



THE SCOTTISH RIVERS HANDBOOK

A guide to the physical character of Scotland's rivers



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A guide to the physical character of
Scotland's rivers

Charles Perfect, Stephen Addy and David Gilvear



CREW: Centre of Expertise for Waters

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Front cover images (top to bottom order): Glen Affric, Highland (© Centre for River Ecosystem Science); the River Dee in the Cairngorm Mountains, Aberdeenshire (© The James Hutton Institute); the River Tummel at Tummel Bridge in Perthshire (© Centre for River Ecosystem Science); the Quoich Water, Aberdeenshire (© Centre for River Ecosystem Science).

Rear cover image: a vegetated gravel bar on the River Spey near Newtonmore, Highland (© Centre for River Ecosystem Science).

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Foreword

At a time of global water stress, we are beginning to appreciate more and more the inherent value of our rivers, and to develop a systems understanding that works across economic, social and environmental sectors that will help sustain and protect them. This is why, in 2013, the United Nations Educational, Scientific and Cultural Organisation, UNESCO, is marking the International Year of Water Cooperation. Scotland has a particular responsibility here as home to some of the most pristine rivers in the UK. Scottish rivers support a range of important ecosystems that provide services that are critical to human well-being and to economic growth.

The *Scottish Rivers Handbook* makes a welcome contribution to our understanding of the processes that make rivers work. Particularly valuable is the 'systems thinking' that underpins the handbook, and the way it is used to illustrate how rivers evolve in time and space: the very essence of fluvial geomorphology. The catchment-based approach is used expertly to demonstrate the influence of the landscape, and the management of that landscape, on river flows and river health. Such understanding is a fundamental precursor to successful and lasting river management. The handbook features some excellent graphics and photographs that help explain and illustrate key processes for different river systems, and to demonstrate both good and bad outcomes of river management so that we can learn from them. I wholeheartedly recommend this book to you.

Professor Louise Heathwaite
Chief Scientific Adviser Rural Affairs and Environment
The Scottish Government

April 2013

1 Introduction



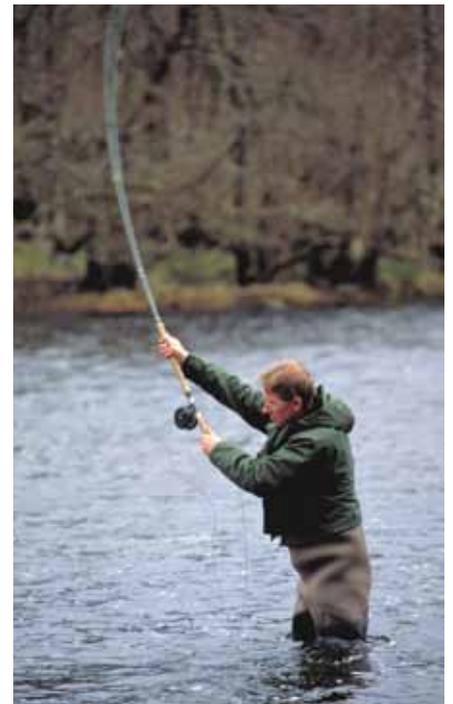
Scotland's rivers are a stronghold for the endangered freshwater pearl mussel. Their occurrence indicates a healthy river system, characterised by clean fast flowing water and pockets of gravel and sand (© The James Hutton Institute).



The Lawers hydroelectric dam in the Tay catchment, Perthshire. Catchments with hydroelectric schemes cover approximately 20% of the mainland area of Scotland (© Patrick Mackie and licensed for reuse under a Creative Commons Licence).



Kayaking on the River Pattack near Laggan in Invernesshire. The great diversity of rivers provides a wide range of difficulty for paddling enthusiasts (© Lorne Gill/SNH).



Fly-fishing for Atlantic salmon on the River Garry in Perthshire. Fishing gives a significant boost to rural economies and on the River Spey in 2003, generated £11.8 million (© Lorne Gill/SNH).

Scotland's rivers are amongst the most physically diverse and dynamic in the UK, contributing significantly to the country's natural heritage. Their importance is reflected in the variety of scientific and environmental designations designed to protect them. In return, society benefits greatly from the ecosystem services that our rivers can provide. Visitors to Scotland come to fish for salmon along the beats of the Tweed and Dee, take home Speyside whisky, and, in the past, travelled to the four corners of the globe on boats constructed on the Clyde. Scotland's rivers may not be contenders for the world's longest or largest, but after a long relationship of management and exploitation, they are iconic the world over. High quality, well-informed management, that recognises the potential value of healthy rivers, is key to safeguarding the benefits they give us.

Best practice river management can be compared to nursing in that prevention is better than a cure. Diagnosing the cause of a problem on a river is preferable to repeatedly treating the symptom. Frequently, the cause may relate to actions at another location, and it can be years or decades before problems develop. Establishing the cause of a problem relies on a sound understanding of river dynamics in the same way that nursing requires knowledge of the way the human body works. As such, effective river management and the restoration of healthy rivers, needs a long-term and river-wide perspective, based on firm scientific principles.

This handbook provides an overview of the physical character of Scotland's rivers. It introduces the different basic components: water, sediment, dead and living vegetation, which constantly interact to shape the character of the river landscape. The study of these forms and processes is the science of fluvial geomorphology. It investigates processes of water and sediment movement from hill slopes to river channels, answering questions around why rivers are the size and shape that they are, and the dynamics of their movement.

Rivers are natural conveyor belts. Silt, sand and gravel; seeds, leaves and branches, and even trees, are transported from headwaters to estuaries. However the processes are not constant. Material is mobilised, transported and deposited periodically in response to the patterns of discharge and the changing morphology of different river reaches. As such, rivers are said to be dynamic in space and time, naturally adjusting their course and character. Understanding these concepts will help the reader anticipate how and why a river responds to impacts, and to modifications of natural processes that commonly take place.

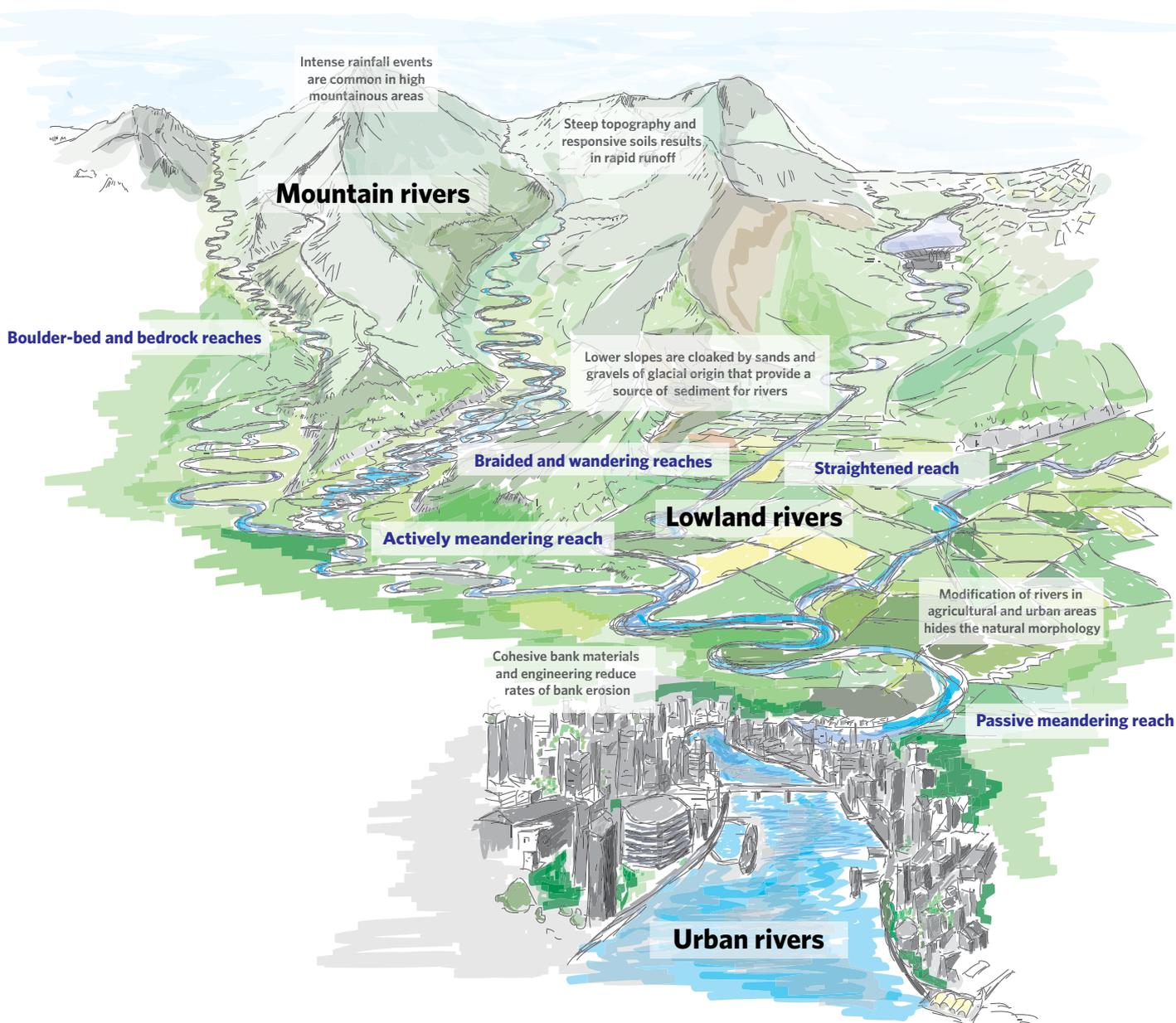
The extensive and continuing contribution of Scotland's rivers to the science of fluvial geomorphology stems from a proud heritage of scientific endeavour into areas of geology, botany and zoology. Many eminent 18th and 19th Century scientists lived and worked in Scotland including James Hutton, widely considered the father of modern geology, who recognised the importance of rivers in shaping landscapes. This tradition is being continued in the field of fluvial geomorphology with numerous world renowned scientists working in Scotland. This reflects both the academic prowess and the rich diversity of river types and landforms. It is our responsibility to maintain this tradition, improving our understanding of rivers and safeguarding our river environment.

The themes presented in this introduction are developed through the following sections of the handbook. Firstly, we consider key concepts within river science, which help explain river forms and processes, and discuss the services that rivers provide. The second section provides information and examples of the different river types found across Scotland and the ways in which we have shaped them. The third section gives an overview of river restoration, an emerging field in Scotland, and examples of how we can best manage our rivers to tackle different problems now and into the future.



**Portrait of James Hutton by Sir Henry Raeburn
(Courtesy of the Scottish National Portrait Gallery.
Purchased with the aid of the Art Fund and
the National Heritage Memorial Fund in 1986).**

2 Catchment controls



Schematic of different river types and their characteristic environmental settings introduced by this book, within a single catchment.

Climate, geology, topography, vegetation, soil type and river management all play a role in shaping the behaviour of river channels. The change in these characteristics across the country gives each of Scotland's rivers a distinctive character. Notable contrasts are caused by differences of rock type and the marked west to east divide in rainfall: average annual rainfall in Glen Quoich is 3000 mm and 700 mm in Dundee. These controlling variables also change within individual catchments and determine the nature of water stored underground or occurring as surface water in waterbodies; the catchment *hydrology*. Hydrology and the other key catchment controls listed above in turn also influence the calibre and availability of *sediment supply* in rivers.

Geology and topography

Rainwater generally runs off rapidly from catchments with 'hard-rock' geologies or areas covered by tarmac and concrete in urban zones resulting in larger floods for a given rainfall event. The steepness of a catchment as determined by its geology and glacial history, together with land cover and land management (whether, for example, undrained moorland, drained farmland or urban areas; see below), are the most important factors that control the rate at which water runs off the land. The product of stream flow and channel slope determines the *stream power* available for rivers to erode, transport and deposit material. Topography also influences the availability of sediment for rivers; the lower slopes of many valleys are cloaked with a mixture of sands and

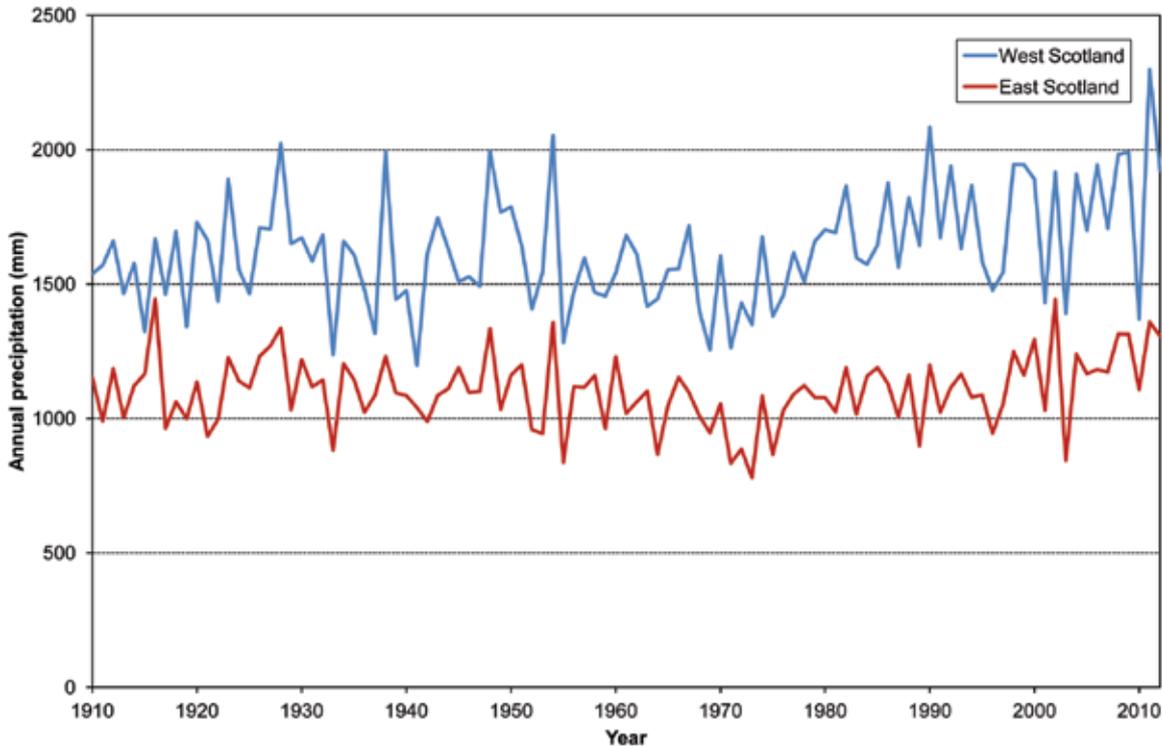
gravels – a by-product of glaciation. These have been, and continue to be, reworked by rivers to produce distinctive landforms associated with specific channel types.

Climate

Climate is directly linked to the hydrology of Scotland's rivers and its importance is well illustrated by the River Tay. The Tay, influenced by a mountain climate, is Scotland's largest and most powerful river and has more than twice the annual discharge of the River Thames despite having less than half the catchment area. Mountainous catchments prone to intense storm events create 'flashy' flow regimes compared to catchments with lower, more even rainfall.

KEY FACTS

Scotland's rivers are highly diverse, reflecting regional patterns of climate, geology, topography, vegetation and soil type. At a finer scale within individual catchments, local variability of these key controls leads to the emergence of distinctive river types.



Regional differences in total annual precipitation in Scotland between 1910 and 2012 (© Met Office, Open Government License).

Vegetation and soil type

Much of the rainfall in a catchment is intercepted by vegetation before reaching the ground. The form and density of the vegetation can in turn influence the hydrology of rivers. Most vegetation types delay the time that rainfall takes to reach the river network to some degree. Woodland and dense herbaceous vegetation significantly slow the rate of surface runoff compared to heavily grazed grasslands. Across woodland areas runoff is further reduced through evaporation of rainfall to the atmosphere from the tree canopy under certain climatic conditions. Once the rainfall reaches the ground surface the structure of the soil will affect the proportion of water able to infiltrate. Poorly drained or heavily compacted soils result in higher rates of overland flow associated with rapid rises in river level. In many catchments, changes in land use have significantly altered the nature of soil and vegetation types and runoff regimes.

River types

In response to specific combinations of catchment controls, rivers have geomorphic traits that can be used to classify *river types* at the *reach* scale. Traits include the morphology of the river bed and banks, the steepness of the channel, the river planform and how *dynamic* the reach is. Typical locations within the catchment for each river type are shown in the schematic

overleaf, but deviation from this idealised downstream sequence is common due to variation of the landscape topography.

Upper catchment

Mountain headwaters are strongly influenced by the boundary material and vegetation. In peatlands with high annual rainfall, the channels can cut deeply into the peat, but the generally low gradients in these areas mean such channels are low energy. Where channel gradients are high or bedrock is close to the surface, high energy bedrock channels develop. Stream beds covered with boulders are associated with cascade or step-pool channel morphologies.

Mid catchment

Stream power tends to be highest in the mid catchment after the confluence of a number of tributaries but where gradient continues to be high. Under these conditions gravel-bed *wandering* and *active meandering* channels migrate across the floodplain through the processes of bank erosion and deposition of point bars. Where the valley gradient flattens out, rivers transporting a large amount of sediment develop a *braided* character as the transport capacity falls in response to reduced stream power. In lower sediment supply conditions or where confinement by valley sides is greater, relatively straight *plane-bed* and *plane-riffle* reaches occur.

Lower catchment

Stream power declines further when rivers reach the low gradient, wide valleys of the lowlands and carselands. As a result, the sediment load becomes increasingly finer but still dominated by gravel. Where uncohesive banks occur the energy of the river may be sufficient for an *active meandering* morphology to develop and adjustment of meanders creates important river corridor habitat. Where cohesive clay banks dominate, the channel is more stable and rivers have *passive meandering* morphologies.

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3 River dynamics and morphology

The spectacular diversity of Scotland's rivers partly reflects the fact that three of the key controls on river form – topography, geology and climate – vary considerably. These catchment level controls determine the rate at which water and sediment are supplied to the river and in turn river form. In addition to these controls, the local channel slope, width and boundary materials further control the shape (i.e. morphology) of a river at a given location. A useful way to understand how energetic a river is, how it was formed and how it might behave in the future, is to consider its stream power. **Total stream power** is a statement of how much energy is contained within the volume of water flowing past a particular location as it is accelerated by gravity down the slope of the river bed. If the total stream power is then divided by the width of the river, it is possible to work out **unit stream power**, which reflects the actual conditions on the river bed. If the river contains little flow but is narrow, it may have a higher unit stream power than a very wide river with much more flow. The power of the river channel is counteracted by the resistance of the bed and banks to erosion. Cohesive bank material, riparian vegetation and coarse riverbeds all increase resistance, therefore reducing the influence of stream power. Different river types have different combinations of stream power and resistance factors.

Along the course of a river, the relative contribution of factors that influence stream power and resistance changes. This produces different channel morphologies with varying levels of channel stability. Rivers follow a general pattern of increasing catchment area and decreasing valley slope moving from the headwaters to the estuary. The result in a simplified river catchment would be a continuum of channel morphology. However, to aid understanding and management, reaches are categorised according to their characteristic morphologies. Along the stream network, the river type may change gradually over kilometres or suddenly as a 'step change' over a few metres. Local topography, river confluences and boundaries between drift geologies (material overlying solid bedrock) are associated with either a change in stream power or resistance producing sudden changes in river morphology.

The interaction between stream power and channel resistance changes with water discharge. The morphology of rivers is often therefore described as being in

dynamic equilibrium. Material entrained and transported during periods of high stream power is replaced by deposition of transported material as floods recede and the capacity of the river to transport sediment falls. In this way, the size, number and precise location of fluvial features within a reach may fluctuate over time, while the general character of the reach is maintained.

In-stream management is often undertaken in response to very large rare floods that cause significant visible changes, but it is the influence of smaller frequent floods occurring every few years that cumulatively have the greatest role in determining the size and shape of the channel. The size of these bankfull floods events, referred to as 'channel forming flows', may change over time in response to flow regulation, land management practices and climate patterns.

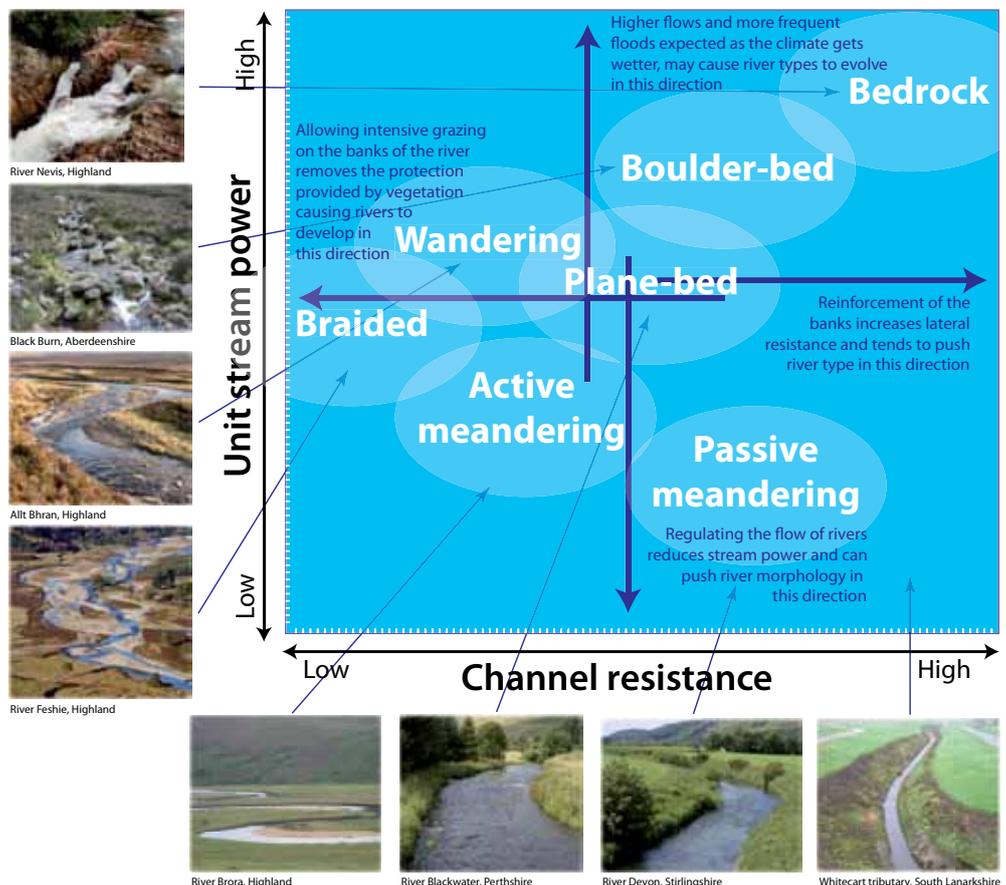
Stream power, channel resistance and sediment transport

The balance of stream power and channel resistance shape channel morphology by influencing the size and volume of sediment that can be transported. Reaches of high stream power and low resistance tend to be a source of sediment to the stream network. Erosion processes in these reaches, excavate

sands, gravels and cobbles from the river bed, banks and valley sides. There is a net movement of gravel from the river valley into the channel followed by export to the downstream river network during flood events. These reaches tend to be highly dynamic with large expanses of exposed gravel. High stream power, high resistance reaches tend to be zones of sediment transfer. The resistance of the bed and banks prevents the entrainment of new sediment and stream power remains sufficient to transport sediment out of the reach. The movement of material may be highly dynamic while the reach morphology remains stable if the input and export of sediment is balanced.

The frequency of bed mobilisation in rivers relates not only to the occurrence of floods (stream power) but also the bed material size. Areas of the riverbed with larger cobble and boulder material are relatively resistant to high stream power and are infrequently mobilised. Finer material, mobilised by smaller floods, is transported more often and moved further, with the very finest sands and silts regularly transported into the lowermost reaches of the catchment.

Reaches of reduced stream power and low resistance tend to export sediment from the river channel back to the landscape. They



Distribution of key river types in relation to different combinations of unit stream power and channel boundary resistance (images © The James Hutton Institute, Centre for River Ecosystem Science and SNH).

KEY FACTS

The morphology of a river depends on the balance of stream power relative to the resistance of its bed and banks. The distribution of river types is further dependent on the spatial and temporal changes of stream power that determine the volume and size of material that can be transported.

Change in stream slope

Sudden changes in stream power occur where steep headwater channels flow onto the valley floor. The sudden drop in channel slope reduces the stream power available to convey material. Sands, gravels and boulders are deposited creating extensive areas of exposed gravel habitat.



Deposited material where the steep headwaters of Glen Ogle reach the valley floor.

Change in discharge

At the confluence of two rivers the combined discharge produces an increase in stream power. This can lead to a change in stream type below the confluence, even without a change in valley slope. Confluences are naturally dynamic because of the flow variability of the two channels is combined.



The development of a multi thread channel below the confluence of two single thread channels, the Allan Water and Muckle Burn.

Change in geology

Where there is a change in the drift geology, such as from unconsolidated sandy soils to cohesive coarse clays, the resistive properties of the riverbed or banks change. The channel responds differently to the stream power resulting in a change in the river morphology or the stability of the channel.



A bedrock outcrop on the River Clyde. A bedrock channel type exists above the waterfall but the river adopts a pool-riffle morphology below.

Examples of locations in the river network where changes in stream power or channel resistance produce sudden changes of river type (images © Centre for River Ecosystem Science).

can be considered as 'sediment sinks' and represent a net loss of sediment from the river network. Sediment is transported into the reach faster than it can be exported, leading to the accumulation of sediment over bars and islands. As these deposits rise and the influence of the river lessens, vegetation encroaches and floodplains form. Individual reaches may fluctuate between eroding and depositing states as the stream power changes, either due to deposition of gravel changing the channel slope or changes in discharge due to climatic variation.

The influence of low stream power during low flow and drought periods may be less obvious but is still important. Finer sediments may still be gradually reworked and deposited and the low levels of disturbance can give vegetation an opportunity to establish, reducing erosion and channel size. Plants play an important role in stabilising stream features and can significantly alter the morphological response to large floods.

Changing the stream power

Widening

Increasing channel width, with the aim of accommodating larger floods, causes a reduction in unit stream power. This is likely to result in deposition of material and aggradation of the riverbed. As the channel reverts back to its natural width, the development of mid-channel gravel bars can deflect water towards riverbanks creating localised erosion in locations that were previously stable. This in turn is likely to increase processes of channel movement and adjustment.

Narrowing and deepening

Increasing the depth of a channel by dredging or reducing its width, increases the unit stream power as more water is conveyed per metre width of channel. The increase in stream power is likely to lead to further deepening and increased sediment transport. Problems associated with aggradation may develop at locations downstream where the sediment is redeposited.

Straightening

Straightening a channel by cutting off meanders increases the channel slope. This raises the stream power and can result in the export of sediment, deepening of the channel and increased riverbank slumping. Within the straightened channel, the natural tendency of flow to follow a sinuous course will trigger erosion and deposition processes and over time the channel will start to regain some of its natural planform. The transported sediment may be deposited downstream causing further issues associated with aggradation.

Alteration of discharge

Flow regulation associated with dams and abstraction reduce the magnitude of flow, which in turn can reduce stream power. This can lead to reduced sediment transport capacity and competence. Over time this may lead to a gradual stabilisation of dynamic river features such as bars and eroding banks as they are colonised by vegetation. The opposite effect may occur where land use changes create a more responsive catchment system that increases run-off and in turn boosts stream power, leading to increased channel activity.

Changing the channel resistance

River bank protection

Reinforcing the riverbanks of meandering channels increases lateral resistance to erosion. Depositional processes will continue on the inner bank with the effect of narrowing the channel and increasing unit stream power. This causes excessive scour and deepening on the outer bend potentially undermining the bank reinforcements. The effect can continue downstream, causing lateral erosion where it did not previously occur.

Removal of bankside vegetation

Tree and shrub vegetation bind river bank soils, increasing their resistance to erosion. When vegetation is removed or heavily grazed and trampled, the resistance properties are reduced leading to greater vulnerability to erosion. Bank erosion can cause river widening. The increased width is likely to result in the deposition of gravel bars and aggradation of the riverbed as the stream power is reduced. The development of mid-channel bars can divert water towards riverbanks creating localised erosion in locations that were previously stable.

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4 Timescales

Implicit in the dynamic nature of rivers is the fact that their morphology responds to environmental fluctuations. Rivers are constantly responding to the changing input of water and sediment from year to year and from decade to decade. Over a defined period of time, if the inflow and outflow of sediment into a reach are in balance, the result is an **equilibrium** condition whereby the basic morphology is maintained. Over long timescales, there may be an imbalance of these processes resulting in a gradual change of morphology that may not be easily noticeable. In contrast, a major flood or input of sediment may lead to a geomorphic threshold being crossed and a rapid, obvious shift in morphology. Because of the complexity involved, separating temporary adjustments from changes related to long-term trends can be difficult. Consideration of timescales is therefore fundamental to understanding river ecosystems.

The following observation, by the writer Henry Coates of Dunkeld following the River Tay floods of 1903, conveys the importance of a river's response to an individual flood event and their ongoing evolution over a longer period and the benefits this natural behavior brings: *"It must be evident that, after a catastrophic occurrence such as this,*

the river, if not interfered with by man, has a large amount of fresh material to work upon and to redistribute in the orderly sequence which it always observes. Thus the river, which becomes to us a living force, spreading its influence from side to side of its valley never at rest, but ever at work preparing a fertile soil for the vegetation, which is at once the glory and protection of the valley floor, and the main source of subsistence for man and beast".

Timescales of adjustment

Months (0-1 year)

The geomorphic response to frequent high-flow events tends to be restricted to in-channel habitats. These flows may occur every month or so and tend to be concentrated in the spring and autumn months. They scour and sculpt fluvial features, altering their shape and size from month to month. Over many millennia, riverine plants and animals have developed both morphological and behavioural adaptation. Many organisms have life cycle stages linked to these events, such as salmonids that use the more frequent high-flow events to get past obstacles in order to reach the shallow burns and rivers in the upper catchment to spawn.

Years (1-10 years)

In unregulated rivers the highest flow of the year will vary from one year to the next. In some years it will be contained within the channel, while in others it will inundate the full extent of the floodplain. The **mean annual flood** describes the average across a number of years. A flow event approximating the size of the mean annual flood is expected to return every few years (2.3 years on average). On natural rivers it is these relatively frequent events that determine the size of the channel. During these events, erosion of a riverbank may be balanced by deposition during the same or subsequent floods, resulting in minor adjustments to the course and a redistribution of sediment, while overall maintaining channel size and form.

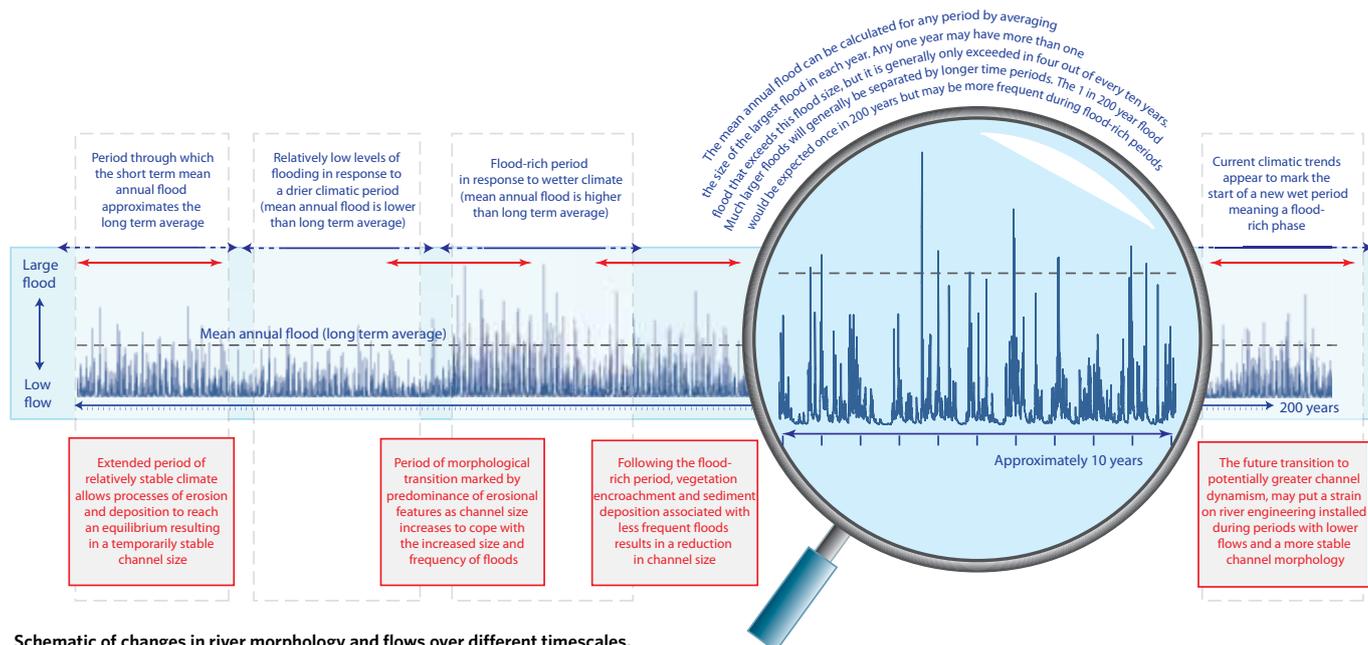
Very active river forms such as dynamic braided reaches, may change course a number of times within this timescale. Colonisation by terrestrial vegetation, which requires a period of substrate stability, is prevented by the rapid adjustments, adding to the mobile character of the reach. Smaller changes to the course of a river through meander migration may be seen on moderately active types.

	DAYS	MONTHS	YEARS	DECADES	CENTURIES	MILLENNIA
River flow	River water level changes in response to rainfall events and evapotranspiration	High flows tend to be 'bunched up' into wetter months	Bankfull flows return every few years	Shifts occur between 'flood-rich' and 'flood-poor' phases	Highest water levels are during the largest floods separated by hundreds of years	
Vegetation	High-flow events may remove vegetation from banks and bars	Density of riparian vegetation responds to seasonal patterns of flow	Clearance of riparian vegetation may occur as part of annual management	Areas of the riparian zone develop to maturity over a number of decades	Community changes in response to climatic changes	
Sediment	Very fine sediment transported in suspension under all flows. Bed grain size changes can be rapid		Floods returning every few years shift and sort sediment within the channel	Average life span of a gravel bar	Very large floods shift large sediment volumes and may significantly alter channel character	Material of glacial origin is transported from the uplands to the lowlands
In-stream wood	Management can rapidly clear a river of in-stream wood		In-stream wood structures may persist before eventually breaking down	New sources of in-stream wood may take decades or more to develop		
Channel form		Small frequent floods scour and sculpt fluvial features which may evolve over a number of months		Channel size is a gradual response to the series of floods that return every few years	Channel gradient changes in response to alteration of sinuosity	Changes to valley gradient, width and in turn channel morphology are very gradual
Planform			Small adjustments and meander enlargement through bank erosion and gravel deposition	Active channels may adjust their planform and switch course during large infrequent flood events	Planform pattern type may change gradually (e.g. braided to single thread, meandering)	
River type			Occasionally channel type can change over a few years in response to major disturbances	Channels fluctuate between more and less active states	Channel types evolve gradually in response to climate and land use change	Bedrock reaches change shape very slowly due to high boundary resistance
Biota	Oscillation of high and low flows determine where living organisms choose to find refuge	Lifecycle stages are triggered by seasonal patterns in river levels		Changes to riparian and in-stream habitat features affect flora and fauna community structure		Species have gradually adapted to the natural, physical habitat template of river systems

A timeframe for different events and processes related to river ecosystems in Scotland.

KEY FACTS

The different types and magnitudes of physical changes in rivers and the ecosystems that depend on them, operate over a variety of timescales. Rivers can evolve in response to natural and human-induced changes whether recent (years) or long-ago (decades to centuries).



Schematic of changes in river morphology and flows over different timescales.

Management plans are often implemented over these timescales, although the full response may be much longer, most notably where restoration of ecosystems is involved. Damage done over a few years may take many decades to restore.

Decades (10-100 years)

Even under stable climatic conditions it is typical for the frequency of large floods to vary from one decade to the next. This can result in adjustments to river size and morphology. As the river enters a flood-rich period, the size of the mean annual flood will increase. The balance between erosion and deposition will tip in favour of erosion, adjusting the channel size to accommodate the increased flows. As flood frequency falls after a flood-rich period, vegetation encroachment and deposition processes begin to dominate. Smaller floods provide an opportunity for terrestrial plants to recolonise flood deposits, reducing channel width until the erosion-deposition balance is restored. This variability is independent of long-term trends in climate, despite appearing to be new over the timescales that river management is undertaken. Flood-rich periods may be separated by a number of decades.

Visible adjustment to the course of moderately active rivers, such as active meandering and wandering channel types, may also occur within this timescale. Significant changes tend to be linked to large floods expected only a few times each century.

In-channel features for example, jams of dead woody material, may be transient when considered over the timescale of 10-100 years. A jam may persist for several years providing habitat to a range of species, before

eventually breaking up. The amount of dead woody material in a reach and its persistence depends on the rate of decay and replenishment of material. Where extensive riparian woodland is present, a high density of such accumulations can occur. Frequently, in Scotland, these woodlands have been removed resulting in less in-channel wood storage than would naturally occur. The long life span of trees means restoration of sources of in-channel wood, such as a fully mature riparian zone, may take many decades.

Human modification and management will cause rivers to evolve towards a new state. The response can be gradual and it may not be obvious that subsequent changes to the river were caused by such work. Such actions may actually increase river instability rather than reduce it when viewed over one or two lifetimes.

Centuries (100-1000 years)

The largest floods are separated by hundreds of years of lower flows and smaller floods. Very large or extreme floods can significantly alter the character of a river, even those sections that have been stable for several lifetimes. These rare events can result in disturbance to habitats, realignment of planform and transport of vast volumes of sediment.

As discussed at the beginning of the book, river type is generally controlled by catchment scale factors, which include climate. A shift from one river type to another therefore often occurs over similar timeframes to climatic changes. In Scotland our rivers have continually evolved over 10,000 years since the last glaciers melted, in many cases shifting material of glacial origin

from the uplands to the lowlands, or into 'U-shaped' valleys where transport may be interrupted by low gradient channels and wide floodplains.



High water marks of River Tay floods inscribed on a pier of Smeaton's Bridge in Perth. Flow gauging on the Tay only dates back to 1952 but historical evidence can be used to put the magnitude of modern day flood events in a longer term context (© The James Hutton Institute).

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5 Linkages

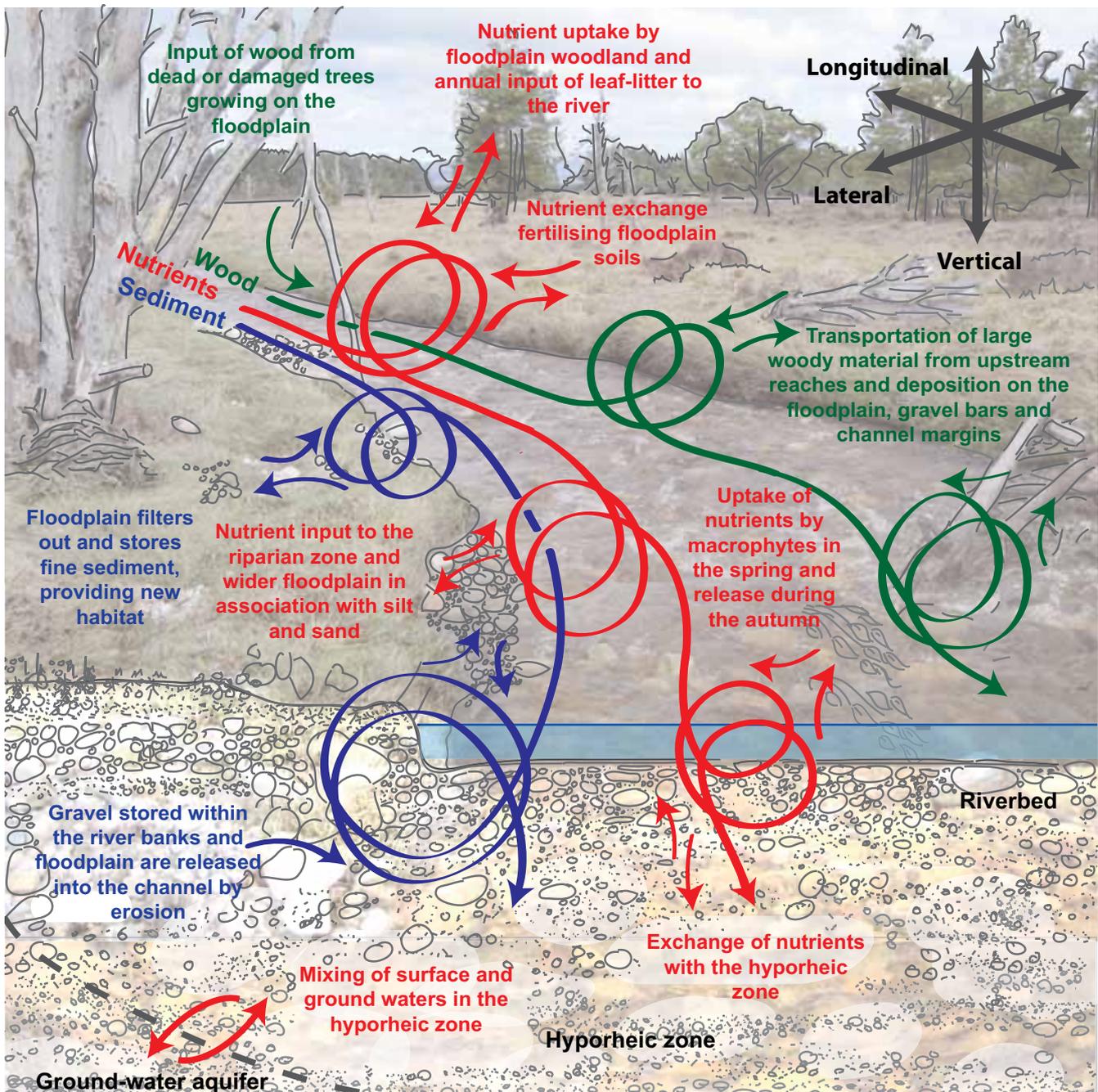
River ecosystems are highly connected at a range of spatial and temporal scales through the exchange of water, nutrients, sediment, particulate organic matter and dead woody material. In a healthy system, connectivity exists in three dimensions: longitudinally linking upstream and downstream reaches; laterally linking the river channel to its riparian zone and wider floodplain; and vertically between the water column, river bed and underlying gravels of the hyporheic zone. Understanding these linkages is key to understanding river ecosystem processes and the manner in which rivers respond to different management pressures.

Longitudinal linkages

The transport of sediment from a point of erosion to a bar downstream, leaves floating downstream from a forested section and a salmon swimming from an estuary to spawn in the upper part of a catchment, are all recognisable longitudinal linkages in a river system. These links naturally extend the full length of the river continuum in both up and downstream directions, highlighting the importance of considering processes at a catchment level.

An appreciation of longitudinal linkages in rivers and the regular change in morphology from headwater to estuary, led to the development of the River

Continuum Concept in the early 1980s. This model provides a simplified view of the river ecosystem that demonstrates how events in the upper catchment are connected through a chain of links to ecosystem functioning lower in a catchment. For example, as leaves are washed into an upland burn, they provide a food resource for aquatic fauna further downstream. As these gradually break down during their transport downstream, their availability as a food resource changes. Initially leaves provide a substrate for microbial activity, then leaf fragments provide food for detritivores such as some invertebrate and fish species, before being small enough to be trapped by filter feeders and ultimately providing nutrients for the



Examples of vertical, horizontal and longitudinal linkages fundamental to sustaining a healthy river ecosystem. Red arrows signify nutrients, green arrows signify woody material and blue arrows signify sediment fluxes.

KEY FACTS

Beyond the natural ecosystem linkages now so apparent in rivers, the importance of linking people and rivers is becoming increasingly well known - healthy rivers are likely to create healthy lives.

estuarine salt marshes that help protect Scotland's coastline.

Longitudinal linkages may be readily broken through management actions and the effects may not be immediately obvious or close to the cause. For example, dams built during the 1950s that interrupt the movement of sediment and water, may have a gradual but long-lasting impact on the extent and quality of habitat used further downstream by spawning salmon through channel narrowing and siltation of gravels.

Lateral linkages

Lateral linkages concern the exchange of elements between a river, its riverbanks and

the floodplain. Although there are obvious examples, such as the deposition of flood-borne sediment on a field, there are many equally important but less visible linkages, such as the exchange of nutrients and fine organic matter. Key to a healthy river reach is the correct balance of exchange. Poor land management techniques can result in a unidirectional movement of nutrients and sediment from the terrestrial environment into the river. Unhindered lateral connections in both directions can be linked to wider benefits for both ecosystems and humans. The storage of water, trapping of sediment and uptake of nutrients in adjacent terrestrial habitats has the potential to alleviate flooding, sedimentation or eutrophication



The River Spey and the inundated Insh Marshes, near Aviemore, Invernesshire. The Insh Marshes act as a temporary storage zone for floodwater that benefits wetland habitats and reduces flood risk downstream (© Iain Thompson and licensed for reuse under a Creative Commons Licence).



The upper River Spey at Laggan, 5 km downstream of Spey Dam in 1946 (four years after dam construction) and in 1995. Narrowing of the channel and stabilisation of previously active gravel bars are linked to a history of upstream flow regulation and straightening (© Centre for River Ecosystem Science).

pressures downstream. The physical nature of the channel margins, the vegetation present and the frequency of inundation, all strongly influence the degree of lateral connectivity. Low bank height allows frequent inundation of the riparian zone and floodplain. These disturbances can strip out patches of vegetation and deposit nutrient-rich sediment, providing new colonisation opportunities and resulting in diverse terrestrial vegetation communities. Where greater structural complexity of bank morphology and mature trees are present, river dynamics and morphology in the river corridor are more varied, further driving habitat diversity. Riparian trees and other vegetation also link more directly with the river through the uptake of nutrients and the delivery of leaf litter and dead woody material.

Embankments designed to reduce flooding are extensive on major Scottish rivers, causing potential loss of lateral exchange. The reconnection of a river to its floodplain may reduce the productivity of farmland, but can offer tangible benefits not only for enhancing biodiversity and water quality, but also for reducing flood risk downstream. For example, flood storage provided by the Insh Marshes in the Spey Catchment creates an estimated average annual saving of £83,000 in downstream flood damages.

Vertical linkages

Rivers are also connected vertically through the exchange of sediment and organic material between the water column and the bed. A less obvious connection occurs with the hyporheic zone where surface and ground waters mix beneath the river bed. Although less well understood, the hyporheic zone is known to have important ecological implications for stream fauna. Gravel bar and riffle features direct flow into the hyporheic zone, providing oxygenated water and nutrients, extending suitable habitat for invertebrate fauna and providing a refuge from predators and high flows. A similar effect is created by the morphology of salmon spawning pits, known as redds, which direct flow through gravels reducing siltation and delivering oxygen to developing fish eggs.

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6 Defining and assessing river health

Defining river health

The concept of river health allows us to think about rivers in the same way as we do the human body. Analogies can be drawn between the two, helping us understand the pressure-response relationship that various approaches to management can have on the freshwater environment. As elements of the river get damaged or removed, not only is the function that they provide lost, but the function of associated ecosystem elements may become impaired, reducing the overall well-being of the system. Furthermore, individual pressures on the river ecosystem may be of limited consequence, but the cumulative effect of multiple pressures may lead to severe loss of function and service. A river where all the interconnected elements of the ecosystem are in good condition and able to function naturally is likely to support the many benefits that society derives from our rivers. A critical component is the presence of natural fluvial processes, discussed throughout the book, that sculpt the river channel and sustain the diversity of river habitats.

Measuring river health

Assessment of river health is useful for predicting future problems, checking compliance with legislation, prioritising management options and for monitoring restoration. Measurement may be a direct measure of well-being akin to a blood test or bone x-ray. Tools include SEPA's Morphological Impact Assessment System, Fish Barrier Assessment Tool, analysis of water chemistry, fluvial audits and flow duration curves. These all assess the underlying factors that support a healthy river system, i.e. physical habitat, water quality and river flow. Measurement may also be diagnostic, basing assessment on indicator organisms and communities. Low salmon numbers may be symptomatic of simplified stream morphology or low oxygen levels. Aquatic insects can be used to assess water quality issues caused by chemical pollution and nutrient enrichment. These approaches would be equivalent to measuring blood pressure or calculating a body mass index.

Whether the health of rivers is measured with regard to its physical condition, the natural biota present or the ecosystem services it is able to provide, the underlying health issues are likely to remain the same. All approaches have a role in informing, guiding, regulating and appraising river management options, and commonly a combination of tools will be used.

Valuing river health

The value of maintaining healthy river networks across Scotland is most easily interpreted in terms of the 'service' that river ecosystems can provide to society. Biodiversity, flood storage, salmon fishing, water sports, drinking water, hydropower, and disposal of effluent are all ecosystem services potentially affected by river health issues. These services have social and economic value. For example, biodiversity, or amenities supported by habitat diversity, may be valued in terms of human well-being or tourism. Flood storage enabled by connection of the river to the floodplain may be valued in terms of the cost of potential flood damage downstream.

Protection

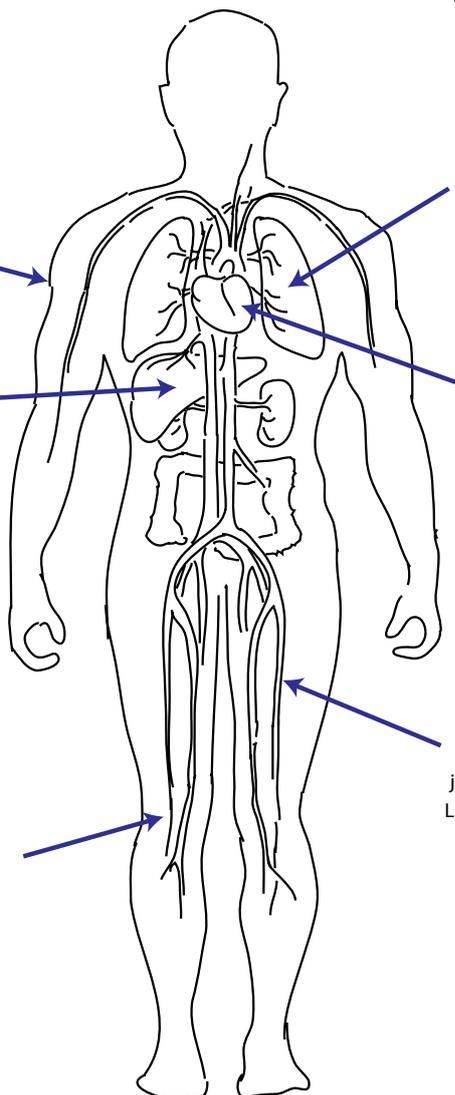
A healthy river can be protected from pollutants by the riparian zone in the same way that skin provides a barrier to disease. The width and diversity of the riparian zone is key to the provision of an effective buffer. Where vegetation is removed, habitats are lost and water quality may be affected.

Purification

Our liver and kidneys provide an important role in removing toxins. Rivers also have some capacity for self purification. Riffles can re-oxygenate water. Vegetation can take up excess nutrients. Riparian tree shading helps cool water down. Individually these factors may have little obvious effect but together they increase the resilience to external impacts.

Structural support

The human body has a skeleton to provide structural support that allows organs to function. The structure of a river is provided by the morphology of the bed and banks, and by large pieces of wood. These deflect flow and shape the river, diversifying the habitats present, and promoting ecological processes.



Breathing space

Space to breathe is an important aspect of river health. Constriction of rivers to a single thread with high, uniform banks is one of the most widespread pressures on Scottish rivers.

Regulation

Flow is regulated by human activity in some form on many rivers. Although this is undertaken for benefits such as hydropower generation, river health can be severely affected. River habitats and biota respond to natural patterns of flow and the pulse of floods. This needs to be considered when planning compensation flows.

Circulation

Blood vessels need to convey more than just blood cells to keep the body healthy. Likewise, healthy rivers convey more than just water. The transport of sediment, nutrients, wood and organic matter across the landscape are all essential to maintaining high ecological condition.

Concepts of human health can also be used to help us understand some of the many factors that contribute to a healthy river ecosystem.

KEY FACTS

River health can be thought of in terms of the ability of a river to deliver the range of natural ecosystem functions and services which can be assessed using a number of methods. Over centuries, human actions have led to a steady reduction of river ecosystem functions and services.

Riparian zone	Meanders	Riffles	Dead and live wood	Backwaters and pools	Exposed bars and berms	Wide river corridor
<p>Vegetation along the river corridor filters out sediments, some pollutants and may take up nutrients. Roots bind the riverbank sediments and provide erosion resistance. The riparian corridor provides a network of linked habitats where animals can shelter, feed and migrate.</p> 	<p>Meandering rivers are longer than straightened channels. This increases the time that water takes to flow downstream. Channel habitat area is greater.</p> 	<p>Turbulence created by riffle features helps to oxygenate the water, essential for creatures that live in the channel. The flow through the gravels also creates conditions that support egg development in salmonids and other fish species.</p> 	<p>Tree trunks, branches and twigs interact with the flow, introducing hydromorphic diversity. Dead wood provides a substrate for insects and offers shelter to small fish. Debris dams trap sediment, slowing its movement downstream. Live trees re-root, stabilising dynamic gravel bar habitats.</p> 	<p>Side channel features increase habitat availability. Areas of still and slow flowing water provide refuge for animals during floods. Pools provide resting habitat for larger fish and other organisms. Fine sediments that settle out provide habitat for juvenile lamprey.</p> 	<p>Deposition of sediments provides fresh habitat for pioneer vegetation including many rare plants. Open areas provide sunny habitats for insects and reptiles.</p> 	<p>A wide and diverse river corridor increases habitat availability and complexity. More area is available for flood waters.</p> 
<p>Service Improved water quality. Enhanced biodiversity. Reduced maintenance.</p>	<p>Service Flood peaks in the lower catchment are delayed and dampened.</p>	<p>Service Improved water quality. Increased salmonid populations. White water for rafting and canoeing.</p>	<p>Service Enhanced biodiversity. Reduced sediment conveyance.</p>	<p>Service Flood water storage. Enhanced biodiversity. Conservation of rare species.</p>	<p>Service Sediment storage. Enhanced biodiversity.</p>	<p>Service Flood water storage. Enhanced biodiversity. Reduced management.</p>

Examples of ecosystem functions and services provided by an upland river in a healthy condition.

These assessments are undertaken by economists and can be balanced against the river restoration and management costs by using a cost-benefit analysis approach. Improvements to river health could, where land owners and managers are willing, involve the return of land to the river corridor to provide habitat space for a buffer zone of riparian vegetation. The costs, including conversion of farmland to riparian woodland, can be compared to the benefits in terms of improved water quality and reduced water treatment for drinking water.

Regulating river health

Efforts to improve the health of Scotland's rivers are being undertaken through Controlled Activities Regulations (CAR).

This requires the licensing of activities that may put pressure on river health and describes general rules governing river management, in order to safeguard the ecosystem services that they provide and the diversity of species they support. The river health analogy has advantages over concepts of naturalness because the focus is on ecosystem function. Knowledge of the natural condition of Scottish rivers prior to human disturbance is obscured by centuries of land management, river engineering and flow regulation. Such activities were particularly prevalent in lowland areas, meaning examples of rivers in a natural 'reference condition' are difficult to find and making management guidance using 'naturalness' problematic.

From a regulatory perspective, the health of rivers is considered in terms of ecological status. Measurements of a range of morphological, physicochemical and biological parameters are used to grade rivers into five ecological status categories from bad to high. Measures for restoring health and achieving good or high ecological status are planned for the rivers in Scotland that are at moderate status or lower. Across Europe, all countries signed up to the EU Water Framework Directive have the same obligation.

Year	Class					Proportion good or better (%)
	High/maximum (%)	Good (%)	Moderate (%)	Poor (%)	Bad (%)	
2007	8	40	31	16	5	48
2008	8	46	23	15	8	54
2009	7	47	24	15	8	54
2010	8	48	23	15	8	54

The ecological condition of rivers in Scotland as monitored by SEPA between 2007 and 2010. Assessment is based on biological, water quality, hydrology, morphological status and river continuity factors.

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7 Wood in rivers

The importance and function of wood in rivers

Dead wood and the riparian woodland that supports it are essential elements of Scotland's rivers. Dead wood includes tree trunks, branches, stumps and roots which may occur as single pieces or can coalesce to form jams that may span the entire width of a channel. Often referred to as large woody debris, these in-stream features play an important role in many ecosystem processes key to sustaining river health. Dead wood may fall directly into the watercourse as a result of old age, bank erosion or storm damage and can be dislodged during floods.

A number of factors have led to a reduction in the amount of wood present in Scotland's rivers. Widespread clearance over the last 5000 years has undoubtedly reduced the extent of riparian forest and in turn the sources of material. More recently it has been common practice to remove accumulations of dead wood because of the perceived impact on navigation, fish migration and the risk of damage to infrastructure. This has directly led to a reduction in the ecosystem services that rivers are able to deliver. Recent research is increasing the evidence base of the role of in-stream wood in a range of channel types and its influence on river forms, processes, habitat and biota. Its importance is increasingly being recognised by river managers. Indeed it has been argued that in-stream wood (and source riparian woodland) is as important as natural patterns of flow and sediment supply for determining the vitality of river systems.

In-stream wood serves a number of ecosystem functions. Bark surfaces provide habitat for the attachment and growth of aquatic plants and invertebrates. The increased hydraulic roughness in channels diversifies flow velocities and depths, creating hydraulic conditions suitable for a range of fish species and other aquatic organisms. The flow variability introduced by accumulations of wood alters the patterns of sediment transport; they may create areas of slack water where fine sediment accumulates and areas of scour at the margins of woody obstacles that coarsen the substrate. The net effect of these processes is a greater variety of freshwater habitat.

Management applications for in-stream wood

Where streams have been cleared of naturally occurring dead wood and riparian woodland is limited, the placement of trunks and branches can be used as a technique to rehabilitate streams. Features may be positioned at random, in ways that mimic natural log jams, or designed to create the maximum diversity of habitats.

Wood can also be used to manage natural hazards that pose a threat to property. Logs anchored to the bank toe, or tree trunks positioned around the outer bend of a meander, are ecologically sensitive and less visually intrusive methods of protecting eroding banks than the more traditional concrete revetments or gabions. When undertaken correctly, this also has the potential to enhance stream habitat. The damming effect of log jams can help to slow the flow and divert water onto floodplain areas, providing temporary storage and reducing the flood

risk downstream. The opposite may be true where wood accumulates at bridges or culverts causing reduced conveyance and in turn greater flood risk for local properties and infrastructure. In such cases, regular removal may be necessary.

The placement of wood into Scottish rivers is yet to be widely adopted as a management or restoration practice. However, given the considerable weight of scientific evidence supporting its positive contribution, the use of artificially placed wood is likely to become more common and should always be considered as a preferable alternative to hard engineering. A trial introduction of the European beaver to parts of Scotland was initiated in 2009, and the effects of riparian felling and dam construction on stream ecology are being monitored over a five-year period. Depending on the outcome of the trial, the potential exists for beavers to be introduced into areas with abundant riparian woodland to naturally enhance river habitats.



Some examples of naturally occurring dead wood in the River Nethy, Invernesshire (© Centre for River Ecosystem Science).

KEY FACTS

In-stream dead wood and the riparian woodland that support it are key components of a healthy river ecosystem. Wherever possible, dead wood should be left in place.



Large amounts of dead wood in a river may appear untidy but they form an important natural component that supports habitat and biodiversity in a range of ways (© Centre for River Ecosystems Science).



A channel spanning accumulation of dead woody material in the Logie Burn, Aberdeenshire. Such accumulations can force the creation of a pool upstream and filter the water of fine suspended sediments (© The James Hutton Institute).

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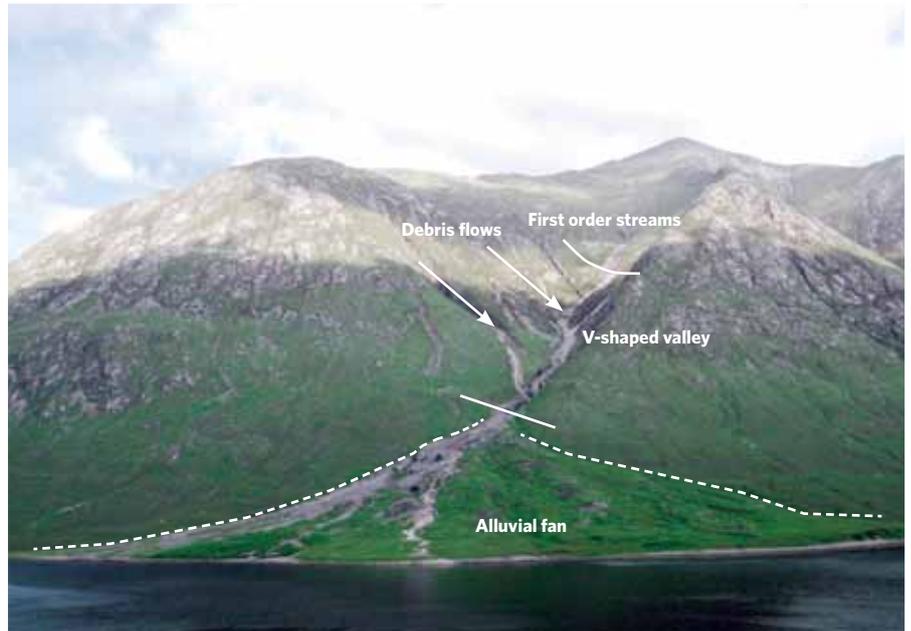
8 Mountain rivers

Mountain rivers can be broadly divided into steep, confined headwater and low gradient, unconfined mountain valley (or 'piedmont') systems. The character of today's mountain rivers strongly reflects the legacy of different phases of landscape evolution. The current river topographies are related to pre-glacial episodes of tectonic and volcanic activity that built the mountains, and subsequent erosion triggered by phases of tectonic uplift or climate change. At a lower altitude, the major valleys that dissect the uplands today were initially formed through the exploitation of weaker bedrock by weathering and the erosive action of rivers over millions of years. During the ice age, successive phases of glaciation etched this ancient landscape. At high levels, slopes were steepened and corries were excavated; at lower levels, ice streams widened the major valleys and deposited material. In some cases the configuration of the pre-glacial river network was completely altered. For example, the current upper reaches of the River Feshie previously flowed into the River Dee but were diverted by glacial deposits during the last glaciation. Finally, the huge release of glacial sediment and water that heralded the start of deglaciation about 18,000 years ago, had a lasting effect by sorting and depositing material and sculpting gorges in the bedrock.

Since deglaciation, unstable sediment on hillslopes that characterise steep headwater zones has been reworked by landslides, debris flows, rivers and deposited in alluvial fans. In lower gradient valley bottoms, fluvio-glacial stores of material have been incised, laterally eroded and re-deposited by rivers to create floodplains and terraces. Mountain valley rivers are dominated by a gravel substrate derived from these landforms, but coarser substrates occur where steep tributaries join or where a river erodes glacial landforms and hillslopes.



Exposed and eroding terrace bluffs composed of fluvio-glacial material deposited during deglaciation, form a major source of coarse sediment for mountain valley rivers (© The James Hutton Institute).



A steep headwater stream system on the west flank of Ben Starav (1078 m) draining into Loch Etive, Argyll and Bute (© The James Hutton Institute).

Superimposed on this template, natural vegetation patterns and human activity have an influence. The combination of these factors in turn creates diverse morphology in mountain rivers that sometimes changes suddenly in response to local geomorphic controls. For example, mountain valley rivers are often interrupted by sudden confinement and steepening where bedrock is exposed, such as the meltwater gorge of Randolph's Leap on the River Findhorn. These interruptions are often marked by waterfalls and result in 'stepped' river profiles, variability of channel width and bed sediment size.

Headwater river types

Small headwater reaches

All rivers begin as small streams, many of which are located within mountainous areas. Despite their size, the total length of these streams within a given river network is large so they play a critical role in influencing the water quantity, quality and ecology of reaches lower down.

The morphology and hydrology of upper headwaters depends on the local topography, climate and geology. In the undulating peat dominated areas of the Flow Country and the Grampians, gradually sloping streams have peat boundaries and begin in shallow hollows that concentrate runoff. Due to the typically saturated nature of peat, overland flow following high rainfall and snowmelt is rapid and a considerable portion of the total stream flow further downstream is generated during these events. This is reflected by the increase in dissolved peat (carbon) that gives the water a brown tinge.

In higher glaciated terrain, most streams form in steep hollows covered by shallow deposits of sediment, peat or are underlain by bedrock. Stream flow is generated by both rainfall and snowmelt that is rapidly delivered to the stream by the steep slopes. In contrast, on the plateaux of the Cairngorm Mountains, streams begin over shallower gradients and are fed by springs that are sustained by ground water stored in fractured bedrock and weathered sediment. These ground-water dominated streams may account for up to 60% of the total annual runoff and serve an important role by maintaining river base flows downstream during drought conditions.

Small headwater streams are generally morphologically insensitive due to the dominance of low flows that are incapable of doing geomorphic work and they provide important habitat for aquatic mosses, amphibians and water voles.

Steep boulder-bed reaches

Further downstream, multiple streams join together to increase the flow of water and valley form adopts a more clearly defined 'V-shape', characterised by steep bottoms tightly confined by hill slopes. Due to the increase in flow, stream power increases which enables the channel to be shaped into distinct forms and transport more sediment. Rapid transport of sand and gravel, combined with the sporadic input of coarse sediment delivered from adjacent steep valley sides by land slides or debris flows, creates river beds that are dominated by boulders and cobbles. Over time, these materials have been arranged into interlocking steps and jammed cascades that can remain stable for decades.

Only flows in excess of bankfull, generated during intense summer storm or snow melt events, are capable of mobilising boulders and reorganising the bed morphology. These rare but catastrophic geomorphic events can lead to a complete reset of channel morphology, as documented on the Allt Mor, on the northern slopes of the Cairngorms, during August 1978. Due to the high energy of these streams, they provide limited habitat for flora and fauna but they do support the dipper – a specialist riverine bird – that preys on macroinvertebrates.

Bedrock reaches

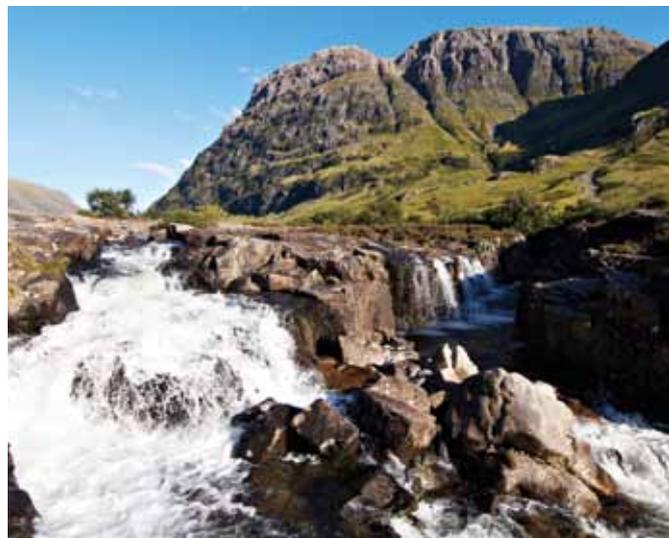
Channel boundaries are composed of bedrock if there is an excess of transport capacity relative to sediment supply. They may occur anywhere along a river, but are most common in headwater streams. They often occur where channel gradient is significantly higher than in adjacent alluvial reaches and form 'knickpoints' in the river's longitudinal profile. Many bedrock reaches reflect the legacy of high energy glacial meltwaters that cut through the bedrock to form spectacular gorges such as the Corrieshalloch Gorge in Wester Ross. These steep narrow gorges readily flush through material delivered from upstream and influence the gradient of upstream reaches by acting as base levels. In other cases bedrock exposure may relate to the downcutting of valley bottom sediments since glaciation or the uncovering of bedrock on the valley walls through lateral erosion. The high energy conditions and dominance of a hard substrate create different habitats that tend not to support large flora and fauna. Bedrock reaches may also create impassable barriers to fish migration.



A steep boulder dominated stream with a step-pool morphology on a headwater of the River Dee, Aberdeenshire (© The James Hutton Institute).

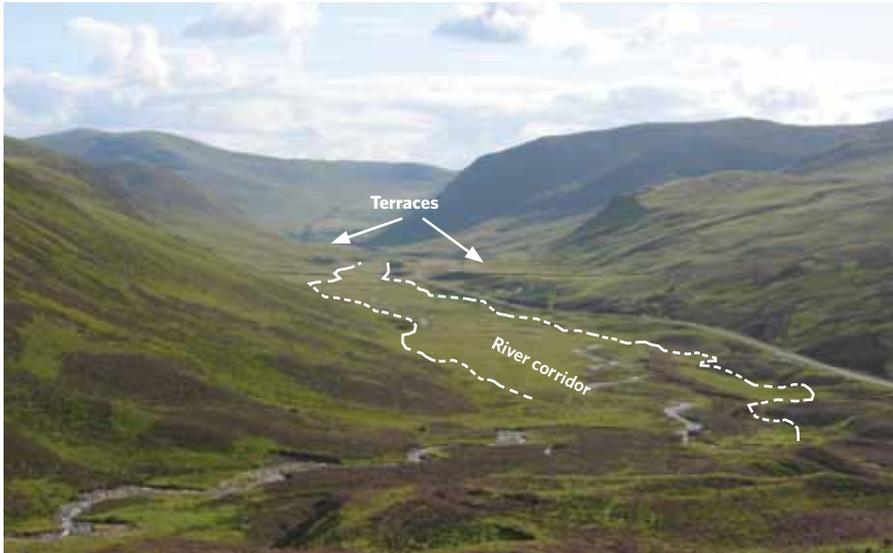


A low gradient headwater stream draining peatland in the River Dee catchment, Aberdeenshire (© The James Hutton Institute).



A bedrock knickpoint and waterfall on the River Coe, Lochaber (© SNH).

Mountain valley river types



A typical glaciated mountain valley, Gleann Beag in the River Tay catchment, Perthshire (© The James Hutton Institute).

Braided reaches

Braided reaches are a rare channel type characterised by a wide active river corridor and numerous pool-riffle channels split by gravel bars or islands. Braided reaches are commonly associated with weak banks made of gravel, high rates of sediment supply and medium stream power. These conditions mean that braided rivers exhibit the highest rates of change of any river type. On the middle River Feshie – a classic example – channel switching through avulsion is frequent and channels can migrate laterally over 10 metres each year. The dynamic nature of braided reaches results in the formation of numerous side channels, flow types and different bar types that provide diverse habitat. Side channels that are subjected to lower energy flows than the primary channel can support habitat for fish and aquatic insects.



The braided middle reach of the River Feshie on the western side of the Cairngorms Massif, Invernesshire (© SNH).

Meandering reaches

Meandering reaches are sinuous single thread channels characterised by regular sequences of meander bends, point bars, pools and intervening riffles. They occur where valley slopes decrease, reducing stream power and resulting in less dynamic systems than braided reaches. In mountainous areas, meandering reaches are usually active especially on meander bends where bank erosion on the outside is balanced by deposition on the inside of the bend. This leads to gradual lateral migration of the channel across the floodplain and a tightening of the meander planform over time. These processes create point bars and meander cut-off backwaters or oxbow lakes. Relatively stable meandering reaches may occur in response to increased bank side tree cover, bank engineering or confinement by valley walls that limit the ability of the channel



Landform features of the upper Derry Burn, an active meandering channel in the Cairngorms, Aberdeenshire (© Gerome Calves).

to adjust. Meandering reaches of all types provide high quality habitat for fish and aquatic insects. Riffles provide spawning habitat for adult Atlantic salmon and nearby pools provide nursery habitat for young fish. Stable meandering reaches such as confined sections of the River Spey and River Dee support freshwater pearl mussels, which have a requirement for stabilised pockets of sand and gravel.

Wandering reaches

Wandering reaches show characteristics of both braided and active meandering reaches. In planform view, wandering reaches exhibit localised braided sections with extensive sediment storage in large point bars, interspersed by longer, single thread, pool and glide sections. Wandering reaches, like the lower River Tummel in Perthshire, tend to be associated with high sediment supply inputs from tributaries, wide floodplains and low bank strength. These conditions, like braided



Features of a wandering reach of the Allt Bhran, a tributary of the River Tromie, Invernesshire (© The James Hutton Institute).

KEY FACTS

Scotland's mountainous areas are home to our most diverse and dynamic river systems. Natural morphological adjustment to high flows or sediment inputs is frequent in sensitive gravel-bed wandering or braided reaches, but less so in resistant boulder-bed and bedrock reaches.

reaches, lead to frequent lateral migration and channel avulsion (change of course). Wandering reaches are more common than braided reaches, but through engineering and land management during the last two centuries have become less widespread. Wandering reaches support important spawning habitats for salmonids given the extensive distribution of gravel substrates suitable for creating redds and the high rates of reworking of bars and the floodplain creates vegetation diversity and important backwater habitats.

Plane-bed and plane-riffle reaches

A less appreciated category of channel types are plane-bed and plane-riffle reaches. Both types are distinguished by a low sinuosity and moderate gradients. Plane-bed channels have a featureless bed topography. Plane-riffle reaches have pool and riffle sequences that are more subtle than observed in meandering reaches. These reach types merge into one another and are common along the mainstem rivers of mountain valleys. They are relatively stable compared to braided and wandering reaches due to the dominance of an armoured gravel-cobble substrate and often established riparian tree vegetation.

Management issues in mountain river systems

Mountain rivers deliver a huge range of benefits to humans but can also pose problems. As a result they have a long history of management even in remote areas. Headwaters are prone to sediment pollution

through muir burn, track construction and recently wind farm development in peat dominated catchments. Peat catchments provide important habitats for a variety of wildlife and serve as very effective traps for atmospheric carbon. This in turn has made their conservation an important issue from both ecological and climate change perspectives.

Further downstream, common responses to dynamic geomorphic processes of bank erosion or channel avulsion and flooding are the manipulation of rivers through channel engineering, dredging or realignment. These manipulations are likely to be detrimental to habitat, costly and ineffective where they don't consider dynamic fluvial processes. On gravel-bed rivers that support lucrative fisheries which are vital for local economies, croys have been constructed to create pools and revetments have been built to reduce sediment inputs from eroding banks. These interventions are costly and can have unintentional negative consequences for the natural well-being of rivers. For example, badly sited bank engineering reduces energy dissipation through erosion, resulting in scouring downstream and deprives the river of a source of sediment needed to maintain habitats. It may also reduce the connectivity of water to the floodplain, resulting in increased flood risk downstream.

The climate and topography of Scotland's mountainous areas are well suited to hydro-electric power production. Since the early 20th Century, networks of dams, weirs and

intakes have greatly altered the natural flow and sediment supply regimes. These modifications can lead to downstream morphological changes of channel narrowing, incision and increased armouring that in turn have ecological implications. For example, habitat area is reduced through narrowing and dams may prevent the movement of certain species such as Atlantic salmon. Recently interest in the potential to harness the power of steep headwater streams by developing micro-hydro schemes has risen. These 'run of the river' schemes divert natural flow but their geomorphic effects are unknown.



A previously eroding terrace bluff on the outside of a meander bend, stabilised by a concrete revetment to protect a nearby road (© The James Hutton Institute).



A plane-bed reach of the upper River Findhorn, Morayshire. Note the large fluvio-glacial terraces in the background (© SNH).

FURTHER READING

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9 Lowland rivers

The low lying areas that fringe the eastern side of the Highlands and extend across the Central Belt and Borders create a distinct type of river landscape. The geological foundation is dominated by Old Red Sandstone and lavas draped by large thicknesses of fluvio-glacial material deposited during deglaciation and reworked by rivers during the Holocene. Towards the coast, estuarine clays and silts deposited during the Mid-Holocene, when sea levels were higher, now form extensive carse lands. The resulting topography, coupled with a drier climate, creates a fertile landscape that has been significantly exploited for agriculture. Draining this landscape is a network of artificial channels, burns and major rivers that feed into the sea. Although lowland rivers comprise only a small length of the total stream network in Scotland, they have the potential to provide diverse habitats where unmodified and form an important conduit linking upstream and estuarine reaches through which species are able to move.

Land use and lowland rivers

The present day morphology of lowland rivers and the expansion of agriculture are closely linked. Prior to the 17th Century, lowland areas were poorly drained and covered by extensive 'wet' woodland cover. River corridors were governed by natural processes of regular floodplain inundation and frequent

channel adjustment. This began to change as technological advancement during the agricultural revolution increased the size and productivity of farms. Natural processes that conflicted with the exploitation of floodplain areas, including bank erosion and regular flooding, were largely addressed through channel engineering. Straightening, dredging and embanking of large rivers was widely practised, both increasing the available land area, reducing the potential for morphological adjustment and rapidly conveying flood flows downstream. Added demand for land came with the 19th Century expansion of the railways and post-war drives for increased food production in the mid 20th Century. In response, existing embankments were raised and extended leading to a further reduction of floodplain connectivity. As a result, examples of entirely natural lowland river corridors are now rare in Scotland.

Lowland river types

Actively meandering reaches

Lowland meandering reaches differ from their mountain equivalents by having finer substrates and lower stream power. Reaches with sufficient energy relative to bank strength are moderately dynamic and develop an actively meandering morphology. Characteristic processes include erosion of the outer bank balanced by deposition of sand and gravels on the inner bank. Following a series of large floods, meanders may be cut

off leaving oxbow lakes on the floodplain that gradually infill and provide an important type of backwater habitat.

Active meandering reaches provide a range of other valuable habitats that are sustained by natural geomorphic processes for a range of animal and plant species. For example, the Endrick Water is a Special Area for Conservation, designated for brook and river lamprey, which require both silt deposits for juveniles and gravels for spawning adults. Natural examples also provide macrophyte habitat both in the main channel and in backwater zones. Exposed gravel bars provide important colonisation habitats for many plant and invertebrate species that in turn provide a source of food for birds and mammals. Actively meandering reaches also create new land for pioneer plant species to colonise and leave an uneven floodplain surface as they migrate across the valley floor. The varied topography supports a diversity of habitats, where the higher ridges favour dryland plants and the lower swales support wetland species.

Passive meandering reaches

Low gradient reaches with banks reinforced by engineering or composed of cohesive silts and clays have a passive meandering morphology. The positions of meanders may change little for hundreds of years, appearing static over human timescales and allowing the development of dense vegetation.



The River Clyde near Carstairs, South Lanarkshire, an actively meandering channel which has laterally migrated across its floodplain at an average rate of up to 2.5 m per year. Reworking of the floodplain has resulted in the formation of oxbow lakes and palaeo-channels (© Patricia & Angus Macdonald Aerographica/SNH).



A passive meandering reach of the River Tweed near Coldstream on the border between Scotland and England (© Walter Baxter and licensed for reuse under a Creative Commons License).

However, through gradual processes acting over very long timescales, meanders can become very large and highly sinuous. Unlike steeper mountain rivers, a variety of slow water zones may be found, allowing silts and sands to settle out and the colonisation by macrophytes which further change and enhance habitat. Examples of passive meandering channels include the meanders below Stirling Castle that have remained unchanged for centuries.

Lowland bedrock reaches

Where outcrops of resistant bedrock occur in lowland regions they exert a significant

control over river morphology. Rivers may be confined through a rock gorge and are often associated with a sudden change in slope, forming rapids or waterfalls over exposed bedrock. The Falls of Clyde and the Rumbling Bridge on the River Devon provide dramatic examples of this river type. Historically they have frequently been exploited to provide hydropower to mills, for example, the UNESCO world heritage site at New Lanark.

Low order tributaries

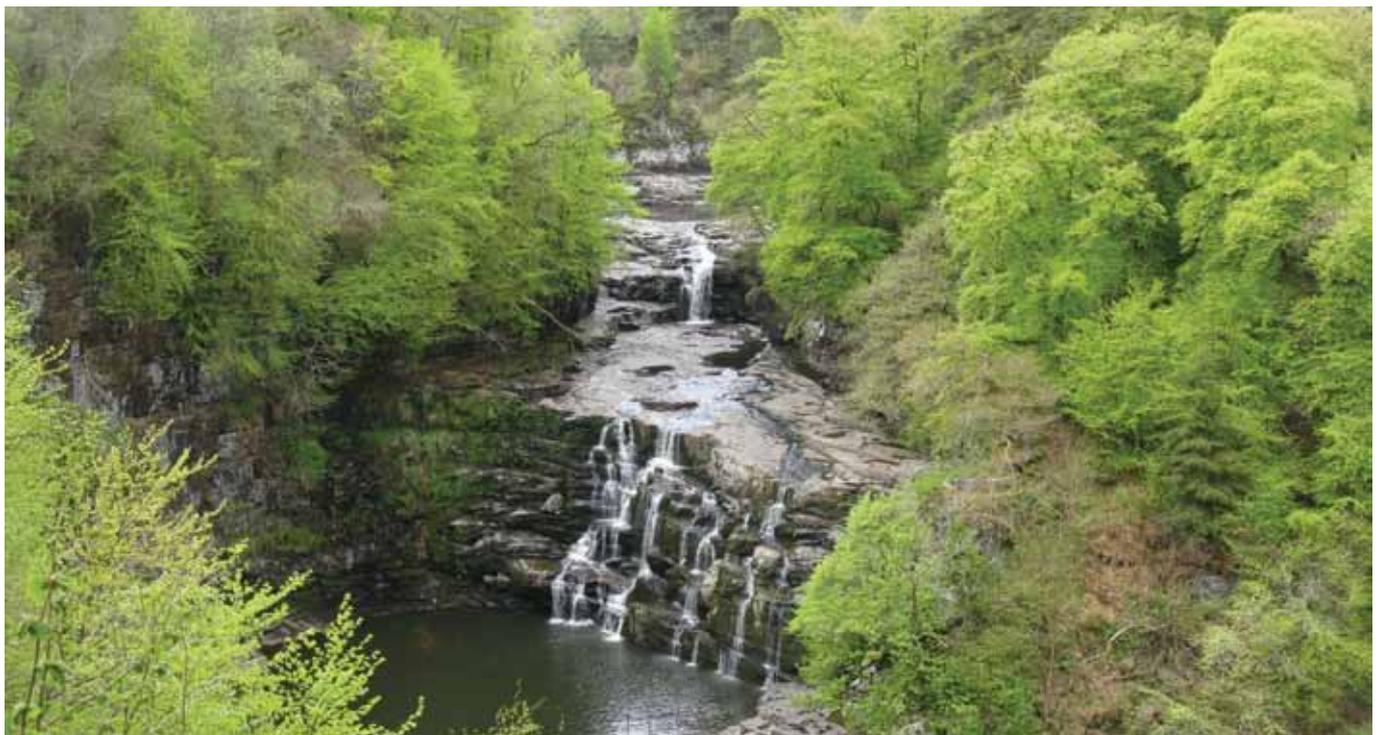
Burns generated in lowland hills are small and often spring-fed. A combination of small catchment size, moderate gradient and lower

rainfall, results in a relatively low stream power and dynamism. Where they flow through unconfined valleys such burns will meander within a river corridor and their morphology is further influenced by vegetation. Where a woodland riparian corridor persists, channels remain relatively stable, with sediment being retained by in-stream wood. However, the riparian areas are frequently deforested and heavily grazed, resulting in greater channel instability. This morphology is typical of the streams running off the lower slopes of the Ochils in Stirlingshire and the Borders. Many of these streams have been extensively modified and often incorporated into the network of drainage ditches around field boundaries. Through forested areas they may be replaced altogether by a network of straight drainage ditches.

Management issues in lowland river systems

Flooding and embankments

Flooding of agricultural land is a major hazard in many areas of Scotland. Agricultural embankments, widely constructed on low-lying productive floodplains, can reduce the impact on farming by preventing floods of moderate frequency and size from inundating land. They also constrain channel adjustment, disconnect back waters and reduce the lateral hydromorphological processes that sustain river corridor and floodplain habitat diversity. The high cost of embankment maintenance and the value of lost ecosystem services



The bedrock reach and waterfalls of Corra Linn, at the Falls of Clyde near New Lanark in South Lanarkshire. (© Mike Richardson and licensed for reuse under a Creative Commons Licence).



A breached flood embankment and scour hole caused by a large flood on the River Tay, Perthshire (© SNH).

mean that the continued construction and maintenance of river embankments may no longer be a cost-effective management approach.

Flood embankment failures and flood overtopping are increasingly a problem in lowland rivers. Failures are particularly prevalent in actively meandering reaches and where the embankment is constructed across the line of former channels. At the point of failure, water is channelled on to the flood-plain creating scour holes, causing sediment deposition and erosion of crops. Controlled flooding of land may offer improved flood protection over longer timescales, by limiting damage, allowing the deposition of nutrient-rich sediments and reducing the pooling of water behind embankments. This can be complemented by the construction of set-back embankments, allowing smaller floods to be conveyed by a widened river corridor and providing space for natural channel adjustment to the flood regime in addition to improving river health and habitats.

Straightening and simplifying

Many reaches on Scotland's lowland rivers have historically been straightened to provide space for agricultural expansion or, more often, for road and rail routes along valley floor 'communication corridors'. Maintaining the straight course can require

constant management when the same processes of deposition and erosion, present in the natural meandering morphology, remain active. Approaches to preventing adjustment include re-profiling, bank reinforcement and dredging that can have wider implications. Macrophytes are heavily impacted by straightening and dredging. This can have a knock-on effect for other species



A historically straightened reach of the Lunan Water, at Inverkeilor in Angus (© The James Hutton Institute).

dependent on the habitat which they create. Straight channels also have the potential to increase flood risk to downstream property by increasing the speed at which water is conveyed.

Riverbank erosion

Erosion of riverbanks can cause problems where, for example, prime farmland is lost; but in many rivers a modest amount of erosion is an important geomorphic process bringing ecosystem benefits and services. Bank erosion allows the channel to adjust to changing flows and climatic conditions; it recycles habitats and thereby refreshes ecosystem dynamics; and eroded banks provide nesting and refuge sites for burrowing insects and birds such as sand martins. Managers and landowners should consider whether the erosion is mainly caused by natural processes – in which case it should, where feasible, be left to continue – or whether it has been accelerated, for example, due to a loss of riparian vegetation.

One of the most effective methods of combating bank erosion is by aiding vegetation recovery through fencing to create 'buffer strips' or by tree planting. In severe erosion cases, strategic placement of large tree trunks and root wads can also be effective.

Lowland rivers have a long history of management mainly for agricultural improvement. Healthy lowland rivers are reliant on healthy upstream rivers and good local land management.



Excessive bank erosion due to a lack of riparian tree vegetation and fine sediment runoff from adjacent fields, can lead to siltation of water courses (© Centre for River Ecosystem Science).

Dredging

Dredging was undertaken historically in an attempt to improve drainage, reduce erosion and control rivers, with a peak after the Second World War in response to a drive to increase agricultural production, assisted by advances in mechanisation. Removal of gravel accumulations is a potentially damaging activity as exposed riverine gravels support rare plant and animal species. The removal of material can also interrupt sediment supply downstream, leading to bed lowering and scour in downstream reaches. Consequences

may include the loss of fish spawning gravels, undercutting of foundations (e.g. bridge footings and revetments) and reduction in the extent of exposed gravel habitats.

In recognition of these impacts, today gravel extraction requires authorisation, which will be issued if it will have a clear and measurable benefit, for example, if removal will reduce erosion of infrastructure or is required for a bridge to be used safely.

Sediment pollution

Poor sediment management practices resulting in excessive sediment loss from agricultural land and forestry (e.g. a lack of buffering between water courses and exposed, unvegetated sediment) can lead to smothering of in-stream substrates with fine silt and sand. The problem is exacerbated by the uniform nature of many impacted streams which have low resilience to sediment pollution. Excessive fine sediment deposition reduces the quality of spawning habitats for salmonids.



Natural erosion of a clay riverbank on the outer bend of a meander on the River Earn, near Bridge of Earn in Perthshire (© William Starkey and licensed for reuse under a Creative Commons License).

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10 Urban rivers

Many Scottish towns and cities have developed adjacent to rivers where crossing points, trade and industry have developed. With urban expansion, rivers have been increasingly exploited for shipping, drinking water, power and the disposal of waste. Barriers to natural processes of erosion and flooding are often required to protect the valuable land and infrastructure constructed where urban zones and river corridors overlap. As a result, urban rivers are frequently heavily modified.

The types of modification vary depending on the purpose. Banks are frequently reinforced where valuable urban real estate or transport infrastructure of roads, railways and bridges are threatened by erosion. Examples of channels lined with concrete to prevent erosion can be seen across much of the White Cart catchment in Glasgow. Weirs and lades have been constructed to divert water to old mills for power, such as the River Clyde at New Lanark. Construction of walls and embankments, preventing both channel migration and overbank flooding as seen on the River Tay flowing through Perth, are also common.

Despite much historical alteration, artificial river corridors have emerged where parkland and footpaths have been created. With careful management, these act as green corridors that provide habitat even for protected animal species such as otters that are now recovering in urban rivers. In contrast, extreme urban constriction of water courses has led to a complete loss of lateral connectivity, floodplain landforms and associated habitats.



An inactive meandering reach of the River Forth in Stirling, as viewed from the Wallace Monument
(© Centre for River Ecosystem Science).

Urban burns

Modifications of smaller streams (<5 m in width), include altered cross-sectional profiles, reinforcement of the banks or installation of artificial beds. Their small size has made it easy for developers to modify their morphology or natural course. The most extreme modifications are culverts which enclose many miles of channel network. The design of culverts is often a compromise between ease of construction and hydraulic efficiency, and rarely considers river health.

Tidal reaches

Scotland's major cities are located on tidal stretches of river. The river discharge combined with the incoming tide can produce large fluctuations in water level and lead to extensive flooding when spate flows coincide with a high spring tides. The problem is exacerbated by the heavy modifications made to the riverbanks that may limit the natural flood carrying capacity. Historically, tidal reaches have provided access for shipping and many miles of riverbank along the River Clyde, River Forth, River Tay and River Dee were modified to create quays. As ships increased in size, channels have been regularly dredged to maintain access.

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An urban burn in Pitlochry laterally constrained by revetments (© Centre for River Ecosystem Science).

KEY FACTS

Urban rivers are heavily modified reflecting a long history of significant exploitation and attempts to reduce flood risk. This has compromised natural ecosystem functioning and services greatly, but to some extent these can be reinstated with careful management.

Wildlife

The plants that grow along rivers play an important role in the creation of habitat for urban wildlife, creating shelter, roost space for birds and food resources. This increases the ecological health of the river as well as providing amenity value.

Flooding

Urban areas may flood as a result of overtopping of banks or flood defences, seepage through poorly maintained embankments or backing up of water in the drainage network. Based on SEPA flood prediction maps, approximately 170,000 residential and commercial properties are at risk from a 1 in 100 year flood event, although climate change may increase this number. Flooding is estimated to cost the Scottish economy £31.5 million annually.

Deposition of gravel

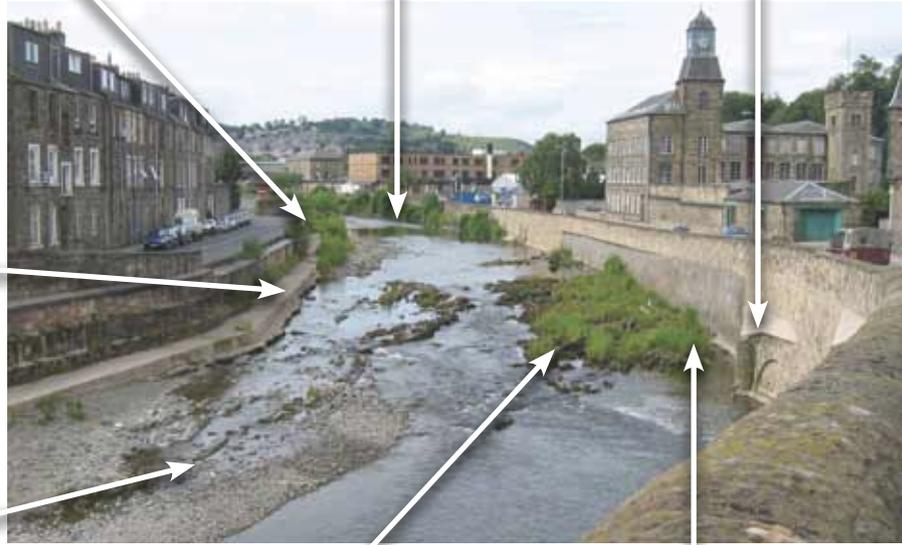
Without consideration of fluvial geomorphology, urban channels are artificially widened to convey floodwaters leading to a reduction of unit stream power. The reduced sediment transport capacity increases gravel deposition particularly on the inside of meanders, reaches with reduced slope and at locations where the flow is slowed by in-stream structures or vegetation. The deposition of gravel can reduce the river's capacity to convey water and blockage of drain outfalls may lead to an increase in flooding frequency.

In-stream structures

Bridge footings, weirs and other in-stream structures are often associated with the concentration of utilities and transport infrastructure. Where these structures reduce water depth or increase flow velocities, they can disrupt the migration of fish and alter the transport of sediment, with further potential consequences for the health of the river.

Runoff

Drainage installed throughout urban areas is designed to convey surface water in to water courses more rapidly than occurs naturally in lowland environments. This reduces flooding locally, but may exacerbate risk of the river overtopping its banks. Modern developments require the implementation of a Sustainable Urban Drainage Scheme (SUDS) to alleviate the problems that surface drainage can cause.



(© Centre for River Ecosystem Science)

Vegetation growth

In-stream vegetation increases channel roughness reducing flow velocities and the capacity of a channel to convey large floods. Growth may be excessive where sources of pollution have raised nutrient levels in the water. Vegetation may also trap sediment and issues associated with sedimentation may arise, although the process may serve to alleviate similar issues downstream. Removal of the vegetation may result in a sudden release of the sediment stored.

Riverbank management

Ongoing maintenance of artificial riverbanks, walls and revetments can be a considerable financial burden to local councils. Reduced maintenance costs can be achieved by restoration. The most sustainable options involve providing more space and allowing natural processes to recover, for example, through the creation of river corridors where possible.

THE EVOLUTION OF URBAN CHANNELS



Natural channel

The natural extent of a river corridor is commonly wider. This allows space for adjustment processes of erosion and deposition that create and sustain habitats. During floods, there is space for water to spill out onto the surrounding floodplains.



Early urban influence

The main channel remains un-altered and continues to convey high flows. Embankments constructed to prevent flooding of surrounding land reduce the overall width of the river corridor.



Urban encroachment

As urban areas expand and encroach on the river corridor, the main channel is enlarged and resectioned to improve flow conveyance. Floodwalls are raised to compensate for the reduced corridor width. Constriction of the river corridor limits habitat availability. Although the banks are reinforced, the beds of urban rivers are often left unmodified.



Gravel deposition

As the river corridor is now confined and the channel widened, sediment transport patterns are altered. Processes of erosion and deposition acting on the bed may raise or lower the bed profile at the reach scale. Sand and gravel may periodically accumulate within the reach, gradually reducing its capacity to convey floodwaters. At a more local scale, scoured material in one location is deposited in another which can compromise the performance of infrastructure. Readjustment, driven by planform change in a natural system, is no longer able to resolve the balance leading to increased deposition.



Managed withdrawal

Allocation of space for the river allows natural processes to recreate and sustain riparian habitats. The need to manage erosion and deposition is reduced. Biodiversity, amenity benefits and water quality are enhanced.

11 River restoration

The natural form of many of Scotland's rivers and burns has been lost through damming, straightening, embanking and dredging, often leading to reduced ecological health. After many years of exploitation and reducing ecosystem service provision, the growing awareness that rivers have significant economic and social value to Scotland has resulted in a change of approach to their management. River restoration can reverse the losses, by aiming to create naturally functioning rivers that support the features and processes appropriate to the river type and therefore restore lost ecosystem services. The new approaches are being pushed forward through both legislative requirements (principally through the Water Framework and Flooding Directives) and the aims of grassroots organisations such as local fisheries trusts and community groups.

Approaches and techniques

A range of restoration techniques have been developed for improving the health of river systems. The appropriate option is dependent on the type of river, location and size of the project and the time it will take for natural processes to recover. Small scale habitat enhancements (e.g. use of rubble mats and crows) are the most established, but are often focused on target species and may have little wider value. Unless sufficient consideration is given to the prevailing river processes, benefits can be short lasting and may even be to the detriment of downstream reaches. Sustainable approaches need to consider both local and catchment scale processes. By acknowledging the connected nature of rivers, projects can be designed to maximise the restoration work done by natural river ecosystem processes, ensuring a more sustainable solution to delivering the desired benefits. A major element is the restoration of connectivity, pertinent in Scotland because of the large number of embankments, weirs and dams that have historically been installed. Restoration may simply be a case of

removing redundant structures or hard engineering and allowing natural processes of erosion, sediment transport and deposition to restore the river over time. In low energy systems or when the rapid restoration of habitat is desired, some level of intervention may be needed. These may include re-meandering, planting river margins with natural tree species or substrate replenishment where upstream trapping or extraction has resulted in the loss of sands and gravels. Where rivers have been heavily modified, the construction of a new channel with a morphology and planform that balances the natural processes may be the most appropriate approach in order to achieve a healthy, functional river ecosystem.

Notable examples of river restoration in Scotland

A range of river restoration projects have been undertaken in Scotland that are helping to disseminate information that will in turn aid the implementation of future restoration projects.

Rottal Burn – Angus

In the 19th Century around 1.2 km of meandering channel on the Rottal Burn – a tributary of the River South Esk – was straightened in an attempt to improve drainage of the surrounding land. Despite this work, most of the surrounding land remained wet. The straightened channel required regular dredging because it was at the foot of a mountainous catchment, where sediment would naturally be deposited on the floodplain. Chronic sediment accumulation meant the channel had to be repeatedly dredged. The floodplain was disconnected and the quality of the impoverished habitats in the channel was highlighted by electrofishing surveys, which showed a significantly degraded fish population. In 2012, with the support of the Water Environment Fund, the Esk Rivers and Fisheries Trust restored the channel to its original meandering morphology. In late



Gravel replenishment on the regulated River Garry, Perthshire. Gravel trapped behind a weir has been excavated and re-deposited below the weir to restore sediment supply to reaches downstream (© Chris Gibbins, Northern Rivers Institute).

2012, several large floods sculpted the channel to create a much more natural and varied series of habitats with very good lateral connection to the floodplain. Atlantic salmon and sea trout have already spawned in the restored section and the site is being monitored for fish, invertebrates, geomorphic changes and flows to measure the benefits.

River Garry – Perthshire

Priorities for power generation during the 1930s and 1950s led to the diversion of flow from the River Garry into Loch Errochty, as part of the River Tummel hydro scheme. Around 20 km of channel was dewatered, only receiving flow from a few unregulated tributaries and at times of dam overspill. Sediment transport has been interrupted for over 50 years, leading to a requirement for periodic removal of material as it builds up behind by the off-take weirs at Loch Garry and Edendon Bridge. Gravels have previously been stockpiled and used as aggregate in local road construction. The planned introduction of a compensation flow by Scottish and Southern Energy, and the use of the stockpiled gravels for substrate replenishment below the dams, will help to restore the habitats that had previously been starved of sediment. With time, a more natural gravel-bed is expected to develop in the dewatered reaches, allowing fauna to return and potentially providing spawning habitats for fish.

Braid Burn – Edinburgh

Many burns through suburban areas have been heavily modified during the mid 20th Century. Typical modifications, including a re-profiled channel and concrete banks, could be seen on the Braid Burn, at Inch Park, prior to restoration works. Efforts to restore a more natural riparian zone and increase habitat



The artificially straightened reach of the Rottal Burn in Angus, prior to re-meandering (© Centre for River Ecosystem Science).



The Rottal Burn in 2012 after re-meandering using the old course of the burn as a template (© Esk Rivers and Fisheries Trust).

KEY FACTS

A range of different river restoration techniques, tailored to particular river types and problems, are available to restore natural river ecosystem functioning.



Before and after the restoration of channel morphology on the Braid Burn, Edinburgh (© The River Restoration Centre).

diversity were completed in 2010 as part of a wider flood management scheme. The concrete channels were replaced with earth banks and a more sinuous planform, allowing the channel to function more naturally in terms of hydrology and ecology, in addition to improving the aesthetics of the park.

Inchewan Burn - Perthshire

Bed reinforcement is undertaken on small high energy channels where processes threaten to damage foundations or property. This can often have unintended consequences for the ecology of the burn. Fish passage had been blocked on the Inchewan Burn, by a short reach where gabions had been used to reinforce the bed and banks. Instead of flowing over the surface, the water ran through the baskets preventing the movement of fish between upstream and downstream habitats. By replacing the artificial bed with a more

natural boulder and cobble substrate, fish passage to the upper catchment has been restored. The project fits within a wider catchment-scale plan including enhancements to the reconnected habitats in upstream sections.

River Tummel - Perthshire

The natural restoration of rivers through changes in management approach is possible but can be a slow process. The maintenance of 19th Century flood embankments, which restricted the lower River Tummel to a single thread channel, was abandoned by the Duke of Atholl in 1903. After successive floods over a period of 100 years, the river has adopted a more natural wandering gravel-bed morphology that supports a range of rare habitats and species. Scotland has much potential for this approach to restoration, allowing naturalisation of the river corridor or wider floodplain habitats.



Gravel bars on the River Tummel, Perthshire. The river has naturally recovered its wandering planform in response to reduced local management of bank protection and recent significant flooding. (© Centre for River Ecosystem Science).



A reach of the Inchewan Burn, Perthshire, before and after replacement of the artificial bed with a more natural boulder and cobble substrate that restored fish passage to the upper catchment (© Centre for River Ecosystem Science).

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12 Good and poor practice river management

Careful consideration of a range of factors is a prerequisite for good river management. These include identifying the true cause and nature of the problem, determining the river type and setting, and assessing the potential geomorphic and ecological impacts of the proposed management activities. The cause of the problem may not be immediately obvious and may relate to an activity many

miles away or a number of years in the past. Various solutions are likely to be available, including the option of doing nothing, but it is unlikely that all will be equally appropriate. For instance, management of erosion on a high energy gravel-bed river will require a very different management approach to a passively meandering lowland stream. However, in all cases, the failure to fully

consider geomorphological and ecological linkages may result in undesirable consequences that extend well beyond the management site, both upstream and downstream, and may persist for decades. The following case studies provide examples of good and poor river management in Scotland and the lessons they teach us on how to best manage our rivers.

CASE STUDY 1 POOR PRACTICE RIPARIAN MANAGEMENT

Motive/issue: Loss of agricultural land due to channel migration.

Management aim: Reclamation of riparian land.

Management action: Large volumes of gravel placed along the margins of the river channel over a period of several weeks to reclaim land, reversing the channel migration and reducing the channel width (1a).

Fluvial response: Within three months of completion high flows have scoured away the new unconsolidated gravels (1b), the channel has begun to restore its natural morphology and fields are still threatened. The group of trees circled in yellow provide a fixed reference point.

Consequence: Management has failed to achieve the desired aims.

Lesson: The dynamic nature of high energy gravel-bed rivers means that attempts to artificially align the margins of a channel can be costly and are likely to achieve only a temporary change in course.



(© SNH)

CASE STUDY 2 GOOD PRACTICE RIPARIAN MANAGEMENT

Motive/issue: Siltation and poor water quality of an agricultural burn due to fine sediment runoff from fields trampled by livestock (2a).

Management aim: Improve water quality and reduce siltation of the stream bed.

Management action: Fencing off the riparian zone to restore a well vegetated buffer strip that filters sediment from agricultural runoff.

Fluvial response: Reduced poaching of soils close to the river and trampling of bankside vegetation allows the riparian zone to revegetate (2b). Over the longer term, planted trees will shade the channel as they mature.

Consequence: Input of silt to the stream is reduced and water quality is improved.

Lesson: By restoring the riparian corridor, farms can take advantage of the natural properties of river side vegetation to filter runoff and trap fine sediment, buffering the impacts of agriculture.



(© The James Hutton Institute)

CASE STUDY 3 POOR PRACTICE CHANNEL REALIGNMENT

Motive/issue: Historic flooding in a town that is near to a river confluence where sediment accumulates naturally.

Management aim: Reduce flooding of residential properties by increasing the channel conveyance capacity.

Management action: A new channel was dredged through the accumulated sediments, deepening it by around 1.5 metres and gravels were piled on the banks.

Fluvial response: Because water was confined within the dredged channel, stream power was higher so the banks rapidly eroded and bed sediments became highly mobile. The dredged channel rapidly filled in again and the lowered section of channel bed began to eat its way upstream.

Consequence: A head cut (a moving knickpoint) developed and lowered the bed upstream for more than 600 m. This went on for over 17 years. The banks increased in height, making them unstable and leading to further problematic bank erosion (3a) that was unnatural compared to upstream (3b).

Lesson: Consideration of geomorphic principles, namely the relationships between bed slope, channel width and stream power, would have allowed the subsequent problems to be predicted and avoided.



(© SEPA)

CASE STUDY 4 GOOD PRACTICE CHANNEL REALIGNMENT

Motive/issue: A number of potentially valuable coal seams extend under the existing course of the river.

Management aim: Divert the course of the river to enable the extension of open cast coal mining.

Management action: Three kilometres of new river channel were excavated on the opposite side of the valley floor, matching the width, sinuosity and slope of a natural meandering upland river (4a).

Fluvial response: Natural hydraulic, geomorphic and ecological processes develop in response to the realignment. Patterns of erosion and deposition drive habitat development and support colonisation by a range of flora and fauna (4b).

Consequence: In-stream and riparian habitats develop and are supported by natural processes increasing ecological resilience. Management costs are minimal and upstream and downstream reaches are unaffected.

Lesson: Working with nature allows management activity, such as channel realignment, to be undertaken without adverse consequences.



(© Centre for River Ecosystem Science)

Good river management requires careful consideration of the causes of the problem, the range of solutions available and their potential impacts. Landowners proposing to carry out work need permission from SEPA and professional guidance on appropriate actions.

CASE STUDY 5 POOR PRACTICE CHANNEL DREDGING

Motive/issue: Repeated flooding of nearby fields.

Management aim: Increase productivity of agricultural land by increasing channel flow conveyance.

Management action: Dredging of the river bed and re-profiling of the bank along a 600 m reach (5a) and realigning a further 50 m of channel.

Fluvial response: Reduction in overbank flooding and dewatering of the floodplain due to a lower channel bed. Higher unvegetated banks in comparison to the unaltered burn (5b), are unstable leading to increased sediment pollution.

Consequence: The natural morphology of the original channel is completely altered. Bed habitats have been lost and reduced floodplain connectivity impacts riparian fauna and flora. Reduced flood storage in the upper catchment increases flood risk downstream.

Lesson: Measures such as dredging, undertaken to reduce flood impact on agricultural land, damage habitats and may have wider implications downstream.



(© SEPA)

CASE STUDY 6 GOOD PRACTICE CHANNEL DREDGING

Motive/issue: High rates of sediment deposition reducing the capacity of a channel to convey water resulting in overbank flooding.

Management aim: Reduce local flood risk in the short term.

Management action: Assessment of upstream sediment sources reveals management of the cause of the problem is not an option. The problem is addressed directly through regulated dredging following a management plan and consultation with a professional geomorphologist to minimise impacts on the local environment (6).

Fluvial response: Channel size is temporarily increased, reducing overbank flows. Over a number of floods, natural sediment transport processes infill the dredged section.

Consequence: Damage to morphology and habitats is localised. Repeated dredging is required to maintain flow conveyance. Frequency depends on the transport capacity of the newly dredged channel and the flux of sediment from upstream sources.

Lesson: Where no other alternative exists to manage causes of sediment deposition (e.g. difficulty of stabilising upstream sediment sources or where channel morphology around structures such as bridges cannot be naturalised), dredging may be considered as an option where flooding threatens properties or significant infrastructure.



(© Tweed Forum)

FURTHER READING

Carleton College Science Education Resource Centre. **River geomorphology videos showing the impact of river modifications.**
serc.carleton.edu/NAGTWorkshops/geomorph/emriver/index.html

SNH. **Gravel Working in Scottish Salmon rivers: A Code of Good Practice.**
www.snh.org.uk/pdfs/publications/designatedareas/gravel_salmon_rivers.pdf

SEPA. **Engineering guidance.**
www.sepa.org.uk/water/water_regulation/guidance/engineering.aspx

Sustainable management of Scotland's rivers in the future

This handbook has used the analogy drawn between human health and river health to communicate the physical nature of rivers. Rivers, like people, exhibit a variety of behaviours that are often not to everyone's liking. We have to accept that rivers will not always behave in a way we expect and cannot be trained to conform with what society would like. It is the diversity of river morphology and behavior that provides Scotland with a precious resource.

The importance of this resource for both ecology and society is becoming increasingly appreciated. This is supported by strong legislation such as the European Union Water Framework Directive and the related Water Environment and Water Services (Scotland) Act, 2003, which require our rivers to be of 'good ecological status' by 2015. In terms of water quality, generally rivers are of high status but physical degradation due to past human modification constitutes a more serious problem. Currently, an estimated 44% of rivers are below good ecological status, reflecting a deterioration of hydrology, biology and morphology. Scotland's rivers are therefore far from being truly natural but have a cultural character that reflects centuries of management, primarily to maximise agricultural productivity, generate hydro-electricity and mitigate hazards such as

flooding and bank erosion. Nonetheless, in a UK context, the diversity and abundance of natural river processes, landforms and river types within Scotland, as introduced by this book, is striking.

Our approach to river management needs to change in the light of a number of drivers. Increased demands for water and food production, urban development, climate change and legislative frameworks will all shape how we manage our rivers in the future. For example, under current climate change scenarios, the increased frequency of high flows is expected to lead to increased rates of lateral migration as rivers accommodate these changes. One approach to manage these changes would be to designate river corridors to allow free channel migration, or to plant trees to increase bank resistance. Ultimately, all different management methods should be considered on a site-by-site basis and selection needs to be underpinned by a sound understanding of the river forms and processes introduced by this handbook.

Given the variety of river environments and issues in Scotland, it is difficult to prescribe universally applicable styles of management. Management decisions will vary from one reach to another depending on the particular

physical and social constraints. However the following general principles for guiding how we should perceive and in turn use our rivers are universally applicable:

- Rivers and floodplains or river corridors are naturally intimately linked systems and should be connected to maximise the ecosystem services that they provide us.
- Processes such as bank erosion and channel movement in all directions are natural and where possible we should learn to live with these changes or adopt 'softer' solutions rather than hard engineering.
- Treatment of river problems at their source is preferable to treating the symptom.
- River networks are connected systems, where natural changes or human modification in one location can have an influence upstream or downstream that may be instant or take longer to become apparent.
- *Ultimately, rivers will need to be resilient to enable them to naturally adapt to future changes and to continue to provide the natural services that we rely on. Where possible, we should strive to work with and not against rivers.*

"Water is the most critical resource issue of our lifetime and our children's lifetime. The health of our waters is the principal measure of how we live on the land."

- Luna Leopold

FURTHER READING

Spray, C. (2011) The Changing Nature of Scotland's Fresh Water Environment. In S.J. Marrs, S. Foster, C. Hendrie, E.C. Mackey, D.B.A. Thompson (Eds), *The Changing Nature of Scotland*, TSO Scotland, Edinburgh, pp 219-236.

Glossary

- Aggradation** The process that increases the bed elevation of a river or stream through the deposition of sediment. This generally occurs where sediment input exceeds the capacity of the flow to transport sediment downstream.
- Alluvial (alluvium)** Sediment moved and deposited by rivers over riverbeds, fans and floodplains.
- Armour layer** Under most conditions a layer of coarse substrate will develop on the bed of a river, preventing finer material below from being washed downstream.
- Avulsion** A sudden, natural change in the course of a river through the creation of a new channel or reoccupation of an old one.
- Bankfull** A hydrological term referring to the river flow that fills a channel to the elevation of the active floodplain (i.e. fills the channel to the top of its banks).
- Bar** An elevated region of channel bed that has been created by sediment deposition. Types of bars include lateral, mid-channel, riffle and point bars.
- Base level** The level of the ultimate downstream control on river bed level created by fixed features (i.e. the sea, a lake, tributary confluence or bedrock outcrop).
- Bedforms** Sub-reach scale (i.e. less than 10–20 channel widths long) physical features found on a riverbed such as riffles, pools and rapids.
- Benthic** An ecological term generally used when referring to the surface of a submerged substrate or habitat. Benthic fauna are animals that live within this zone.
- Bluff** A short section of the valley side or terrace that has been eroded through lateral migration of the river channel.
- Boulder** A particle larger than a football in size (specifically with an intermediate axis in excess of 256 mm).
- Braided** A channel planform type consisting of multiple channels separated by sand or gravel bars.
- Cascade** A chaotic, white-water flow type associated with boulder-bed streams.
- Catchment** The area of land upstream of a given point on the river network from which surface runoff contributes to the flow of the river.
- Coarse sediment** Sediment that is greater than 2 mm in diameter. Includes gravels, cobbles and boulders.
- Cobble** A particle approximately between the size of a tennis ball and a football (specifically with an intermediate axis ranging between 64 mm and 256 mm).
- Competence** The ability of a river to mobilise a sediment particle. Rivers with a high competence are capable of moving large particle sizes whilst rivers with a lower competence are only capable of moving smaller material.
- Confinement** The restriction imposed on the lateral movement of a river channel by valley sides, river terraces or artificially constructed embankments.
- Croy** Artificial, partially submerged structures, constructed from wood or boulders, that project out from the riverbank to encourage bed scour creating diversity of water depths and velocities (also called groynes or deflectors). These are often constructed in an attempt to create permanent fishing pools.
- Degradation** The process of decreasing bed elevation on a river or stream through the erosion of sediment. This generally occurs where sediment export exceeds input to the reach.
- Discharge** A measure of the volume of water flowing through a channel per unit time. This is usually expressed in cubic metres per second but can also refer to longer periods such as the annual discharge of a river.
- Dredging** The excavation of gravels, sand or silt from the bed of a river or stream, often undertaken to increase the water conveyance capacity of the channel.
- Drift** The material on the surface that overlies the solid bedrock in a landscape. For example, alluvium or glacial till.
- Ecosystem** A concept in ecology linking the many interacting components of the environment to the organisms that live within it. An ecosystem includes both living organisms including animals, plants and bacteria, and non-living components such as water, rocks and sunlight.
- Ecosystem services** Ecosystem services are the aspects of healthy ecosystems valued by humankind for their contribution to human well-being, such as plentiful and potable water, productive fisheries and detention of high flows.
- Equilibrium** Rivers that when viewed over a defined period of time, have a stable morphology due to equal inputs and outputs of sediment.
- Evapotranspiration** The loss of water from the Earth's land surface to the atmosphere through both evaporation and transpiration from plants.
- Fine sediment** Sediment that is less than 2 mm in diameter. Includes sands, silts and clays. Excessive fine sediment can clog spawning gravels reducing the viability of salmon eggs.
- First order** The first grouping of a classification system (stream order) used to grade rivers by size. A headwater stream with no contribution from other tributaries is a first order stream.
- Floodplain** The area of the valley bottom that is frequently inundated by river flood water.
- Flow type** A sub-reach scale (i.e. less than 10–20 channel widths long) unit of a channel characterised by a particular type of flow and morphology. Examples include riffles, glides, cascades and pools.
- Fluvial geomorphology** The study of river landforms and the processes that create and rework them.
- Fluvio-glacial features** Surficial drift or landforms created as a result of the deposition of glacial material by meltwater during deglaciation.
- Gabion (basket)** A wire basket, generally filled with stones and widely used in river engineering to stabilise riverbanks and construct croys.
- Geomorphic** Landforms and associated processes that form them.
- Glaciation** A period during which the landscape becomes covered by ice sheets and glaciers. This ice cover repeatedly expanded and contracted during the Pleistocene (between 2.6 million and 11,500 years ago).
- Glide** A flow type characterised by smooth, slow and laminar flow. Quicker flowing and shallower than a pool.
- Gravel** A particle approximately between the size of a tennis ball and a pea (specifically with an intermediate axis size ranging from 2 mm to 64 mm).
- Head cut** A moving knickpoint associated with the erosion of a river bed in an upstream direction triggered by natural or artificial over-deepening of the bed.
- Holocene** The current warm, post-glacial period (i.e. the last 11,500 years).

Glossary

- Hydraulics** The study of flow patterns, depths and velocities
- Hydrology** The study of the water cycle: water evaporation, precipitation, storage, distribution and runoff. Also used to refer to the flow characteristics of a river or catchment.
- Hydromorphology** Term used in EU Water Framework Directive documentation to encompass the physical nature of river systems (i.e. hydrology and fluvial geomorphology) that support freshwater habitats.
- Hyporheic** An aquatic zone beneath the bed of a river where ground- and surface-waters mix, thought to provide an important refuge and nursery habitat for aquatic organisms.
- Ice age** The period of alternating cold (glacial) and warm (interglacial) phases that began 2.6 million years ago.
- Invertebrates (stream)** Small animals (without a backbone) that live on the bed or surface of the river and amongst vegetation. Includes fly larvae, beetles, snails and leaches amongst others. They form an important source of food for larger animals and can be a useful indicator of stream health.
- Knickpoint** A geomorphic term describing a short steep section of riverbed marking the upstream limit of headward erosion, or where a river crosses resistant bedrock to form a step in the longitudinal profile.
- Lateral connectivity** A concept that quantifies the linkages between river channel and habitats at the margins and on the floodplain, including the flow of water and exchange of sediments and organic material.
- Longitudinal profile** Delineation of the downstream change in channel gradient from source to mouth. Profiles are typically concave with steep headwaters and low gradients towards the sea.
- Low order stream** A first or second order stream. First order streams refer to the channels at the very start of the river network, e.g. flowing from a spring. When two first order streams join they form a second order stream.
- Macrophytes** Small to large plants that grow entirely or partially submerged in water or float on the water surface.
- Mainstem** The principal river channel within a stream network. This can normally be identified in the upstream direction by following the largest channel at each confluence, from the river mouth to its source. The catchment will frequently be named after the mainstem.
- Meander** A curve in the planform of a river.
- Morphology (stream)** The size and shape of a stream and nature of its component fluvial habitats.
- Multi thread** A river channel that is divided by bars or islands.
- Natural Flood Management (NFM)** An approach to managing flood risk through the conservation, restoration or enhancement of natural features and processes, that store and slow the flow of water, with the aim of reducing flooding downstream.
- Overland flow** The flow of water over the ground surface. This occurs when infiltration is impeded due to saturated soil, impermeable geology or during heavy rainfall when the rainfall exceeds the infiltration rate.
- Oxbow (lake)** A small lake formed by the cut-off of a river meander bend.
- Palaeochannels** Remnants of channel marking a historic course of the main river and often hidden by vegetation. These may be in-filled with sediment, or open, but convey flow during large floods.
- Piedmont** A mountain valley floor characterised by moderate gradients.
- Planform** The morphology of a river when viewed from above or as depicted on a map.
- Pool** A deep, very low velocity flow type associated with areas of low river channel topography.
- Physicochemical** Synonymous with physical chemistry. In river systems common physicochemical variables collected are temperature, conductivity, dissolved oxygen and the concentration of dissolved nutrients.
- Quaternary** The period of alternating cold (glacial) and warm (interglacial) phases that began 2.6 million years ago.
- Reach** A term used to refer to a length or section of river as delineated by specific factors or features of interest. For example, a reach may contain a characteristic assemblage of bedforms (e.g. pools and riffles) and be marked out by a change in river type.
- Realignment** An alteration to the course of a river channel. Realignments have often been constructed to permit urban development and are increasingly used as a tool for channel restoration.
- Revetment** Revetments are constructed to protect a surface against erosion, most commonly as part of coastal defences but also to stabilise river banks. They may involve an artificial surface of concrete, stone or wood.
- Riffle** A shallow steeper section of river characterised by higher water velocities and unbroken standing waves appearing as ripples on the water surface during average discharge conditions.
- Riparian** A term used in river science to refer to the transition zone between aquatic and terrestrial habitats.
- River corridor** The area including the current active river channel and its adjacent land.
- River health** A measure of the 'functional' status of a river ecosystem.
- Rubble mat** Artificial structure used to enhance in-stream habitat.
- RRC** The River Restoration Centre. A national information and advisory centre on all aspects of river restoration and enhancement, and sustainable river management. www.therrc.co.uk
- Sand** Fine sediment that feels gritty when rubbed between thumb and forefinger. Specifically with an intermediate axis size that ranges from 2 mm to 0.0625 mm.
- Sediment** An inorganic particle of any size.
- Sediment supply** A measure of the delivery of sediment load to a section of river from external sources (e.g. hill slopes) or internal sources (e.g. river bed and bars).
- SEPA** Scottish Environment Protection Agency. The governmental body tasked with protecting and improving Scotland's environment through regulation of harmful activities, and ensuring compliance with legislation and good practice. www.sepa.org.uk
- Silt** Fine sediment that feels smooth when rubbed between thumb and forefinger. Specifically with an intermediate axis size that ranges from 0.0625 mm to 0.001 mm.
- Siltation** The deposition of very fine sediment and organic matter that smothers the original substrate, infilling spaces between existing gravels or accumulating on the substrate surface.
- Single thread** A river channel that is undivided by bars or islands.
- Sinuosity** An index that describes the length of the river channel relative to the length of the valley through which it flows. High values correspond to tighter curving meanders or a greater number of meanders.

Glossary

SNH Scottish Natural Heritage. The governmental body tasked with improving and promoting education, care and sustainability in all matters relating to Scotland's natural environment. They are also responsible for conservation sites. www.snh.gov.uk

Step-pool A bed morphology consisting of alternating boulder steps and pools.

Stream order A classification system used to grade the tributaries within a stream network by downstream order. A number of different approaches have been developed.

Stream power A numerical measure of a river's ability to erode, transport and deposit sediment. Stream power is dependent on channel slope and stream discharge.

Stream power (Unit) A measure of stream power per unit width of the river channel or floodplain.

Substrate The material that the bed of a river channel is composed of.

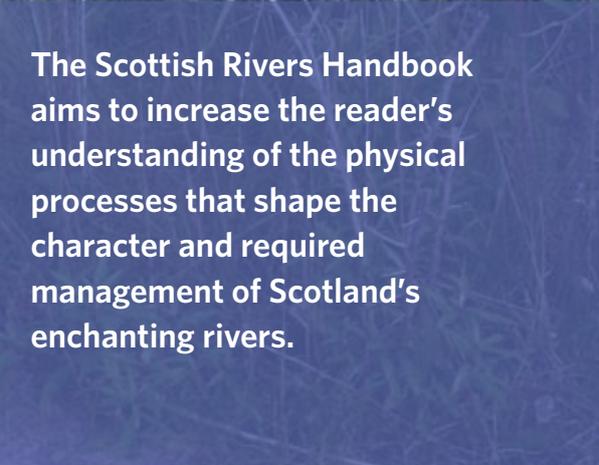
Suspended sediment Sediment carried in suspension in the water column.

Terrace Relict floodplain surface found at the margins of the valley floor. These are formed through incision by a river of glacial, fluvio-glacial or alluvial deposits. Where a river has incised bedrock, strath terraces are formed.

Thalweg The deepest and most continuous path of water flow within a river channel.

Transport capacity (Sediment) The ability of a river channel to transport a sediment load (i.e. the total quantity of sediment).

Tributary A stream or river that joins a mainstem of a river network.



The Scottish Rivers Handbook aims to increase the reader's understanding of the physical processes that shape the character and required management of Scotland's enchanting rivers.