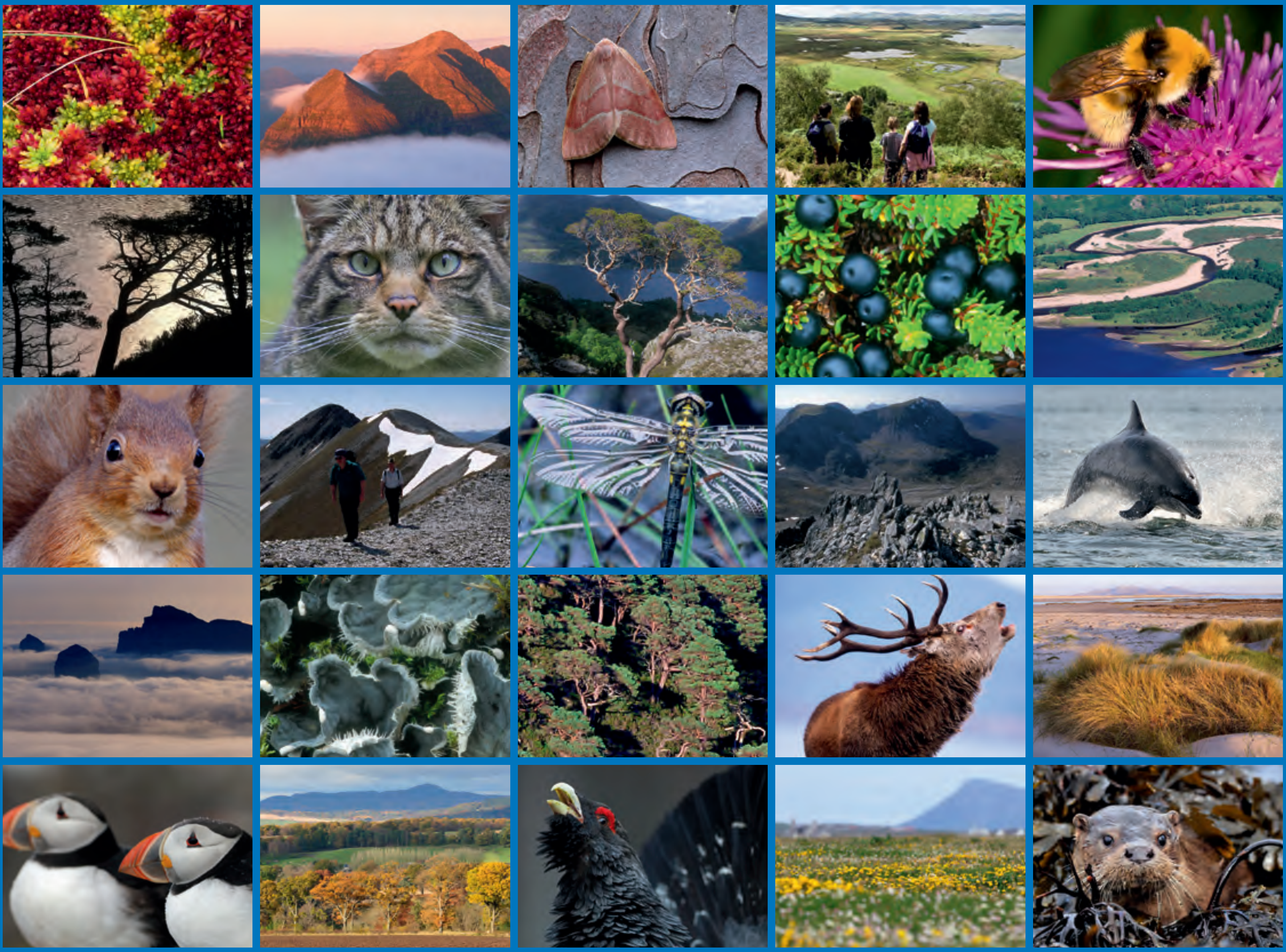
Scottish Natural Heritage
Commissioned Report No. 817

River restoration and biodiversity



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COMMISSIONED REPORT

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River restoration and biodiversity

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COMMISSIONED REPORT

Summary

River restoration and biodiversity

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Keywords

Water Framework Directive; river habitats; river processes; ecosystem services; Natura 2000; hydromorphology; catchments.

Background

Over the last 20 years there has been a growing interest in restoring river habitats by restoring physical processes. This report acts as the basis of Phase 1 of a three-phased project, to be carried out under the auspices of the IUCN National Committee, for reviewing river restoration in the UK and Ireland. The study presents an updated review of river restoration and biodiversity across the United Kingdom (UK) and the Republic of Ireland (ROI).

Main findings

- A broad range of policy and legal obligations has provided a framework for river restoration to develop and river restoration fulfils multi-benefits across a range of policy and advice.
- Currently river restoration is being framed as a way of improving the ecosystem services offered by rivers and is seen to be one of the key drivers for the release of river restoration-related government funding in the UK.
- There is a growing evidence base for the benefits of restoration activities but projects are seldom appraised in sufficient detail to discern benefits or effectiveness of techniques
- Restoration activities have been widespread across regions with catchment projects now taking the lead and increasing focus on hydromorphology.
- Process-based river restoration is central to schemes in Scotland due to the habitat requirements and long-term development aims for the target species. Scoping studies have identified physical damage to the rivers and projects are currently under way to design and implement measures that benefit freshwater pearl mussels and salmonids.
- Monitoring rarely reflects the timescale of ecosystem recovery.
- In Wales and Northern Ireland, river restoration currently has no formal delivery mechanism for catchment-scale approaches such as WEF in Scotland, the CRF in England and the EREP and enhanced maintenance programmes.
- There are varied delivery mechanisms and strategies for restoration across the region.

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Acknowledgements

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1. INTRODUCTION

1.1 Background

Ecus Ltd. working in partnership with Centre for River Ecosystem Science (CRESS) were commissioned to produce this review of river restoration and biodiversity across the United Kingdom (UK) and the Republic of Ireland (ROI). The work covers Phase 1 of a proposed three-phase project. This first phase of the project reviews the present status of river restoration in the UK and Ireland.

Over the last 20 years there has been a growing interest in restoring river habitats by restoring physical processes. This report acts as the basis of Phase 1 of a three-phased project, to be carried out under the auspices of the IUCN National Committee, for reviewing river restoration in the UK and Ireland. The IUCN NCUK river restoration project has been set up to promote best practice in river restoration for supporting biodiversity, for enhancing ecosystem services, and for developing a more consistent approach to meeting the aims of the EC Water Framework Directive, the Habitats Directive and the Floods Directive.

It builds on work carried out by the project partners and other bodies in the UK, Northern Ireland, Republic of Ireland and other parts of Europe. The work has the support of the IUCN, Scottish Environment Protection Agency, Environment Agency, Northern Ireland Environment Agency, Rivers Agency (Northern Ireland), Natural England, Natural Resources Wales, Loughs Agency (NI) Office of Public Works (ROI), Inland Fisheries Ireland (ROI) and the River Restoration Centre.

Habitat restoration may be considered part of the wider ‘ecosystem approach’ which has increasingly gained support since it was incorporated in the 1992 Convention on Biological Diversity (CBD). One of its 12 ‘principles’ states that the ‘conservation of ecosystem structure and functioning, in order to maintain ecosystem services, should be a priority target of the ecosystem approach’. This study contributes to the CBD’s Aichi Target 14, and to a range of objectives and approaches developed by the organisations supporting this project.

At present there is wide variability in the river restoration work undertaken throughout the UK and Ireland. This makes it difficult to assess (a) how restoration is contributing towards ecosystem structure and functioning (and therefore ecosystem health), and (b) whether river restoration is benefiting habitats and species (e.g. those protected under the Habitats Directive) while also enhancing a range of ecosystem services such as the maintenance of sustainable fisheries and reducing flood risk.

The first phase of this project has evaluated the effectiveness of a variety of approaches to river restoration in different catchment settings. This will help guide advisers and practitioners in designing restoration and monitoring work, and will be used to develop the subsequent phases of the work.

1.2 Purpose and scope of work

Process-based river restoration and rehabilitation are a key focus for achieving our obligation to improve rivers for the benefit of biodiversity and our ecological, societal and cultural well-being. This first phase of the project reviews the present status of river restoration in the UK and Ireland and aims to report on the effectiveness of particular techniques and outcomes.

The principal focus for examination of river process is on physical habitat restoration rather than water quality improvement, although it is recognised that there are links between the two. The review also considers the effects of structures associated with flow regulation but not the impacts of abstraction. The report seeks to place the findings of the review within the context of whole-catchment management, although focused on freshwater rather than estuarine systems. The work is relevant to all sizes and types of rivers in the UK and Ireland.

1.3 Objectives

The key focus for this report is on river corridors, and the restoration of upstream and lateral connectivity between channels, banks, riparian areas and floodplains. The objectives are:

(a) To review the link between river processes and biodiversity, by gathering evidence of the benefits of restoring natural processes for river, riparian and floodplain biodiversity.

(b) To describe the main causes and extent of physical habitat damage in rivers in the UK and Ireland and to review the need for restoration in the light of this information.

To assess the current status of river restoration in the UK and Ireland, including a comparison of each of the five countries.

2. APPROACH

2.1 Overview

This section reviews the sources of information collated to develop the evidence base for this project (Section 2.2) along with a succinct summary (Section 2.4) of the databases used and spreadsheets generated for analysis of literature on river restoration, the data interrogated to determine the damage to rivers in the UK and Republic of Ireland and case study information collated to determine the current state of river restoration activity. The key study components and project inter-linkages are shown in a River Restoration & Biodiversity Road Map in Section 2.6.

2.2 Sources of data & information

An array of information has been collated for this study from a wide variety of sources to assimilate an evidence database that permits the identification of potential knowledge gaps in an understanding, analysis and comparison of the damage caused to rivers in the UK and Ireland. It also provides an indicative view of the effectiveness of a variety of techniques applied in different river restoration case studies.

The key sources are:

a) Scientific papers published in peer-reviewed journals, research reports and 'grey literature':

  - Summarise research and detail scientific studies exploring river processes and biodiversity.
  - Specifically document a range of examples of restoration where extensive pre- or post-monitoring has taken place.
  - Examine evidence base for success of different techniques.

b) EU REFORM, WISER, WikiRESTORE projects:

  - Evaluate the river restoration case studies within the RiverWiki.tool that provide a conduit for sharing best practices and lessons learnt for policy makers, practitioners and researchers of river restoration.
  - Investigate links between river processes and potential restoration activities using the WISER database to identify prospective case studies.
  - Use the REFORM information system which relates hydromorphology and ecology across a range of European rivers to identify case studies of restoration and rehabilitation projects and document experiences of success or failure of different restoration measures.

c) Provision of data, information and evidence from statutory and voluntary bodies with experience of river restoration work

  - Environment Agency
  - Scottish Environment Protection Agency
  - Northern Ireland Environment Agency
  - Rivers Agency (NI)
  - Loughs Agency (NI/ROI)
  - Inland Fisheries Ireland (ROI)
  - Office of Public Works (ROI)
  - River Restoration Centre
  - Natural England
  - Scottish Natural Heritage
  - Natural Resources Wales
  - Rivers Trusts and Fisheries Boards

2.3 Process evidence

Process based restoration was extensively examined by Feld *et al*. (2011) as part of the EU FP7 REFORM project. The evidence matrix produced by Feld *et al*. (2011) has been examined and documented in a spreadsheet by citation and linkages with specific restoration activities and outcomes. The spreadsheet was interrogated to examine the evidence linkage, to aid the review process and identify areas where gaps exist in the evidence, and to show where the research into process restoration has been focused.

2.4 Project databases

The project database developed as part of this study has been constructed using a subset of 1552 projects from the NRRI database which was supplied by the RRC. Project data supplied by other statutory bodies were also used to ensure that the database was updated. The following sources of data were used in conjunction with personal communications:

- River Restoration Centre – National River Restoration Inventory (NRRI[1])
- RESTORE (RiverWiki) – online resource as updated January-July 2014
- SEPA (Restoration Fund and WEF projects 2009-2014)
- River restoration at the catchment scale in Scotland: current status and opportunities, (Gilvear and Casas, 2008) Centre for River Ecosystem Science -137 projects in Scotland pre-2008
- Environment Agency – EA Priority Habitats list
- Northern Ireland Environment Agency – primarily fisheries projects with some ROI projects included
- Inland Fisheries Ireland – description of works programmes and available project data

This design of the database has enabled further categorisation for additional analysis required to meet the objectives of this report as best could be achieved with time and resources. Each project has been classified based on the regional location (Scotland, Wales, England, Northern Ireland, Republic of Ireland). A sub-set of projects was selected and further classified according to the scale, reinstated process(es) and the drivers behind the project. The scale of each project refers to the scale of the works carried out which covers local to regional scales. An additional level of categorisation showing what restorative actions were undertaken was assigned to projects carried out either entirely or partly to improve the condition of fisheries.

Projects could be classified many times for each analysis with the exception of scale. For example, a project designed to reinstate fish passage was deemed to have reinstated connectivity and ecological processes as fish could now complete their migration as an essential part of their life cycle. In addition, such projects were classified under improved passage and spawning habitat for the fishery analysis. Such projects also fit under multiple drivers including fish population enhancement, biodiversity and legislation.

A matrix of techniques used in river restoration projects was developed using project information where available and further substantiated by expert knowledge by CRESS. Each of the projects within the sub-set was included within the matrix. If no details on the technique used were available from the database additional research was carried out to ensure the matrix was populated as accurately as possible.

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[1] The RRC receives contributions from seven UK environmental agencies to maintain and update the NRRI. The output from this IUCN project will be amalgamated within the RRC NRRI and RiverWiki (Managed by RRC on behalf of ECRR), to enable the continual development and updating of these UK and EU-wide resources.

The project database was filtered using a simple classification scheme which aimed to be relatively easy to assign based on limited information. The categories used in each of these classification exercises are shown in Tables 2.1 and 2.2. The scale and process categories were used to filter the projects from the main project list. Drivers were then assigned to the short-list. Fish population enhancement and viability projects were further categorised by the main goals for the restoration project.

Table 2.1: The categories used for different elements of analysis

Scale of project (applied to full dataset)	**Process objectives (applied to sub-set)**	**Driver (applied to sub-set)**	**Fishery (applied to fisheries projects in full dataset)**
local (reach-based)	landscape and floodplain objectives	water quality	improved passage
sub-catchment	connectivity/continuity	fish population enhancement & viability	spawning habitat
catchment	hydromorphology objectives	sustainable flood management	juvenile habitat
regional	biotic/ ecological	climate change	water quality
	physico-chemical	hydromorphology	other
		biodiversity	
		policy	
		landscape	
		socio-economic	

Categorisation of project drivers

All projects have been classified based on the information provided in the databases or if this was inadequate, after further research into the project. Projects could be classified under multiple drivers depending on the discernible aims of the project.

- Water quality improvement - Projects that were either addressing the issues of diffuse or point source pollution or where sediment inputs or water temperature were causing a deterioration in water quality. These projects were excluded from the detailed analysis unless they were in tandem with other measures.

- Fish population enhancement and fisheries viability - Projects that aimed to improve the habitat for fishes of any species (including eels). Any project that aimed to create spawning, refuge, juvenile habitats or improve water quality and improve fish passage were classified under this driver.

- Sustainable flood management - For projects that included flood alleviation works or if the design of the project had to ensure that flooding was not increased as a result of the restoration or was part of a flood alleviation scheme.

- Climate change concerns - This includes projects where the aim of restoration was to increase the resilience to climate change.

- Hydromorphology - Any project that addressed issues that affected the continuity of water flow including the lateral and vertical movement between the channel and the changes to planform, channel bed or marginal areas.

- Biodiversity objectives - Any project that improved conditions for individual species (including fishes) covered by the Habitats Directive or aimed to improve the conditions to support river habitat within the channel and riparian zone.

- Legislative drivers and achievement of WFD objectives - Projects which stated that improvements were made for the benefit of species covered under the Habitats Directive or commenced after the implementation of the WFD were included in this. If projects were designed to alleviate flooding or ensure that the risk was not increased elsewhere they were included in this category.

- Landscape objectives - This is for projects that aimed to re-establish habitats that have been lost due to human modifications. It also refers to projects that incorporated land management changes.

- Socio-economic - For projects that specifically aimed to improve the economy of the area by improving the local recreational facilities.

- Other - This includes projects that were not specifically restorative – for example, re-diversion projects.

Table 2.2: Techniques used in river restoration projects based on available project information and expert knowledge.

Riparian & landscape-scale measures	**Reach and channel-scale measures**	**Continuity & connectivity measures**
Riparian planting	Introduction of gravels	Construction of fish pass
Riparian fencing	Soft engineering	Obstacle removal
Riparian or floodplain wetland scrapes or pools	Bank re-profiling	Creation of new channel & re-meandering
Land management	Deflectors and vortex weirs, etc.	Obstacle modification
Livestock watering	Channel narrowing	Creation of backwater
Species specific habitat creation	Bed re-profiling.	Reconnection of relict channel
Riparian clearance**	Large woody debris (LWD)	Reconnection of backwater
Removal of non-natives	Multistage channel	Bypass channel
Manipulation of flow (discharge)	Rock placement in bed	Embankment removal
Blocking drainage	Erosion protection	Embankment set back
Reintroduction	Weir construction*	
Managed retreat	Opening or removing culvert	
	LWD removal**	
	Silt removal	
	Dredging main channel**	
	Offtake improvements	
	Removing concrete bed	
	Sediment replenishment	

* Technique used to create variation in flow in uniform channels

** Techniques cited by restoration managers but not traditionally considered as restoration

2.5 Assessment of damage

The extent of damage within each region is based on data that were collected for WFD categorisation purposes. These data were either extracted from WFD categorisation databases from statutory agencies, or from individual 2009 river basin management plans for individual districts and refer to the pressures affecting water bodies that can lead to impacts on the quality of the water environment.

For Scotland the damage assessment was further substantiated by the Morphological Impact Assessments (MImAS) which SEPA has carried out for all water bodies covered by WFD legislation. This includes an assessment of both the channel bed and bank and riparian zones.

The data are limited in several ways:

- There is a reliance on WFD data for damage to rivers and this limits an accurate assessment of physical damage.
- Reporting and assessment methods vary across the region and direct comparisons are rarely available.
- Project information is often sparse and subject to interpretation
- Reporting and assessment methods vary across the region

2.6 Statistical and spatial analysis

Software

Information was recorded in an Excel spreadsheet and analysed using the R statistical programming language (version 3.1.0). Graphics were also produced in R. GIS processing of data was done in QGIS Dufour 2.0.1.

Data

Missing location data and information on the restoration tools used were obtained from the web using project information contained within the RRC, RESTORE, CRESS and SEPA databases. Individual web searches were undertaken project by project. Information was widely available on the type of activities completed from a variety of sources. In addition to the RRC and SEPA spreadsheets, sources included the RESTORE database, Fisheries and Rivers Trust websites, the RRC website and the Defra biodiversity action reporting system.

Water bodies in the second cycle of the WFD (2009; total 5818) were used for the England and Wales data analysis. Although individual water-body shapes files were not available for Cycle 2, the RBD information was available. This allowed the more up-to-date ‘2013 reasons for failure’ database to be used and analysed at the RBD scale. These data were extracted from the national collation of reasons for failure data, produced following completion of the hydromorphology (MS decision code) refresh exercise carried out between October 2010 and March 2011 (2013 RFF data v.01Feb2013). It should be noted that these data represent a snapshot of the current understanding of the reasons for failure at the time of collation. Regions and areas are continuing to collect and record reasons for failure as part of their continuing programme of investigations.

RBD data were extracted from WFD_RBD_f1v4 (http://www.eea.europa.eu/data-and-maps/data/wise-river-basin-districts-rbds-1) under the EEA standard re-use policy: re-use of content on the EEA website for commercial or non-commercial purposes is permitted free of charge, provided that the source is acknowledged. Copyright holder: Directorate-General for Environment (DG ENV). Spatial information for restoration projects and River Basin Districts (RBDs) (including Sub-RBDs in Scotland) allowed restoration activities to be linked to the locations of pressures and reasons for failure at the RBD and Sub-RBD scale. The analysis was completed by creating distance matrices between restoration locations and the vertices of RBD shapefiles.

SEPA water body and WFD physical pressure information was extracted from the SEPA MImAS and RBD databases.

2.7 Methodological roadmap

Figure 2.1 outlines a methodological roadmap which shows for each chapter the relevant objective being tackled, the key evidence and data used, the key elements generated and developed relating to the study components and the way all these relate to the reporting outputs. The methodological roadmap demonstrates how this study approached the key issues that in turn focus the aims for Phase 2 of the ICUN project.

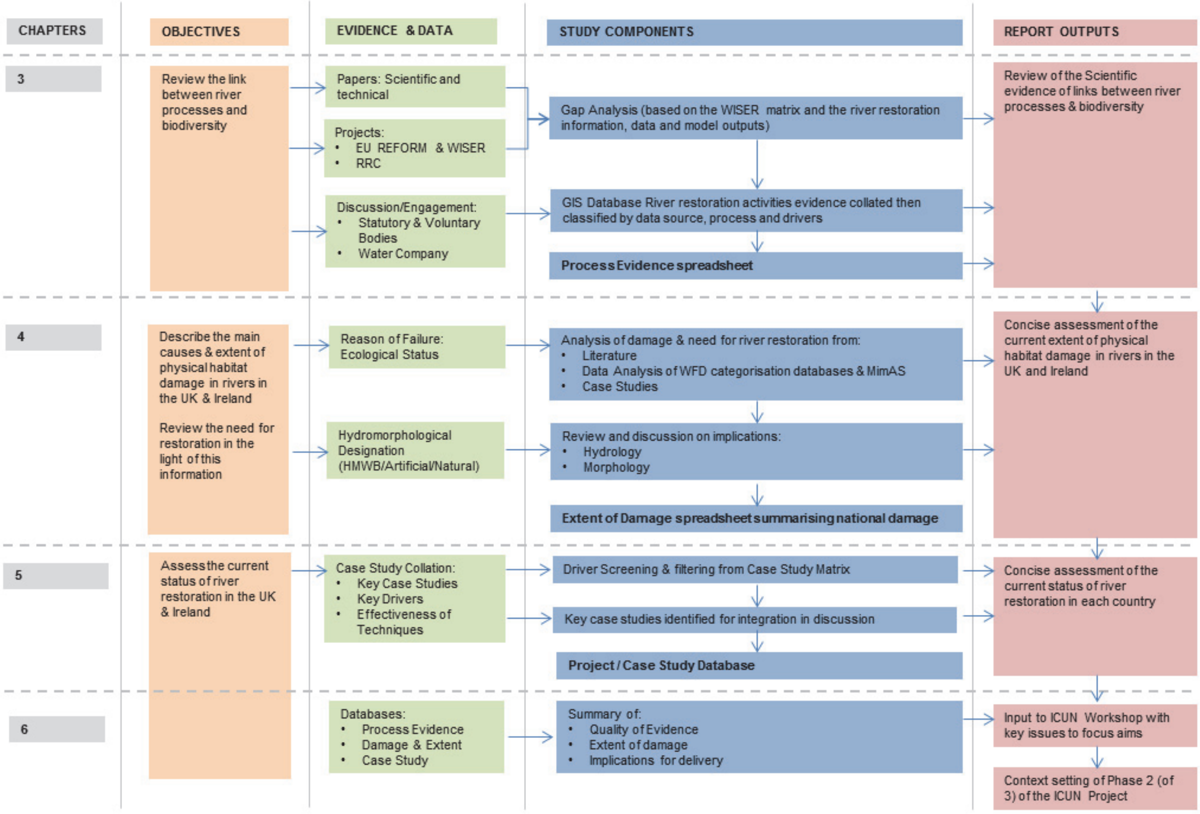


Figure 2.1: River restoration and biodiversity roadmap.

3. PROCESS-BASED RESTORATION

3.1 Overview

This section provides a review of the scientific evidence of the links between river processes and biodiversity. Increasingly, river managers are turning away from the traditional hard engineering solutions that were used to create specific habitat conditions which would be perceived as 'good' or meet uniform habitat standards (Wohl *et al*., 2005, Newson & Large, 2006) which could often result in unnaturally static or artificial habitats. Instead they are now focusing on ecologically based restoration activities in order to improve degraded waterways and improve biodiversity. River restoration projects aim to re-establish, where possible, the naturally occuring conditions and processes that have been lost to help promote the natural recovery of habitat and biological diveristy while protecting downstream and coastal ecosystems and ensuring flood risk is not increased onsite or elsewhere. There is growing interest in applying river restoration techniques to counteract river habitat degradation, yet there is little agreement on what constitutes successful river restoration.

A wide variety of factors govern the physical processes in rivers and hence their morphology and ecology. The main broad-scale physical factors (Church, 1996) are:

- the volume and timing of water supplied from the upstream catchment;
- the volume, timing and composition of sediments supplied from upstream;
- the nature of the substrate through which the channel flows and the local geological history of the landscape; and
- secondary factors such as local climate, the nature of riparian vegetation, land use and direct human modification.

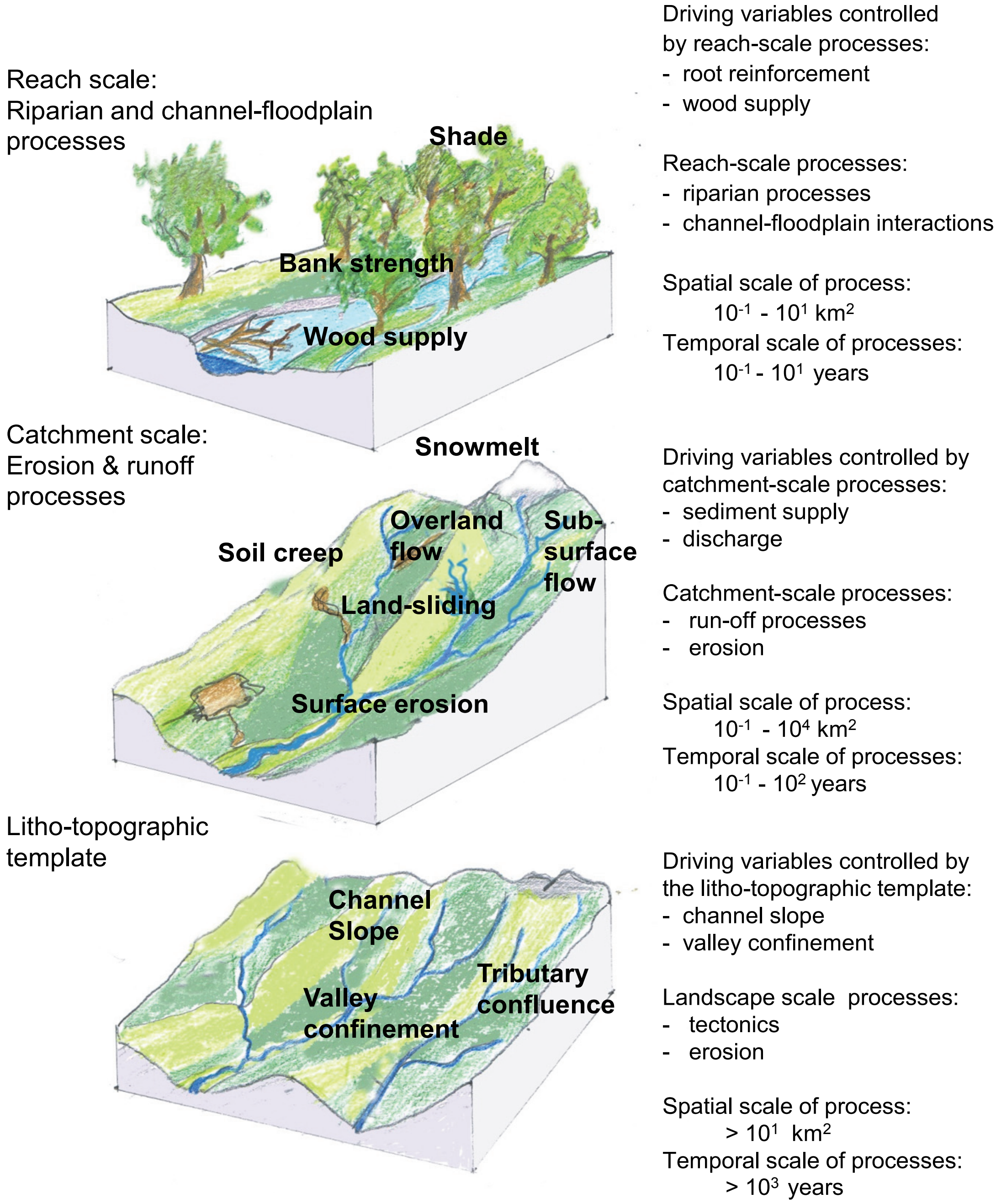
The driving force in streams and rivers is the flow of water from the source to the estuary. The study of this, hydrology, forms the basis of much river research today. Magnitude, frequency, seasonality and duration of formative flows shape the rate of change of physical habitat of streams and rivers (Biggs *et al.,* 2005; Brierley & Fryirs, 2005). Stream hydrology, the responding structure of the physical habitat and the hydraulic habitat that it creates, shapes the riverine and riparian floral and faunal communities (Giller & Malmqvist, 1998). Some of these species interact with the hydraulics and hydrology, stabilise sediments, process nutrients and in doing so begin to alter their environment, creating new habitat and opportunities for new species to invade. In this way rivers are mosaics of continually changing patches at different stages of development. Distance between populations, local climate, and migratory fauna all influence and help shape the ecosystem to different degrees at different times. The result is a highly complex ecosystem with many interacting components. This is concisely summarised by Harper & Everard (1998) who describe rivers as '…dynamic ecotones, controlled by processes that operate over a range of timescales and geographic extent, and that compromise a matrix of interdependent, transient habitats'.

The main processes driving river habitat dynamics and biota are presented in Table 3.1, focusing on processes commonly disrupted by human land and water uses and illustrating the use of the process-based principles in habitat restoration. Figure 3.1 illustrates the hierarchy of processes that control the dynamics of habitat features and species assemblages. The litho-topographic template generally controls slope and valley confinement; catchment-scale processes control discharge and sediment supply; and reach-scale processes control local habitat structure, thermal regimes, and species assemblages.

The concepts of diversity cross from both ecological, hydrological and geomorphological disciplines. Biological diversity or 'biodiversity' is a key concept in ecology and a focus for this report. Technical definitions cover a wide variety of aspects in addition to species richness but the frequent use of diversity as a synonym in this regard (e.g. Waide *et al.*, 1999) has rather simplified its definition. The focus of this study requires the interpretation of diversity at the stream ecosystem level. This includes aspects of community diversity and physical habitat diversity.

Table 3.1: Examples of catchment-scale and reach-scale processes that control river ecosystem dynamics.

Ecosystem feature	**Driving processes**
	Catchment Scale
Sediment	Sediment delivered to river systems through land sliding, surface erosion, and soil creep.
Hydrology	Runoff delivered to streams through surface and subsurface flow paths.
Organic matter	Tree fall, leaf litter fall.
Light and heat	Solar insolation and advective heat transfer to the water column.
Nutrients	Delivery of dissolved nutrients via groundwater flow.
Chemicals	Delivery of contaminants, pesticides from agricultural or industrial sites through surface runoff or shallow subsurface flow.
Biota	Migration of aquatic organisms, seed transport.
	Reach Scale
Channel morphology and habitat structure	Channel migration, bank erosion, bar formation, and floodplain sediment deposition create a dynamic mosaic of main-channel, secondary-channel, and floodplain environments. Wood recruitment results in part from bank erosion and channel migration, and wood accumulations reduce bank erosion rates or enhance island formation. Sediment and wood transport and storage processes drive channel cross-section shape, formation of pools, and locations of sediment accumulation. Bank reinforcement by roots reduces bank erosion rates and may force narrowing and deepening of channels. Animals such as beaver physically modify the environment and create new habitats.
Thermal regime	Local stream shading and exchange of water between surface and hyporheic flows regulates stream temperature at the scale of habitat units and reaches.
Water chemistry	Delivery of dissolved nutrients through groundwater and hyporheic exchange; uptake of nutrients by aquatic and riparian plants. Delivery of pesticides and other pollutants at point sources damage health and survival of biota.
Riparian species assemblages	Seedling establishment, tree growth, succession drive reach-scale riparian plant assemblages.
Aquatic species assemblages	Photosynthesis drives primary production of algae and aquatic plants. Leaf-litter inputs drive detritus-based food web strands. Habitat selection, predation, feeding, growth, and competition drive species composition of invertebrate, amphibian, and fish assemblages.



Driving variables controlled by reach-scale processes:
- root reinforcement
- wood supply

Reach-scale processes:
- riparian processes
- channel-floodplain interactions

Spatial scale of process:
10^{-1} - 10^{1} km^2
Temporal scale of processes:
10^{-1} - 10^{1} years

Driving variables controlled by catchment-scale processes:
- sediment supply
- discharge

Catchment-scale processes:
- run-off processes
- erosion

Spatial scale of process:
10^{-1} - 10^{4} km^2
Temporal scale of processes:
10^{-1} - 10^{2} years

Driving variables controlled by the litho-topographic template:
- channel slope
- valley confinement

Landscape scale processes:
- tectonics
- erosion

Spatial scale of process:
> 10^{1} km^2
Temporal scale of processes:
> 10^{3} years

Figure 3.1: Examples of catchment-scale and reach-scale processes that control river ecosystem dynamics (from Beechie et al., 2010).

3.2 Physical processes

3.2.1 Hydrology

Patterns of variability in flow can have a major influence on geomorphological and ecological aspects that provide the structure and function of lotic ecosystems (Moss, 1998; Tockner *et al.*, 1998; Biggs *et al.*, 2005). Natural disturbance in a stream system is introduced by variability of flow, which acts at a range of scales from spate flows and droughts, to disturbance at the micro-scale caused by the lapping of river margins. In upland gravel bed channels, hydrology, specifically spate flows, is the dominant force shaping the physical habitat (Moss, 1998) and many argue that it is equally dominant over the development of invertebrate communities (e.g. Brown, 2007) and may override the effects of competition and predation. The most evident influence of hydrology is the presence of fluvial features such as gravel bars but it is also a determining factor of channel form and planform (Brookes, 1995; Gilvear, 2004). The influences within the channel are well documented but also extend well into the riparian zone (Hupp & Osterkamp, 1996; Francis, 2006; Wintle & Kirkpatrick, 2007) and across the floodplain, such as through processes of scouring and deposition (Gurnell *et al.*, 2006).

Aside from the indirect effects that hydrology has on biota through shaping the physical habitat, large-scale events such as infrequent spate flows may also determine ’high level characteristics of ecosystem structure’ (Biggs *et al.*, 2005). A major mechanism that may be important in this respect is the effect on colonisation patterns such as the generation of propagules, regeneration of seeds and propagules between channel and floodplain and the dispersal and redistribution of macroinvertebrates by passive mechanisms. In this respect hydrology may have a significant influence over the colonisation patterns in river channels.

Understanding these and other influences on biota is important for river management (Biggs *et al.*, 2005). For example, high flow events can severely disturb benthic communities but equally may be important in maintaining biodiversity (Townsend *et al.*, 1997). Hydrology should therefore be taken into account in conservation strategies that are dependent on the effects of engineering projects (Vaughan *et al.*, 2009), land use (Davies *et al.*, 2008; Krause *et al.*, 2008), and other river modifications. The effect of flood flows in shaping biological communities is still only partly understood (Renofalt *et al.*, 2007), with the exception of some studies that report behavioural responses to increasing flow velocities (e.g. Holomuzki & Biggs, 2000).

The effect of flooding, important for the sustainability of natural systems, may also have the potential to reduce ecosystem integrity in modified and fragmented riparian zones (Hawkins *et al.*, 1997). Biggs *et al.* (2005) hypothesize that a hierarchy of flow variability is probably the ’underlying reason for many temporal and spatial patterns of biological characteristics at different scales in lotic ecosystems’.

The hydraulic diversity that results from development of a complex channel form includes eddies and slack water areas. These are the most effective features in trapping seeds under natural flow conditions (Merritt & Wohl, 2002) and marginal vegetation complexity and seed trapping potential positively correlates with plant species richness (Andersson *et al.*, 2000). Eddies and slack zones may also play an important role in invertebrate drift.

3.2.2 Geomorphology

The physical structure of stream and river environments has been widely studied for many years (Gilvear *et al*., 2000; Boruah *et al*., 2008; Thorndycraft *et al*., 2008) but has generally remained focused on natural or regulated rivers rather than restored channels. A range of methods and indices have been developed to describe the river channel form (Fozzard *et al*., 1997; Western *et al*., 1997) and variability (Bartley & Rutherfurd, 2005). Further studies have attempted to elucidate geomorphological processes behind channel form and relate both form and process to the creation and persistence of ecologically functional habitat (Gurnell *et al*., 1998; 2006). Less research has focused on whether geomorphological processes can be relied upon to create complex riverine and riparian habitat following restoration activities. The alternative approach, focused on restoring a static physical element of the stream structure, fails to recognise that the very nature of stream channels is a condition of dynamic equilibrium (Palmer *et al*., 1997) continually clearing and re-creating habitats. Physical stasis or stability in no way ensures ecological sustainability and in the long term may adversely affect morphology, hence the importance of gathering data about the potential restorative effect of reinstating geomorphological processes.

It has been proposed that an approach to restoration and channel design in line with modern geomorphic principles is more likely to achieve desired levels of dynamism and sustainability (Kondolf, 1998; Gilvear, 1999) but as yet there have been few attempts to establish whether or not empirical data support this view. The development of in-channel sediment stores such as mid and point bars and riffles has been demonstrated to occur within six months (Sear *et al*., 1998) on the River Cole. However, predictions of geomorphic development are difficult to develop and often unreliable (Hughes *et al*., 2005; Vaughan *et al*., 2009). This is in part due to the complex inter-relationships of channel factors such as form and substrate, and external factors such as discharge and a general paucity of empirical data. It is possible that designs relying solely on hydrological and geomorphological processes fail to recognise the importance of the wider river environment.

It is important to remember that patterns of biodiversity also occur independently of those determined by geomorphological boundaries (Parsons *et al*., 2003). An example is catchment land-use which can be a major factor influencing stream communities (Brisbois *et al*., 2008) and the effect can continue for many years after the land use has changed (Harding *et al*., 1998; Newson, 2002). Biogeographical factors are also important such as the climate of the catchment, dependent on its wider geographical position.

Geomorphology acts on more than just the sediment that it transports. Differences in bank substrate and external factors such as woody material serve to add variability to the fluvial processes, driving a greater level of physical heterogeneity. In this way sediment systems can be said to have memory such that present geomorphological patterns in natural rivers are strongly influenced by past form and processes (Newson, 2002) and therefore an appreciation of geomorphological history is important for interpreting present processes, and predicting responses of river channels to human interventions (Sear *et al*., 1998).

The structure of the stream has a major influence on the range of habitats available. Some elements of river structure are widely recognised; the stream bed and banks, islands and backwaters, pools and riffles. It has long been known that invertebrate species respond to factors relating to the range of habitat elements (Badcock, 1949; Maitland & Penney, 1967; Egglishaw, 1969). There is often a deterministic relationship between stream biota and the physical features of river systems (Giller & Malmqvist, 1998). Some habitat elements are less obvious because they are less visible (e.g. the hyporeic zone), or less well-defined (e.g. the riparian zone). Communities respond to extent and diversity of each habitat, which in turn is very much defined by the hydrological regime. This circle is completed by the strong feedback mechanisms that allow the flora and fauna present in a habitat to change ecosystem structure and processes extensively.

Feedback processes

It is possible that feedback is a significant mechanism in the development of restored channels. For example, as aquatic plants colonise they will modify habitat conditions that feed back into hydrological, geomorphological and ecological processes (Naiman *et al.,* 1999). Some aquatic bryophytes may actually increase substrate stability by lowering the drag of the rocks on which they grow. Results from flume experiments by Suren *et al*. (2000) suggest that they may streamline rocks, making them less prone to movement and increasing their suitability for additional colonising biota. As well as changing physical conditions such as water velocities, blocking sunlight, increasing oxygen levels and reducing the availability of primary substrate (bare rock) macrophytes can act as attachment surfaces and ovipositioning sites, trap detritus, and provide food and refugia (Biggs, 1996). This may result in increased suitability for colonising invertebrates.

Feedback mechanisms also have the potential to reinforce ecosystem development to an undesirable endpoint. More attention is now being paid to the ecological constraints that create internally reinforcing feedback by managers of restoration projects (Suding *et al*., 2004). It is important to recognise that the dynamics of a newly engineered state may be very different from those of the pristine or target condition. Barriers to restoring functional ecosystems can develop as a result of feedback mechanisms between habitats and internal or external factors such as invasion of inappropriate species, remoteness of native colonists and landscape fragmentation. Failure to accept the possibility that feedback mechanisms may internally reinforce a degraded system/state, risks the adoption of inappropriate management strategies resulting in an unexpected or undesirable new state, or the failure to perturb the system from the degraded state (Suding *et al*., 2004). In addition to providing a template on which processes can act, restoration techniques may also require innovative or adaptive management to overcome the constraints that starting conditions of the system invariably impose (Suding *et al*., 2004).

3.2.3 The development of morphological features

The topography of the river bed is characteristically diverse in gravel bed rivers (Knighton, 1998; Gilvear, 1999) resulting in a range of different habitat features or 'morphological habitat units' and associated variability in flow patterns (Bartley & Rutherfurd, 2005). Classic examples are pools and riffles, which have been used to represent hydraulic character and substrate composition (Parsons *et al*., 2003). Development of in-channel sediment storage in the form of gravel bars can dominate the early morphological development of new channels (Sear *et al*., 1998). Rather than being a gradual process, however, formation is rapid and related to bedload transport capacity and stream power during early flood events (Gilvear & Bradley, 1997).

Morphological habitat units have been shown to support distinct invertebrate assemblages (Parsons & Norris, 1996). Resh *et al*., (1988) related increased abundances of stream insects in the upper sections of riffle features to increased stability but provided no explicit evidence. Conversely, high levels of disturbance in pool areas of gravel bed rivers (Andrews, 1984) have also been used to explain their relatively low invertebrate diversity. Even riffles with a very similar general morphology can have very different composition, structure and hydraulic conditions, with differences both between riffles and across individual riffles (Pedersen & Friberg, 2007). Morphological alterations to rivers have often left no capacity for sediment transport, severely limiting the development of geomorphological formations such as point bars and gravel islands. Sedimentary structures are characteristic of gravel-bed rivers and, because they vary greatly in size, form and type, contribute considerably to habitat complexity (Gilvear & Bradley, 1997; Ward, 1998).

In lower energy environments such as chalk rivers or lowland rivers the bed character is less likely to be frequently modified by the flow regime, and the restoration of physical processes may be more challenging due to the lack of energy. In these situations techniques at the reach scale may be more appropriate in instigating processes within these lower energy systems.

3.2.4 Planform

The planform exists within a zone of potential geomorphological activity in which the river moves over long timescales, eroding and depositing material. In the early days of stream engineering there was some appreciation of the importance of giving rivers the space to meander and shift within this zone. More recent floodplain agriculture and urban development has had a tendency to encroach on this area of the river and as a direct result erosion here has often been referred to as a problem in the past (Gardiner, 1988).

Although there is little legislation in place in the UK or Ireland that recognises the importance of this area, some progress has been made elsewhere. Since 2001 mine sites in France have not been allowed within the 'space of mobility' of rivers following a décret from the French Environmental Ministry (Piegay *et al*., 2005); and in Spain following a decret from the Spanish Environment Ministry (Roberto Martinez, pers comm.) where activities are highly restrictive both within the 'Hydraulic Public Domain' (HPD), which is based on hydrologic and geomorphologic elements, including historic planform extents, and a contiguous margin of 5m each side of the HPD, preventing the planform dynamic from being altered.

In many circumstances bank erosion ought to be viewed in a positive light and the process may need to be preserved (Piegay *et al*., 2005) as related processes are essential for balanced sediment transport and result in gravel bar formation and maintenance, promoting healthy aquatic and riparian ecosystems (Wallick *et al*., 2006). The use of channel stabilisation efforts that reduce disturbance processes may reduce a river's ability to develop new geomorphic surfaces (Wallick *et al*., 2006). However, a reduction in geomorphic diversity can also result from excess fine sediment entering the system (Bartley & Rutherfurd, 2005) with considerable impacts demonstrated on a wide range of biota (Wood & Armitage,1997). Re-meandering is a widely used restoration technique, partly for this reason, and has many benefits for stream health (Friberg *et al*., 1998).

Studies have shown a very close relationship between channel width and meander form (Leopold,1982). Greater curvature results in greater secondary flow strength producing an increase in near-bank-flow erosivity, exerting large influences on channel movement, possibly irrespective of bank material (Wallick *et al*., 2006). Secondary flows are also responsible for driving the curvature of planform in the first place, so there is a strong element of process–form feedback. However, there is considerable inaccuracy and uncertainty in quantitative models of planform adjustment through space and time for alluvial rivers (Sear *et al*., 1998; Piegay *et al*., 2005). This may be because of the limitations associated with factoring in the diversity of hydrology and sediments (Piegay *et al*., 2005) and riparian vegetation which also exerts a major control on the way in which planforms evolve. In some cases the influence of channel stabilisation upstream can affect the downstream patterns of erosion by limiting sediment replenishment (Piegay *et al*., 2005).

3.2.5 Cross-sectional form

The controlling variables of channel form can be divided into the driving variables, boundary characteristics, and existing channel form (Newson, 2002). Driving variables include the discharge hydrograph and sediment supply and transport capacity. Boundary characteristics include valley slope and topography, bed and bank materials, and riparian vegetation and woody material and rocks (Olson-Rutz & Marlow, 1992).

Channel form includes cross-sectional geometry or morphometry (width and depth), long profile and planform. All have a strong influence on channel shape which, in turn, determines the local hydraulics. The variability in width, depth and water velocity that this introduces has important implications for the nature and extent of habitats available to biotic communities. However, information on the exact benefits to ecological diversity is limited. One recent study (Nakano & Nakamura, 2008) showed a high level of invertebrate richness at the reach scale compared with channelised 'controls' and established a relationship between both invertebrate density and richness and the shear velocity at each sampling location, (with the highest richness at low velocities).

Despite the importance of variability in stream channel form being widely known (Ward *et al*., 2001), and furthermore, widely used to evaluate responses to management (Bartley & Rutherfurd, 2005) little is known about its development in man-made or restored channels. The limited research in the area suggests that factors are scale-dependent and include vegetation and bank material (Anderson *et al*., 2004). Feedback from vegetation growth may occur early on in development (Gurnell *et al*., 2006). The use of natural bank materials in restored channels allows erosion processes to develop the channel form. Because the literature has historically focused on the many perceived adverse impacts of bank erosion (e.g. Gardiner, 1988) such as damage to property and infrastructure or the loss of land and the potential impacts that the sediment can have on channel morphology and capacity, bank erosion is often considered a hazard by river managers (Piegay *et al*., 2005) rather than a natural process of channel adjustment and evolution.

Cross-sectional area, width, depth and width–depth ratio provide some information about geomorphological characteristics. Channel shape can reveal further information but is often reported as observations rather than repeatable measurements. Indices of channel shape can provide information about change undetected by the more traditional width–depth ratio (Olson-Rutz & Marlow, 1992). Changes in channel area associated with movements of the river-bed and river-bank materials may represent natural flux or act cumulatively leading to substantial long-term changes (Olson-Rutz & Marlow, 1992).

3.3 Elements of river ecosystem habitat

3.3.1 In-channel habitat

The most indisputable element of the stream ecosystem is perhaps the river bed as it is permanently or semi-permanently aquatic. Bed sediments can be characterised by differences in size, variability, sorting and packing and are influenced by water depth, gradient, sediment supply and the frequency and magnitude of flood flows (Jowett, 2003). Differences in bed sediment are likely to have a major influence on the range of habitats available for colonisation by benthic communities (Wene & Wickliff, 1940; Williams & Smith, 1996). Information on fish, macroinvertebrate and macrophyte substrate preference at the species level is remarkably sparse (Wolter *et al*., 2013) and is currently hampering the development of indicator species that could take advantage of the relationship between substrate characteristics and flow conditions. ASCE (1992) highlights bed sediment characteristics as 'the primary influence of community composition and density'. As such, development of a natural physical form of stream bed is likely to be vital for ecosystem development within heavily degraded channels such as engineered or re-sectioned reaches or when creating new bed substrate conditions. The size of interstitial spaces, for example, has been reported to affect colonisation in macroinvertebrates (Townsend *et al*., 1997; Schmude *et al*., 1998) with large interstitial spaces providing little in the way of shelter for smaller invertebrates that will colonise gravels to a much greater degree. Large pebbles (>40 mm) provide a more stable substrate to attract clinging sedentary invertebrates (Khalaf & Tachet, 1980; Malmqvist & Otto, 1987).

In this respect, the initial un-cohesive, uncompacted nature of the bed sediments in newly created channels will be more easily mobilised than the armoured layer of natural gravel beds. However, the resulting supply of sediment can be an important driver of morphological development in downstream reaches (Sear *et al*., 1998). Restoring stream habitat requires more than instigating a natural substrate structure; rather, restoration success depends on the development of a diversity of bed conditions. A study by Sarriquet *et al*., (2007) illustrates this point. In a project that aimed to restore bed sediments, interventions produced little increase in species richness. This, they explained was because the intervention simply changed the habitat from one condition to another, significantly altering the composition of invertebrate assemblages but not increasing richness.

Natural rivers, even across single geomorphic units are a mosaic of variable bed substrate conditions and even with the greatest of planning and design it may be impossible to emulate without the restoration of suitable driving processes.

Organic matter in the channel

The importance of organic matter and nutrient cycling in stream ecosystems is not always fully acknowledged (e.g. Parsons *et al*., 2003). The amount of organic matter trapped by different morphological units, for example, is likely to be an important aspect affecting colonisation and development towards a functioning stream ecosystem. Riparian zones are donors of organic matter and the main source of energy to the upper reaches of rivers (Allan, 1995). Organic matter has been shown to correlate well with the benthic diversities of stream invertebrates (Egglishaw, 1964). Furthermore, Bird & Hynes (1981) have shown that given a lack of organic matter, new colonisers will rapidly move on to a new area. Coarse Particulate Organic Matter (CPOM) is an important habitat for microbial activity, promoting nutrient retention (Aldridge *et al*., 2008) as well as being used directly by macroinvertebrates as a food resource and building material (Merritt & Cummins, 1996).

Many stream ecosystems depend on organic matter inputs (Vannote *et al*., 1980, Mulholland *et al*., 2001) and as a result retention of organic matter is likely to play a major role in controlling channel development and functioning. Large woody material is an important component of many stream ecosystems with the potential to significantly enhance channel morphology through providing habitat niches (Kail *et al*., 2007; MacInnis *et al*., 2008) and altering channel dynamics (Muotka *et al*., 2002; MacInnis *et al*., 2008) and even establishing a tree population (Opperman & Merenlender, 2007). Although fine woody material may not influence stream habitat heterogeneity in the same way as coarse debris (Gippel *et al*., 1996; Bennett *et al*., 2008) it may still represent important invertebrate habitat (Milner & Gloyne-Phillips, 2005).

Retention of organic material within bed sediments is recognised as an important ecosystem process within river systems but there has been limited published research in this area. Muotka & Laasonen (2002) found the retention capacity of newly restored channels, bare of bryophytes, to have reduced retention capacity. Experimental releases of wooden dowel (Bocchiola *et al.,* 2006), plastic leaves (Speaker *et al.,* 1988) and 'Aqua-spheres' (Milner and Gilvear, 2012) have been used in an attempt to assess the retention capacity of river reaches and fine-scale bed features. This process has not been widely assessed in restoration projects and potentially represents a significant gap in the understanding of basic river processes.

3.3.2 Riparian zone

The defined extent of the riparian zone is a little vague with some authors restricting it to the bankfull discharge (Hupp & Osterkamp, 1996) while others extend it out across the floodplain (Stanford *et al*., 1996). Riparian zones can be physically, geomorphically, biologically and ecologically diverse, often considered more so than other ecosystems (e.g.

Tockner *et al*., 1998). Naiman *et al*. (1993), for example, stated that 'Natural riparian corridors are the most diverse, dynamic and complex biophysical habitats on the terrestrial portion of the Earth'. There is certainly plenty of corroborative evidence[2] although this is best described and documented for vascular plants and tends to be limited elsewhere (Nilsson, 1992).The biodiversity and productivity observed in the terrestrial–aquatic transition of riparian zones may be related to high levels of available resources, disturbance regime and corridor structure (Tabacchi *et al*., 2005).

Although dependent a little on where the outer edge of the riparian zone is deemed to be, the main hydrogeomorphic processes behind the disturbance regime that shapes the riparian habitat are thought to be flooding, erosion and the accumulation and reworking of sediment (Salo, 1990; Steiger *et al*., 2005). The value of these processes in channel construction projects has been demonstrated on the River Cole through overbank deposition of gravels (Sear *et al*., 1998). Certainly most research into the influence of hydrology on the riparian zone has been focused on the effects of high flows and flood events (Hupp & Osterkamp, 1996; Hawkins *et al*., 1997). Flooding can lead to direct impacts which can be detrimental to extensive areas of riparian zones, however from an ecological point of view these events can be of benefit by resetting successional processes. Hawkins *et al*., (1997) found that up to 40% of pre-flood vegetation cover could be stripped away during exceptionally high flows. Obviously catastrophic levels of flooding can seriously reduce species diversity. They may serve a similar ecological function to forest fires in adapted ecosystems, initiating a sequence of successional processes (Hawkins *et al*., 1997) assuming they are sufficiently infrequent. An intermediate level of disturbance (in both frequency and scale) has been hypothesised to maintain high levels of biodiversity (Townsend *et al*., 1997) in rivers and streams.

Trailing riparian habitat has been shown to play a role in assisting colonisation within developing streams by some invertebrate taxa; for example, colonisation of unconsolidated sediments by EPT[3] taxa in new branches of braided rivers (Milner & Gloyne-Phillips, 2005). Vegetation also has a role in controlling erosion, stabilises soil and reduces current velocity during floods, as shown in a number of studies (e.g. Nilsson, 1992; Anderson *et al*., 2004; Francis, 2006). Restoration of the floodplain area is increasingly recognised as a desirable and effective objective for process-based restoration (Asselman, 1999; Palmer *et al*., 2005). Connectivity between the river and floodplain is a major element of theories on river ecosystem functioning, and loss of connectivity in this respect can reduce the diversity and productivity of aquatic habitats (Rahel, 2007) affecting stream structure and functioning (Aspetsberger *et al*., 2002). However, there are often constraints to floodplain restoration or creation. These include limited scientific understanding, the complexity of floodplain governance and the generally high economic value of the land (Adams & Perrow, 1999).

3.3.3 Variability, heterogeneity and patchiness

Stream habitats can be considered as a variety of interconnected patches of variable size each with different physical characteristics. This mosaic form is promoted by the dynamic conditions in the riverine and riparian ecosystems and can be particularly complex in upland rivers (Arscott *et al*., 2000). The study of variability can focus on almost any aspect or element of the ecosystem but is often overlooked. For example, most biotic research fails to recognise explicitly the effects that flow variation at different temporal scales can have on

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[2] More than 260 species of vascular plants (representing 13% of the vascular plants found in Sweden) were recorded along a single Swedish river, Vindel River (Nilsson, 1992). Around 900 species were found in a survey of the Ardour River, France (Tabacchi *et al*., 1990). A survey of approximately 200m of riparian zone along the Ore River, Sweden, found 264 species of invertebrates and a study looking at patterns in diversity across a the riparian transition identified 426 morphospecies of invertebrates (Dangerfield *et al*., 2003).

[3] EPT Ephemeroptera, Plecoptera and Trichoptera

ecosystem components and processes (Biggs *et al*., 2005) despite the links becoming increasingly clear. Biggs *et al*. (2005) demonstrated a range of species interactions and behaviours that are a direct response to flow variability from a scale of years, through weeks and days to minutes, seconds and less. Other studies, although not explicitly looking at the hierarchical scales, also reveal direct biotic responses (Egglishaw, 1969; Rader & Belish, 1999) that act over and above the influences flow can have through shaping physical habitat. More specifically, heterogeneity, a particular form of variability, is a concept becoming increasingly prevalent in ecology. The distribution of stream biota is known to be highly variable, with patches of high and low taxon density and richness. This patchy distribution is likely, in part, to result from the heterogeneous nature of the habitat. Certainly invertebrate densities have been related to habitat factors including flow conditions, distribution of organic debris (Egglishaw, 1969) and the physical nature of the substrate.

Renofalt *et al.,* (2007) found that riparian diversity along turbulent reaches was less affected by flood disturbance than diversity in more tranquil reaches suggesting that hydraulic conditions during low flow periods can influence the susceptibility of the riparian zone to damage under high flows. The riparian community has long been recognised for its high species richness. Seed banks within a riparian zone may be a hotspot for the reinstatement of biodiversity (Tabacchi *et al*., 2005). Riparian corridors are interfaces between terrestrial and aquatic ecosystems. As such they tend to encompass sharp environmental gradients (Naiman *et al*., 1993). They are zones of active ecological processes resulting in a diverse mosaic of landforms, communities and environments (Naiman *et al*., 1993). An analysis of species distributions within this zone would substantially improve understanding of these active ecological processes (Nilsson, 1992).

3.3.4 Refugia

Sedell *et al*. (1990) define refugia as habitats or environmental factors that confer spatial and temporal resistance and resilience to biotic communities affected by disturbances. This includes both flood and drought flows but could equally be extended to refuge from predation. Parker *et al*. (2007) provide initial evidence that small sedentary herbivores in freshwater systems can gain predator-free space by feeding on plants that are chemically defended from larger consumers. Furthermore, refuge from flow for invertebrates may also provide a space where organic matter can accumulate during and after floods. Nikora *et al*. (1998) suggested that bryophytes may create hydraulically quiescent regions around them, and that these regions could in part explain the high invertebrate densities and the algal and detrital biomass within mossy boulder communities. This may also explain the high abundances of macroinvertebrates that have been found associated with dead wood in streams (Milner & Gloyne-Phillips, 2005).

The nature of refugia is highly variable. It can be hydro-geomorphological (e.g. Lancaster, 2000), biological (e.g. Lancaster and Hildrew, 1993) or chemical (e.g. Parker *et al*., 2007) and as a result tends to vary in spatial and temporal extent. Examples vary from live vegetation to woody debris, single boulders to large debris dams, and can be in backwater, pool and riffle areas. The existence of many of these elements is dependent on there being sufficient physical diversity.

3.3.5 Connectivity and continuity

River–riparian connections are now widely recognised as important in sustaining natural levels of functioning in many stream systems. The importance of re-establishing connectivity between the riparian zone and the river channel has become widely advocated (e.g. Gurnell *et al*., 1998; Harper *et al*., 1999). Loss of connectivity can reduce the diversity and productivity of aquatic habitats (Rahel, 2007). The River Continuum Concept (RRC), (Vannote *et al*.,1980) focused many environmental projects on the importance of longitudinal connectivity defining a continuous gradient of physical conditions, such as width, depth, velocity, flow volume, and entropy gain, from the headwaters to the mouth of any river. The concept generated much productive debate (Giller & Malmqvist, 1998) although criticisms included the failure to tackle anthropogenic modifications. Lateral connectivity lagged behind a little but was soon addressed by the flood pulse concept (Junk *et al.*, 1989) illustrating the importance of processes that cross the riparian–riverine ecotone and allow the transfer of sediment and nutrients.

The maintenance of lateral connections through frequent inundation of the floodplain is important in balancing sediment budgets (Pringle, 2003), providing food, supplying woody material (Gurnell *et al.*, 1998) and transferring and storing sediment, which can be significant in the early development of new channels (Sear *et al.*, 1998). In addition to this continuity in landscape structure, concepts of connectivity extend to meta-population dynamics and the explanation of species distributions (Moilanen and Nieminen, 2002) and hydrological connectivity of water-mediated fluxes of materials, energy and organisms within and among components of the ecosystem (Pringle, 2001; Kondolph *et al.*, 2006). A summary of selected concepts is provided in Table 3.2 and illustrates the development of interest in this spatial perspective of the river ecosystem.

Table 3.2: Selected connectivity 'concepts' in stream ecology grouped according to the extent of their spatial perspective (from Ward et al., 2001)

Longitudinal perspective	**Floodplain perspective**
Colonisation cycle (Mueller, 1954)	Hydrological connectivity (Amoros and Roux, 1988)
Universal zonation scheme (Illies and Botosaneanu, 1963)	Flood Pulse (Junk *et al*., 1989)
Stream and its valley (Hynes,1975)	Aquatic–terrestrial ecotones (Naiman and Decamps, 1990)
River Continuum Concept (Vannote *et al*., 1980)	**Groundwater perspective**
Nutrient Spiralling (Elwood *et al.,* 1983)	Surface water–groundwater ecotones (Gibert *et al.,* 1990)
Serial Discontinuity (Ward and Stanford, 1983)	Telescoping ecosystem model (Fisher *et al.,* 1998)
Catchment Hierarchy (Frissell *et al.,* 1986)	**Longitudinal+floodplain+groundwater**
Stream hydraulics (Statzner and Higler, 1986)	Four-dimensional perspective (Ward, 1989)
	Fluvial hydrosystem (Amoros and Petts, 1993)
	Hyporheic corridor (Stanford and Ward, 1993)

While continua broadly exist in natural rivers, they are interrupted by other phenomena (e.g. changes in rock type, tectonic activity, and glacial processes) which can disrupt them and cause discontinuities. As a result, the concepts of process domains (Montgomery, 1999), and functional process zones, where ecological communities are influenced by hydrogeomorphic patches (Thorp *et al.,* 2006), have been introduced and associated with concepts of nested stream habitat hierarchies (Frissell *et al*., 1986), and ecological patchiness (Statzner & Higler, 1986; Poole, 2002). Accordingly, river systems provide a hierarchical, longitudinal array of functional process zones, which support different types and dynamics of river channels, with species assemblages equally differentiated from neighbouring, upstream or downstream communities, based on local processes (Poole, 2002; Thorp *et al*., 2006).

Connectivity principally enhances available area and accessibility of different habitat patches, and thus contributes to habitat complexity and heterogeneity. However, local species diversity strongly depends on the regional species pool and turnover (Ricklefs, 1987; Legendre *et al*., 2005; Heino, 2009; Passy, 2009; Kolasa *et al*., 2012); thus, neither the amount of change nor the improvement of particular species or target species can be predicted and related to increasing complexity or heterogeneity of habitats in general (e.g. Palmer *et al*., 2010). Connectivity is crucial in the context of restoration but many reach-scale restoration projects have been unsuccessful as they are implemented in isolation from the wider catchment context (Wohl *et al*., 2005; Palmer *et al*., 2010).

Although connectivity is often considered to be a positive attribute for river ecology, connectivity may not always be naurally high, and increasing connectivity over natural levels may also have adverse consequences, such as preventing isolation of species pools from invasive species or upsetting natural dynamics in fish populations (Kondolph *et al*. 2006).

3.4 Ecosystem processes

There is an extensive literature on the ecology and functioning of river systems that incorporates a broad range of accepted ecological principles. The link between hydraulic diversity and biodiversity (Statzner and Higler, 1986; Extence *et al*., 1999), concepts of spatial refugia (Sedell *et al*., 1990; Lake, 2003), micro-habitats (Townsend, 1989; Lake, 2000) and the role of riparian vegetation and buffer zones (Vannote *et al*., 1980; Milner & Gloyne-Phillips, 2005), are ecological principles that have been incorporated into restoration project design at the reach scale. Process-based restoration aims to reinstate these processes at the catchment scale through the naturalisation of flow and physical form.

The remainder of this section looks at the following river ecosystem processes and their relevance to biodiversity:

- Disturbance
- Nutrient cycling and trophic linkages
- Feedback processes
- Sustainability and resilience
- Succession and end points

3.4.1 Disturbance

It has long been recognised that intermittent or intermediate disturbances, such as high or low flows, perform a vital function in the structuring of river communities (Sousa, 1984; Pickett and White, 1985; Resh *et al*., 1988; Townsend, 1989; Reice *et al*., 1990; Flory and Milner, 1999; Hildrew and Giller, 1994; Negishi *et al.,* 2002). The removal of hydromorphological heterogeneity and diversity through man-made damage has largely removed these regulatory factors leading to reduced biotic abundance and diversity (Negishi *et al*., 2002).

Disturbance in streams occurs at a range of spatial and temporal scales and drives the dynamic element of the system central to the maintenance of high biodiversity (Muotka & Virtanen, 1995; Ward, 1998). The physical effects of hydrological disturbances are evident through the formation and reshaping of fluvial features, and in the riparian zone where frequent disturbance by flood and debris flows create a complex shifting mosaic of landforms

(Naiman *et al*., 1993). High flows have in the past been considered disturbances because of their localised damaging effects (Scott, 1950; Eljabi & Rousselle, 1987; Steinman, 1992), and as the term has taken on a more scientific meaning, floods have often been identified as the main disturbance within river ecosystems. However, with the increasing appreciation of the role of disturbance in shaping habitat, the term has become more useful as a subtle concept to describe a specific ecosystem process.

A focus on the role of disturbance in shaping invertebrate assemblages within streams is common in the literature (Mackay & Currie, 2001; Death, 2002; Brown, 2007).Although developed as a model to explain patterns in vegetation development, the Intermediate Disturbance Hypothesis (Grime, 1979) has been applied to benthic communities (Townsend & Scarsbrook *et al*., 1997; Death, 2002) and used to explain the exceptional diversity found in some riparian zones. Its application predicts that habitats disturbed intermittently produce communities composed of both pioneer and climax taxa and are expected to be the most diverse (Death & Winterbourn, 1995).

Evidence for the influence of high flows on physical habitat is extensive. In upland gravel bed rivers, where sediments tend to be less cohesive and stream power can reach very high levels, the entire river bed can be mobilised and reshaped (Gilvear & Bradley, 1997). Jowett (1997) found that the types of bed movement associated with frequent floods reduced abundance and affected species composition. At the extreme, low frequency high flow events can reset entire benthic invertebrate communities (Scarsbrook & Townsend, 1993). When disturbance levels are suitably low in magnitude or infrequent there is the potential for macrophyte growth. Macrophytes have been described as 'biological engineers' (Carpenter & Lodge, 1986; Bouma *et al*., 2005; Cotton *et al.,* 2006; Franklin *et al*., 2008; Gurnell *et al*., 2012).

Aquatic macrophytes modify their surroundings in a number of ways, e.g. by stabilising the sediment (Hickin, 1984; James *et al*., 2009), altering the flow velocity regime (Marshall & Westlake, 1990; Cotton *et al.,* 2006), increasing water depth (Hearne & Armitage, 1993), providing substrate and habitat (Flynn *et al.,* 2002; Weber *et al.,* 2012), trapping sediment (Sharpe & James, 2006; Wharton *et al.,* 2006), or increasing habitat complexity (Champion & Tanner, 2000).

A range of ecological functions provided to small freshwater invertebrates by plants has been hypothesised and tested. The provision of habitable living spaces (Lodge, 1985), entrainment of particulate matter (Brusven *et al.,*. 1990), surfaces for epiphytic algal growth (Suren, 1991), shelter from turbulent flow (Linhart *et al.,* 2002) and chemically defended refugia from predation/consumption (Parker *et al.,* 2007) are reported.

Both floods and droughts might be considered to cause high magnitude disturbance. The drag disturbance that occurs during floods and associated dislodgement of biomass by high water velocities and associated abrasion by mobilised bed sediments has a strong influence over invertebrate and plant communities as has the deprivation of water during periods of drought. The conditions in both situations are outside the tolerances of individuals of most species. During stable and low flow drag-related disturbance declines in relative importance replaced by the increasingly dominant mass-transfer processes (Biggs *et al.,* 2005). Mass transfer is a broad term encompassing processes such as food uptake by invertebrates through grazing/predation, predation by fish, and uptake of inorganic nutrients by autotrophs. At small frequent scales of variation, mass transfer processes are likely to control growth and sustainability of individuals with moderate to high frequency flow events influencing processes that act on the organisation of populations within the community (Biggs *et al.,* 2005). Moderate to high frequency, low magnitude events also influence invertebrate communities (Biggs *et al.,* 2005). The development of community structure and the existence of guilds may be an indicator that ecosystem functioning relies on the existence of small-scale high frequency variability introduced by this type of disturbance. Small-scale disturbance can have a negative effect on invertebrate communities. By turning over rocks Robinson and Minshall (1986) changed the flow conditions for the resident invertebrates. Different feeding strategies and levels of mobility can affect the ability of invertebrates to adapt to this type of disturbance (Mackay, 1992). Robinson and Minshall (1986) found a significant reduction in invertebrate density and species richness with increasing disturbance frequency. Shallow stable areas of river bed have been found to provide important habitat for macroinvertebrate communities where they are generally poorly adapted to high magnitude disturbance (e.g. Nakano & Nakamura, 2008).

The intensity and frequency of disturbance requires consideration when assessing how appropriate restoration activities are for different river systems. The appropriate approach to restoration depends on the prevailing conditions (the most important of which are disturbance frequency and intensity, e.g. floods). A conceptual framework is presented in Figure 3.2 and illustrates the idea that a process-based approach would be too slow, and have a greater risk of progressing to an undesirable endpoint in infrequently disturbed environments. Likewise, where disturbance intensity is low there is less chance of the prevailing processes having the power to 'restore the habitats' and more chance of development being dominated by early colonists (which may or may not be desirable).

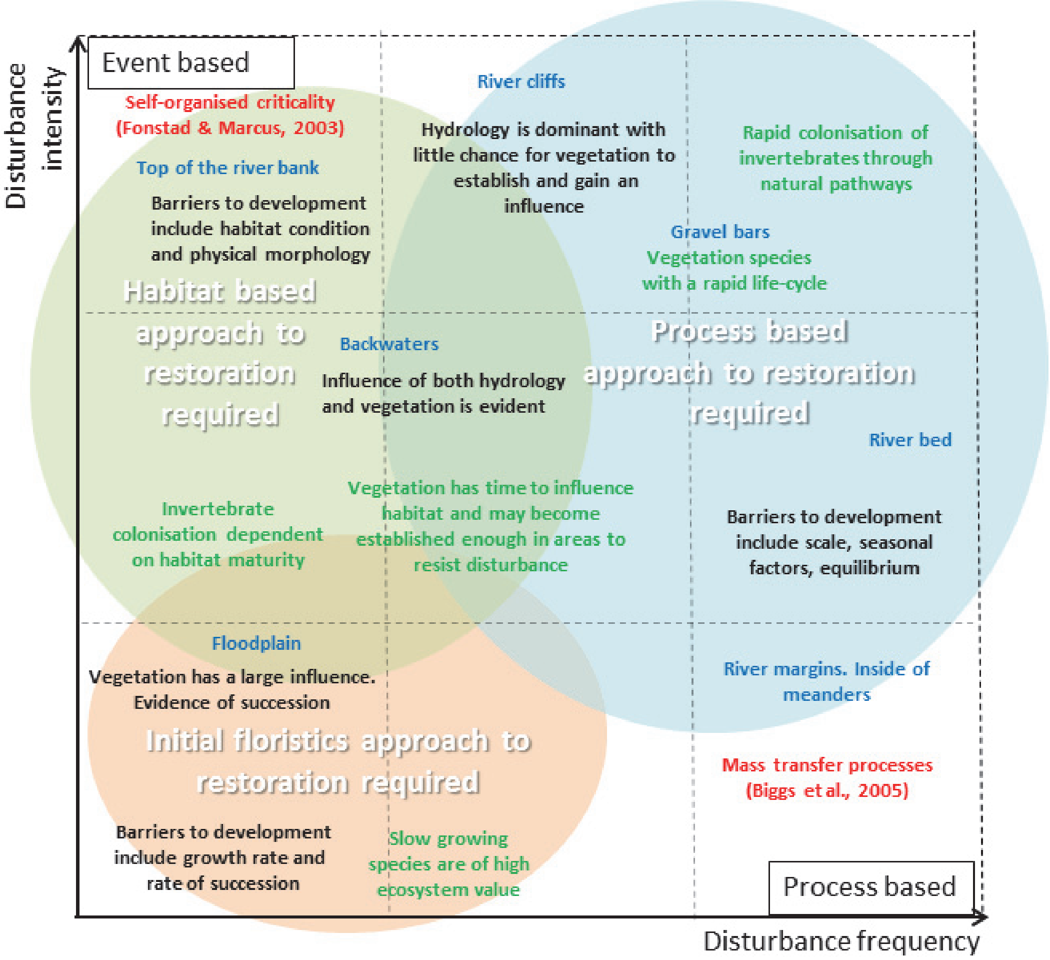

Figure 3.2: River restoration techniques appropriate to different disturbance regimes and intensities (from Perfect, 2010)

3.4.2 Nutrient cycling and trophic linkages

Macroinvertebrates have a key role in nutrient cycling and the transfer of trophic energy through the ecosystem. They have been shown to play a significant role in the breakdown of leaves at certain times of year. Exclusion of invertebrates from leaf packs by Nelson and Anderson (2006) reduced the loss of organic matter and nitrogen loss by 25% and 65% respectively. Forms of disturbance such as desiccation, sedimentation and freezing are cited as reasons for the limited macroinvertebrate processing at other times of year. Drifting invertebrates are a major source of food for a number of freshwater fishes (Merritt & Cummins, 1996). Macroinvertebrate density and diversity were found to be among six variables which best explains patterns in salmonid biomass (Annoni *et al.,* 1997). Trophic interactions such as herbivory and predation are often altered in degraded systems creating patterns resilient and resistant to restoration efforts (Suding *et al.,* 2004). Riparian corridors can also play a potentially important role in the removal of nutrients from runoff from terrestrial areas of the catchment (Lowrance *et al.,* 1984). The nutrients taken up by the riparian zone may eventually reach the stream as coarse particulate organic matter (CPOM). This has been identified as an important allochthonous carbon source in many streams (Pozo *et al*., 1997), often identified as an important role of riparian woodlands. However, inputs from herbs and grasses, although poorly understood, may represent a significant terrestrial–aquatic linkage and an important allochthonous energy source for non-forested streams (Menninger & Palmer, 2007).

3.4.3 Sustainability and resilience

Ecological resilience can be described as the speed at which a system returns to its former state after it has been perturbed and displaced from that state. In the context of restoration, resilience can refer both to a system's return to a restorative ‘goal’ state following a degradative perturbation, or a system's return to a degraded state following a management perturbation (Suding *et al*., 2004). Ecological resistance is the amount of change or disruption (or management perturbation) that can be absorbed before processes change that control the structure and behaviour of a system (Suding *et al*., 2004). Healthy ecosystems generally exhibit an ability to withstand (resistance) or recover rapidly (resilience) from disturbance events. It is obvious that diversity may take a temporary knock but the nature of the ecosystem as a heterogeneous entity and the presence of colonisation processes ensure diversity can be maintained in the longer term. The concept of ecosystem adaptability/flexibility is also important to consider. With mounting evidence of climate change influencing habitat conditions a healthy bio-diverse ecosystem (species and genetic) will be in a stronger position to adapt to the changing conditions and continue to provide valuable ecosystem services.

3.4.4 Succession and end points

It is generally accepted that many ecosystems are subject to temporal changes in community composition. The term 'succession', used to describe this change, can be sub-divided into primary and secondary succession (Grime, 1998). Primary succession occurs during colonisation and development of a new ‘skeletal’ habitat. Secondary succession occurs in circumstances where habitat is disturbed and re-colonised. Succession is thought to be a major driver of the structure and function of riparian vegetation (Milner & Gloyne-Phillips, 2005). Tied into this view of habitat evolution is the concept of the ‘end-point’, which represents the habitat conditions towards which successional changes are directed. There are many examples of restoration efforts relying on successional pathways that have had unexpected endpoints (Suding *et al*., 2004). A more successional based approach assumes that the re-establishment of the historical physical environment will allow natural successional processes to reinstate the original ecosystem condition and biota (Suding *et al*., 2004). Removing degrading pressures such as grazing intensity may be a viable rehabilitation option in some circumstances but the expectation that this should always be sufficient to allow successional recovery is naïve. The persistence and resilience of degraded ecosystems is increasingly documented by research (Suding *et al.*, 2004) and can represent ‘alternative states’. There is evidence that degraded communities are highly resilient to restoration efforts (Suding *et al.*, 2004). A link between theoretical models of alternative ecosystem states and restoration ecology is beginning to emerge (Suding *et al.*, 2004).

3.5 Benefits of process-based restoration

River restoration activities in the earliest forms aimed to reinstate form with little focus or awareness of process with an approach largely based on expert judgment rather than empiricism (Hey, 1994; Zedlar, 2000; Hansen, 2001). When viewed at a reach scale these projects may fulfil the project aims and objectives but ultimately be unsuccessful due to continuing pressures, or development of unfavourable conditions. This has led to the development of process-based restoration practices which seek to introduce natural dynamism and have long-term goals to return rivers to natural conditions where possible based on hydromorphic and ecological principles.

Process-based restoration aims to re-establish uninterrupted physical, chemical, and biological processes that create and sustain river and floodplain ecosystems. Processes are typically measured as rates, and they involve the movement of, or changes to ecosystem parts and features (Beechie & Bolton, 1999). Processes include erosion and sediment transport, storage and routing of water, plant growth and successional processes, input of nutrients and thermal energy, and nutrient cycling in the aquatic food web. Process-based restoration focuses on correcting human disruptions to these processes, such that the river–floodplain ecosystem progresses along a recovery trajectory with minimal corrective intervention (Sear *et al.*, 1994; Wohl *et al.,* 2005). Restoration of critical processes also allows the system to respond to future perturbations through natural physical and biological adjustments, enabling river ecosystems to evolve and continue to function in response to shifting system drivers (e.g. climate change).

Common pitfalls of engineered solutions, such as the creation of habitats that are beyond a site’s natural potential, piecemeal stabilisation of habitat features, and restored habitats that are ultimately overwhelmed by pressures which continue to act on biota. Legal mandates, whether international or national, have driven the need to restore narrowly defined aspects of river ecosystems such as water quality, species, or structural features. These aims or techniques often fail to address root causes of habitat degradation, and therefore restoration projects fail to accomplish the desired environmental and legal objectives.

Because complete restoration of catchment and river processes is rarely possible (Stanford *et al.,* 1996), river restoration employs strategies ranging from fully restoring processes, to habitat-creation efforts that construct artificial habitat features as a substitute for natural functions. Full-restoration actions restore habitat-forming processes and ultimately return an ecosystem to its pre-disturbance or normative range of conditions and dynamics. Partial-restoration actions restore selected ecosystem processes and functions, but do not return the system fully to pre-disturbance conditions and dynamics. Habitat-creation actions are focused on building habitat rather than addressing the root causes of degradation. Given that full restoration is often difficult to achieve, even at individual sites, partial restoration frequently becomes the best achievable goal (Stoddard *et al.,* 2006).

On the basis of a synthesis of recent literature, Beechie *et al*. (2010) proposed four main principles of process-based restoration:

i. Target root causes of habitat and ecosystem change
    - Requires assessment of processes that drive habitat conditions.
    - Actions are designed to correct human alterations to driving processes.

ii. Tailor restoration actions to local potential
    - Restoration actions need to redirect channel and habitat conditions into range that suits the channel and riparian conditions based on its physiographic and climatic setting.

iii. Match the scale of restoration to the scale of the problem
    - If disrupted processes are causing degradation at a reach scale, restoration actions at individual sites can effectively address root causes. If it's at the catchment scale then many individual site-scale options are required.
    - Recovery of wide-ranging fishes (e.g. Atlantic salmon) requires restoration planning and implementation at the scale of population ranges.

iv. Be explicit about expected outcomes
    - Process-based = long-term.
    - Often long lag times between implementation and recovery.
    - Need to quantify the restoration outcome – critical for setting appropriate restoration expectations.

3.6 Evidence base for linkages between process restoration and biodiversity

Further to the detail provided on habitat, process and ecosystem properties of the river environment, the following section reviews the evidence base for process restoration and biodiversity.

Detailed assessments of process-based restoration have been conducted by Paul and Meyer (2001), Allan (2004) and Feld *et al*. (2011), the last as part of the WISER[4] project at the European scale. Feld *et al.* (2011) produced a series of conceptual models totalling 64 links between restoration measures, hydromorphological processes and variables, matter retention, nutrient state and the four WFD biological quality elements (phytoplankton, macrophytes, macroinvertebrates and fish). Although the single links were supported by studies and empirical evidence, the concerted effect of all possible linkages on biota was very difficult to disentangle and even more difficult to quantify and measure. Three conceptual models were investigated and evidence for biological response was undertaken in relation to restoration 'state changes' (process-based outcomes) and evidence was gathered to support the theoretical linkages. The evidence base for ecological attributes of fish, benthic macroinvertebrates, macrophytes and phytobenthos is summarised in Figure 3.3 with the total supporting citations for biotic response across the three conceptual models and illustrates that the majority of research reviewed focused on the responses of fish and macroinvertebrate assemblages. An example of the range of process-related changes detected due to the enhancement of instream habitat structures is provided in Figure 3.4. Much of the body of evidence examined failed to support or was neutral in outcome of the process linkage examined. The following summary highlights links found in the study that were well supported.

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[4] WISER – Water Bodies in Europe: integrative systems to assess ecological status and recovery (http://www.wiser.eu/)

While the ecological assessment according to the WFD is mandatorily based on phytoplankton, macrophytes, macroinvertebrates and fish, it has been demonstrated that phytoplankton does not directly respond to hydromorphological processes (e.g. Pottgiesser *et al*., 2008, Wolter *et al.,* 2009, Mischke *et al.,* 2011, Marzin *et al.,* 2012). Feld *et al.* (2011) found no evidence for process and function, sensitivity and tolerance and diversity of phytobenthos during their review. Of the limited relationships described, Coe *et al.* (2009) found increased phytobenthos biomass due to the increase in habitat surface area provided by the addition of wood, while other studies demonstrated a negative relationship for algal biomass (Davies-Colley & Quinn, 1998; Parkyn *et al.,* 2003; Ghermandi *et al.,* 2009; Quinn *et al.,* 2009) and composition and abundance (Parkyn *et al.,* 2003) attributed to the influence of shading from riparian areas.

3.6.1 Riparian buffers

There is a widely accepted view that restoring buffer zones has a range of beneficial outcomes for biota by increasing water quality and habitat complexity, reducing fine sediment and water temperature and providing new sources of wood to the river system, (Feld *et al*., 2011). Simple fencing activities and allowance for space in the river coridor are often conducted as part of restoration activities in the UK and Ireland and initially the driver was for pollution regulation and fine sediment control. Hence much of the literature has focused on responses of macroinvertebrates and fish to water quality and potentially missed the importance of the habitat in contributing to biodiversity and river process. Changes in benthic invertebrate diversity, composition and abundance in response to (water quality) improvement of riparian buffers were found in 56 studies. There was no evidence of negative impacts of this activity and only four studies failed to find any benefits.

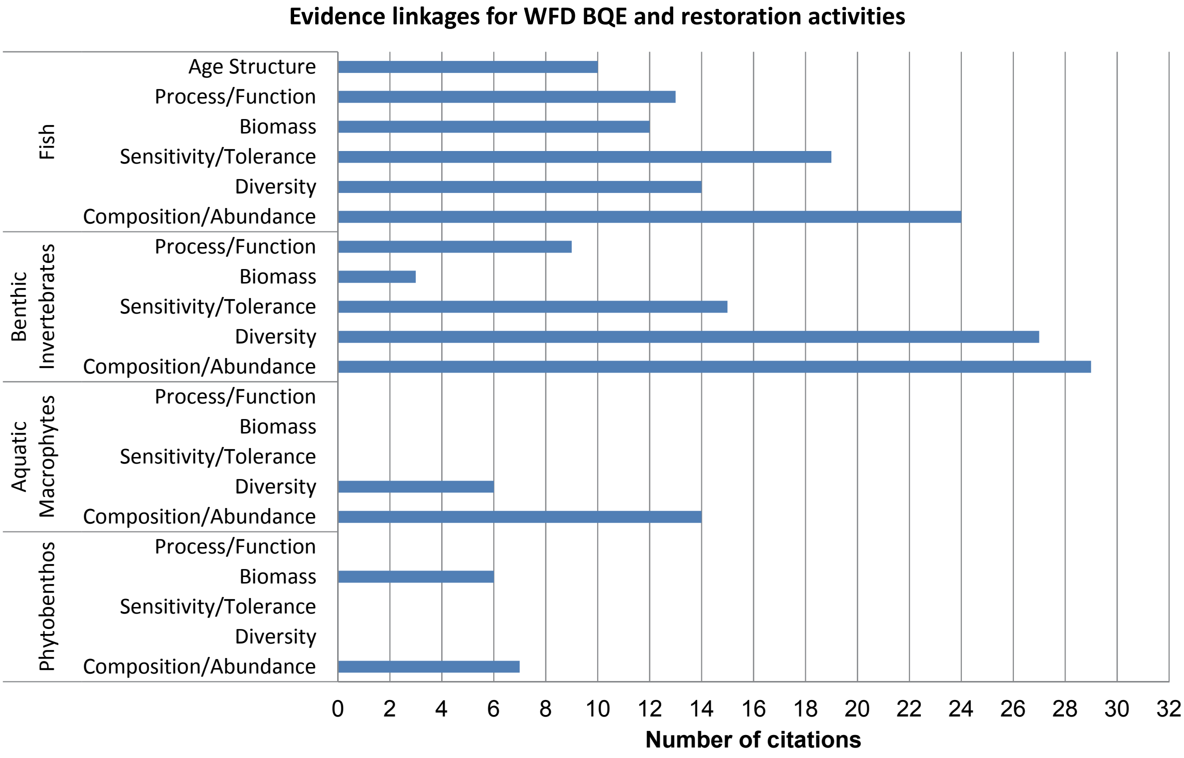

Figure 3.3: Evidence linkages for the WFD BQE found in conceptual models (Feld et al., 2011).

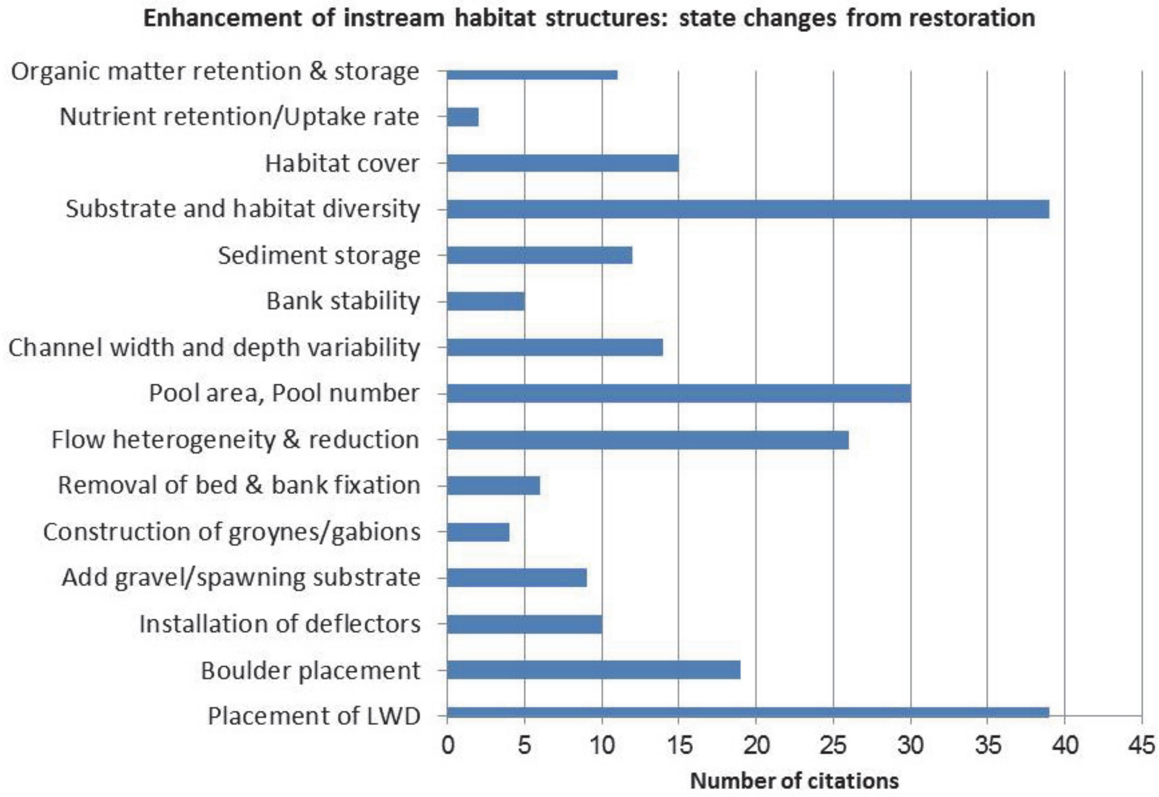

Figure 3.4: Example of citations for the observed changes derived for restoration activities from the conceptual model of instream habitat structures (Feld et al., 2011).

The importance of LWD was highlighted in many of the studies with the strongest relationships being as direct habitat for macroinvertebrates but also flow refugia and shelter for juvenile fish (Brooks *et al*., 2004). Parkyn *et al*., (2003) found a negative effect on macrophyte composition and abundance relating to shading from riparian buffer strips. Conversely, macrophyte abundance and diversity was improved by riparian buffers (Moustgaard-Pedersen *et al*., 2006) due to the heterogeneity in riparian margins and edge habitats where bank profiles were suitable to allow lateral connectivity and transmission between the channel and floodplain. If suitable connectivity existed then introduced woody material was shown to aid the recruitment process of species from the bankside to the channel and also allow in-channel structures to develop. For fish, the only adverse effect of riparian buffers was found for fish growth and biomass due to reduced water temperature (Weatherley & Ormerod, 1990). Brown trout (*Salmo trutta*) could reach a body weight in the region of 30% higher at the end of their second growing season in moorland streams compared with forested streams. The development of adequate shading and reinstatement of sources of LWD requires sufficent development time in improving channel form. Opperman & Merenlender (2004) found that in a stream where the restored riparian vegetation had developed for >20 years, LWD in-channel frequency was similar to that of mature hard-wood forested streams. Beneficial channel narrowing had occurred in some experimental sites with riparian planting. However, these sites had characteristically high sediment loadings and several years of high flows, (rather than the restoration action) could have prompted overbank deposition and channel narrowing processes.

Although there was good evidence to support nutrient and sediment retention and water temperature and instream habitat, there was a surprising lack of evidence for strong quantifiable relationships with biota and links and models of restoration mechanisms (Feld *et* *al*., 2011). Irrespective of these findings it was felt that in the case of riparian buffers there is sufficient evidence that the techniques employed result in improvments to biodiversity and that best practice guidance can be developed, founded on sound scientific evidence (Feld *et al*., 2011).

3.6.2 Restoring physical habitat: morphological enhancement of the channel

The introduction of substrates and features to the channel is often aimed at providing habitat for fish and macroinvertebrates, while artificial structures and removal of bank reinforcement is aimed at re-establishing dynamic processes. This frequently applied group of restoration activities has been subject to considerable review (Roni *et al*., 2008; Miller *et al*., 2010; Palmer *et al*., 2010; Feld *et al*., 2011). Miller *et al*. (2010) focused on 24 studies and performed a meta-analysis to try to determine whether it supported the common assumption that restoring physical habitat diversity automatically increases biodiversity. They demonstrated that increasing heterogeneity of the habitat provided significant positive effects one year after restoration, especially in forested reaches. Certain restorative measures proved more successful; for example, the addition of large woody debris had the most consistently positive results on species richness, compared with other techniques, including boulder placement, which was shown to have more varied outcomes.

Haase *et al.* (2013**)** investigated the effects of 24 river restoration projects in Germany, comparing hydromorphological parameters and biological diversity of macroinvertebrates, fish, and macrophytes in restored reaches, with nearby unrestored sections. While hydromorphological condition changed significantly in the restored sections, biological differences between restored and unrestored sections were less apparent. Positive restoration effects were observed only for fish (11 of 24 cases). Based on the synthesis of results from the different organism groups, only one of the 24 restored sections reached 'good ecological status' and pressures other than hydromorphological degradation were thought still to affect the biota in restored sections.

Given the widespread use of these techniques in river management and broad acceptance that habitat heterogeneity promotes biodiversity (sensu Harper & Everard, 1998) there is a surprising lack of evidence for habitat heterogeneity being a primary factor controlling macroinvertebrate diversity (Palmer *et al*., 2010), or fish productivity (Roni *et al*., 2008). Studies that detected little or no effect of restoration often described continuing pressures within the catchment such as water quality or fine sediment inputs which limited restoration success, rather than true absence of effect (Feld *et al*., 2011). Furthermore, the lack of sound, repeatable study design (i.e. BACI[5]) and choice of unimpaired controls to detect effects, was responsible for the poor partitioning of restoration effects from inherent system variability, disturbance regime or overriding pressure (Miller *et al*., 2010).

3.6.3 Restoration and removal of weirs and dams

In the UK and Ireland, barrier removal and associated fish passability represents a considerable challenge as there are thousands of structures causing connectivity issues across the region. Although the potential hydromorphological and ecological behaviour post-removal are generally appreciated, little or no research has examined the potential negative impacts that this activity could have, rather focusing on the clear success that fish passage brings in opening up new habitat. It is estimated that 14 WEF[6] projects in Scotland opened up 3,052 km^2 of new river to migratory fish with an estimated £40 per km^2 spend, between 2009-2011. It is apparent that WFD objectives for some water bodies could be substantially met through this restoration activity and much interest is placed in restoring fish populations across the region. Although discussion here is focused on weirs and dams there are

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[5] Before After Control Impact design

[6] WEF Water Environment Fund – data from SEPA 2011 Restoration Fund Review of Progress

similarities with flow deflectors such as croys[7] with respect to sediment release after removal and potential instabilities downstream.

Dam and weirs can have a significant influence on the hydrology and water level of a river for considerable distances upstream and downstream, interrupt sediment supply and conveyance and severely limit the range of migratory fish (Bednarek, 2001). Removal of dams and weirs may best be considered as ecological disturbances resulting from tranformation from lentic to lotic conditions upstream leading to the release of stored fine sediment and subsequent pulse to the downstream reaches (Thomson *et al.*, 2005). As such they represent interesting studies from both a hydromorphological and ecological perspective, as they result in the removal of a man-made 'serial discontinuity' in the river system.

Feld *et al.* (2011) examined 36 studies predominantly in North America (only three studies were found from Europe) and identified five consistent effects relating to channel morphology (width and depth relationships); substrate particle size (and gravel bar formation); flow diversity (and turbidity); and temperature and conductivity. Few of the studies provided any quantitative evidence for effectiveness of restoration but the findings did indicate that negative impacts of removal on biota were shortlived, while beneficial changes in biota and physical habitat were likely to occur in the longer term.

Following removal recovery of connectivity is clearly rapid, as is the effect on water temperature and free-flowing conditions but biological recovery to the pre-barrier state may require several years or even decades, especially when considering the timescales for the re-distribution of fine sediments downstream. The studies examined were primarily from low energy systems. The timescales and impacts on biota of this sediment release depend largely on the sediment quality and quantity released, stream power and the specific methods of removal (Bednarek, 2001). This author estimated full recovery in periods of up to 80 years. As the literature rarely included post restoration monitoring for longer than 5 years, this timescale and trajectory of recovery remains speculative without further long-term monitoring of these activities (Feld *et al.*, 2011)

Little effort was made to determine impacts downstream although some studies considered this disturbance as trivial when compared with the natural variability of the system (Orr *et al.*, 2006). Hart *et al.* (2002) speculated that the removal process can lead to ecological damage but over time this can be mitigated by several responses such as the colonisation of species, nutrient transport and genetic changes in the population; although potentially timescales for recovery are very long as biota adjust to the changes in channel form following structure removal. Using 3 years before and after monitoring, Maloney *et al.* (2008) compared the upstream and downstream reaches following dam removal on the Fox River, Illinois and compared it with the same monitoring strategy from three nearby intact dams. After one year, the physical habitat of the former impounded section resembled that of the free-flowing sections. Not only had the bed particle size and flow rate increased but the width and depth of the channel had decreased. After 2 years, changes in macroinvertebrate assemblages of the previously impounded sections resembled those of free-flowing conditions. In response to a lack of research into the ecological responses following dam removal, Bushaw-Newton *et al.* (2002) undertook an interdisciplinary study to determine the ecological responses following the removal of a 2m high dam in Pennsylvania. Within the previously impounded area there was a rapid shift in macroinvertebrate taxa from lentic to lotic assemblages following the resumption of free-flowing conditions. Although there is evidence showing that macrophytes can benefit from such restoration measures (e.g. Tszydel *et al.*, 2009) this

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[7] Croys – (often) large-scale flow deflectors designed to alter flow behaviour to the benefit of reach-scale fishing interests

primarily related to the rapid colonisation of previously impounded areas rather than changes in physical condition in the stream bed.

Studies demonstrating benefits of process-based restoration
A strategic assessment of 36 renaturalisation projects in Germany (Lorenz *et al.,* 2013), covering streams and rivers selected to avoid significant water quality problems, found generally wider and shallower channels with greater depth and substrate variation and greater occurrence of shallow, fast-flowing areas suitable for spawning and juvenile development of a range of fish species. This included small species such as bullhead, minnow and stoneloach, where all life stages benefited from shallow areas of water, as well as larger species such as brown trout, barbel, dace and chub which benefited from the complex mosaic of spawning, juvenile and adult (deeper water) habitat

An assessment of two large-scale river restoration initiatives in Germany (Lüderitz *et al*., 2011) found large increases in habitat extent and diversity, including a 1.6-2.4-fold increase in bank length and a substantial associated increase in substrate diversity. These changes were associated with a 2- to 3-fold increase in macroinvertebrate diversity and fish assemblages that were more similar to reference (unimpaired) communities for the rivers involved.

Jähnig *et al.* (2009) conducted a comparative analysis of restoration measures and their effects on hydromorphology and benthic invertebrates in 26 central and southern European rivers. They found that restoration measures addressing relatively short river sections (several hundred metres) were successful in improving habitat diversity of the river and its floodplain. These ‘active’ restoration measures are suitable if short-term changes in hydromorphology are desired but to improve benthic invertebrate community composition, habitat restoration within a small stretch is generally not sufficient. They concluded that:

- restoring habitat on a larger scale, using more comprehensive measures and tackling catchment-wide problems (e.g. water quality, source populations) are required for recovery of invertebrate communities.
- Habitat may be engineered to be more diverse, neither active nor passive restoration approaches result in significant changes in stream benthic invertebrate colonisation.
- Passive river restoration, which is less cost-intensive, less interventionist and more easily applicable to longer stretches of a river might eventually lead to the same improved state of a water body or catchment, as would much more expensive active restoration measures.
- Actively improving aquatic habitats along a short river reach may even come at the price of causing degradation of the riparian zone, e.g. to facilitate earth moving, but will not necessarily enhance ecological quality. Rather, efforts at a larger scale, i.e. catchment wide, including more comprehensive measures and tackling all pressures, are likely to have effects on the invertebrate community – eventually improving ecological form and functioning.

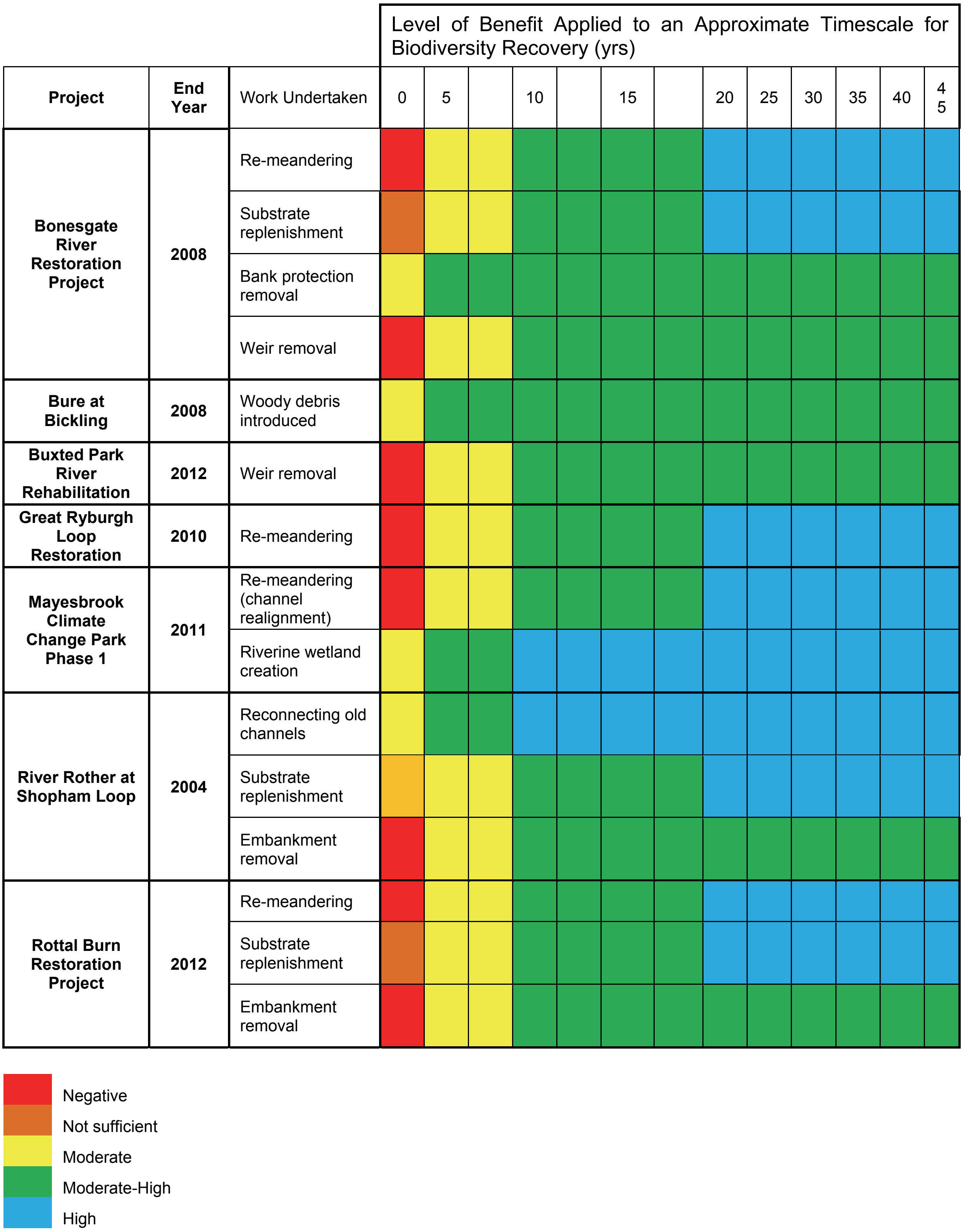
3.7 Challenges for restoration

Timescales of recovery or restoration success are important to consider when appraising the biodiversity gains for different river restoration activities and determining success or failure of methods. The development of functional physical habitat can be started through restoration activities but positive biological response may take considerably longer especially if there are other catchment pressures (Bernhardt *et al.,* 2005; Palmer *et al.,* 2010), if at all (Roni *et al.,* 2008; Bernhardt & Palmer, 2011; Violin *et al.,* 2011). Theoretical timeframes for restoration success for different activities are presented in Figure 3.5 with examples of projects that provide research opportunities for assessing specific process-based techniques. At a European scale it was found that the necessary timeframes to complete the assessment of recovery are seldom resourced and that the lack of solid long-term data-gathering exercises is constraining the appraisal process (Feld *et al*., 2011). The study highlighted a number of key points:

- **The spatial scale -** must be great enough to promote recovery (i.e. at the catchment). Distance or absence of source populations and lack of connectivity results in dispersal limitations and colonisation barriers.

- **Timescales of monitoring** – development and maturation is needed for recovery and development of the stream ecosystem for many restoration schemes. Response times for organism groups in rivers are lacking, because the literature rarely includes monitoring of more than 5 years, and it is uncertain whether biological responses of some species in rivers occur within this period. The potential benefits of most instream structures such as groynes or flow deflectors will be short-lived (<10 years) unless coupled with riparian planting or other process-based restoration activities supporting long-term recovery of key ecological and physical processes.

- **Multiple pressures often present -** mostly only one or a few pressures were tackled, others were forgotten or were technically infeasible to address. Confounding abiotic processes affect recovery, such as upstream ‘hidden’ stressors, e.g. internal phosphorus loading; biological interactions, e.g. the early arrival of non-native species; and factors such as climate change and the potential impacts of management and maintenance strategies, (e.g. dredging).



			Level of Benefit Applied to an Approximate Timescale for Biodiversity Recovery (yrs)												
Project	**End Year**	Work Undertaken	0	5		10		15		20	25	30	35	40	45
Bonesgate River Restoration Project	**2008**	Re-meandering	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦
		Substrate replenishment	🟧	🟨	🟨	🟩	🟩	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦
		Bank protection removal	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
		Weir removal	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Bure at Bickling	**2008**	Woody debris introduced	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Buxted Park River Rehabilitation	**2012**	Weir removal	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Great Ryburgh Loop Restoration	**2010**	Re-meandering	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦
Mayesbrook Climate Change Park Phase 1	**2011**	Re-meandering (channel realignment)	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦
		Riverine wetland creation	🟨	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
River Rother at Shopham Loop	**2004**	Reconnecting old channels	🟨	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
		Substrate replenishment	🟧	🟨	🟨	🟩	🟩	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦
		Embankment removal	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Rottal Burn Restoration Project	**2012**	Re-meandering	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦
		Substrate replenishment	🟧	🟨	🟨	🟩	🟩	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦
		Embankment removal	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

🟥 Negative
🟧 Not sufficient
🟨 Moderate
🟩 Moderate-High
🟦 High

Figure 3.5: Theoretical timescales for recovery for different activities and example projects (Adapted from Gilvear et al., 2013)

3.8 Monitoring and restoration frameworks

The monitoring of restoration is limited in the UK and Ireland with few detailed published studies (e.g. Sear *et al.*, 1998). Of the 2,309 projects compiled for this study, only 429 reported any form of monitoring, primarily photographic records or fisheries survey. Only a few projects reported any detailed assessment and this is discussed in Section 5. More recently, projects are being conducted that build monitoring into their programmes at an early stage (e.g. LIFE+ Pearls in Peril on the River Dee in Scotland and the Catchment Restoration Fund projects in England). This historical lack of restoration monitoring, especially of process, is not unique to the study region and has long been recognised as an issue (e.g. Boon *et al.*, 1992). Of the wider European and global efforts to enhance the hydromorphological state of rivers (Bernhardt *et al.*, 2005, Roni *et al.*, 2005, Feld *et al.*, 2009, 2011, Wolter 2010), very few have been monitored in detail (Palmer *et al.*, 2005, Roni *et al.*, 2005, 2008, Alexander & Allan 2006, Kail *et al.*, 2007, Feld *et al.*, 2011). The projects evaluated further showed that many measures did not have the desired effects on biodiversity (Brooks *et al.*, 2002, Pretty *et al.*, 2003, Lepori *et al.*, 2005, Roni *et al.*, 2005, Suren & McMurtrie 2005, Jähnig *et al.*, 2009, Palmer *et al.*, 2010) maybe because of inappropriate assesssment techniques or overriding confounding pressures, (Miller *et al.*, 2010, Tockner *et al.*, 2010, Feld *et al.*, 2011).

Historically, design and analysis of biological monitoring data from river restoration projects has often relied on the use of standard indices and scores. However, these were developed for other purposes, i.e. to detect organic pollution or nutrient enrichment, as this was considered the overwhelming issue with the quality of freshwater habitats at the time that they were first developed. Therefore, although comparisons between scores may show improvements due to river restoration, the indices are not designed to detect changes that result from differences in geomorphology, flow and associated habitat complexity.

Wolter *et al.* (2013) examined existing databases and around 1,000 papers and reports on ecological requirements of plants, macroinvertebrates, and fish with relevance to hydromorphology, to elucidate specific requirements, preferences, and limitations of potential indicator species. The meta-analysis aimed to identify those species or taxa that respond sensitively to hydromorphological variables and processes and thus might become diagnostic indicators for hydromorphological integrity as well as pressures and impacts on hydromorphology. The study identified a group of potential indicator taxa showing reliable preferences for coarser bed material and higher shear forces and more general thresholds were derived of tolerable flow velocities and shear forces, setting physical boundary conditions for habitat suitability and thus relevant in restoration planning. The data on species response to hydromorphological changes was rather limited, as illustrated in Table 3.3, and significant gaps in knowledge were identified regarding the ecological classification and habitat requirements of riverine species. A primary recommendation from the study was that although data exist, and further meta-analysis may be beneficial, the current knowledge gap is only likely to be fully addressed by field surveys, and that this effort could potentially yield further sensitive indicator species for hydromorphological changes, and potential target species for river rehabilitation design and evaluation.

Table 3.3: Evidence for species preferences for substrate size and flow velocity thresholds and shear stress tolerance for macroinvertebrates

BQE	**Approximate species richness**	**Gravel size requirements**	**Flow velocity thresholds***	**Shear stress thresholds**
		No. of species with quantified preferences		
Macrophytes	500	10	75	-
Macroinvertebrates	20,000	56	78	164
Fish (including lamprey)	550	28	550*	-

**derived from regression functions based on total length of fish by Wolter et al. (2013)*

For any river or floodplain restoration project it is necessary to demonstrate its success for wildlife and the benefits of working with natural river processes. Roni and Beechie (2013) provide a useful framework for a catchment-based approach to identifying sound process-based options (Figure 3.6). To do this, project assessments are required and must be a fundamental part of the project and considered at each stage of project development. Further to this framework, the idea of adaptive design is illustrated in Figure 3.7 which demonstrates an idealised iterative and adaptive monitoring and management process for newly restored channels. This allows for intervention and hydromorphic or ecological maintenance to steer a project in a desired direction.

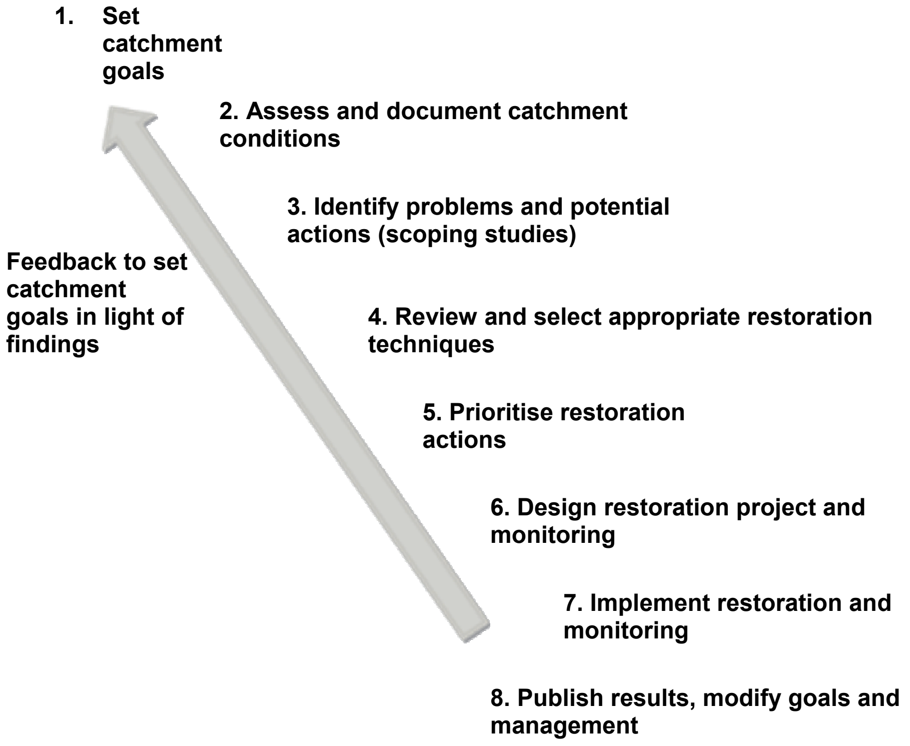


Figure 3.6: Major steps in the restoration process required to develop a comprehensive restoration programme and well-designed restoration projects (adapted from Roni and Beechie, 2013).

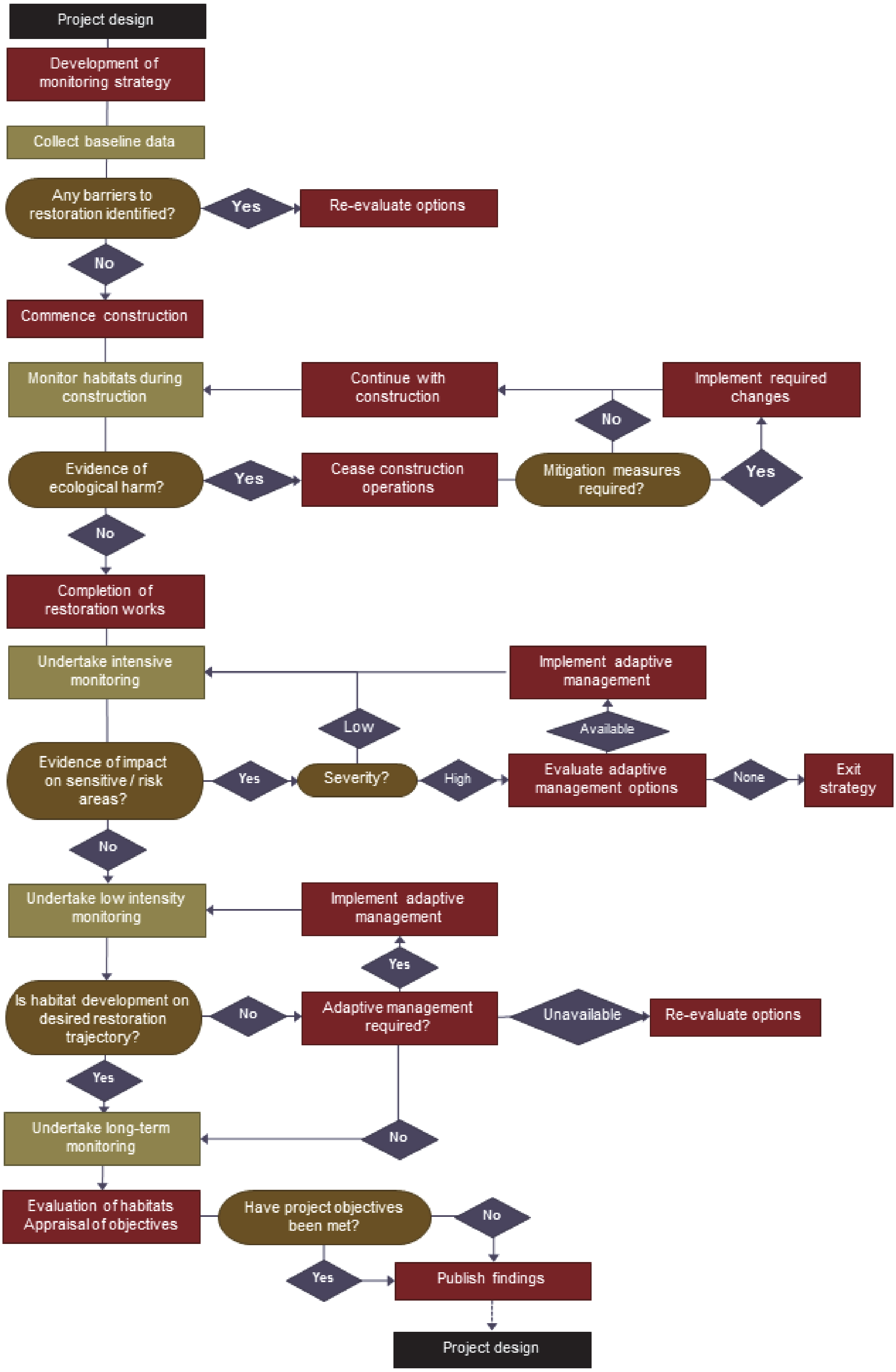


Figure 3.7: Proposed framework for adaptive design and management processes for an idealised restoration project. The framework provides further guidance to Steps 6-8 in Figure 3.6.

Well defined and targeted project objectives are important when considering project appraisal. Due to the ‘ad hoc’ nature of project monitoring, and the need for clear guidance the PRAGMO document (RRC, 2011) was devised to provide information to involved parties that will help them determine the required level of monitoring based on variables such as physical form of river and the size and complexity of the restoration project. The identification of risk and project scale is highlighted and general concepts advocated are synthesised in Figure 3.8.

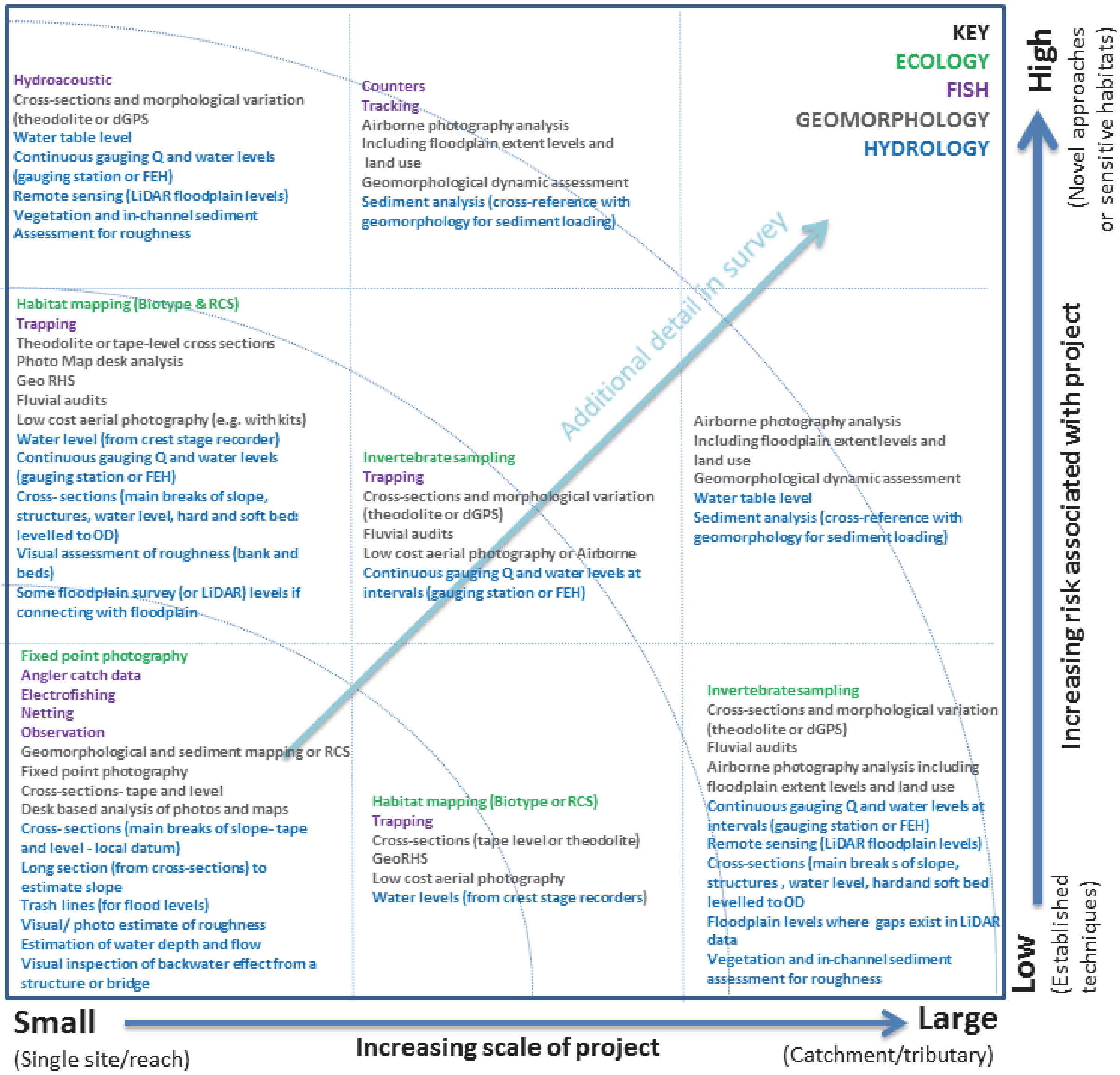


Figure 3.8: Synthesis of PRAGMO monitoring guidance illustrating scale of project and increasing risk associated with restoration activities.

3.9 The emerging themes in process-based restoration

The process linkages between hydrology, geomorphology and ecology represent a ‘new frontier’ for development in river conservation. Eco-hydromorphology aims to develop concepts, theories and observations and determine greater process and functional understanding to underpin conservation objectives. This multi-disciplinary approach requires dialogue on mutually valued questions and the adoption of mutually acceptable methods and there are significant barriers and issues to overcome (Vaughan *et al.,* 2009).

In summary the following challenges exist:

- Current scientific understanding is generally sparse - especially at the quantitative levels required for effective prediction and management. Numerous (mainly observational) studies have described links between biological pattern, ecological processes, and river form and physical processes, yet the underlying mechanisms are often only known in outline.

- Although evidence linkages are strong for many key process-based activities such as riparian planting and floodplain continuity, evidence for positive responses to process-based restoration activities is sparse and hampered by project timeframes and longevity, lack of BACI, etc. and timings of recovery.

- Riparian and floodplain environments are less widely studied than those in the wetted channel – there is a need to consider whole catchments and river landscapes (‘riverscapes’) in the development of eco-hydromorphic research (Eyre *et al*., 2002). In the case of riparian buffers, there is clear evidence that the techniques employed are effective and that best-practice guidance can be developed, founded on sound scientific evidence (Feld, 2011).

- Biological indicators of physical modification are still preliminary, rarely described or poorly founded, (Vaughan *et al*., 2009) while few biological models diagnose how physical effects contribute to biological departures from expected conditions (Davies *et al*., 2008). Major challenges arise in distinguishing the influences of hydromorphic modifications on organisms or processes from other potentially confounding effects such as pollution (Allan, 2004). The definition of expected or reference conditions is challenging given the inherent variability in both physical habitat and biology (Nijboer *et al*., 2004).

- Riverine assemblages react to disturbance differently depending on the conditions before and after, species loss and interruptions in the transition to a process-based outcome.

- As some organisms are more mobile than others, the recovery of organisms from restoration disturbance is likely to be relatively rapid for in-channel biota (excluding sensitive moss and lichen taxa) but the development of vegetation and marginal complexity is a time-consuming process as the channel margin can be a hostile environment, especially during primary colonisation. The drive to cover river banks rapidly must also allow the natural seedbank to compete and bring a more diverse and suited species composition to the banks.

- It is relatively easy to restore basic function and form but recovery of biodiversity and re-bound to a desired pre-disturbance state may be a long process, or timescales of improvement may be short-lived (e.g. in the case of small-scale interventions), The installation of channel forms that are not in keeping with driving processes, for instance, artificially incorporating structures in flood-prone or high energy environments may not have long-term beneficial effects because of overriding energy and removal or destruction of the engineered feature. The target biotic response may also be affected by localised extinction of taxa, distance to source populations or other prevailing pressures upstream that delay recovery trajectories.

4. PHYSICAL HABITAT DAMAGE IN THE UK AND IRELAND

4.1 Overview

This section provides a summary of the threats to river biodiversity (Section 4.2), leading on to the links this has with the damage to rivers and catchments from a historical perspective (Section 4.3). Section 4.4 assesses the quantification of damage and the impact on biota. A detailed assessment of damage to rivers in the UK and the Republic of Ireland is provided in Section 4.5, followed by discussion on the implications this has for river conservation (Section 4.6).

4.2 Threats to river biodiversity in the UK

The British Isles host a diverse range of organisms that inhabit or are closely associated with rivers or their riparian areas. On the UK mainland there are 353 red list species (IUCN, 2014) associated with rivers including critically endangered species: the eel, (*Anguilla anguilla*), and the moss *Thamnobryum angustifolium*. In Ireland there are 273 red list species associated with rivers, with the eel the only critically endangered species (IUCN, 2014). Pearl mussels have an important stronghold within the British Isles and pearl mussel habitat quality is closely tied to morphological processes and the life-cycle of salmonids.

The biodiversity of several key groups is well characterised due to the use of these taxa in monitoring or because of economic importance, e.g. fisheries. Less well understood taxonomic groups are the fungi, bacteria and deep river substrate communities of the hyporheos. The following summary provides a brief summary of river biodiversity:

- The phytobenthos of the UK is varied and the number of discrete taxa is difficult to ascertain. The Diatom Assessment of River Ecological Status (DARES) methodology[8] for monitoring and identifying benthic diatoms includes approximately 5,940 different taxa that occur in UK rivers.

- In total, 1,097 macrophyte species have been recorded[9] in the UK (since 1977) with 645 recorded from river channels and 1010 species in the adjoining bankside areas. Macrophytes regularly hybridise adding to the diversity and distinctiveness of macrophyte assemblages found in rivers. For example, *Potamogeton* spp. regularly hybridise, with 21 true species and 26 recognised hybrid combinations (Preston, 1995).

- In total, 4,228 species of aquatic macroinvertebrates have been recorded[10] (since 1978) although some of these species are currently considered extinct in the UK. Focusing on specific taxonomic groups of macroinvertebrates, Ephemeroptera (mayflies), Plecoptera (stoneflies) and Trichoptera (caddisflies) orders have 51, 34 and 198 species respectively (FBA, 2011).

- There are 36 native fish species that commonly occur in UK rivers[11]; in Ireland, there are 23 freshwater fish species (Inland Fisheries Ireland) with *Salmo nigripinnis* found in a single catchment[12].

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[8] DARES Project Description http://craticula.ncl.ac.uk/DARES/dares_project.htm

[9] JNCC River Macrophytes Database

[10] Guide to the National Invertebrate Database (NID), CEH Report

[11] CEFAS http://www.cefas.defra.gov.uk/our-science/fisheries-information/species-of-conservation-importance.aspx

[12] The species is endemic to Lough Melvin (21 km²), Ireland.

- Bird species such as dipper (*Cinclus cinclus*), kingfisher (*Alcedo atthis*) and sand martin (*Riparia riparia*) are ubiquitous but other species such as corncrake (*Crex crex*) were historically dependent on floodplain meadows. A few wildfowl and wader species such as goosander (*Mergus merganser*) and common sandpiper (*Actitis hypoleucos*) are reliant on the river directly; and many other species benefit from the abundance of feeding opportunities rivers and streams provide.

- The diversity of native aquatic/riparian mammals in UK rivers includes water vole (*Arvicola terrestris*) and otter (*Lutra lutra*) which are both UK BAP species and are found throughout the UK mainland. Water voles have not been recorded in Ireland. Other mammals do occupy the lower reaches and estuaries of UK rivers (e.g. seal and porpoise).

4.3 Historical damage to rivers and catchments

Rivers have been described as under siege, suffering years of physical abuse (Feld *et al.,* 2011). The rate of river channelisation in the region exploded during the middle of the twentieth century. In a survey of the period 1930 to 1980 in the UK, Brookes *et al*. (1983) estimated that 8,500 km of river channel were heavily channelised equating to a density of 0.06 km km^{-2}. In England and Wales only 23% of rivers can be described as near-natural on the basis on their geomorphology (Sear *et al*., 1998). A similar figure has been reported for lowland rivers in Scotland (Werritty & Hoey, 2004), although the remote geography of much of Scotland may push the percentage of pristine river channel closer to 50% for upland rivers (Werritty & Hoey, 2004).

Rivers and stream water bodies are affected by all the activities and changes in their catchments (Newson, 2002). Rivers are linear, and complex pressures may grow in severity along the gradient from source to sea and integrate the adverse effects of various activities; from agriculture, deforestation, urbanisation, storm water treatment, flow regulation and water abstraction (Palmer *et al*., 2010). River systems in the British Isles have undergone extensive physical modification over many centuries (Raven *et al*., 1998; Sear *et al*., 2000), resulting in major changes in physical habitat (Figure 4.1). The physical effects of these modifications on river ecology vary widely depending on the nature and scale of the modifications and the natural environmental behaviour of the river. Loss of habitat complexity is a common theme, along with loss of river length and therefore habitat extent.

Components of river habitat that are often reduced in extent in lowland areas are shallow water, coarse substrates, gently sloping banks (Moustgaard-Pederson *et al*. 2006) and woody debris and leaf litter (Hladyz *et al*., 2011). In upland, high gradient rivers, channelization reduces river length and hence often increases stream gradient significantly, leading to loss of slack water areas (including pools) and uniformly high hydraulic stress throughout the river channel. In these higher energy environments the river is often pinned into a fixed position by bank reinforcements, again creating loss of marginal wetland transitions and preventing the river from renaturalising its planform and reforming a characteristically diverse mosaic of in-channel and riparian habitats.

Channel deepening (often in conjunction with close-fitting floodbanks) disconnects the river from adjacent wetlands, which are drained and lost unless weirs and dams are constructed that impound the river and maintain water levels at critical times of the year. Such impoundment causes siltation, loss of coarse sediment supply to downstream reaches, obstacles to biological movement, water level stabilisation, and associated loss of wetland transitions, running water habitats and ephemeral habitats such as seasonally exposed sediments. Armitage & Pardo (1995) and Salant *et al*. (2012) illustrated the loss of characteristic habitat mosaics that typically occur when a river is impounded by small weirs, whilst Graf (2006) and Brown & Pasternack (2008) described the increased uniformity of habitat conditions downstream of large dams.

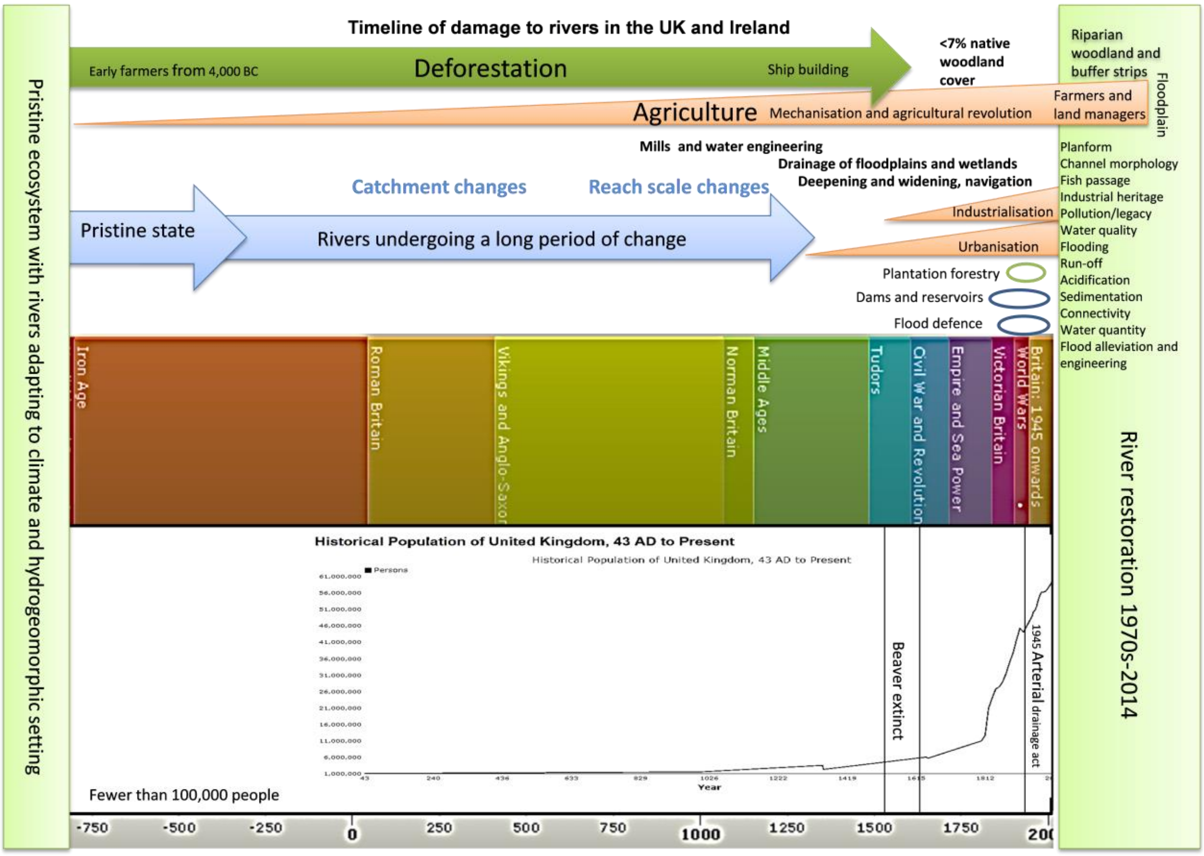

Figure 4.1: Timeline of damage and key milestones in river damage.

The deterioration of the physical habitat (from a pristine state) provided to riverine biota fall within the following four broad categories:

Landscape change

- Land-use changes associated with agriculture / farming
- Land drainage activities (this varies within some regions over many centuries)
- Urbanisation which has generally accelerated over the last 200 years as population has increased.
- Flood defence which has generally accelerated in line with urbanisation

Hydrological (flow impacts - quantity and natural flow variation)

- Climate change - a future pressure with emerging evidence
- Reduced floodplain storage within catchments - peak flows increase
- Diversion – hydropower and water supply
- Abstraction – impacts on chalk streams due to aquifer deficit
- Impoundment – change from lotic to lentic habitats, flow buffering, etc.

Morphological (physical modification, changes in sediment regimes)

- Modification of channel planform, straightening and reduced sinuosity
- Reduction in large wood entering river systems

- Dredging and navigation having impacts on river width and depth
- Barriers and structures affecting sediment behaviour
- Constraint of floodplain such as flood defence schemes
- Removal of substrates, e.g. gravel abstraction/sediment regime
- Bank protection, e.g. stabilisation of planform
- River management activities, e.g. macrophyte cutting or bank vegetation management
- diffuse pollution and industrial legacy, e.g. mining

Ecological damage – linkages to hydromorphological changes

- Shading and carbon influx, e.g. reduction in riparian tree cover
- River management activities, e.g. weed cutting
- Persecution of species (otter, beaver)
- Reduced floodplain extent, connectivity and riparian zone

4.4 Quantification of damage and impact on biota

The assessment of river damage and impact on biota is currently a focus for the WFD and Phase 2 of the RBMP. In 2009 ecological status across the UK was reported and, where possible, river-specific data were collated for water bodies and reviewed for each river basin district (RBD).

Each RBD in the UK and Republic of Ireland (ROI) with their respective EUCD RBD code is shown in Figure 4.2. As shown in Table 4.1, this report focuses on river basin district information for each of the countries within the UK as well as the Republic of Ireland. It is recognised that these data have limitations with respect to damage but they provide the only available comparison between countries in the region. The UK has identified 16 river basin districts. There are 11 in England and Wales, one in Scotland and four in Northern Ireland (including three international RBDs). One river basin district, Solway Tweed, is in both England and Scotland.

Figure 4.2: River basin districts in the UK and Republic of Ireland

Table 4.1: Overview of the UK river basin districts (European Commission, 2012)

RBD	RBD Name	Size (km^2)	Countries sharing RBD
UK01	Scotland	113,920	-
UK02	Solway Tweed	17,511	-
UK03	Northumbria	9,029	-
UK04	Humber	26,109	-
UK05	Anglian	27817	-
UK06	Thames	16,175	-
UK07	South East	10,195	-
UK08	South West	21,201	-
UK09	Severn	21,590	-
UK10	Western Wales	16,653	-
UK11	Dee	2,251	-
UK12	North West	13,140	-
UKGBNIIENB	Neagh Bann	8,121 (6,100 in UK)	ROI
UKGBNIIENW	North Western	14,793 (4,900 in UK)	ROI
UKIEGBNISH	Shannon	19,452 (2 in UK)	ROI
UKGBNINE	North Eastern	4,068	-

The United Kingdom shares three international river basin districts with the Republic of Ireland: Neagh Bann, North Western and Shannon.

River basin management plans were adopted in December 2009 with an assessment of the River basin management plans for the UK undertaken by the European Commission (2012), which identified a series of strengths and evidence gaps.

Strengths in assessing damage and impact to UK rivers:

- The monitoring network in the UK is extensive, although not all quality elements are monitored. The statistical approach used for assessment of confidence in classification of river and lake water bodies is also identified as a strength.
- The programme of measures (PoMs) is detailed with information at a water-body level, although relatively few measures are proposed. In Scotland the PoMs describe the steps to be achieved for phased implementation of the measures to ensure achievement by 2015, 2021 and 2027.
- Work on the international RBDs is well co-ordinated between the UK and Ireland.
- Good information at a water-body level is available in separate factsheets for England/Wales and Scotland.

Evidence gaps in assessing damage and impact to UK rivers:

- Gaps mostly related to the use of biological quality elements for assessment. In some cases, methods for assessment have not been developed, or not included in surveillance monitoring programmes.
- Changes to the typologies used (although now more ecologically relevant).
- Limited information on the methods used to identify significant pressures.
- Large uncertainties reported in relation to the status, the pressures and the effect of potential measures, despite the relatively high intensity of monitoring in the UK, have been used to justify the inclusion of very few specific new measures.
- Despite agriculture being identified as a significant pressure, no new mandatory measures have been agreed in the plans.

Overview of the RBDs

The main pressures identified as reasons for failure in meeting good ecological status within the UK and ROI are presented in Figure 4.3 (a-c). In all regions changes in morphology were considered as the main pressure after water quality.

Figure 4.3a is a map showing the percentage of the water bodies within each WFD RBD indicated as failing based on available data. The key headlines are:

- RBDs with the greatest percentage of failing water bodies (80-90%) include Anglian, Humber and South West in England, the Solway Tweed, as well as North Eastern and Neagh Bann in Northern Ireland.
- The greatest percentage of water bodies within each RBD indicated as failing in ROI was between 50% and 60%.
- The greatest percentage of water bodies within each RBD indicated as failing in Wales was between 60% and 70%.

Figures 4.3b and c show the percentage of water bodies within each RBD indicated as failing for reasons other than physical modification (4.3b) and failing for reasons of physical modification (4.3c). The key headlines are:

- The South West RBD had the highest percentage (80-90%) while Western Wales RBD had the lowest percentage indicated as failing for reasons other than physical modification.
- There are no data for the percentage of water bodies within each RBD indicated as failing for reasons other than physical modification for Northern Ireland and the Republic of Ireland included in the analysis.
- The South West and Anglian RBDs had the highest percentage (50-60%) indicated as failing for reasons of physical modification.

Figures 4.4a and b show the number of water bodies with a) non-physical modification pressures and b) physical modification pressures as a percentage of the total number of failing water bodies. The key headlines are:

- The majority of RBDs in England and all RBDs in Scotland contain the highest number of water bodies (>90%) with non-physical modification pressures as a percentage of the total number of failing water bodies. Water bodies in RBDs in Wales in addition to those in Northumbria and Severn have a lower percentage (Figure 4.4a).
- There are no data for the number of water bodies with non-physical modification pressures for Northern Ireland and the Republic of Ireland (Figure 4.4a).
- Water bodies within the Western Wales and Anglian RBDs have the highest number of water bodies (70-80%) with physical modification pressures as a percentage of the total number of failing water bodies (Figure 4.4b). They are followed by water bodies (50-60%) in South West Severn, Humber, North West and Solway Tweed as well as the Western RBD in ROI. The lowest number of water bodies (10-20%) with physical modification pressures as a percentage of the total number of failing water bodies are within the Thames RBD and the South Western RBD in ROI.

Figure 4.4c shows the number of water bodies with physical modification pressures as a percentage of the total pressures listed by the Reason for Failure database. The key headlines are:

- Western Wales, Dee and Severn RBDs have the greatest number of water bodies (40-50%) with physical modification pressures as a percentage of the total pressures listed by the Reason for Failure database.
- Scotland and the Thames RBD have the lowest number of water bodies (0-10%) with physical modification pressures as a percentage of the total pressures listed by the Reason for Failure database.
- There are no data for Northern Ireland and the Republic of Ireland.

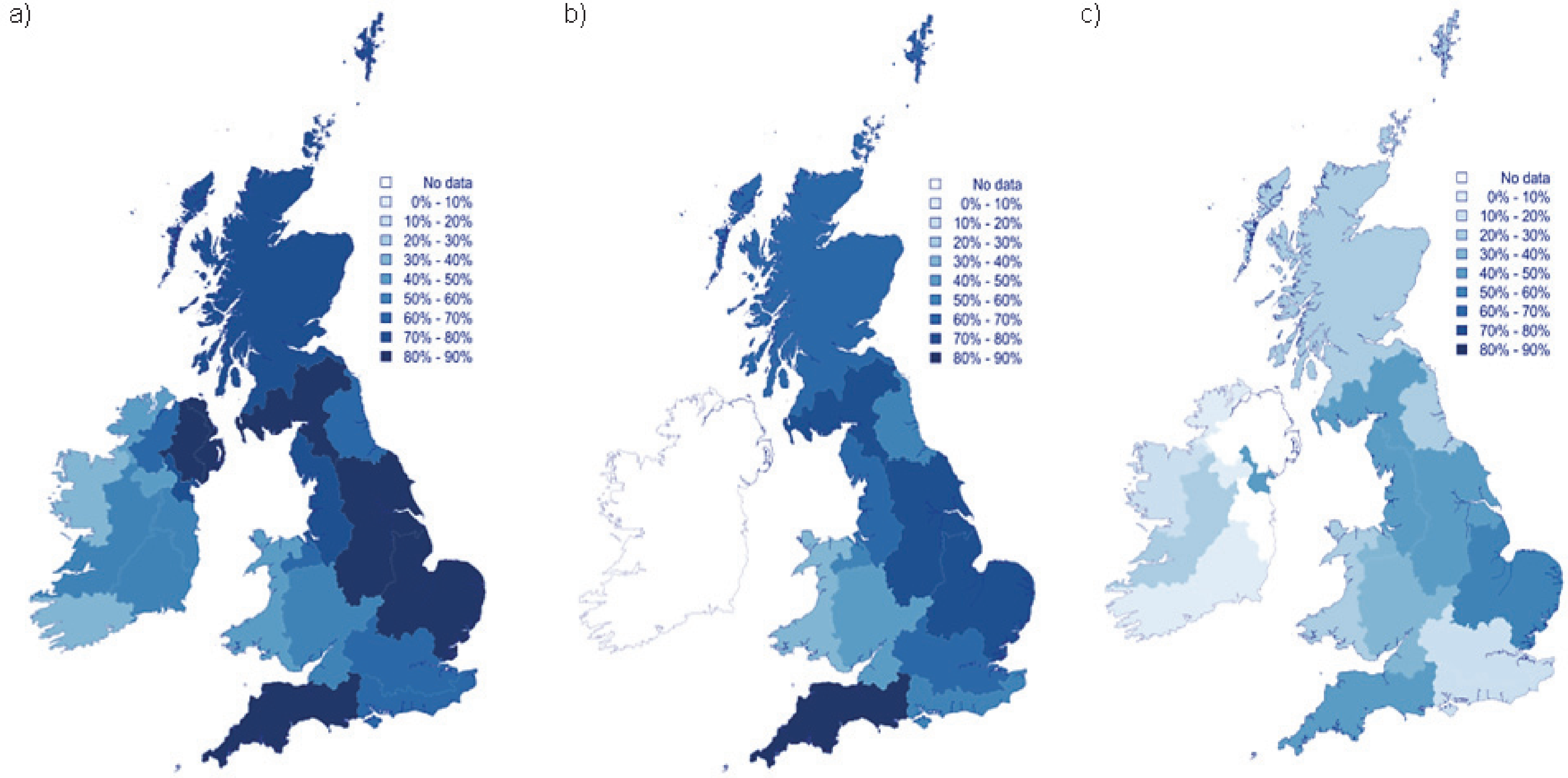

Figure 4.3: Maps showing the percentage of the water bodies within each WFD RBD indicated as: a) failing to meet good ecological status based on available data, b) failing for reasons other than physical modification based on available data, and c) failing for reasons of physical modification based on available data

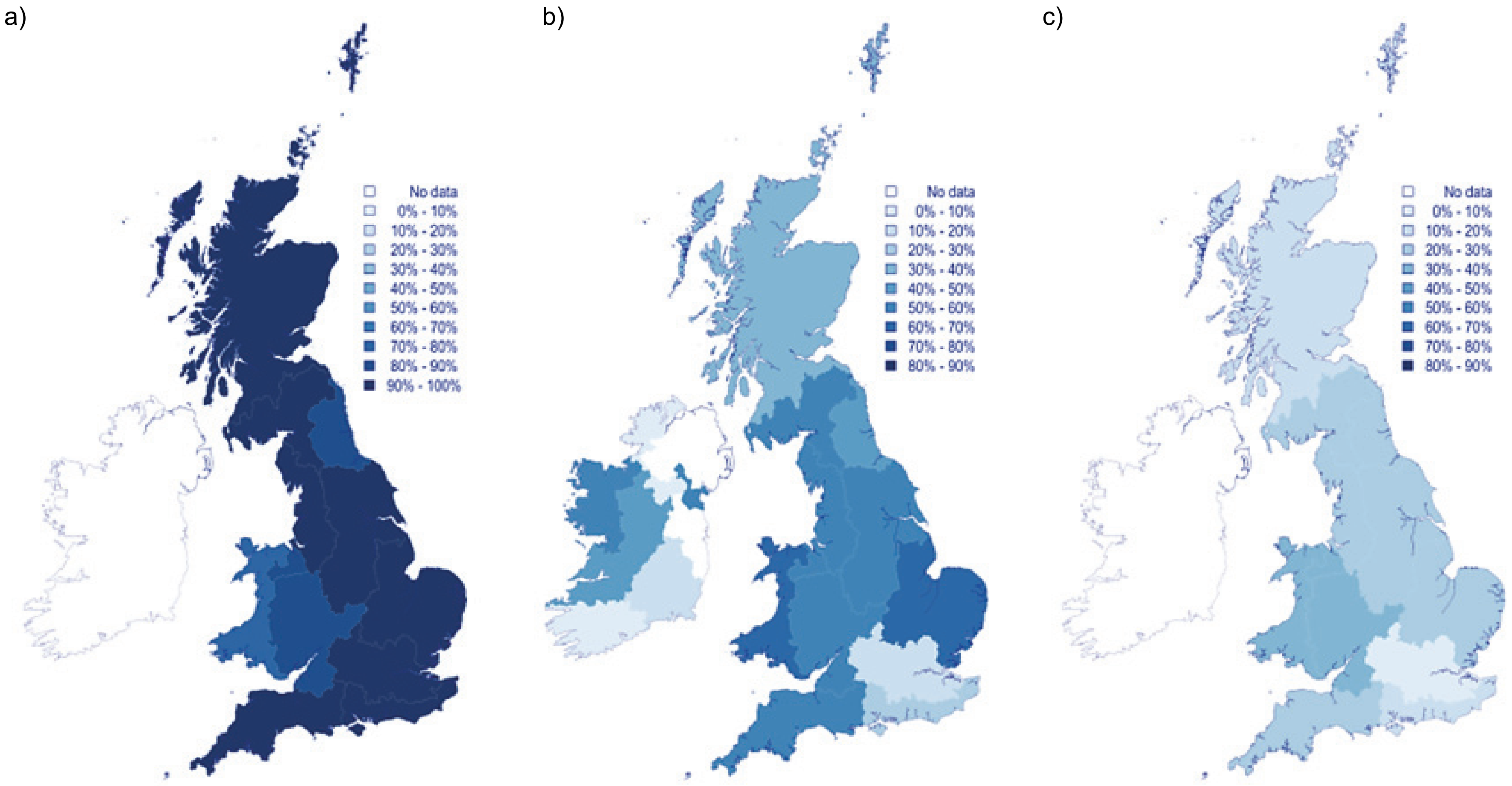

Figure 4.4: Maps showing the number of water bodies with a) non-physical modification pressures as a percentage of the total number of failing water bodies, b) physical modification pressures as a percentage of the total number of failing water bodies, and c) physical modification pressures as a percentage of the total pressures listed by the Reason for Failure database.

4.5 Assessment of damage to rivers in the UK and the Republic of Ireland

4.5.1 Damage to rivers in Scotland

In order to assess the damage to rivers in Scotland, data have been collated from nine RBMP sub-basins and presented in Table 4.2, outlining the overall classification and the significant pressure(s) that can subsequently lead to detrimental impacts on the aquatic environment.

Table 4.2: WFD ecological status classification and associated pressure for river features in the two Scotland river basin districts and the regional management areas

	Ecological classification %						**% of pressure types recorded for the water bodies**						
River basin district	**Bad**	**Poor**	**Moderate**	**Good**	**High**	Total number of water bodies	**Point Source Poll.**	**Diffuse Source Poll.**	**Abstraction**	**Flow Regulation**	**Morphological Alteration**	**Alien Species**	Total number of pressures recorded
Scotland	**8.9**	**14.9**	**20.2**	**46.4**	**9.5**	*2013*	**11.8**	**19.9**	**21.2**	**12.6**	**34.1**	**0.4**	*1898*
-Argyll	**9.2**	**4.0**	**18.4**	**45.2**	**15.2**	*250*	**0**	**5.0**	**33.5**	**27.4**	**34.1**	**0**	*179*
-Clyde	**13.6**	**22.0**	**28.0**	**34.5**	**1.9**	*264*	**18.0**	**24.7**	**14.7**	**11.9**	**30.7**	**0**	*361*
-Forth	**10.6**	**42.9**	**27.8**	**18.2**	**0.5**	*198*	**19.6**	**24.3**	**11.0**	**6.2**	**38.6**	**0.3**	*337*
-North East	**6.8**	**15.1**	**38.7**	**34.1**	**5.4**	*279*	**13.2**	**31.8**	**11.1**	**0.7**	**43.2**	**0**	*296*
-North Highland	**6.0**	**10.2**	**12.1**	**65.9**	**5.8**	*431*	**2.7**	**10.7**	**28.9**	**22.0**	**35.4**	**0.3**	*291*
-Orkney & Shetland	**2.9**	**8.6**	**20.0**	**62.9**	**5.7**	*35*	**0.0**	**22.2**	**16.7**	**16.7**	**44.4**	**0**	*18*
-Tay	**17.0**	**16.7**	**20.0**	**33.7**	**12.6**	*270*	**12.1**	**19.0**	**31.9**	**11.2**	**24.4**	**1.4**	*348*
-West Highland	**2.8**	**4.5**	**3.8**	**64.0**	**24.8**	*286*	**6.9**	**5.6**	**30.6**	**26.4**	**30.6**	**0**	*72*
Solway Tweed	**4.4**	**12.4**	**38.6**	**43.7**	**1.0**	*526*	**8.7**	**32.8**	**11.7**	**10.0**	**35.1**	**1.7**	*299*

Over 50 % of Scotland's rivers are classified as good status with nearly 10% achieving high status. Morphological alteration affects a high proportion of rivers in Orkney and Shetland (44%), Forth (39%) and North East (43%) management areas.

As Scotland's WFD-competent authority, SEPA is responsible for assessing the morphological quality of river water bodies, preventing deterioration in morphological quality and restoring habitat. The starting point for all these areas of work is an assessment of existing quality, made using the River **M**orphological **Im**pact **A**ssessment **S**ystem (MImAS).

MImAS is based on the concept of system capacity. A pristine river system retains 100 % of its capacity to absorb the effects of human activities (pressures) but, as pressures are applied, some of this capacity is used up. Once certain amounts of capacity, termed morphological condition limits (MCLs), have been used, it is assumed that there is a risk of deterioration in WFD ecological status. The MCLs for the five status classes were set by expert judgment at 5% (High-Good), 25% (Good-Moderate), 50% (Moderate-Poor) and 75%

(Poor-Bad).The amount of capacity used is calculated for each individual pressure using equation (1) in each of two zones, the channel bed zone and the bank and riparian zone, and status is assigned based on the zone using the greatest amount of capacity (Table 4.3).

Table 4.3 Example classification calculation. The water body is at bad status based on the bed zone score.

Pressure	**Capacity used (%)**	
	Bed zone	**Bank & riparian zone**
High impact channel realignment	92.67	65.72
Embankments and floodwalls, no bank reinforcement	12.80	6.61
Riparian vegetation	12.22	12.71
Pipe and box culverts	12.13	7.00
Low impact channel realignment	2.65	1.32
Bridges	0.91	0.58
Intakes + outfalls	0.02	0.02
Total	**133.40***	**93.97**

*In heavily impaired water bodies total capacity can exceed 100%

The amount of capacity used (*CU*) is calculated from:

$$CU(\%) = \left(\frac{\text{Impact rating x Pressure footprint (m)}}{\text{water body length (m)}} \right) \text{x } 100 \tag{1}$$

where the *impact rating* is a dimensionless weighting factor that takes into account the nature of the human pressure and its impacts on river channel processes and the sensitivity of the river channel (channel type) to those impacts; the *pressure footprint* is generally the length of the pressure; and *water body length* is the total length of the WFD reporting water body. The input data for the calculations come from three datasets. The Morphology Pressures Database (MPD) is an inventory of the type and location of 15 different engineering modifications to river channels (structures such as embankments or bridges or activities such as dredging, see Figure 4.5). The Riparian Vegetation Database (RVD) describes the location, extent and nature of modifications to the structure of riparian vegetation. The Channel Typology Database (CTD) describes the sensitivity of each part of the baseline river network[13] to these pressures and is composed of five types (A: bedrock, cascade; B: step-pool, plane-bed; C: plane-riffle, wandering, braided; D: actively meandering and F: passively meandering).

Figure 4.5 shows the distribution of the engineering modifications listed within the MPD as a percentage of capacity used. Most of the morphological alterations were extracted based on remote sensed data (aerial imagery, maps). To date, no more than 130 water bodies have been fully field surveyed, for this reason many high impact realignments and embankments are not fully represented in rural areas due to the difficulty of gathering this information by remote sensing. This means that the classification for morphology of rural water bodies could be worse than the current one after undertaking field survey. Seventy-nine per cent of total capacity used relates to riparian vegetation loss, and low and high impact channel re-

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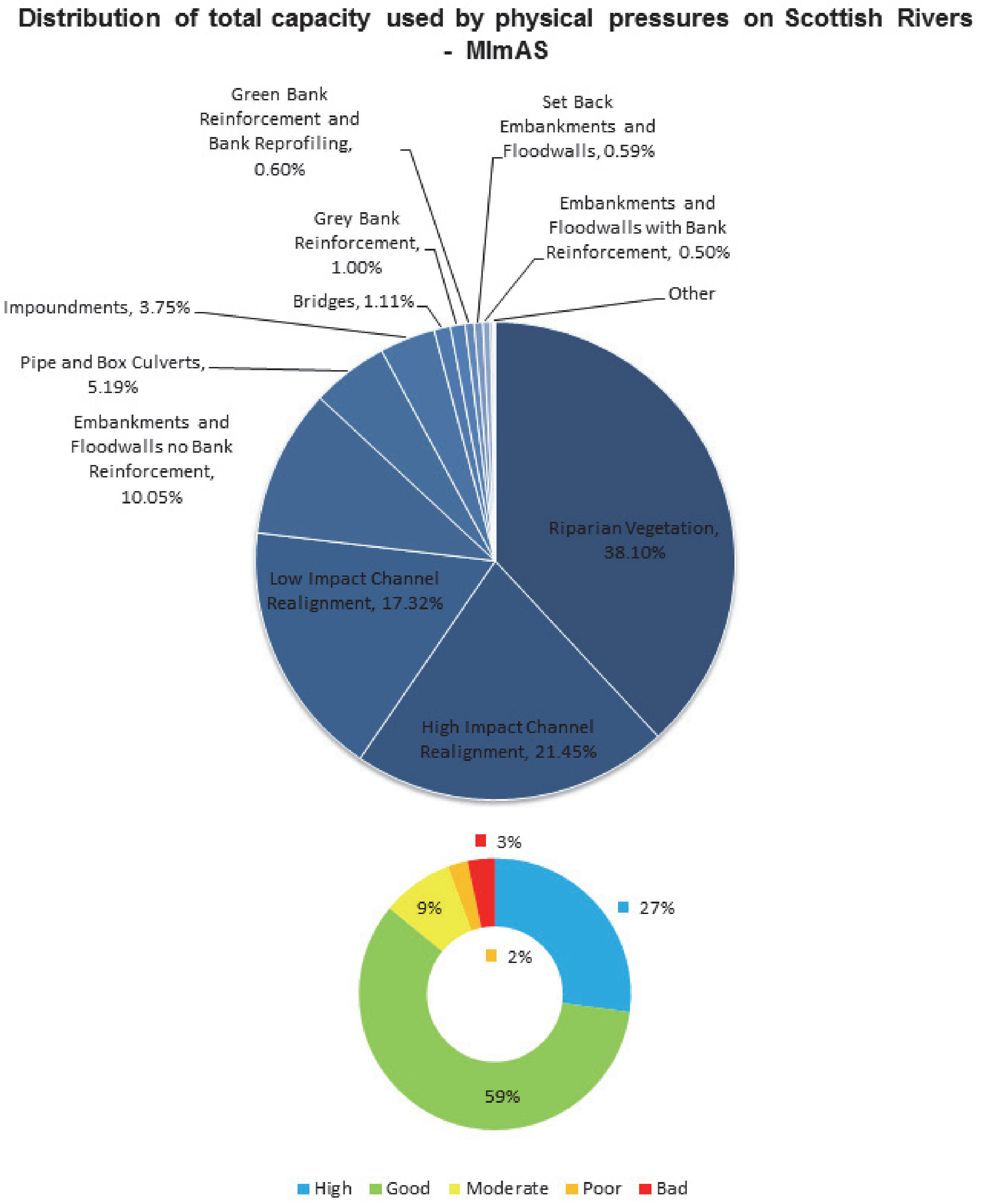
[13] The baseline river network is the approximately 26,000 km of river that SEPA must assess the condition of and report on to the European Commission.

alignment. Eighty-six per cent of the rivers in Scotland are considered to be at high or good status according to this morphological assessment. Figure 4.6 displays four types of modifications from the MPD where restoration techniques could be applied (riparian vegetation, floodplain modification, planform modifications and impoundments) and the occurrence of these morphological pressures (number of water bodies) according to the frequency of restoration activity undertaken at the sub-river basin district scale. For each of the 10 sub-RBDs within Scotland the number of water bodies where the pressure has been recorded is shown in the upper graph and the number of targeted restoration activities undertaken within the same sub-RBD is shown below.



Source: SEPA. Classification of morphology based on Morphological Impact Assessment System (MImAS). June-2014. Values are percentage of all recorded impacts on Scottish rivers by activity class.

HMWBs will be classified for morphology in a different way; the method is still to be defined by SEPA. The classification applied is: <5% capacity used (high status), >5 % and <25% (good status), >25% and <50% (moderate status), >50% and <75% (poor status) and >75% (bad status).

Figure 4.5: Impacts of engineering activities on Scottish rivers as assessed by MImAS. The pie charts show the distribution of the 15 pressure categories as a percentage of capacity used based on data from June 2014.

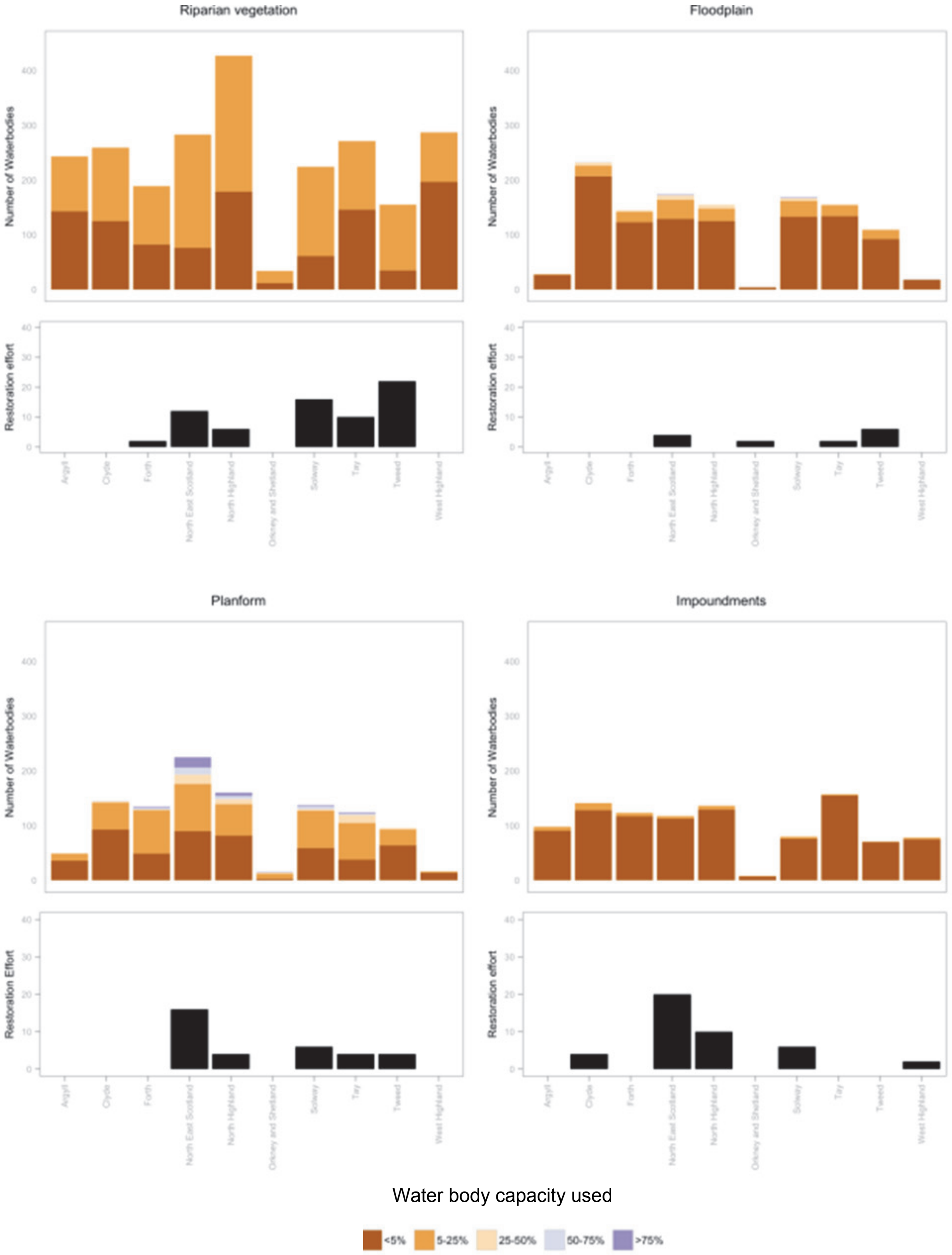


Figure 4.6: Links the occurrence of morphological pressures to the frequency of restoration activity (number of projects) undertaken at the sub-river basin district scale. For each of the 10 sub-RBDs within Scotland the number of water bodies where the pressure has been recorded is shown in the upper graph and the number of targeted restoration activities undertaken within the same sub-RBD is shown below. Source: MImAS 2014 and project database.

Physical habitat damage can be extensive even on rivers that are considered to be of significant biodiversity value. Table 4.4 provides a summary of the 2013 Site Condition Monitoring on the River Tweed SAC mainstem. This demonstrates that river damage is extensive across the River Tweed Evaluated Corridor Sections (ECSs) and this relates to extensive planform modification and resectioning, constrained floodplain and artificial instream features.

The impacts of habitat damage for the River Tweed SAC catchment are summarised below:

- Historic alterations to planform and river habitat (resectioning) are extensive throughout the catchment, which, combined with instream structures such as weirs and bridges resulted in the majority of ECSs failing to meet condition assessment targets related to naturalness of the channel (planform and habitat modification).

- Targets for bank and riparian zone vegetation naturalness were also seldom reached, mainly due to the open nature of the river to the adjacent (predominantly grazing pasture) land use throughout the catchment, without fencing or buffer strips.

- The failure to reach the bank vegetation targets was probably influenced also by the modified nature of the channel and banks, which is likely to have disrupted the natural inundation regime. This may have caused more terrestrial and artificial vegetation types to dominate the banks rather than the natural wetland/transitional riparian communities that would be expected on a river with less modification. Despite these modifications it is likely that fencing to prevent stock access to the banks would encourage more natural riparian strips to develop and may help to improve the condition of the SAC.

- The majority of ECSs failed to meet the condition assessment targets for woody debris, reflecting the relative paucity of bankside trees within the catchment.

Table 4.4: Physical habitat damage of the River Tweed as assessed as part of the Site Condition Monitoring of the River Tweed SSSI and SAC.

River Tweed SCM summary	**ECS1**	**ECS2**	**ECS3**	**ECS4**	**ECS5**	**ECS6**
RHS sites (n=75)	13	8	16	20	11	7
Channel planform	🟥	🟥	🟥	🟥	🟥	🟥
Habitat ModificationScore	🟥	🟥	🟥	🟥	🟥	🟥
Bank vegetation naturalness	🟩	🟥	🟨	🟥	🟥	🟥
Riparian zone vegetation naturalness	🟨	🟩	🟨	🟨	🟨	🟩
In-channel structures	🟩	🟨	🟨	🟥	🟥	🟩
	🟩	Pass				
	🟨	Marginal fail				
	🟥	Fail				

4.5.2 Damage to rivers in England and damage to rivers in Wales

In order to assess the damage to rivers in England and in Wales, data have been collated from the 11 RBMPs and are presented in Table 4.5, outlining the overall classification and reason for failure. Figure 4.7 highlights the proportion of natural, artificial and heavily modified water bodies (HMWBs) across England and Wales and particularly illustrates the high proportion of HMWBs in the Anglian RBD. The picture for reasons for failure in England is far more balanced across a range of pressures but a considerable percentage of watercourses have unknown reasons for failure or are unclassified.

Table 4.5: WFD classification and associated pressures for river features in England and Wales river basin districts and management areas

	Ecological classification %						**% of total Reason for Failure**											
	Bad	**Poor**	**Moderate**	**Good**	**High**	Total number of water bodies	**Abstraction**	**Acidification**	**Alien species**	**Diffuse pollution**	**Point source pollution**	**Diffuse &/or Point source pollution**	**Physical modification**	**Flow alteration**	**Other**	**Unknown**	**Unclassified**	Tota number of reasons for failurel
Anglian	**1.3**	**12.5**	**68.5**	**17.4**	**0.0**	718	**4.8**	**0.0**	**1.3**	**37.5**	**21.1**	**0.0**	**21.8**	**0.3**	**0.2**	**9.6**	**3.3**	2747
Humber	**3.2**	**19.2**	**64.7**	**13.0**	**0.0**	877	**1.8**	**0.1**	**0.3**	**19.0**	**26.0**	**0.7**	**23.5**	**1.2**	**0.1**	**23.2**	**4.1**	3522
North West	**4.5**	**12.6**	**57.0**	**25.8**	**0.0**	484	**0.5**	**0.3**	**0.1**	**23.3**	**21.8**	**0.7**	**12.1**	**0.7**	**0.2**	**34.8**	**5.6**	3521
Northumbria	**2.0**	**17.7**	**46.3**	**33.4**	**0.6**	356	**3.3**	**0.4**	**0.5**	**13.2**	**13.7**	**4.2**	**23.0**	**0.5**	**0.4**	**33.5**	**7.4**	570
Severn	**1.9**	**18.4**	**53.3**	**26.4**	**0.0**	734	**1.5**	**1.5**	**0.7**	**19.8**	**7.5**	**0.1**	**16.9**	**0.3**	**0.1**	**42.5**	**9.2**	1473
South East	**3.4**	**12.5**	**69.1**	**15.0**	**0.0**	327	**3.4**	**0**	**0.8**	**19.1**	**19.9**	**0.0**	**27.6**	**0.4**	**0.1**	**21.7**	**7.0**	960
South West	**1.4**	**9.5**	**60.1**	**29.0**	**0.0**	918	**1.5**	**0**	**0.2**	**33.1**	**7.6**	**11.2**	**13.5**	**0.6**	**0.3**	**14.7**	**17.2**	1299
Thames	**2.3**	**29.5**	**31.5**	**14.3**	**0.0**	441	**2.9**	**0.8**	**0.6**	**17.6**	**14.3**	**0.6**	**19.4**	**0.1**	**0.2**	**14.7**	**28.7**	2635
Western Wales	**0.1**	**5.8**	**65.1**	**28.9**	**0.0**	667	**0.1**	**2.4**	**0.0**	**4.6**	**1.5**	**1.8**	**4.5**	**0.0**	**0.1**	**4.9**	**80.2**	892
Dee	**0.0**	**15.3**	**63.5**	**21.2**	**3.5**	85	**2.0**	**1.4**	**0.0**	**29.3**	**19.7**	**0.0**	**24.5**	**0.0**	**0.0**	**15.0**	**8.2**	147

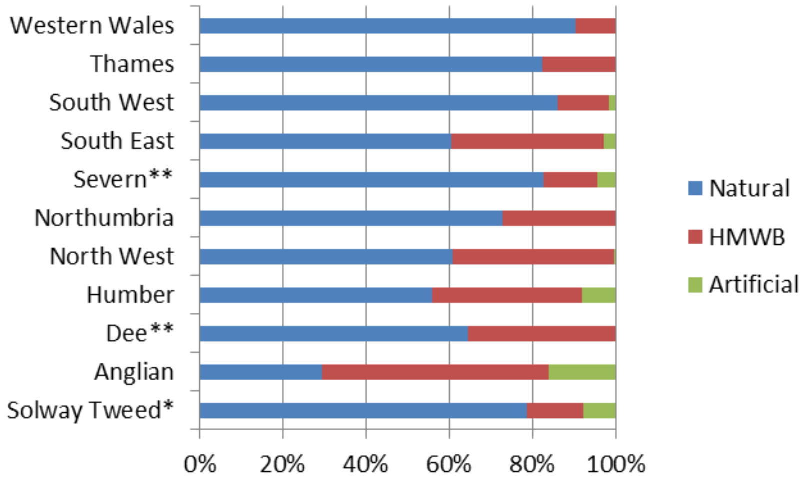


*Figure 4.7: Percentage of natural, HMWBs and artificial water bodies by RBD. This is based on 2010 Surface Water Status & Objectives (not including canals, SWTs, SSSI ditches) *Only includes English data ** includes both Wales and England*

The report into the ‘The state of river habitats' (EA, 2010) provided analysis of the entire River Habitat Survey (RHS) database. The total score for each survey was used to place the river into one of five Habitat Modification Classes (HMCs), ranging from near-natural (class 1) to severely modified (class 5). Figure 4.8 shows the percentage of 500m river lengths represented by the five HMCs in 2007-08. The key headlines for England and Wales are:

- 43% of 500m river length is resectioned and 8% of river length is reinforced.
- 13% of 500m river lengths have no riverside trees and 23% of 500m river lengths have continuous tree cover and 79% shaded by trees, with 36% shaded for a third or more of the length.
- 43% of baseline survey sites contain large woody debris and 47% have exposed tree roots**.**
- 21% of baseline survey sites had ‘extensive silting’. This was defined as where silt is a channel substrate for more than a third of the 500m survey length.
- 47% of baseline survey sites contained unvegetated mid-channel, side or point bars.
- Since 1995-1996 for England and Wales as a whole, there have been no large changes in reinforcement, extent of trees, non-native invasive species and extensive silting**.**

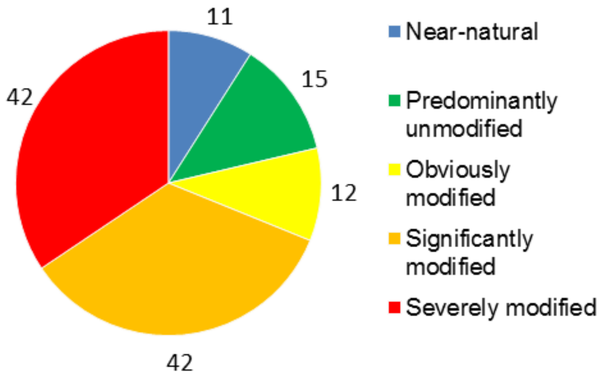


Figure 4.8: Extent of bank and channel modification 2007-08, expressed as a percentage of the total number of 500m river lengths in England and Wales.

The Challenges and Choices[14] consultation database provides an additional evolution of this evidence for the scale of physical damage to rivers across England and Wales. The classification of morphological pressures was recorded (where known) for each water body and is shown in Figure 4.9 by River Basin District (RBD).

For eight of the 11 RBDs in England and Wales (see Table 4.5) the majority of rivers have not been fully assessed, in particular for the Humber, South West and Anglian regions. Unlike other RBDs, the reason for failure in the Solway Tweed is accounted for by land drainage activities and in the North West, accounted for by urbanisation. In the north of England and for Wales the predominant reason for failure is the presence of instream barriers and impoundments. The Northumbrian region is characterised by a varied range of reasons for failure. Other notable reasons for failure include flood protection (greatest in Northumbria, Dee and the North West RBDs), agriculture, farming and horticulture (greatest in Solway Tweed) and heritage, industry and landscape (greatest in Northumbria RBD).

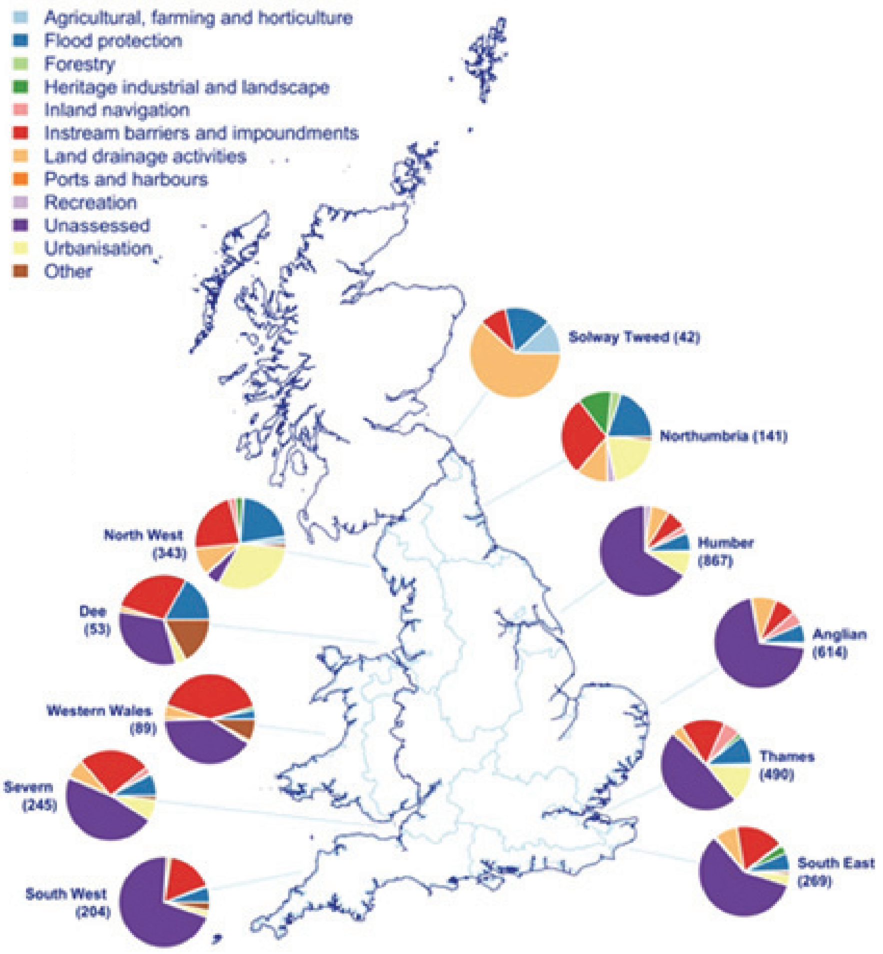


Figure 4.9: Tier 2 pressure category for morphology (from the EA 2013 Reasons for failure database: rivers).

England

Of all the regions, England has the most complex range of issues associated with its diverse landscapes, relatively high population, extensive urbanisation and associated historical legacies. The North East, Northumbria and Solway–Tweed RBDs are well categorised by

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[14] Challenges and Choices EA – based on 2013 dataset

the Challenges and Choices consultation, with the remaining river basins having significant proportions (>60%) of unknowns.

The only water bodies to attain 'high' classification are in Northumbria and the Welsh Dee, the latter the only area not to include a bad status classification in both England and Wales. In Northumbria the majority of rivers attain moderate status (46%) and good status (33%) classification and the predominant reason for failure is considered to be physical modification.

Throughout the remainder of England the classification is predominantly moderate with Severn and Thames also having relatively high proportions of poor status rivers. The latter is attributed to physical modification although diffuse pollution and point-source pollution also have a considerable impact. For the South East the majority of rivers attain moderate status with the main reason for failure cited as physical modification and to a lesser extent diffuse pollution and point-source pollution. South West RBD again shows most rivers at moderate status (60%). The main reason for failure in this area is considered to be diffuse pollution. For Anglian and the eastern districts the predominant reason for failure is diffuse pollution with other contributing factors of point-source pollution and physical modification. From the RBMP data, the North-West has the highest proportion of rivers attaining bad status across the districts. The known reasons for failure are shown as diffuse pollution and point-source pollution, followed by physical modification.

Wales

Wales has a distinct historical legacy. The principal human-induced morphological impacts on Welsh rivers are aggregate extraction, river engineering for erosion control and flow management and navigation (Duigan *et al.*, 2009). The historical legacy of mining remains in the form of contaminated sediments which can be further mobilised. In some of the coal mining areas rivers would run red with ochre as a fine sediment, illustrating that chemical problems such as acid mine drainage can also interact with morphology and ecology.

For the Western Wales area most rivers (65%) attain 'moderate' status. The reasons for failure are considered to be diffuse pollution and physical modification. To a lesser extent, but still significant, is acidification. However, it should be noted that the majority of reasons for failure fall within the unclassified category (715 out of 892).

The Dee RBD also shows the predominant overall classification as moderate with 54 rivers out of 85 in this category. In addition, 13 rivers are classified as poor but no rivers are classified as bad. For those rivers failing the main reason is considered to be diffuse pollution followed by physical modification. The Severn includes 734 rivers, of which the majority (391) attain moderate status with a further 135 with an overall classification of bad. The main reasons for failure have been given as diffuse pollution and physical modification.

4.5.3 Damage to rivers in Northern Ireland and the Republic of Ireland

In order to assess the damage to rivers in Northern Ireland and the Republic of Ireland, data have been collated from eight RBMPs and presented in Table 4.6, outlining the overall classification and risk from pressures which can then lead to adverse impacts for water bodies and those species that rely on them. It was not possible to derive information for some of the RBDs from the RBMPs. The reason for this is that North Western and Neagh Bann are international RBDs, therefore the data in Table 4.6 should be interpreted with caution as they only cover ROI water bodies due to differences in the recording of data in the plans. The number of water bodies affected by hydromorphological damage are presented in Table 4.7 for Northern Ireland, with approximatelly 50% of rivers in North Eastern and Neagh Bann affected with North Western being relatively unimpaired compared with 12% affected by hydromorphological pressures.

Table 4.6: The ecological status/potential and risk for rivers in river basin districts in ROI/NI

River Basin District	% Ecological Status						% of total risks											
	Bad	Poor	Moderate	Good	High	Total number of water bodies	Agriculture	Wastewater & industry	Wastewater from un-sewererd properties	Forestry	Landfill, mines & cont. land	Physical modification	Water abstraction	Dangerous substances	Aquaculture	Invasive alien species	Other pressures	Total number of risks reported
North Eastern	8.1	25	52	14	0	111												
Neagh Bann	4.3	40.4	43.8	18.8	0.3	324	46.3	17.9	4.9	0	0	30.9	0.0	0	0	0	0	123
North Western	0.6	21.7	31.6	40.7	11.5	861	33.8	11.9	20.9	14.9	0	6.3	12.2	0	0	0	0	444
South Eastern	1.3	17.7	33.8	39.3	7.8	677	67.4	18.6	2.9	0.6	0	5.3	5.3	0	0	0	0	720
South Western	0.1	7.2	25.6	35.2	31.9	891	60.8	18.0	5.4	3.5	0	3.0	9.3	0	0	0	0	367
Shannnon	1.4	26.2	29.4	38.0	5.1	906	49.3	13.5	4.7	2.5	0	26.4	3.5	0.1	0	0	0	903
Western	1.0	16.8	15.8	47.1	19.2	963	15.1	2.2	11.6	8.4	0	28.8	33.8	0.2	0	0	0	604
Eastern	4.7	21.4	31.2	39.2	3.6	365												

* Only ROI data are included for % of total risks for Neagh Bann and North Western IRBDs in Table 4.6 due to differences in reporting for the international RBDs. There is one artificial water body in the Neagh Bann RBD which is not included in this analysis.

Table 4.7: The number of water bodies affected by morphological pressures in Northern Ireland as identified for the first River Basin Plans in 2009.

	North Eastern	Neagh Bann	North Western
River water bodies (n)	111	255	209
River water bodies with identified morphological pressures (n)	54	118	26

Despite the Shannon and South Western RBDs having very similar numbers of rivers, the South Western RBD achieves a higher status classification with 31% of rivers with a high classification. In the North Western, South Western and Western RBDs the majority of rivers meet WFD objectives. The risk of diffuse pollution from agriculture is leading to rivers within every RBD (for data available) failing to meet WFD objectives and is the predominant risk for each district with the exception of the Western RBD where the main source of pollution is from unsewered properties. Physical modification and damage affects a significant number of rivers within the Neagh Bann RBD. Shannon and South-Western districts also have a high proportion of rivers affected by physical modification. The values for the physical modifications and damage for the Western and Neagh Bann districts represent those at risk from land drainage and there could be a significant number of rivers at potential risk.

Northern Ireland

From work that has been carried out on river continuity and hydromorphology, several issues have been highlighted by the Department of the Environment in Northern Ireland. These include the loss of connectivity in larger rivers, not only reducing the connectivity between the river and its floodplain in response to channel deepening (often as a result historic drainage schemes) but also the increase in unit stream power. Even for the region's smaller rivers, over-widening and resectioning, which can lead to subsequent problems from erosion and deposition, are a major concern resulting from physical modifications. Urban development and the encroachment onto floodplains have also limited the space available for rivers to interact naturally with the wider environment.

Reduced tree cover, removal of bankside vegetation and intensive land-use practices including agriculture not only limit the buffering capacity of the riparian zone in protecting water quality from diffuse pollutants, but also the general loss of bankside vegetation leaves the areas susceptible to erosion which can be exacerbated if they are poached by livestock. Vital ecological processes have also been affected with barriers prohibiting fish passage, which is especially detrimental to those species where upstream migration is essential for reproduction. Although fish barriers predominantly affect industrialised areas, HEP schemes, engineered structures including bridge aprons, loss of fish habitat, the spread of non-native invasive species and abstractions for drinking water are also major river modification issues.

Republic of Ireland

The situation in the Republic of Ireland reflects a very similar picture in relation to major river modification issues as seen in Northern Ireland. Arterial drainage has been widely practised since the implementation of The Arterial Drainage Act 1945 (ROI) and has resulted in impacts to many rivers at a catchment-wide scale. Although many drained channels still have a good quality riparian zone, impacts such as loss of lateral connectivity between the river and the floodplain, homogenisation of the longitudinal profile and gradient, and over-widening were common following arterial drainage works. These have resulted in uniform hydromorphological characteristics and a loss of stream power which have affected the interactions between the bed, banks and flowing water. The design of the drainage works has also lowered the water-table level. This has inadvertently led to a reduction in gravel replenishment (except during spates) as the gravel-rich banks have been cut through. This is further compounded in areas that have been widened because the reduced stream power limits erosive capabilities of the water flow leading to reduced gravel replacement.

In the Foyle and Carlingford regions, the main river modification issues arise from the extensive drainage schemes that have been carried out. This has resulted in uniform channel characteristics, over-widening and a reduction of natural processes which would normally allow substrate replenishment and the creation of new fish habitat. The creation of flood embankments has also caused a loss of lateral connectivity with the floodplain which has subsequently affected the hydro-geomorphological processes.

Impacts arising from agricultural practices include unauthorised drainage works and uncertainties relating to buffer zone creation. The generation of hydroelectric power has resulted in abstraction and impoundments, and the lack of ecological consideration within the water abstraction and impoundment regulations in both Northern Ireland and the Republic of Ireland has compounded the problem.

Fish migration and longitudinal sediment conveyance has also been impeded due to the presence of historical weirs. In addition, over-grazing in the uplands and a lack of native trees has caused increased runoff and sediment entering the channels. Other land uses that are causing concern include land reclamation which has involved fitting drainage ditches with flap valves, sand and gravel quarrying activities with impacts on groundwater, and the historical legacy of large-scale illegal dumping of cars and the presence of community middens that have affected some river banks – for example, the tidal reaches of the Foyle.

4.6 Summary of damage to rivers

- The British Isles host a diverse range of organisms associated with river habitats (including riparian species) which are at threat. On the UK mainland there are 353 red list species associated with rivers, including two critically endangered species, while in the Republic of Ireland there are 273 red list species associated with rivers, with the eel being the only critically endangered species.

- River systems in the British Isles have undergone extensive physical modification over timescales of millenia (in the case of deforestation of catchments) to many centuries (e.g. river engineering) resulting in major changes to physical habitats. The damage to and deterioration of physical habitats can be accounted for by changes in landscape, hydrology, morphology and ecology.

- RBDs with the greatest percentage of failing water bodies (80-90%) include Anglian, Humber and South West in England, the Solway Tweed, as well as North Eastern and Neagh Bann in Northern Ireland.

- The differing approaches across the five countries hinders direct comparisons and data analysis. The first round of RBMP planning information is not comprehensive and considerable knowledge gaps are apparent across much of the region. A unified morphological assessment framework is required and may be critical for assessing the true impacts of hydromorphological damage across the region.

- Primary problems such as diffuse pollution or over-abstraction can override the benefits of hydromorphological improvement but once these pressures are addressed, restoration of physical form then becomes a greater priority in the rehabilitation of water bodies.

- Scotland is more advanced than the other four countries in assessing and characterising morphological impacts using the MImAS tool. More than 86% of river water bodies are at high or good status for morphology according to MImAS.

- Of the five countries, England has the most complex range of environmental impacts associated with its diverse landscapes, relatively large population, extensive urbanisation and associated historical legacies.

- Based on work that has been carried out relating to river continuity and hydromorphology, the Department of the Environment in Northern Ireland has observed damage to river biodiversity caused by a loss of connectivity and increased urban development and its encroachment onto floodplains.

- The situation in the Republic of Ireland reflects a very similar picture in relation to major river modification issues as seen in Northern Ireland. Damage to river biodiversity has been caused by the implementation of arterial drainage, increased agricultural practices and changes in land use.

- Morphological assessment is often qualitative, relying on expert judgment. However, even the limited, quantitative, long-term data sets provide the potential to identify suitable restoration activities, supported by credible evidence on their effectiveness.

5. RIVER RESTORATION IN THE UK AND IRELAND

5.1 Overview

River restoration refers to a wide variety of ecological, physical, spatial and management measures and practices. These are aimed at restoring the natural state and functioning of the river system in support of biodiversity, recreation, flood management and landscape development and improve ecosystem health. By restoring natural conditions, river restoration improves the overall ecosystem resilience of the river systems to factors such as climate change and other human pressures, and provides a framework for the sustainable multifunctional use of estuaries, rivers and streams. River restoration is an integral part of sustainable water management and is in direct support of the aims of the Water Framework Directive, and national and regional water management policies.

The drivers for river restoration and conservation are discussed in Section 5.2 which provides an overview of legislative and process-based drivers for Scotland, England and Wales. Technical measures that help to bring rivers closer to their natural state include the creation of fish passes and weir removal through to broad-scale catchment approaches including zoning regulations and participatory approaches. These measures are discussed in detail within the River Restoration Manual (RRC, 2013) by the UK River Restoration Centre and the EU REFORM project and are discussed below in Section 5.3. Catchment-based approaches ultimately involve interventions at the reach scale or within the riparian or wider landscape and a varied range of techniques are applicable to the varying physical characteristics and energy of rivers and streams across the region. The status of restoration across the region is discussed in Section 5.4.

The rise of river restoration interest in the worldwide scientific literature was examined by Smith *et al*. (2014) illustrating the rise in interest in river restoration (Figure 5.1). Figure 5.2 identifies keywords that appear in the titles of articles discussing river restoration. The largest single category relates to habitat restoration, followed by restoration aimed at improving fisheries, emphasising the strong ecological focus in the way in which river restoration has been framed and the lack of a strong focus on hydromorphology.

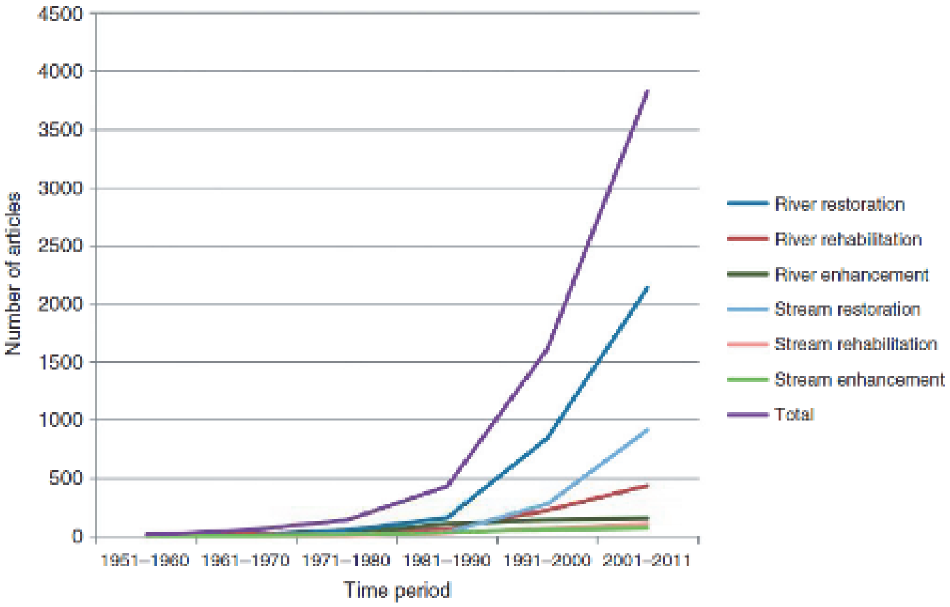

Figure 5.1: Timeline illustrating the growing interest in river restoration and associated search terms from academic research (Smith et al., 2014).

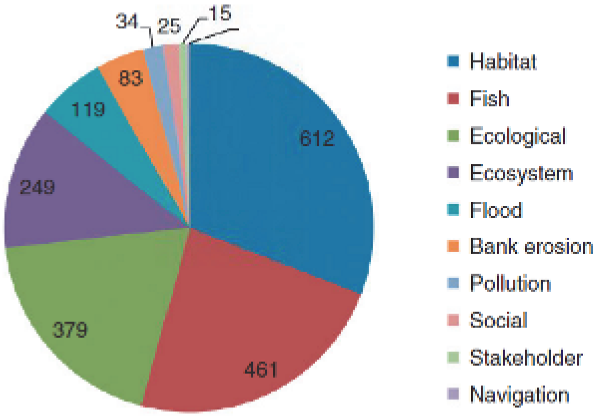

Figure 5.2: Proportion of keywords that appear alongside river restoration terms in the international literature. Data from Smith et al. (2014)

5.2 River restoration drivers

River restoration is undertaken to fulfill a wide range of objectives including ecological improvement, flood risk management, climate change resilience as well as landscape and visual benefits. Increased environmental awareness throughout the 1970s and 1980s opened the political space for the introduction of a range of legislation that provided the conditions for river conservation and restoration activities to grow. In Europe, national environmental legislation is driven by directives at the European level, which are then transposed into national laws.

The timeline of primary legislation, policy drivers and significant reports are provided in Table 5.1. The EC Habitats Directive (92/43/EEC) was a key element in the increased focus on restoration for biodiversity objectives (Duigan, 2009; Mainstone & Holmes, 2010; Smith *et al.*, 2014) and was followed by the EC Water Framework Directive (2000/60/EC) in 2000, which has become the primary legislation controlling fluvial ecosystems in Europe (Palmer *et al.,* 2007; England *et al.,* 2008; Newson, 2010). The EC Floods Directive of 2007 emphasises natural approaches to flood risk management that are more consistent with conservation and restoration activities. Investment in specific river restoration activities may also be linked intimately to a range of other environmental policy drivers such as urban regeneration, sustainable flood management, biodiversity action planning and diffuse pollution control. It is important to note that river restoration can potentially fulfil a broad range of legislative obligations and in the long term will be beneficial to society and biodiversity. River restoration must not be viewed independently from catchment or land-use management, and the importance of the latter to alleviating the pressure on the region's flowing waters cannot be over-emphasised.

At present, river restoration is being framed as a way of improving the ecosystem services offered by rivers and is asserted by Smith *et al* (2014) to be one of the key drivers for the release of river restoration-related government funding in the UK. The ecosystems found within the UK and Ireland have developed over thousands of years as a result of interactions between the inhabitants and the environment. Interactions and the degree of their effect have varied, not only over time but also due to geographic location; however, the most recent period of change began in the 1940s when there was a drive to increase landscape production and improve infrastructure. This socio-economic development came with consequences for river ecosystems and the services that they provide: activities such as land conversion, pollution of terrestrial and aquatic habitats, natural resource exploitation, spread of non-native invasive species and climate change (UK NEA, 2011) have had detrimental impacts on the environment.

Table 5.1: Legislation and policy drivers that have influenced or enabled river restoration and conservation activities

Act or Report	Year	Summary	England	Wales	Scotland	Northern Ireland	Republic of Ireland
Arterial Drainage Act	1945	Catchment-wide arterial drainage schemes for land drainage and flood alleviation					*
Wildlife and Conservation Act	1981	The need to 'further and promote the conservation and enhancement of natural beauty'	*	*	*	*	
North Atlantic Salmon Conservation Organisation	1983	The management and conservation of Atlantic salmon including habitat restoration and fisheries management	*	*	*	*	*
Statutory Instruments 1199 (Town and Country Planning) and 1217 (Land Drainage Improvement Works)	1988	Environmental assessment required if developments likely to significantly impact river environment	*	*			
Water Act	1989	Created the National Rivers Authority (NRA)	*	*			
Environmental Drainage Maintenance Programme	1990	Creation of maintenance standards based on river corridor ecology and site characteristics					*
Tourism Angling Measure	1990	Facilitated fish habitat improvements that would benefit the tourism industry					*
Water Resources Act	1991	First piece of legislation that allows conservation and enhancement as goals in their own right	*	*			
EC Habitats Directive	1992	To achieve favourable conservation status of listed habitats and species including meeting the conservation objectives of Special Areas of Conservation	*	*	*	*	*
Biodiversity Action Plans	1994	Described the biological resources within the UK and provided detailed plans on how to conserve them.	*	*	*	*	*
Environment Act	1995-6	Environmental regulatory bodies formed	*	*	*		
Salmon & Fisheries Action plans	1997	Undertake habitat related management measures to protect and enhance salmon and other fisheries.	*	*	*	*	*
EC Water Framework Directive	2003	Requirement to be working toward 'good ecological status or potential' by 2015	*	*	*	*	*
Making Space for Water	2004	Recommends holistic approach to flood management	*	*			
European Eel Regulation	2007	Requirement for 40% of eels to escape inland waters for spawning by improving passage, limiting fisheries & stocking.	*	*	*	*	*
Environmental River Enhancement Programme	2008	To undertake environment enhancement works and monitor the impacts on river corridor biodiversity & hydromorphology within OPW drained channels				*	*
Catchment Flood Management Plans	2009	Identify catchment-based measures to reduce flood-risk, including targeted out-of-bank flooding to increase temporary floodwater storage	*	*			
Flood Risk Management (Scotland) Act	2009	A modern and sustainable approach to flood risk			*		
Flood and Water Management Act	2010	Devolves responsibility of flood risk management to lead local authorities	*	*		*	*

Government target on sites with national designations for wildlife	2010	Bring 95% of SSSIs by area into favourable condition (or favourable management that will lead to favourable condition)	*				
Local Flood Risk Management Plans	2011	Prioritise actions based on surface water flooding vulnerable areas			*		
Defra Natural Environment White Paper	2011	Encourages restoration of ecosystem services, including freshwater systems	*	*			

The services that ecosystems provide relate to benefits that improve human welfare, measured by the quantifiable economic value of the services. After the Millennium Ecosystem Assessment (MEA) 2005, four categories of service were differentiated based on their function of the service they provide: provisioning, regulating, supporting, and cultural (Maltby *et al.* 2011). Examples of the main services and their important economic benefits are shown in Table 5.2.

Table 5.2: Ecosystem services and examples of services in the water environment. (Source: adapted from Maltby et al., 2011)

Provisioning	**Regulating**	**Supporting**	**Cultural**
Fish	Flood regulation	Biodiversity	Science & education
Reeds, osiers & watercress	Flow regulation	Ecosystem processes	Religion
Water	Water quality regulation	Energy transfer	Tourism & recreation
Navigation	Local climate regulation	Water & sediment transfer	Sense of place
Health products	Fire regulation		History
Power generation	Human health regulation	-	-

Rivers and their floodplains in their natural form have benefited society by providing an array of ecosystem services. Not only did they provide a vital navigation network for early societal development, but they have also acted as a vital source of food, energy and construction materials. In degraded rivers, naturally occurring processes may be altered or lost to such an extent that the river network can no longer provide value to society.

Despite four categories existing, Wallace (2007) proposed that if a service provides a benefit to society or human welfare it should only be considered and valued if it brings benefit directly to humanity rather than indirectly via supporting other ecosystem services. If services directly benefit humanity they were classed as ‘final services’. Based on this, in some instances supporting services are not considered as services because they contribute towards the other categories and are instead ‘intermediate services’.

Assigning a monetary value to ecosystem services can only be achieved with the implementation of a form of economic valuation (Gilvear *et al*., 2013). This relies on the determination of which services provide final services. For example, those services that are classed as 'provisioning' are generally easier to value using a market-based economic tool (market prices) as it is relatively easy to assess who the beneficiaries are and the service has a direct use, such as the provision of food and other materials where the demand is often market-driven. The valuation of regulating and cultural services is more difficult to ascertain. For regulating services, upstream/downstream divides can exist regarding the importance of the service provided. For example, the natural regulation of flood water can hold greater importance depending on the beneficiaries' location where the actions carried out upstream can severely impede downstream areas, thus affecting the value. Cultural services similarly prove difficult as it is difficult to assign a price to spirituality, where personal preferences will affect perceived value. In these cases, valuation methods such as choice modelling and travel cost (TCM) methods can be applied. Integration of the ecosystem services approach within frameworks such as the sustainable livelihoods approach (Figure 5.3) may be complementary in determining economic models for river restoration. Examples of economic assessments to date predominantly relate to fisheries interests where there is an obvious economic model but river restoration spans a broad range of ecosystem services that are harder to evaluate. A recent study (Mellor, *in press*) specifically examines river restoration and the monetary value of ecosystem service provision.

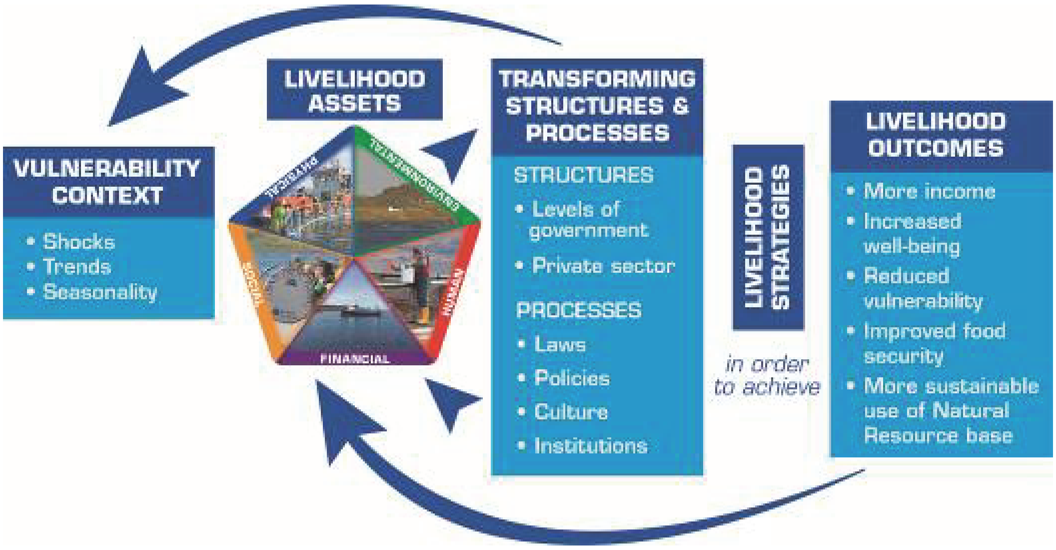

Figure 5.3: Sustainable Livelihoods approach (DFID, 1999).

Project drivers

This study considers a driver to be the current mechanism that enables certain river restoration activities to be prioritised and advanced at that time. For the purpose of this report we have considered the following as drivers:

- Water quality improvement
- Fish population enhancement and fisheries viability
- Sustainable flood management
- Climate change concerns
- Hydromorphology objectives – improvement to channel form and function
- Biodiversity objectives – Habitats Directive species or targeted biodiversity projects
- Policy drivers and achievement of WFD objectives
- Landscape objectives
- Socio-economic objectives

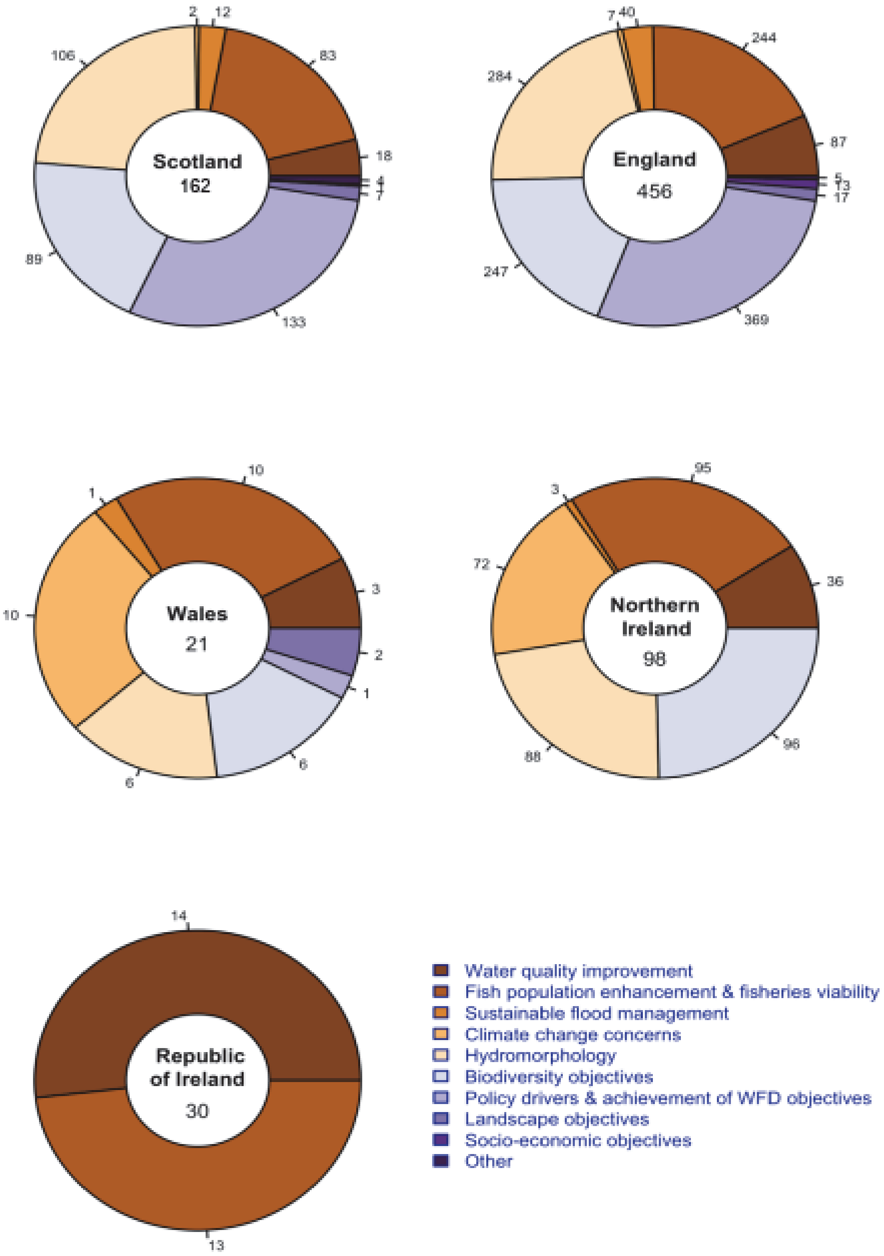

Figure 5.4: Proportions of drivers reported for projects by country. Note ROI data for individual projects is limited and therefore poorly reflects the range of drivers listed. The number of projects examined is presented in the centre of the pie charts and the proportions of reported drivers are presented around the outside.

Based on Figure 5.4, for both Scotland and England, the main four drivers are fish population enhancement and viability, hydromorphology, biodiversity objectives and greatest of all, legislation and policy drivers and achievement of WFD objectives. A similar trend can be seen in Northern Ireland; however, it is important to note that there are fewer drivers overall compared with the rest of the UK and water quality improvements play a greater role. In Wales sustainable flood management is a more frequently observed driver in contrast to the influence of policy drivers and achievement of WFD objectives. Based on limited data for the ROI, the two key drivers are fish population enhancement and viability in addition to water quality improvements. It should be noted that the extensive works of the Office of

Public Works (OPW) in Ireland may include many of the drivers listed but have been excluded from this analysis due to the different mechanism of delivery. Further discussion of restoration measures for the ROI and Northern Ireland is provided in Section 5.3.

There are learning points that can be garnered by assessing the number of projects broken down by driver (Figure 5.5). Before 1992 there are very few restoration projects where the drivers for restoration activity can be identified accurately. By 1998 the number of river restoration projects peaked at approximately 20, with the predominant drivers being fisheries, hydromorphology, biodiversity and policy. The inception of the Water Framework Directive and Habitats Directive most likely gave rise to these drivers influencing the direction of river restoration activities. By 2000, socio-economic and landscape were a minor driving force but water quality drivers were on the increase. From 2003 to the present day, landscape has had a greater role in driving river restoration projects, which may be explained by the increasing number of flood defence strategies and flood alleviation schemes (supported by the increasing proportion of flood management drivers). The number of river restoration projects exceeded 60 by 2011 by which time the predominant drivers were landscape, policy, hydromorphology and fisheries.

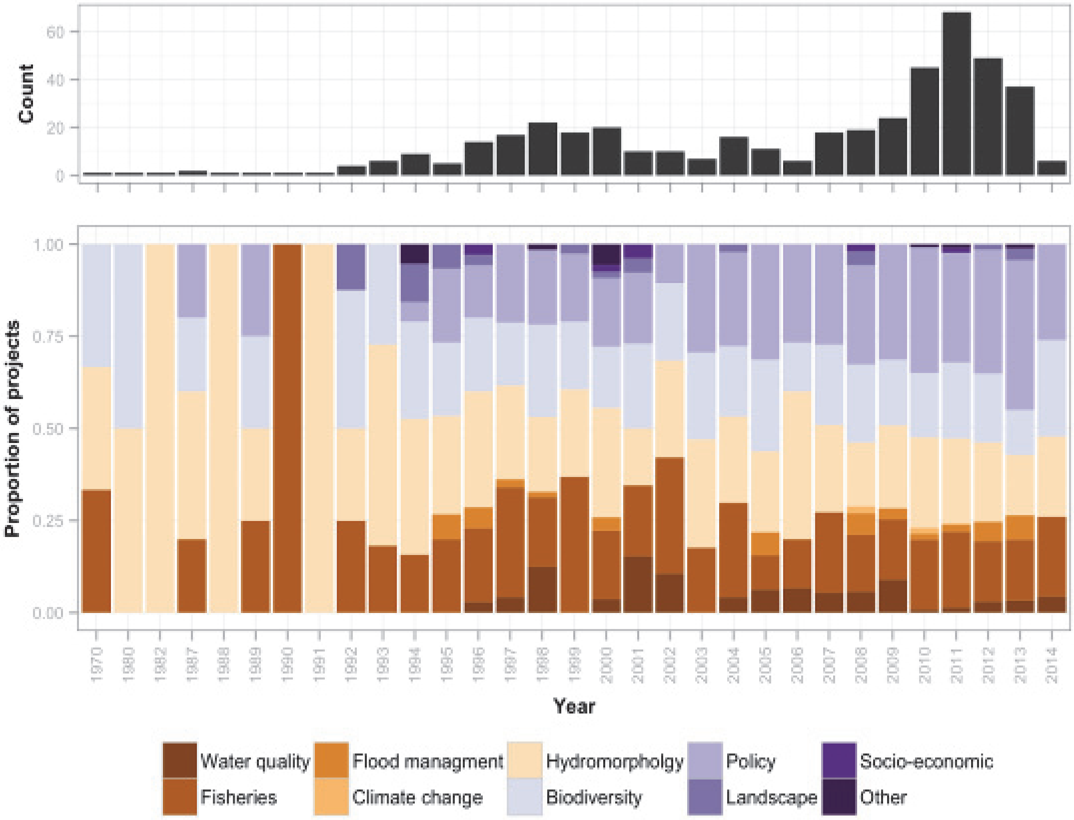

Figure 5.5: Drivers through time from 1970 to 2014 (the count on the top graph relates to the number of projects (where it was possible to attach a project date) with the proportion of projects for each driver per year underneath)

5.3 River restoration activity in UK and ROI

Prior to the mid 1990s restoration projects tended to be small-scale, and by 1996 only a handful of major re-alignment/re-meandering river restoration schemes had been undertaken across the UK, both in England (Holmes & Gough, 2009): the Bear Brook as part of a flood alleviation scheme and the River Cole scheme (Holmes & Nielsen, 1998). The situation has dramatically changed and in less than 17 years there has been a considerable acceleration in activity (Figure 5.6). Overall the majority of activity has taken place in England but up until recently most restoration projects have focused on reach-scale and local issues. The development of catchment-based approaches and understanding the importance of process-based activities has been a more recent development. For example, in 2004 the RRC identified 35 projects as having a catchment approach in the UK but found that no truly integrated catchment-scale river restoration project existed at that time. Project aspirations recorded relate mainly to enhancing habitat and improving conditions for fish, based on the categories in the RRC National River Restoration Inventory categories shown in Figure 5.6.

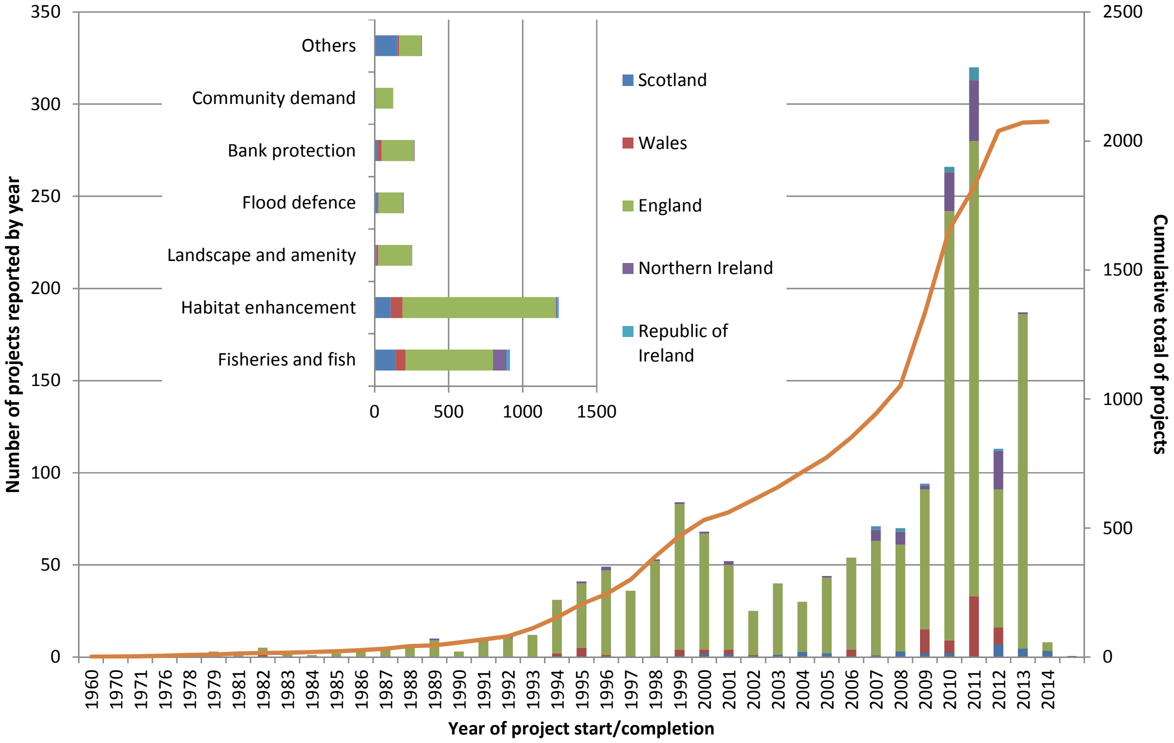

Figure 5.6: Restoration projects across the region and primary reported aspirations for restoration projects.

Figure 5.7 shows the increasing proportion of restoration activities focused on river planform and fish passage. From 1996 onwards (with a slight decline between 2002 and 2006 mirrored by a drop in the number of projects) it is evident that riparian restoration was predominant as well as an increased proportion of projects focusing on the installation of large woody debris. From 2007, there has been a steady increase in restoration activities associated with fish passage, along with restoration of instream morphology.

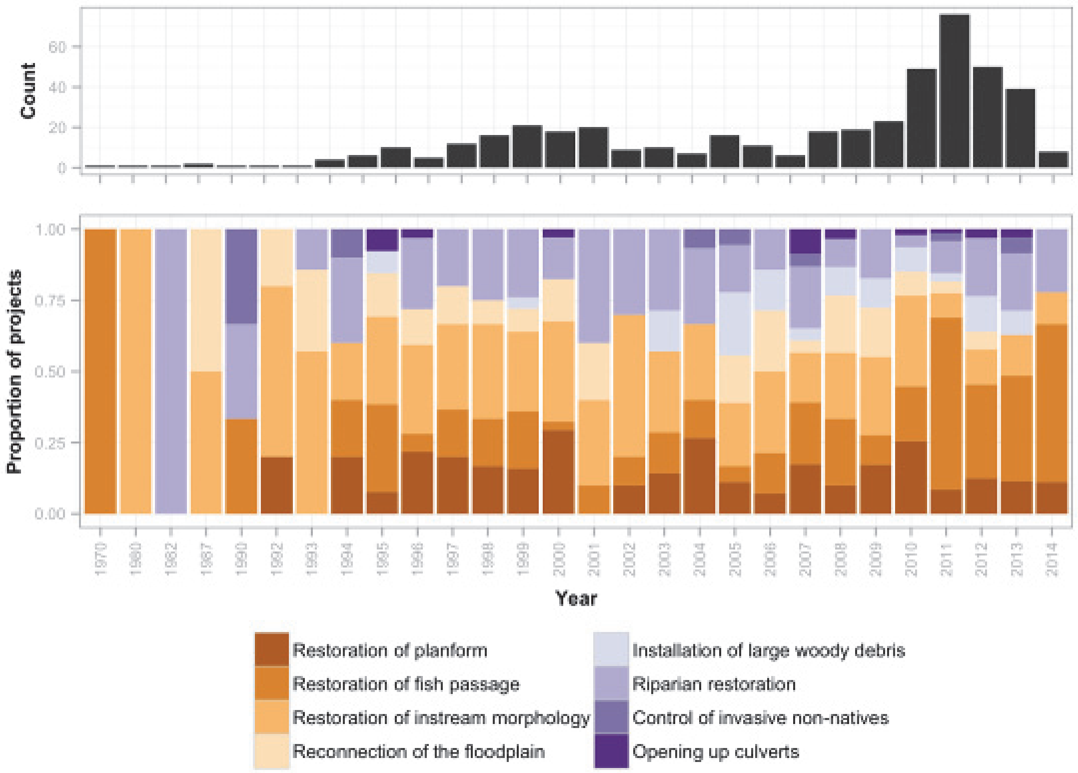

Figure 5.7: Sub-categories of restoration activity between 1970 and 2014) - Number of projects (where data available) represented by top graph with the corresponding proportion of projects for each restoration activity used underneath.

Figure 5.8 shows the location of river restoration projects examined in this study, broken down into eight restoration activities (discussed in Section 3). It is evident that the majority of these activities are in England, with some in Scotland and Wales. Activities in Northern Ireland and the Republic of Ireland are described separately in Section 5.3.

River restoration activities have primarily focused on restoring planform, fish passage, instream morphology, floodplain and riparian areas. Restoration of planform and instream morphology is clearly evident in the South West, Thames, South East and Humber RBDs (with a heavy cluster of activities) and to a lesser extent in Severn, Northumbria and Scotland RBDs. A similar conclusion can be made for restoring fish passage and riparian areas; however, there is a heavy concentration of activities in Scotland, Solway Tweed, Northumbria and North West RBDs. Restoration by reconnecting rivers with their floodplains tends to be located in the South West, South East, Thames and Anglian RBDs.

Restoration projects

Restoration of planform

Restoration of fish passage

Restoration of instream morphology

Riparian restoration

Reconnection of the floodplain

Control of invasive non-natives

Installation of large woody debris

Opening up culverts

Figure 5.8: Spatial distribution of sub-sample of restoration projects within England, Wales and Scotland, by activity. The INNS control projects are shown when included within the projects as additional benefits.

River restoration and rehabilitation projects are implemented to achieve given objectives which are translated in the physical environment into aims for improving hydromorphological and/or ecological conditions in the river system. The methods or activities used to achieve these aims are usually called 'measures'. REFORM (http://wiki.reformrivers.eu/index.php/Category:Measures) provides a web-based information tool for 60 restoration and rehabilitation measures that have been compiled by the FORECASTER[15] consortium and information provided by the then Environment Agency of England and Wales. The measures have been organized according to their aims into the nine measures groups and are detailed in Table 5.3.

The broad process categories identified from the projects are provided in Figure 5.9. Only 18 projects explicitly referenced process-based restoration within the information available. A large proportion of projects included multiple process categories within the aims and objectives. As would be expected, relatively few projects tackled process at the landscape scale given the relatively recent adoption of catchment and land management based approaches.

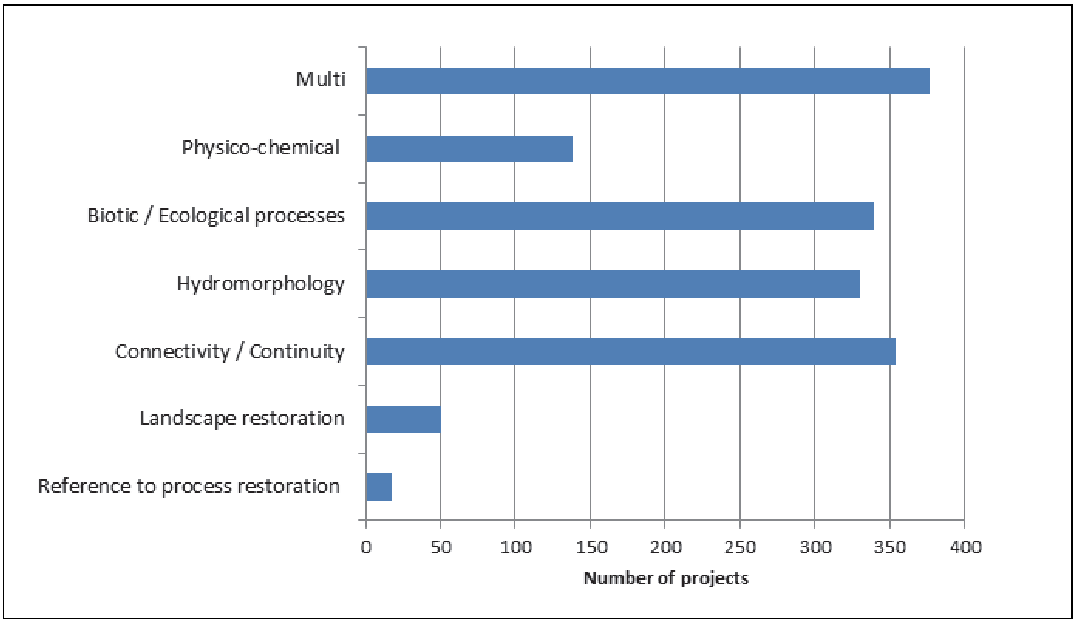

Figure 5.9: Process categories identified from projects.

The project identified a total of 1,121 individual measures applied across 667 projects. Many of the specific REFORM measures are not easily apportioned to project techniques or measures applied during restoration projects. Although many of the measures detailed in the REFORM list are identified in this study there are a number of hydrological (e.g. flow quantity) methods that were not recorded. It is not to say that these activities are absent across the region, but form programmes and agreements with statutory authorities and water

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[15] FORECASTER Facilitating the application of Output from REsearch and CAse STudies on Ecological Responses to hydro-morphological degradation and rehabilitation. FORECASTER is an EU project funded by the IWRM-Net and Delft Cluster which ran from October 2008 to September 2010. The project aimed at linking science with practical implementation of robust, cost efficient rehabilitation strategies for improving rivers and standing waters. The main objective of the project was assessing research output (national, European and North American) and case studies concerning the ecological effects of hydromorphological degradation and positioning hydromorphology in river rehabilitation strategies.

resource users and are generally outside the scope of river restoration projects recorded in the project database.

The current study categorised 40 measures across the project sample. For simplicity we have classified the measures according to three main categories:

- Longitudinal and lateral connectivity
- Channel and reach-scale
- Riparian, landscape and management

The use of different measures is presented in Figure 5.10. The main landscape techniques used are riparian planting, fencing and creation of wetland and floodplain features. The addition of gravels, soft engineering for protection against bank erosion, bank re-profiling and the addition of flow deflectors were commonly used techniques. More than 40 projects recorded the addition of large woody material, with six projects also citing removal as a measure. For addressing connectivity the construction of fish passes, obstacle removal and modification and artificial remeandering are the most common measures.

Table 5.3: Aims and measures based on the REFORM classification (see http://wiki.reformrivers.eu/index.php/Category:Measures).

Aims	Measures
Water flow quantity improvement	Improve water retention
	Improve/ create water storage
	Increase minimum flows
	Recycle used water
	Reduce groundwater extraction
	Reduce surface water abstraction with return
	Reduce surface water abstraction without return
	Reduce water consumption
	Water diversion and transfer
Sediment flow quantity improvement	Add/feed sediment
	Improve continuity of sediment transport
	Manage dams for sediment flow
	Prevent sediment accumulation in reservoirs
	Reduce erosion
	Reduce undesired sediment input
	Trap sediments
Flow dynamics improvement	Ensure minimum flows
	Establish environmental flows/ naturalise flow regimes
	Favour morphogenic flows
	Increase flood frequency and duration in riparian zones or floodplains
	Link flood reduction with ecological restoration
	Manage aquatic vegetation
	Modify hydropeaking
	Reduce anthropogenic flow peaks
	Shorten the length of impounded reaches
Longitudinal connectivity improvement	Facilitate downstream migration
	Fish-friendly turbines and pumping stations
	Install fish pass/bypass/side channel for upstream migration
	Manage sluice and weir operation for fish migration
	Modify culverts, siphons, piped streams
	Remove barrier

River bed depth & width variation improvement	Allow/increase lateral channel migration
	Create low flow channels in over-sized channels
	Narrow watercourses
	Remeander watercourses
	Shallow watercourses
	Widen watercourses
In-channel structure and substrate improvement	Add sediments
	Initiate natural channel dynamics to promote natural regeneration
	Introduce large wood
	Modify aquatic vegetation maintenance
	Recreate gravel bar and riffles
	Reduce impact of dredging
	Remove or modify in-channel hydraulic structures
	Remove sediments
Riparian zone improvement	Adjust land use to develop riparian vegetation
	Adjust land use to reduce nutrient, sediment input or shore erosion
	Develop riparian forest
	Remove bank fixation
	Remove non-native substratum
	Re-vegetate riparian zones
Floodplains/off-channel/lateral connectivity habitats improvement	Construct semi-natural/artificial wetland or aquatic habitats
	Improve backwaters
	Isolation of water bodies
	Lower river banks or floodplains to enlarge inundation & flooding
	Reconnect backwaters & wetlands
	Remove hard engineering structures that impede lateral connectivity
	Restore wetlands
	Retain floodwater
	Set back embankments, levees or dikes
Other aims to improve hydrological or morphological conditions	Other measures

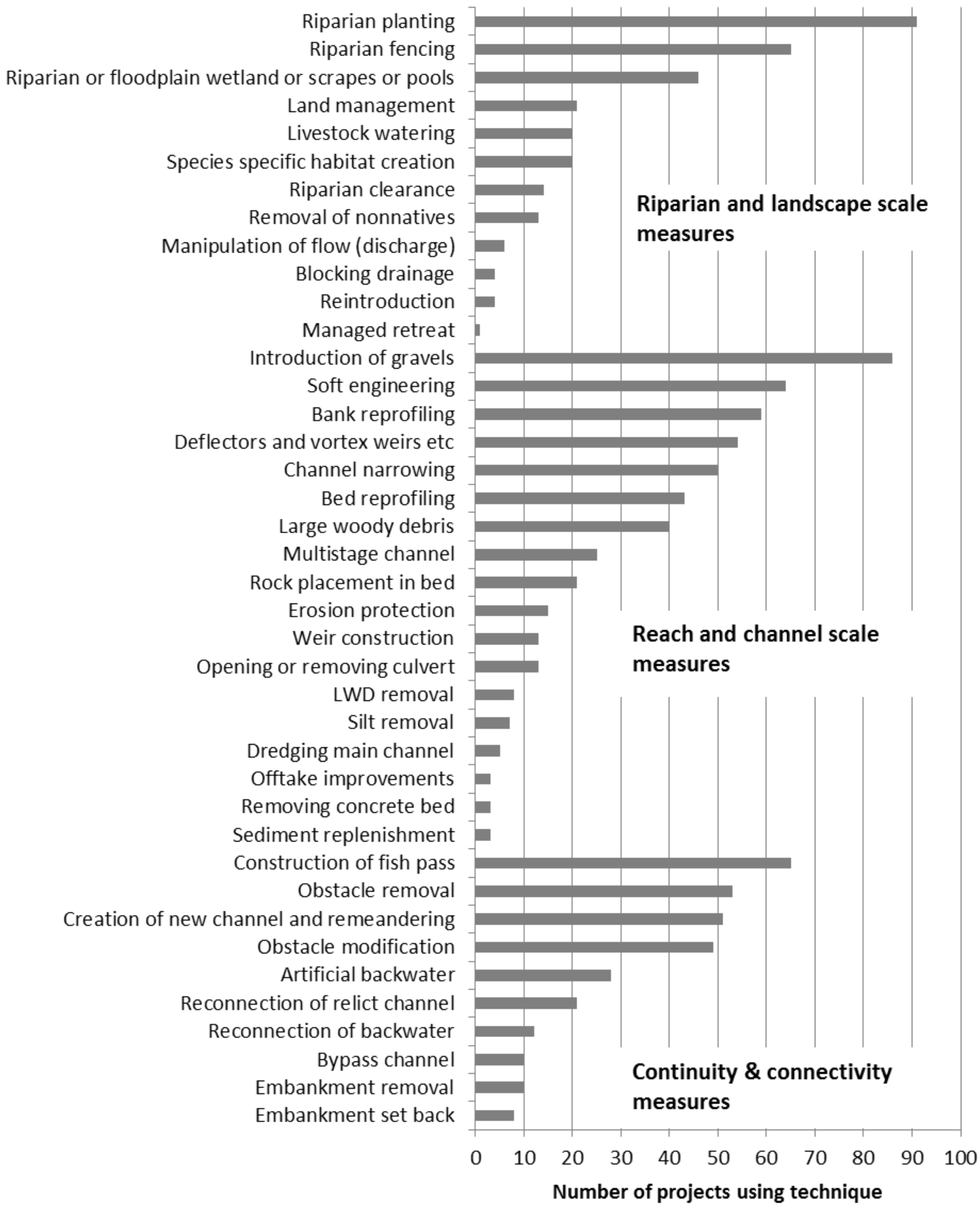

Figure 5.10: Range of measures used in river restoration in Scotland, England and Wales

In Northern Ireland and the Republic of Ireland projects are primarily driven by fisheries enhancements. The following discussion details the broad range of techniques employed principally at the reach scale. Measures employed include bank protection, riparian improvements and some examples of flood protection. Similar techniques are used across approximately 100 km of degraded channels in ROI annually by the OPW, including riparian planting and fencing and broader habitat improvements. Dedicated teams in the OPW Drainage Division conduct this work and this is further described in Section 5.4.5. This provides an interesting contrast to the UK where often large partner and stakeholder groups are involved in undertaking projects, and from a process perspective, an example of reach-based intervention measures and modifications that are likely to be the only way of returning a level of variation or dynamism to the system. Trying to reinstate process may take a very long time or may never be realised due to lack of energy in the system.

Examining the 138 NI and ROI projects in the dataset identifies improvement of spawning habitat as the main objective, followed by improving juvenile habitat and then improved fish passage (Figure 5.11). The ‘other’ project objective category included the sole aims of flood protection and bank stabilisation. Projects are not conducted exclusively for fisheries objectives and 41 projects provided multiple benefits such as non-fishery habitat or riparian improvements. There are a varied range of techniques applied (Table 5.4) and in many cases good monitoring data for fish have been collected which backs up the effectiveness of these techniques.

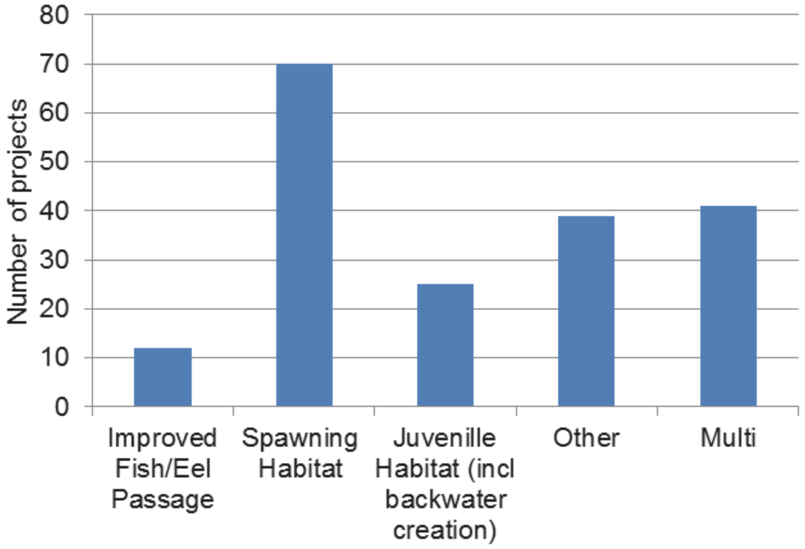

Figure 5.11: The main objectives of fisheries projects in Northern Ireland and ROI

Table 5.4: Measures applied in fisheries projects in Northern Ireland and ROI

Measure applied	**Number of projects using measure**
Substrate addition	77
Banktop trees planted	63
Artificial substrate	49
Bank reinforced	48
Channel re-meandering	35
Bank re-profiled	35
Addition of deflectors	34
River narrowed by berm or two-stage channel creation	34
Banktop fenced	33
River narrowed by D-groynes	32
Change of riparian land use	23
Addition of horseshoe or other groyne	20
Channel re-grading	13
Fine sediment removal and gravel cleaning	13
Native tree planting in riparian zone	9
Macrophytes cut /removed for spawning habitat	7
Ford, culvert replacement	6
Substrate removed (e.g. cobble, pebble)	5
Addition of weirs (full width of channel) as flow variation	5
Alien bank vegetation removal	3
River widened	2

5.4 Status of restoration across the region

5.4.1 Status of restoration in Scotland

In Scotland the first project to champion a catchment-based approach to improving rivers was initiated by WWF in the mid 1990s via its 'Wild Rivers' Initiative. The importance of catchment-based approaches was recognised by SNH commissioning a review and evaluation of integrated catchment management in the mid 1990s (Werritty, 1995). Restoration activity at the catchment scale in Scotland is well documented up to 2008 by Gilvear and Casas (2008). The study identified catchment-based approaches across Scotland and examined the drivers and mechanisms for restoration. In Scotland during this period river restoration was principally being undertaken for salmonid habitat enhancement and for biodiversity objectives (Gilvear and Casas, 2008). In the former, fisheries organisations took the lead and in the latter, SEPA.

A number of one-off catchment-scale initiatives, including river restoration as a component, were evident across Scotland, such as The River Devon Sustainable Flood Management Project. The South West Scotland Catchment Management Initiative began as a pilot project in 2000. It aimed to meet the objectives contained within the wetland section of the Dumfries & Galloway Local Biodiversity Action Plan but is seen as a precursor to the forthcoming requirements with regards to river basin planning. At that time, the concept of catchment management planning was fairly new and was focused on diffuse pollution rather than hydromorphology. Fisheries Trusts in Scotland appeared to be most active in undertaking river restoration at the catchment scale via their habitat enhancement initiatives (Gilvear and Casas, 2008). In many cases, although directed at improvement to fisheries habitat, the works bring about benefit for biodiversity in general although the latter aim was rarely quantified and monitoring was focused on the fishery. The Galloway Fisheries Trust and the Tweed Foundation were early pioneers in taking a catchment-scale approach. A range of completed and continuing catchment initiatives are provided in Table 1, Annex 1, illustrating the shift towards more strategic assessments and projects that focus on river morphology and wider benefits.

In 2008 the Restoration Fund was created, now the Water Environment Fund (WEF). The WEF provides funding to projects to help restore Scotland's catchments from the source, down through rivers, lochs, floodplains into the estuaries and out to sea. The primary focus of the funding is to tackle impacts on the physical condition of these ecosystems. Funding of £2 million is available annually by SEPA and the Scottish Government. The fund is managed by SEPA, with support from Scottish Natural Heritage, Forestry Commission, and Scottish Government. Funding is available to restore hydromorphology affected by historic pressures.

The WEF funded 82 scoping reports between 2008 and 2012 in order to assess where the Fund should focus, and a selection of these and other scoping studies is provided in Table 2, Annex 1. All of these have recently been reviewed to determine how they should be taken forward. There are 19 improvements that are already being progressed through detailed design to works such as the Almond Barriers project and the Avon (Forth) barriers project. There are 24 barrier removal/easement improvements and channel engineering improvements that now require further involvement from key stakeholders. The majority of these could be taken forward by partners such as the rivers and fishery trusts or a local authority. The Scottish Government granted £2million for restoration projects and pilot catchments in 2013/14 (SEPA, 2014). This was supplemented by the Scottish Government and SEPA with an additional £370,753 for projects; £346,664 of this funding supported the pilot catchment project which is described in more detail below.

SEPA commenced a pilot catchment project in 2012 to test and evaluate the practicality of identifying and integrating measures that address both morphological pressures and provide natural flood management benefits, while looking to incorporate wider social and environmental benefits.

Through the development and application of a robust catchment selection process, four catchments were chosen across Scotland; the catchments representing a mix of land-use, urban and rural environments and varying geographical scales:

- River Dee
- River South Esk
- River Nith
- Glazert Water (part of the River Kelvin catchment)

Essential to this work was getting out on site to verify the nature and extent of hydromorphological pressures. Importantly, this showed the hydromorphological condition across all water bodies surveyed to be worse than originally thought, highlighting that the scale of the river restoration task across Scotland is likely to be significantly larger than currently expected. This has led SEPA to schedule a detailed programme of field work from 2014 until the middle of the second RBMP cycle to secure a robust knowledge base.

In the four catchments, the improved information on morphological classification was used to look strategically across the catchment to identify discrete river reaches (essentially sub-water body scale lengths of river) where restoration would be important for achieving the WFD objectives or realising natural flood management benefit. These reaches were then assigned priorities based on these and wider social and environmental benefits.

This has enabled the development of restoration catchment plans, and is the basis of a focused programme of landowner engagement, options appraisal and measures design, with groundworks expected to be undertaken in some reaches in the 2015-16 financial year. The work to date is underpinning the development of objectives for the second river basin management plans, and the approach developed through the project will be used to attain these objectives.

'Pearls in Peril' is a LIFE+ NATURE project co-funded by 14 organisations across Scotland, England and Wales and aims to safeguard important populations of freshwater pearl mussel (*Margaritifera margaritifera*). The project spans four years from 2012 to 2016. In that time, a wide range of conservation measures will be implemented in key river systems. The project aims to restore the habitat of freshwater pearl mussel and salmonids (salmon and trout); secure the long term survival of existing freshwater pearl mussel populations; and communicate with local, national and international audiences to raise awareness of freshwater pearl mussel conservation issues. A total of 21 rivers across Britain will be involved, all of which are Natura 2000 sites and are designated as Special Areas of Conservation (SACs). In Scotland, these SACs are the Dee, South Esk, Spey, Evelix, Naver, Borgie, Oykel, Foinaven, Abhainn Clais an Eas, Allt a'Mhuilinn, Ardvar & Loch a'Mhuilinn Woodlands, Inverpolly, Moidart, Kerry, Glen Beasdale, Ardnamurchan Burns, Rannoch Moor, North Harris, Moriston and Mingarry Burn on Mull. In England, the project will involve the River Ehen in Cumbria, and in Wales the Afon Eden in Snowdonia. Process-based river restoration is central to the success of these initiatives due to the habitat requirements and long-term development aims for the pearl mussel populations. Scoping studies have identified physical damage to the rivers, and projects are currently under way to design and implement measures that benefit freshwater pearl mussels and salmonids. For example, several reaches of the River Dee have artificial structures that are reducing morphological integrity. It is important to understand how their removal will improve habitat, while ensuring that measures used have no detrimental effect on downstream receptors or factors such as flood risk.

5.4.2 Status of restoration in England

England has been the most prolific country in the UK with respect to river restoration activity over the last 20 years, as demonstrated in the proportion of projects in Figure 5.4. Pioneering projects such as the River Cole and Skerne set early precedents for the development of activities across the country. A study for the EA by Holmes (1998) provided a detailed appraisal of projects up to the formation of the River Restoration Centre and this organisation has become the primary advocate and adviser for activity in England and across the UK.

A recent significant move towards catchment- and process-based activities has been provided by the Catchment Restoration Fund, with 42 projects approved (see RRC website and EA, 2014), with a combined value of £24.5 million. Project value ranges from £89k up to £2.1m. Approval was given to those projects that were of a high priority within their catchment and with high confidence in their successful completion. Many of the successful bids embraced partnership funding, collaborative working and in some cases also supported innovation. In total a further £5.25m has been secured in partnership funding through a combination of direct finance, benefit in kind and volunteer activity. The second year of the Catchment Restoration Fund has seen a significant acceleration in projects undertaken. The Environment Agency currently collects data relating to 29 different ‘output measures’ with highlights including:

- 3 technical fish passes installed
- 29 weirs/barriers to fish movement removed
- 17 large-scale fish easements completed
- 21 small-scale fish easements completed
- 24 eel passes installed
- 225 m deculverting undertaken
- 20,235 m channel features created/restored
- 79,593 m bankside features created/restored
- 96,940 m of fencing put in place
- 57 agricultural businesses have improved their work practices
- 241 community events held
- Over 2,000 volunteers involved

The programme has also integrated monitoring into the budgets and provides the opportunity for good long-term monitoring projects to assess the effectiveness of the varied techniques applied.

Details of catchment-based projects in England are given in Table 3, Annex 1.

Strategic whole-river restoration planning (SWRP)

In England whole-river restoration plans are required for river SSSIs for which physical modification is identified as a Reason for ‘Unfavourable Condition’. A strategic ‘whole river’ approach to river restoration is needed, based on identifying key habitat features, linking fluvial geomorphology and ecology, and phased implementation of restoration works that encourage assisted natural recovery. Process-based and targeted river restoration activities are required to contribute to meeting obligations under the WFD, in respect of achieving protected area objectives and good ecological status or good ecological potential (GES/GEP). The process of SWRP identifies all the actions necessary to address the impacts of physical modifications that are the principal reason for an 'unfavourable' classification and also identifies a range of costs for each restoration and applies an aspirational date to the actions. The following process stages are proposed by the EA, NE and RRC for projects on SSSI rivers, providing a framework for projects:

- Geomorphological appraisal and ecological interpretation: developing a clear picture of anthropogenic physical modifications and their ecological significance within the river catchment. Examine historical hydromorphological change and any biological records and determine likely causality of poor status or degradation in condition.
- Generating a whole-river vision: determining the practical action most appropriate to resolving the adverse ecological consequences, initial consultation with stakeholders, development of initial vision, evaluate costs and mechanisms.
- Consultation and stakeholder feedback: finalise and agree whole-river vision in partnership with stakeholders – may require workshops or hosted consultation meetings or one-to-one interviews.
- Establishment and implementation of whole-river plan and reach-based delivery plans: Identifies actions required to allow river SSSIs to be classified as in favourable or unfavourable recovering condition with regard to physical habitat quality.
- Confirm condition status through assessment and the development of monitoring plans and protocols.
- Monitoring: checking success of management actions against plans using standard, repeatable and cost-effective methods.
- Modification of plans: prioritisation and programming of schemes as necessary and intervention in schemes that are not succeeding or failing to meet aims and objectives.

5.4.3 Status of restoration in Wales

Before 2013, CCW, the Environment Agency Wales and the Fisheries Trusts were primarily responsible for carrying out restoration projects and this responsibility now falls to Natural Resources Wales as the lead regulatory and conservation organisation. There is at present no formal mechanism for river restoration established equivalent to the WEF in Scotland or CRF in England. Duigan *et al*. (2009) reviewed the policy environment and development of river conservation and river rehabilitation in Wales. River restoration was initially undertaken by sensitive flood defence works or as part of fishery enhancement projects. The emphasis shifted to larger-scale projects in the mid-90s that reinstated natural structure and functioning (Duigan, *et al*. 2009), especially reconnecting the channel and the floodplain (Duigan, 2009). The Ogwen restoration project (1998) is one of the most extensive examples of this approach on an upland river in the UK. Located near Bangor in North Wales the scheme rehabilitated a high-energy mountain river restoring, as far as possible, the channel, riparian, and floodplain habitats and landscapes of the Nant Ffrancon U-shaped valley (Holmes & Gough, 2009).The Monnow Fisheries Project[16] (2003-2006) and the Irfon SAC LIFE+ Restoration Project are examples of catchment-based approaches conducted in Wales. The latter provides an example of extensive activities across the Irfon SAC.

In 2008 the Wye & Usk Foundation submitted a successful bid with partners including the Environment Agency Wales, the Rivers Trust and the National Museum of Wales. The Irfon is an important sub-catchment of the Wye SAC, and the project aimed to enhance the river for some of the most important species and habitats in the UK. The work provides a good test bed for examining the techniques used if reference conditions can be found. Monitoring appears to be concentrated mainly on fish. Measures and studies included:

- Water quality – acid waters monitoring using a network of 22 sites recording pH, diatoms, water chemistry and invertebrates
- Water quantity – working with forestry interests to try to reduce the rapid run-off from the forestry drainage ditch network and reinstate floodplain and other wetlands
- Restoration of the instream and riparian habitat across the main tributaries of the Irfon

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[16] http://www.monnow.org/index.php/projects/projectsarchive/39-rmp (2003-2006) Included for a 10 year monitoring programme for trout and grayling. Main activity was a programme of stock fencing and coppice management of bankside tree growth offered to farmers and included smaller streams.

  - Double bank fencing, erosion repair, coppicing and riparian measures
  - Introducing instream features
  - 32 km of SAC were restored by these means
  - New techniques for pleaching[17] riparian trees into the channel and soft revetments using hawthorn were developed and proved be effective at a catchment scale.
- Protecting Annex II species
  - Atlantic salmon - acid waters work and habitat restoration activity increased the survival rates of juveniles;
  - White clawed crayfish, freshwater pearl mussel and captive breeding programmes were also established for these species.
  - Other target conservation species include the lampreys (*Petromyzon marinus, Lampetra fluviatilis, Lampetra planeri*) shad (*Alosa fallax, Alosa alosa*) bullhead (*Cottus gobio*), otter (*Lutra lutra*) and *Ranunculus* sp. Fish populations were studied by annual electrofishing surveys, (baseline established by EA Wales in 2010) and the project also assessed otter and *Ranunculus* distribution.

5.4.4 Status of restoration in Northern Ireland

For projects that aim to address fishery habitat restoration the primary driver for these is the North Atlantic Salmon Conservation Organisation (NASCO) programme whose work includes fisheries management, aquaculture and habitat protection and restoration. Although large scale WFD projects have not commenced at this time, a grant-aided scheme aimed at small projects (the Water Quality Improvement Grant) ran from 2012-2013, with work carried out by local groups and NGOs to help achieve the objectives of the WFD. This is being superseded by the Challenge Fund in 2014 which should have the scope for larger works. The majority of WFD work to date has been focused on water quality and programmes have been put in place, for example the Nitrates Action Programme to help address water quality issues. The fishery agencies have worked on fish passage issues; this has mainly been on mitigating measures such as the installation of fish passes rather than barrier removal. These projects are primarily driven by NASCO but they can also be incorporated into flood alleviation schemes carried out by the Rivers Agency. The Rivers Agency has also been able to undertake restoration work as part of flood alleviation schemes. An inter-agency group, whose make-up reflects the differing roles of various agencies, has been set up to co-ordinate overall river restoration and continuity work. It includes representatives from Inland Fisheries Ireland. It is likely that in the future, large-scale projects in Northern Ireland will have several drivers, for example biodiversity and not just the Water Framework Directive.

5.4.5 Status of restoration in the Republic of Ireland

As described in Section 4.5.3, river habitats in the Republic of Ireland have been changed by the implementation of the Arterial Drainage Act of 1945. This led to major arterial drainage schemes being undertaken at a catchment scale. These schemes have affected the natural form of rivers with the engineering design dictating the longitudinal profile and cross-sectional form without any consideration of fish habitat either in the design or construction phases. Riparian habitats were also lost in many cases where a completely new channel was constructed at a lower Ordnance Datum. Both the construction and subsequent maintenance of drainage schemes have been the responsibility of the Office of Public Works (OPW) Drainage Division. During the 1980s the OPW and the Central and Regional Fisheries Boards began addressing the adverse effects on fisheries and considering options for improving fish habitat, while ensuring channel conveyance was not adversely affected. Initial trials began on important tributaries in the Boyne catchment which used the installation

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[17] Pleaching or plashing is a technique of interweaving living and dead branches through a hedge for stock control. Trees are planted in lines, the branches are woven together to strengthen and fill any weak spots until the hedge thickens

of instream features to modify the hydraulic uniformity before being extended to new drainage schemes on the Monaghan, Blackwater, Boyle and Bonet.

In 1990 the OPW commissioned the Central Fisheries Board (now Inland Fisheries Ireland) to examine the effects that channel maintenance activities were having on fish communities and habitat and assessed the feasibility of maintenance works that would benefit habitat and hydromorphology. This programme, the Experimental Drainage Maintenance (EDM) programme and subsequently the Environmental Drainage Maintenance programme, eventually led to the development of a new 10-step 'standard maintenance' standard for staff based on river corridor ecology. An important aspect of the EDM was the requirement for site visits and walkover surveys carried out by fisheries, technical and EDM team members to determine the level of implementation and the most appropriate steps of the maintenance standard to be used based on site characteristics.

Additional opportunities for improving river and lake habitats for fish came from EU funding under the Tourism Angling Measure (TAM) during the 1990s. Projects of varying scales benefited from this which aimed to facilitate improvements for tourism angling. This involved bank protection and fencing works to reduce soil loss and subsequent siltation of the channel bed. Installation of low-level weirs and deflectors and the introduction of gravel were also used to improve spawning and nursery habitats.

Since 2008 a new programme for the OPW, the Environmental River Enhancement Programme (EREP), began incorporating both river enhancement and channel maintenance aspects primarily driven by the hydromorphology element of the WFD. This programme identified the arterially drained channels as being 'probably at risk' of failing to meet WFD objectives. The EREP has a target of annually improving the hydromorphology of 100 km of channels within the OPW drainage network using instream and riparian enhancement measures ('capital works') or ensuring the robust implementation of channel maintenance guidance ('enhanced maintenance') to enhance biological diversity by improving the range of physical habitat niches. Capital works projects involve fencing and improving the habitat for specific target fish species (mainly salmon and brown trout) using heavy machinery to construct in-channel features only after the water quality and underlying topographic conditions have been deemed suitable for achieving the desired outcome. The enhanced maintenance approach uses OPW scheduled maintenance operations for low-gradient channels and ensures that the appropriate elements of the OPW maintenance guidance are followed to maximise hydromorphological change and include measures such as aquatic vegetation management and the redistribution of spoil to create in-channel features.

5.5 Summary of river restoration in the UK and Ireland

- A broad range of policy and legal obligations has provided a framework for river restoration to develop and river restoration fulfils multi-benefits across a range of policy and advice. Currently river restoration is being framed as a way of improving the ecosystem services offered by rivers and is seen to be one of the key drivers for the release of river restoration-related government funding in the UK.

- Projects may be classified under multiple drivers depending on the discernible aims of the project including water quality improvement, fish population enhancement and fisheries viability, sustainable flood management, climate change concerns, hydromorphology, biodiversity objectives, policy drivers and achievement of WFD objectives, landscape and socio-economic objectives.

- For both Scotland and England, the four main drivers are fish population enhancement and viability, hydromorphology, biodiversity objectives and greatest of all, legislative drivers and achievement of WFD objectives. A similar trend can be seen in Northern

Ireland; however, water quality improvements play a greater role. In Wales sustainable flood management is the main driver. Based on limited data for the ROI, the two key drivers are fish population enhancement and viability in addition to water quality improvements but the hydromorphological element of the WFD is a principal driver for the work of the OPW EREP scheme which has been under way since 2008.

- Process-based river restoration is central to schemes in Scotland due to the habitat requirements and long-term development aims for target species. Scoping studies have identified physical damage to the rivers, and projects are currently under way to design and implement measures that benefit freshwater pearl mussels and salmonids.

- In England whole-river restoration plans are required for river SSSIs for which physical modification is identified as a reason for ‘unfavourable condition’. A strategic ‘whole river’ approach to river restoration is required, based upon identifying key habitat features, linking fluvial geomorphology and ecology, and phased implementation of restoration works that encourage assisted natural recovery. Process based and targeted river restoration activities are needed to meet obligations under the WFD, in respect of achieving protected area objectives and good ecological status or good ecological potential (GES/GEP).

- In Wales and Northern Ireland, river restoration currently has no formal delivery mechanism for catchment-scale approaches such as WEF in Scotland, the CRF in England and the EREP and enhanced maintenance programmes.

- In Northern Ireland WFD projects have mostly been small-scale grant-aided works. Much emphasis has been placed on fish passage with works also linked to flood alleviation schemes. It is likely that in the future large-scale projects in Northern Ireland will have several drivers – for example, biodiversity and not just the Water Framework Directive.

- In the Republic of Ireland, the enhanced maintenance approach uses OPW scheduled maintenance operations for low-gradient channels and ensures that the appropriate elements of the OPW maintenance guidance are followed to maximise hydromorphological change and include measures such as aquatic vegetation management, riparian works and the redistribution of spoil to create in-channel features.

- Scotland and England have broadly similar catchment-based and process-based approaches. In Wales, NRW is responsible for developing similar programmes. In Northern Ireland attention has primarily been given to reducing water quality pressures and fisheries measures but improving hydromorphological integrity will be the next challenge. The primary restoration activity in the ROI is on heavily degraded arterially drained catchments and aims to improve river processes and form where natural processes may no longer have the ability to change the channel.

6. SUMMARY

Main findings

- Through thousands of years of human activity, the river systems in the British Isles and Ireland have undergone extensive physical modification. This is either directly as a result of river engineering or due to changes in hydrology, the landscape, land management or extensive drainage operations. Consequently this has resulted in a high proportion of rivers within the region suffering from some form of physical degradation or morphological alteration. Within some river basin management districts morphological degradation outweighs pressures that historically were of greater concern, such as water quality.

- The physical effects of these modifications on river ecology vary widely depending on the nature and scale of the modifications and the natural environmental behaviour of the river. Although differences exist across river types and upland and lowland rivers, key themes are the reduction in habitat complexity, extent and connection of rivers with the floodplain. Based on this it is essential that restoration activities are specifically aimed at addressing the consequences of physical modification while ensuring that the selected restoration technique(s) are best suited to the river type and wider catchment conditions.

- In the early days, restoration activities were traditionally focused at the reach scale and were often heavily dependent on engineered solutions. Now, however, there is a growing consensus that efforts should be directed towards catchment-scale restoration activities restoring natural processes such as connectivity and continuity whilst incorporating additional benefits such as natural flood management. This is evident from the increase in projects that have concentrated on restoring channel planform or reinstating fish passage to ensure that lost connectivity is reinstated, which is both of hydromorphological and ecological importance.

- The evidence supporting process-based restoration has been extensively investigated in a number of reviews that have often described limited or no significant benefit. The lack of effect is attributed to insensitivity of the monitoring to hydromorphology, or other confounding catchment pressures. A number of recent European studies have demonstrated good relationships between restoration activities and improved biodiversity. It is therefore necessary to identify sensitive indicator species for hydromorphological changes, and potential target species for river rehabilitation design and evaluation.

- Although there is a growing evidence base for the benefits of restoration activities, projects are seldom appraised in sufficient detail to discern benefits or effectiveness of specific techniques. In order to overcome this, it is important that appraisal is a fundamental part of the restoration activity from project conception to final completion and designed to be specific not only to the river type but also to the techniques used. This will ensure that the true benefits of a technique applied under different settings are assessed and that only suitable techniques are selected. It is especially important that practitioners share their experiences even if the restoration has not been successful, considering the high costs that can be associated with restoration projects and the importance of preventing future expense in rectifying misguided restoration attempts.

- Monitoring rarely reflects the timescale of ecosystem recovery. Although this is not a new issue, it becomes more important at a time when restoration is increasingly concerned with restoring river habitat processes at the catchment scale and includes multiple actions. In these situations a monitoring strategy has to be developed not only for measuring the success of restoration in meeting the project aims, but also for allowing recovery which may take several decades.

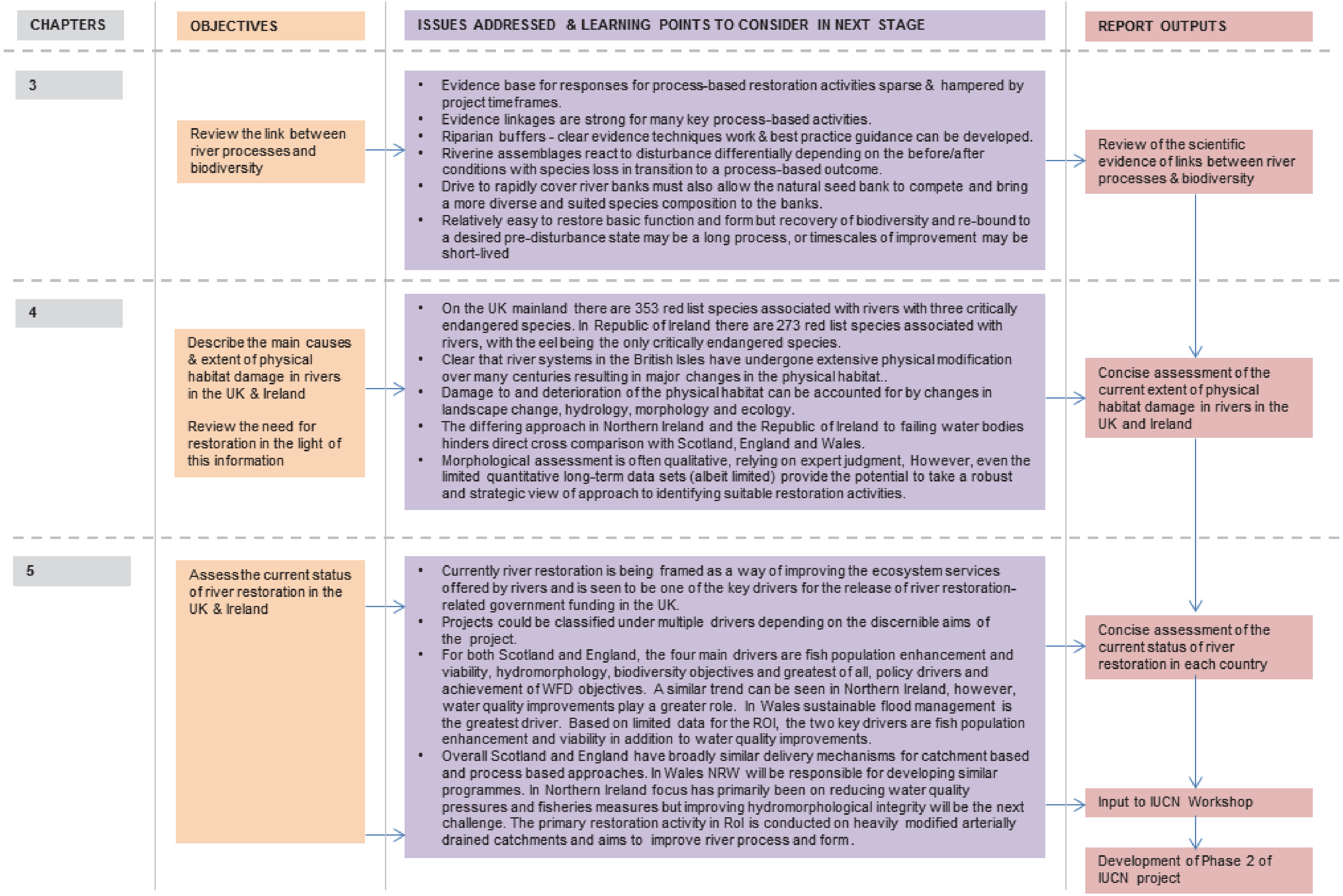
- With the passage of key pieces of legislation such as the EC Habitats Directive and the EC Water Framework Directive, there has been an increase in river restoration activities aimed at improving river habitats for particular species, or those that seek to improve the present condition of river habitats and prevent further deterioration to meet legislative objectives.

- There are numerous inter-connected drivers for river restoration. In Scotland and England, the main drivers have been the requirements of legislation objectives, improving fish populations and fisheries viability, hydromorphology and biodiversity. Although these also apply to restoration in Northern Ireland and Wales, addressing water quality and sustainable flood management are key drivers in both countries respectively. Restoration in the Republic of Ireland is primarily for fisheries and water quality reasons although improving hydromorphology has been more important since the Environmental River Enhancement Programme (EREP) in 2008 by the Office of Public Works to respond to damage caused by extensive arterial drainage works.

- The status of river restoration varies between the countries included in this study. England has traditionally been at the forefront of river restoration in the British Isles since the 1970s. Catchment projects were initially championed in Scotland in the 1990s and are now gaining impetus in other regions, including projects such as ‘Pearls in Peril’ (LIFE+ NATURE) which is a collaboration between several organisations across Scotland, England and Wales.

- A ranged of approaches and strategies for restoration have been developed in the UK and Ireland. In Wales and Northern Ireland, river restoration has no formal system at present for catchment-scale approaches such as the WEF in Scotland, the CRF in England and the EREP and enhanced maintenance programmes in the Republic of Ireland. These initiatives represent a significant move towards catchment- and process-based activities that support innovative approaches and include assessment and monitoring of the methods used. While the approaches used in Scotland and England involve a wide range of stakeholders and means of participation, the model in the Republic of Ireland is quite different, with restoration activities conducted by dedicated specialist teams within the OPW.

The summary in Figure 6.1 has been adapted from the methodological roadmap (Section 2, Figure 2.1). This shows the links between the approach adopted in this study and the key learning points identified.



CHAPTERS	OBJECTIVES	ISSUES ADDRESSED & LEARNING POINTS TO CONSIDER IN NEXT STAGE	REPORT OUTPUTS
3	Review the link between river processes and biodiversity	• Evidence base for responses for process-based restoration activities sparse & hampered by project timeframes. • Evidence linkages are strong for many key process-based activities. • Riparian buffers - clear evidence techniques work & best practice guidance can be developed. • Riverine assemblages react to disturbance differentially depending on the before/after conditions with species loss in transition to a process-based outcome. • Drive to rapidly cover river banks must also allow the natural seed bank to compete and bring a more diverse and suited species composition to the banks. • Relatively easy to restore basic function and form but recovery of biodiversity and re-bound to a desired pre-disturbance state may be a long process, or timescales of improvement may be short-lived	Review of the scientific evidence of links between river processes & biodiversity
4	Describe the main causes & extent of physical habitat damage in rivers in the UK & Ireland Review the need for restoration in the light of this information	• On the UK mainland there are 353 red list species associated with rivers with three critically endangered species. In Republic of Ireland there are 273 red list species associated with rivers, with the eel being the only critically endangered species. • Clear that river systems in the British Isles have undergone extensive physical modification over many centuries resulting in major changes in the physical habitat.. • Damage to and deterioration of the physical habitat can be accounted for by changes in landscape change, hydrology, morphology and ecology. • The differing approach in Northern Ireland and the Republic of Ireland to failing water bodies hinders direct cross comparison with Scotland, England and Wales. • Morphological assessment is often qualitative, relying on expert judgment, However, even the limited quantitative long-term data sets (albeit limited) provide the potential to take a robust and strategic view of approach to identifying suitable restoration activities.	Concise assessment of the current extent of physical habitat damage in rivers in the UK and Ireland
5	Assess the current status of river restoration in the UK & Ireland	• Currently river restoration is being framed as a way of improving the ecosystem services offered by rivers and is seen to be one of the key drivers for the release of river restoration-related government funding in the UK. • Projects could be classified under multiple drivers depending on the discernible aims of the project. • For both Scotland and England, the four main drivers are fish population enhancement and viability, hydromorphology, biodiversity objectives and greatest of all, policy drivers and achievement of WFD objectives. A similar trend can be seen in Northern Ireland, however, water quality improvements play a greater role. In Wales sustainable flood management is the greatest driver. Based on limited data for the ROI, the two key drivers are fish population enhancement and viability in addition to water quality improvements. • Overall Scotland and England have broadly similar delivery mechanisms for catchment based and process based approaches. In Wales NRW will be responsible for developing similar programmes. In Northern Ireland focus has primarily been on reducing water quality pressures and fisheries measures but improving hydromorphological integrity will be the next challenge. The primary restoration activity in RoI is conducted on heavily modified arterially drained catchments and aims to improve river process and form.	Concise assessment of the current status of river restoration in each country Input to IUCN Workshop Development of Phase 2 of IUCN project

Figure 6.1: Key Learning Points from this study based on our methodological approach.

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ANNEX 1: CATCHMENT-BASED PROJECTS

Table 1: Selection of catchment-based approaches in Scotland

Project	Duration	Description
Pilot Catchments project	2012-ongoing	Four catchment projects testing and evaluating the practicality of identifying and integrating measures that both address morphological pressures and provide natural flood management (NFM) benefits, while seeking to incorporate wider social and environmental benefit on the River Dee, River South Esk, River Nith and Glazert Water (part of the River Kelvin catchment).
Allan Water NFM	2012-ongoing	To identify the potential for NFM measures in the Allan Water catchment to reduce the severity of flooding for affected communities; improve the ecological status of water bodies within the catchment and develop a methodology which is applicable for use in catchments across Scotland.
Eddleston Water	2010-ongoing	To investigate whether changes to land-use management and the restoration of natural habitats can help improve the river valley for wildlife and reduce the risk of flooding in Eddleston and Peebles. Channel restoration of straightened sections. Includes ever-increasing activities including a hydrometric monitoring network and the opportunity for examining catchment- and process-based approaches in a small catchment.
Bowmont Phase II	2011-2013	Works on five farms to implement NFM and restoration measures including: living flexible bank protection; engineered log jams on floodplain to restore natural vegetation and stabilise sediment; planting long, wide hedge to increase rainfall interception and infiltration.
Eye Water Catchment Restoration	2011	Creation / expansion of the riparian zone in agricultural catchments through fencing and tree planting.
River Naver Catchment Restoration (PIP) Project	2010-2011	The development of a catchment restoration plan to meet the WFD objective of good ecological potential, with prominence given to improving the habitat conditions for freshwater pearl mussels and sustainable flood management.
Fisheries Management Plans	2008-2014	Sets out a programme of measures that are required to protect and enhance populations of native fish and their habitats from pressures, including diffuse and point source pollution, exploitation, abstraction and morphology.
River Devon and Black Devon LIFE + Catchment Project	2008	A catchment approach to address multiple pressures including climate change, flooding and the threat from alien invasive species.
Tay Western Catchments Initiative	2007-2008	A catchment-scale project focusing predominantly on riparian habitats and the land uses that affect them within the western Tay network.
River Devon Project	2003-2006	To demonstrate the importance of stakeholder engagement and a catchment approach to achieve sustainable flood management.

River Kerry Conservation Strategy	2003	Part of a demonstration project (Life in UK Rivers) to develop methods for conserving habitats and species within SACs to maintain favourable condition status.
The Ythan Project: Sustainable Land Management in the Ythan Catchment	2001-2005	Working with land managers to address excessive algal growth in the estuary and other water quality issues by encouraging the adoption of sustainable land management practices, including nutrient budgeting and agri-environment schemes.
Tarland Catchment Initiative	2001-2004	To make improvements to the condition of streams and management options that have had an adverse impact on water quality or habitat conditions.
River Cree Life Environment Project	1999-2003	This 3-year project is designed to demonstrate techniques for the protection and enhancement of water quality and aquatic biodiversity in areas of extensive commercial forestry. The study areas are the Cree in south-west Scotland, and the Viskan on the west coast of Sweden. Both of these catchments are heavily afforested and have problems of surface water acidification with impacts on aquatic biodiversity, especially juvenile salmonid populations.
Tweed Riparian Habitat Enhancements	1999-2002	Targeting streams throughout the Tweed catchment with multiple benefits for wildlife, landscape, access, recreational potential, education, interpretation and involvement through local angling associations.
The River Almond Catchment: A Plan for Integrated Management	1999	A comprehensive catchment approach to address poor water quality originating from the previous mining legacy of the area and current land-use including urban and agricultural.
Tweed Foundation Habitat Enhancement Project	1990	Improving habitat conditions for juvenile salmonids that have been adversely affected by previous and current land management activities and contributed to diminished natural productivity in the river SSSI.

Table 2: Selection of scoping projects in Scotland, highlighting the move to catchment-based approaches and projects that allow measures to be directed to where they are most needed

Scoping project	Completion date/ Status	Description
Lunan Scoping	In progress	Morphological and hydrological study of the Lunan Water to enable catchment approach to restoration and flood management.
Lunan Water Scope	In progress	Catchment scope to provide catchment framework for sustainable river management, including scoping restoration and NFM opportunities.
Priority Catchment Restoration Options	In progress	Developing restoration options at the catchment scale in four SEPA Diffuse Pollution Priority Catchments.
Bervie Water Scope	Application approved	Catchment scope to provide catchment framework for sustainable river management, including scoping restoration and NFM opportunities.
Crooksmill Burn Restoration Scope	2013	Develop a catchment plan for morphology, considering reinstating natural fluvial processes and sediment transport, creating a wildlife corridor, re-naturalising floodplain and channel form.
Glen Hurich Catchment Restoration - Phase 1	2013	Produce a catchment scope with options appraisal for Glen Huriach, including restoration of gravel pit into wetlands, removal or easement of dam, and woodland creation.
Moniak Burn Restoration	2013	Scope restoration options for 4.2km stretch of straightened river including a section that passes over a culverted stream.
Carradale Water	2011	Scoping study of the watercourse including geomorphic audit; at present fine sediment is a problem here.
PAN Scotland RAFTS Barriers Scope I-II	2011	Scoping removal of weirs and / or creation of fish passes. Scoping studies of barriers at six separate locations.
Peffrey Catchment	2011	Catchment-scale project looking at non-native species removal, litter clearing, bank planting, geomorphological survey and instream demonstration sites.

Table 3: Catchment-scale approaches in England

Project	Duration	Description
Limestone Ribble Restoration Project	In progress	Certain watercourses within this agricultural and industrial catchment are failing to meet WFD objectives due to diffuse pollution and obstructions to fish passage. Restoration has focused on reinstating fish passage, a natural flow regime, sediment transport and water quality.
River Frome Rehabilitation Plan	In progress	A collaborative project to achieve targets for the River Frome SSSI. A fluvial geomorphological study has been carried out to determine the physical dynamics of the river and how these interact with river ecology to develop a suitable plan for physical restoration. A range of reach- and catchment-scale actions have been identified to help restore the river to favourable condition.
River Irwell Restoration Project	In progress	Restoration of urban watercourses that are often brick-lined while maintaining or enhancing flood protection.
River Rea Restoration Project	In progress	Declining fish stocks are preventing some rivers within this catchment meeting WFD objectives. Using CRF funds, pressures such as sedimentation, diffuse pollution, degraded habitat quality and fish passage obstructions will be addressed.
Source to Sea Programme	In progress	This project concerns multiple river catchments that flow into Morecambe Bay and includes carrying out restoration projects on a range of watercourses and protected sites and priority habitats. Restoring connectivity between the river and its floodplain and headwaters will restore habitats and removing structures will improve fish passage. Buffer strips and wetland habitats will also be created in areas where diffuse pollution is affecting water quality to help achieve WFD objectives.
Telford Urban Catchment Restoration	In progress	Works have concentrated on the Lydebrook and Madebrook catchments that have been degraded through years of industrial activity. This has modified the catchments which suffer from poor water quality and deteriorating macroinvertebrate populations. Work will focus on riparian areas, and instream features will be installed to improve the oxygen content of the water.
The Axe and Exe River Improvement Project (AERIP)	In progress	Using CRF funding, the project will improve connectivity by removing obstacles to fish migration that are also affecting the movement of sediment through the system that affects spawning habitats. Diffuse pollution and bank erosion due to cattle poaching are also causing a deterioration in water quality; these areas will also be addressed.
The Dart and Teign River Improvement Project (DTRIP)	In progress	CRF will provide funding to improve water quality and restore fish passage in the Dart and Teign catchment to improve habitat quality and meet good ecological status.

The River Deerness Project	In progress	Water quality issues and barriers to fish migration have resulted in significant areas of the catchment failing due to fish. The project aims to improve habitat connectivity for fish migration and access to spawning and feeding areas. The project also includes site walk-overs to help alleviate diffuse pollution.
The South Hams River Improvement Project (SHRImP)	In progress	This CRF project will address poor water quality from sedimentation and fertiliser-rich run-off which are adversely affecting river ecology. This is further compounded by the low pH of the water as a result of areas of acidified moorland within the catchment. It will also address barriers to fish migration that are preventing access to spawning grounds and impeding the natural conveyance of sediments through the river system.
The Taw River Improvement Project (TRIP)	In progress	This project will improve habitat within the catchment, using CRF funds. It aims to improve water quality and biodiversity and increase the amenity and economic value by improving recreational use and fishery conditions.
Wansbeck 100	In progress	Poor water quality as a result of sediment and nutrient inputs are depleting fish populations putting some tributaries at risk of failing WFD objectives. There are also structures impeding fish migration and a lack of riparian and instream habitats. This project will address these issues by working in collaboration with farmers and land managers to help reduce run-off entering the watercourses.
Wensum River Restoration Strategy	In progress	A long-term project to restore the River Wensum SSSI and SAC to create a naturally functioning ecosystem that supports typical Norfolk chalk stream communities.
Haltwhistle Burn Restoration Project	2013-ongoing	With funding from the CRF, this project will address multiple pressures including quarrying, urbanisation, agriculture and industry which were collectively damaging river habitats and fish populations. Riparian tree planting and bank and channel restoration have already been carried out.
Sherborne Windrush Restoration Project	2012-ongoing	Dredging has degraded the habitat of the River Windrush and Sherborne Brook, which are also affected by diffuse pollution from agricultural areas. The restoration activities will be focused on reinstating fish spawning habitats, instream habitat heterogeneity, connectivity and water quality.
Eden Crayfish Restoration Project	2012-ongoing	The River Eden in Cumbria is designated as an SAC. In addition to hosting a number of important species, including the endangered white-clawed crayfish. Within the catchment, many water bodies are failing to meet WFD objectives largely due to water quality issues, invasive species and poor habitat quality. Natural riparian and channel feature creation in conjunction with farmer engagement and farm works were used to reduce diffuse pollution and improve the habitat for white-clawed crayfish and other species such as lamprey, salmonids, eels, otters and water voles.

The South Cornwall River Improvement Project	2012-ongoing	This umbrella project includes restoration works on eight south Cornwall river catchments that are at risk from a range or pressures including modified flow regimes, habitat degradation, diffuse pollution, barriers to fish migration, loss of fish spawning areas and impacts from the historic mining legacy in the area.
Nine Chalk Rivers Project	2012-ongoing	Included 16 restoration activities across nine unique river catchments in Norfolk. The rivers were impaired by the loss of floodplain connectivity, canalisation, decreasing water quality and low flows which were damaging the ecological condition of the river and floodplain.
Diffusing the Issue in Rural Ribble	2012-ongoing	A multi-catchment project focused on reducing diffuse pollution. This included improving farm infrastructure, riparian buffer creation and habitat reconnection.
MORPH 10	2012-2013	Funded through CRF this project aimed to restore the Middle Ouse in Sussex in a multi-agency collaboration to improve ecology within the catchment for WFD objectives. Works have included increasing floodplain storage capacity for natural flood management and restoring connectivity by removing and bypassing structures.
Irwell GEP Project	2012-2013	This project covered the removal of redundant structures to restore connectivity.
River Ecclesbourne Pilot Scheme for Catchment Restoration	2012	Pilot catchment restoration scheme to meet WFD objectives which included the rehabilitation of a side channel and structure removal.
Colne Water Restoration Project	2009-ongoing	In partnership with the CRF this project on rivers within the Ribble catchment addressed issues including diffuse pollution, altered flow regimes, poor riparian habitat and obstructions to fish passage. Riparian planting and upland drain blocking were used to mitigate pollution and reinstate sustainable flow regimes to restore sustainable salmonid populations.
River Avon STREAM Project	2005-2009	A strategic approach to river restoration and management in response to historical engineering which has resulted in habitat degradation of rivers within the Avon catchment. Ditch restoration was also part of this project due to blockages within the ditch network which has obstructed the movement of species.
New Forest LIFE Project	2003-2006	Restoration of Highland Water and the Blackwater which have been historically straightened, with large wood features also removed. Habitats for fish and macroinvertebrates were improved with LWD and CWD additions and re-meandering to increase habitat and flow diversity while encouraging over-bank flooding to maintain LWD inputs and encourage pool and riffle sequence development.
Upper Derwent Enhancement Project	1998-2001	Using riparian and in-channel restoration to improve the upper catchment for wildlife, social and economic purposes.

River Tone Catchment Project	1998	Funded by the EC initiative Joint Approach to Managing Flooding this project worked with farmers on the Tone and Parrett rivers to reduce runoff which contributes to flooding and sediment inputs that have caused water quality deterioration.
River Esk Regeneration Programme	1997-2001	To improve the condition of the River Esk and the riparian area to support fish and other wildlife. It was also hoped that the project would add economic value to the river for the rural community.
Avon Catchment Rehabilitation	1987-1994	A catchment approach to habitat and landscape rehabilitation in response to degraded wildlife and fisheries habitats caused by agricultural intensification and historic drainage activities. Works included backwater and wetland creation and riparian planting. Instream features including pools and riffles were also formed.

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