits can be presented in ranges. Sensitivity analysis should be used to assess the extent to which key parameters and values might change with different assumptions or scenarios, and what difference this would make to the result. Techniques used to explicitly capture non-monetised impacts in the assessment include the use of implied, imputed or switching values. Where appropriate, modifications to the options can be considered which would increase benefits and/or reduce costs.

Risks

When an intervention is being considered the associated risks of such intervention should be assessed in order to develop the right solution and it has to be recognized that GI approaches are not applicable in all circumstances. The following table provides a list of possible risks associated with each of the success factors discussed above.

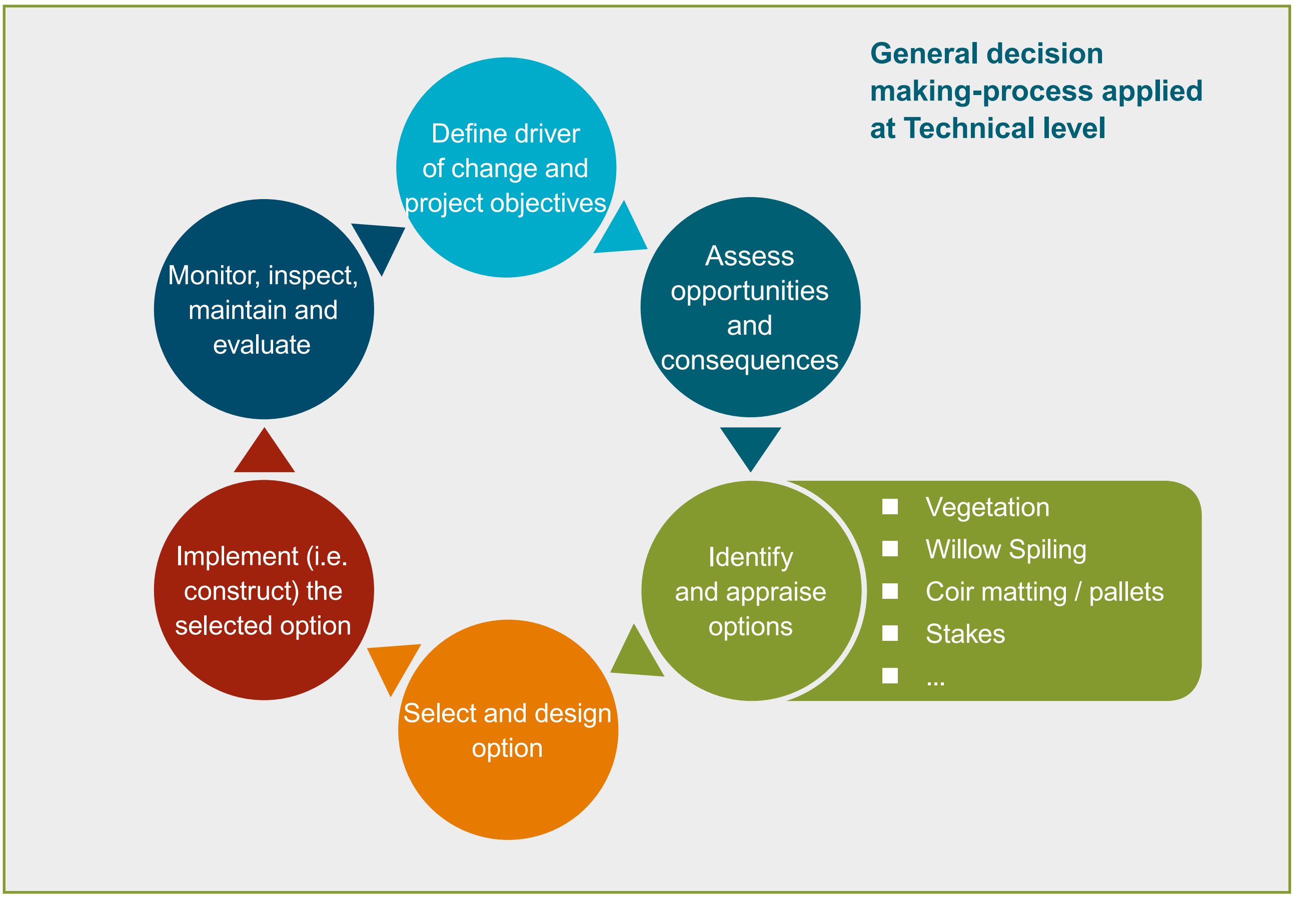
Success factors		Sources of uncertainty
Motivation		■ Governance arrangements such as levels of responsibility and required follow-ups can be unclear ■ It can be difficult to obtain permits or regulatory approvals ■ Lack of public engagement and/or understanding of the benefits of green measures
Engineering performance		■ Evidence of performance is often related to particular site conditions and, therefore, there is very little evidence of the general applicability of these measures ■ Engineering community has little expertise in designing them ■ It is unlikely that they will perform satisfactorily in environments with high velocities and high river energy or under extreme weather conditions although they may be part of the solution in less exposed areas ■ Vegetation growth may cause difficulties in inspections of nearby structural assets and, therefore, maintenance would be required ■ Implementation time to ensure a complete establishment of the measure to provide the required functionality may be long (years)
Costs		■ There is limited information about the whole life costs of various GI measures
Benefits (or ecosystem services)	General	■ Ecosystem services are currently not comprehensively valued and quantified as part of technical evaluations ■ There is a lack of recognised ecosystem design standards
	Environmental	■ Potential negative aspects may be linked to the growth of invasive species
	Social	■ Public may perceive the measure as less safe than conventional Grey options

Technical support framework

Overall view

The Technical Support framework aims to support the implementation of a selected GI measure or solution. The options considered in this booklet are those described in Chapter 2.

The general decision cycle is detailed here taking into account the type of decisions made at this level.



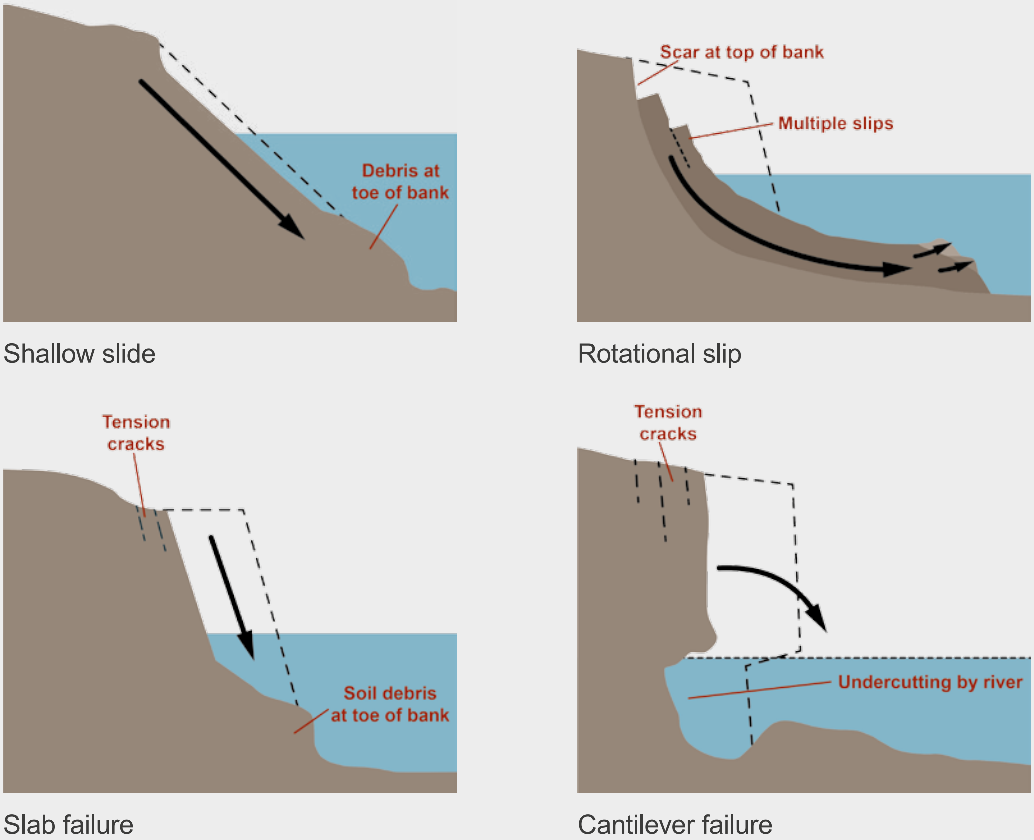
At this technical level, it is necessary to take into account the success factors that can minimize the risks, and thus, the consequences, of a potential failure. A list of technical conditions for success has been developed to help the user select and apply a successful intervention using the measures described in Chapter 2. They are presented in the table below, which highlights the stage in the decision-making cycle at which they are likely to be relevant. Detailed descriptions, recommendations and examples for each of these success factors are provided later in this chapter. In some cases, a simple check of the technical condition could be sufficient; in others, more detailed studies, involving for example collection of new data or some calculations, may be required.

Technical conditions for success	Stage 1 - Drivers of change	Stage 2 - Opportunities and consequences	Stage 3 - Appraisal of options	Stage 4 - Select and design option	Stage 5 - Implementation (construction)	Stage 6 - Monitoring, maintenance and evaluation
Geomorphological assessment	✓		✓			
Loading conditions	✓	✓	✓	✓	✓	✓
Spatial implementation			✓	✓	✓	✓
Selection of species		✓	✓	✓		
Sizing of material				✓		
Design of transitions				✓		
Design of bank slope			✓	✓		
Provision of filters and/or drainage				✓	✓	
Scour and toe protection			✓	✓	✓	
Time of year of implementation		✓	✓		✓	
Condition of live species					✓	
Installation					✓	
Avoidance of diseases					✓	✓
Human and animal access to the bank			✓	✓	✓	✓
Light			✓	✓	✓	
Deterioration of material			✓	✓		✓
Control of vandalism				✓		✓
Maintenance				✓		✓

STAGE 1: Defining drivers of change and project objectives

At this stage, it is assumed that as a minimum, the type of information required for the Business Case has already been collected. This implies understanding the causes of the problem taking into consideration the wider catchment context. However, at this technical level, more detailed information is likely to be required.

For example, in the particular case of bank failure, understanding the type of failure (shallow slide, rotational slip, slab-type or cantilever), should help to define the problem and, hence, the preferred solution. For example, regrading is likely to be necessary in banks that are prone to either slab-type or cantilever failures. It is important to recognise that geotechnical bank instability cannot be addressed solely by provision of erosion protection measures (including GI) and geotechnical investigations and other measures may be necessary.



Sketch of typical bank failures. Dotted line represents original profile. Arrows indicate the direction of movement.

When assessing the causes of the problem, a more detailed understanding will be needed. At this level, some understanding of hydraulic parameters such as channel water levels, groundwater level and flow velocities, will be required to be able to assess the different options.

STAGE 2: Assessing opportunities and consequences

The main opportunities to apply GI measures related to the statutory framework should have been identified when assessing the Business Case. Under the Technical framework, more detail may be needed about current legislation and special designation areas to ensure that the selected option complies with the applicable laws and statutes.

The more detailed understanding of the causes of the problem gained in Stage 1, should help to better define the possible consequences of the problem assessed such as loss of land or access to the banks and damage to properties and infrastructure.

STAGE 3: Identifying and appraising options

At this stage, the possible options for Green and Green-Grey measures (including the river management techniques) defined in Chapter 2 are assessed to identify those most suitable for the conditions of the site.

A series of diagrams and flowcharts is presented to gain insight of the likely measures applicable under different conditions. While these aid decision making, they are not a definitive decision tool as local issues and conditions must also be assessed and the engineering judgement of the decision maker also plays a role in good decision making.

The diagrams and flowcharts are based on recommendations provided in existing guidance. As the aim of this document is to be brief and focused, these recommendations have necessarily been summarised. Consequently, the information presented here does not cover all the possible alternatives. For example, in a high energy river with a steep bank and land use constraints that limit available space, the flowchart suggests use of willow spiling. However, other measures may also be applicable, depending on local conditions.

The first flowchart shows the likely measures to be applied depending on the type of action that it is necessary to undertake to address the problem. The other flowcharts provide decision trees to select *a priori* the most suitable options to protect the bank face and toe, including modifying the morphology of the channel using engineering techniques, if necessary. In applying these flowcharts, users must factor in their understanding of local conditions as well as their personal motivation to blend the appropriate mix of Green, Green-Grey and Grey measures with the right amount of channel modification, employing sound engineering judgement throughout the decision making process. The properties and capabilities of any specified product should be confirmed with the material provider at the design stage.

Bank protection

Coir matting/ pallets

(Source: Terraqua)

Willow spiling

(Source: Salix)

Stakes

(Source: Terraqua)

Vegetation

(Source: RRC)

Veg. concrete blocks

(Source: NCHRP)

Geo Cell Systems

(Source: Terram)

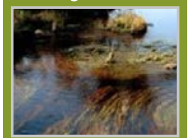
Veg. reinforced earth

(Source: Filtrex)

Veg. reinforced mattresses

(Source: Salix)

Toe protection

Aquatic vegetation

(Source: Painet)

Rock rolls

(Source: NRW)

Veg. rock rolls

(Source: Salix)

Bank and toe protection

Coir rolls

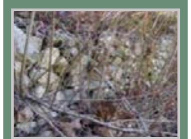
(Source: RRC)

Faggots/ fascines/brushwood

(Source: Salix)

Woody material

(Source: NCHRP)

Veg. gabions

(Source: NCHRP)

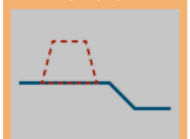
Veg. riprap

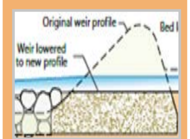
(Source: NCHRP)

Geotextile

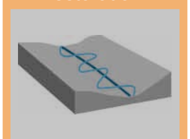
(Source: NCHRP)

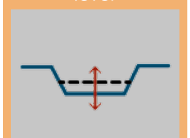
Modify river shape

Embankment removal


Lowering/removal of weirs & culverts


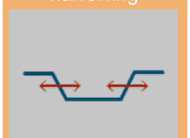
(Source: NCHRP)

Meander restoration


Changing bed level


Regrading of banks

(Source: NCHRP)

Widening/ narrowing


Bank protection

High energy river? (e.g. bankfull velocity > 3 m/s, coarse bed material like cobbles and/or steep slopes)

Yes

Bank slope >45° or limited space available?

Yes

Veg. reinforced earth

(Source: Filtrex)

+ Long lifetime
+ Mass slope failure mitigated
- Complex
- Labour intensive

Veg. gabions

(Source: NCHRP)

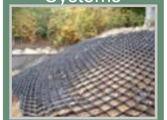
+ Common technique
+ Bank & toe
- Limited lifetime and not as flexible as its direct alternatives

\+

Geotextile *

(Source: NCHRP)

Geo Cell Systems



(Source: Terram)

+ Flexible
+ Large schemes
- Bank slope <60°
- Susceptible to infill wash-out and construction errors

\+

Geotextile

(Source: NCHRP)

No → Bank subject to considerable waves (> 0.15 m)?

No

Bank slope >45° or limited space available?

Yes

Willow spiling

(Source: Salix)

+ Quick establishment
+ Strength grows over time
- Terrace height max. 1m

No

Does the river transport fine sediment and is accretion desirable?

Yes

Faggots/ fascines/brushwood

(Source: Salix)

+ Successful in tidal conditions
- Reduced life when expos. to air

\+

Stakes

(Source: Terraqua)

No

Will the bank be exposed to the river flow before the end of the first growing season?

Yes

Coir matting/ pallets

(Source: Terraqua)

+ Immediate cover
+ Low complexity
- Limited lifetime
- Requires good fixing to ground

\+

Stakes *

(Source: Terraqua)

No

Vegetation

(Source: RRC)

+ Cheap
+ Strength grows over time
- Vulnerable to trampling
- Strength during winter

Bank subject to considerable waves (> 0.15 m)?

Yes

Veg. rock rolls

(Source: Salix)

+ Can be pre-filled
+ No large rock req.
- Not applicable for high bank load
- Possible need for anchoring

Veg. riprap

(Source: NCHRP)

+ Flexible
+ Level of protect. after failure
- Amount of rock
- Rock size

Veg. concrete blocks

(Source: NCHRP)

+ Strength
+ Known properties
- Aesthetics
- Danger of outflanking

\+

Geotextile *

(Source: NCHRP)

No

Veg. reinforced mattresses

(Source: Salix)

+ Resistance to high velocities
+ Allows high conveyance
- Need for proper fastening
- Transitions

Woody material

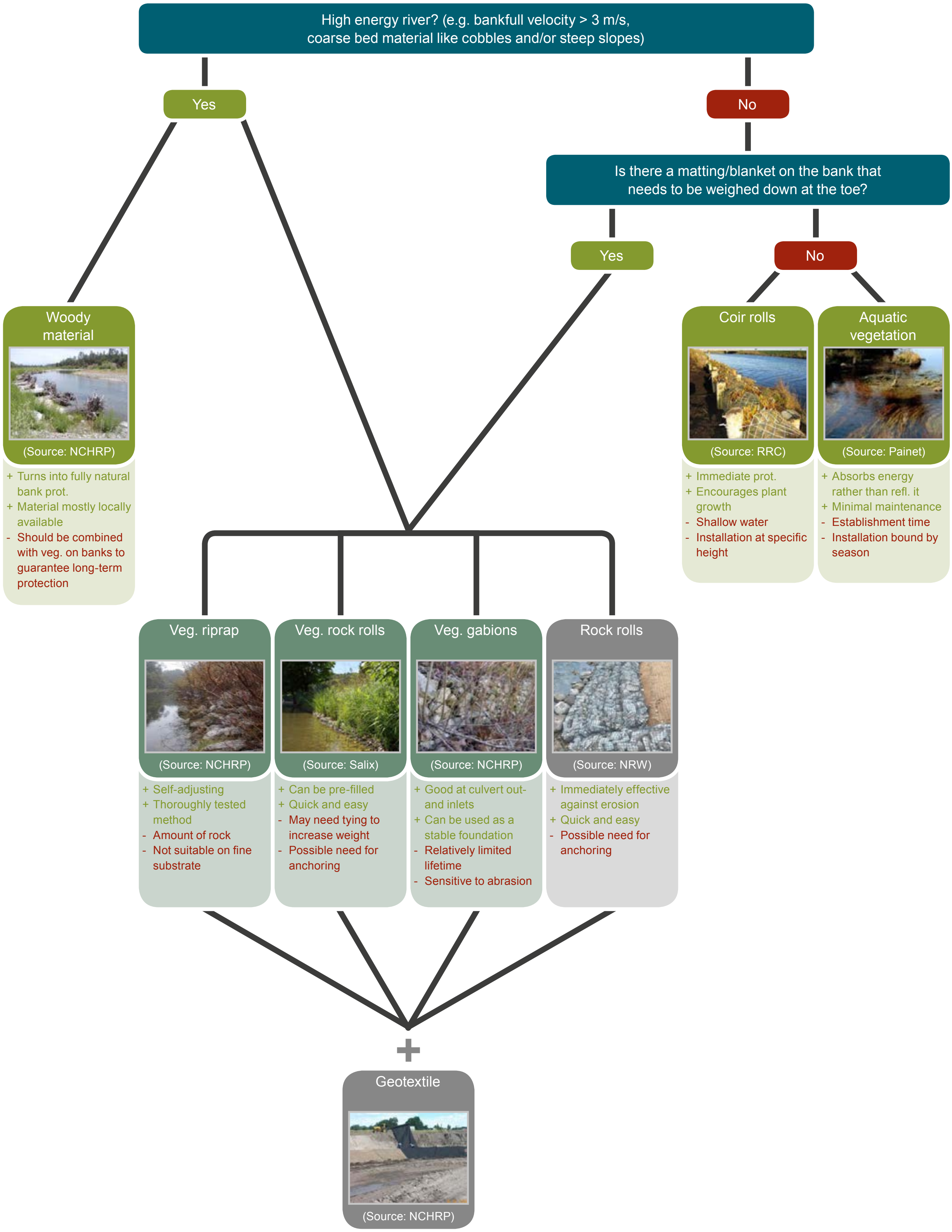
(Source: NCHRP)

+ Resistance to high velocities
+ Allows high conveyance
- Need for proper fastening
- Transitions

* The ‘ transparent’ geotextile measure is optional; it depends on the local conditions. It may be combined with other measures wherever appropriate and feasible.

This flowchart is only to be used to gain insight into likely applicable measures. It is strictly NOT a definite decision instrument and local conditions always need to be taken into account.

Toe protection



* The ‘ transparent’ geotextile measure is optional; it depends on the local conditions. It may be combined with other measures wherever appropriate and feasible.

This flowchart is only to be used to gain insight into likely applicable measures. It is strictly NOT a definite decision instrument and local conditions always need to be taken into account.

Modify river shape

Ask yourself these questions (one does not exclude the others!)

Are the banks unstable due to their slope? Do they need re-profiling in order to implement bank or toe protection?

Yes

Regrading of banks

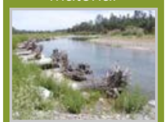
(Source: NCHRP)

+ Mitigates slope instability
+ Smaller gradient slopes are more easily vegetated
- Usually has to be combined with toe and bank protection
- Requires access during construction

Does the flow need to be redirected or deflected away from the banks?

Yes

Woody material



(Source: RRC)

+ Material can be locally sourced
+ Creates valuable aquatic habitat
- Requires anchoring against flow and buoyancy forces

Does the conveyance need to be adjusted?

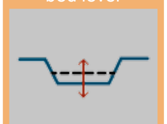
Yes

Widening/ narrowing

+ Changes velocities and sediment transport capacities
+ More effective against siltation than changing the bed level
- Laborious when banks are protected/ strengthened
- Limited lifetime when there's no sediment transport equilibrium

Or

Changing bed level



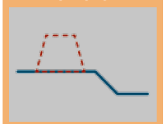
+ Changes velocities and sediment transport capacities
+ More effective modifying flow velocity than widening/ narrowing
- Possible construction limitations in wide channels
- Limited lifetime when there's no sediment transport equilibrium

Or

Does the flood storage capacity need to be significantly increased?

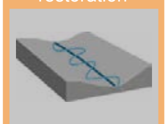
Yes

Embankment removal



+ Connects the river with its floodplain
+ Reduces the flood risk downstream and maybe upstream
- Possible change of land use on the floodplain
- Needs reassessment of vegetation on banks and floodplains

Meander restoration



+ Creates fluvial, ecological and visual diversity
+ Decreases the bed slope which can mitigate general bed degradation and reduces the flood risk downstream
- High complexity due to the difficulty of predicting erosion and deposition
- Possible increase of flood risk upstream of the reach

Is flow and morphological diversity desired?

Yes

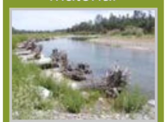
Vegetation

(Source: RRC)

+ Cover for aquatic life
+ Strength grows over time
- Only for low energy conditions
- Establishment time

Or

Woody material



(Source: RRC)

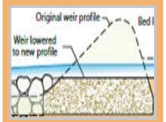
+ Can redirect or dissipate river flows
+ Material can be locally sourced
- Requires anchoring against flow and buoyancy forces

Or

Are there any weirs or culverts obstructing fish passage, which can be lowered or removed?

Yes

Lowering/removal of weirs & culverts



(Source: RRC)

+ Water depth varies (more) natural, no more minimum depth
+ Possible improvement of conveyance
- Possible sedimentation/ erosion and flood risk impacts up and downstream

This flowchart is only to be used to gain insight in what are the likely application fields of the measures. It is strictly NOT a definite decision instrument and local conditions always need to be taken into account.

STAGE 4: Select and design option

Once the technical suitability of the applicable options has been appraised, the preferred option is selected and taken to detailed design. However, the level of effort required in designing the solution varies, depending on the complexity of the preferred option and the risk to property or infrastructure if the protection should fail.

Any engineering intervention affects the river upstream and downstream of the project site and it is necessary to assess whether the off-site impacts of the project are likely to be significant for the river, river users or other stakeholders. Of particular concern is whether stopping erosion of one reach of the bank is likely to exacerbate erosion for neighbouring landowner. While protecting a bank in a way that does not solve the problem but transfers it elsewhere is not an ideal solution, it may be acceptable if the consequences of triggering bank erosion in an area other than that being protected are deemed to be acceptable. Nevertheless, construction of in-stream structures and engineered changes to boundary roughness, cross-sectional geometry or long-stream slope of the channel are likely to significantly impact river forms and processes. They may, for example, alter in-channel conveyance and hence, flood elevations and sediment dynamics, leading to complex morphological responses such as accelerated deposition in widened areas (due to reductions in flow velocities) and accentuated erosion downstream (due to reduced sediment input from upstream).

STAGE 5: Implementing the selected option

In this stage the selected solution is implemented. As reflected in the Table of Technical conditions for success, at this stage, it is necessary to take into account the timing of the work in relation to the growing season, as well as ensuring that the live plants to be used are in good condition.

It takes time for live plants to become fully effective in providing erosion protection. Consequently, the selected option may require temporary measures to provide short-term protection until the live plants become established. Alternatively, provision may be made for repairs to make good any damage to the project that occurs during the first year after implementation.

STAGE 6: Monitoring, inspecting, maintaining and evaluating

During the establishment phase, the works should be periodically inspected and monitored to ensure that its development is satisfactory. Particular attention should be paid to the growth and health of live plants used to ensure they have enough light, that they have not been adversely impacted by disease infection, pest infestation or vandalism, but are establishing themselves as required to provide the intended level of protection. If the states of the civil works or live plants cause concern, or the objectives of the project are not being met, aftercare or adaptive management may be required and should be triggered.

Technical conditions for success (or failure)

In this section the technical conditions that may lead to the success or failure of GI measures are described and examples and illustrative recommendations are provided. The conditions for success may be applicable at different stages of the decision-making cycle (see Table Technical conditions for success).

Geomorphological assessment

Description: When designing any type of management or engineering solution, it is necessary to understand the watercourse type. This will ensure that appropriate measures are used and that their impact will not be detrimental to the watercourse or its users. As stated in Sear et al (2003), geomorphological assessments 'gather descriptive and semi-quantitative data necessary to characterize existing channels, identify flow and sediment processes and estimate the severity of any flow or sediment related instability processes'.

A geomorphological assessment will help to answer questions like: 'what is the cause of the channel instability and is it a temporary or long-term issue?'; 'is the measure appropriate given the morphological characteristics of the site?'; 'how will sediment transport be affected?'; 'will sediment accumulation be an issue?' and 'will the measures trigger channel change elsewhere?'.

Recommendations & tips: To gain further understanding of applied geomorphology for river management and engineering, see for example, Sear et al (2003 and 2010).

Loading conditions

Description: Loading conditions are the actions and/or forces that the GI measure will have to withstand. They include water depths, inundation durations, flow velocities, possible overtopping and overflow, wave action, groundwater seepage, geotechnical pressure and shear stresses related to the steepness of the slope and/or weight of nearby infrastructure, buildings or vehicles.

Understanding these loads is necessary to be able to answer questions like: 'will the measure cope with the hydrology of the stream?'; 'can the measure withstand the stream velocities?'; and 'are engineering techniques such as regrading the bank sufficient to prevent geotechnical loadings?'.

Recommendations & tips: Explanations on how to estimate loading conditions related to river stages and flow velocities can be found in CIRIA (2015) and other bank protection design guidance documents.

Measures may be subjected to high loadings before their vegetative elements have had time to fully establish and the capacity of the solution to withstand this situation must be assessed. For example, seeded grass should provide continuous cover by the middle of the first growing season, but will not deliver its full protective function until the second growing season.

The risk of damage to the GI during the vegetation establishment period can substantially be reduced by including short-term structural elements in the design. For example, faggot bundles are most suitable for slowing near-bank flow velocities to lower loading conditions on establishing vegetation while also encouraging deposition of sediments, seeds and plant propagules that can also help stabilise the bank. However, to be effective, elements such as bundles must be securely anchored in place.

Large wood in a river requires careful consideration of the resulting risks. For example, wood structures can significantly raise water surface elevations during high, in-bank flows. This may be desirable, to improve hydraulic connectivity between the river and its floodplain and reduce the frequency of flooding in an urban area downstream, but is not allowable in reaches running through areas where the floodplain has been developed. It follows that rigorous, risk-based engineering design is essential when using wood, just as would be the case if it was proposed to use a Grey equivalent, in the form of groynes built using artificial materials such as steel or treated wood piles.

Limited data is available on velocity tolerance of GI measures (and more so for the establishment phase). Some of this data is summarised in the table below.

	Measure	Max. permissible velocity (m/s)	Max. bank slope (degrees)	Design life (years)	Observations
Green*	Aquatic vegetation	2.4	34	∞	For bank height < 1.5m
	Coir matting/pallets	2.4	45	3 - 5	Velocity value for when vegetated
	Coir rolls	1.8	34	6 - 10	
	Faggots/fascines/brushwood	2.0	45	30 - >100	Live fascines have higher resistance
	Stakes (live)	1.5	45	40 - >100	
	Vegetation	2.4	34	∞	
	Willow spilling	2.5	84	40 - >100	
	Woody material	3.0	90	5 - 15	
Green-Grey	Geo cell systems	up to 4.0	60	5 - 20	Velocity value for low bank loads and duration up to 2 hours
	Vegetated concrete blocks	4.1	34	50 typical	
	Vegetated gabions	4.5		15	
	Vegetated reinforced earth	3.3	90	>10	
	Vegetated reinforced mattresses	4.2	45	5 - 50	
	Vegetated riprap	3.4	34	∞	Velocity values depends on riprap size
	Vegetated rock rolls	4.0	90	∞	Application mainly at the toe
Grey	Geotextile	4.0	34	50	When covered by other measures
	Rock rolls	4.0	N/A	∞	Application at the toe

* Values for green measures assume full establishment

Notes: The indicative values in this table were obtained from various sources and some averaging was necessary to obtain typical values. Given the wide range of characteristics of these measures, the indicative values need to be used with caution and confirmed by suppliers/ designers/contractors.

Spatial implementation

Description: The spatial distribution of GI measures needs to be considered, including their elevation relative to those of the river water and phreatic surfaces, orientation relative to the flow, and position relative to the river planform. For example, the roots of live plants must be able to draw moisture up from the water table, but should not be saturated for extended periods, and in watercourses with high sediment loads, plants low in the bank can be damaged by high turbidity or rapid sedimentation. Curvature of the reach is also a key consideration.

Examples: Lack of plant colonisation due to bed level below Mean High Water Neap tide level (Source: EA)

Recommendations & tips: Grass roots cannot tolerate prolonged submergence and should therefore be placed only on upper banks. Conversely, stakes must be moist during the growing season and are best installed low in the bank, where the establishment of woody plants is desirable but conditions do not exceed the species' water tolerance.

Guidance can be found in RSPB, NRA and RSNC (1994) for example.

Selection of species

Description: Parameters such as soil type, water quality, light/shade conditions and inundation depths must be considered when selecting live species for use in GI measures. For example, some plant species, e.g. reeds (Phragmites), need to be submerged most of the time whereas others e.g. grasses (Poaceae) can withstand only infrequent, short duration submergence. Vegetation must also have an adequate growth medium (e.g. soil) to allow roots to penetrate and anchor the plants effectively.

Examples: Different types of vegetation planted up the bank profile (Source: HR Wallingford)

Recommendations & tips: Establish soil and environmental conditions at the site prior to selecting plants for use as GI measures, paying special attention to the availability of adequate sunlight, nutrients and moisture throughout the growing season. Also check that selected species can tolerate any low/freezing temperatures characteristic of the installation site. For example, designers can choose from a huge range of types of grass (Poaceae or Gramineae): some thrive in hot, dry conditions, while others can withstand extremely cold and wet conditions. As a rule, a mixture of plant types is more likely to be successful than a monostand of a single species. In addition to their engineering performance, in selecting plants, consideration should be given to ecological and environmental performance. For example, mixtures should include native wildflowers to increase biodiversity and support microbes and insects and, in all cases, native species of local provenance that are appropriate to the location should be preferred.

Where dense clays or highly compacted soils inhibit root growth, treatments to lighten or break up the soil may be necessary. There may also be social and cultural dimensions to the selection of plants that should be explored with stakeholders and landowners.

Above all else, it is essential to avoid introducing non-native or invasive species and use plants of known provenance. Also, biosecurity is of paramount importance, with stringent steps taken to ensure that plants and products used in GI measures are free from contaminants, pests and parasites, as well as being of relevant size for the scheme.

Time of year for implementation

Description: When using GI that includes live plants, it is essential to consider the time of the year at which the measures will be implemented. Of particular concern are predicted temperature, rainfall, stream flows, groundwater conditions, and light availability. Seasonality is clearly a factor, with river conditions being unsuitable during the wet season due to high water levels and velocities, which may preclude successful implementation. Attention will be necessary to the timing of work to avoid disturbance to nesting birds and spawning or migrating fish. All relevant environmental statutes and laws must also be followed, particularly with respect to checking for the presence of protected species and taking the steps necessary to avoid damaging listed-species or their habitats.

Recommendations & tips: Generally, live plant materials such as whole trees, shrubs or stakes/posts/cuttings should be collected and planted during the dormant season (October to March in the Northern Hemisphere), avoiding high flows and waterlogging.

Planting of grasses (Poaceae or Gramineae) and reeds (phragmites) requires warm and damp conditions and therefore, April-May and September are recommended in the Northern Hemisphere.

Willow spiling should be installed between October and April; for optimum growth willows require warm temperatures and high moisture levels experienced during April and May.

Aquatic wetlands marginal plants are most successful when installed in the Spring, although autumn installation is also possible.

Sizing of material

Description: In the case of Grey elements in Green-Grey solutions, riprap, gabions and concrete blocks need to be sized to withstand the expected loading conditions. Similarly, when planting live materials, spacing and density as well as plant size must also be matched to the expected loading conditions.

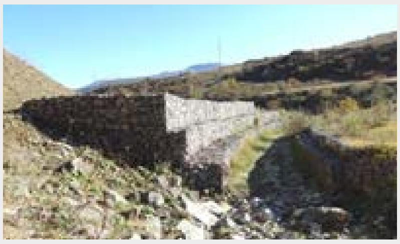
Recommendations & tips: Apply conventional design equations to size Grey components (e.g. CIRIA, 2015). In the case of boulders, cobbles and gravel, the following table provides indicative sizes necessary to withstand specified flow velocities.

Class name		Size range (in mm)	Maximum Velocity (m/s)
Boulder	Very large	4,096 - 2,048	7.6
	Large	2,048 - 1,024	5.8
	Medium	1,024 - 512	4.3
	Small	512 - 256	3.0
Cobble	Large	256 - 128	2.1
	Small	128 - 64	1.5
Gravel	Very coarse	64 - 32	0.9
	Coarse	32 - 16	0.8

Design of transitions

Description: Edges and transitions between Green/Grey or Grey measures and unprotected banks need to be carefully designed as they are more susceptible to erosion. If bank protection materials are outflanked and washed downstream, they may create hazards by, for example, causing blockages at culverts. Protection must extend up and downstream of the reach of bank that needed protection and should be gradually transitioned to the natural bank cover and/or keyed into the bank sufficiently to prevent flanking due to scour of the adjacent, unprotected bank.

Recommendations & tips: Apply existing design recommendations about edges (e.g. CIRIA, 2015).



Examples: Upstream edge of gabions protection without transition (Source: HR Wallingford)

Design of bank slope

Description: Failure of bank protection measures is often related to the steepness of the bank. It is therefore necessary to consider carefully the risks associated with using GI measures on steep slopes.

Recommendations and tips: Eroded banks with very steep slopes, commonly referred to as 'river cliffs' typically require regrading to accommodate GI measures.

For grass cover to be stable, the bank slope must be less than 45 degrees, and preferably much less.

When using willow spiling on steep slopes, terracing is recommended for banks higher than 1 metre (approximately) but distance from the water (and water table) also affects location.

Provision of filters and/or drainage

Description: Filters are layers of granular stone or geotextile placed between the underlying soil and the bank protection to prevent loss of fine material through the protective layer. Poor design of filters (or filters poorly or incorrectly installed) can lead to loss of substrate material. Failures of block stone protection or Green-Grey measures are often due to lack of adequate filtering between the underlying soil and the stone rather than to inadequacy of the stone as a protective material.

Bank drainage may be necessary to reduce or avoid seepage-related damage or failure.

Recommendations & tips: Apply existing design equations for filters and drainage systems (e.g. CIRIA, 2015).

Use a suitably designed geotextile behind/beneath revetments or toe protection, especially for block stone.

The long-term risks of burying an artificial material such as a geotextile in a stream bank must be assessed in terms of potential decomposition and contamination of surrounding areas.

Examples: (Left) Example of loss of material behind rocks due to lack of filter (Source: NRW), (Right) Example of loss of material behind willow spiling due to lack of filter (Source: RRC)

Scour and toe protection

Description: Scour is a common cause of failure in many river bank protection schemes. Scour occurs naturally along the toe of stabilised banks where fluvial loadings are greatest and can also develop at the up and downstream terminations of the protection. Local scour may also develop around any elements that protrude into the flow (such as large wood pieces or poles that generate excessive turbulence.

The toe of the bank is the most vulnerable area and it needs to be adequately designed to resist scour and withstand under-mining due to lowering of the elevation of the bed adjacent to the works.

Recommendations & tips: Vegetation alone is rarely sufficient to prevent toe scour. More robust solutions employing rock (rock rolls, vegetated riprap), tree trunks and root wads are usually necessary.

Where possible, re-establish the riparian corridor adjacent to the protection to help bind the soil and develop medium to long term stability to the untreated banks up and downstream of the protection.

Examples: Failure of vegetated gabions due to development of scour and outflanking (Source: HR Wallingford)

Costs

Description: The costs of live materials may include harvesting, transportation, handling, fabrication and storage as well as installation. Other GI measures may have manufacturing or extraction costs.

Costs vary depending on access to sources, the availability of live materials, the time of year and prevailing labour rates.

Fabrication and installation costs of vegetated elements are usually low compared to those for Grey solutions.

Recommendations and tips: Detailed costs of some Green and Grey measures and river management techniques considered in this booklet are presented in table below. Costs of Green-Grey measures are not included as the values consulted were considered preliminary.

Measure		Capital cost (£)			Units
		Low	Central	High	
Green	Aquatic vegetation	120	185	245	m^2
Green	Coir matting/pallets	25	30	35	m
Green	Coir rolls (unplanted)	15	20	25	m
Green	Coir rolls (planted with suitable vegetation)	25	30	35	m
Green	Faggots	60	105	145	m
Green	Stakes	15	25	30	m
Green	Vegetation	120	185	245	m^2
Green	Willow spiling	80	100	120	m
Green	Woody material	140	145	155	m
Grey	Geotextile	100	195	295	m
Grey	Rock rolls	30	60	90	m
River management techniques	Embankment removal	95	130	165	m
River management techniques	Lowering/removal of weirs & culverts [1]	95	130	165	m
River management techniques	Changing bed levels [2]	15	25	50	m
River management techniques	Regrading of banks (or re-profiling)	15	25	50	m
River management techniques	Widening/narrowing	5	20	30	m

Source: Costs obtained from Environment Agency (2015a) and Environment Agency (2010)

Notes: Costs updated to 2016 prices; where only low and high estimates are available from sources, the central estimate is taken as the average of these; where only central estimates are available from sources, low and high estimates are calculated as 50% (low) and 150% (high) of the central estimate; costs include transport and installation.

[1] Costs considered similar to those of removing embankments.

[2] Costs considered similar to those of regrading banks.

Examples: The case studies described in this booklet contain some cost information.

Condition of live species

Description: Live material (such as willow-based material) needs to be properly handled during the implementation phase. The material should be dormant and free of splits, rot, diseases and insect infestation and it should be harvested from plants that are at least 2 years old.

For all live material and plants, it is also essential to ensure that vegetation is properly watered before and after planting.

Recommendations and tips: Cut willow stakes should not be stored longer than a few hours otherwise they may dry out and die. It is recommended to soak them for a minimum of 24 hours in cool, aerated water prior to installation or planted the same day as harvested if they are watered.

Examples: Cuttings soaking in the creek until installation (Source: Greenbank)

Installation

Description: Installation of any protection measure needs to be carefully planned and performed by experienced installers.

Stakes and other woody materials need to be adequately secured or driven into the soil to sufficient depth. Local soil conditions may present unexpected difficulties, which will need to be properly addressed prior to and during the work.

Common problems are related to the incorrect positioning/filling/fixing of Green-Grey cellular systems and mattresses. Grey elements such as gabions may not be adequately filled or may have their edges inadequately transitioned to the natural bank.

Mattresses, cellular systems and geotextiles can easily be damaged during installation (for example by puncturing or tearing) which leads to loss of integrity and affects performance.

Examples: Failure of geo cell system due to inadequate connection and with improper infill (Source: Greenfix)

Recommendations and tips: Installation of stakes may be as simple as tamping the live cutting into the ground with a hammer. At least two buds should be present above the ground. Leaving long lengths of stakes exposed increases the risk of desiccation and reduces survival rates.

Avoidance of diseases

Description: Live material can become diseased or infested during the implementation, establishment or consolidation phases.

Recommendations and tips: Diseases such as alder disease and ash dieback can have an impact on river banks protected by GI measures incorporating alder (Alnus) or ash (Fraxinus).

Use native plants of local provenance and take special care when using species known to be vulnerable to disease (e.g. alder, ash), avoiding them if there are viable alternatives.

Human and animal access to the bank

Description: Uncontrolled access to a protected section can damage any bank protection measure. Also, some types of protection (live stakes or vegetated gabions for example) may pose risks to people and animals because they present tripping or falling hazards. Hence, liability alone issues may dictate exclusion of people or animals.

Recommendations and tips: It may be necessary to limit the access by fencing, especially until the live vegetation in a GI measure is well established.

Fencing on the channel side of willow spiling is an effective method for protecting the young willows from waterfowl.

Examples: Cattle on a bank showing evidence of 'poaching' which is the combined impact of over-grazing and trampling (Source: HR Wallingford)

Light

Description: Some vegetation, mainly aquatic plants, can be adversely affected by shading by trees during the summer months and may be unable to develop properly as a result.

In urban environments, intense shading by nearby buildings may also prevent riparian and terrestrial plants from establishing or flourishing.

Recommendations and tips: Willow spiling, as most other vegetative measures, requires direct sun-light in order to thrive.

Examples: *(Top) Example of planting failing to thrive. Dearth of plants on left concrete wall attributed to shading by high rise building (Source: HR Wallingford), (Bottom) Example of vegetation growth being curtailed by insufficient light despite efforts to include light in the culverted River Bollin (Manchester airport) (Source: RRC)*

Deterioration of material

Description: Bank protection materials may deteriorate with time. For example, woody vegetation may decay and live plants may die or artificial components of Grey elements, such as the wire making up gabion baskets, may corrode.

Rotten wood may leave iron fixing bars and tying wire protruding which may pose safety or aesthetic issues.

Examples: Failure of gabion mattress attributed to mobile bed load abrasion (Source: RRC)

Control of vandalism

Description: Vandalism (removal or damage of elements) can compromise any bank protection measure or scheme. Removal of (live) stakes by dog owners for example (an example of unintentional vandalism) has also been found to compromise the integrity of bank protection using green measures.

Recommendations and tips: Consider the possibility of vandalism when selecting the preferred option, especially in urban areas. If the risk is high, avoid lighter materials (such as faggots) if possible or, if they are used, ensure they are well fixed in place and consider limiting access to the bank.

Maintenance

Description: Maintenance requirements will vary depending on the measures selected for the scheme (e.g. type and species of plant), the weather and the characteristics of the watercourse (e.g. velocity, flood frequency).

Maintenance should take into account the environmental impacts that it may cause, including potential for damage to listed species or their habitats.

Recommendations and tips: The Aquatic Vegetation Management Handbook (EA, 2014) provides information on different techniques to manage aquatic and riparian vegetation, timing of operations, likely costs, health and safety issues, etc.

The Channel Management Handbook (EA, 2015) provides detailed information on multiple issues to be considered when planning and implementing management, maintenance and capital works in rivers.

It is likely that repairs, maintenance or adaptive management will be needed in the first months of the project life, when vegetation is still becoming established. Maintenance requirements are likely to reduce over time.

It is recommended that the scheme be inspected at least twice during the first year after installation and once a year thereafter. Also, the works should be checked after significant flood events.

Immediate repairs are essential if significant undercutting and/or flanking is observed during post-project inspection.

Chapter 4

Case studies

The main purpose of the Case Studies presented here is to provide examples and evidence of the performance of Green and Green-Grey solutions combined with river management techniques. Twelve case studies are presented herein and references to other case studies are also provided to give a broader picture of solutions including different types of measures and different types of rivers.

The twelve Case Studies are referred to in this document by the numbering provided in the table.

Case study	Type of intervention	Type of measure	River	River type*	Location
1	Bank protection	Willow spiling/bundles	Ellen	Inactive Single Thread Channel	Oughterside (Cumbria)
2	Bank and toe protection	Stakes, logs, willow mattress	Eamont	Inactive Single Thread Channel	Sockbridge (Cumbria)
3	Bank and toe protection	Re-profiling, turf reinforced mattresses, rock rolls	Elwy	Inactive Single Thread Channel	Sint Asaph (Denbingshire)
4	Bank and toe protection	Re-profiling, turf reinforced and coir mattresses, live root wads, rock rolls, faggot bundles	Rhiw	Wandering Channel	Refail (Powys)
5	Bank protection	Live stakes, woody material, hazel faggots, geotextile, re-profiling, revegetation	Clun	Active Meandering Channel	Purslow (Shropshire)
6	Bank and toe protection	Re-profiling, coir matting, rock rolls, stakes	Monnow	Inactive Single Thread Channel	Kentchurch (Herefordshire)
7	Bank protection and modification of river shape	Stakes, faggots, rock rolls, turf reinforced mattresses, woody material	Gwendraeth Fach	Tidal river – Tide locked channel	Kidwelly (Carmarthenshire)
8	Bank protection	Stakes, brushwood mattresses	Usk	Tidal river – Tide locked channel	Newport (Monmouthshire)
9	Modification of river shape	Meander restoration, re-profiling, vegetation, narrowing & changing bed levels	Ravensbourne	Modified Urban Watercourse	Brookmill park (London)
10	Modification of river shape	Woody material, re-profiling, Boulders/ rocks/gravel	Avon	Inactive Single Thread Channel	Amesbury (Wiltshire)
11	Bank and toe protection	Coir matting, rock rolls	Cwm Mill Stream	Ditch or Small Drain	Ferryside (Carmartheshire)
12	Bank and toe protection	Vegetated reinforced mattress, rock rolls	Washford	Step pool channel	Roadwater (Somerset)

* Refer Flowchart on river typology in Chapter 3

Information provided for Case studies

For each case study the main success factors in the Business Framework are described: motivation, engineering performance (including aspects on inspection, maintenance and design life), costs and additional benefits (or ecosystem services). Site characteristics and a brief description of how successful the scheme has been are also included.

The following scores were used when summarising information on four main success factors at the beginning of each case study:

Parameter		Scores		
Engineering performance		Severe damage	Minor damage	Endured high flows without damage
Inspection and maintenance		None	> 6 monthly	< 6 monthly
Costs		< £20,000	< £100,000	> £100,000
Additional benefits		Little	Some	Substantial

Data on the engineering performance of GI solutions is the hardest to obtain due to a common lack of detailed records of discharges and water levels in the river and data defining the behaviour of Green and Green-Grey measures. In the process of collating data it was apparent that the performance of Green and Green-Grey measures was better understood for the lower flow range than for flood events. For the case studies, where possible, information on the conditions in the river during flood events was obtained from nearby gauging stations and typical cross-sections were obtained from LiDAR. With this information, the highest flow velocities likely to occur at the sites were estimated using the freely-available modelling tool, the Conveyance Estimation System (CES).

When the costs of the works were not provided by the owner or stakeholders of the scheme, they were estimated based on costs extracted from literature (see the Table presented in Chapter 3).

As stated in most of the case studies, the main purpose of the works was to protect the bank and therefore, environmental and enhancement of other benefits were not considered; however, these benefits are still generated by GI. They have been estimated using a scoring system ranging from 1 (no benefit) to 5 (high benefit) and are displayed in a "benefits wheel" for each case study. The categories considered in the wheel are described in the table below.

Category	Benefit	Description	Impact most likely where
Environmental	Water quality	Change in ecological, chemical or biological parameters of water quality in river or other waterbody	■ There is pollution or water quality issues in the area currently (from point or diffuse sources) ■ Growth or climate change is expected to change risk of pollution or water quality ■ Option includes measures which will trap or dilute sediment or pollutants
	Habitat provision	Change in in-stream or floodplain habitats for plants and animals	■ Area includes a designated site (e.g. SSSI, SAC, SPA), Habitats of Principal Importance (BAP priority habitats), a site of local importance for nature, or a non-designated site of local or regional value ■ Option will improve these sites, or create new sites

Category	Benefit	Description	Impact most likely where
Environmental *(Continued)*	Climate regulation	Change in the amount of atmospheric greenhouse gases	■ Option involves new or additional planting (including trees)
	Low flows	Change in frequency or severity of low flow episodes	■ Watercourse suffers from low flows currently, or is expected to in the future (e.g. due to climate change) ■ Option includes measures which will enhance flows during low flow periods (e.g. reduced velocity, increased storage)
Social	Health access	Contribution to the physical or mental health and wellbeing of local residents or visitors	■ Option involves green infrastructure (e.g. tree planting) which could encourage residents or visitors to spend more time outdoors or participating in physical activity/exercise ■ Option has the potential to reduce the occurrence or severity of high temperatures in summer and cold temperatures in winter
	Air quality	Significantly change in the level of air pollution	■ Area includes an air quality management area ■ Option involves green infrastructure (e.g. tree planting) ■ Close to or includes populated areas or a transport corridor
	Flood (surface water or ground water)	Change in probability or consequence of surface water or groundwater flooding	■ Option includes measures that will attenuate flow and increase or improve floodplain storage ■ Area is currently at risk of surface water or groundwater flooding (including downstream)
	Flood (fluvial)	Change in probability or consequence of fluvial flooding	■ Option includes measures that will attenuate flow and increase or improve floodplain storage ■ Area is currently at risk of fluvial flooding (including downstream)
Cultural	Aesthetic quality	Change in the attractiveness or desirability of the area	■ Option includes landscaping or improvements in visual attractiveness ■ In or close to a populated area, or an area used for recreation, work, commuting, tourism, etc ■ Option includes measures which be visible to those living nearby or passing by
	Cultural activity	Change in ability of area to provide opportunities for spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences	■ Option includes improvements that create or enhance opportunities for cultural activity ■ In or close to a populated area, or an area used for cultural activity ■ Option includes measures which be visible to those living nearby or passing by

Classification of case studies

The table below relates the types of GI measure with the Case studies compiled and provides complementary examples from other references that are described in the Appendix.

Type of measure	Case studies described in this booklet	Examples provided in other references (Appendix)
Aquatic vegetation		M
Coir pallets/ matting	4, 6, 11	F,I
Coir rolls		D, E
Faggots/ fascines/ brushwood	4, 5, 7, 8	C, G,I
Stakes	2, 5	A, C, I
Vegetation	5	
Willow spiling	1	
Woody material	2, 4, 5, 7, 10	G
Geo Cell Systems		B
Vegetated concrete blocks		K
Vegetated gabions		L
Vegetated reinforced earth		O
Vegetated reinforced mattresses	3, 4, 5, 7, 12	
Vegetated riprap		
Vegetated rock rolls		N
Rock rolls	3, 4, 6, 7, 11, 12	
Embankment removal		J, O
Lowering/ removal of weirs & culverts		I
Meander restoration	9	H
Changing bed level		H
Regrading of banks	3, 4, 5, 6, 9	G, H, I
Widening/ narrowing	9	H

Additional references to other examples of GI measures compiled by the Environment Agency are also provided in the Appendix.

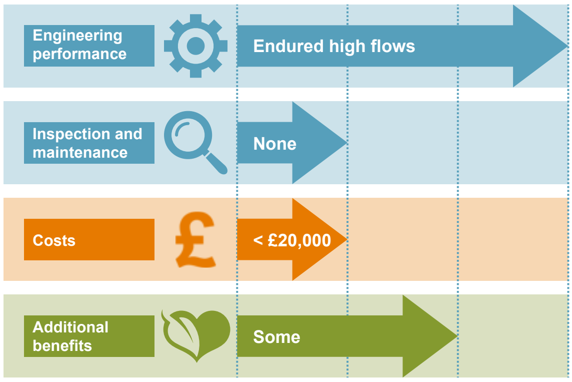
Case study 1

River Ellen - bank protection

Willow spiling terraces were installed on the River Ellen, Oughterside, Cumbria, in 2014 to protect an eroding bank that was threatening the integrity of the nearby road.

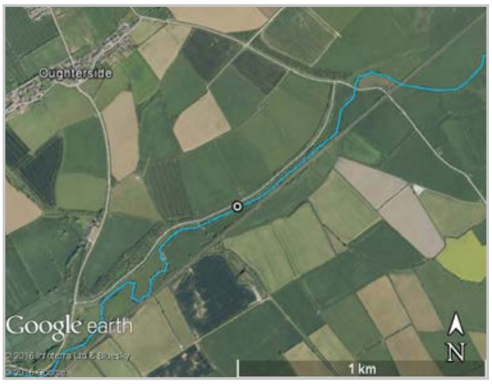
How successful has this scheme been?

Vegetation is well established and the scheme has survived 2015 and 2016 floods. The willows were installed at a time of the year when temperature and moisture levels were optimum, and the site benefits from unobstructed light, providing the necessary conditions for willows to thrive.



Site characteristics

The River Ellen at the protected stretch is an inactive single thread river with an estimated slope of 0.0019 (1:526). The catchment up to the scheme covers an area of 90 km^2. The median annual maximum flood is 37 m^3/s and the bankfull discharge is estimated to be around 15 m^3/s. The maximum gauged flow to date was of the order of 57 m^3/s in December 2015. The river runs between a railway line on the left bank and a public road on the right. The area around the site is agricultural land as is most of the catchment.



Aerial view of the river reach

Motivation

The river was probably redirected and straightened in the decades after 1840 when the railway line was open, as the 1866 OS map shows the river diverted to north of the railway as opposed to the south where it was previously. Later in the 1970s a road was built along the right bank thereby confining the river between the railway and the road. Gradually the river started to adjust to a more meandering course, eroding the bank and causing concern about the integrity of the road.

Description of the scheme

The bank protection includes four terraces of willow spiling. The scheme was led by the Highways Department of the County Council and was commissioned in April/May 2014. The original design from the Council only considered treated timber uprights. The final design however, incorporated modifications made by an expert on willow spiling on behalf of a landscaping firm who were the main contractors for the County Council.

Engineering performance

Since implementation, the scheme has endured several bankfull flow conditions and high flows without suffering any damage. Flow discharges and velocities were estimated based on available information. For bankfull flow of the order of 15 m^3/s (at around 38.9 mAD water level), the average flow velocity is 0.8m/s, and along the bank it goes up to 0.85 m/s. For the 2015 flood event, with a water discharge of 57 m^3/s, water level is estimated at 39.59 m AD and average flow velocity at 1.1 m/s, and up to 1.4 m/s along the bank.

Design life

No whole life costing was undertaken and no allowance was made for inspection and maintenance. This was considered a permanent repair with no assigned design life.

Inspection and maintenance

No future inspection or maintenance plans were considered.

The scheme immediately after completion. Source: Phil Bradley

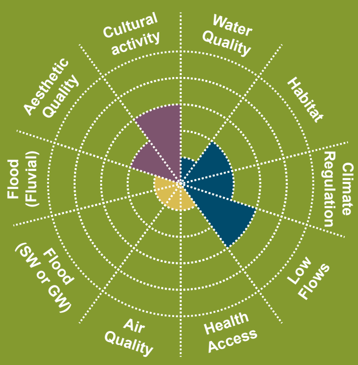
The scheme after one growing season. Source: Phil Bradley

Costs

Costs for each tier of willow spiling 600-900 mm high were £80-£100 per linear metre, with the higher value corresponding to when reinforcement mesh and turf are added. It is noted that these were costs for local consultants/contractors and therefore represent a lower cost bracket. Based on £100 per linear metre, the overall cost was estimated to be around £16,000, considering four 40m long terraces of willow spiling.

Additional benefits

Ecological enhancement or creating additional benefits were not considered in the design. The scheme is only intended to prevent further bank erosion and preserve the road embankment. Nonetheless the scheme has delivered some additional benefits, which have been quantified in the wheel chart.



Site location

Oughterside, Cumbria

54°44'42.25"N 3°21'41.66"W

Contact details

Westwood Landscape Ltd: www.westwoodlandscape.co.uk

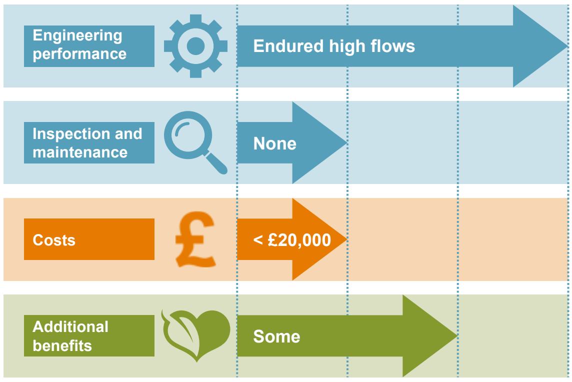
Case study 2

River Eamont - bank and toe protection

An eroding bank on the River Eamont, Sockbridge, Cumbria, was protected in 2013 with locally sourced materials (stakes (toe), logs (bank and toe) and live willow cuttings and brash bundles/ mattress (bank)) to prevent wider erosion and impact on a footbridge downstream.

How successful has this scheme been?

The protection survived record high flows in December 2015, while keeping its structural integrity, following some initial repairs. The scheme was well installed with logs adequately secured to prevent lifting during floods and, after construction, the site was protected from livestock damage by a fence.



Site characteristics

The River Eamont is a single thread river with limited dynamics in this section. The catchment up to the scheme covers an area of 200 km^2. The slope of the river at the scheme (Sockbridge, Cumbria) is estimated at 0.0036 (1:280), with a bankfull discharge of around 40 m^3/s and average velocity of 1.6 m/s. The site is in the River Eden Special Area of Conservation (SAC) and Site of Special Scientific Interest (SSSI). The area around the site is very rural, consisting mainly of agricultural land, as is most of the catchment.

Aerial view of the river reach

Motivation

Bank erosion was occurring and the County Council was concerned about the possible impacts on a footbridge located downstream. The main drivers for the choice of GI measures were the site's SAC and SSSI designations, the prospect of improving the 'Moderate' overall status under the Water Framework Directive and the local availability of material. The landowner was also knowledgeable of these practices and was happy to collaborate with the project.

The eroded bank and footbridge downstream with strainers in place (left) and with completed protection (right).
Source: Tom Dawson, Northern Habitat, Countryside Contractors

Description of the scheme

The protection was installed in 2013 and included posts driven in front of the bank with footing logs braced behind them. A live brush mattress was placed on top and covered with logs and willow cuttings. The logs were strapped down to prevent lifting during flood events. The site was fenced from livestock for its first growing season. Materials were obtained from the site.

No formal design was carried out for the scheme apart from dimensioned drawings for planning purposes.

First layer of brush mattresses on top of footer logs (left) and second layer of brash mattresses and top logs (right), looking upstream.
Source: Tom Dawson, Northern Habitat, Countryside Contractors

Engineering performance

During a visit in 2015, two years after completion, it was noted that a length (<5m) of willow protection had disappeared. The cause of this damage is unknown and possible causes could have been: less vigorous growth of the willow at that location, a collision tree or less robust protection locally - or a combination of these. Since the rest of the structure was still intact, the protection was just patched up.

After that repair, the scheme endured the highest flows ever recorded since 1976 without any damage.

The discharge at the site for that event in 2015 is estimated from the existing records at upstream tributaries as roughly 300 m^3/s, with an average velocity above 2 m/s, and around 1.6 m/s near the bank.

Design life

This was a permanent repair but with no assigned design life.

Inspection and maintenance

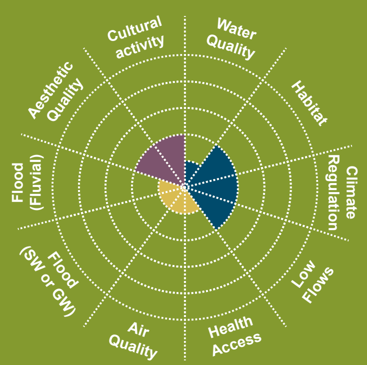
Ad-hoc inspection and maintenance is provided by the landowner.

Costs

The scheme was paid by the County Council at a cost of £10,000.

Additional benefits

Ecological enhancement or creating additional benefits were not considered. Nonetheless the scheme has delivered some additional benefits, which have been quantified in the wheel chart.



Site location

Sockbridge, Cumbria

54°38'27.56"N 2°46'34.50"W

Contact details

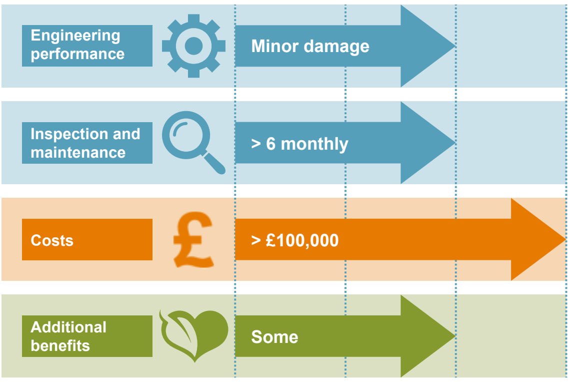
Environment Agency (enquiries@environment-agency.gov.uk)

Case study 3
River Elwy - bank and toe protection

A failing bank protection of gabions on the river Elwy in Wales was replaced in 2015 with a regraded bank with turf reinforced mattresses and rock rolls toe.

How successful has this scheme been?

The scheme is performing well, the bank is well protected and vegetated, and no further erosion is taking place. Thanks to a good design for high flow, the scheme withstood the largest flood recorded in the region with only minor damage at the transition. Well graded rock rolls have encouraged vegetation growth, and potential animal and human damage has been prevented with a new fence.



Site characteristics

The Elwy is a single thread river classified as a heavily modified river following the Water Framework Directive with an overall status of ‘good’. The river is part of the Clwyd catchment, its slope is estimated as 0.004 (1/265) and the bankfull discharge at the section is estimated as 86 m^3/s.

Aerial view of the river reach

Motivation

Due to the failing of an original protection with gabion baskets, the bank needed to be restored.

The bank of the scheme is close to a gas main from Wales & West Utilities and to some electric cables just downstream. Gabion baskets were placed initially in the ditch required for the installation of the gas main. As they were becoming outflanked, the gabion protection was extended to a larger scheme. It is thought that, due to its poor design, it started causing erosion problems downstream. Scour holes up to 2.5 m deep were found in front of the gabion toe.

The old failing gabion baskets (left) and the new V-Max matting and (vegetated) rock rolls (right). Photo supplied by Salix Ltd

Description of the scheme

The main driver for the choice of GI measure was the capability to withstand the high flows. The work involved regrading the banks to roughly a 30 degree angle for an approximately 100 m length. The bank is protected with turf reinforced mattresses (Vmax commercial type), and rock rolls and boulders at the toe. Several bathymetric surveys were undertaken to support the design. Even though the bank is about 4 m high, there is hardly any loss of land due to the re-profiling compared to the stacked gabion baskets. The old fencing along the bank was replaced to continue to prevent cattle from going to the waterside.

Engineering performance

A few months after completion, at the end of December 2015, the site experienced record high flows, of the order of the 100 year flood event. At the downstream end of the protection there was some damage, with rock rolls moving due to the old riprap revetment failing and being removed from beneath the rock rolls. This was at the transition of the protection to some natural boulders downstream. It is thought that these pre-existing boulders were part of an old bridge abutment. Transitions are always weak points and usually the first places for a scheme to fail. All the rest of the protection and turf reinforced matting stayed unharmed. The protection was designed to withstand flow velocities up to 4.5 m/s.

The rock rolls became vegetated in a few months. It is considered that the small rock grading had a beneficial effect: it stimulated siltation, which formed the base for future vegetation.

Design life

The rock rolls and turf reinforced matting are expected to last for over 50 years.

Inspection and maintenance

Wales & West Utilities are responsible for the inspection and maintenance of the scheme. Annual inspections of the asset are planned.

The few rock rolls which were disturbed by the high flows. Photo supplied by Salix Ltd

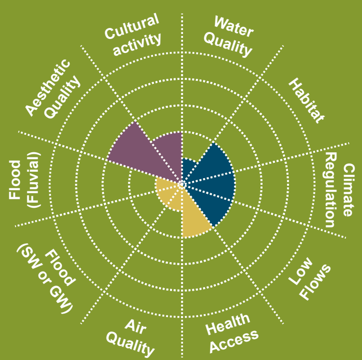
Costs

The cost was £140,000 for 130 m length of bank.

Additional benefits

Ecological enhancement was not a driver for this scheme, so no pre or post surveys have been done. However, the scheme has delivered some additional benefits, which have been quantified in the wheel chart.

It is considered beneficial that the barrier between the waterside and the top of the bank created by the gabion protection was removed. The whole bank now looks fully natural and is well vegetated. As the scheme is close to a popular bathing area, this is considered a positive value.



Site location

Saint Asaph, Denbighshire, Wales

53°14’56.86”N 3°26’23.75”W

Contact details

Natural Resources Wales: enquiries@naturalresourceswales.gov.uk

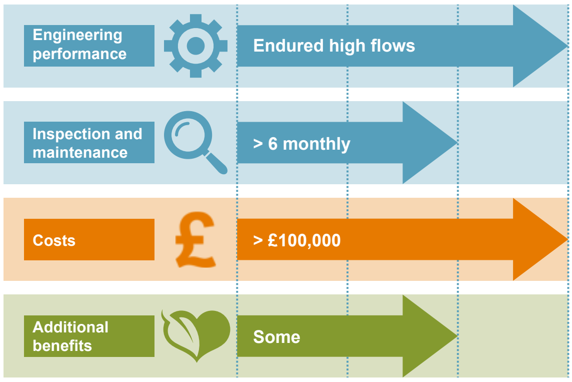
Salix River and Wetlands Services Limited: info@salixrw.com

Case study 4
River Rhiw - bank and toe protection

A number of different green measures were used in 2013 to protect a bank on a highly mobile reach just upstream of the confluence with the River Rhiw and the Severn in Wales, where erosion was threatening a gas main.

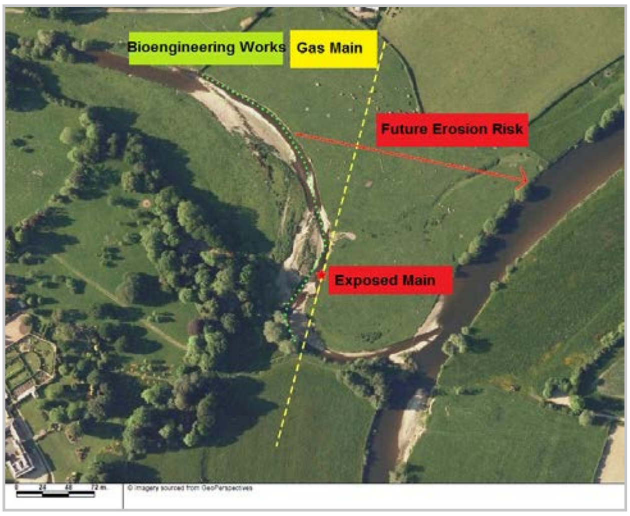
How successful has this scheme been?

The protection is successful in preventing the wandering river causing further bank erosion along the nearby gas main, and has survived high flows without damage. The site is used by the local Natural Resources Wales staff to showcase and provide training on the different techniques: re-profiling of bank, coir matting and willow sprouts (bank), live root wads, faggot bundles, logs and rock rolls (toe). The root wads were implemented with a good spatial distribution, and the willows were installed at a time of the year when temperature and moisture conditions are optimum and have established well. Fencing of the site was key to protecting the sprouting willows from livestock.



Site characteristics

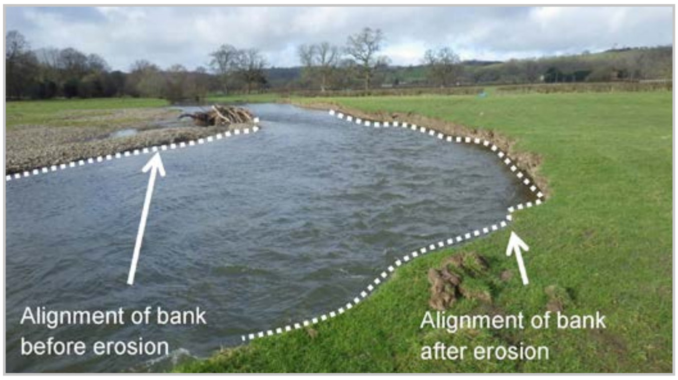
The site is located on the Rhiw River, just upstream of the confluence with the River Severn, and it is part of the Severn Uplands catchment that has an overall Water Framework Directive status of 'good'. The river slope at the site is estimated as 0.0028 (1:357), and the bankfull discharge at the section is estimated as 30 m^3/s, with a maximum velocity at the bank of 1.3 m/s.



Overview of the location with the River Severn on the right. Photo supplied by Salix Ltd.

Motivation

The scheme is located in a highly mobile river reach with fine bank material. During a high flow event, the left bank retreated roughly 10 m overnight. This was very concerning for the Wales & West Utilities company who has a gas main buried near the left bank that was becoming exposed. Initially the company proposed a full protection of block stones. This option was dismissed because of: (1) the requirement for geomorphological surveys in order to obtain relevant permits; (2) the prospect that this would probably only transfer the problem to another location; and, (3) the need for continuous maintenance due to the localised scour expected in front of the block stones. Therefore, the company was persuaded to use a green approach although the closest area to the gas main was still protected with block stones. That part of the protection did not perform correctly, possibly due local scour, and was replaced with green measures afterwards.



Description of the scheme

The new protection, installed from March to May 2013, contains different measures over a length of roughly 300 m. All measures are meant to increase the general roughness and slow down flow velocities and associated erosion.

On the upstream part there are live root wads, which deflect the river flow away from the banks. The live root wads are located at such a distance from each other that when the eddies generated by one root wad reach the bank again, another root wad is in place protecting the bank. Root wads were constructed by firstly excavating the bank, putting the trunk of the root wad in, and then backfilling the excavated part around the trunk. Downstream of the root wads, the bank protection consists of a combination of staked-down coir mattresses overlaid by willow sprouts and topped with 100 mm of soil. The toe is protected with faggot bundles weighed down with logs, and a double layer of rock rolls just behind. All materials used in the scheme were sourced from within the catchment and the root wads came from a nearby landowner. Eventually the bank is expected to be fully vegetated by the live root wads and willow cuttings and slow down the mobility of the river.

The scheme benefited from a high level of design.

Stakes and faggot bundles. Photo supplied by Salix Ltd

Part of the protection: coir matting, stakes, willow sprouts (bank) and rock rolls, logs, faggots staked down (toe). Photo supplied by Salix Ltd

The root wad bank after 4 months.
Photo supplied by Salix Ltd.

Engineering performance

The protection is working well, preventing the wandering river causing further bank erosion. The scheme has endured both drought and high flows without damage.

The bank appears well vegetated. Willow was placed only 100 mm underground, but the root system established itself well enough to not dry out and it was already sprouting two weeks after installation. However during one flood after implementation, the electrical fence was washed away and not fixed immediately resulting in the sheep eating the willow sprouts. After the re-installation of the fence, the willow recovered completely.

During a large flood event in the construction period, two root wads became loose due to the scour pool around them, and had to be reinstalled. Nevertheless, the root wads are considered to be one of the success factors of this scheme.

Design life

A design life was not defined.

Inspection and maintenance

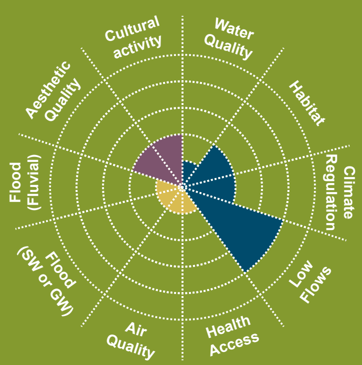
Wales & West Utilities is responsible for annual inspection. The site is also sometimes visited by Natural Resources Wales to check on the different measures. There are no maintenance plans in place. It is considered that some areas may need adjusting or cutting in the future, but that will be decided on an ad hoc basis.

£ Costs

The total cost of the scheme was £140,000, of which £60,000 were for the live root wads.

Additional benefits

The scheme consists of natural materials and the root wads create flow and morphological diversity. In contrast to the block stone scheme originally planned, now the waterside is accessible from the flood plains. The site is used by the local Natural Resources Wales staff to show case and provide training on the different techniques.



Site location

Refail, Powys

52°35’37.04”N 3°11’1.42”W

Contact details

Natural Resources Wales: enquiries@naturalresourceswales.gov.uk

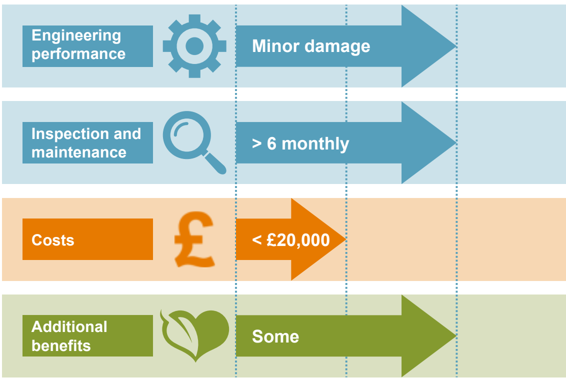
Salix River and Wetlands Services Limited: info@salixrw.com

Case study 5
River Clun - bank protection

Various bank protection measures such as live stakes, large woody debris, dead hazel faggots, seeded geotextile and bank regrading were trailed in 2013 on the fast eroding banks of the river Clun near Purslow (Shropshire) to offer short to medium term protection to a new riparian zone while vegetation was establishing.

How successful has this scheme been?

Even though no detailed design or study was made, the scheme has survived high flows and reduced bank erosion, allowing the vegetation planted in the riparian zone to establish well. Three years after implementation, about half of the protection works are well established and vegetated, whereas others have suffered damage, especially where bank heights were larger. Of the techniques tried and the materials used, the live wood revetment showed greater durability and longevity. This could have been improved if staked with live willow instead of fence posts, which are not suited for a wet environment. The site was protected by a fence but cattle were still let inside and the scheme was damaged.



Site characteristics

The River Clun is a single thread wandering river with an estimated slope at the scheme of 0.00227 (1:440). The bankfull discharge is estimated as 24 m^3/s, with an average velocity of 1.2 m/s. Floodplains are wide and approximately at the same level, which allows for river meandering. The area around the site is agricultural land, just like most of the catchment. The scheme is located 10 km upstream of a Special Area of Conservation.

Aerial view of the river reach

Motivation

Water pollution problems were detected near a drinking trough where cattle were trampling the river banks. The responsible farmer had the option to either face law enforcement for the pollution caused or adopt catchment sensitive farming practices for which he could get funding by signing up to Natural England's Higher Level Stewardship scheme. The fact that aerial photos showed significant loss of land due to river meandering (up to 1 m per year at the fastest eroding banks) contributed to the farmer's decision to change his current farming practices.

The trampled and polluted river corridor.
Source: Environment Agency

Description of the scheme

The riparian zones were established by fencing 6 to 20 m wide buffer zones. Vulnerable or unstable trees in these areas were either coppiced or pollarded to retain bank stability and to reduce the negative impacts of Phytophthora, a large group of pathogens affecting crops and natural ecosystems, which are prevalent in the catchment. The Woodland Trust undertook extensive planting to help develop better shrub and tree habitat and provide improved bank stability and thermal regulation of the river. Two ford crossing points were formalised with controls over stock access, and drinking bays were installed along with solar powered troughs. All feeding stations and mineral licks for cattle were located away from the river.

A range of bank protection techniques were trialled at key points to reduce the erosion rate and provide short to medium term bank protection while the vegetation and habitat structure developed in the riparian zones. There was no hydraulic study to underpin the design, and the protections used the excess woody material from the riparian zone.

The techniques used included:

- Placement of woody material in front of eroding banks; the material was live coppiced and pollarded material, dead stakes and dead hazel faggots;
- Bank reprofiling to reduce the height of vulnerable banks;
- Use of seeded geotextile to protect exposed soil.

Post being driven into the bank to place the faggots.
Source: Environment Agency

One year after implementation the bank is well vegetated.
Source: Environment Agency

Woody products from the coppicing and pollarding staked at toe of bank immediately after the works in March 2013 (left); in June 2013 (centre) showing the first growth of the grass and live willow protection; and in June 2014 with good willow and marginal growth.

Engineering performance

Three years after implementation, about half of the initial protection works are well established and vegetated. The other parts show signs of further erosion but are not considered to be critical for the overall scheme. Since most of the live protection is well established, the riparian zones are given time to develop.

High flows occurred in the first season (2013-2014) and the faggots, which were placed on the fastest eroding banks, were outflanked. As they were protecting a bank near a road, they were reinstated. After that, the dead faggots did trap silt and were vegetated by Himalayan Balsam. This invasive species was planned to be controlled by the sheep, which the farmer could let to graze along the river course. However the farmer also let his cattle in, which knocked over some trees and damaged the site slightly.

Design life

All the measures were devised on the spot and thus there was no consideration of lifetime expectations. However, for the river bank protection works, it was hoped that they would last for 3-5 years, allowing the buffer zones time to become fully grown. When these riparian zones are well developed, the scheme is expected to last for decades.

Inspection and maintenance

Inspection is done ad hoc by an occasional walk along the site, roughly every six months. The farmer is responsible for the maintenance of all the vegetation within the riparian buffer zone according to Natural England's Higher Level Stewardship scheme.

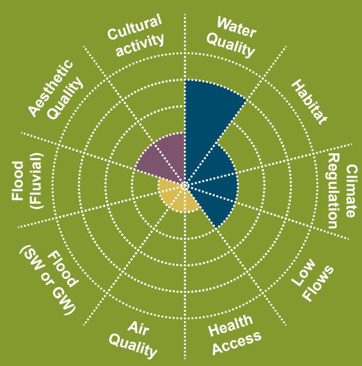
Costs

The cost of the bank protection was approximately £12,000.

Additional benefits

The ecosystem benefits delivered by the scheme have been quantified in the wheel chart.

The Environment Agency's initial concern about pollution due to fine sediments and nutrients entering the watercourse has been reduced. There is a public walkway adjacent to the river and a footbridge close to the protection works from where the natural protection can be seen.



Site location

Purslow, Shropshire

52°25'7.13"N 2°57'4.83"W

Contact details

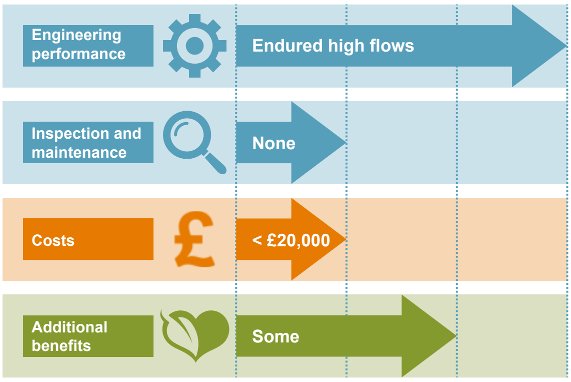
Environment Agency: enquiries@environment-agency.gov.uk

Case study 6
River Monnow - bank and toe protection

A 250m long bank that was eroding on the River Monnow, Kentchurch after the removal of a weir downstream, was protected in 2013 by bank regrading, coir matting, rock rolls and stakes toe protection, and bankside tree planting.

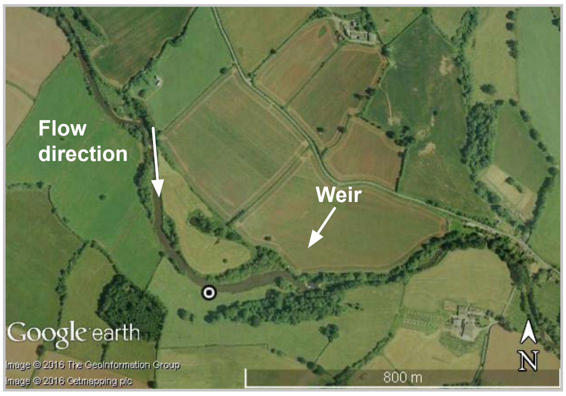
How successful has this scheme been?

The scheme is protecting the bank from erosion and has endured high flows without damage. The bank was regraded to an appropriate slope for a good grass cover, and the matting and toe protection were securely installed. The site is also protected from animal damage by a fence at the top of the bank.



Site characteristics

The River Monnow is a meandering river with a catchment up to the protected bank covering an area of 354 km^2. The slope at the restored section is estimated as 0.0017 (1:588), with an estimated bankfull discharge of 108 m^3/s. The waterbody has an overall Water Framework Directive status of 'good'. On either side of the scheme there is agricultural land.



Aerial view of the river reach

Motivation

Following the removal of a weir as part of a river restoration scheme to improve fisheries, erosion had occurred along 250 m of an outer bank upstream. Natural Resources Wales, who has years of experience working with a specialist bioengineering company, decided to move away from hard engineering and use a green protection for the eroded bank.

Bank erosion following the weir removal.
Source: Natural Resources Wales

The protection works finalised
Source: Natural Resources Wales

Description of the scheme

The work involved bank regrading, toe protection and tree planting.

The bank was regraded to roughly a 30 degree angle and a ‘V’ channel was excavated at both the top and bottom of the bank to allow the seeded coir matting to be stretched, pegged and laid in vertical strips on the bank. The ‘V’ channel at the top of the embankment was packed in with excess fill material to hold the top of the coir matting in place while also planting some willow along this area to help regeneration. Rock rolls were placed on the toe to weigh the matting down and were further secured by driving in a series of 750 mm long chestnut stakes. Branches of cut willow from the adjacent bank were wired down between the chestnut stakes with the purpose of entrapping sediment and encouraging growth at the toe.

Engineering performance

The scheme was completed in 2013 and high flows happened very soon after completion, which did not allow for the stakes to establish properly. Small pockets of erosion were detected at the toe but the coir mat did not suffer any damage. During this over-bankfull event, with discharges up to 168 m^3/s, the velocities along the outer bank are estimated to have been between 2.1 m/s and 2.7 m/s.

Design life

The expected design life would be longer than 10 years.

Inspection and maintenance

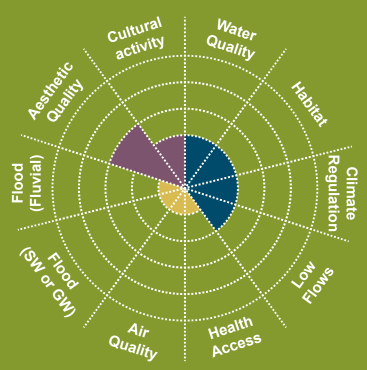
This was a one-off scheme with no Operational Responsibility to undertake long term repairs and therefore no allowance was made for inspection and maintenance from an Operations perspective. Any inspections are carried out by the NRW Fisheries Department, who would contact NRW Operations for any remedial work needed. The site has been visited once since the flood after completion of the scheme in 2013 (i.e. in three years). There has not been any maintenance so far nor is this expected in the future.

£ Costs

The cost was estimated at £18,000, considering £25/m for planted coir rolls and £46/m for rock rolls over a length of 250 m.

Additional benefits

Additional benefits provided by the scheme have been quantified in the wheel chart.



Site location

Kentchurch area, Monmouthshire, Wales

51°55’35.75”N 2°52’10.31”W

Contact details

Natural Resources Wales:
enquiries@naturalresourceswales.gov.uk

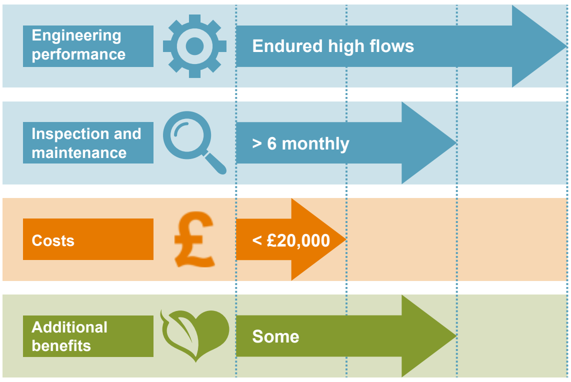
Case study 7

River Gwendraeth Fach - bank protection and modification of river shape

A shoal in the river Gwendraeth Fach was causing bank erosion in a residential area in Kidwelly, Wales. Two wooden groynes were installed to divert the flow away from the banks, which were protected with willow faggots and stakes, and rock rolls at the toe.

How successful has this scheme been?

The scheme is performing well and fulfilling its functions. The banks are now protected thanks to vegetation encroachment and accretion on the right bank, and no weaknesses have been exposed. Groynes have also helped to slow down accretion in the main channel. The scheme was easy to deliver given the site constraints. The materials that needed to be imported were minimal compared to what could have been needed if harder engineering had been used. The banks are well protected and vegetated above the high tide level, and so far no maintenance has been required.



Site characteristics

The Gwendraeth Fach is a single thread channel which is affected by high tides. The river catchment covers an area of 86 km^2. The calcareous water body has an overall Water Framework Directive status of 'good'.

At the scheme, the river slope is estimated as 0.002 (1:500), with an estimated bankfull discharge of 170 m^3/s. On either side of the scheme there are residential areas and the Special Area of Conservation of Carmarthen Bay estuary is one kilometre downstream of the scheme.

Aerial view of the site in 2010 with shoal

Motivation

A gravel shoal in the middle of the stream was diverting the flow towards the banks causing significant erosion near a residential area. This kind of shoals can be common upstream of bridges in tidal reaches.

The main drivers for the selection of a green approach were the construction constraints: soft soils and limited access to the river banks for heavy machinery; but it was also thought that the chosen measures would be well accepted by local residents.

Aerial view of the site in 2015 without shoal.

Description of the scheme

Two wooden pile groynes (one on each bank) were constructed to divert the flow away from the banks and prevent a shoal from forming in the future. They were placed as far upstream in the area to protect as was possible for an excavator to work. Manual installation of the wooden pile groynes further upstream was deemed impossible due to the very soft soil conditions.

The river banks were protected with willow faggots fixed with stakes and covered by gravel extracted from the river island. The willow faggots should stimulate accretion in case the top gravel layer eroded. The willow was harvested from an area close by where it was choking another river reach, so both systems benefited from the clearance of the willow. Rock 'mattresses' were placed at the toe; these were made of four rock rolls linked together, with rock 4-6 inches in size.

Faggots staked down above the rock roll mattresses.
Source: Natural Resources Wales, 2013

Wooden pile groynes diverting the flow away from the banks.
Source: Natural Resources Wales, 2013

The shoal in 2013 before the intervention.
Source: Natural Resources Wales

The smaller shoal in June 2016.
Source: Natural Resources Wales

Engineering performance

The scheme has endured some high fluvial and tidal flows. The most severe fluvial loading was in January 2016, with water levels below bankfull, an average flow velocity estimated as 1.8 m/s and up to 1.2 m/s near the banks.

The site was inspected on the 14th of June 2016 and the scheme was considered to be settling well. The left hand groyne is definitely promoting sedimentation behind it. Although some scour is developing at the edge of the groyne, this is not considered to be a problem at this stage. However, monitoring will be needed. The island is starting to reform, albeit still small at present. The flow seems to be shallower now that the island is smaller, as it is spread across wider channels. The banks above the high tide level are well vegetated.

Based on current performance, a possible improvement of the scheme suggested by local asset managers would consist of adding a groyne on the left bank downstream the existing groynes, which would contribute to further train the low to moderate flows.

Design life

A minimum lifetime of 10-15 years is expected for the wooden groynes. Since the faggots would be covered by silt due to tidal flows and thus prevented from having contact with oxygen, their lifetime is estimated to be much longer than the minimum 15 years.

Inspection and maintenance

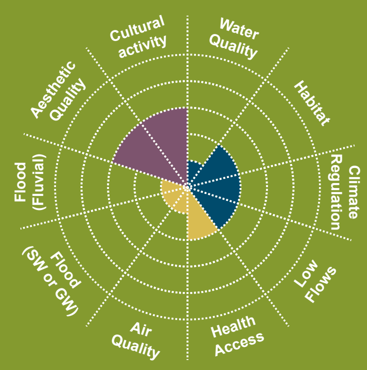
The site is under National Resources Wales's six monthly inspection for flood protection assets. So far no maintenance has been required. The willow faggots should require minimum maintenance because they are covered by the gravel and silt. In the future the willow stakes might need coppicing, which can be done when the flood bank behind is being cleared as well.

Costs

The cost was estimated at £18,000, considering £46/m for rock rolls, £30/m for hazel faggots and £100/m for mattress, over a length of 100 m.

Additional benefits

The works look natural and the site appears untouched, except for the two wooden pile groynes. The environmental performance of the scheme it not measured at inspections, but the additional benefits of the scheme have been estimated in the wheel chart.



Site location

Kidwelly, Carmarthenshire, West Wales

51°44'15.70"N 4°18'26.38"W

Contact details

Natural Resources Wales,

enquiries@naturalresourceswales.gov.uk

Case study 8

River Usk - bank protection

The replacement of an old retaining wall on the river Usk at Newport in 2011 presented a good opportunity to trial the addition of a regraded bank with brushwood mattresses and stakes that would help improve the waterbody status.

How successful has this scheme been?

The scheme is promoting siltation on the river bank as expected, and is also providing a natural appearance to the river. Consideration was given in the design to loading conditions, spatial implementation, bank slope and materials, and the scheme has withstood high tidal flows without suffering any damage. So far no maintenance has been required.

Engineering performance	Endured high flows
Inspection and maintenance	> 6 monthly
Costs	< £100,000
Additional benefits	Some

Site characteristics

The Usk is a single thread river with a catchment area of around 1,200 km^2. The tides dominate the river flow at the location of the scheme. The site is in the city of Newport, 7 km upstream of the Severn estuary, where the tidal range is about 12 m. The river contains important fish species and is a Special Area of Conservation and a Site of Special Scientific Interest.

Aerial view of the protected bank along the retaining wall

Motivation

The existing 75 year old retaining wall on the left bank was in very poor condition and needed replacing. In addition, scour pockets had developed in front of the wall. This was replaced with a primary flood defence consisting of a new steel sheet pile retaining wall. Physical modification of the river banks is the major cause within the Usk catchment area for not achieving a 'good' waterbody status according to the Water Framework Directive (WFD). As the new wall is stable on its own, this presented the opportunity for the use of measures such as a regraded bank in front of the wall and soft materials to help trap silt transported by the tidal flows.

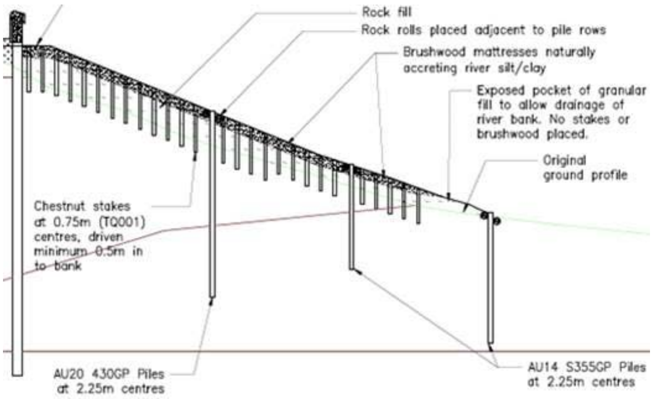
Description of the scheme

The scheme consists of a regraded bank against a sheet piled wall, with brushwood mattresses, hardwood stakes, and a 0.5 m thick rock fill layer on top.

The design slope of the river bank is no greater than 22 degrees to allow river silt/clay to remain on the stabilised slope. The purpose of the brushwood mattresses is to stimulate accretion and siltation on the bank, and to avoid scour holes deeper than 2 m which could destabilize the wall. The rock fill layer was placed over the brushwood to protect against changing water levels and counterbalance uplift forces.

All the materials used were dead and no live vegetation was included. The stakes were up to 2.5 m long (to permit the use of UK-sourced Forest Stewardship Council-certified timber). The 0.1 m diameter stakes were placed at 0.75 m centres. The stakes penetrate the rock fill and the river bank by another 0.5 m. Brushwood mattresses are formed from two perpendicular layers of 0.25 m diameter and 2-4 m long hazel and chestnut brushwood faggots.

The protected bank is mainly affected by tidal flow and therefore fluvial loading was not considered in the design. The flood protection scheme is designed for a 200 year tidal event. The design standard for the river bank slopes was based on several codes of practice (BS 6031: 1981 in combination with BS6349-1:2000). River bank slope stability analyses were also conducted. The construction of the bottom rows of stakes was done from a barge.



Schematization of the works carried out.
Source: Natural Resources Wales

Scheme at the final stages of construction. The bottom part of the brushwood mattresses is already covered in silt.
Source: Natural Resources Wales

Engineering performance

The scheme is stable and no further scour has occurred. Since the works were completed there have been some high tides and also some high river flows.

Design life

The sheet piles of the primary flood defence have a design life of 50 years, while the stakes and mattresses have a design life of 10-15 years. However, it is anticipated that the stakes and mattresses will function as a binder for the silt and, when encased by the silt, will last much longer.

Inspection and maintenance

Flood defences (i.e. the sheet piles) are inspected once a year. During the visit a cursory glance is given to the brushwood mattresses but no thorough inspection is deemed necessary. So far no maintenance has been required, nor any is expected in the future.

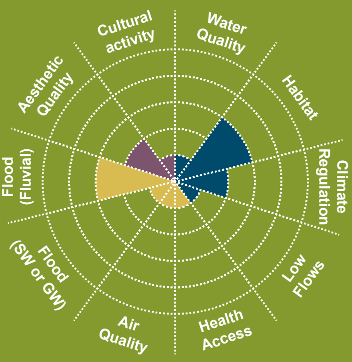
Natural Resources Wales assesses the condition of their water bodies through monitoring which produces an annual classification of the current status of the water environment for the Water Framework Directive.

Costs

The total cost of the scheme including land acquisition and additional mitigation costs was £266,000, so the bank protection scheme was estimated at less than £100,000.

Additional benefits

Additional benefits or ecological enhancement were not considered in the flood defence design, but these have been estimated in the wheel chart. There is no access to the waterside since this involves getting over the retaining wall. Nevertheless the accreted material provides a natural habitat.



Site location

Newport , Wales

51°35’31.85”N 2°59’34.30”W

Contact details

Natural Resources Wales
enquiries@naturalresourceswales.gov.uk

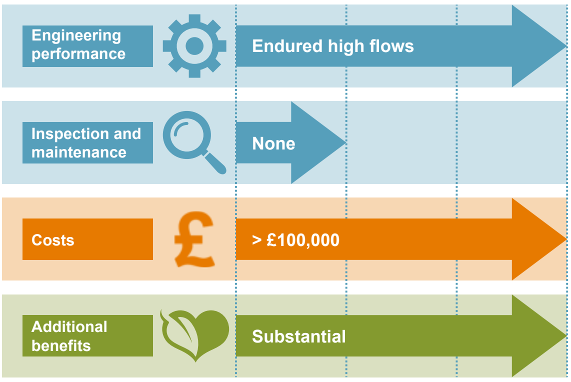
Case study 9

River Ravensbourne - modification of river shape

The old concrete lined channel of the river Ravensbourne at Brookmill Park in the London area was restored in 1998 into a meandering channel with sloping banks and vegetation.

How successful has this scheme been?

The scheme is a good example of combining flood risk management with environmental and social interest. With the modification (naturalisation) of the river shape, the flood storage capacity has been significantly increased and environmental and social values have been created. The scheme has withstood many high flows without suffering any damage. Movement of the river banks has not been observed. From a flood risk perspective, no maintenance is required. However, invasive species are controlled annually by volunteers.



Site characteristics

The scheme is located in the Ravensbourne River (in Brookmill Park) a heavily modified tributary of the River Thames in south London that has a median annual maximum discharge of around 20 m^3/s. The river catchment covers a densely populated area of 180 km^2. The levels at the site are partially controlled by a tide lock at the confluence of the Ravensbourne with the Thames river.

The river Ravensbourne at Brookmill Park.

Motivation

In 1998, the concrete lined channel of the river Ravensbourne was in the area for Docklands Light Railway's (DLR) proposed new railway line, and thus the channel had to be diverted. This provided the perfect opportunity to restore this section of the river.

Description of the scheme

The river was reshaped into a new 300 m long meandering 3-stage channel with a natural gravel bed, sloping river terraces with native landscaping, wildlife features and increased flood storage capacity. The 1st stage channel is a low flow channel that conveys river discharge during low flows protecting the aquatic life. The 2nd stage is the main channel of the river that conveys normal flows. The 3rd stage is now a floodplain meadow which was originally grassed and designed to accommodate flood flows of up to a 1 in 100 year flood. The 2nd and 3rd stage channels are defined by hard landscaping in the shape of porcupine blocks (rounded concrete blocks stacked to form a wall).

The new river channel is close to a chalk aquifer which is used for drinking water. This was identified early on and any possible pollution of the aquifer was mitigated by applying a waterproof membrane below the new river bed.

Porcupine block bank protection and access to the river. Source: HR Wallingford

Site after completion of the scheme. Source: Environment Agency

The site in 2016, 18 years after completion. Source: HR Wallingford

Engineering performance

The scheme is performing well. Since completion there has been extensive vegetation growth along the waterside and siltation on the berms from the 2nd stage channel. The storage capacity of the scheme is more important than its conveyance, so the increased roughness from the vegetation is not regarded as a potential threat. Siltation within the channel itself is also not considered to be a problem since the channel is expected to be self-cleansing.

The results of a simple hydraulics study show that high flows are unlikely to be an issue at this site and that there is sufficient freeboard in the bank heights for the scheme to be able to cope with higher flows in the future. On the contrary, the concern is that periods of low flows may harm the aquatic life, due to elevated temperatures. During five percent of the year the water depth is extremely shallow (a few centimetres), with some deeper pools (around 0.20 m), but the trees along the banks provide shading which helps control the water temperature.

Design life

Specific information on design life of the scheme was not available but materials with short design life were not used.

Inspection and maintenance

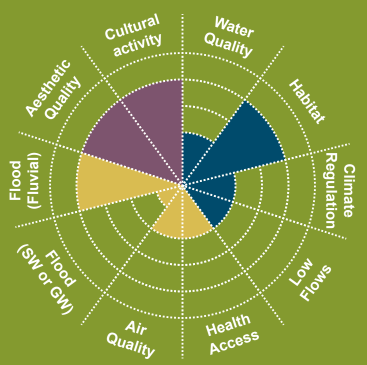
The scheme does not require any maintenance from a flood management perspective. The vegetation is cut down on an ad hoc basis, but mostly from an aesthetical perspective so that the view on the river is undisturbed. Invasive species like Himalayan Balsam are controlled on a regular basis by the '3RiversCleanUp' initiative, a three-week long intensive annual volunteer campaign to improve the rivers Ravensbourne, Pool and Quaggy in South East London.

Costs

The cost of the scheme is estimated at around £110,000.

Additional benefits

Before the scheme was constructed, the concrete lined channel did not provide any habitats. Now all planted vegetation is well established and fish have returned to the river. The river has been used by schools to study 'river life'. The park itself is one of the few green areas in the Borough of Lewisham and the diverted channel offers a valuable asset. During a visit in August 2016 many different bird species as well as dace and eels were spotted.



Site location

Brookmill Park , Lewisham, London

51°28'10.17"N 0° 1'6.32"W

Contact details

Environment Agency,

enquiries@environment-agency.gov.uk

Case study 9 - River Ravensbourne

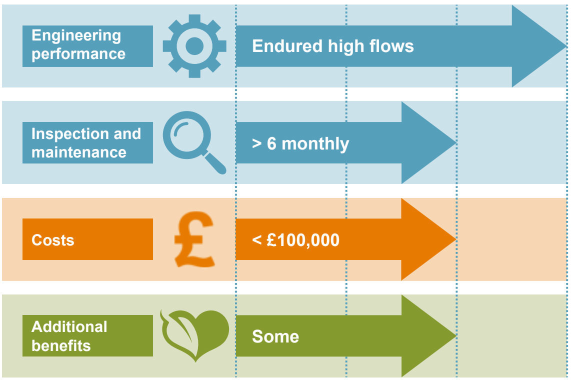
Case study 10

River Avon - modification of river shape

A 850m reach of the river Avon at Amesbury was restored in 2008 with large wood debris deflectors, gravel shoulders and bank regrading to reinstate the habitats lost by historical dredging.

How successful has this scheme been?

The River Avon restoration project at Amesbury has benefited from a higher degree of environmental design than most schemes using green measures. Although the site's potential for restoration was limited by a weir downstream, the project is regarded as successful. New habitats have been created and flow and morphological diversity have returned to the site.



Site characteristics

The river Avon at Amesbury is a single thread chalk river, surrounded by a mix of agricultural, residential and unused floodplain land. The river catchment upstream covers an area of 320 km^2. The median annual maximum discharge through the restored section is 11 m^3/s. The reach has a bridge and the flow is controlled by a weir downstream.

The River Avon and its main tributaries are designated as a Special Area of Conservation (SAC) and a Site of Special Scientific Interest (SSSI), and downstream of the scheme the Avon Valley is designated as a Special Protection Area (SPA) for birds.

Motivation

Past dredging activity during the 1950s and in 1967, when the river was realigned during construction of a road, had resulted in many parts of the river channel being oversized (widened and deepened) and the natural bed material being removed. This had caused silting up of naturally clean river gravels and destruction of habitats.

The objective of the scheme was to create a diversity of morphology and flow for species, particularly a gravel substrate for migratory salmonids to spawn on, large woody debris for bullhead, and well sorted, fine sediment in shaded, marginal areas for brook lamprey. Amesbury was one of the six sites restored as part of the £1 million four-year conservation project STREAM (STrategic REstoration And Management), aimed at reinstating a dynamic and diverse chalk stream habitat that is sustained by the river natural flow.

The 'crucifix' as it is placed in the trench before being backfilled. Source: Natural England

Description of the scheme

The scheme included: large woody debris deflectors over a length of 850 m; two gravel bars and three gravel deflectors on alternate banks upstream of the weir; narrowing of the channel downstream of the bridge by sliding the front edge of vegetation put into the channel and regrading the bank behind it. Construction started in mid-September and finished mid-October in 2008.

The flow deflectors consisted in large whole trees installed horizontally as groynes on either bank. The trees protruded roughly 7m into the channel to narrow the width by 35% to 50%, and were placed pointing upstream at an angle of 45º to 60º to help deflect the flow towards the centre of the channel. The effect of the resulting lower conveyance during high flows was deemed acceptable based on a flood study.

Three different techniques were used to fix the trees to the river banks: (1) a timber crucifix design where the bank material was suitable; (2) ground anchoring with steel cables; and (3) a staking technique where the presence of vole colonies prevented the cutting of slots that would disturb the soil. In all methods, the trees were additionally pinned to the river bed to a depth of 2 m with 3 m long by 40 mm diameter steel bars to ensure that they did not move or pull free from the bank. These steel bars were a requirement to get flood defence consent for the work.

Channel narrowing caused by the wood deflectors.
Source: River Restoration Centre

Gravel shoulder, Source: River Restoration Centre

Engineering performance

Being the last reach of the STREAM project to be restored, the scheme at Amesbury benefited from lessons learned on the other reaches. However the flow was controlled by a weir downstream which reduced the potential for restoration.

The flow deflectors have increased the flow diversity, creating a more varied habitat with silty marginal dead water areas for lamprey and adult bullhead, and faster flows in the middle of the channel that help remove the silt and keep a clean gravel bed for spawning. The slack flows around the deflectors have induced siltation at the banks, promoting the growth of vegetation. The woody material also traps cut weed, forming rafts that provide cover for fish.

The gravel deflectors and shoals have been found to be insufficient for the depth of the channel and therefore have had a comparatively lower effect on flows.

Inspection and maintenance

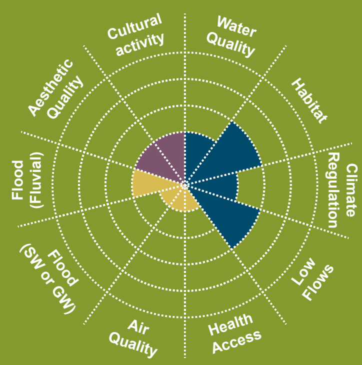
Pre and post restoration surveys were undertaken at the site as part of the STREAM project. The surveys included fluvial audit, physical biotope mapping, river corridor survey and repeated fixed point photography. Information on the hydraulic performance of the measures is however not available. Aquatic plants are annually managed by cutting throughout the River Avon catchment, and the bank vegetation maintenance regime has been altered to ensure a 1-2 metre strip of vegetation is kept along the bank, with small viewing slots cut into it. Also, vegetation had to be cut off at the outer ends of the submerged trees in order not to affect fishing lines and the operation of cut weed vessels.

£ Costs

The scheme was executed at a cost of £34,000.

Additional benefits

The scheme is considered to be successful in creating a diversity of habitats as shown by the post-construction surveys. The dominant vegetation remains similar to that observed prior to restoration and new species were observed in the following year, including water crowfoot, watercress and water mint. The site is also publicly accessible and a popular footpath runs alongside it.



Site location

Amesbury, Wiltshire

51°10’45.70”N 1°46’28.23”W

Contact details

Natural England: enquiries@naturalengland.org.uk

Additional information

The STREAM project: http://www.streamlife.org.uk/.

River Restoration Centre (2002), Manual of river restoration techniques. Fixing whole trees into the river bank for flow diversity, Silsoe, U. K. (Available at http://www.therrc.co.uk/MOT/Final_Versions_%28Secure%29/5.6_Amesbury.pdf).

Natural England (2009). Physical and biological monitoring of STREAM restoration projects. Year Four Report. (Available at http://webarchive.nationalarchives.gov.uk/20110303155229/http://www.streamlife.org.uk/pdf/STREAM_Monitoring_report_year_4.pdf).

STREAM River Restoration techniques advice note. Available at: http://www.streamlife.org.uk/pdf/STREAM_restoration_techniques_advice_note.pdf.

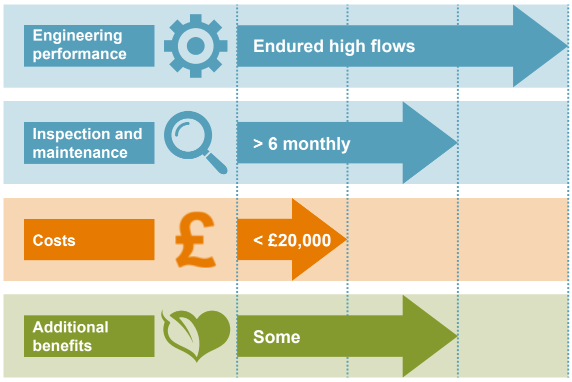
Case study 11

Cwm Mill Stream - bank and toe protection

An eroding bank on the small Cwm Mill stream near Ferryside in Wales was protected in 2015 with coir matting on the bank and rock rolls at the toe.

How successful has this scheme been?

The scheme has met its objectives. High flows soon after completion produced no damage to the embankment.



Site characteristics

The Cwm Mill Stream is a small stream less than 2 m wide at Ferryside in Wales. The river slope at the site is estimated as 0.066 (1:15), with an assessed bankfull discharge of 2 m^3/s and an average velocity of 1.7 m/s. The waterbody has an overall Water Framework Directive status of 'good'. There are 69 properties at the site at risk from a combination of fluvial and surface water flooding. Although close to the estuary of the River Towy, the site is not tide- influenced due to the presence of a non-return sea door.

Motivation

The flood bank which lies between the stream and the main road had a history of erosion. Two areas had been repaired in April 2010 and in 2015 another section eroded and repairs were required to prevent a reduction in channel conveyance. Lining with rock rolls at the toe to prevent erosion was a technique that had been used in the past on similar rivers to good effect and it was also adopted here.

Flood embankment showing signs of erosion. Source: Natural Resources Wales

Repair work underway. Source: Natural Resources Wales

Completed works in September 2015. Source: Natural Resources Wales

Description of the scheme

The scheme is approximately 40 m long and consists of a floodbank protected by rock rolls and coir matting on the bank to prevent erosion.

Engineering performance

The embankment is well vegetated and the bank is protected. High flows occurred in December 2015 but no damage was observed even though grass cover had not yet fully developed. This is attributed to the correct performance of the coir mat protecting the embankment.

Design life

Lifetime was not considered as a parameter in the design.

Inspection and maintenance

There is a six monthly inspection regime for this site. If significant damage is detected, in-depth analysis will be carried out.

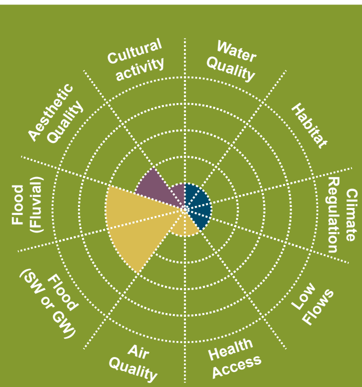
High flows on 30th December 2015 showing no damage to the embankment. Source: Natural Resources Wales

Costs

The cost of the scheme is estimated at £3,000, considering £25/m for planted coir rolls and £46/m for rock rolls over a total length of 40 m.

Additional benefits

The additional benefits of the scheme have been quantified in the wheel chart.



Site location

Ferryside, Carmarthenshire

51°46’27”N 4°21’37”W

Contact details

Natural Resources Wales,

enquiries@naturalresourceswales.gov.uk

Case study 12
River Washford - bank and toe protection

A rotted wood piling protection on the outside of a bend in the high energy river Washford in Roadwater (Somerset) was replaced in 2013 with a vegetated reinforced mattress on the bank and rock rolls at the toe.

How successful has this scheme been?

The bank protection has bedded in well and some natural vegetation has colonised the toe and bank. The high resistance reinforced mattress is well suited for this high energy river, so in the two years since completion there has been no appreciable damage to the scheme.

Engineering performance	Endured high flows
Inspection and maintenance	> 6 monthly
Costs	< £100,000
Additional benefits	Some

Site characteristics

The Washford River is about 17 km long from source to mouth. At Roadwater in Somerset it is a fast response, high energy river with a mobile cobble bed and with properties at both sides. The river slope at the scheme is estimated as 0.0077 (1:130), with a bankfull discharge of 7 m^3/s. The waterbody is heavily modified in this stretch and has an overall Water Framework Directive status of 'moderate'.

Motivation

The existing 1980s large wooden pin pile protection of an outside bend had become rotten and needed replacing. A cost-effective and more environmentally sensitive protection was sought to replace the steep, artificially created bank.

Left: Installation of toe protection (2013); Right: Completed works (2013). Source: Environment Agency

Description of the scheme

The site works comprised a 40 m long reach and were completed in ten days in November 2013. The solution included toe protection in the form of rock rolls placed on the river bed (i.e. not trenched in), and bank protection using vegetated reinforced mattresses. The proprietary mat used was rated to withstand flow velocities up to 6 m/s and allowed native vegetation to colonise the turf, providing a more natural look from the second year onwards.

Engineering performance

The reinforced vegetated mattresses eroded in one small patch, initially exposing the inner synthetic mesh, but this did not compromise the works and has now become re-vegetated through natural seeding. The scheme has experienced maximum flows of 8.11 m^3/s, which corresponds to a maximum mean channel velocity of approx. 2.2 m/s, with no real damage. The long term performance of the rock rolls nylon mesh in highly abrasive environments like the Washford River at Roadwater is uncertain.

Design life

Lifetime was not considered as a parameter in the design.

Inspection and maintenance

The site is inspected annually and a routine maintenance schedule is in place for managing riparian vegetation in order to maintain conveyance.

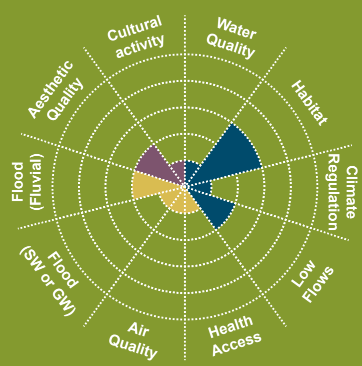
Two years after completion, natural vegetation has colonised both the toe and the bank. Source: Environment Agency

£ Costs

The budget for this scheme was £28,000.

Additional benefits

The additional benefits of the scheme have been quantified in the wheel chart. The main purpose of the scheme is to provide erosion protection to the bend, but the rock rolls have been trapping some finer gravels and silt and allowing some vegetation to grow at the foot of the bank. This, combined with natural vegetation colonising the bank, has improved the habitat conditions at this site.



Site location

Roadwater, Somerset

51°8'28"N 3°22'47"W

Contact details

Environment Agency,

enquiries@environment-agency.gov.uk

Chapter 5

Further reading and information

Further details and descriptions of the different green measures can be found in several publications:, Environment Agency (1997), Escarameia (1998), NCHRP (2005), SEPA (2008).

The following publications are manuals providing more detailed information about selections and applicability of measures: Environment Agency (1997), NCHRP (2005), RRC (2013). There are many other manuals available on-line as for example Alo Terra Restoration & Golder Associates (2016) and Alaska Department of Fish and Game (2005).

The SEPA Good Practice Guide (SEPA 2008) provides information to identify solutions to bank erosion that balance environmental protection with social, economic and technical constraints.

Another SEPA publication that leads with river bank erosion protection involving trees is SEPA (undated).

SEPA also runs a scheme to gather information from demonstration sites applying techniques with trees or parts of trees. The scheme started in October 2016: http://www.sepa.org.uk/regulations/water/engineering/grant-scheme-for-riverbank-repair-demonstration-sites/#Further.

"Aquatic and riparian plant management: controls for vegetation in watercourses" (Environment Agency, 2014b) provides guidance to inform decisions on when and how to manage vegetation and provides further information on river typology. Environment Agency (2015b) also provides detailed information on channel typology.

The CIRIA Manual on scour at bridges and other hydraulic structures (CIRIA, 2015) provides detailed information on how to estimate loading conditions to design a protection.

Useful fluvial geomorphology concepts can be found in Sear et al (2010) and in an earlier version Sear et al (2003) which is freely accessible.

Chapter 6
References

All the links were accessed in April 2017.

Alaska Department of Fish and Game (2005) Streambank revegetation and protection. A guide for Alaska. Revised 2005. http://www.adfg.alaska.gov/static/home/library/pdfs/habitat/98_03.pdf.

Alo Terra Restoration & Golder Associates (2016) Living streambanks. A manual of bioengineering treatments for Colorado Streams. https://coloradoewp.com/sites/coloradoewp.com/files/document/pdf/Biostabilization_Manual_072416.pdf#pdfjs.action=download.

CIRIA (2015) Manual on scour at bridges and other hydraulic structures. Second Edition. C742 http://www.ciria.org/Resources/Free_publications/manual_on_scour.aspx.

Environment Agency (1997) Waterway bank protection: a guide to erosion assessment and management. R&D Draft Technical Report W5/i653/3.

Environment Agency (2010) Flood risk management estimating guide - update 2010. Bristol: Environment Agency.

Environment Agency (2014a) Working with natural process to reduce flood risk. R&D framework: initiation report. SC130004/R1.

Environment Agency (2014b) Aquatic and riparian plant management: controls for vegetation in watercourses". Project SC120008/R2. https://www.gov.uk/government/publications/aquatic-and-riparian-plant-management-controls-for-vegetation-in-watercourses.

Environment Agency (2015a) Cost estimation for channel management – summary of evidence. Report – SC080039/R. http://evidence.environment-agency.gov.uk/FCERM/Libraries/FCERM_Project_Documents/SC080039_cost_channel_mgmt.sflb.ashx.

Environment Agency (2015b) Channel management handbook. Report SC110002, https://www.gov.uk/government/publications/channel-management-handbook-for-flood-risk-management.

Escarameia, M. (1998) River and channel revetments. A design manual. Thomas Telford, London.

Millennium Ecosystem Assessment (2005) Ecosystems and human well-being: synthesis. Island Press, Washington, DC. http://www.millenniumassessment.org/documents/document.356.aspx.pdf.

NCHRP (2005) Environmentally sensitive channel and bank protection measures. Report 544. http://www.trb.org/Publications/Blurbs/156479.aspx.

RRC (2013) Manual of River Restoration Techniques http://www.therrc.co.uk/manual-river-restoration-techniques.

RSPB, NRA and RSNC (1994) The new Rivers & Wildlife Handbook. The Royal Society for the protection of birds. UK.

Sear, D.A., Newson, M.D. and Thorne, C.R. (2003) Guidebook of applied fluvial geomorphology. R&D Technical Report FD1914. Defra/Environment Agency http://randd.defra.gov.uk/Default.aspx?Module=More&Location=None&ProjectID=10695.

Sear, D. A., Newson, M. D. and Thorne, C. R. (2010) Guidebook of Applied Fluvial Geomorphology, Thomas Telford, London, UK, ISBN 978-0-7277-3484-6, 257 pages.

SEPA (-) Reducing river bank erosion. A best practice guide for farmers and other land managers. http://www.sepa.org.uk/media/219450/bank_protection_guidance.pdf.

SEPA (2008) Engineering in the Water Environment. Good Practice Guide. Bank Protection. Rivers and Lochs. https://www.sepa.org.uk/media/150971/wat_sg_23.pdf.

TCPA (2008) The essential role of green infrastructure: eco-towns green infrastructure worksheet http://www.tcpa.org.uk/data/files/etws_green_infrastructure.pdf.

USACE (2000) Stream management. By Fischenich, J. C. and Allen, H. H. ERDC/EL SR-W-00-1. US Army Corps of Engineers, Engineering Research and Development Center.

Websites

The National Ecosystem Assessment (NEA), http://uknea.unep-wcmc.org/.

The Economics of the Environment and Biodiversity (TEEB) http://www.teebweb.org/.

The State of Natural Capital reports https://www.gov.uk/government/publications/natural-capital-committees-third-state-of-natural-capital-report.

Appendix

Table A1 - Additional examples of application of GI measures

Example	Type of intervention	Type of GI measure	River	Location	Date of intervention
A	Bank protection	Stakes, geotextile	Stour	Muscliffe Park, Bournemouth, Dorset	2016
	http://www.cainbioengineering.co.uk/2016/05/13/river-bank-erosion/				
B	Bank protection	Geo-Cell system	Small Brook	Clitheroe	Unknown
	http://www.abg-geosynthetics.com/request-file.act?target=302				
C	Modifying river shape	Faggots, stakes	Itchen	-	2011
	http://www.wildtrout.org/content/upper-itchen				
D	Bank protection	Coir rolls	Thames	Laleham	2009
	http://www.ecrr.org/Portals/27/Riverbank%20Repairs%20at%20Thames%20Side,%20Laleham.pdf				
E	Bank protection	Coir rolls, stakes, geotextile	Cam	Cambridge	2011
	http://www.ecrr.org/Portals/27/River%20Cam%20Soft%20Revetment%20Project.pdf				
F	Bank protection	Coir pallets, vegetation	-	Medmerry (West Sussex)	2013
	http://www.salixrw.com/solution/medmerry-managed-realignment-water-vole-habitat-mitigation/				
G	Bank protection, modifying river shape	Cobbles, woody debris, re-profiling, faggot & brushwood bundles	Coln	Gloucestershire	UNK
	http://www.wildtrout.org/content/river-coln-gloucestershire				
H	Modifying river shape	Meanders, fine gravel used in bed and toe	Whit Beck	Cumbria	2014
	http://westcumbriariverstrust.org/projects/river-restoration-strategy/whit-beck				
I	Weir removal, bank	Faggots, stakes, coir matting	Lesser Teise	Kent	2015-2016
	http://www.southeastriverstrust.org/tag/river-restoration				
J	Embankment removal	Reprofiling	River Ribble (Long Preston Deeps)	North Yorkshire	2011-present
	http://longprestonfloodplainproject.org/river-ribble-restoration.php https://restorerivers.eu/wiki/index.php?title=Case_study%3ALong_Preston_Deeps_Flood_Plain_Project#Project_summary				
K	Bank protection	Vegetated concrete blocks	Welney Wash; Middle Level Barrier Banks	Cambridgeshire	2001-2005
	http://www.armortec.co.uk/downloads/WelneyWash.pdf				
L	Bank protection	Vegetated gabions	Wheelwright Creek	Exeter, New Hampshire, USA	2004-2005
	https://www.landandwater.com/features/vol50no5/vol50no5_1.html				

Example	Type of intervention	Type of GI measure	River	Location	Date of intervention
M	Toe protection	Aquatic vegetation	River Thames	Penton Hook Reach, Thames Side, Laleham, Surrey	2009
	http://www.ecrr.org/Portals/27/Riverbank%20Repairs%20at%20Thames%20Side,%20Laleham.pdf				
N	Toe protection	Vegetated rock rolls	River Ebbw	Risca, South Wales	
	http://www.salixrw.com/solution/river-ebbw-bank-stabilisation/				
O	Bank protection	Vegetated reinforced earth	River Lossie	Elgin, Moray, Scotland	2012-2014
	http://www.ecrr.org/Portals/27/Elgin%20Flood%20Alleviation%20Scheme.pdf				
P	Bank protection	Vegetated riprap	Columbia River	Trail, British Columbia, Canada	2006
	http://www.terraerosion.com/InstallationofVegetatedRiprap.htm				

Table A2 - Compiled case studies (Source: Environment Agency; date of compilation 24/03/2016)

Measures	Case study	EA Area
Hazel faggots	Eastburn Beck and West Beck - part of river restoration project in 2014	Yorkshire
	Sherborn Brook (River Windrush)	West Thames
	Monkbretton, tidal River Rother, Rye, East Sussex	Kent and South London
	River Taw Devon near Abbots Marsh (example of a failed scheme)	Devon and Cornwall
	Maidenhead Ditch @ Bray Wick, River Adur @ Shipley	West Thames
	1) Ashlone Wharf, 2) Olympic Park, 3) Hampstead Heath	Hertfordshire and North London
	River Kent South Cumbria	Cumbria and Lancashire
	River Worfe Catchment; Worfield, Hilton, Claverley	Shropshire Herefordshire Worcestershire and Gloucestershire
	1) Medmerry, 2) Riverside FAS, Newport.	Solent and South Downs
	TA05007 56700 West Beck - Whinhill fish farm. Stream restoration works: R Hull headwaters chalk streams	Yorkshire Wildlife Trust http://www.ywt.org.uk/living-landscapes
	Oak Weir, River Medway, Kent	Kent, South London and East Sussex - http://www.southeastriverstrust.org/
	River Allen and River Frome	Wessex

Measures	Case study	EA Area
Planted fibre rolls	Clifton-on-Bowmont, Yetholm, Scottish Borders (Filtrexx)	SEPA e.g.
	Rydings reservoir, Rochdale	Greater Manchester Merseyside and Cheshire
	Perry park, Birmingham	Staffordshire Warwickshire and West Midlands
	River Mersey - SJ 81096 92541	Greater Manchester Merseyside and Cheshire
	Windermere	Cumbria and Lancashire
	River Test & River Itchen, Hampshire	Solent and South Downs
	1) Olympic Park, 2) River Ray, 3) Hampstead Heath, 4) Warnham Mill, 5) Willowbank	Hertfordshire and North London
	1) Medmerry; 2) Rossett FAS	NRW e.g.
	Avonmouth	Wessex
	Abergele	NRW e.g.
	West Beck - Whinhill fish farm. TA05007 56700	-
	R Hull headwaters chalk streams. SE99856 58142	-
	Elmswell Beck - R Hull Headwaters chalk stream	Yorkshire
	Brunton Park Flood Alleviation Scheme, Ouseburn, Newcastle	Northumberland Durham and Tees
	River Frome	Wessex
	River Cray, through Foot Cray meadows, London. River Wandle through Ravensbury Park	Kent and South London
	Arrowe Brook, Upton, Wirral	Greater Manchester Merseyside and Cheshire
	Steeple Bumpstead	Essex, Nortfolk and Suffolk
Reinforced earth	Sydling Chalk Stream, Dorset	-
	North Wyke weir removal, Devon	Devon and Cornwall
	1) Olympic Park, 2) Hampstead Heath	Hertfordshire and North London
	North Wyke weir removal, Devon	Devon and Cornwall
	Banbury	West Thames
	Coir matting Brunton Park Flood Alleviation Scheme, Ouseburn, Newcastle	North East
	Banks of the Stour Estuary, west of Sandwich, Kent	Kent, South London and East Sussex

Measures	Case study	EA Area
Rock rolls	River Mersey - SJ 81096 92541	Greater Manchester Merseyside and Cheshire
	Winchester, and in other parts of the catchment	Solent and South Downs
	Steeple Bumpsted	Essex, Nortfolk and Suffolk
	1) Olympic Park, 2) Hampstead Heath, 3) Willowbank, 4) St Michaels on R Wyre	Hertfordshire and North London
	Dymchurch	Kent, South London and East Sussex
	Arrowe Brook, Upton, Wirral	Greater Manchester Merseyside and Cheshire
Timber piling	Clifton-on-Bowmont, Yetholm, Scottish Borders (Filtrexx)	SEPA e.g.
	R Derwent NY25502380, NY23702345, NY01152935	Cumbria and Lancashire
	Piling using sweet chestnut poles at Rye Harbour in East Sussex	Kent, South London and East Sussex
	Rusland Pool, Cumbria	Cumbria and Lancashire
	Aspenden Brook	Hertfordshire and North London
	River Thames, Deptford Creek	Kent, South London and East Sussex
	River Till Wetland Creation Project; Cheviot Futures; Belford Catchment Solutions Project, all Northumberland	North East
	Theale	Thames

Measures	Case study	EA Area
Willow spiling	Clifton-on-Bowmont, Yetholm, Scottish Borders (Filtrexx)	SEPA e.g.
	Buxted Park- River Uck	-
	NGR - TQ48831 22577	Solent and South Downs
	Yokefleet, River Ouse, various habitat improvement projects on the River Hull Headwaters SSSI	Yorkshire
	River Otter, Devon, River Axe, Devon	Devon and Cornwall
	1) Olympic Park, 2) River Wensum, 3) St Michaels on R Wyre	Hertfordshire and North London
	Bodfach, Llanfyllin, Afon Cain. Afon Dulas (Glan y avon Halt), Afon Tannat (Penybontfawr)	NRW e.g.
	River Ecclesbourne, Derbyshire. Undertaken by Derbyshire Wildlife Trust	Derbyshire Nottinghamshire and Leicestershire
	Easton walled garden	Lincolnshire and Northamptonshire
	TA05007 56700 West Beck - Whinhill fish farm. Stream restoration works: R Hull headwaters chalk streams	Yorkshire
	River Browney Burnhall Willow Spiling, Wear (Durham). Blyth Improvements - Northumberland Wildlife Trust. Northumbria River Basin Rural Diffuse Pollution Partnership - many examples across the North East delivered by Rivers Trust partners,e.g. Upper Tees, Rede, Aln, Coastal Streams in Northumberland	North East
	Wraysbury	Thames
	East Peckham, River Medway, Kent	Kent, South London and East Sussex
	Plym Bridge, Plymouth - high energy system, high banks	Devon and Cornwall
	Hadham Ford, Little Hadham, Herts	Hertfordshire and North London

978-1-898485-16-2