For the future of our environment

Will the river do the work?

A practical guide for assessing river recovery potential and directing when passive river restoration measures can be used to allow rivers to self-heal

June 2023

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Executive Summary

River channels have undergone significant modifications, resulting in degraded habitats and reduced biodiversity (see Figure 8). Finding ways to create more resilient and sustainable riverscapes at the landscape scale is essential for delivering multiple benefits including increased biodiversity, improved water quality, supressed and less frequent flood peaks, improved drought resistance, greater retention of valuable soils and increased carbon capture. Restoring channel morphology, through allowing more diverse and better condition habitats to form, is integral to delivering this. Whilst full scale restoration will be necessary in some locations, in others it is perceived that the river will be able to 'self-heal' in situ with little or moderate intervention. The ability of a river to 'self-heal' is implicitly linked to its energy environment and its sediment load (Figure 9). Therefore, this report sets out how channel energy referred to as 'recovery potential' can be assessed and used to develop restoration approaches which work with the functioning of the system, decreasing the costs and increasing the scales at which restoration can be applied.

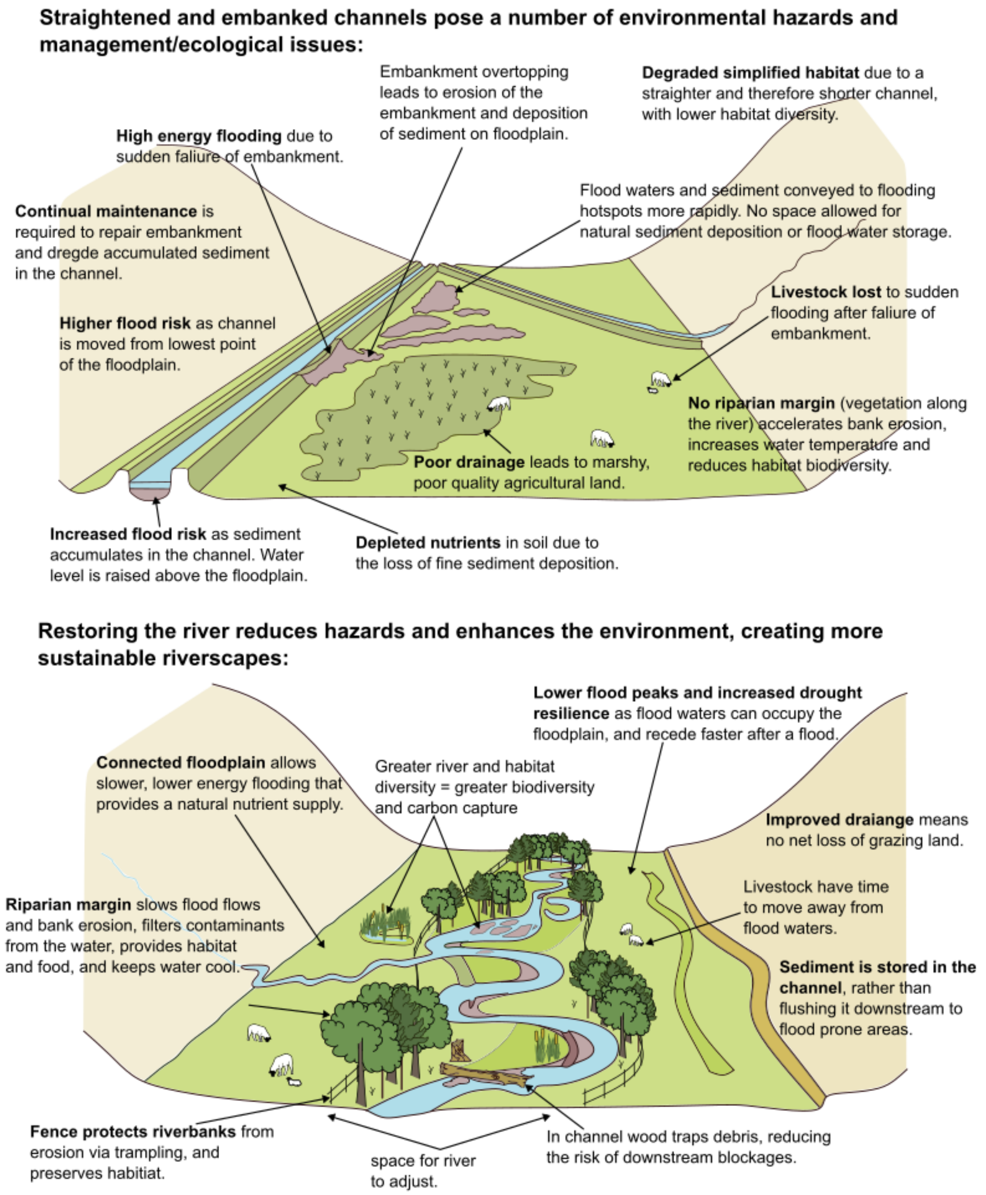


Figure A: Differences in the functioning between straightened and 'natural' rivers. Modified from Environment Agency/Jacobs (2010).

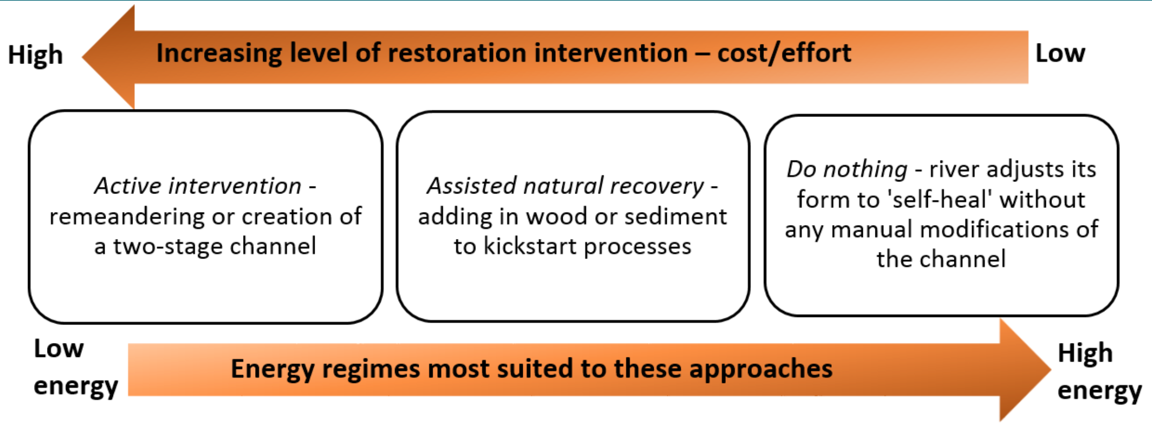
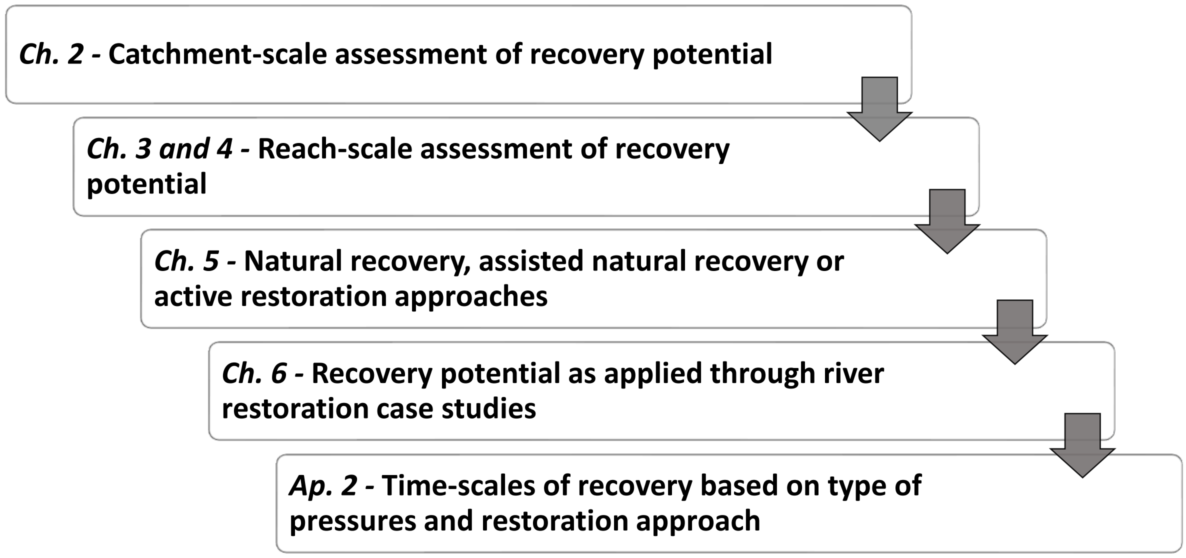


Figure B: Continuum of where different river restoration approaches can be used based on the energy regime of the river and cost and effort required for delivery.

The report covers the following five topics, each of which are summarised below.



This guide is primarily intended for anyone interested in either carrying out catchment scale scoping for river restoration/waterbody improvements or designing a river restoration scheme. This includes regulators, consultants, river trusts and river managers. Whilst it has been written for a generalist ‘river practitioner’ audience, some basic understanding of geomorphology and river processes are expected.

Chapter 2 - Catchment scale assessment of recovery potential

Chapter 2 describes the approach to analysing recovery potential at the catchment scale. This was carried out using specific stream power (SSP) which was mapped remotely at every 50 m for baseline waterbodies (catchment area > 10 km^2) across Scotland. This provides a measure of channel energy based on the discharge and slope of a reach of river. 7235 kms of river were walked and the river type recorded. River types were then categorised based on qualitatively assessed recovery potential (inherently linked to the character and behavior of that type of river – see Table 1). From this, thresholds were created so that SSP values could be used to directly map recovery potential, predicting how much a river can adjust, thus being able to improve its condition and self-heal (see key on Figure C). This allowed the recovery potential to be mapped across Scotland (Figure C), providing a key tool for use in catchment planning. These data can be viewed on Map | Scotland's environment web. Through understanding where rivers have the energy to self-heal, restoration can be designed to work with this natural capacity for recovery. In addition, it allows identification of where rivers have lower energy and would not be able to self-recover within practical timescales, meaning these reaches will require more hands-on active restoration.

Table 1: Table indicating which river types fall into which catchment-scale recovery potential category.

Recovery Potential Category	**River Type**
Resilient to Change (RTC) – Confined valley and bedrock dominated reaches, unable to undergo significant adjustment	Bedrock, Cascade
High Recovery Potential – An ability to adjust channel form rapidly in response to changes in channel processes with a high capacity to self-heal	Step-pool, Plane-bed, plane-riffle, braided, wandering
Moderate Recovery Potential - Still have the energy required to adjust following change but over longer timescales, compared to high recovery potential reaches	Active meandering
Low Recovery Potential – Low energy and therefore slow recovery times with limited capacity to self-heal within realistic timescales.	Passive meandering, Peat

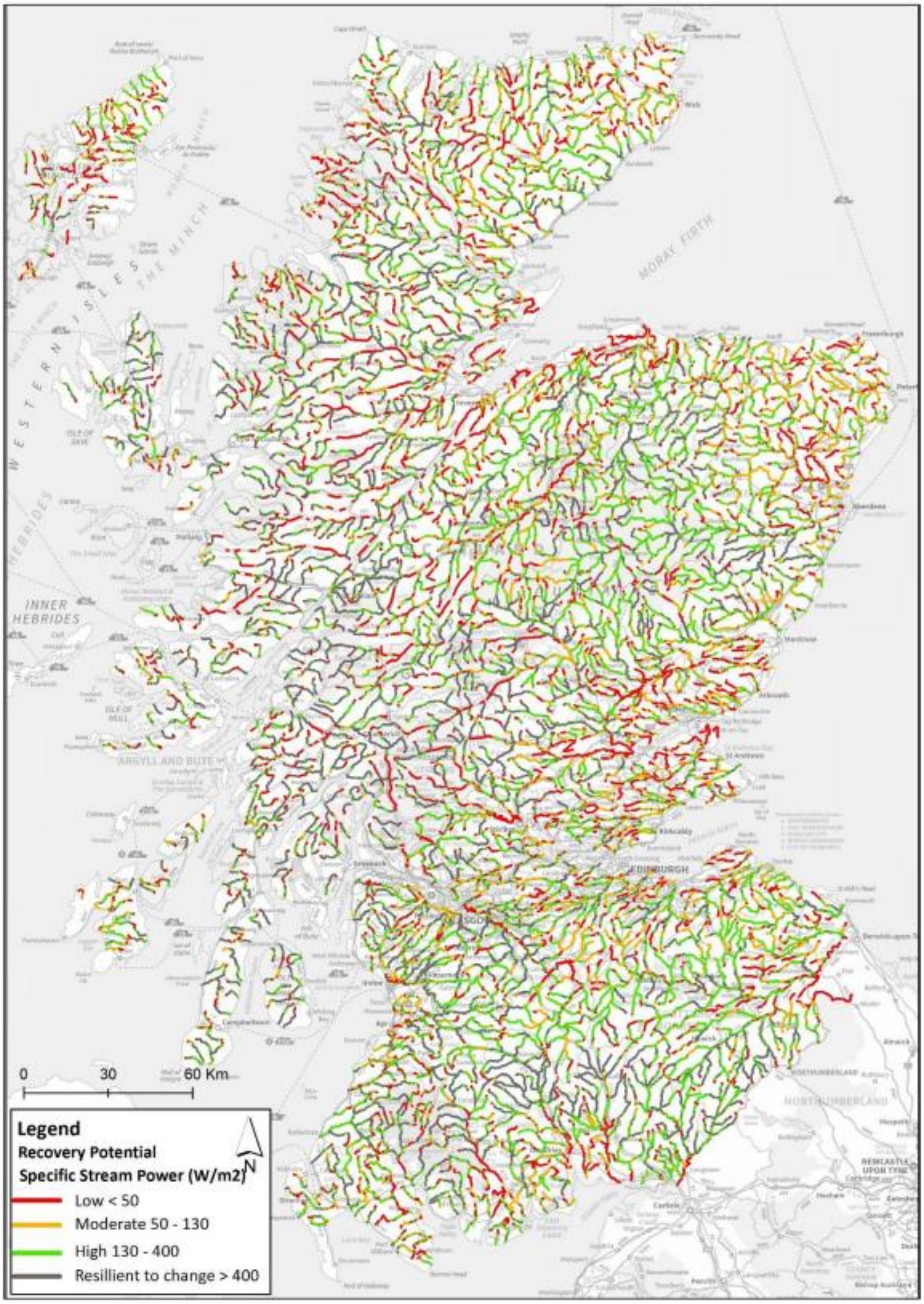


Figure C: Map displaying the recovery potential for all baseline river waterbodies in mainland Scotland. The key shows the specific stream power values that were used to delineate between recovery potential categories.

Chapters 3 and 4 - Reach-scale analysis of recovery potential

Whilst catchment-scale Recovery Potential is useful for understanding the distribution of river energy across the catchment, uncertainties exist as would be expected for remotely sensed data at a national scale This includes the exclusion of consideration of sediment load, a key determinant of river behaviour. Therefore, once reaches have been identified for restoration through catchment scale scoping, recovery potential should then be assessed in more detail, through a reach-scale geomorphic field survey. This report provides a simple, user-friendly guide to carry out a reach-scale assessment of recovery potential through identifying the key geomorphic attributes that both control (e.g. valley confinement, bank material) and describe (bed material size and bar frequency) the energy and sediment load of a reach (see Figure D for full list of geomorphic variables).

Figure D: List of geomorphic variables and what they indicate about the recovery potential of the system and summary of the different river types, the likelihood of them needing restoration, type of restoration required and their recovery potential category.

Each variable is assessed specifically to maximise understanding regarding the energy, sediment load and capacity for adjustment of the reach, creating targeted outputs that describe recovery potential. Each variable is described in detail, with figures and descriptions guiding the user to carry out an assessment, regardless of geomorphic training (though a baseline understanding of river processes is required). Figure D provides an example for the river type variable, showing how the assessment of river type is tied back to the functioning of the river and the types of restoration that are likely to be successful.

River Recovery Potential Field Sheets:

Site name:		WB ID:	
Date:		Surveyor:	
Flow conditions:		Weather:	
US grid ref:		DS grid ref:	

Instructions: 1) Fill in the boxes below describing each of the attributes. 2) Circle the recovery poten judged for each attribute. Recovery potential categories are ***(X)** resilient to change*, ***(H)** high recove* ***(M)** moderate recovery potential*, ***(L)** low recovery potential and **(A)** anthropogenic influenced*. 3) Trans potential score to summary table and use this to calculate overall recovery potential.

1. Valley confinement

(X)	*(H)*	*(M)*	*(L)*
Describe your valley setting:			

2. River Type (Reference – i.e. what it would have been in its natural state)

(X)	*(H)*	*(M)*	*(L)*
Describe the characteristics of your river type:			

3. Bed Material

(X)	*(H)*	*(M)*	*(L)*
Describe range of bed material			

4. Bar Frequency

None due to bedrock (X)	*Many (H)*	*Some or few (M)*	*None (L)*	*anti*
How frequent are bars within the reach and where are they located?				

5. Bank Grain Size

(X)	*(H)*	*(M)*	*(L)*
Provide a description of the characteristics of your banks sediment, including how cohesive it is.			

Summary of attributes:

This river was a medium energy active meandering channel with sand on the margins, and gravels and cobbles on bed. It exhibited a lot of bank erosion, partly due to poaching and grazing and partly from recovering from past straightening. This included erosion on straight sections of the bends.

Geomorphic variable	Description	Recovery potential category
Valley Confinement	Moderate gradient unconfined valley setting	**M**
River Type	Medium energy active meandering	**M**
Bed material size	Cobbles, gravels and sand on margins	**M**
Bar frequency	Few	**M**
Bank grain size	Silt	**M**
Bank erosion	High as present on the straight sections as well as bends	**H**
Flow Types	A mix of moderate to low riffle – run – pool and glide units	**M**
Overall recovery potential – Moderate (M)		

Preferred restoration option:

This channel is at the higher end of moderate and is not incised. The preferable restoration option would be assisted natural recovery, using Engineered Log Jams or similar to kick-start adjustment. Once sinuosity has increased, planting a riparian margin would be essential to improve overall condition.

Figure E: Example of reach-scale assessment field sheet and overall output assessment table for a reach of the Mye Water, a tributary of the Forth in Stirlingshire.

Chapter 4 describes how the outcomes of each variable are combined to present an assessment of the overall recovery potential of the reach. This chapter also defines each recovery potential category, relating the energy and sediment environment to the type of management that is likely to be successful in that setting. An example of the field sheet and a reach-scale recovery potential output assessment table is provided in Figure E. Full field sheets enabling simple and straightforward data collection are provided in Appendix 1.

Chapter 5 - Natural recovery, assisted natural recovery or active restoration approaches

Chapter 5 discusses different restoration techniques, assessed with regards to how they fit within a continuum of effort from passive restoration to active restoration (see Figure F). These are separated into the following three categories; Natural Recovery, Assisted Natural Recovery and Active Intervention. Each are described below;

- 'Natural recovery' involves actions within the vicinity of the river that allow recovery to commence. For example, withdrawing maintenance or planting a riparian margin. This may also include removing bank or bed protection and breaching embankments if these pressures are impeding natural recovery. This does not include measures which manually alter the channel form.
- Assisted natural recovery (ANR) includes removing hard engineering and kickstarting processes in-situ. For example, installing wood structures or injecting coarse sediment to alter patterns of erosion and deposition, causing the river to increase its sinuosity (and as a result channel diversity). This should alter the dynamics of the channel, so that the river starts moving along a recovery trajectory.
- Active restoration includes measures whereby the pressures are manually removed and a new river is designed and physically altered to restore a more natural, pre-modified alignment and/or channel characteristics. Most commonly, this includes remeandering the channel to increase sinuosity but can also include embankment removal or creating two-stage channels.

This presents a framework that combines the assessment of recovery potential with practicalities of the types of river management that are most likely to be successful at a given location. This means management can be better designed to work with and enhance the existing channel processes.

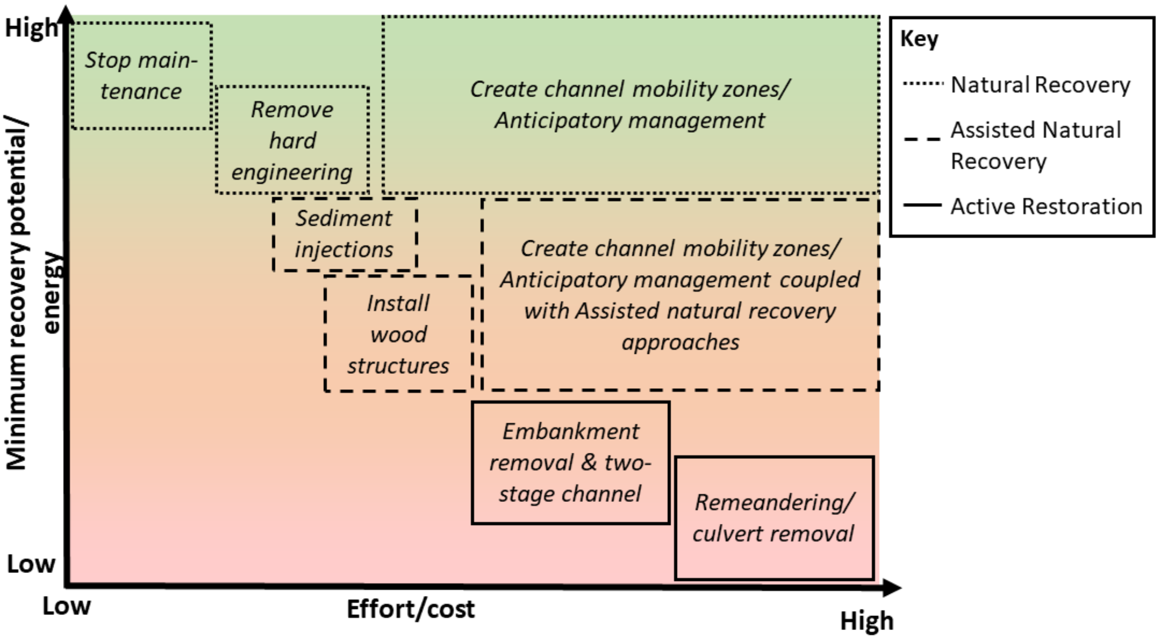


Figure F: Continuum of restoration options based on the minimum recovery potential needed for that approach to be successful and costs and degree of effort required for each approach. Approaches are separated into natural recovery, assisted natural recovery and active restoration categories.

Chapter 6 - Recovery potential as applied through river restoration case studies

Chapter 6 presents restoration case studies. This showcases a range of restoration approaches that have been applied mostly within Scotland on rivers within different energy environments. Reach-scale assessments of recovery potential prior to restoration are presented for each case study. The restoration approach and channel response are then assessed based on understanding how the channel's recovery potential shaped this recovery. For example, the Allt Lorgy had a high recovery potential. The restoration approach was assisted natural recovery and included removing embankments and bank protection and installing large wood structures. Due to the high sediment load and energy of the reach, recovery was swift and it has now undergone significant increases in habitat diversity (Figure G), illustrating the value in using ANR techniques in these landscape settings. Overall, this found the recovery potential approach to be successful in predicting outcomes based on the type of restoration applied. The success of this demonstrates the applicability of the approach and highlights the use of the framework for designing river restoration.

Figure G: Pre and seven years post restoration photographs of the restored section of the Allt Lorgy showing the dramatic increase in channel diversity following embankment removal and installation of wood to increase channel diversity. Pre photos supplied by H. Moir, cbec and post by Richard Williams, University of Glasgow.

Appendix 2 - Time-scales of recovery based on type of pressures and restoration approach

Appendix 2 uses recovery potential to predict how long it would take for a river to recover from each type of engineering pressure (e.g. straightening, bank protection, culvert removal, etc.) depending on the type of restoration that is carried out (natural recovery, assisted natural recovery or active restoration). Table 2 provides an example of predicted recovery times for rivers that have been impacted by straightening with little recovery (i.e. high impact realignment). This presents a useful tool for river basin planning, to decide what approaches to use and what recovery times might be acceptable. This also allows these time scales to be communicated both for planning purposes and for stakeholder engagement so realistic expectations are set, and project success linked to realistic timescales.

Table 2: Recovery times for rivers that have been straightened and are high impact realigned (HIR) based on a reaches recovery potential and the type of restoration delivered.

Recovery potential	Treatment	Recovery time (years)	Comments
High	*Active intervention*	< 6	Fast recovery based on full remeandering
	Assisted Natural Recovery	6 - 12	This is based on using ELJs and if necessary, gravel injections to kick-start processes. May require pressure removal (i.e. bank protection) if present
	Natural Recovery	6 - 18	Recovery based on if there is nothing impeding adjustment – i.e. bank protection. Depends on the energy and sediment of the reach
Moderate	*Active intervention*	< 6	Fast recovery based on full remeandering
	Assisted Natural Recovery	12 – 18	This is based on using ELJs and, if necessary, gravel injections to kick start processes. May require pressure removal (i.e. bank protection) if present
	Natural Recovery	18 - 42	Time would vary depending on energy of reach
Low	*Active intervention*	6 - 12	Fast recovery based on full remeandering even for low energy
	Assisted Natural Recovery	18 - 30	This is based on using ELJs and if necessary, gravel injections to kick start processes. May require pressure removal (i.e. bank protection) if present
	Natural Recovery	36 +	This could take a very long time if energy is very low, especially for peat systems or those with clay banks

Conclusion

This report presents an approach which uses both catchment and reach-scale analysis of energy to assess a rivers ability to self-recover. The former provides a coarse resolution overview of the recovery potential through a catchment that can be useful for planning, whilst the latter assesses the geomorphic attributes of a reach and is essential to ground the coarser scale of analysis as well as providing the detail needed for local scale restoration planning. The key is identifying where natural recovery and assisted natural recovery restoration approaches can be delivered successfully, with the channels recovering within acceptable timescales. If the use of this approach can be optimised, then restoration can be carried out over longer reaches of river at a lower cost, maximising the environmental benefit and ensuring the restoration works with the natural functioning of the river. It also allows the river to 'self-heal', rather than the habitats being designed, meaning the river can enhance the existing condition, rather than starting from scratch with a new, constructed channel. Having healthy and well-functioning channel and riparian margins is key to protecting and enhancing biodiversity, reducing flood flows by better connecting the river with the floodplain and creating more resilient and sustainable riverscapes.

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Chapter 1: Introduction

River systems are one of the most degraded and oversimplified ecosystems on earth, leading to disproportionately high extinctions of freshwater biota (WWF, 2016). In addition, the threat of climate change increasing flood risk means that how these systems are managed has significant implications for whether this risk is amplified or supressed. Thus, finding ways to create more resilient and sustainable riverscapes at the landscape scale is essential for delivering the multiple benefits possible from these systems including increased biodiversity, better water quality, supressed and less frequent flood peaks, improved drought resistance, greater retention of valuable soils and increased carbon capture. Restoring channel morphology is integral to delivering this. Primarily this includes restoring channel form and processes, allowing more diverse and better condition habitats to form, which support greater biodiversity. Natural channels also slow the movement of water through the catchment, through more sinuous, rougher channels which can be reconnected to the floodplain, thus, reducing flood peaks in the lower catchment. Riparian margins can work with restored morphology to reduce water temperatures, increase food input to the river and filter pollutants, enhancing the benefits to both nature (biodiversity) and people (water quality). More diverse river systems which are connected to the floodplain retain more soils and woody material, increasing the capacity of the reach to store the soil needed for agriculture and increase the retention of carbon. Finding techniques and tools to improve the morphology of river systems at the catchment/landscape scale of the problem is essential for reaping these benefits. This report presents an approach for identifying where rivers have the energy to adjust and 'self-recover', meaning management can be designed to work with that recovery across greater scales, reducing the need for more expensive interventionist forms of restoration.

Rivers within Scotland have undergone substantial anthropogenic modifications, meaning their ability to adjust as they would naturally is significantly impaired, reflected in many failing Water Framework Directive (WFD) objectives due to physical pressures. These modifications to the baseline river network include a legacy of channel straightening (4150 km or 17%), embankment installation (1519 km or 6%) and bank protection (570 km or 2.3%), which have degraded channel morphology, making rivers unable to support the diverse and healthy ecosystems they would naturally. River restoration has been developed as an approach to reverse these anthropogenic channel alterations and associated ecological impacts. Restoration schemes are most often based on intensive techniques that actively construct a new channel. While this delivers the desired results, such an intensive approach to restoration is expensive, and not feasible to carry out on all the degraded rivers in Scotland. In addition, if a reach has already undergone some recovery (e.g. a previously straightened channel increasing its sinuosity via bank erosion), it may be less damaging and yield better results to work with this recovery (e.g. using wood structures to accelerate lateral adjustment), rather than resetting the whole system in the form of digging a new river channel.

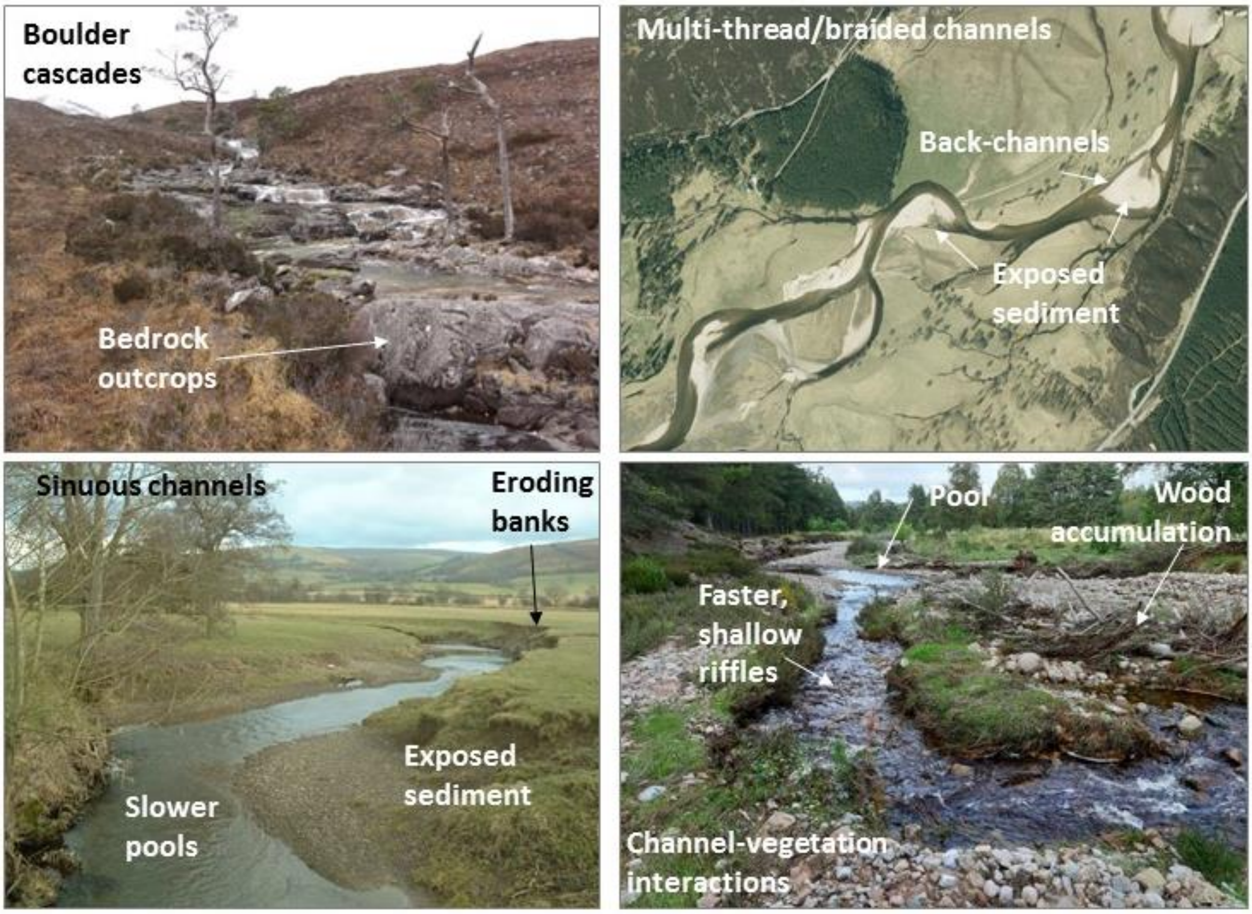
The river recovery approach outlined in this guide is based on assessing the geomorphic processes of a river channel. Geomorphology is the study of landforms, their processes, form and sediments at the surface of the Earth (British Society of Geomorphology, 2019). Fluvial geomorphology applies this to rivers specifically, looking at how a river adjusts and the impact of this resulting morphology upon aquatic habitats.

This guide assesses the geomorphic characteristics of a reach of river considering how much energy the channel has to adjust. This is carried out at a coarse resolution at the catchment-scale based on stream power (energy) and at a finer resolution at the reach scale based on field-based assessment. This provides a foundation, which is used to identify the likely recovery time for passive and active approaches to restoration, based on the types of anthropogenic pressures impacting the reach. Finally, the document reviews active, assisted natural recovery (ANR) and passive approaches to restoration, discussing where each is best applied and provides case studies of river restoration that have been delivered. Thus, this guide provides the tools to answer the question of 'will the river do the work' necessary to improve its morphological condition, and how much assistance will managers need to provide? A full step by step outline of the approach is presented in Section 1.4. The next section provides an overview about the importance and benefits of rivers with healthy morphology.

1.1 Why is restoring morphology important and how does it benefit people?

This section provides greater detail on why morphological diversity is important and integral to river health, and how different types of anthropogenic modifications have impacted systems.

Natural rivers and their associated floodplains are physically diverse with features such as;



Through a legacy of channel modification, much of this diversity has been simplified or just lost. Whist these modifications achieved benefits for people, they had unintended consequences which have created a costly cycle of erosion protection, dredging, flood protection and maintenance and have resulted in loss of biodiversity and declining freshwater fisheries. Examples of modifications include;

- Straightening sinuous rivers to enable easier use for agriculture (create straight field boundaries).
- Deepening and sometimes widening of rivers to improve land drainage.
- Building embankments along river banks to prevent inundation of the floodplain.
- Reinforcement of river banks with rock and other matter to prevent erosion.
- Removal of trees, shrubs and tall grasses from river banks and floodplains.
- Weirs and dams to store, divert and/or abstract water.
- Bridges and culverts to provide crossing points for roads, railways and services.

These modifications have had significant effects on the processes of change (see Figure 8) with direct and in-direct effects on habitats and other benefits such as;

- **Straightening** both decreases the channel length and increases the channel bed slope. Shorter river channels means a *decrease in the area of habitats. Habitats also* *become simpler and more uniform* as the bends in the river create the diverse habitats i.e. deep pool and faster riffle habitats disappear.

- **Embanked** rivers contain more water (and therefore energy) within the channel during floods, *preventing the dissipation of energy* and filtering of fine sediment in the floodplain.
- Straightening or embanking rivers i*ncreases stream energy and erosion*. This results in finer sediments, plants, fishes and bugs being flushed downstream, leaving a channel bed with coarse and *oversimplified habitat.*
- **Straighter/deeper channels** transfer flow downstream more quickly, *increasing flooding*.
- **Regular maintenance (dredging and bank repairs)** is then needed to keep the channel straight, *damaging habitats* further.
- **Bank reinforcement** prevents erosion (an important energy dissipation mechanism) and therefore stops the adjustment of the channel, *fossilising the habitats* within the channel. This also results in e*rosion upstream and downstream of the protection*, as erosion (energy dissipation) is simply transferred elsewhere.
- **Removal of trees, shrubs and tall grasses from the banks and floodplain** removes an important energy dissipation mechanism and reduces the cohesion of bank material. This can *increase bank erosion* and increase the speed which water moves downstream, *increasing flood risk* for downstream reaches.
- **Weirs and dams** create altered flow regimes and slows or stops the natural transfer of sediment down a river. This often means the river is "hungry" for sediment and *results in severe erosion downstream which degrades habitats*. *Habitat upstream of the weir is usually drowned out and covered in fine sediment.*
- **Bridges and culverts** fix the river in place at a particular point and can also restrict flow. This can lead to *localised erosion/bed lowering which can damage/undermine the structure* and prevent upstream and/or downstream *passage for fish and other ecology.* Creating more sustainable, resilient riverscapes relies on undoing the damage of these modifications where feasible and giving river channels the room to adjust to recreate the diversity that is synonymous with natural systems.

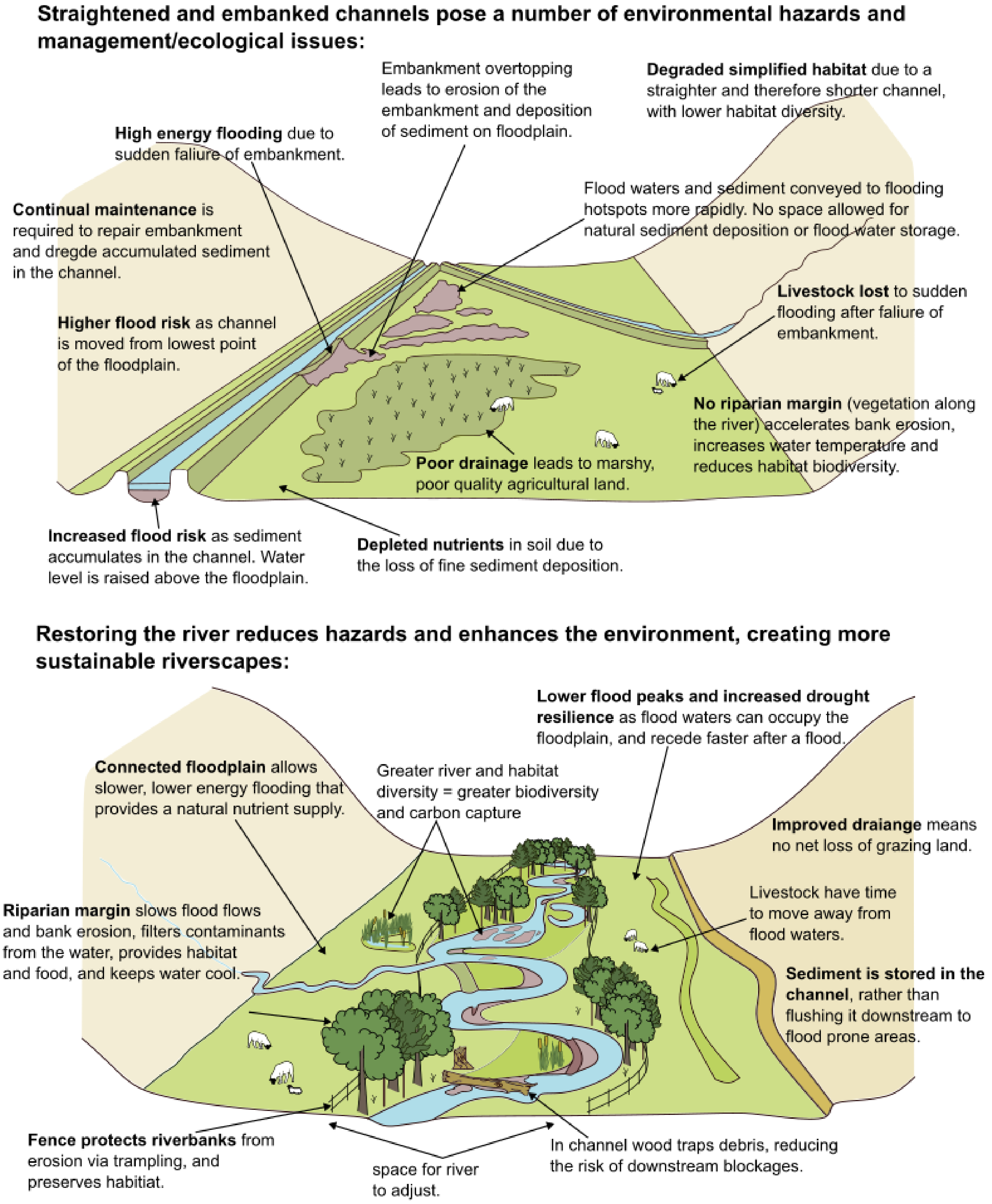


Figure 8: Differences in the functioning and between straightened and 'natural' rivers. Modified from Environment Agency/Jacobs (2010).

<u>What creates diversity within river systems?</u>

- Channel diversity is driven by differing rates of erosion and deposition over time and space in response to changing flow.

- Sediment transport and erosion and are key mechanisms by which rivers dissipate energy. For example, energy is used eroding and transporting sediment.
- Vegetation on the bed, banks and floodplain play an important role in the processes of change by providing roughness, which helps to dissipate flow energy, decreasing erosion of these surfaces. It also increases physical diversity by creating complex flow patterns.

Supporting this natural functioning creates a range of benefits to people and wildlife as summarised in Table 3.

Table 3: Summary of the benefits of diverse and dynamic riverscapes.

Variable	How healthy river systems benefit each variable
Ecology	Provides a constantly changing and diverse range of habitats for ecology to utilise
Food chain	A healthy riparian margin provides the primary food which supports the food chain (insects → fish → us and other larger species)
Resilience to climate change	More intense rainfall = more frequent high flows. Rivers will need to change more to adapt to this change in flow regime. Rivers with room to adjust can absorb additional change more easily
Flooding	If water can temporarily be stored on the floodplain during floods, this can help slow the flow and reduce flood peaks downstream
Drought resilience	slowing the flow increases groundwater rechange. In-channel diversity provides habitat refugia such as pools and back channels for biota to hide in during low flow periods
Soil health	Regular inundation of the floodplain helps to retain soil and replenish nutrients (though large floods can scour land adjacent to the river).
Sediment transport	More natural rivers can regulate the patterns of erosion, transport and deposition of sediment in the river system. In constrained rivers, these processes can be amplified, leading to excessive erosion or deposition (i.e. either eroding and lowering or depositing and raising the channel bed)
Reduced maintenance	More natural systems are less likely to require expensive and damaging maintenance, such as dredging to retain their form
Decreasing blockages	Large wood and trees in rivers, on river banks and on floodplains trap other wood and debris, reducing the risk of these blocking structures such as culverts and bridges
Water quality	A functioning riparian margin can filter out fine sediment which can carry other pollutants and smother habitats. A healthy riparian margin consisting of trees also provides soil protection, reduced nutrient and other diffuse pollution run off, increased infiltration, increased roughness to slow floodwater, provides shade and helps regulate water temperature and has biodiversity improvements including reducing excessive algal growth
Drinking water quality	If the water supplied is less polluted, then less treatment is required to turn it into drinking water
Increased carbon capture	Rivers with a greater heterogeneity have a greater ability for the retention of wood, and coarse particulate organic matter, whilst those that are connected to their floodplains allow soil to be deposited on these surfaces. Both mechanisms increase carbon sequestration

Overall, restoring more resilient and natural systems presents an opportunity for mitigation of effects from changing climate by allowing the channel to adjust, storing a greater volume of water, dissipating energy of high frequency events, whilst the riparian areas store carbon and reduce temperatures in river. Hence, by physically restoring rivers, the natural environment is able to adjust and adapt to increase resilience to the effects of climate change.

1.2 What is 'self-healing' and when can rivers do it?

Whilst full scale restoration will be necessary in some locations, in others it is perceived that the river will be able to 'self-heal' in situ with little or moderate intervention (though this may include removing the pressures which have been impeding the recovery, such as bank protection) (Kondolf, 2011). Where this is possible, it allows rivers to reset their own form in response to changes in processes (i.e. sediment and water flows), allowing a more sustainable recovery compared to 'designed' river restoration. While the legitimacy of the letting the river do the work approach is well recognised in the literature, there is currently little guidance on how to identify when or where passive or active approaches could be applied. In addition, guidance regarding how to design and deliver passive approaches to restoration is not commonly available. This report aims to provide a simple, process-based methodology, which fills this deficit.

The ability of a river to 'self-heal' is implicitly linked to its energy environment and its sediment load. Therefore, the type of restoration measure to be implemented (Figure 9) should reflect these physical properties of the river system. For example, a high energy river with a high sediment load will recover faster from historical straightening than a low energy river with a low sediment load, as it possesses the energy to erode banks, increase sinuosity and has the sediment supply necessary to create depositional features (sediment bars), leading to a more diverse river. In contrast, a low energy river with a low sediment load is likely to require active restoration measures such as remeandering to improve geo-diversity (i.e. the diversity of the geomorphic structure), as natural recovery would take far longer in this type of system. Thus, recovery times vary according to the energy of the river and the degree of intervention carried out. This report will guide the user to assess the river type, energy regime and time scales of recovery.

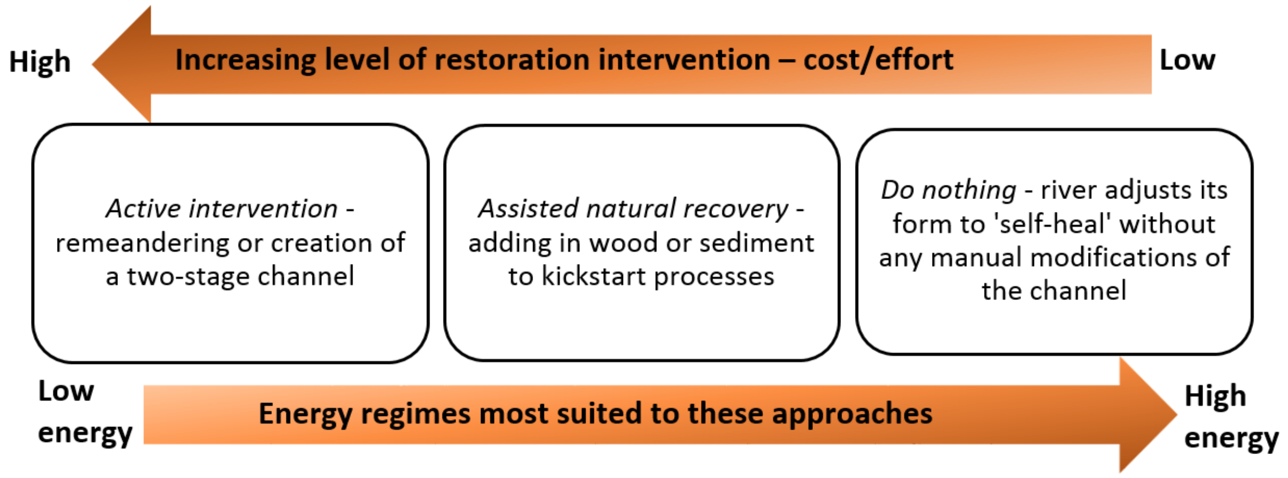


Figure 9: Continuum of where different river restoration approaches can be used based on the energy regime of the river and cost and effort required for delivery.

It is commonly overlooked that rivers still have to recover from more interventionist restoration (e.g. remeandering), meaning that in some circumstances applying more passive approaches can be ultimately less damaging for the system. This is because when we design river channels we have to predict what the structure should look like, which is difficult given the complexity of river systems. In addition, once a river has been restored, the previous structure is destroyed and replaced with a simplified template, upon which the river has to sort the sediment, to create the micro-scale diversity of habitats needed to support a diverse range of fauna. In contrast, a river which is allowed to 'self-heal' can slowly adjust its structure over time, creating a structure which is perfectly in-tune with the prevailing sediment and water fluxes. Habitats are created as this adjustment takes place and ecology similarly adapts accordingly. This report aims to understand and communicate the balance between the degree of intervention and recovery time (i.e. different levels of intervention may result in the channel recovering to a similar condition, depending on the energy of the system). Practitioners should therefore identify whether restoration via natural recovery, assisted natural recovery or active intervention should be applied for a particular reach, based on the local geomorphology, a function of its energy and sediment load. This aims to ensure that approaches are location specific and deliver improvements using minimal effort/cost and achieve maximum gain, maximising the opportunity to deliver WFD objectives.

This report separates restoration approaches into three categories, which are used throughout the document to describe differences in passive and active restoration;

Natural Recovery – This includes measures, which do not have any direct impact upon channel morphology, such as withdrawing maintenance from a previously maintained system or working adjacent to the channel (e.g. riparian planting or fencing). This also includes removal of pressures which may be inhibiting recovery, such as bank protection or breaching of embankments (if needed based on the how intact these are and the likelihood of the river to erode them). The key premise is, that anthropogenic impacts in the environment affecting the river channel are reduced, to allow natural recovery to start. Thus, in-channel processes are not directly impacted. Consequently, this approach may take longer to reach its endpoint than active intervention or ANR (both which include in-channel change), but like ANR this approach has the added benefit that the river will have created the most appropriate channel form for its setting and prevailing conditions.

Assisted Natural Recovery (ANR) – ANR includes passive measures which are installed to kick-start processes and encourage the river to adjust in-situ, so that it moves towards a more natural and healthy morphology. This includes (similar to Natural Recovery) removing hard engineering (e.g. bank protection) and/or breaching embankments, which does not actually cause river adjustment, but removes or reduces constraints that were preventing recovery. However, this differs from Natural Recovery as it also includes measures designed to alter the in-channel processes, increasing erosion and encouraging the channel to create a more diverse form. Examples include installing in-channel features such as deflectors made of wood, channel narrowing and inputting additional sediment. These measures are commonly implemented with the aim of increasing sinuosity in a straightened river by creating erosion where meander bends are predicted to develop, as a sinuous river would be associated with a greater diversity of in-channel features (e.g. riffles, pools, bars, eroding banks). Effective use of ANR first involves assessing what the river should be like under conditions of low human intervention and then using measures to encourage the river to adjust towards this endpoint. As a result, it can take longer for reference geomorphic processes (and the habitats they support) to be re-established, in comparison with active intervention. However, because the river will have created the end result, its morphology and associated habitat assemblages are more likely to be appropriate for the channel characteristics. While this is lower risk than active restoration, there is an inherent risk if the measures are not specifically designed based on the energy level of the system and these measures may need to be maintained over time.

Active Intervention – This refers to full restoration where a new river channel is constructed and land is actively moved. The most obvious example of this is remeandering a channel. However, culvert removal and raising or lowering floodplains can also be included. This involves designing what the river should look like and then building to that endpoint. This often includes designing the channel attributes including bed material size, channel geometry, channel bed slope and bank slopes. Although this form of restoration can move the river closer to the desired endpoint faster (than other approaches), there is a risk that the design parameters may not be appropriate, meaning the new channel will have to subsequently adjust its form to one more appropriate for the setting. In some cases, this may restrict the river's ability to support quality habitats.

Full descriptions of restoration measures which are included under these approaches including case studies of where they have been applied in Scotland can be found in Sections Chapter 5: (should active or passive measures be used for restoration?) and Chapter 6: (case studies).

1.3 Who is the report intended for?

This guide is primarily intended for anyone interested in either carrying out catchment scale scoping for river restoration/waterbody improvements or designing a river restoration scheme. This includes functions within the Scottish Environment Protection Agency (SEPA) such as the Water Environment Fund (WEF) and River Basin Management and Planning (RBMP). It also includes restoration practitioners who work within Rivers Trusts, and environmental consultants who may be looking to deliver river restoration within higher energy environments. Whilst it has been written for a generalist 'river practitioner' audience, some basic understanding of river processes is assumed. For example, the reach-scale assessment of recovery potential requires simple, field-based analysis of a range of geomorphic variables, and a full guide detailing how this is carried out is included. This should enable river restoration practitioners who are less experienced in geomorphology to still be able to apply it. This guide has been written specifically for use within Scotland, and as such, the descriptions of river type and the majority of the case studies are based here. However, it could be applied elsewhere, especially within Great Britain, though the range of river types may need to be expanded based on what is present at a certain location (e.g. chalk streams).

1.4 Report Outline

This report can be framed around six steps, which guide the analysis. These are referred to as Steps A – F (see Figure 10). The following document goes through each step providing assessment techniques to answer each question. At the end of this approach, you should understand i) the broader scale distribution of energy across the catchment, ii) know how much energy and sediment load an individual reach has, iii) understand how likely it is to recover, iv) be able to evaluate whether active or passive restoration approaches should be used and finally v) have predicted the timescales of recovery based on specific pressures.

A

- **Chapter 2: How much energy do rivers in Scotland have?** This uses specific stream power data for all baseline waterbodies across Scotland to provide a coarse-scale prediction of recovery potential for use in catchment-scale planning.

B

- **Chapter 3: How can i assess the geomorphic processes of a reach to predict reach-scale recovery potential?** This presents a field-based tool which assesses the channels characteristics including energy regime and sediment load to assess its ability to self-heal.

C

- **Chapter 4: What is the recovery potential for my reach?** This section describes how reach-scale recovery potential is calculated including descriptions of characteristics and expected adjustment for rivers in each recovery potential category (i.e. High, Moderate, Low and Resilient to change).

D

- **Chapter 5: Should active or passive measures be used for restoration?** An overview of specific restoration techniques which fall into each of the natural recovery, ANR and active intervention categories to help assess whether active or passive restoration approaches are more beneficial for a specific scenario**.**

E

- **Chapter 6: Examples of restoration case studies.** Overview of restoration case studies from across Scotland which demonstrate the range of restoration approaches and assess the recovery potential of each reach, to show how recovery potential directly influences restoration outcomes.

F

- **Appendix 2: Using the rivers recovery potential, what are the times-scales of recovery based on the pressures present in the system?** This section predicts the time it takes for the river to reach good condition based on the type of pressure present and the type of restoration (natural recovery, ANR or active intervention) that is carried out.

Figure 10: Overview of the Chapters within this document and the individual steps that are contained which describe the approach to recovery potential.

Chapter 2: How much energy do rivers in Scotland have?

This section presents a Scotland-wide map of predicted catchment-scale recovery potential. At this scale, recovery potential is assessed using specific stream power, a measure of the energy a section of river has, calculated based on channel slope, discharge and channel width. This section describes the methods that were used to generate the map and presents catchment scale maps of recovery potential of existing restoration schemes.

2.1 Methods

The aim of this component was to provide a map of catchment-scale recovery potential across all baseline waterbodies in Scotland, based on the energy characteristics of each reach. Both slope and specific stream power were investigated to see which variable was best at identifying different types of river and therefore, categorising recovery potential.

Within rivers, energy is calculated as stream power (Ω). This expresses the rate of potential energy expenditure per unit length of channel (or the rate of doing work).

$$\Omega = \rho \, g \, Q \, s \qquad \text{(W/m)}$$

ρ is the specific weight of water, g is the acceleration due to gravity, Q is Discharge and s is slope. ρ and g are standard constants. Slope was derived remotely using the 5 m Nextmap DEM that is derived from radar data. Discharge was calculated for the 1 in 2 year return period peak flow using FEH method (CEH, 1999) which predicts discharge at a point using catchment area and data from the gauge networks across the UK.

$$\omega = \Omega / w \qquad \text{(W/m}^2\text{)}$$

This was converted into specific stream power (ω) by dividing stream power by the channel width (w), so that it expresses the energy per unit area of channel. Channel width data was extracted from the channel outline on the 2008 Ordinance Survey maps. This normalises the output so that wider channels do not have higher energy than narrower channels, making streams of different sizes comparable. Data was presented as one point every 50 m along baseline waterbodies.

The second channel attribute that was assessed was slope. This was extracted from the stream power layer as it is one of the inputs used to calculate stream power and was also derived from next map as described above.

Table 4: Table indicating which river types fall into which catchment-scale recovery potential category.

Recovery Potential Category	River Type
Resilient to Change (RTC)	Bedrock, Cascade
High Recovery Potential	Step-pool, Plane-bed, plane-riffle, braided, wandering
Moderate Recovery Potential	Active meandering
Low Recovery Potential	Passive meandering, Peat

At a coarse scale, recovery potential can be largely categorised based on river type (Table 4; this is covered in more detail in Section 3.2). This is because the type of river is a function of energy and sediment load. Table 4 presents the river types, which were allocated into each recovery potential category. 7235 km of river length was walked in Scotland by geomorphologists and the reference river type (the type of river that should be there if it wasn't modified) recorded. Reference type is not the optimal river type to use, as it describes what river should be there when it is restored, rather than what is currently there. Therefore, this was used to indicate the specific stream power ranges for the different types and then specific stream power used to calculate recovery potential. This provided a large field-based dataset which was used to analyse the range of specific stream power and slope values for each river type to see if they differed. Waterbodies were then split into reaches which were characterised based on having similar characteristics, namely slope and channel width (see SEPA, 2013). This meant that differences in energy for individual reaches could be identified at a finer resolution than the waterbody scale. Both specific stream power and slope were extracted and averaged for each homogeneous reach, which was then plotted based on river type. The output of this was used to identify thresholds which delineated reaches into recovery potential categories based on the specific stream power for their river type.

2.1.1 Identifying recovery potential thresholds

Overall, both specific stream power and slope showed that the different river types have distinct values that reflect the different recovery potential categories (Figure 11; Figure 12). There were two main exceptions. Specific stream power was lower than would be expected for step-pool river types, whereas slopes were comparable with the bedrock/cascade river type in the resistant to change (RTC) recovery category. This is because step-pools were located at steep locations but have low catchment areas (reflected in discharge) meaning that specific stream power is lower than would be expected. However, the specific stream power for step-pool streams was comparable for other river types in the 'high' recovery potential category, making this difference acceptable. In contrast, the peat river types had very low stream power as would be expected, but very high slopes, overlapping with the bedrock/cascade river types. These streams have low energy due to their small catchment area and discharge, despite high channel slopes. Peat streams were determined to have low recovery potential, meaning using specific stream power was needed to correctly allocate the recovery potential for these systems. For these reasons, specific stream power was determined to be more appropriate than slope for classifying recovery potential.

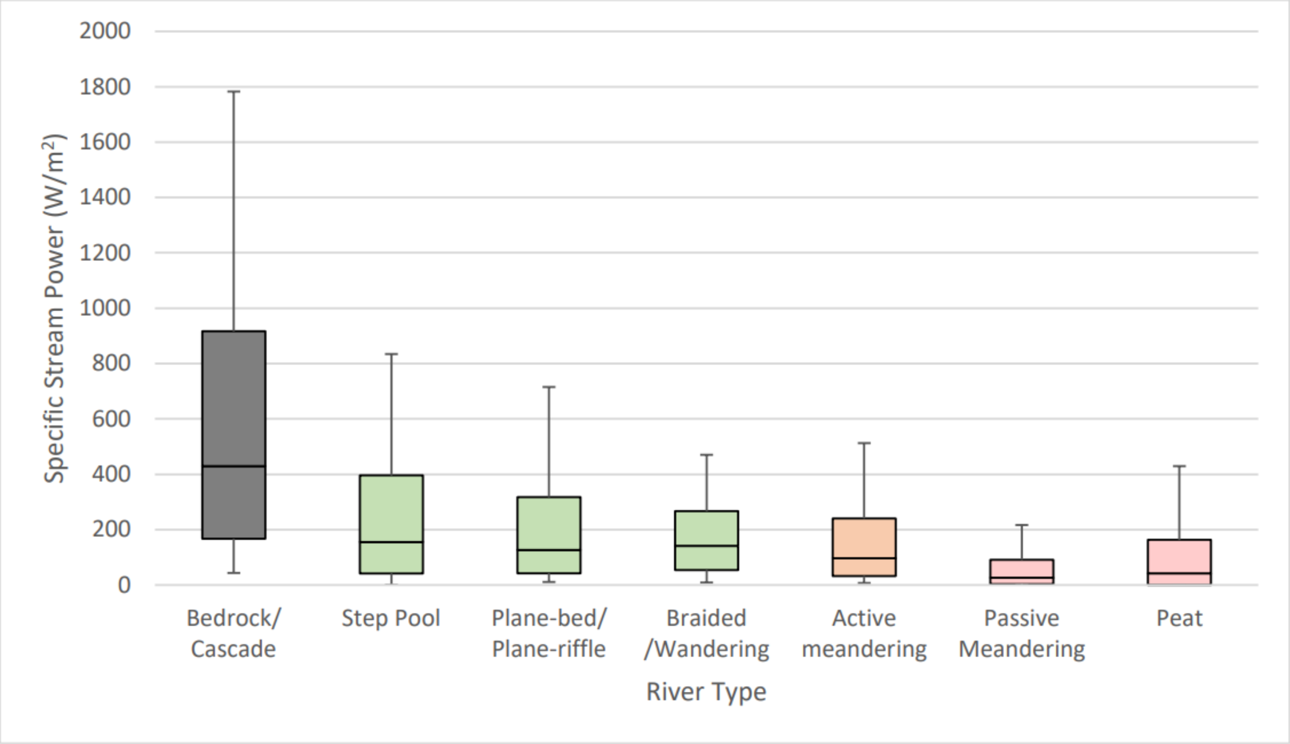


Figure 11: Box and whisker plot showing the distribution of specific stream power for reaches based on river type. River type was derived using 7235 km of walkover data. The different river type categories are coloured based on the recovery potential of each river type (red - low, orange - moderate, green – high and grey is resilient to change).

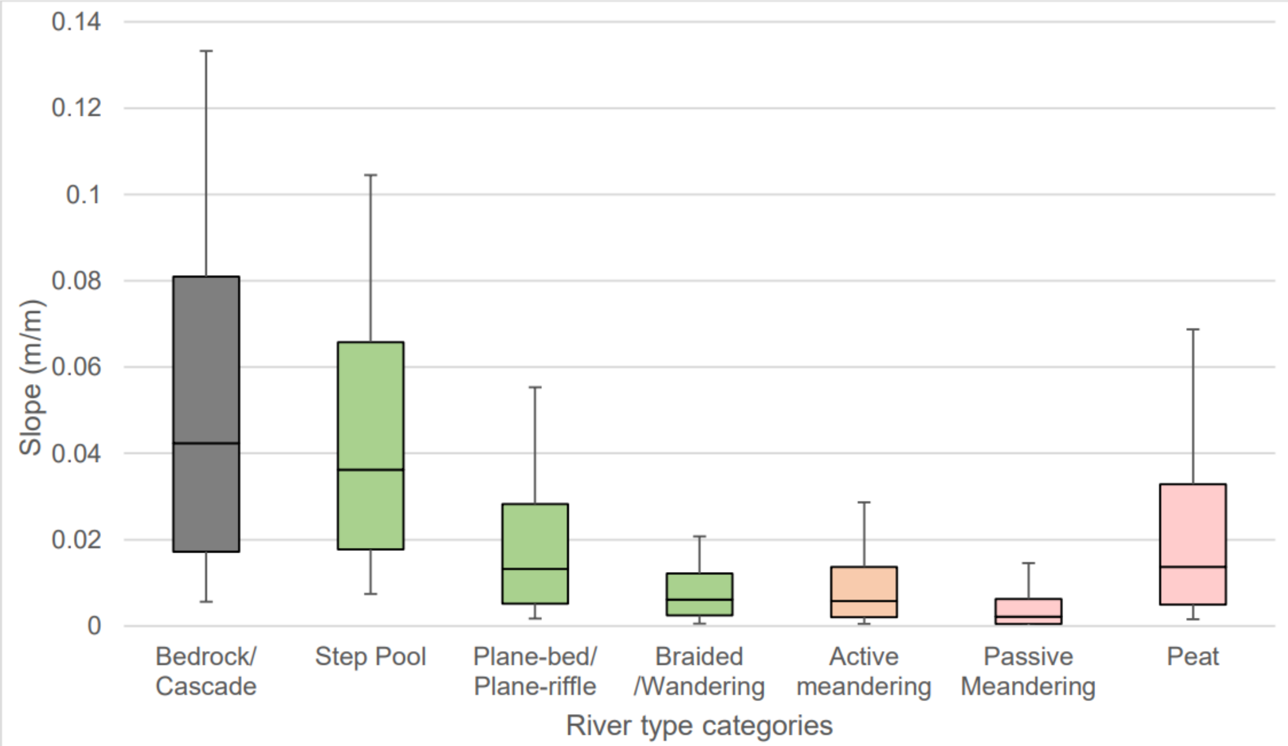


Figure 12: Box and whisker plot showing the distribution of slope for reaches based on river type. River type was derived using 7235 km of walkover data. The different river type categories are coloured based on the recovery potential of each river type (red - low, orange - moderate, green – high and grey is resilient to change).

Table 5: This shows the percent of reaches in each river type that fall into the correct recovery potential category based on the boundaries selected. The line highlighted in light grey shows the boundaries which were selected to create the catchment-scale recovery potential map.

Classification boundaries – Specific stream power (W/m²)			Bedrock/ Cascade (%) – *RTC*	Braided/ wandering/plane - riffle/bed/step- pool (%) *- High*	Active meandering (%) *- Moderate*	Passive meandering/ peat (%) *- Low*	Total (Sum of % correctly classified)
Low – mod	Mod - high	High – RTC					
30	150	330	58	22	39	50	169
40	150	330	58	22	34	56	170
50	150	330	58	22	29	60	169
60	150	330	58	22	25	63	168
50	150	350	57	23	29	60	169
50	130	330	57	26	25	60	168
50	130	350	58	27	25	60	171
50	150	400	53	26	29	60	168
50	**130**	**400**	**53**	**30**	**25**	**60**	**168**

To classify recovery potential, different specific stream power values were proposed for each threshold, and then the proportion of river types that fell into their ‘correct’ recovery potential categories calculated. Sensitivity analysis was carried out by varying these threshold values and seeing how the proportion ‘correctly’ classified changed (Table 5). As it was perceived as more important to correctly characterise the low and moderate energy systems, more weighting was given to correctly classifying the passive and active meandering river types (i.e. low and moderate recovery potential rivers) as these were the categories that had a greater influence on the type of restoration intervention delivered. Initially, only three categories were investigated, being low, moderate and high recovery potential. However, it was recognised that high recovery potential covered a large range of specific stream power points and diversity of river types. To remedy this a ‘Resilient To Change’ (‘RTC’) category was introduced to identify where specific stream power values were very high.

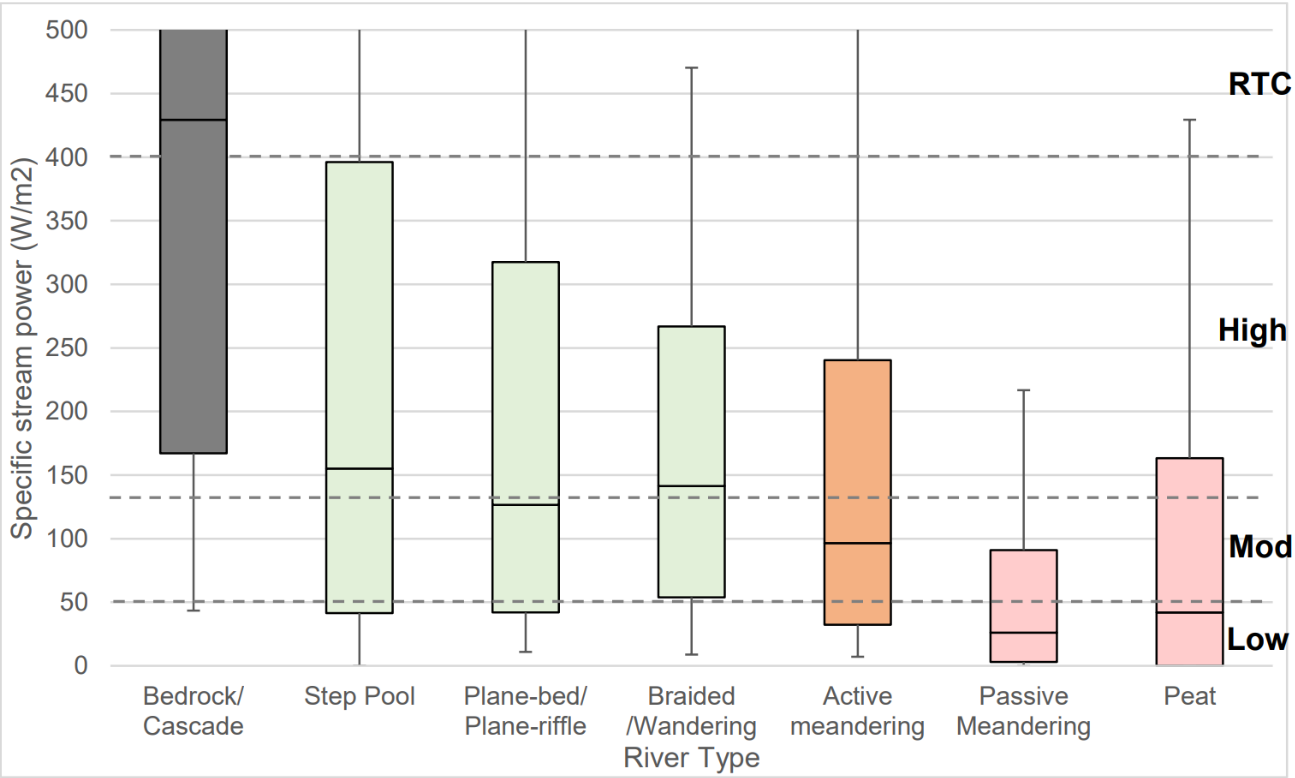


Figure 13: Zoomed in distribution of specific stream power values based on river type for the waterbodies where typology was surveyed in the field. This is annotated with the thresholds that were identified to delineate the different recovery potential categories.

The final thresholds selected as shown in Table 5 and Figure 13 were:

- The low – moderate boundary was selected as 50 W/m^2 because it was the best compromise between delineating between low and moderate recovery potential. This is the most important threshold, as restoration approaches differ the most between active and passive meandering river types. This threshold resulted in 60% of passive meandering and peat rivers falling into the low recovery potential category and 25% of active meandering into moderate recovery potential. This number appears lower as some of these fall into the high recovery potential category. Overall, 67% of the active meandering rivers are not assessed as ‘low’ recovery potential indicating the value of 90 to be good at delineating between low and moderate Recovery Potential for these river types.

- The moderate – high threshold was selected as 130 W/m^2 because it maximised the number of active meandering river types that were ‘correctly’ classified. A higher threshold was investigated, however, this meant that the medians for both braided/wandering and plane bed/plane riffle types no longer fell in this category (instead of just the plane bed types). Therefore, this slightly lower value of 130 W/m^2 meant that fewer of the moderate recovery potential rivers were correctly classified (at 25%) but more of the mid-range of the high recovery potential river types were correctly classified (with an overall correct rate of 30%). This threshold was deemed less crucial for deciding whether to use active or passive restoration measures.
- A value of 400 W/m^2 was delineates the high – RTC rivers to identify only those with the highest specific stream power values. This results in 53% of RTC being correctly classified. This is similar to the low category in that the percent is higher as it is not split over two categories. This threshold was selected to capture the median value of the RTC rivers and only those > 75% percentile of the high category.

In summary, the chosen thresholds effectively delineate the different river types into their expected recovery potential categories. While overlap is evident the aim of this analysis was to provide a coarse-scale assessment that can be used for planning at the national and catchment scale. This also recognises that recovery potential does vary within river types, and the specific stream power value can be used to understand where a reach might sit with a river type category, creating greater insights to recovery. The more detailed analysis described in the reach scale assessment (Chapter 3:) is designed to further refine results where necessary, dealing with this uncertainty.

1.1 Results

This section presents the output of the analysis in the previous section, presenting maps which display recovery potential based on the specific stream power of each reach across Scotland. Catchment-scale examples of the distribution of recovery potential for existing restoration sites are also presented.

2.1.2 Scotland-scale recovery potential

The output of this section is a map of recovery potential for all of the baseline river waterbodies in Scotland (Figure 14 & Figure 15). This can be viewed in greater detail on Map | Scotland's environment web. Overall, this map shows that areas with high recovery potential (or are resilient to change) are clustered in the highlands and in the hill country in the Scottish Borders. Rivers with low recovery potential are located generally in the central belt, Fife, and along the coast from Perth to Aberdeen and around to Inverness. There was also lower recovery potential for those rivers that drain to the northern most coast of Scotland, the Solway Firth and some of the rivers that drain flatter sections of the islands, such as Lewis, Uist, Orkney and Shetland. While these broad-scale patterns are clear, it is also evident that significant variability exists within this. This highlights the importance of analysing catchment scale patterns of recovery potential, and contextualising model output with the underlying landscape topography and river character.

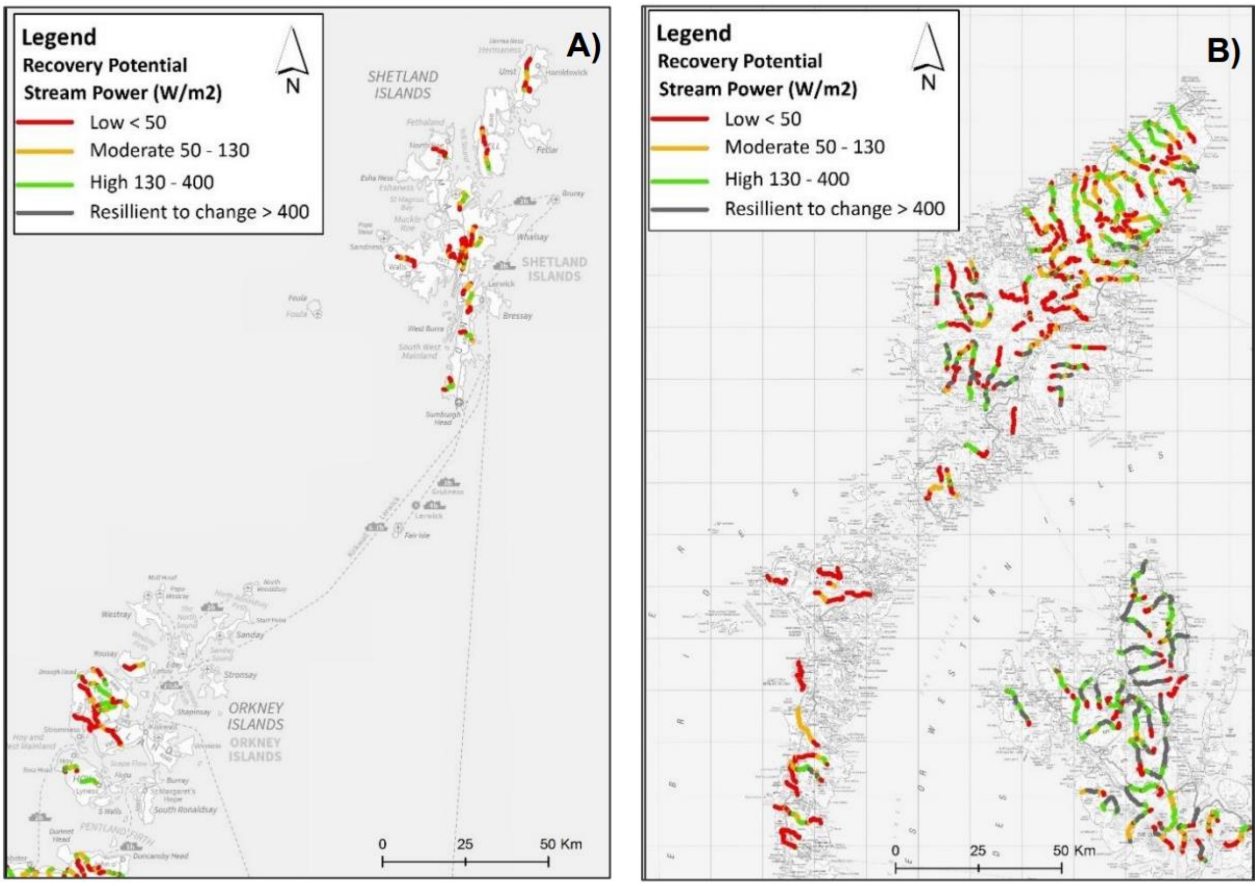


Figure 14: Recovery potential for baseline waterbodies in A) Orkney and Shetland and B) Lewis and Uist.

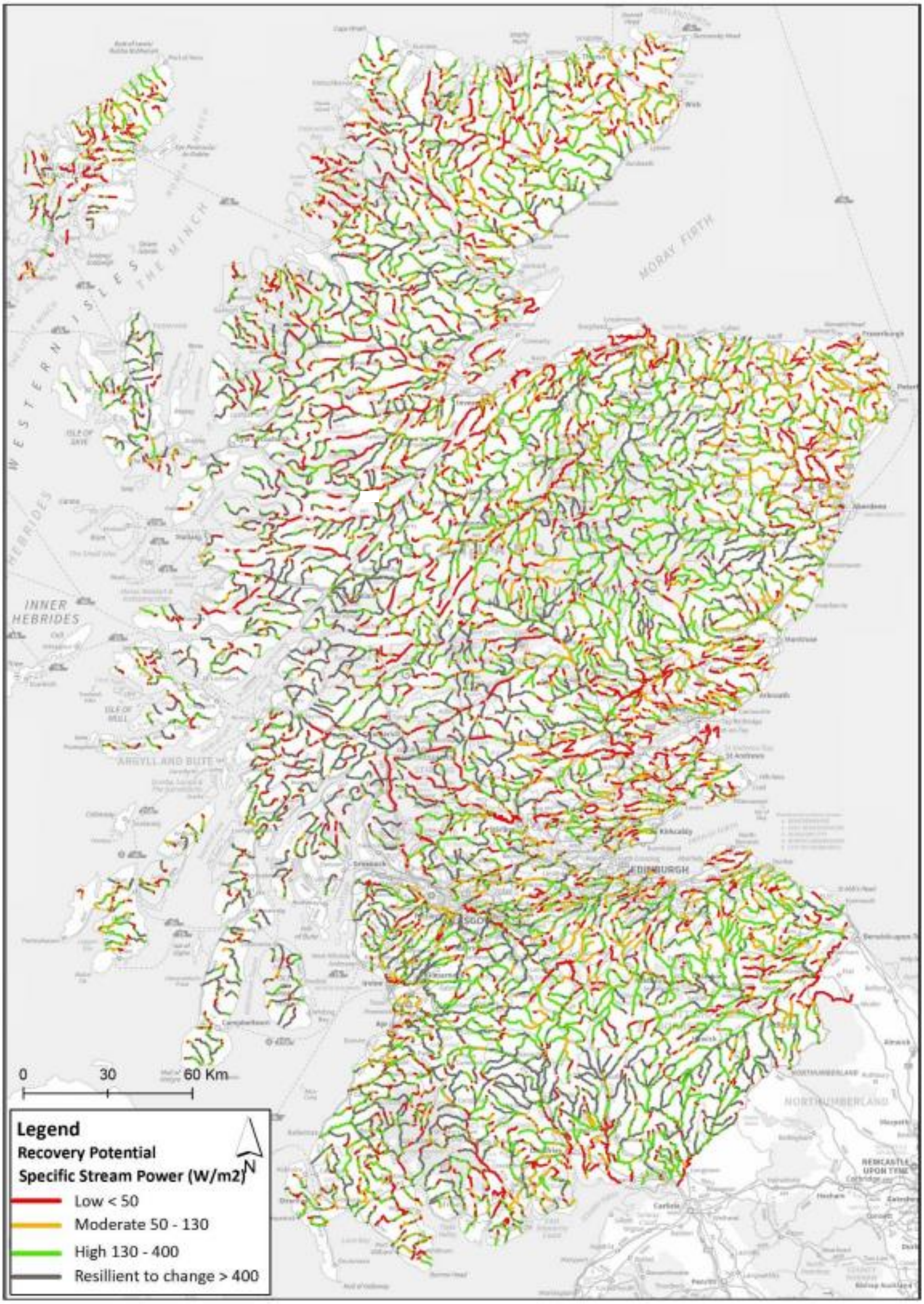


Figure 15: Map displaying the recovery potential for all baseline river waterbodies in mainland Scotland.

2.2 Recovery potential for restoration sites

To test the quality of the output, catchment-scale maps of recovery potential for river restoration sites which have been completed were extracted. These are the same sites as those presented as case studies in Chapter 6:, including reach scale descriptions, photographs and analysis of reach scale recovery potential. The results below present the catchment scale pattern of recovery potential to illustrate how this can be used to provide context for a site. Note, the recovery potential dataset was not available when these sites were restored, so it was not considered as part of the restoration design. However, it provides a useful dataset to look at these schemes post restoration to assess how their recovery potential has shaped their recovery post restoration.

2.2.1 Stane Gardens

Stane Gardens was a concrete open culvert pre-restoration and there was little evidence to determine what the natural morphology would have been. Therefore, the channel had to be designed and constructed from scratch, with a natural recovery approach not possible. The recovery potential assessment (Figure 16) is particularly useful in this context, as it shows the energy environment within the catchment, which indicates the type of river needing to be designed has a high recovery potential (see Section 6.1.2 for details). The designed channel sits within a narrow valley with a coarse cobble bed and is best described as a plane-riffle bed morphology (which is a river type in the high recovery potential category). This shows that what was designed and constructed was in-sync with the predicted stream power for the reach.

The restoration was delivered using an active approach (as is the only option for a culverted channel), by removing the culvert and creating a new meandering channel. This allowed rapid recovery as the channel did not have to undertake much work to restore channel form. Section 6.1.2 documents this recovery, showing bars, riffles and pools that have formed in what was originally homogeneous (but sinuous) channel immediately post construction.

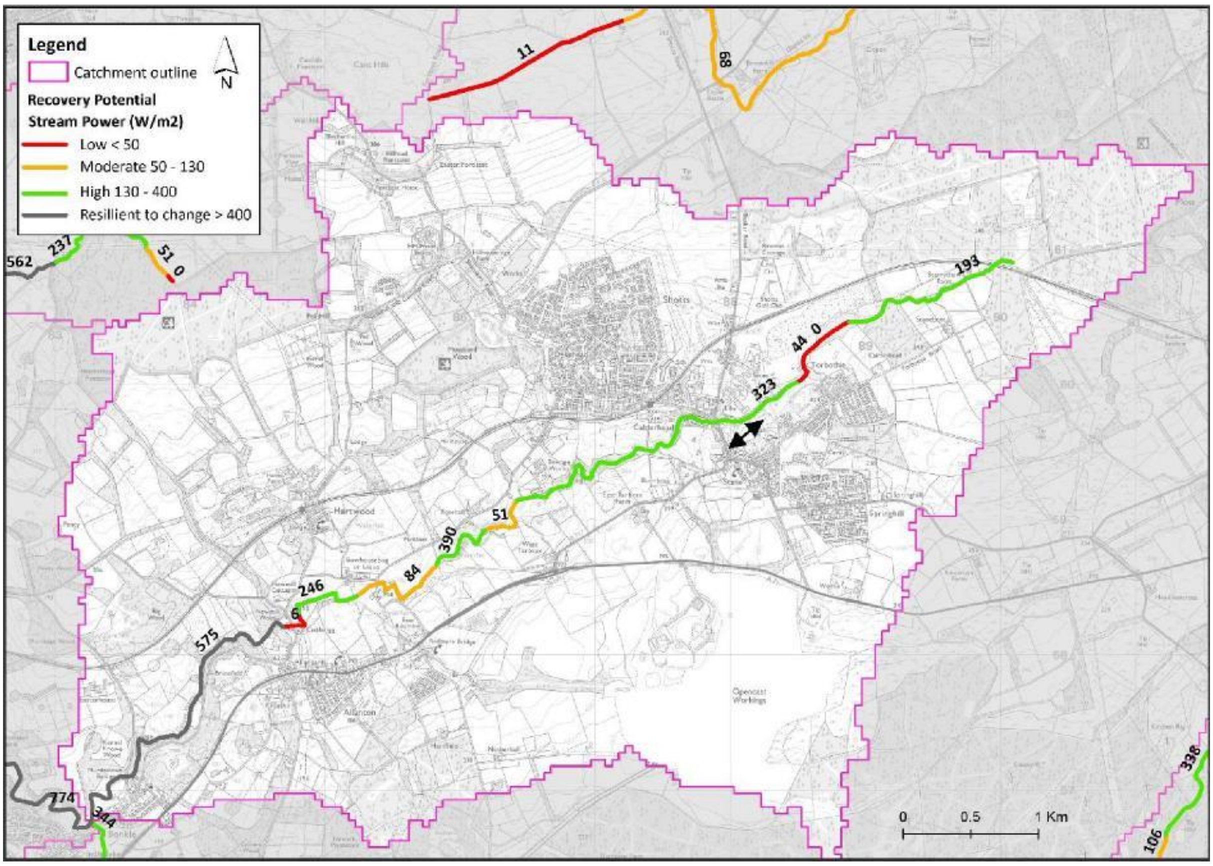


Figure 16: River Recovery potential based on specific stream power thresholds for the Stane Gardens catchment in North Lanarkshire. The arrow shows the location of the restoration site.

2.2.2 River Nairn at Aberarder

The upper-most reaches of the River Nairn have low recovery potential (Figure 18). Despite being located in steep hills, the small catchment area (and resulting low discharge) results in specific stream power being quite low, reflected in a narrow but steep stream at this location. Recovery potential increases downstream, reflecting the catchment area increasing and the river getting bigger. This is especially evident downstream of the Allt Mor tributary, where the recovery potential increases from moderate to high and this is reflected in its step-pool morphology, with sections of wandering and cascade here. This point also coincides with some significant landslides and gully erosion where large volumes of sediment are being delivered directly into the river channel network (Figure 17). Below this, the channel remains step-pool with some localised gorge sections and becomes RTC, reflecting increased catchment area and the remaining relatively high slope.

Downstream of the RTC section the valley starts to widen and the gradient decreases. Typology becomes dominated by a plane-bed river type with some step-pool sections. At the road bridge the valley becomes unconfined and the gradient decreases further (to 0.017 and 0.007 for each sub-reach). This is reflected in the pre-restored river type changing from plane bed to dynamic pool-riffle with some plane-bed. These pre-restoration river types reflected both past engineering (straightening) and the high sediment load from upstream. Post restoration the river type has changed to an active meandering channel, which represents a more active river type with a higher recovery potential than would be predicted by the specific stream power alone. This is due to the high sediment load delivered from the landslides upstream (see Figure 17), and the sudden decrease in stream power creating a deposition zone, resulting in high volumes of sediment being stored in the channel as bars, driving an increased rate of adjustment. This demonstrates the importance of reach scale assessment to verify recovery potential, particularly where sediment load could have as strong as, or greater influence, on recovery potential than stream power alone.

The restoration approach used was a mix of active (remeandering) and passive (installation of wood structures) approaches. Recovery was rapid as the sinuosity was reset by digging the new channel and in channel diversity was able to quickly form due to the wood structures combined with the high sediment loads driving adjustment (see section 6.1.3 for full details).

Figure 17: Aerial photograph showing gully/hillslope erosion adjacent to the high recovery potential section which is delivering high loads of sediment directly into the channel. Location within the catchment is shown on Figure 18.

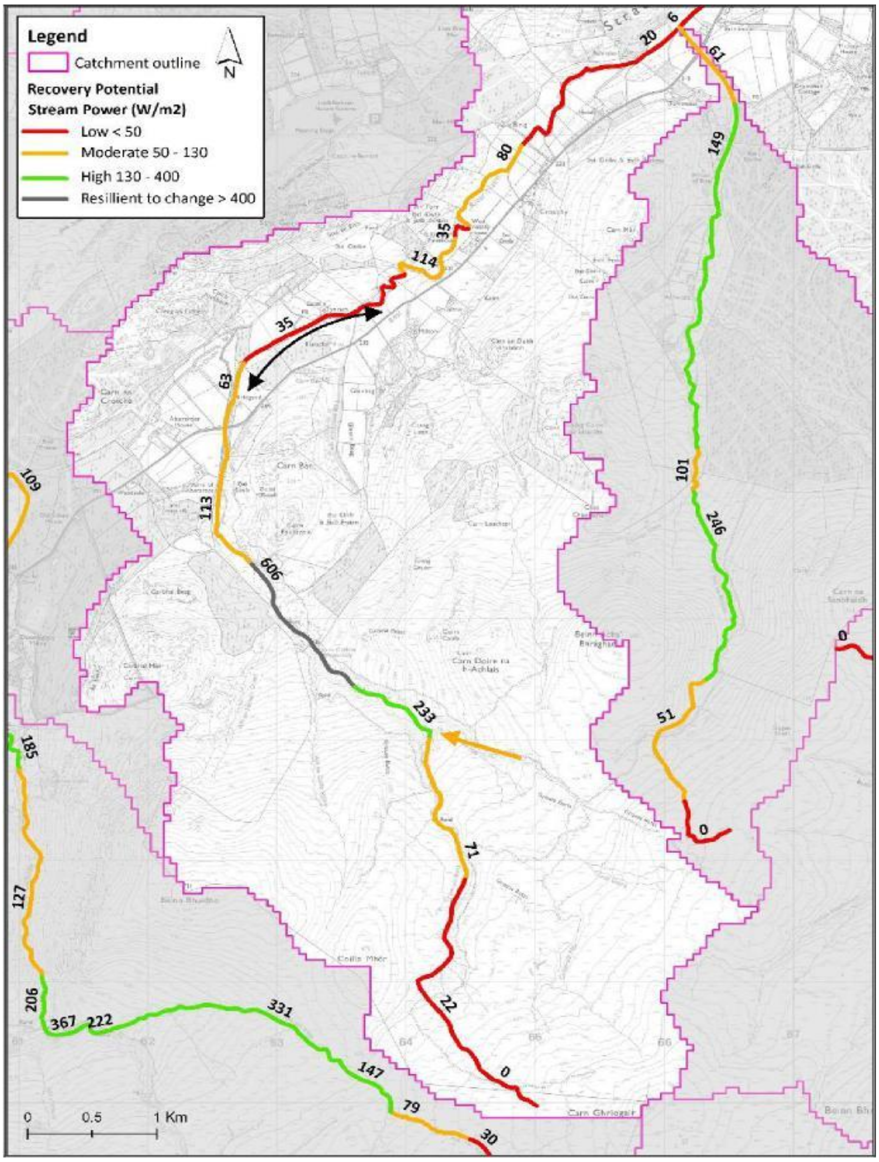


Figure 18: Catchment-scale recovery potential based on specific stream power thresholds for the Upper Nairn catchment. The black arrow shows the location of the restoration site and the orange arrow the landslide location (see Figure 17).

2.2.3 Allt Lorgy

Catchment scale relationships in the Allt Lorgy are relatively straightforward (Figure 19). There is a short upper section, which has a low recovery potential, due to the small catchment area and therefore low discharge. Below this, a short section has a moderate recovery potential. This appears to be active meandering or plane-riffle where the valley is narrower. The rest of the channel has either high recovery potential or is described as resilient to change, demonstrating very high specific stream power. River type along much of this stretch is a mix of Wandering or high energy active meandering, seen in some extensive bar features. The restored section had previously been straightened and embanked and had high-energy straightened morphology, characterised by poorly developed pools-riffle sequences. The catchment scale recovery potential for this section was RTC, which is higher than reflected by the actual morphology on site. Post-restoration, this section has adopted a wandering type morphology which is characteristic of a river with high recovery potential. This likely reflects the increased energy in the channel caused by straightening and being maintained by embankments and bank protection as well as the influence of the high sediment load off the hills causing the channel to split around accumulations of sediment (widening bankfull channel width) and thus, lowering its energy compared to the straight and narrower channel present pre-restoration (i.e. that used to determine catchment scale recovery potential).

The restoration approach used was assisted natural recovery, using engineered log jams and removing the embankments and bank protection. Recovery has been very rapid, illustrating the strength of such an approach in higher energy environments (see Section 6.1.4).

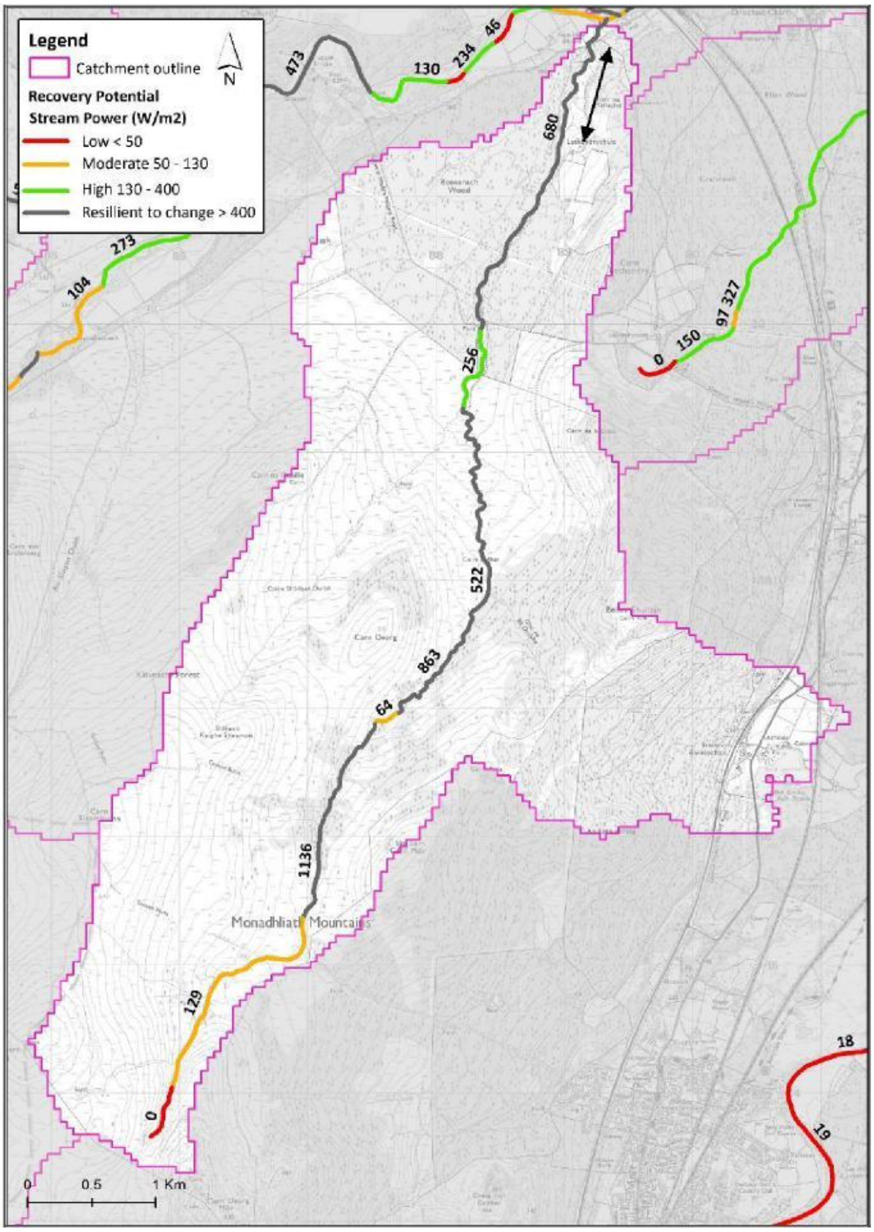


Figure 19: Catchment-scale recovery potential based on specific stream power thresholds for the Allt Lorgy catchment. The arrow shows the location of the restoration site.

2.2.4 Pow Burn

Pow Burn consists of multiple tributaries that run parallel to each other, three of which contribute to overall classification of the waterbody classification and another five of which do not (Figure 20). This results in a low to moderate recovery potential because each tributary individually drains a small catchment area, resulting in a small volume of water in each channel. Energy is also lower due to the relatively flat topography, so that the Pow Burn typically has a low or moderate recovery potential along most of its length, even where these tributaries combine into a large channel. The exception is in the middle section before the Red Den and

Lilylorn Burns joins which has a high recovery potential with a short section of RTC, mostly characterised by a plane-riffle river type. However, the section where restoration was carried out has a low recovery potential. This is similar to the outcome of the reach-scale analysis, which identified the restoration reach at the upper end of low (see Section 6.1.5). The restoration carried out here involved creating a 2-stage channel by lowering an inset floodplain and installing some wood deflectors to try and increase diversity in the channel. Due to the low energy, recovery is likely to take decades in this system. However, restoration was a mix of active (creation of an inset floodplain) and passive (installation of wood structures) measures, which is appropriate for a lower energy site, recognising that the in-channel diversity may require longer time scales to become fully established. This example demonstrates that catchment scale recovery potential performs best where the energy regime (stream power) is the major influence on recovery potential and coarse sediment supply is of less importance.

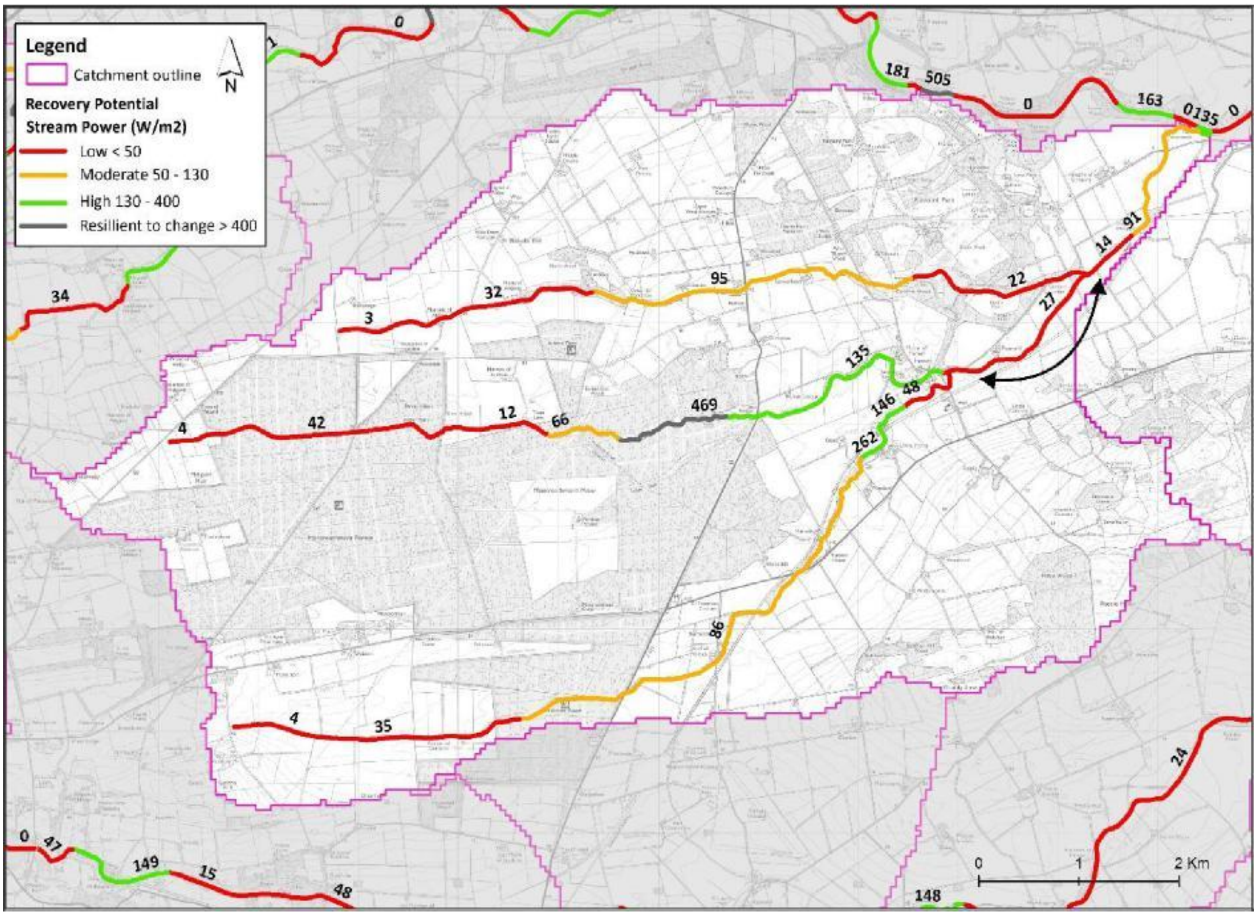


Figure 20: Catchment-scale recovery potential based on specific stream power thresholds for the Pow Burn catchment in Angus. The arrow shows the location of the restoration site.

1.2 Uses and Limitations

Catchment scale recovery potential is very useful for understanding the patterns of energy along a catchment to better understand the broader catchment characteristics. This allows interpretation of river types and associated energy, process zones (where deposition or erosion is likely due to increases or decreases in energy) and likely rates of channel adjustment. Most catchment assessments include an initial desktop survey to be used to identify stretches of river that are likely to be worked in (i.e. also including layers such as land use and channel modifications). This layer provides key information that shapes the type of restoration approach (active or passive) that can be used during early stages of investigations, to potentially identify areas where quick wins (high energy reaches requiring passive restoration) may be possible. However, prior to any channel design or restoration works this data does require ground-truthing using field-based surveys. Chapter 3 provides a guide describing how to assess recovery potential in the field, by assessing a range of geomorphic variables. Before deciding restoration approaches based on recovery potential it is essential that the reaches of interest *must be assessed in the field* using the reach-based approach. Reasons for the limitations of only using this remotely sensed catchment scale approach are described below. The most significant being that the catchment based approach only uses energy to calculate recovery potential, and does not consider sediment load, which is a key influence on channel character and behaviour.

Limitations are listed below;

- The most significant limitation of this work is that it does not consider sediment supply, as identified in the River Nairn at Aberarder example (Section 2.2.2). Channels with a high sediment supply are more mobile and likely to be characterised by more channels or depositional features such as bars. The reach scale assessment methodology does include assessment of sediment and these insights are incorporated in the more detailed analysis described in the rest of this guidance.
- Some reach lengths are shorter than others. These short sections will only be based on a few stream power points, so may inherently have more error given the resolution of the DEM used for slope and small scale at which the waterbodies were mapped (i.e. local “errors” could have a greater influence on the average stream power value). Therefore, if a short section is being assessed it should be analysed within its landscape setting and the recovery potential of the sections both up and downstream.

- Slope and channel width data used to calculate specific stream power was not based on the reference channel, but on the actual river attributes. In contrast, river type is based on the reference river type. This means that for straightened rivers, slopes may be higher and widths narrower than would be expected for the reference river type, which would increase some error in the calculations, with rivers having higher energy than they would in their reference type.
- Overlap does exist in stream power between the different river types and recovery potential categories. This is expected to some extent, given the actual channel form reflects a continuum that straddles the generalised river type classification. However, this does also mean that some reaches will be placed in the incorrect category. Again, this gives another reason for the need for the field-based assessment to support this broader scale analysis.
- The thresholds were selected to increase the accuracy of the classification for reaches in the moderate and low recovery potential categories. For this reason, there is greater confidence that reaches in these categories have been correctly classified. Although there could be more errors in the other categories, the distinction between moderate and high recovery potential reaches is less crucial to determining the most appropriate restoration approach, and the highest recovery potential reaches (in general) are more likely to be in parts of the catchment where restoration is less necessary.

The order of the recovery potential of the reaches in a catchment can be used to predict where adjustment might be more than expected. For example, if there are steep, high recovery potential reaches that drain headwaters and flow into reaches with lower energy, then a depositional zone would be likely at this location. The Upper Nairn at Aberarder case above (Section 2.2.2) is an example of this. SEPA also have a Scotland-wide dataset produced using the ST:REAM model (Clifford et al., 2015). This also uses specific stream power as an input, but predicts the dominant geomorphic processes for a reach, ranging from erosion to deposition. Thus, it is possible to use this dataset to help identify the depositional reaches, where adjustment may be greater than the specific stream power alone would indicate. Thus, ST:REAM, although not without its own sources of uncertainty, provides an additional dataset to aid in the interpretation of catchment-scale recovery potential.

In general, the catchment-scale assessment of recovery potential presents a simple, yet powerful way to understand the energy environment within a catchment. However, this recovery potential dataset must be used in sync with catchment scale understanding of sediment delivery, anthropogenic history of the catchment (i.e. historic contingency) and how this can be reflected in changes to river type. This dataset can be used at initial planning stages to indicate the nature of the restoration likely to be successful across a catchment. However, for detailed planning, field-based investigation is essential to ground-truth these catchment scale observations.

Chapter 3: How to assess recovery potential at the reach scale using indicators of geomorphic processes?

The Scotland-wide map of catchment-scale Recovery Potential presented in Chapter 2: is useful for providing a general indication of the distribution of the likely energy level of reaches across the catchment. Thus, this should be applied for scoping at wider (i.e. catchment) scales. In contrast, the analysis described in this section is carried out at the reach scale based on field assessment and provides a far better grounding for assessing recovery potential and scoping restoration approaches and options. This section describes how to assess each geomorphological variable used to classify reach-scale recovery potential. These variables are listed in Figure 21.

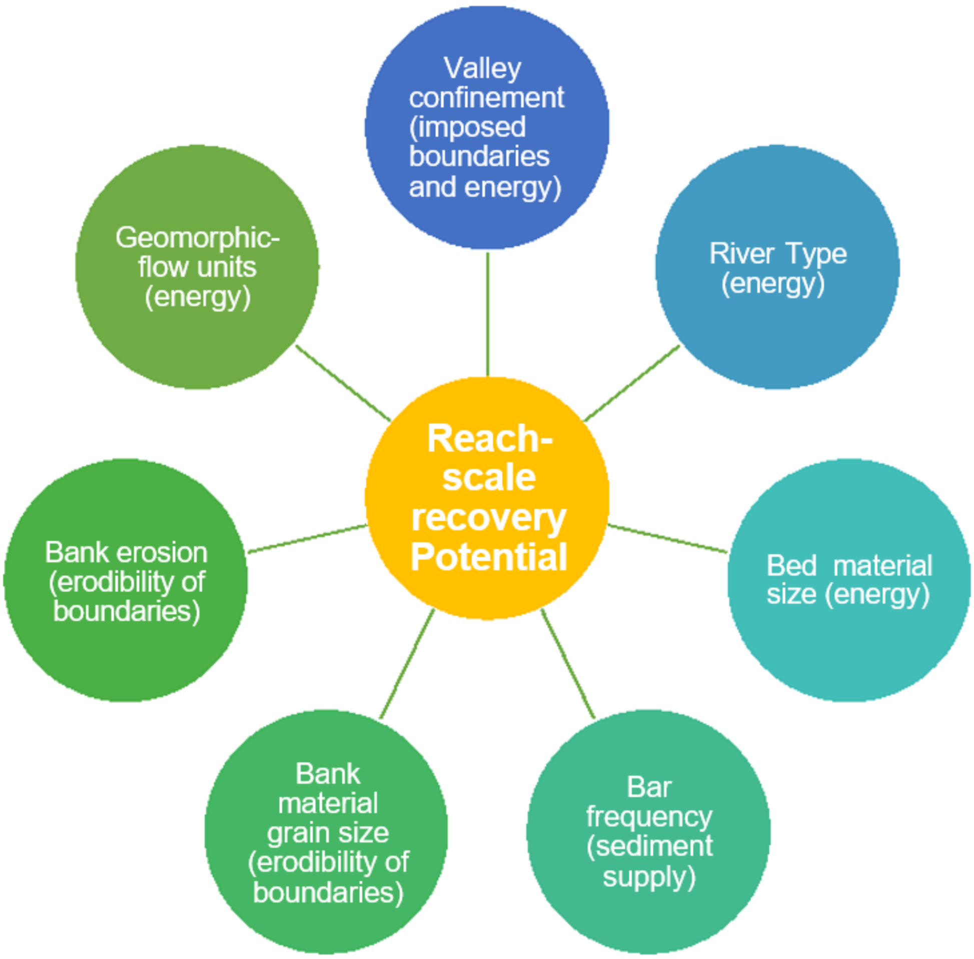


Figure 21: List of geomorphic attributes (and what they indicate about the system) assessed to determine the reach-scale recovery potential.

While valley setting and reference river type ultimately represent the energy regime of the river, it is also important to look at within-reach indicators that will give us greater understanding of the energy and sediment attributes for a reach. This is especially important because i) the river type may have changed due to previous anthropogenic modifications which obscure its reference river type and ii) river types do not always fit easily into energy categories, and there can be considerable variation within a river type (especially an active meandering river type). Many of these indicators are descriptive and it can be difficult to definitively categorise a reach. However, the methodology is that all of the indicators align with the valley confinement and river type classifications to build up a picture of detailed reach-scale recovery potential. The aim is also that the assessor actively thinks about the characteristics and morphology of the river, rather than over-simplifying the process in order to reach a rapid conclusion. This means that when it comes to assessing recovery potential, we have a more solid foundation and understanding to base our assessments on.

Assessments should be carried out at the reach scale, which can be defined as a length of river where channel type and processes are similar. The most beneficial approach is to walk the section of interest and carry out another assessment when a change in river type or condition is noticed. However, it is also possible to use the methodology to carry out assessment on discrete reaches. If only a single point is visited, then the output will be limited to the characteristics at that location and may be misleading. Therefore, at least a 100 - 150 m stretch of river should be walked (preferably more) for a discrete assessment. If the section is straight but there is a bend downstream, then it is important to look at the bend also, as it may have attributes missing from the straight section. For example, bank erosion and/or bars are more common at bends, which can help indicate the recovery potential of the reach. More sinuous sections may also indicate how the channel would have adjusted prior to straightening and give an idea of the reference condition. It is also important if possible to avoid surveying around bridges, especially at large road crossings. Bridges locally alter the processes and it can be difficult to understand how much of what exists is influenced by alterations associated with the bridge, rather than being illustrative of river processes.

This section provides a framework whereby each variable is assessed in the field and defined as having a high, moderate or low recovery potential category. The outcomes from each variable are then used to classify the overall recovery potential of a reach (described in Section 4.1). A field sheet is supplied in Appendix 1, which is designed to be used to record the information needed to assess each category. Each attribute assessed is individually listed and discussed in the following section.

3.1 Valley Confinement

The valley setting provides a key constraint on;

i. the types and direction of adjustment a reach can undergo,
ii. how it can become degraded,
iii. the energy of the river and
iv. its potential for recovery.

Valley type will determine whether a river can move laterally due to bank erosion and bar deposition and/or vertically, through erosion or deposition of sediment on the channel bed. In a confined valley, the river is constrained by the valley margins and cannot move laterally, in an unconfined valley, channel adjustment is generally unimpeded by the valley form. Valley setting is also important to understand the sources of sediment and how energy is dissipated (or concentrated) during flood events, acting as a key control on geomorphic processes. Therefore, understanding valley setting is a simple check which can be assessed quickly and easily and is a key consideration for delivering river restoration. The main valley settings are described below, with the aim of providing an explanation that can be used to assess this in the field. Table 6 describes the valley settings that fall into each Recovery Potential category.

Table 6: Description of the valley setting for each Recovery Potential category.

Recovery Potential categories	**Resilient To Change**	**High**	**Moderate**	**Low**	**Anthropogenic modification**
Description of valley attributes	Confined, 'v' shaped valley where the channel is confined by valley margin along 90 – 100% of its length.	Partly confined with narrow floodplain pockets. The floodplain locally widens but the channel remains in contact with the valley margin along 50% – 90% of its length. Steep but unconfined alluvial fans should also be in this category.	Partly confined with wider floodplain pockets where the channel is in contact with the margin 10 – 50% of the time or moderate gradient unconfined but the floodplain still has a reasonable slope to drive processes.	Low gradient unconfined. Very low valley slopes with low energy rivers	Valley completely reshaped due to anthropogenic modification

3.1.1 Confined valley setting

A confined valley setting is where the valley slopes up away from the river channel on both sides, forming a ‘V’ shaped valley (Figure 22). This ‘V’ can be distinct and easy to see in some locations, but more subtle in others where the slopes are gentler, so needs to be carefully assessed. Sometimes bedrock will be visible immediately next to the channel edge, whilst other times, the bedrock will be covered with a thin layer of soil and may slope away from the channel gently, rather than forming steep sides. This valley setting will most commonly be associated with high-energy cascade, bedrock or step-pool river types, which are highly resilient due to the lack of lateral and downwards channel adjustment that is possible.

The valley and channel are well-connected and sediment may be delivered directly to the channel by fluvial erosion or landslides. These reaches act as source zones, whereby sediment supply exceeds deposition along the reach. Channel slopes tend to be steep due to their headwater location. During floods the water is constrained by the valley, concentrating energy and increasing the energy available to transport sediment as it flushes finer material and retains only that large enough to withstand the flow.

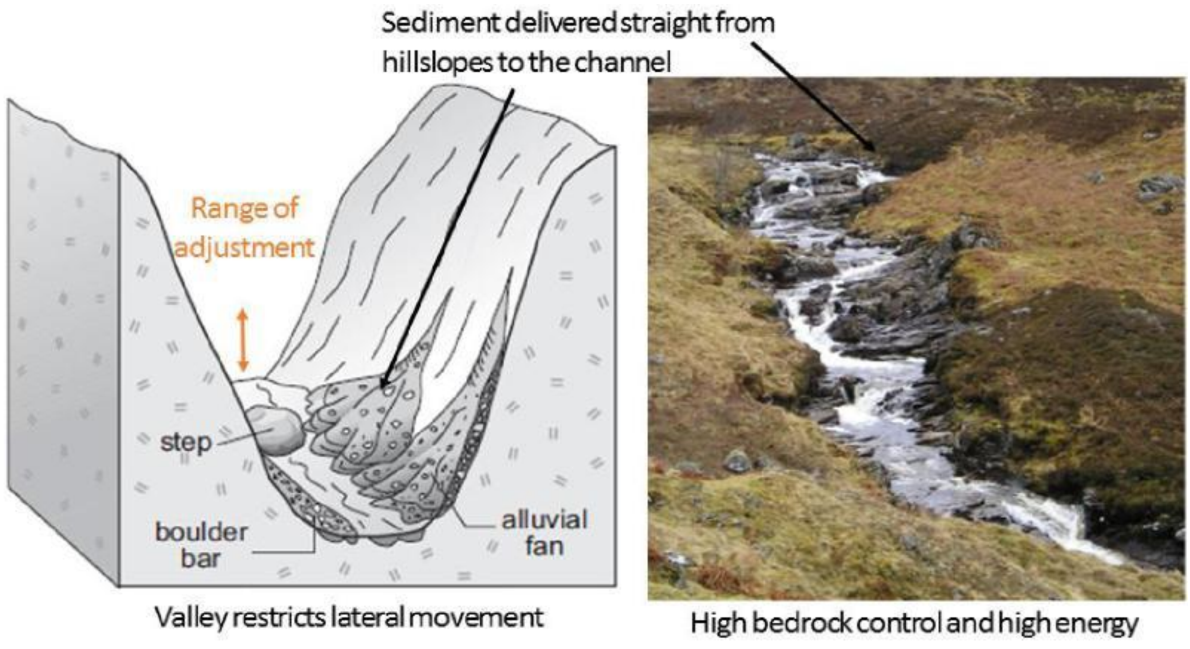


Figure 22: Schematic showing the attributes and features seen in a confined valley setting. Modified from Fryirs and Brierley, 2012.

Figure 23: Photograph of the Davington Burn in Eskdalemuir, in the eastern Borders, showing that the channel has cut down into rolling hills comprised of glacial till to create a confined valley.

Impacts from human pressures on river form are less common in these confined valleys, due to the lack of adjustment they can undergo and, typically, the lack of development in the headwaters. However, weir removal is sometimes required in confined valleys, so restoration may be undertaken by recreating a ‘stable’ channel form in the zone where the weir and backwater was. Step-pool restoration can also be carried out in this valley location, whereby stable steps have to be constructed to stop the whole channel bed mobilising. This type of restoration requires a complex design that is out with the scope of this report.

Within Scotland a common type of confined valley can be found where rivers have incised into gently rolling glacial till, formed from a matrix of clay with coarser sand – boulder grains held in the mix. These were shaped during the ice-age when glaciers carved out valleys and deposited this material on mass. Over time, water and rivers have reshaped this landscape, with the drainage network cutting down into it (see Figure 23 for example). This specific valley character warrants a mention due to how common it is and because the valley slopes are far gentler than the steep ‘V’ shaped valleys (as conceptualised in Figure 22) meaning they may not immediately be recognised as a confined valley.

Importantly, terraces can also provide significant erodible river boundaries. These exist where the channel has cut down into a floodplain, creating a new inset valley and functional floodplain within this. The valley margin is then characterised by vertical alluvial features, the top of which is disconnected from the contemporary river regime.

Therefore, an assessor should stand in the river and ask does the land surface slope uphill from here *or* is the surrounding land low gradient, deposited floodplain which is still connected to the river? If it does slope away for more than 90% of the channel length of the reach being assessed then the channel should be classified as confined. All reaches in confined valleys are classified as resilient to change (RTC) (Table 6).

3.1.2 Partly confined valley setting

Partly confined valley settings exist where the river has eroded sections of the valley, creating disconnected pockets of floodplain (Figure 24). This means that the direction and extent of channel adjustment will vary depending on the size and location of these floodplain pockets. These commonly start as smaller discontinuous pockets, widening out further downstream. Within this setting, the valley still has a significant influence on the morphology. Often the river will flow from valley margin to valley margin, creating a channel alignment that may appear unnatural due to tight bends when compared with an unconfined valley margin. This can make it more difficult to predict what the channel alignment would naturally be in these locations. The width of the valley will determine the extent to which energy is concentrated during floods and the space within which the river has to adjust. Rivers within narrower valleys will most likely be steeper than those within wider valleys where they can increase their sinuosity and decrease their slope. How connected a channel is with the valley sides will also influence how much sediment can be delivered directly to the channel from this source. Reaches within this valley setting are located within the transfer zone, whereby sediment supply is about equal to deposition, with no significant increase or decrease in the volume of material stored. Importantly, all river restoration should be related back to the land which the river can access and identifying the width, continuity and connectivity of floodplain pockets is a key step to this.

Partly confined valleys are defined as having a channel that abuts the valley margin along 10% to 90% of the predefined reach being assessed. For the purpose of assessing reach-scale recovery potential, they have been separated into two categories; narrow floodplains where the channel abuts the valley margins between 50% – 90% of the time (high recovery potential) and wider floodplains connecting the channel and valley margin 10% – 50% of the time (moderate recovery potential). Narrower floodplains can be characterised by the valley margin having a greater direct impact on the channel morphology by both constraining channel processes and supplying sediment load. They also tend to contain higher energy river types (see Section 3.2). Wider floodplain pockets tend to contain lower energy active meandering river types which have a lower recovery potential than those within the narrower valleys. This is why this valley type falls into the two recovery potential categories. This describes the transition before the channel becomes fully unconfined. Use discretion when assessing this category and consider channel-valley connectedness, valley slope and the energy of the reach.

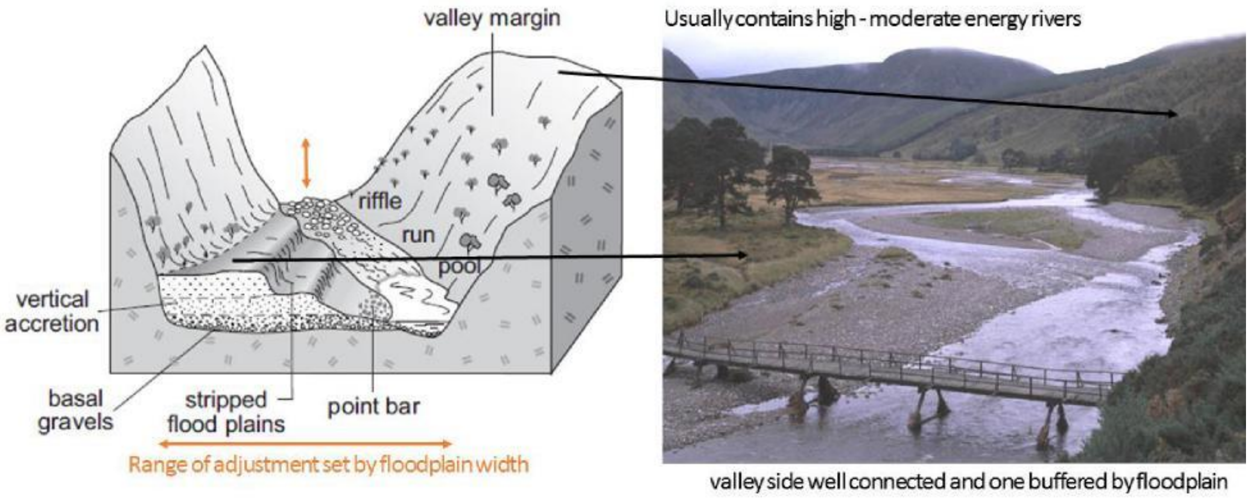


Figure 24: Schematic showing the attributes and features seen in a partly confined valley setting. Modified from Fryirs and Brierley, 2012.

3.1.3 Unconfined valley setting

These valleys are fully alluvial, meaning the river is surrounded by low gradient floodplain which have been deposited by rivers over time (Figure 25). In this setting, the river's adjustment is unconstrained. During floods, energy spills out of the river onto the floodplain meaning that energy can be dissipated rather than concentrated in the channel. No valley controls on channel form exist, which means the river can adjust its sinuosity (and therefore slope) to reflect its sediment load. Reaches within this valley setting will tend towards being depositional, where more sediment is delivered into the long-term storage of the floodplain than is eroded and transported downstream. In straightened systems, previous channels are commonly present on the floodplain, which can indicate past channel location and characteristics. Long term processes of erosion or deposition can be assessed by assessing whether terraces (resulting from the river eroding into the floodplain) are present or not.

Unconfined valleys contain a range of river types and thus are separated into two recovery potential categories. These are either ‘unconfined valleys with a moderate gradient’ which have a moderate recovery potential or ‘unconfined valleys with a low gradient’ which have a low recovery potential. Valleys with a low gradient would be expected to be very flat, and contain rivers with a low energy regime, such as the passive meandering river type. It should be used to describe a very low energy environment with limited potential for natural geomorphic adjustment. In contrast, the moderate valley gradient contains rivers that are more geomorphically active with larger sediment size, such as the active meandering river types. When deciding if a floodplain has a moderate gradient, it should be possible to see some slope on the valley, rather than it appearing as flat. Making the distinction between a moderate or low slope is important, as it differentiates between these energy environments and recovery potential within this valley setting.

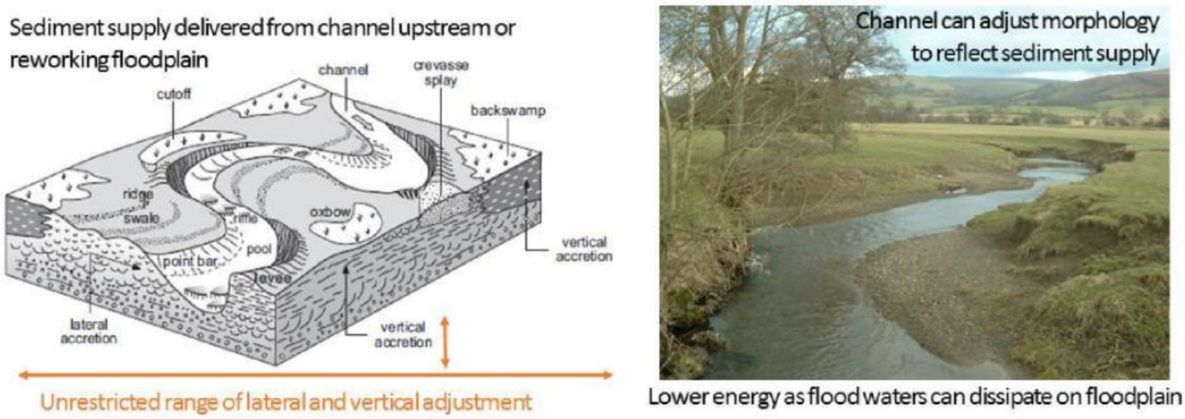


Figure 25: Schematic showing the attributes and features seen in an unconfined valley setting. Modified from Fryirs and Brierley, 2012.

3.1.4 Anthropogenically modified valley setting

Valley setting can also be categorised as being significantly ‘anthropogenically influenced’. This should be used if the whole valley has been modified and as a result the channel confinement has changed. This is not a common scenario and should only be used where large-scale change has taken place, such as where mines have been restored or where large scale earth movement has fundamentally altered the degree of channel confinement and created a landscape which is significantly different from what would be there naturally. This would not include dense urban areas. Whist the river will not be able to access its floodplain in a similar way to prior to development, the actual valley shape has not changed. See case study in Section 6.1.2 for an example of this type of valley setting.

3.1.5 Additional valley evidence

Whilst valley setting is critical as it significantly influences the energy environment of a river, it can also hold additional information about how the channel has adjusted in the past, both on contemporary time scales (10s to 100s of years) and longer geological timescales (1000s of years).

To facilitate a correct assessment of these historical changes, additional data sources can be used to complement what is observed in the field, especially if the valley is well vegetated or urbanised and its morphology difficult to observe. You may consider including in your assessment:

- Geological drift maps of the distribution of alluvial fill, showing the area the river has reworked within the valley margin in the last 10,000 years (since the Holocene).
- Solid geology maps can be useful for understanding the strength of the underlying lithology which can indicate how much erosion is likely to take place and as a result the type and quantify of the sediment load (i.e. soft geology such as sandstone and mudstone erodes faster than hard volcanic stone).
- Historic maps on the National Library of Scotland website (http://maps.nls.uk) which can show how the channel has changed in the past 150 years (or 270 years if the less detailed Roy Military maps are used). Sometimes this will include a map of the river prior to human modification. This is also useful for assessing reference river type.
- Aerial photographs can be used to identify evidence of previous channel locations on the floodplain. Often these will appear as wet and swampy areas with clear channel outlines.
- If available, LiDAR data can also be used to identify past channel locations and understand the heights of different floodplain surfaces (and connectivity) relative to the river. These data also show how confinement changes for different sections of river.

This information is also important for classifying the reference river type (Section 3.2), which aims to understand what the river type would have been before it was modified. The valley setting provides clues as to river adjustment prior to modification.

3.2 River type

Internally, SEPA already has a layer describing River Type which has been derived from a mix of remotely-sensed and field-based data (please contact SEPA if you need a copy of these data). However, as with all nationally derived datasets, there is some error associated with this layer, so river type should always be validated in the field. It should be noted that this assessment aims to classify type based on what river would have existed at this location if it had not been modified (reference typology) and not its current typology, which is the product of anthropogenic modification. Notable exceptions occur when the morphology is completely altered (such as by being concrete lined) and all natural characteristics have been obscured. In this situation, river type should be recorded as being ‘anthropogenically influenced’. This section will summarise the characteristics of each river type to facilitate its accurate classification.

Importantly, when undertaking this classification we should remember rivers exist along a continuum. Sometimes rivers do not fit discretely into any of the boxes below, but will contain elements of two or more reference types. In these situations, discretion should be used as to which type it is closest to. This may be resolved by simply looking at a longer stretch of river. Also, human modifications to rivers can cause them to significantly change their state. For example, a straightened river could go from a reference meandering type to a plane-riffle. Therefore, the challenge here is to look at the current river type and assess what type of river it would have been if it had not been modified. The valley setting assessment in the previous section is crucial to understanding what river type should exist at a location.

River types, corresponding to those used for MImAS classification are discussed below. This section will aim to outline:

i) the general physical characteristics of each river type;

ii) their energy and sediment regime; and

iii) implications for recovery and their likely ability to self-heal. Those types where the rivers are resilient and therefore unlikely to need restoration have been identified and will not be dealt with in the following sections.

3.2.1 Bedrock and Cascade types

Bedrock and Cascade rivers have high energy and are particularly resilient to change (Figure 26). Bedrock outcrops and a confined valley setting limit lateral adjustment and bed lowering. As they are usually located in the steeper uplands which can be characterised by minimal human development, they are unlikely to be subjected to high degrees of anthropogenic influence. As a result, restoration is seldom carried out on these systems. In situations where restoration was required, then we would classify them as high energy and very able to 'self-heal' with minimal need for assistance (as long as they carry an appropriate sediment load). As an example, where weir removal is deemed an appropriate restoration strategy, the frequent presence of bedrock would make the channel resistant to changes following removal. This river type is therefore categorised as being 'resilient to change', indicating that it is unlikely to require active restoration.

Figure 26: Photographs of A) bedrock and B) cascade channels. Note the steep topography and high degree of bedrock influence.

3.2.2 Step-pool river type

Step-pool systems are also high energy, though usually with smaller catchment area and thus lower discharge than bedrock/cascade streams (Figure 27). They are typically located in steep confined valley settings, minimising the degree of adjustment they can undergo. Sediments are generally coarse, with boulders creating the steps which dissipate energy, associated with a generally steep valley slope. These river types naturally have high geo-diversity due to the high energy regime and the large material combining to create a mosaic of habitats. Typically, they are not commonly restored. As long as they retain an appropriate sediment supply, including boulders which act as key-stones, and retain their high energy regime they are generally able to restore themselves. However, the removal of weirs or deculverting has meant that restoration is now being undertaken in this channel type.

Whilst this river type does typically have enough energy to restore itself, the limiting factor of natural recovery is the number of large boulders needed to make the steps, and the time and flows needed to arrange these boulders into step features which are resistant to the prevailing flood flows. If this resistance is not present then the channel will incise, transporting available sediment and destabilising the reach.

In many of these systems, these key-stones have been delivered to the channel over long time-scales. If these larger stones are not available, it may be a long time before they are naturally delivered to the channel. Therefore, if sediment large enough to be key-stones are not present, step-pool systems should not be restored using passive measures. Instead, these need careful design and construction, in order to create features that are stable. However, despite this, this river type falls into the 'high recovery potential' category due to its high energy characteristics and confined valley setting. This is because it has lower energy compared to the RTC river type and a greater likelihood of becoming destabilised. However, on the continuum, this river type is more similar to the RTC rivers compared with the other river types included in the high recovery potential category.

Figure 27: Photographs of step-pool channels. Note the large boulders that act as 'key-stones' providing resistance and holding the bed in place.

3.2.3 Plane-bed rivers

Plane-bed rivers are typically characterised by a boulder and cobble dominated bed, which tends to be uniform and featureless (Figure 28). The channel planform alignment is relatively straight, and it has few or no exposed bar features. This is a very stable river type, characterised by reduced morphological diversity and extremely low rates of lateral and vertical channel adjustment. Valleys for this river type are usually gently confined and banks are cohesive. Energy levels are typically moderate and lower than the river types discussed above.

When assessing river typology, it should be noted that rivers that have been straightened can appear to have a plane-bed morphology. Therefore, when looking at this river type an assessment as to whether the lack of planform diversity is natural or a result of straightening is critical. Together with a field-based assessment of the presence of bank protection, valley setting (and associated energy regime) will provide clues as to whether this river is naturally occurring in this location (i.e. if the valley is wide and flat than the channel is likely to have adjusted across it in the past). Also, straightened rivers are often very straight, whereas plane-bed rivers should be characterised by low sinuosity. Looking at old maps, aerial photographs and LIDAR data can support an assessment of whether this is the natural alignment of this channel (considering that, in some cases the historical realignment of channels pre-dates the first available OS maps).

Figure 28: Photographs of plane-bed river type. Note the low sinuosity planform and high energy flow types.

True plane-bed rivers seldom require restoration given their naturally low morphological diversity. They naturally have low planform sinuosity and low rates of channel adjustment, so are not usually artificially straightened. Typically, restoration options are limited to the removal of in-channel structures, without further active intervention required to return them to their reference condition (as long as the bed does not become destabilised). Due to their high energy they are classified as having a high recovery potential.

3.2.4 Plane-riffle channels and dynamic pool-riffle channels

Plane-riffle and dynamic pool-riffle river types are intermediaries between the higher energy, more confined plane bed channel and the lower energy, less constrained active meandering channel (Figure 29). The plane-riffle represents a higher energy type, typically displaying greater valley confinement. The pool-riffle type is generally set within a wider functional floodplain with a lower energy regime, allowing lower energy pool units to develop. For these river types, valleys have typically started to widen and the channels increase their sinuosity to fit within this greater space, whilst still retaining a slightly curved, low sinuosity planform. Importantly, these ‘hybrid’ types are characterised by a significant increase in morphological diversity with frequent transition between plane/ riffle/ pool units, as opposed to the homogenous plane-bed type above.

Figure 29: Photographs of plane-riffle (right) and dynamic pool riffle (left). Note that both are relatively high energy, but the pool – riffle has been able to excavate pools as part of its form.

Again, this river type needs to be assessed within its history and valley setting. For example, as a straightened active meandering river can go through a stage where it presents the above properties before it develops the full meanders that would be present under reference conditions. These river types are also less likely to be straightened and modified as their higher energy characteristics generally mean they are less frequently located where human development is high. They are also a river type characterised by a relatively low sinuosity, so straightening only has a minor impact upon river form. Dredging, however, may be more harmful as it significantly impacts the availability of sediment that supports its characteristic bedforms. Where restoration is required, due to the high energy nature of this river type, passive restoration such as engineered log jams, is likely to successfully restore reference condition geomorphic diversity rapidly. Otherwise, they are likely to self-restore relatively quickly following the removal of anthropogenic pressures. As a result, they are judged as having a high recovery potential.

3.2.5 Wandering channels

This is a transition between a braided and an active meandering river. They are typically located where the valley widens out, in a partly confined or unconfined valley setting. This river type has a higher sediment supply than the meandering river, and is characterised by extensive bars, islands and a channel that splits frequently, maintaining between 1 to 3 wetted courses (Figure 30). This river type tends to occur on larger rivers with a high width/depth ratio and a wide functional floodplain.

Figure 30: Photographs of wandering channels.

This typology is more common in Scotland than the braided river type. The most common impacts within this river type are gravel mining, laterally constraining the channel to reduce the width (embankments or bank protection) and complexity of the planform (i.e. cutting off back-channels) or decreasing the sediment supply (reservoirs). Due to the high sediment load and relatively high energy, this river type is highly likely to be able to self-restore. In most situations by removing the constraints (i.e. bank protection) the river will be able to adjust and improve its morphology. For this reason it has been judged as having a high recovery potential.

3.2.6 Braided channels

Braided channels exist where the volume or size of sediment supplied is greater than the channel can transport, creating a highly dynamic system, with multiple active channels that frequently change position within a wide functional floodplain (Figure 31). The valley setting is generally unconfined, giving the channel the space to rework and store this material. This river type is fairly uncommon in Scotland, due to rivers rarely having enough sediment supply to generate this channel type. Thus, it is infrequent that this type of river would require river restoration. The main impact would be removal of gravel to narrow the channel, or installing embankments or bank protection to try and laterally restrain the river. This river type has the energy and the sediment supply to restore its form if it has been modified. Therefore, as long as anthropogenic modifications are removed, then the river will be able to recover its form very rapidly (i.e. within a couple of years) with little active restoration. This would be contingent on there being no changes to the upstream sediment supply such as gravel mining off-site, or ongoing regulation of flow and/or sediment. Braided rivers are, therefore, classified as having a high recovery potential.

Figure 31: Photographs of braided reaches within Scotland.

3.2.7 Active meandering channels

Active meandering rivers occur in wide valleys where the river has the energy and space to laterally adjust, creating a meandering planform through alluvial floodplain deposits (Figure 32). Migration rates if unimpeded, should be < 2 m/year. This river type encompasses a range of energy types, covering the energy continuum from the wandering river type to the low gradient passively meandering channels. Flow types predominately include a range of riffle, run, glide and pool units. Point bars are often present on the inside of meander bends. Due to its location in flatter, wider valleys, it is commonly altered by humans, and is the most common river type to be restored. This is further complicated by the frequent overlap between their floodplains and high value agricultural land. Impacts mostly include planform straightening, bank protection, gravel removal and installation of embankments. Some of these pressures can increase the energy in the channel during high flows, causing the river to incise into its bed, creating an over-deepened channel geometry. In turn, this over-deepened and constrained geometry increases the 'flushing' of sediment delivered to the channel, highlighting that alterations to the reference planform and sinuosity can also alter the vertical placement of the channel.

Assessing restoration approaches in this river type can be more complex due to variations in energy, sediment size, degree of deviation from reference conditions and vertical bed location. This means both active and passive approaches can be applied in this environment. Each reach should be individually assessed using the attributes described in Table 7 to decide what the recovery potential is and therefore, which restoration approach is most suitable. In some locations, there have been problems with restoration practitioners uniformly trying to restore a historically meandering planform to a river where this was not presently suitable, resulting in some dramatic and expensive restoration failures (c.f. Uvas Creek in California; Kondolf, 2006). For this reason, passive restoration approaches may be preferable, as rather than trying to design an 'ideal' planform and channel geometry, the channel is supplied with the tools and the room to create appropriate habitat. A correct assessment of energy levels, sediment load and ease of adjustment is however crucial before deciding whether passive approaches are likely to result in successful restoration.

Figure 32: Photographs of an active meandering river.

This river type operates across a continuum and therefore, active meandering rivers are separated into three energy sub-categories: high, moderate and low, which can then be split into moderate and low recovery potential (Table 7). Discretion needs to be used when allocating the river a category and understanding that energy environments can change over space and time.

Table 7: Description of the different types of active meandering river that fall into each recovery potential category.

Energy of active meandering river	Description	Recovery potential category
High energy active meandering rivers	Characterised by larger bed material (coarse cobble) and higher energy flow units - more riffles and fewer glide stretches	Moderate recovery potential
Moderate energy active meandering river	Relatively common, characterised by a mix of cobbles and gravels on the channel bed and riffle – run – pool units	Moderate recovery potential
Low energy active meandering river	Channel beds that are dominated by finer gravels and sand with the frequent presence of lower energy units such as glides when compared to the previous two types. They may still have well-spaced riffles. Their form indicates lower overall rates of adjustment of planform and/or bedforms (i.e. bank erosion is less common).	Low recovery potential

3.2.8 Low gradient passively meandering channels and Peat channels

This river type is located in unconfined, flat valleys and can be characterised by low energy and slow rates of channel adjustment (Figure 33). Bed material is typically fine, consisting of sands or silt and bars are rare. Adjustment is much slower for this river type, which is reflected through minimal erosion rates and the presence of well-vegetated, stable, cohesive banks. Flow types are also dominated by glides and other low energy types, which are often deeper than the active meandering type. Given that reaches of this type are generally located in flatter lowland locations, it is highly likely that they will have been modified by anthropogenic activity. For example, they are common in urban and agricultural areas.

Low gradient peat channels are also included within this classification. These are channels which drain flatter areas of headlands and have low catchment areas, resulting in small, low energy channels with cohesive banks. Development is less likely in these locations, though many have been straightened or dredged to improve drainage for agriculture.

Figure 33: photographs of passive meandering river type. The photo on the right is a peat channel type, which fits into the passive river type category.

It should be noted that passive meandering channels have limited capacity to adjust their form and improve their condition following channel degradation without active intervention. For example, if measures such as wood deflectors were to be installed, this would likely increase the diversity of flow types, but timescales for recovery of channel morphology would likely be too long for most restoration projects. For this reason passive approaches are less likely to be appropriate in these environments, given their much longer recovery times, especially if the reference sinuosity which is the restoration target is much greater than the current sinuosity. Instead, methods which actively modify the river such as remeandering are more likely to be appropriate. In addition, these channels are often over-widened, commonly due to past dredging or in response to changes to the hydraulic regime. In these situations, restoration can include building depositional berms or installing deflectors to narrow the channel and increase sinuosity and diversity in-situ. Therefore, this river type is classified as having a low recovery potential.

3.2.9 Anthropogenic River Type

The Anthropogenic river type describes a situation where all of the characteristics have been modified or engineered (Figure 34). This would include a channel which is concrete, brick or block-stone lined and where no natural features remain. To classify a reach as belonging to this type, we would expect there to be little or no remaining features that indicate natural fluvial processes are operating in the reach, such as shown in Figure 34. Thus, this is not a 'true' river type, but rather a category which indicates that the rivers' characteristics are so obscured that it is not possible to assess river type accurately.

Figure 34: Photographs showing sections of river that should be assessed as having an 'anthropogenic influence' rather than a natural river type.

3.2.10 Summary

The characteristics, likelihood of needing restoration, energy and recovery potential categories for each river type are presented in Figure 35. This highlights that the active meandering and passive meandering river types are the most likely to be degraded and have lower recovery potential. This is because they are located in low gradient, wider valleys, where anthropogenic development is often more intensive. Both river types are i) less resilient to anthropogenic pressures and ii) more likely to have a greater number of pressures affecting them. They also have lower energy and so take longer to recover. Therefore, these require greater consideration as to whether active or passive measures are likely to be appropriate.

These more sensitive unconfined rivers are more likely to have undergone a change in river type due to human modifications. For example, once straightened, a meandering river can adopt a plane-bed morphology (commonly helped by embankments and/or bank protection). It is important to look beyond what type is currently present and assess river type based on what should be there if no modifications had taken place (i.e. the reference type). To do this, it is important to 'get your head out of the channel' and assess the catchment location and floodplain characteristics at the same time as assessing river type. Section 3.1.4 provides examples of the type of evidence available in the valley setting. This includes understanding how the river may have changed both over space and over time.

Figure 35: Summary of the different river types, the likelihood of them needing restoration and their recovery potential category.

Rivers also do not always fit neatly into the classification boxes described above. This is because river classification creates categorised boxes along a continuum where energy, sediment load and landscape setting combine to create diverse river forms. Transitional rivers are common, which fit between two categories making them difficult to define. For example, the Pow Burn has attributes of both active and passive meandering river types and does not fit neatly within either category (Figure 36). When rivers do comfortably fit within a category, there can still be significant variation in behaviour between different reaches. Therefore, river type should be classified based on the best fit. The additional indicators assessed in the following section will build upon this classification, and it is the outcome of all these indicators which determines overall reach-scale recovery potential.

Figure 36: The Pow Burn is a good example of a transitional river type, exhibiting characteristics of both active and passive meandering. In this situation the channel has to be assessed for evidence of potential energy, and any interventions designed in a way which will utilise this.

3.3 Bed material size

The size of sediment which makes up the bed of a river can be a hugely valuable resource for understanding the energy of the system. River form is a result of impelling forces (from the flow regime) and resisting forces. Grain size at a point represents the energy at that point, as the sediment has to be large enough to resist being entrained. It is particularly useful to look at how grain sizes change along your reach and across the different geomorphic units to get an idea of how energy changes within these locations. Riffles and the bar heads (upstream coarse sections of bars) commonly contain the maximum size of material the river is able to entrain and transport. If areas of the river bed where coarse sediment would naturally be expected are smothered in fine grained sediment, this may be due to excessive volumes of silt being delivered to the system, rather than a direct expression of energy.

Table 8: Table describing different grain sizes with photographs of each class. Modified from Environment Agency, 2003.

Channel substrate	Size (mm)	Processes and energy	Photo	Energy
Bedrock	N/A	• The bed is exposed bedrock or has bedrock outcrops. • Very high energy as all sediment which is supplied to the reach has been eroded. • This may occur when the river has incised into its bed removing material till it reaches the valley bottom as a result of channel straightening. • Resilient to change		***Very High***
Boulders	> 256 mm	• Largest coarse boulder material which makes up the stream bed in steeper areas (i.e. Cascade and step-pool river types). • Larger than head sized. • It creates the structure such as steps and/or coarse riffles within steeper, higher energy river types.		***High***
Cobbles	64 - 256 mm	• Material which is larger than gravel (half-fist sized) but not as big as the boulders (large head sized). • Creates a relatively rough and coarse channel with steps and riffles dissipating energy.		***High - mod***
Gravels	2 – 64 mm	• Gravels include the smaller loose material which can be described as being between conker and half-fist sized. • In coarser channels it is the material which is transported frequently and makes up the slower flow units. • If a channel is predominately gravel then the energy is lower. • Important for fish spawning (Salmon and Trout).		***Mod – low***
Sand	62 µm - 2 mm	• Fine and uncohesive material which is easily transported. • Moved frequently by small floods, and deposited in the slower backwater areas.		***Very Low***

		• If the whole channel is sand this would be a low energy system. However, the margins are likely to be very erodible, so the river may still be able to undergo lateral adjustment, despite its low energy.		
Silt/mud	3.9 - 62 µm	• Silt includes material which is not as coarse as sand, but not as cohesive as clay. • It tends to be located in very low energy settings, and macrophytes often colonise the bed to add habitat and structure. • When silt is wet it becomes mud. • Can cover gravel beds if supply is excessive or energy levels low, potentially smothering habitat.		***Low***
Clay	0.98 - 3.9 µm	• Rivers with clay beds are not very common. They occur where the channel has incised into clay (often old glacial material). • Usually would be relatively low energy, with a narrow channel and vertical banks. • Lateral adjustment would be expected to be minimal.		***Low***

Table 8 provides an overview of the different sediment size classes commonly present in river beds, which we can use to understand the energy of the river and its potential to adjust. Bedrock indicates a river is resilient to change. Boulders and cobbles are defined as high recovery potential; cobbles and gravels as moderate; and silt and mud, sand and/or fine gravels are in the low recovery potential category. If the channel bed is completely concrete, blockstone or brick-lined then the river should be ranked in the 'anthropogenic influence' category, indicating that the bed material has been fundamentally altered and it is not possible to use it as a characteristic to assess channel energy.

3.4 Number and extent of bars

One of the key attributes that determines whether a river will recover and the extent of adjustment that can be expected is its sediment supply. Whilst grain size is a key attribute for energy, the sediment load (volume of sediment being delivered) is also essential for understanding the rate of morphological adjustment. Rivers with a high sediment supply need to adjust their form to store sediment and may recovery more rapidly. However, the rate and form of this adjustment will differ depending on the river type. For example, a higher energy river such as a dynamic-pool riffle type is likely to only moderately adjust its sinuosity to store this sediment within the channel, due to the relatively low erodibility of boundary materials. In contrast, an active meandering river type set within a wider, more erodible floodplain is more able to carry out bank erosion and increase sinuosity, in association with lateral channel migration and the development of point bars.

Patterns of sediment erosion and deposition can be influenced by measures such as wood deflectors that create increased variation in channel bed forms at specific points (as well as contributing to whole-scale channel change). Some restoration schemes (see Alt Lorgy case study in Section 6.1.4) injected sediment into the channel to reduce recovery times, which worked successfully. Sediment load can be (crudely) calculated based on the number and extent of bars present within a reach. The following questions can be used to assess this;

i. Are there bars present at a reach? What is the scale of the bars? Are there any? Are there a few, scattered along the reach, or are there a moderate number, or are bars very common, driving the planform of the reach.

ii. How large is the sediment which the bars are made up of? Are they coarse and appear relatively static (this can be assessed by how much lichen or discolouration the sediment has) or clean gravel (indicating that it is transported relatively frequently)?

iii. Are there modifications such as embankments, bank protection or active gravel removal which are stopping bars from forming? If so, this means that using barforms to assess sediment load could prove misleading.

iv. Is the sediment supply to this point likely to be high? Is the river upstream well connected to the sediment source of the headwaters (i.e. a relatively steep cobble/gravel channel that is moving bed material to this point)? Are there banks or terraces present which are actively eroding and delivering high volumes of coarse material (what is the calibre of this?) to the channel? Or, are there any features upstream that might be blocking sediment supply such as a dam, loch or feature that may act as a sediment sink (something that stores the material that is delivered from upstream). Table 7 presents the categories which are used to describe the bar frequency within the reach. These categories are descriptive, and the assessor should use their best judgement as to what category each reach is placed within. The additional information in the questions above can be used to understand more about the characteristics of the reach. In addition, this assessment should not just be carried out at a single point, but along the whole stretch of river included in this assessment as bar distributions are not always consistent along a reach.

Table 9: Categories that describe the frequency of bars along a reach.

Bar number	Description	Implications for recovery	Recovery potential Category
Many	Bars are very common along the reach and the channel has a wandering/braided planform, indicating that sediment supply is very high to this location.	Sediment supply is high. Passive approaches to restoration are likely to be successful at this location, and recovery times for the river short.	**High**
Some	Bars are scattered along the reach, not just on the inside of bends, but channel does not have a multi-channeled wandering/ braided morphology.	This channel is more likely to have the tools it needs to recover. Again, if the sediment on the bars has been recently mobile and is loose, then recovery times would be expected to be shorter.	**Moderate**
Few	Small bars generally located on the inside of the bends.	This reach has some sediment supply. This will help the river to recover, but it may take longer than rivers with 'some' bars. Assess how mobile and fresh the sediment on the bars is to understand how recently it was delivered, which can be used to infer how likely channel recovery is.	**Moderate**
None	No bars are present within the reach.	Sediment supply is very low to this location, or it is a reach that flushes the material through. Determine whether this is due to anthropogenic modifications or natural (if anthropogenic see category below)? If the low sediment supply is natural, then rates of recovery are likely to be low and active restoration techniques more likely to be required. Alternatively, this may be a high energy reach which is resilient to change and if the reach is bedrock than it may be put in that category instead.	**Low (or if bedrock RTC)**
Anthropogenic	Anthropogenic factors such as embankments or bank reinforcement linked with straightening restrict room for sediment to be deposited.	Anthropogenic impacts can limit the available space for bars to be stored within the channel. This means that a channel can appear to have no sediment supply which can be misleading. Therefore, this variable should be discounted in this situation. It should be used where embankments, bank protection or other modifications on both banks have constrained the river, causing sediment to be flushed through, and restricting the space available for the channel to store sediment.	**Anthropo-genic influence**

3.5 Bank grain size

As well as understanding the nature of the bed material grain size, it is also important to assess what sized sediment makes up the banks, as indicated in the grain size table below (Table 10). Most commonly, banks consist of a mix of grain sizes. Therefore, it is important to work out which sizes are dominant, and the implications of this for how easily your river can adjust. The output of this assessment doesn't necessarily fit neatly into boxes, so the assessor will need to describe what they see and use this to interpret how erodible banks are likely to be.

Table 10: Description of how to assess bank material characteristics.

Grain size	Description	Recovery potential
Mixed river deposited material – gravels, cobbles and boulders	• Banks can be made up of old river deposits such as gravels and boulders. Larger clasts are commonly suspended in a matrix of sand, silt or clay (clay would mean the material is likely to be glacial). This matrix should be assessed based on the categories below to ascertain how strong your bank will be. • If the bank consists only of coarse material, then there is very low cohesion and it is likely to be very erodible (High recovery potential). • If the coarse sediment is held within clay or a cohesive matrix then it will have a moderate recovery potential. • The size of the coarse material adds to the weight of the bank and this can help it to erode. However, the eroded material can form a line at the bank toe, providing a layer of protection. Therefore, this bank type is more complex and ease of erosion should be linked to 1) the cohesion of the material in the matrix and 2) the size of the coarse material making up the bank and how easily this appears to erode. To get a best estimate agitate the bank and look at how solid it appears or look at how much erosion is occurring elsewhere along the reach.	**High or moderate depending on whether it is within a cohesive or uncohesive matrix**
Sand	• Sand is non-cohesive, so the grains are loose and not bonded together and it is very easily mobilised by the channel. • Can be often mixed with silt (i.e. forms the hard grainy bits when you rub between your fingers). The more sand in a bank, the more erodible it will be. Try and form a ball and if this is not possible then the sand content is high.	**High**
Silt	• Coarser than clay and less cohesive. You should be able to feel the grains in between your fingers and when you try and form it into a ball it should crack or crumble and not hold together in the way that clay does. • When wet it will form mud which can slump. Often will be dark brown indicating that it is organic rich. • This sediment type has a moderate resistance to erosion. This can increase if it is mixed with clay or decrease if it is mixed with sand.	**Moderate**

Clay	• Sediment with very fine particles which is sticky and solid. When you rub it between your fingers you cannot feel the individual grains. For pure clay you should be able to form a ball when it is damp without it cracking. This material is cohesive (has strong bonds) and can form quite a hard boundary. • Clay will increase the cohesion of your banks and the resistance to bank erosion, creating more vertical banks. Therefore, rivers with clay banks will need to do more geomorphic work to erode them compared with other bank types.	**Low**
High density tree roots and vegetation cover	• Is there thick vegetation on the bank top or covering the bank face? Is it possible to see tree or plant roots in the bank exposure creating an extra layer of protection? Are the roots thick and solid or is there a finer root matrix? Look at the banks and visually assess how the vegetation (or lack thereof) is contributing to bank structure. • High density tree roots can greatly increase the bank stability and may mean that a silt bank is categorised as low instead of moderate potential due to the increase in bank stability. This is especially true if there is little or no erosion elsewhere along the reach, indicating the high stability of the banks.	**Low**
Anthropogenic Influence	• If the banks are predominately obscured by stone, concrete or gabions and it is not possible to accurately assess what is underneath, then a reach may be defined as being 'anthropogenically influenced'. If it is possible to see a section of the bank material through this, then it should be based on what is visible. This is because if the hard engineering was removed then recording the underlying material would tell us the resistance of the banks once the hard protection was removed.	**Anthropogenic Influence**

Assessing the cohesion of the banks provides an indication of how much work the river will have to do to adjust laterally, linking directly to channel recovery (for rivers which have been straightened and where channel migration would be expected). A high sand content will mean that banks have a low cohesion, and can be easily eroded. In contrast, high clay content will mean banks have a high cohesion and are more difficult to erode. Table 10 also provides advice on how this can be assessed (i.e. can the material be formed into a ball?). In addition, bank cohesion is able to be assessed to some degree visually. Steep and stable banks are generally more cohesive, whereas banks that are stable at a gentler gradient will have a lower cohesion. Table 11 presents examples of banks which fit into each recovery potential category.

Table 11: Examples of banks with different levels of resistance to erosion. Note: that a river that was highly resistant to erosion would have a low recovery potential, as the channel would take longer to migrate and obtain good condition.

	**<u>Low resistance to erosion –</u>** **<u>High recovery potential</u>** Banks are made of sand and not able to remain stable at a steep angle. As a result, the material slumps to create a lower gradient. If the slumped material is removed, and the gradient increases, then the banks will collapse again.
	**<u>Moderate resistance to erosion –</u>** **<u>Moderate recovery potential</u>** This is a composite bank. The lower section is coarse gravel material is held within a more cohesive matrix of silt. Above lies silt, deposited as the floodplain built up. The silt is not as cohesive as clay, but more cohesive than sand. Once the gravel in the lower section of the bank is eroded it will be deposited at the bank toe to provide some degree of protection.
	**<u>High resistance to erosion –</u>** **<u>Low recovery potential</u>** High clay content in the terrace (sourced from glacial till) means that even though it is eroding, the rate of this is slow and is able to support a very steep slope without collapsing. There are some gravels in this mix but the majority is clay, providing the stability despite the height of the bank.

3.6 Bank erosion

This indicator assesses how much bank erosion is present in the reach assuming that, where more bank erosion is present, the channel possesses a greater capacity for geomorphic work and is more likely to recover following the removal of anthropogenic pressures. Bank erosion is a useful aspect to understand as it illustrates the relationship between the energy regime of the reach and the erodibility of its boundary. The following questions can be used to help assess the recovery potential category of a reach based on observed bank erosion patterns.

1. Is bank erosion present within this reach? If not, is this a function of the reference river type or a product of anthropogenic modification?
2. Is it located on the outsides of the bends (which is where we would predominantly expect it be due to lateral channel adjustment) or on straight sections as well?
3. If there is no bank erosion, are there man-made structures stopping it? For example, bank protection? Note: if bank protection is present then this is an indication that the reach may have the energy to laterally adjust, leading to the need to fit protection. As a result, the recovery potential cannot be accurately assessed for that section.

Table 12 presents the categories of bank erosion used to assess recovery potential.

- The first category includes rivers which are resilient to change due to their geomorphological resilience and stable banks, often dominated by bedrock.
- High recovery potential reaches describe those which can readily adjust, seen in erosion being present on both the bends and straight sections.
- Moderate recovery potential reaches have some bank erosion, but it is located only where we would expect to see it, namely on the outside of bends (in lower sinuosity rivers this can include points opposite gravel deposition as the channel starts to increase its sinuosity). This indicates that the channel has the energy to recover and using techniques such as deflectors to enhance this recovery is likely to be successful.
- Reaches with low recovery potential have stable banks exhibiting little or no adjustment.

- Anthropogenic influenced reaches exist where human impacts restrict or increase bank erosion, meaning that if it was assessed at face value, the results would be misleading. By selecting this category, the bank erosion attribute will be excluded from the overall recovery potential score, so that assessment biases associated with anthropogenic modifications are excluded.

Table 12: Table summarising the different bank erosion categories.

Bank erosion recovery potential	Description	Photograph
Resilient to change	Banks are either non-erodible bedrock or boulders and so are very unlikely to be able to adjust. Recovery would not be expected through lateral adjustments. Therefore, absence of bank erosion should not be deemed an obstacle to recovery of reference morphology, but more irrelevant for rivers that fall within this category.	
High	Erosion is prevalent throughout the reach, not just on the outside of bends but may be on straight sections or insides of bends as well. This indicates that the sediment load may not be in-sync with the channel processes and that the channel has the energy to readily adjust its form. Banks also tend to have lower cohesion.	
Moderate	Bank erosion occurring at locations expected for that river type, i.e. on the outside of bends. This shows that the channel has the energy and the banks the resistance to allow channel adjustment at a fairly natural rate.	
Low	Very little erosion present. Banks appear to be stable often held together by cohesive sediments and/or vegetation. This channel can still have the potential to recover, but it just might take longer and need more active restoration.	

Anthropogenic influenced	Bank erosion is either not occurring due to bank protection or is occurring but not due to fluvial (river) processes. For example, poaching can cause bank slumping (see photo below of slumping on inside of bend). This category is designed to exclude this bank erosion from the recovery calculations. If a stream has a mixture of both natural and anthropogenic bank erosion, then selecting a category is more complicated. It should be based on assessing the level of erosion that has not been caused by anthropogenic factors and selecting the appropriate category.	 

In addition, bank erosion observed should be related back to the time of year and whether stock have access to the riparian margin. In the summer there is a lot more vegetation which both protects and covers erosion, so banks can appear more stable than at winter when they are more exposed and thus more vulnerable to erosion. Floods and rainfall events are also more frequent in winter, again increasing the likelihood of erosion. Understanding the recent weather events, such as significant named storm events (i.e. Storm Frank in January 2016) is important for contextualising the degree of adjustment that is observed in the field. This means looking under vegetation for erosion, or looking for erosion that has recently stabilised should also be used as indicators when deciding which category to place your reach in. In addition, it is important to actively look for artificial bank protection. Sometimes this can be quite hidden, either by vegetation or by being buried into the bank. This is especially true if the bank protection was created using river boulders as these can blend into the river bank and appear natural (e.g. Figure 37).

Figure 37: Boulder bank protection buried into the bank and obscured by trees and vegetation.

Field maps can be used to provide evidence regarding the degree and locations of bank erosion within a reach. This could be in the form of a rough sketch map of the reach annotated with the locations and severity of bank erosion. This can be used at later stages to identify pressure points and assess in which direction the river is adjusting. This information is also vital for deciding where to install passive measures such as wood deflectors (see Section 5.2.2). These can be used to amplify existing erosion, working with the natural processes to increase the diversity and sinuosity of the reach, thus reducing the time required for recovery.

3.7 Geomorphic-flow units

Flow and geomorphic unit type provide useful indicators of the energy of the system. Flow types refer simply to the characteristics of flow at a given time. Geomorphic units can provide a more useful descriptor as they consider flow, sediment and depth characteristics as well as current flow conditions. This means that a riffle should be defined as a riffle whether the river is at high or low flow. In contrast, if we were only looking at flow, the same unit may be classed as a run at higher flows and a riffle at lower flows, as the turbulence changes. Therefore, we will refer to these as geomorphic-flow units within this report and classification of the units should be based on both flow and morphology.

Table 13 provides a description of all the geomorphic-flow units described in this document. Table 14 summarises the range of flow types that we would expect to see in different recovery potential categories. Reaches should be classified using the range of flow types present, and not just a single flow type as they are usually made up of a combination of multiple types.

Table 13: Description of different flow geomorphic-flow unit categories as used to understand the energy of a reach. Flow descriptions sourced from Newson and Newson, 2000; Reid et al., 2008; Fryirs and Brierley, 2013.

Flow Category	Description	Photograph
Waterfall	Water falls vertically and without obstruction from a distinct feature, generally more than 1 m high and often across the full channel width. Bedrock underpins this flow type. It is very high energy in a very resilient valley setting.	
Cascade	White-water “tumbling” waves with the crest facing in an upstream direction. Associated with “surging” flow. Underlain by bedrock and boulders. Indicates very high energy and steep channel bed slopes, but located in a very resilient valley setting.	
Step	Fast, smooth boundary turbulent flow over boulders or bedrock. Flow is in contact with the substrate, and exhibits upstream convergence and downstream divergence. The steps are channel-spanning features like stairs that are separated by flat pool-like units. These units are major energy dissipaters.	

Riffle	Undulating standing waves in which the crest faces upstream without breaking. These should be topographic highs on the bed and are usually located in the straight sections between bends. Often formed of tightly packed coarser sediments. Usually the steepest elements on medium energy rivers.	
Run	Surface turbulence does not produce waves but symmetrical ripples which move in a general downstream direction. They have uniform morphology though boulders may protrude through. Shallower and swifter than glides, but not as topographically defined as a riffle.	
Glide	Flow in which relative roughness is sufficiently low that very little surface turbulence occurs. These are homogeneous units, typically found in lower energy or degraded settings. Bed material tends to be finer with little variability. If the channel is dominated by glides it is likely to have a low recovery potential.	

Pool	Slow moving water that occurs over the full channel width. They are better defined and deeper than glides. These are scoured out on the outside of the bends or where forced due to bedrock, wood or resistant bank vegetation during high flows, creating deep pools. Bed material can be quite coarse, with fines, sand and organic debris deposited between flood events. In high energy rivers they alternate with steps and in moderate energy rivers with riffles	
Anthropogenically modified	This is flow that has been completely altered due to significant anthropogenic modifications to all elements of the river channel. For example, creating a flume like flow. Concrete steps would also be put in this category.	

Table 14: Description of geomorphic-flow units that would be expected in each energy categories.

Recovery potential category/channel energy	Range of geomorphic flow units expected
Resilient to change	Very high energy flow types such as waterfalls and cascades, where bedrock makes channels resilient to any adjustment. May also include step-pool units if they are part of a bedrock-cascade dominated system.
High	Higher energy riffles, runs and pools are included in this category. This also includes step-pool sequences.
Moderate	The channel has a wide range of geomorphic-flow units including riffles, runs, but also includes slower energy glides and pools.
Low	The channel is mostly made up of slow-moving glide or pool geomorphic units with some slower runs. There are no faster riffles present in this reach.
Anthropogenic influenced	This is flow that has completely been altered due to significant anthropogenic modifications to all elements of the river channel, making it difficult to assess what type of channel would have naturally been here. Any reach with a completely concrete, gabion or block-stone bed will fall into this category.

Chapter 4: What is the River Recovery Potential of my reach?

This section will describe how reach-scale recovery potential is classified. This predicts the ability of a section of river to be able to improve its condition, and self-heal. This combines the individual recovery potential outputs for each variable discussed in Chapter 3: to generate an overall reach-scale recovery potential classification. The first section describes how to classify recovery potential based on all the variables in the section above.

Table 15 provides a summary of these variables separated into high, moderate or low recovery potential, as well as the ‘anthropogenic influence’ and ‘resilient to change’ categories. The following section discusses constraints that should be considered when deciding restoration approach based on recovery potential. The third section describes the characteristics of each reach-scale recovery potential category, linking these to the recovery times in Appendix Appendix 2: and the most appropriate restoration measures presented in Chapter 5:.

4.1 Classifying recovery potential

The reach-scale recovery potential category can be defined based on the number of geomorphic variables that fall into each category. If a reach has mostly highs, then the river is defined as having ‘high recovery potential’, and so forth. If there is a mix of categories, then the one with the overall majority is selected. If it is a mix of highs and lows, then 1 high and 1 low would cancel out to be counted as moderate. If a score is tied between 2 categories, then the outcome is that the system is on the threshold between the 2.

This approach is also designed to allow the interpretation of the assessor to have some bearing on the outcome. Through the process of assessing all the variables an understanding should be gained regarding the character of a reach and its ability to recover, and that is as important as the resulting score. These insights should form some of the basis of which recovery potential category the reach is placed within. For example, if it has a mix of moderate and low scores but falls into moderate, then it is at the lower end of moderate. Insights around understanding the processes and form of the river can be used to plan your restoration approach.

This assessment process is written for streams with natural attributes and processes that have been degraded. For example, streams which have been straightened. It has not been designed for use in reaches where all the geomorphic variables have been completely modified, such as concrete lined channels. This is because these systems have been so altered that the remaining channel characteristics cannot be used to indicate what the recovery potential of the reach may be. Alternative approaches such as assessing proxy reaches are more valuable than using this approach in these circumstances. However, if any of the variables have been significantly altered by anthropogenic modifications as to conceal the natural characteristics of the reach, then this should be given an anthropogenic influence rating and the variable should not count towards the recovery potential. **In order to assess recovery potential, information from at least three variables is needed**, otherwise it should be considered too modified to assess accurately. If there are fewer than three natural variables able to be assessed, then the channel can be defined as being ‘anthropogenically influenced’.

A full field sheet to be used when assessing recovery potential can be found in Appendix 1. This should guide the user through recording the variables in Table 15. This can then be used to assess how long the reach is likely to take to recover, as outlined in Chapter 6:.

Table 15: Summary table of each variable indicating its recovery potential.

Variable	**Recovery Potential**				
Geomorphic Variable	**Resilient to change (X)**	**High (H)**	**Moderate (M)**	**Low (L)**	**Anthropogenic influence (A)**
Valley Confinement	- Confined	- Narrow floodplain pockets partly confined or steep alluvial fan	- Wide floodplain pockets partly confined - Moderate gradient unconfined	- Low gradient unconfined	- Valley reconfigured by anthropogenic modification
River Type	- Bedrock and cascade	- Wandering - Braided - Plane-riffle and pool-riffle - Plane bed - Step-pool	- Higher energy active meandering - Moderate energy active meandering	- Lower energy active meandering - Passive meandering and peat	- Concrete or blockstone lined channel
Dominant bed material size	- Bedrock	- Boulders - Cobbles	- Cobbles - Gravels	- Silt and mud - Sand - Fine gravels	- Concrete - Blockstone
Bar frequency	- None due to confined planform and high energy	- Many	- Some (higher recovery potential) - Few (lower recovery potential)	- None	- None due to anthropogenic controls on channel form
Bank Grain Size	- Bedrock - Boulder	- Sand - Coarse river sediment in an uncohesive matrix	- Silt (assess cohesion) - Coarse river sediment in cohesive matrix	- Clay - High density tree roots and vegetation i.e. willow	- Banks not visible due to anthropogenic modification
Bank erosion	- None due to bedrock or boulder margins	- High	- Moderate	- Low	- None due to anthropogenic bank protection
Flow Types	- Waterfall - Cascade	- Higher energy riffle - run units - Step-pool units	- A mix of moderate to low energy riffle- run- pool and glide units.	- Low energy glides, runs and pools.	- Flume flow or similar caused by modification.

4.2 Description of recovery potential categories

This section describes the characteristics of each river recovery category. This categorises processes which operate across a continuum so some flexibility should be used when assessing the results. Reaches can fall at the top or bottom of each category, and insights into this should be used to interpret the types of restoration likely to be practical.

4.2.1 Resilient to change

The first section includes rivers which are resilient to change and therefore unlikely to need to recover. These are located in confined valleys, with high energy flow units and non-erodible boundaries such as bedrock.

4.2.2 High recovery potential

Rivers with high recovery potential can be characterised as having high energy and/or high sediment load, with the ability to adjust their form in response to changes in channel processes. These rivers have a very high capacity to self-heal and will normally recover rapidly from channel degradation. If they have been straightened it is likely that simply removing anything impeding adjustment (i.e. bank protection or embankments) may be enough for the channel to recover by itself within an acceptable timescale (estimated at 6 – 18 years). Engineered log jams could also be used to decrease the time necessary for recovery. However, these low intervention approaches should not be carried out if the channel is perched above the floodplain, as this lateral adjustment could cause the channel to breach its banks and create a new channel alignment across the floodplain. In general, more interventionist approaches are unlikely to be necessary here, unless the recovery has to be controlled due to proximity to important infrastructure, such as in urban areas. However, in these locations, it can be possible to create hard boundaries (i.e. buried rock armour) which set the acceptable boundaries for adjustment and let the channel migrate within this.

This category does also include step-pool channels, which can exhibit instability if the steps are destabilised. Step-pools systems can fix themselves if sediment of the right size is available within the system. If this is not the case, commonly where these channels are diverted, then the channel can erode into its bed and cause significant instability. Approaches to the restoration of this river type involves complex engineering, whereby steps have to be constructed and is out with the scope of this report.

4.2.3 Moderate recovery potential

Rivers with a moderate recovery potential are located where valley margins start to widen and the energy and sediment load decrease. These rivers still have the energy regime required to adjust following degradation. However, this recovery is likely to occur over longer timescales, compared to high recovery potential reaches. Using an assisted natural recovery approach is likely to be the preferred option in these locations.

4.2.4 Low recovery potential

These channels have much lower energy and are likely to have more resistant and cohesive banks, which impede channel adjustment. If these channels were left to self-heal recovery times would be very long. Assisted natural recovery is also likely to take a long time in these situations and is unlikely to be appropriate in this setting unless there are signs of adjustment within the reach. Instead, approaches that require greater intervention such as remeandering the channel are likely to be necessary to improve the condition of these low energy systems within appropriate timescales.

4.3 Constraints to river recovery

There are some constraints that should always be considered when assessing reach-scale recovery potential. This is because they can impede the ability of the channel to recover as, despite the energy of the river, it may have to do a lot more geomorphic work to reach good condition. Therefore, this can be integral as to whether a passive or active approach is possible.

The most commonly encountered constraint is channel incision. When channels are straightened the energy increases which commonly leads to erosion, bed lowering and disconnection from the floodplain. It is more difficult to incorporate passive approaches in this setting, as any adjustment would cause erosion and would be expected to deliver high sediment loads into the channel as the banks are higher than they would be naturally. This could cause deterioration downstream as well as having possible adverse ecological impacts. In addition, it could take more energy to remove the increased sediment load, resulting in a longer recovery time, with the river getting worse before it gets better. Therefore, all sites should be assessed as to the degree of incision, and the volume of bank material that would be washed downstream in order for the river to adjust to the point where sinuosity has increased sufficiently to reach the desired outcome.

In direct contrast to incised channels, perched channels are those that have been depositional over time, and have built up to be higher than their surrounding floodplain. Commonly, these are straightened rivers with high sediment loads, which historically were frequently dredged. This dredged material is used to form embankments on the channel margins, which build up as the channel bed does. As dredging becomes a less acceptable way of managing rivers (due to its impacts on morphology and habitats), the likelihood of rapid geomorphic adjustment in these channels increases. During floods, these channels can become filled with sediment leading to a rise in river bed levels (channel aggradation), causing their embankments to breach and the river to rapidly change course (channel avulsion), occupying a lower course within the floodplain. If we allowed natural recovery in this situation, the channel would flow from its current path and create a new, more natural path on the floodplain. However, this rapid channel evolution would entail considerable uncertainty and is unlikely to be a viable restoration option in most locations, considering the value of land in surrounding floodplains. Therefore, active restoration may be necessary to reset the bed level and ensure future adjustment will not negatively impact adjacent land uses (for example, see Aberarder case study, Section 7.1.3).

Another common constraint is infrastructure, which may be impacted by an increase in rates of channel adjustment. This includes those which you can see, like buildings or footpaths, and that which is hidden, such as buried service pipes (i.e. water or gas). Plans should also consider how adjustment at one point in the river network may impact other sections. This is especially true where a small section within an urban setting is restored using passive approaches, which could lead to infrastructure being impacted in the neighbouring reaches. Thus, as with all restoration plans, passive approaches should be designed with regard to impacts that may occur both up and downstream of the restoration reach.

4.3.1 Recovery potential case studies

This section will provide a series of case-studies showing how real rivers have been assessed using this framework to provide examples of how different reaches fit into the different categories. This also demonstrates what the output of the assessment is expected to look like.

4.3.2 River Knaik upstream of Braco

Summary of attributes:

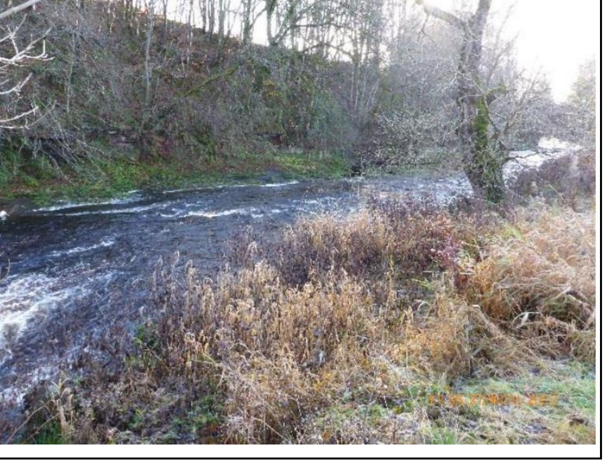
The River Knaik at this point flows over bedrock, with the flow being characterised by high energy cascade units. The bedrock limits the adjustment possible and as a result, the river is very stable.

Geomorphic variable	Description	Recovery potential category
Valley Confinement	Confined	**X**
River Type	Bedrock	**X**
Bed material size	Bedrock	**X**
Bar frequency	None due to confinement and high energy	**X**
Bank grain size	Bedrock	**X**
Bank erosion	None due to bedrock and boulder margins	**X**
Flow Types	Cascade	**X**

Overall recovery potential = Resilient to change (X)

Preferred restoration option:

No restoration is necessary for this reach, as it is not degraded and is resilient to change.



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4.3.3 Mye Water

Summary of attributes:		
This river was a medium energy active meandering channel with sand on the margins, and gravels and cobbles on bed. It exhibited a lot of bank erosion, partly due to poaching and grazing and partly from recovering from past straightening. This included erosion on straight sections of the bends.		
Geomorphic variable	**Description**	**Recovery potential category**
Valley Confinement	Moderate gradient unconfined valley setting	**M**
River Type	Medium energy active meandering	**M**
Bed material size	Cobbles, gravels and sand on margins	**M**
Bar frequency	Few	**M**
Bank grain size	Silt	**M**
Bank erosion	High as present on the straight sections as well as bends	**H**
Flow Types	A mix of moderate to low riffle – run – pool and glide units	**M**
Overall recovery potential – Moderate (M)		
Preferred restoration option:		
This channel is at the higher end of moderate and is not incised. The preferable restoration option would be assisted natural recovery, using Engineered Log Jams or similar to kick-start adjustment. Once sinuosity has increased, planting a riparian margin would be essential to improve overall condition.		

4.3.4 Goodie Water

Summary of attributes:

This was a lower energy active meandering reach. There was a lot of bank slumping along the reach, but this was caused by over grazing and livestock poaching rather than by fluvial erosion. The channel was also very incised, making recovery difficult and it is likely more interventionist methods would be required here. Flows were slow and homogeneous.

Geomorphic variable	Description	Recovery potential category
Valley Confinement	Moderate gradient unconfined valley setting	**M**
River Type	Lower energy active meandering	**L**
Bed material size	Silt, mud, sand and fine gravels	**L**
Bar frequency	None	**L**
Bank grain size	Silt	**M**
Bank erosion	High, but significantly influenced by life-stock grazing and poaching causing slumping rather than fluvial action.	**A**
Flow Types	Low energy glides, runs and pools.	**L**

Overall recovery potential – Low (L) *but at the higher end of low.*

Preferred restoration option:

This channel does not appear to be straightened. It has just incised either due to being dredged or changes in hydrology and land use. The best restoration option would be to install a 2-stage channel that includes riparian planting. This would take the pressure off the channel, reducing energy during high flows and allowing a more diverse range of geomorphic units to be established. Natural deflectors could also be used to enhance this habitat.

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4.4 Timescales of recovery

The recovery potential category of a system can be used to predict how long it will take for a river to recover back to good condition. This may not involve obtaining the exact pre-modification form, but the system should contain the correct geomorphic unit assemblages expected for that river type, with the units displaying good habitat conditions and diversity. Recovery times are calculated based on:

i) The type of anthropogenic pressure that the reach has been modified by and,

ii) The recovery potential of the reach and,

iii) The restoration approach categorised as *active intervention* - which includes works that actively constructs the morphology of the channel, *assisted natural recovery* - which refers to restoration that works with the channel in its current location such as installing engineered log jams to kick-start channel adjustment or *natural recovery* - which refers to the length of time it would take the river to recover if no action was taken.

Appendix 2 provides guidance which predicts the rates of recovery based on the type of anthropogenic modification and the recovery potential of the reach it is located within.

Chapter 5: Should active or passive measures be used for restoration?

This section discusses different restoration techniques, presenting them with regards to how they fit within a continuum of effort from passive restoration to active restoration (see Figure 31). These are separated into three categories; Natural Recovery (Section 6.1), Assisted Natural Recovery (Section 6.2) and Active Intervention (Section 6.3).

- The natural recovery category, involves actions around the river so that it can start recovery. For example, withdrawing maintenance or planting the riparian margin. This may need to include removing bank or bed protection and breaching embankments if these are sufficiently robust as to not fail naturally. This does not include measures which manually alter the channel.
- Assisted natural recovery (ANR) includes removing hard engineering and kickstarting processes in-situ. This should alter the dynamics in the channel so that the river starts moving along a recovery trajectory.
- Active restoration measures include those whereby earth is manually moved to alter the characteristics of the channel such as remeandering or embankment removal.

The aim is not to provide a full summary of how you undertake these options, as these are already available in other guidance documents (i.e. see the River Restoration Centre 'Manual of River Restoration Techniques', RRC, 2019). Instead, it aims to highlight the positives and negatives of the different approaches, outlining why they are more or less appropriate for rivers with different recovery potential. This will start with the lowest level of intervention (natural recovery) and increase to full active restoration. Thus, this uses the assessment of recovery potential and the predicted time-scales of recovery to understand the detail of what specific active and passive restoration approaches may entail.

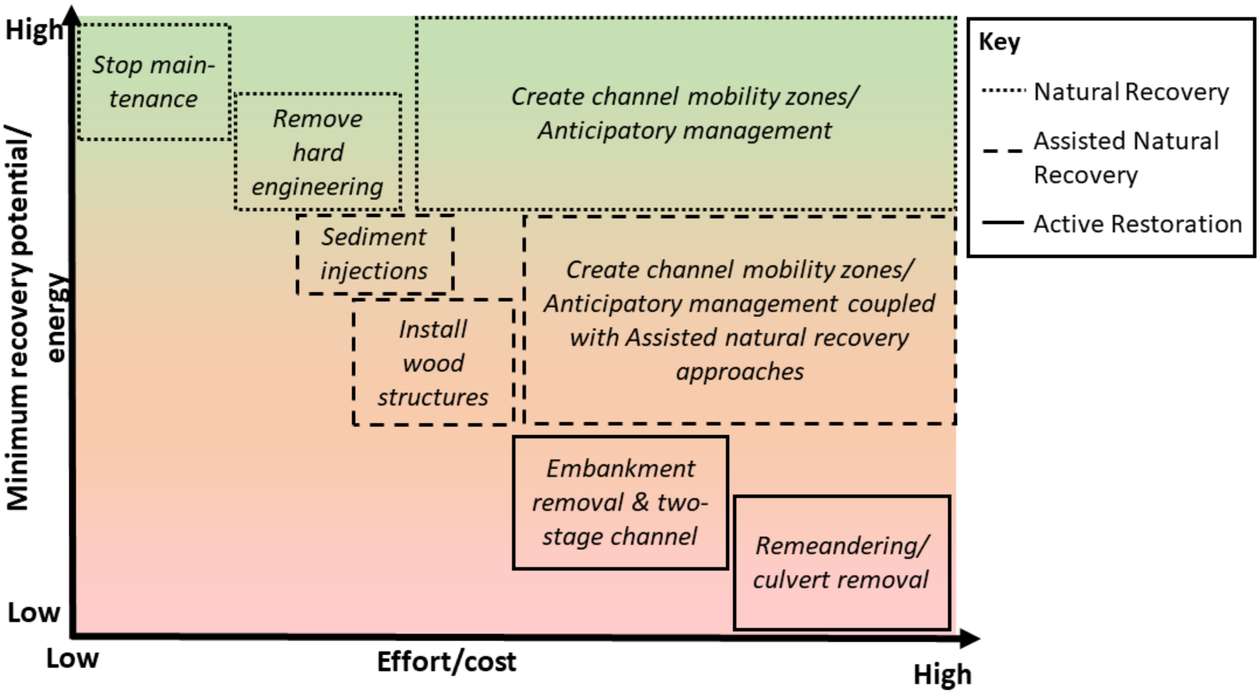

Figure 38: Continuum of restoration options based on the minimum recovery potential needed for that approach to be successful and costs and degree of effort required for each approach. Approaches are separated into natural recovery, assisted natural recovery and active restoration categories.

5.1 Natural Recovery and letting the river self-heal

One option is to stop maintenance, allowing natural recovery by letting the river self-heal. This can be favourable, as it has little or no costs associated with it. The exception is where there is robust hard engineering, which is unlikely to be removed through erosion (i.e. a concrete wall). In this case, the reinforcement would need to be removed before the river can start to recover. Following assessment and removal of such hard engineering, recovery times may still take far longer than is acceptable and understanding a reaches recovery potential is key to assessing this. The key considerations are assessing how long it is likely that the reach of interest is going to take to improve its condition till it is in a state that has improved sufficiently for its WFD status to be upgraded, and whether this length of time is acceptable. There are a number of steps to this.

A. Has the river changed in a way that makes it unable to recover naturally?

For example if a river has incised (eroded into its bed) or aggraded (built up its bed), then it cannot improve its condition without the channel bed or surrounding floodplain being raised or lowered to be better connected (see Section 4.1 for details). In this situation, more active work would likely be needed.

B. Is there something stopping the river from naturally adjusting?

Commonly, this would be an anthropogenic influence stopping the river from adjusting its planform or bedforms, such as bank or bed protection. Sometimes bank protection can be buried into the bank or overgrown, so it is important to ensure this is correctly identified and removed where possible. This means carrying out an active measure to allow natural recovery to start. Once these pressures have been removed, this will mark the beginning of recovery for that reach.

C. How long since the river was modified?

The key aim is to work out the rate of adjustment for a system, and thus the rate of recovery. To do this, try and establish when the modifications (e.g. straightening) were carried out and whether these pressures are still constraining the system (e.g. bank protection). This is best done by looking back at historical maps and aerial photographs. Often modifications to planform pre-date the earliest 1800's maps. In some circumstances it is possible to identify that the modifications were relatively new. The second stage is to assess whether modifications, such as dredging, have been repeated during more recent time periods to hinder recovery. This is an important element as, for example, each time the river is dredged the recovery of the reach will be reset and bedforms, channel geometry and potentially planform will again be fully degraded. Many rivers were actively and invasively managed until the 1970s - 1980s when regulation became more stringent. There are ways to establish the past management regime such as talking to the landowner or the local rivers trusts.

D. How much recovery has occurred over this time?

The final point is to work out how much adjustment and recovery has occurred over this time, where possible. If there are imposed boundaries stopping adjustment and recovery, we can say the recovery clock is set at 0. This is because no recovery has been able to occur. In these situations, it is essential to analyse the sediment load and energy of the reach, and if possible find locally unmodified river analogues to estimate whether the river is likely to be able to recover without help, and how long this is likely to take. An analogue should be a reach with a similar catchment position and characteristics, which can be used to understand the characteristics and likely rates of adjustment in the restoration reach.

In other situations, the river may have had time to recover, and this degree of adjustment (i.e. rate of lateral migration across the floodplain) can be used to predict how long till the river reaches a state where it is deemed in good morphological condition (i.e. the key features and processes expected in the reference type are restored). In addition, the presence of good condition bedforms and in-channel habitats can be used to assess the degree of channel recovery. However, it should be noted that generally only rivers with high energy and high sediment load are able to self-restore within an appropriate time-scale and no help, unless there has been significant recovery prior to assessment. If there is any doubt, then the assisted natural recovery approach can deliver relatively low-cost measures with markedly faster recovery times.

As the recovery associated with this approach is not as controlled, there is the potential for greater uncertainty in the degree/type of adjustment that may occur. Therefore, assessing and finding ways to manage risk may need to be part of the scope of future management. Establishing a riparian margin will increase the bank strength and bank roughness which would slow rates of adjustment. Different vegetation that is more resistant to erosion (e.g. willow) could be planted at locations where it is less desirable for the channel to be located. If necessary, protection can be planned if there are points of sensitivity. For example, boulders could be buried in a trench to protect infrastructure (i.e. a pipe) which would get exposed if the channel ever got to that location. Ultimately, analysis of the geomorphic characteristics of the channel and its past adjustment will provide a template for predicting the likely rate and type of channel response.

Using the natural recovery approach can be applied in an active way (beyond the assessment and removal of hard protection as discussed above). For example, it can include agreements with landowners to stop maintenance that was sustaining the poor condition of the system, such as dredging straightened rivers. This can also include leaving a river that has started to form a new channel across the floodplain to naturally adjust and form this new habitat. It can also include approaches such as fencing or riparian planting, which will improve the condition of the channel and its habitats over longer timescales.

One approach to 'natural recovery' is to establish channel mobility zones, which are areas where channel adjustment is allowed (Figure 31). Existing research indicates that around 5 times the channel width, including the wetted channel is the area required to contain a natural functioning channel (c.f. Biron et al., 2014; Magdaleno and Martinez, 2014; Parish Geomorphology, 2004). Ideally, these zones should be fenced and planted and are especially advantageous on sections of floodplain that are boggy and not viable for agriculture and in upland areas, where the channels tend to have more energy and land is of lower agricultural value. Ideally, such approaches need to be supported by subsidies or grant schemes that support the landowner to fence the river, plant the appropriate vegetation and subsidise the loss of earnings. Establishing these vegetated river zones can have significant benefits felt far beyond the reach they are applied, including increasing both terrestrial and aquatic biodiversity, decreasing sediment loads downstream, filtering pollutants from the water, keeping rivers cool, increasing carbon capture and slowing flood waters. Hence, establishing channel mobility zones is key to creating sustainable riverscapes as needed given the challenges of both climate change and the significant decline in biodiversity. Channel mobility zones can also be combined with assisted natural recovery approaches to give the channel space to recover, whilst also working to accelerate the rate of that recovery.

5.2 Assisted natural recovery

Assisted Natural Recovery (ANR) refers to either removing pressures which are inhibiting recovery or installing measures to kick-start processes and encourage the river to adjust so that it moves towards a more natural morphology. This is significantly different from active interventions such as remeandering, which involve designing and building a new channel and then moving the river to this location. The major constraint of assisted natural recovery is determined by the characteristics of the river itself with regards to;

i) whether the reach has the energy to respond to the intervention;
ii) whether the reach has the tools to recover (i.e. the appropriate sediment load to create the habitat needed) and;
iii) whether past activities have changed the river to the point whereby its boundary conditions have been so altered that more active measures are needed to improve its condition. For example, if the channel has undergone significant incision, the volumes of sediment that would be input into the system though promoting an increase in channel sinuosity may be greater than is acceptable (see section 4.1).

In settings where assisted natural recovery can be feasibly applied, it can have significant benefits over active interventions and natural recovery strategies.

The most significant benefit of ANR is that it works with the river as it adjusts to enhance recovery. This is less resource intensive than more intrusive construction approaches (e.g. remeandering). It also builds on any recovery which may have already occurred. For example, straightened rivers can start to adjust and improve their sinuosity over time, improving the habitat in-situ. By remeandering a reach, recovery gets set back to 0 as the channel has to sort the sediment available and create habitat. In some instances, this recovery can be relatively rapid, whilst in others it can take a long time for appropriate sediment to be delivered to the reach and good quality habitats to be re-established. For example, the finer gravel material may be delivered relatively quickly, but larger cobble and boulder material may take longer to enter the reach, if it is not been made available as part of the restoration at the locations it is needed. This means some habitats such as riffles may take a long time to form. ANR measures will work with the current condition of the reach, and any recovery that has already taken place, rather than resetting the channel condition. In this sense, they work with the existing channel characteristics such as bed material and channel size to improve the rivers' condition, rather than starting from scratch with attributes which have been purposively designed. Importantly, each reach should be assessed as to whether it has recovered sufficiently that carrying out active restoration could be undoing existing significant improvements.

The other key aspect as to whether ANR is appropriate refers to the length of time recovery is likely to take. Inherently, with ANR a channel will not go from being impacted (i.e. high impact realignment) to being in good condition immediately, as is possible with some active interventions. Rather, it will undergo a journey of recovery, from high impact realignment, to low impact realignment, to a state consistent with its reference conditions. This means that ANR restoration should involve *actively monitoring this evolution and tweaking it*, where necessary. For example, new wood deflectors may need to be installed if the old ones are washed away or the river migrates away from them. Recovery may take up to 20 or 30 years, depending on the energy of the site. However, if longer reaches of river are given more room and these less active interventions are applied, restoration can be delivered over longer stretches of river. In addition, this approach gives us the opportunity to learn about specific reaches, building on the knowledge of the energy regime, and learning about the success of different approaches in each situation. This strategy can, therefore, provides us with specific knowledge on the efficacy of the different approaches in each environment, decreasing the likelihood of failure in future restoration projects.

The use of ANR also needs to be related to the vision of how the channel would appear in good condition. Often, the most important characteristic that is targeted is sinuosity. Not all rivers are expected to have fully meandering planforms, and this should not be the target for all reaches (though commonly has been). The reach should be contextualised by its valley setting, using evidence from old maps, adjacent reaches and evidence of past channels on the floodplains to set what the desired sinuosity is likely to be. If a fully meandering, high sinuosity channel is the aim, then the river has a greater degree of adjustment to carry out before it has obtained a meandering planform compared with the river type which would naturally have a lower sinuosity. Timescales can be predicted based on the energy regime and estimated rates of adjustment. For more naturally sinuous systems, the river will need to erode and deliver more sediment to the channel before it reaches a good condition, and the resulting impact on the condition of the reaches downstream should be considered (i.e. do they have the energy to flush this to the sea), meaning active restoration may have less impact. In contrast, rivers which naturally would have a lower sinuosity (e.g. plane-riffle), require less geomorphic adjustment to go from straight to their reference condition planform. As the overall degree of recovery is less in these systems, ANR can be a particularly useful and relevant approach.

Ultimately, the most important determinant as to whether ANR should be applied is the energy regime. Again, this needs to be assessed on a site-by-site basis using expert opinion and using the guidance supplied within this document (i.e. see Sections 3 and 4). The key question to ask is whether the energy present is sufficient to create the erosion needed to increase the channel sinuosity to a point where the realignment pressure is removed.

5.2.1 Removal of pressures

The represents a very light touch approach to ANR, which includes removing pressures such as embankments and bed and bank protection which are stopping the river from functioning naturally. These also need to be assessed using a natural recovery approach and removed if they are more robust than the channel is likely to be able to remove naturally. Within ANR, the systems have a lower energy and therefore the need to actively remove these is greater as they are less likely to naturally be removed within an appropriate timescale. These are included as ANR rather than active restoration, as there is no significant change to the channel morphology as would be expected under active restoration. Bank protection removal is a key example, as once this has gone the channel can start to recover, rather than being frozen in time. Another example is the breaching of embankments. This allows the channel to recover, minimising the impact of this pressure on the system. These approaches are at the very lower effort end of ANR, and in most cases would be recommended to be paired with the use of measures which directly impact in-channel processes such as engineered log jams (described below).

5.2.2 Engineered log jams and deflectors

Engineered log jams (ELJs) and deflectors are key tools which can be used for assisted natural recovery. Ideally, they should be installed in the channel at locations which are already showing signs of adjustment. They can enhance existing adjustment, causing the channel to erode its outer bank and increase its sinuosity, contributing towards the recovery of a reference morphology. Deflectors should not aim to only locally increase flow and habitat diversity, but be designed to increase whole-scale channel adjustment. If the channel is degraded due to straightening, this measure would aim to increase sinuosity, kick-starting erosional and depositional processes and improving in-channel habitats (e.g. Figure 39 and Figure 40). ELJs should not be designed using a cookie cutter approach, where one design is applied everywhere at regular spacing. To increase diversity, deflectors should be more diverse in form and materials and designed to work with the location in which they are placed. The Aberarder, Allt Lorgy and Pow Beck case studies in Section 7 provide examples of how different types of wood structures have been used for ANR in Scotland.

Figure 39: Examples of how wood has been used on the Aberarder restoration scheme to increase in-channel diversity and help the channel recover following remeandering. These photos were taken shortly after restoration. Photos taken November 17 by Alice Tree.

Figure 40: Photograph of bank-attached ELJs, designed to enhance channel diversity. Sourced from Wheaton et al. 2019.

Wheaton et al. (2019) provides a comprehensive guide on how to design and install a variety of 'low-tech' process based ELJs, which is freely available online (Figure 40, Figure 41 & Figure 42). This includes descriptions on how to make them more effective, how they have been designed to influence the morphology in different ways and how to secure them into the bed, improving the longevity of the features. It is outside of the scope of this report to detail the specifics of design, as other manuals do it more effectively (e.g. Wheaton et al., 2019).

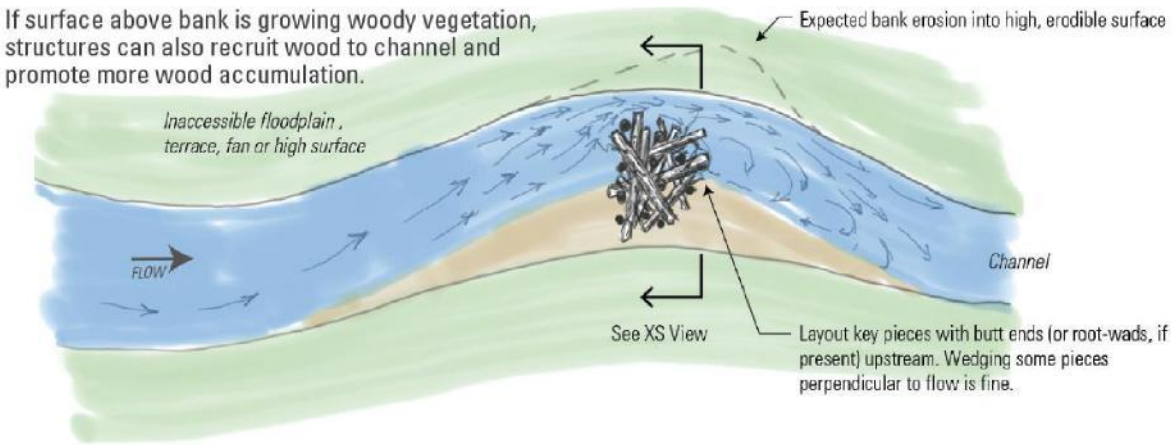

Figure 41: Detailed conceptual diagram of bank-attached ELJs, designed to enhance channel diversity. Sourced from Wheaton et al. 2019.

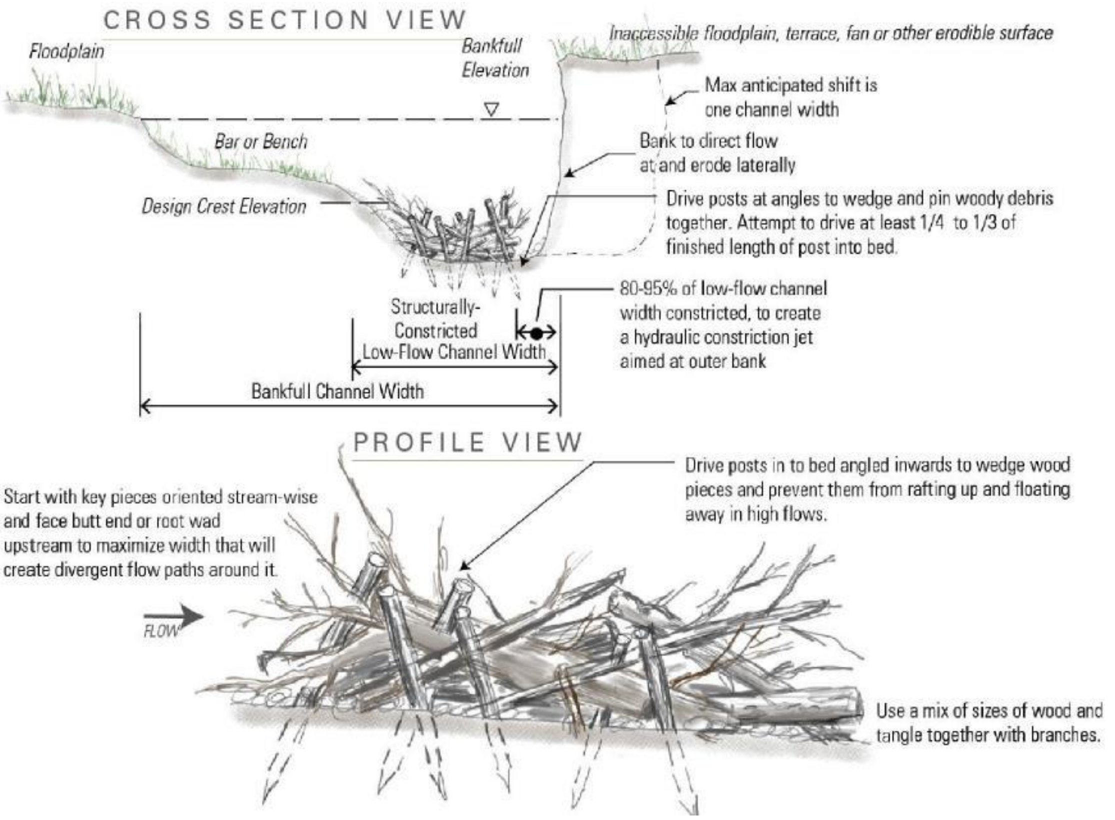

Figure 42: Cross-sectional diagram of a bank attached ELJ. Sourced from Wheaton et al. 2019.

6.2.3 Sediment injections

Sediment injections can also contribute to ANR restoration strategies by increasing the volumes of coarse sediment (such as gravels or cobbles) that can be eroded and deposited within the restoration reach. Where a lack of coarse sediment supply presents a limitation to ANR, sediment can be manually delivered into the system to accelerate habitat turnover and rates of channel adjustment. The mechanisms of channel adjustment are driven by the deposition of grains within the channel as bars. This causes the opposite bank to erode, increasing sinuosity and in-channel diversity. However, before this measure is applied, any impacts on flood risk at the site or downstream should be considered.

Sediment augmentation is also commonly used downstream of weirs, reservoirs or intake structures which disconnect the river from the sediment supply upstream. At these locations, the input should be designed to be delivered to the river slowly, so that the material can mix with the existing sediment on the channel bed, rather than swamping it. The aim of this technique within this context is more about maintaining habitats then kick-starting channel adjustment.

If this method is to be used, the grain sizes of the sediment to be augmented need to be selected based on the range of sizes of material the river would carry naturally. This means inputting cobbles or boulders into a sand bed stream is not an appropriate restoration approach. In some circumstances, it may be logical to target a specific grain size. For example, many streams in upland systems in the UK contain boulders, which have been delivered to the channel from eroding down into sediment deposited by glaciers. These can be larger than would be delivered through contemporary hydraulic processes. If one of these streams are straightened, the recruitment of this larger material can take longer timescales than appropriate. Therefore, in this case it would be appropriate to target these larger grain sizes. In summary, this restoration approach needs to consider river processes, which means grain sizes that are selected should be those which are the most effective at restoring the reference river type. Figure 36 gives an example of sediment augmentation in the River Tat in Norfolk. This stream had undergone significant straightening and channel modifications and the gravel bed had incised and was covered by a layer of silt. The existing bed material was excavated and redistributed within the reach, allowing the river to create more heterogenous structure.

Figure 43: Example of habitat before (left) and after (right) following gravel augmentation in the River Tat in Norfolk. Photo credits to Adam Thurtle © Environment Agency.

Figure 44 shows the Eddleston Water in East Lothian. Restoration was carried out upstream, which increased the sediment supply to the reach below, resulting in bars forming that resulted in bank erosion, increasing the sinuosity. This illustrates how changes in the processes at one point in a system, can have impacts on the process in adjacent reaches. The Allt Lorgy restoration case study (Section 7.1.4) presents an additional example of how injecting sediment into the system has been used to kick-start geomorphic adjustments in an active meandering river in Scotland.

Figure 44: Photographs taken on the Eddleston Water downstream of a restoration site. Prior to restoration these sites were straight and homogeneous with a plane bed. A) shows the top of the bar that has formed (to the right of the photo) with an eroding bank on the left. B) shows the downstream point of the bar where sinuosity has increased resulting in an increase in in-channel habitat diversity.

5.3 Active restoration

The final category is active restoration, whereby the pressures are manually removed and the river is mechanically altered to restore a more natural, pre-modified alignment and/or channel characteristics. Most commonly, this includes remeandering the channel to increase sinuosity. This can include building in-channel geomorphic units, such as step-pool features if the gradient is steep, or riffle-pools if the channel has a lower gradient. Active intervention can also include altering channel floodplain connectivity and dynamics, by either lowering sections of floodplain to create in inset connected floodplain or removing/setting back embankments. Culvert removal usually falls into this category, assuming that after a culvert was removed, a channel would have to be reinstated. Overall, this represents a high interventionist, manual approach to restoring rivers, but one that commonly has shorter recovery times.

Table 16 provides a summary of the advantages and disadvantages of an active intervention approach to river restoration. One of the key issues with this restoration strategy is the high monetary cost and effort associated with design, consenting and delivery of the project. It would not be possible to deliver SEPA's morphology objectives by using full restoration across all rivers that are downgraded. Therefore, restoration requires a strategic approach that identifies when lower intervention or more intensive active restoration approaches are needed. This is likely to be reflected in a split between urban and rural rivers, where urban streams require greater intervention due to complex histories, limited space and a greater public profile. However, rural streams can still be in close proximity to sensitive infrastructure or land uses that may mean more intensive methods are needed. Higher energy upland streams, which tend to be in rural locations are likely to be able to be restored with more passive approaches compared to lower energy lowland systems.

Table 16: Comparison table of pros and cons between active restoration, ANR and natural recovery.

Variable	Natural Recovery	Assisted Natural Recovery	Active Intervention	Explanation
Cost	• No or very low cost (dependant on if any infrastructure needs to be removed) • Can cover large spatial area • May require on-going agricultural subsidies	• Low to moderate cost • Can cover large spatial area • May require on-going agricultural subsidies	• High to very high cost • Can only usually cover small spatial area	It can be very expensive and require a lot of time for both design, consenting and installation. This means that it is usually only delivered for short reaches. In contrast, ANR strategies can be delivered across larger spatial scales, which is a significant advantage for delivering restoration objectives. However, natural recovery and ANR may require ongoing agricultural subsidies to support adjustment
Design	• No design required • Channel self-heals so there is little risk of instability	• Only limited design may be necessary • Channel self-heals after kick starting of processes, so there is a low risk of instability	• Detailed design required • Design needs to be consented • Most channel parameters are designed so there is a higher risk of instability than if naturally created	River restoration can be difficult to design. Even with modelling, it is difficult to determine if a design is correct for a system and may cause instability to the channel. E.g. the wrong size of bed material may lead to an imbalance in geomorphic processes as the river adjusts to find a new equilibrium. In contrast, natural recovery or ANR allow the channel to ‘self-heal’ based on existing channel attributes and so result in a channel that is most appropriate for that configuration or setting
Ability to self-heal	• Works with the current morphology of the system • Doesn’t undo any existing recovery	• Works with the current morphology of the system • Doesn’t undo any existing recovery	• River has to start adjustment from scratch as all parameters are reset • Can reverse the recovery that has already occurred	Active restoration can be a shock to the river, where the controls are all changed overnight, and the river has to adjust to form its new habitat. In contrast, ANR will work with the current characteristics of the river and create change which is gradual. This gives the river time to adjust and self-heal, rather than resetting the system to a new state where it has to create habitat from scratch. For rivers that have already undergone some recovery, full restoration can reverse some of the recovery that has already occurred.
Highly modified systems	• May cause significant issues in highly modified systems, e.g. erosion of contaminated ground	• May cause significant issues in highly modified systems e.g. erosion of contaminated ground	• Can be necessary in rivers that are highly modified, as natural recovery or ANR may cause more issues	Some rivers have been significantly altered and require active intervention. E.g. urban or mining rivers which may need to be clay lined to avoid contamination or rivers which have become perched or incised may need a channel to be set at the correct level in relation to its floodplain.

Increased control for restoration in sensitive locations	• May adjust in ways that is unpredictable which may impact infrastructure	• May adjust in ways that is unpredictable which may impact infrastructure	• Proximity to sensitive infrastructure can be designed into the plan to lower the risk • Lower rate of adjustment expected post restoration compared with the other approaches.	Active intervention should be more predictable and controlled. This is important in areas where river adjustment may not be appropriate, such as in urban areas next to sensitive infrastructure (i.e. next to pipes or houses). In these locations, restoration can be delivered with protection installed at the points needed to be protected, or the river can be manually moved away from high risk zones (if this is morphologically 'sensible').
Recovery rate	• Rate is highly variable and can be difficult to predict • Depends on existing recovery • Can be quite fast	• Rate is highly variable and can be difficult to predict • Depends on existing recovery • Can be quite fast	• Usually swift if design is appropriate as the planform has been reset • River needs to arrange the sediment and form the habitats	Actively restored rivers can undergo very swift recovery because they don't need to alter their planform, just sort sediment and create the habitat within the new planform (if the design is appropriate for the location). This can be good for delivering objectives on time and with less uncertainty around recovery rates and pathways.
Ease of communicating restoration	• It's a process so harder for people to understand/ quantify success • Stakeholders may not like to see erosion and instability	• It is a process so harder for people to understand/ quantify success • Stakeholders may not like to see erosion and instability	• The difference between the river condition pre and post restoration is clear and easier for people to understand/ quantify success	In restored rivers, it is often easy to see rapid improvement in river health which can be used as a tool to communicate why we need to restore rivers and how habitat and ecology can change as a result. In comparison, assisted natural recovery may take longer and involve bank erosion and channel instability, which stakeholders may perceive as messy, damaging and not appropriate in all circumstances.
Funding cycles and objectives	• This should require minimal funding except for initial hard engineering removal • May require long term subsidies to support on-going adjustment • Monitoring needed to check when objectives met	• Measures may need to be progressively added and updated (e.g. ELJ installations) so can fall into multiple funding cycles • May require long term subsidies to support on-going adjustment • Monitoring needed to check when objectives met	• Can fit into single funding cycle and then be ticked off • Easy to track changes and when objectives have been met	Active restoration can be delivered within a single funding cycle and the objective shown to be delivered. It is more complicated to deliver passive restoration whereby a river has to be monitored over years, with small amounts of funding drip fed as more measures are installed. As recovery is gradual, it is more difficult to link the funding and achieving the objectives, which is usually upgrading a waterbody.

Active approaches are commonly being installed in locations where a more complex arrangement of anthropogenic pressures are present. For example, in urban or mining areas where contaminated land may be present, or where the channel is close to important infrastructure. A key issue frequently emerges in these contexts, when restoration is designed based simply on mathematical formulas (to determine, for example, reference cross sectional area or planform sinuosity). Rivers are very complex and designing the correct combination of channel form, slope, bed material and geomorphic units attributes is difficult. This means there can be problems following installation, if the design is not appropriate for the conditions of the site, with rapid adjustment frequently observed before the channel re-sets its balance. Problems also occur when misguided restoration schemes include measures which fix the channel in place (i.e. hard bank protection), meaning the channel can’t adjust its form and self-heal. Rather, this can lead to more adjustment at different points in the system. When considering this strategy, we should remember that the aim of active restoration is to reinstate natural processes and morphology, not just move the channel to a different location.

Finally, active intervention usually delivers river improvements far more rapidly than passive approaches. This is especially true for rivers where the energy and sediment supply is low and passive restoration could take a long time, making it infeasible/impractical within acceptable time-scales. This rapid delivery of objectives is often preferred by funders, as they can allocate funding, and then sign off the objective as being delivered. In contrast, passive approaches may have to be drip fed money over longer time-scales, with the objectives delivered outside of the funding and River Basin Management Planning cycles. Therefore, passive approaches will require more flexibility in terms of charting success from funders and those setting the objectives. Finally, they would be most beneficially delivered with the support of long-term subsidies that encourage landowners to allow adjustment on their land. This would require the ways in which we fund and support this type of restoration to be revisited.

5.3.1 Realigning or remeandering a channel

The most common type of active intervention is to remeander or realign a stretch of river. This involves selecting a planform and sinuosity which is perceived to be more natural for a specific reach. Within this, most restoration can be split into two categories

1. *Where the location of the old channel is known* (e.g. from old maps or paleo-channels still present on the floodplain). Within these, realigning a river can be relatively easy, as the top soil can be removed and the original channel bed uncovered. This tends to be far more straightforward than the second situation, assuming the prevailing catchment conditions such as hydrological regime or sediment load have not been altered since the channel was modified.
2. *Where the pre-modification configuration is unknown*. The channel attributes have to be designed from scratch including planform, cross-sectional geometry, slope and bed material characteristics. Consequently, this scenario is more complicated than the first and has more risks and as such, the design has to rely more heavily on modelling. This is because all the channels attributes have to be predicted. The river then has to adjust its form to ensure it has appropriate resistance for the prevailing energy conditions.

In lower energy rivers, errors can be less of an issue, as the channel will respond slower and any adjustment may be spread over time. In contrast, higher energy systems can undergo much greater degrees of adjustment, including bank migration and eroding or depositing bed material, causing the bed to incise or aggrade. Channel bed resistance is not just a product of the size of material on the bed, but also the arrangement of that material into structures which increase roughness. For example, in high energy streams, step – pool features are formed due to the larger keystone boulder clasts holding the bed together and dissipating energy over these steps. Therefore, stability can be linked not just to the bed material and calibre chosen during the design process, but also how well these bedforms have been formed during construction. Therefore, step-pool restoration is likely to need active restoration. Figure 45 shows where steps have been constructed in previous restoration schemes, and what these commonly look like.

Figure 45: Examples of constructed step-pool systems that have been used in restoration schemes. A) shows steps installed in the upper tie in of Whit Beck, to hold the bed where the more constrained reach flows into the restored reach. B) more natural restored step-pool on the Mains of Dyce ~ 10 years following construction.

By contrast, in lower energy systems, the creation of geomorphic resistance units can be less important. Examples of units that may be constructed are riffles on straight sections, pools on the outside of the bends and bars opposite the pools. However, for the medium energy rivers, if the planform and the bed material is correct, the channel can swiftly create an appropriate morphology once it has sorted the sediment supplied to the channel (Figure 46). Installing wood as added in-channel resistance can also aid in the development of these units. Where possible, allowing space and time for the river to create these units is necessary for restoring a diverse and healthy system.

Figure 46: Examples of habitat in the remeandered Whit Beck, in Cumbria following restoration. A) shows Whit Beck 1 week after the channel was restored in August 2014 and B) shows it 2 years after it was remeandered in September 2016. This demonstrates how the channel has to actively sort its bed and rework the banks, to create the habitat appropriate for its location.

Realigning rivers has become more common over the past few decades. As a result, there is more guidance available regarding how to design a river restoration scheme. Key texts include;

- River Channel Restoration: Guiding Principles for Sustainable Projects by Brookes and Shields (1996);
- Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools by Simon et al., 2011 and;
- the RRC Manual of river restoration techniques (2019).

These provide more detail regarding how to design a channel restoration scheme than is within the scope of this report.

5.3.2 Floodplain reconnection

Floodplain reconnection is used when the channel has become disconnected from the floodplain and works are required to reconnect these units. The most common example is when the river bed has incised (eroded) and sits below the floodplain. This means during floods, all the water and energy is contained within the channel. As a result, the channel bed coarsens and habitats get eroded and become over-simplified. If it is not easy to raise the channel bed to its previous position, then sections of the floodplain may be lowered to create an inset level that can store water during floods (Figure 47 & Figure 48). This is referred to as a two-stage channel, and the process of creating it, as floodplain stripping or lowering. By creating an inset floodplain, flows during floods can be stored on the floodplain as well as in the channel, dissipating the energy and reducing the scour of the channel bed. This allows a more natural range of in-channel habitats to form. This also creates a better connection between the channel and this new floodplain surface, where a wider range of plants and habitats can be established.

The second approach can be delivered where embankments are removed or breached to reconnect the channel and floodplain, which is relatively straightforward. However, this can become more involved if the channel bed has become lowered or raised. If it is raised then the channel bed may need to be manually lowered. If it has lowered, then embankment removal may need to be combined with floodplain lowering.

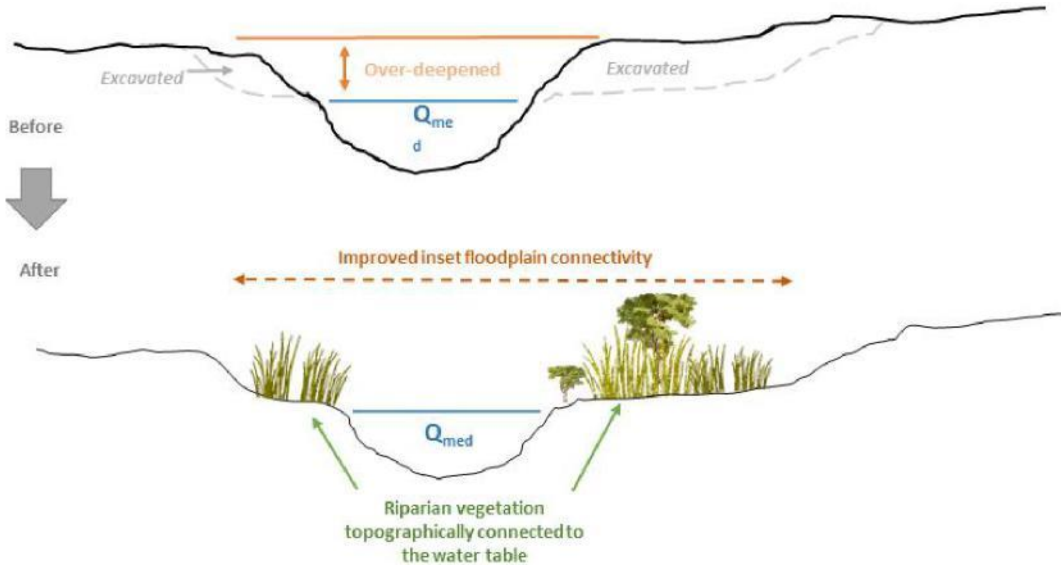

Figure 47: Schematic giving an example of how a two-stage channel can be excavated. Figure supplied by Roberto Martinez.

A two-stage channel is an ideal tool to deliver restoration for a channel that has incised, but it does not attempt to deal with any straightening that may have occurred. If the channel has been straightened, then additional work will be needed to increase the sinuosity and remove the straightening pressure. This can either be through natural recovery (if the recovery potential is high), ANR, through installing wood deflectors to encourage channel adjustment (see Pow Burn case study, Section 7.1.5), or active intervention, through remeandering. Even for these incised channels, it is important to assess the recovery potential to understand the best restoration approach to use after the channel and floodplain has been reconnected.

Figure 48: Photograph of the inset floodplain and set-back embankment on the River Nith taken 1 month after construction had finished in August 2019.

As well as improving morphology, floodplain reconnection has a role in potentially reducing flood risk downstream. During floods, water can be stored on the floodplain, rather then being flushed downstream as fast as possible. This can work to create a flatter, more elongate flood peak, reducing the frequency and severity of flooding. This can also be combined with additional 'Natural Flood Management' (NFM) approaches, such as installing leaky dam/wood structures, and channel remeandering again to slow the flow, illustrating the significant overlap between NFM and assisted natural recovery approaches. Understanding the implications on flood risk of different restoration approaches is important to assess the benefits and risks of a scheme. Full details on these approaches can be found as part of the Environment Agencies Working with natural processes to reduce flood risk - GOV.UK (www.gov.uk) and SEPA's SEPA's Natural Flood Management Handbook For Practical Delivery - CaBA (catchmentbasedapproach.org).

Chapter 6: Examples of restoration case studies

This section will present case studies of river restoration schemes that have taken place mostly in Scotland. This builds on the previous section, providing examples of different types of active and passive restoration that have been delivered. Maps of catchment-scale recovery potential for each example are presented in Section 2.3. Below are the results for the more detailed reach-scale assessments of recovery potential. The type of intervention that was carried out is then described, including assessment of how the system responded or recovered.

6.1.1 Lyvennet remeandering case study

The Lyvennet is an active meandering river draining the upper Eden Valley in Cumbria. It was straightened, which significantly coarsened the bed and greatly reduced habitat diversity and quality. Whilst straightening had taken place prior to the first map, the course of the old channel was still visible on the floodplain. 1 metre resolution LiDAR data provided a detailed topographic survey of the reach and was assessed so that the location of these channels could be mapped (Figure 50). Trial pits along the channel were dug to ensure that the bed material was still present under the turf. While an ANR approach could have been applied in this location due to its moderate recovery potential (Table 23), remeandering was carried out due to the ease of design and delivery with such well-defined paleo-channels. In addition, the straightened channel bed was about 1 m lower than that found in the paleo-channel, meaning that active restoration was needed to reconnect the channel with the floodplain.

Post restoration the channel was seen to develop a wider range of habitats. This included pools, which were largely absent before, more defined riffles and exposed gravel bars (Figure 49). The channel bed became finer and exhibited a greater diversity through the reach, replacing the coarse and homogeneous tightly armoured bed that was present prior to restoration. These changes demonstrated a rapid, significant improvement in habitat quality (Figure 51). This was reflected in fish spawning being observed two months after works completion, in a reach where spawning had not previously been observed. The channel also became better connected to the floodplain, meaning floodwater could spread onto the floodplain, dissipating energy and achieving additional flood risk benefits.

Table 17: Reach-scale channel recovery for the Lyvennet prior to restoration.

Geomorphic variable	Description	Recovery potential category
Valley Confinement	Moderate gradient, unconfined	**M**
River Type	Medium energy active meandering	**M**
Bed material size	Cobbles and gravels	**M**
Bar frequency	Few – mostly gets washed through	**M**
Bank grain size	Silt	**M**
Bank erosion	Moderate	**M**
Flow Types	Riffle – run - pools	**M**
Overall recovery potential – Moderate recovery potential		

Figure 49: A) Image of the character of the habitat prior to restoration, showing it to be homogeneous, taken August 2013. B) Photo of a similar reach take just under 1 year post-restoration, showing the dramatic change in the character and habitat of the river. Photo credit Helen Reid.

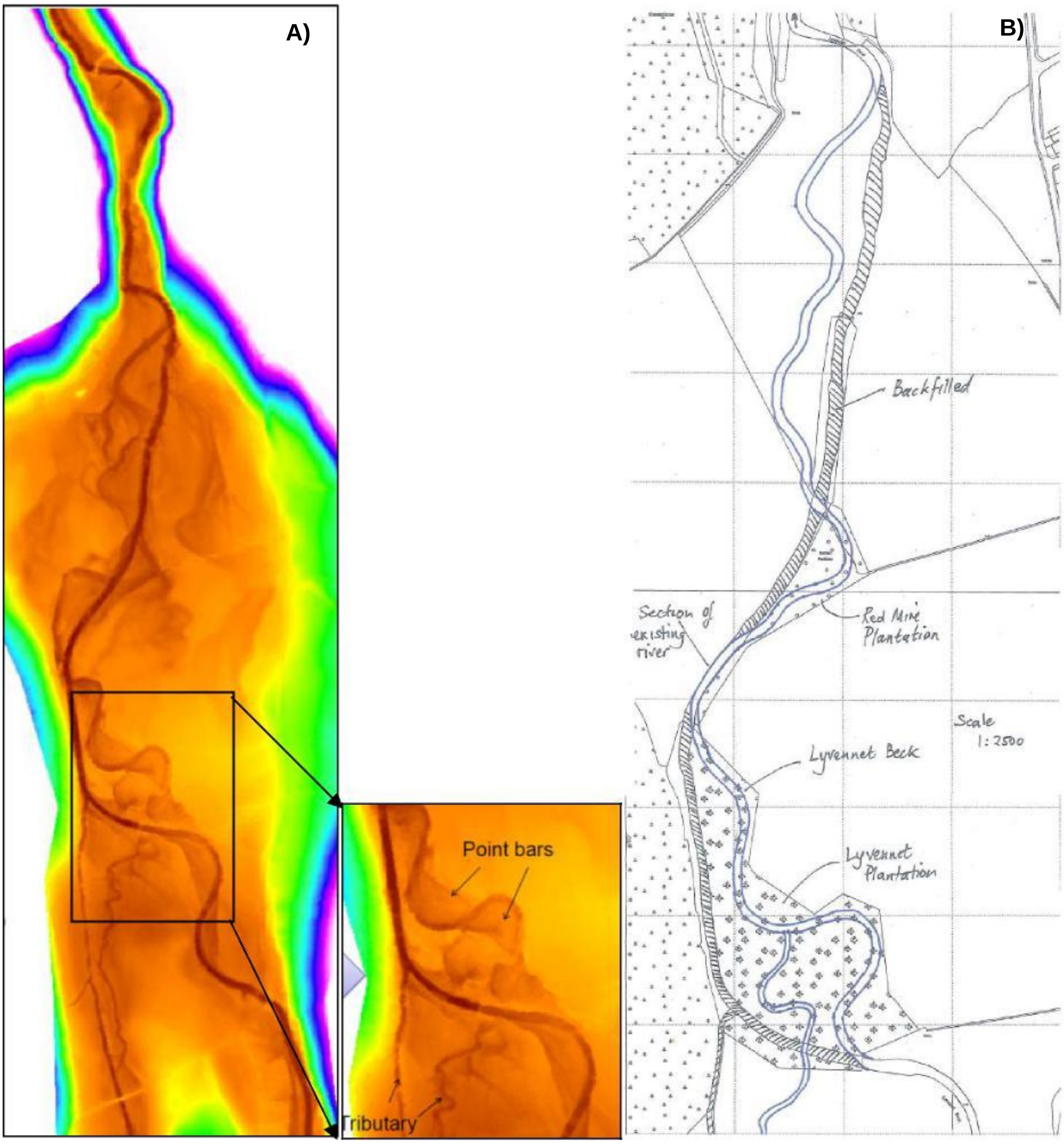

Figure 50: A) 1m LiDAR image of the river Lyvennet river restoration site, and B) resulting river restoration design based on the location of the previous channel. Design shown in B is sourced from Hey, 2013.

Figure 51: Photographs of the channel post restoration showing the improved diversity. Supplied by Olly Southgate, Environment Agency.

This case study demonstrates that this type of active restoration in a river with moderate recovery potential results in very swift recovery of morphology following the remeandering works. Despite the moderate recovery potential of the reach, an active approach was preferred here for a number of reasons. Although ANR (e.g. large wood structures) is likely to have eventually recreated a more diverse habitat, the bank erosion would not have generated a sufficient gravel supply because the river flows across a floodplain composed of old lake sediments (i.e. fines). Consequently, the required sediment load would have had to be delivered from upstream and this would have resulted in a slower recovery time. The use of paleo-channels meant that the bed material in the restored reach was suitable for the system, ensuring a sufficient gravel supply immediately, but also significantly reducing the uncertainty and risk associated with the design. Furthermore, the channel was incised and so it would have been more difficult to restore natural floodplain connection with ANR and the necessary bank erosion would have resulted in more sediment being delivered to the channel. These predominantly fine sediments would have been transported to the reach downstream where they could have smothered existing habitat. Consequently, the combination of a lower risk design, channel incision and rapid recovery time observed for the scheme (ANR is estimated to have taken around 12 – 24 years) meant that active intervention was deemed more appropriate in this case.

6.1.2 South Calder (Stane Gardens) urban deculverting case study

This restoration focussed on a 700 m long reach of the upper South Calder at Stane Gardens in Shotts, North Lanarkshire. This included the removal of sections of closed culverts at the upstream and downstream ends of the reach. The middle section consisted of a straight concrete lined channel, which acted as an open culvert with no natural morphological features remaining. This area was an iron works during Victorian times, which included several mines and collieries on site as well as multiple coke blast furnaces. This contaminated the surrounding land whereby hydrocarbon pollution was visible (i.e. oil was coming out of the ground) and the surface waters had elevated levels of heavy metals. In addition, the iron works completely reshaped the landscape, creating a steep and confined valley. Past maps show that prior to this industrial use the channel was sinuous, indicating the presence of floodplain.

Table 18: Channel recovery for the South Calder at Stane Gardens prior to restoration.

Geomorphic variable	Description	Recovery potential category
Valley Confinement	Valley is fully confined, but this is artificial based on landscaping for the Iron works.	**A**
River Type	Concrete lined channel/open culvert	**A**
Bed material size	Bed material is concrete, so artificial.	**A**
Bar frequency	No bars are present as any sediment that gets delivered would get washed through.	**A**
Bank grain size	No banks as the edges are concrete.	**A**
Bank erosion	No bank erosion as banks are concrete.	**A**
Flow Types	Flume like flow. Constant run-riffle with artificial steps.	**A**
Overall channel recovery potential = Not able to be determined due to complete anthropogenic modification of channel and valley.		

Channel recovery potential could not be defined in this situation as every attribute of the channel has been fundamentally altered by anthropogenic modification. This meant that more intensive restoration was required at this site. In order to restore the Stane Gardens site, the whole valley had to be reshaped. This involved excavating floodplain material to create an inset valley (Figure 45). However, this was not as wide as the pre-modification valley, so still provided some constraint. Three hundred and fifty metres of concrete and culverted channel was moved from its previous location and a 500 m long section of more natural sinuous channel was created. This included an impervious clay layer under its bed so that the channel would be disconnected from the underlying contaminated ground. Bed material was designed to be slightly oversized based on being reworked in the 1 in 5 year flood compared with what would be naturally found in a channel of this size. This ensured that the river would not adjust and erode the clay lining, connecting the contaminated ground, but still providing good habitat.

Figure 52: A) The south Calder at Stane Gardens prior to restoration showing the straight, concrete lined channel with steep valley margins. B) shows the river immediately post restoration showing how an inset valley was created and a sinuous channel within this. Photos from Alan McCulloch.

Figure 53: A) removal of the old channel after the river had been diverted into the new one, November 2016. B) Looking upstream at the newly connected restored reach in March 2016, C) looking at the restored reach in August 2017, almost 1 year following restoration and D) in 2021 5 years post restoration showing the recovery that has occurred in the form of bars, pools and riffles. Photos from Alan McCulloch and Francis Hayes.

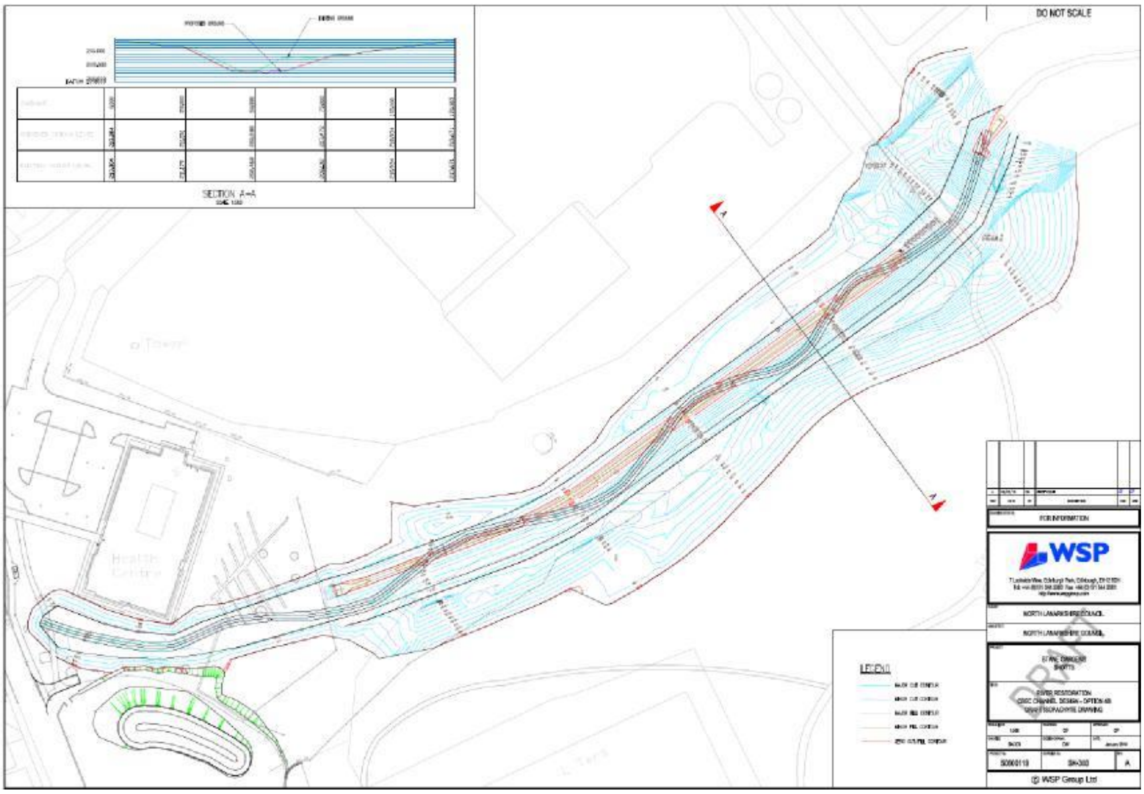

Figure 54: Construction map of the Stane Gardens restoration scheme. The red lines indicate the pre-restoration channel and the black the post restoration. The difference between these shows the areas which were deculverted. The floodplain was widened to accommodate the new sinuous channel. River Isopachyte drawing by WSP, January 2014.

The South Calder provides a good example of circumstances where high intervention, active restoration is necessary. The channel and the valley had been significantly modified from what was originally here, pre-Victorian revolution, and required full landscape restoration. The soil contamination meant that the river had to be restored in a way which would disconnect the channel from the groundwater and underlying soil, requiring very specific design criteria of a clay lining, and a channel design which would not erode this, while still able to be reworked enough to provide habitat. In these situations (as well as for many urban streams) an ANR approach would not have been appropriate and a more complex active intervention approach was necessary to improve the condition of the stream.

6.1.3 Aberarder remeandering and ANR case study

Aberarder is a site on the upper River Nairn, south of Inverness. It was straightened and embanked in the middle reaches. The river has a very high sediment supply due to landslips of glacial material in the upper catchment, and high energy to transport the material into the middle sections of the catchment. However, the catchment scale river recovery potential (Figure 18) suggests that the restored reach has a low recovery potential due to its apparently low slope in the data used to derive specific stream power. However, in reality it has a moderate recovery potential (though on the cusp of being at high), as demonstrated by the reach scale analysis. This is more accurate than the catchment scale analysis because it reflects the significant sediment loads being generated from landslides upstream, which result in a channel that is more dynamic than the specific stream power alone would indicate. Prior to restoration the channel was straightened, embanked, had its banks reinforced throughout the reach, and was perched above the floodplain. This led to significant issues with sediment being deposited in the channel, raising the bed level and causing the channel to spill out over the floodplain, which was temporarily alleviated through dredging. As a result, restoration was designed to reinstate a more naturally sinuous channel that allowed sediment storage, meaning the system would not be reliant on dredging to maintain the status quo.

Despite the moderate recovery potential, the river could not be left to readjust along most of its length, as the channel and its embankments had become elevated above the floodplain. Therefore, if the embankments were simply removed, the channel would have changed its course and formed a new path at the lowest point in the floodplain. This would have recovered, but would have resulted in a longer recovery time while the river reinstated a new channel, and would increase the risk and uncertainty over how the channel would adjust, which was not appropriate for the landowner. Therefore, a new channel was excavated as shown in Figure 55. This design includes gaps in the new alignment, which represent wetland sections which were seen to offer an opportunity to maximise the ecological and physical benefits of the scheme. Within these zones the river was left to create a fairly diverse route through the wetland. In the upper section, downstream of the road but above the realignment, sections of embankment were removed. Engineered Log Jam (ELJ) structures have been built into the banks to increase the diversity of in-channel habitat along the section with a lower sinuosity (Figure 55).

In summary, this represents a novel approach to restoration as it incorporates a mix of active intervention where the channel was constructed, combined ANR restoration where the channel diversity is left to adjust due to the log-jams (Figure 58), and through allowing the river to form its own channel through the wetlands (Figure 60). The distribution of the different approaches is based on the types of historical modification. For example, full restoration was carried out on the sections of channel that were perched, and that could not be left to restore naturally. In contrast, the wetland sections were left to self-restore as these had lower elevations, so the risk of letting the channel adjust within these sections was lower. The Upper

Nairn was rated as having a reach-scale moderate (almost high) recovery potential, and this is evident already because the river has been able to move and sort sediment and create diverse channel habitat within days and months of the restoration being delivered (Figure 57; Figure 59). This rapid recovery is largely due to the very high sediment supply coming into the stream, indicating that assessing recovery potential by specific stream power alone (i.e. catchment-scale recovery potential) can be misleading (see section 2.3.1). This scheme has restored a more sustainable channel form, removing the need for the expensive and damaging dredging that was required prior to the works.

Table 19: Channel recovery for the River Nairn at Aberarder prior to restoration.

Geomorphic variable	Description	Recovery potential category
Valley Confinement	Unconfined but within a 600 m valley with a moderate gradient	**M**
River Type	Active meandering when unconstrained, though on the cusp of wandering	**M (almost H)**
Bed material size	Mostly cobbles and gravels (though some boulders and sand too)	**M**
Bar frequency	Some but less than expected due to embankments and bank protection. Scored as 'many' due to very high sediment supply	**H**
Bank grain size	Mostly silt	**M**
Bank erosion	Anthropogenic due to bank reinforcement and dredging	**A**
Flow Types	Higher energy riffle, run, pool units	**H**
Overall recovery potential – Moderate recovery potential		

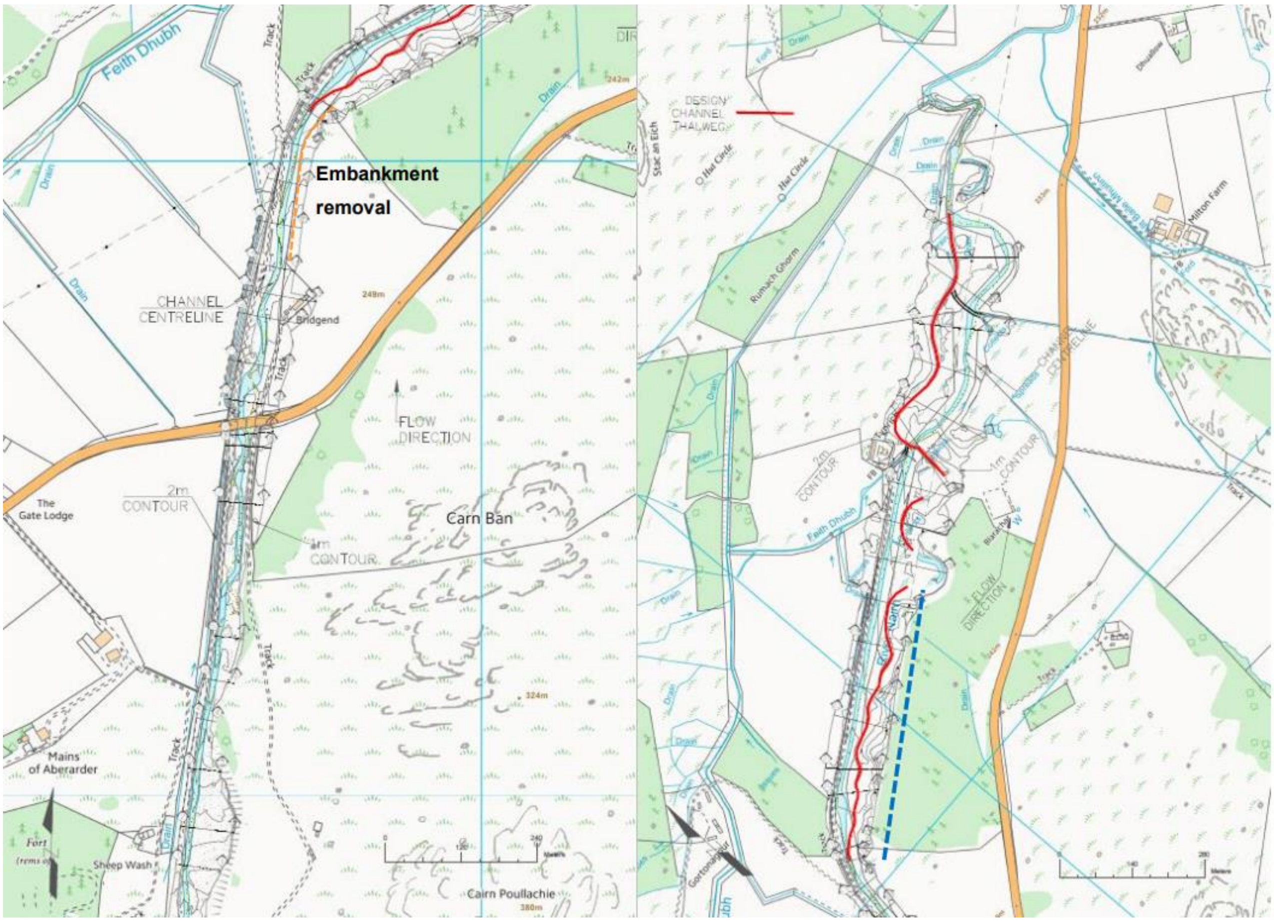

Figure 55: Aberarder channel design sourced from cbec, 2016. The dashed blue line indicates the section where ELJs were installed on every bend and the dashed orange line the area of embankment removal.

Figure 56: Post construction showing the old channel (on the right) and the restored channel going through the wetland sections. Photo taken by Chris Bowles (cbec).

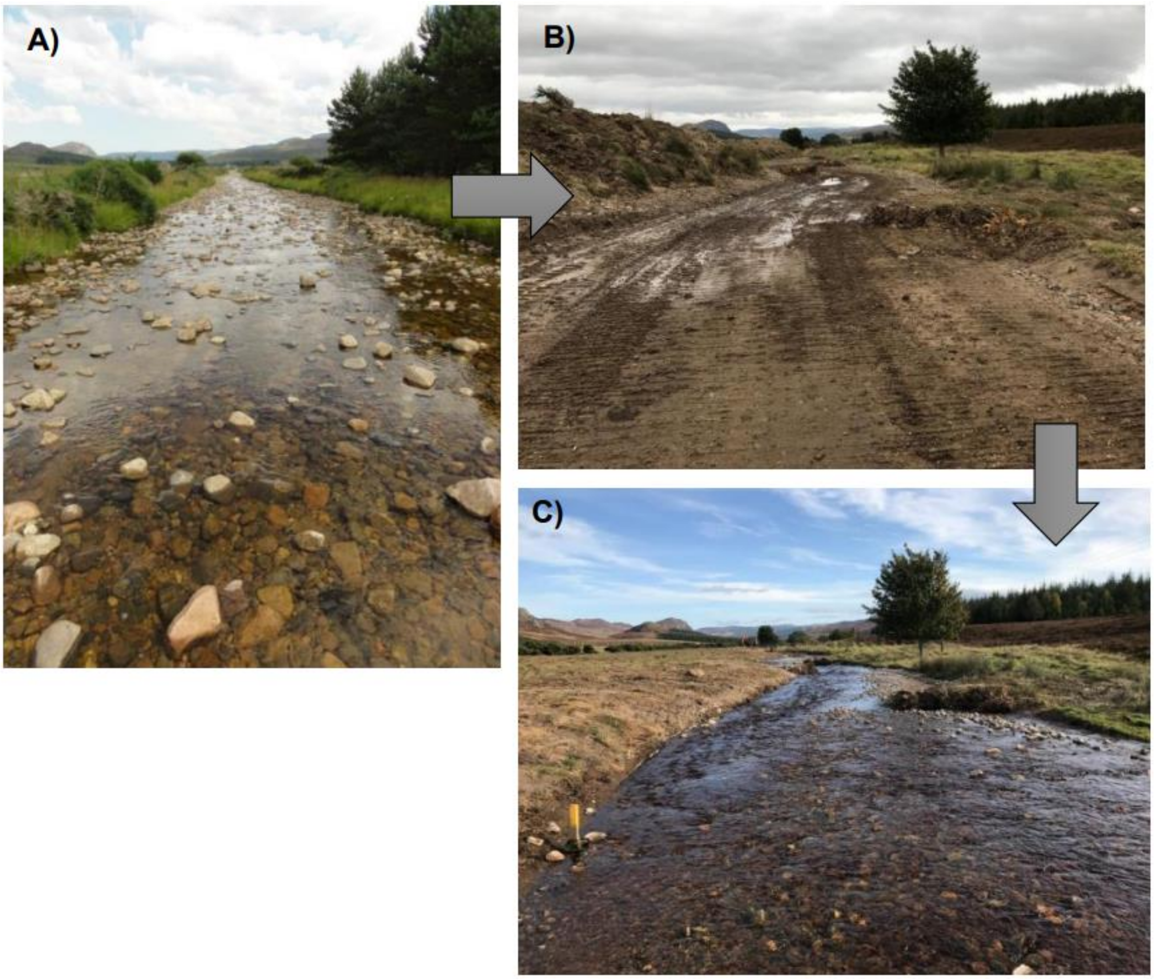

Figure 57: Photographs showing the sequence of restoration from A) pre-restoration channel taken 20th Sept 17, B) during construction of the new channel also taken 20th Sept 17 and C) post-restoration 9th of October 17. This shows the very high potential for physical adjustment at the site as this adjustment was caused by a single event which was smaller than bankfull flow. Photos taken by H. Moir (cbec).

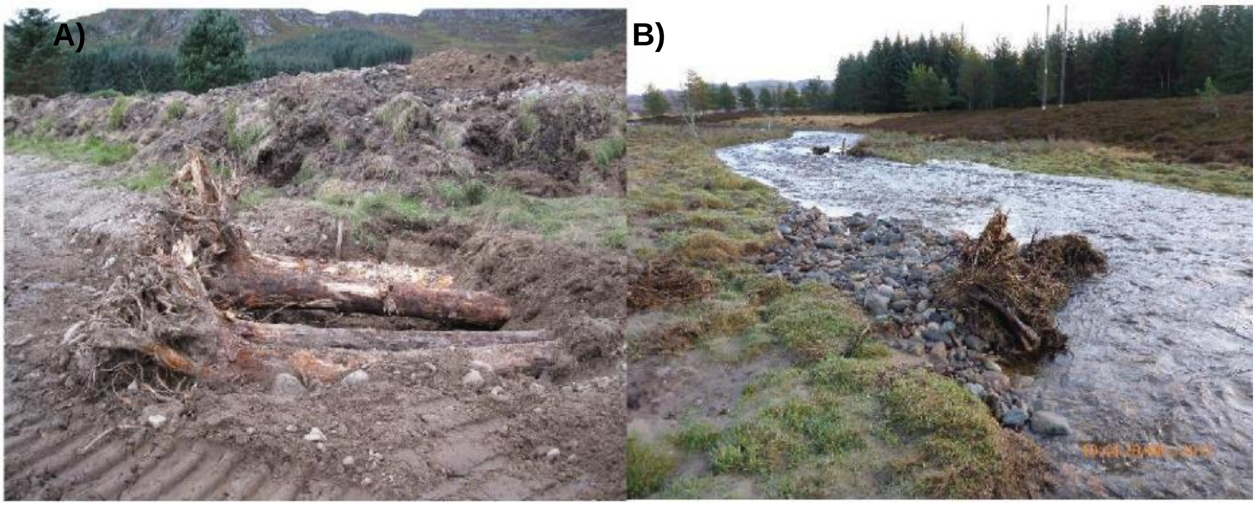

Figure 58: Showing how trees have been used to diversify habitat. A) shows how the wood was installed during construction. The other photos show how the presence of the trees have interacted to form more diverse habitat. A) taken September 2017 by Alice Tree, and B) taken December 2017 by Helen Reid.

Figure 59: Photos shows the further evolution of the reach taken in October 2019. Supplied by Richard Williams.

Figure 60: River flowing into the upstream wetland section and the headcut at the downstream point of the third wetland, showing how the channel is eroding into the bed of the wetland to create a distinct channel. Both photos taken October 2019 by Richard Williams.

6.1.4 Allt Lorgy Assisted Natural Recovery case study

The Allt Lorgy is a tributary of the Dulnain, in the Spey Catchment which is located in the Cairngorms National Park just north of Aviemore. This stream had been straightened, with embankments created along the edges using sediment dredged from the channel. Boulders had been installed along the banks to train the channel and stop migration, as well as across the bed in places to form grade control structures, to limit vertical adjustment. This had changed the morphology of the river from a complex wandering planform to a straighter single channel alignment. The reach-scale recovery potential is high (Table 20), which is slightly lower than the catchment-scale recovery potential assessment that classifies it as

RTC (see Section 2.3.2). Regardless, these two categories have similar management implications meaning such a discrepancy is less of an issue.

Table 20: Channel recovery for the Allt Lorgy prior to restoration.

Geomorphic variable	Description	Recovery potential category
Valley Confinement	Partly confined – wide pockets	**M**
River Type	Wandering	**H**
Bed material size	Cobbles and gravels	**M**
Bar frequency	Some but less than expected due to embankments and bank protection. Scored as 'many' due to high sediment supply.	**H**
Bank grain size	Mostly coarse river sediment in an uncohesive matrix	**H**
Bank erosion	There is some bank erosion, but significantly reduced due to large boulders along the edge and embankments that are falling in.	**A**
Flow Types	Higher energy riffle – run – pool units	**H**
Overall recovery potential – High recovery potential		

Restoration was designed to allow ANR to take place, taking advantage of the high sediment load and energy of the reach. This included removing the embankments and boulders that had been placed artificially to decrease constraints and adding large wood and gravel to kick-start adjustment (Figure 61). As a result, the channel was seen to adjust rapidly, significantly increasing its sinuosity, especially at points where recovery had already started and at locations proximal to large wood placement (Figure 62). This was associated with a marked increase in geomorphic unit diversity and as a result, habitat (Figure 63). This is illustrated in Figure 64, which shows how the depths and habitat diversity was enhanced by the presence of the wood.

Figure 61: Photographs showing A) the boulders which lined sections of the banks which were removed and B) wood structures immediately after installation which were put in to increase channel diversity. Photos from H. Moir, cbec).

This case study provides an applied example of ANR. It illustrates how in a setting with high - moderate recovery potential, the channel can adjust relatively rapidly once the constraints that are holding it in place are removed. This also highlights the important role that wood structures can play in driving channel adjustment and accentuating diversity. However, one of the characteristics that enabled this approach to be applied on its own was the lack of an incised (due to erosion) or perched (due to deposition) channel prior to restoration. If this had been the case, then despite the moderate - high energy and sediment load, active intervention may have been required to reset this vertical offset, perhaps in combination with ANR.

Figure 62: Photos of sections of the Allt Lorgy that have adjusted following the assisted natural recovery restoration. Note the locations of large woody material at the upstream of bars helping to increase channel sinuosity. Those photos marked A) show the river immediately after the works were completed in September 2012, B) in Sept 2016 and C) in September 2019 (supplied by Richard Williams). Thus, these all show the successive adjustment and recovery of the river.

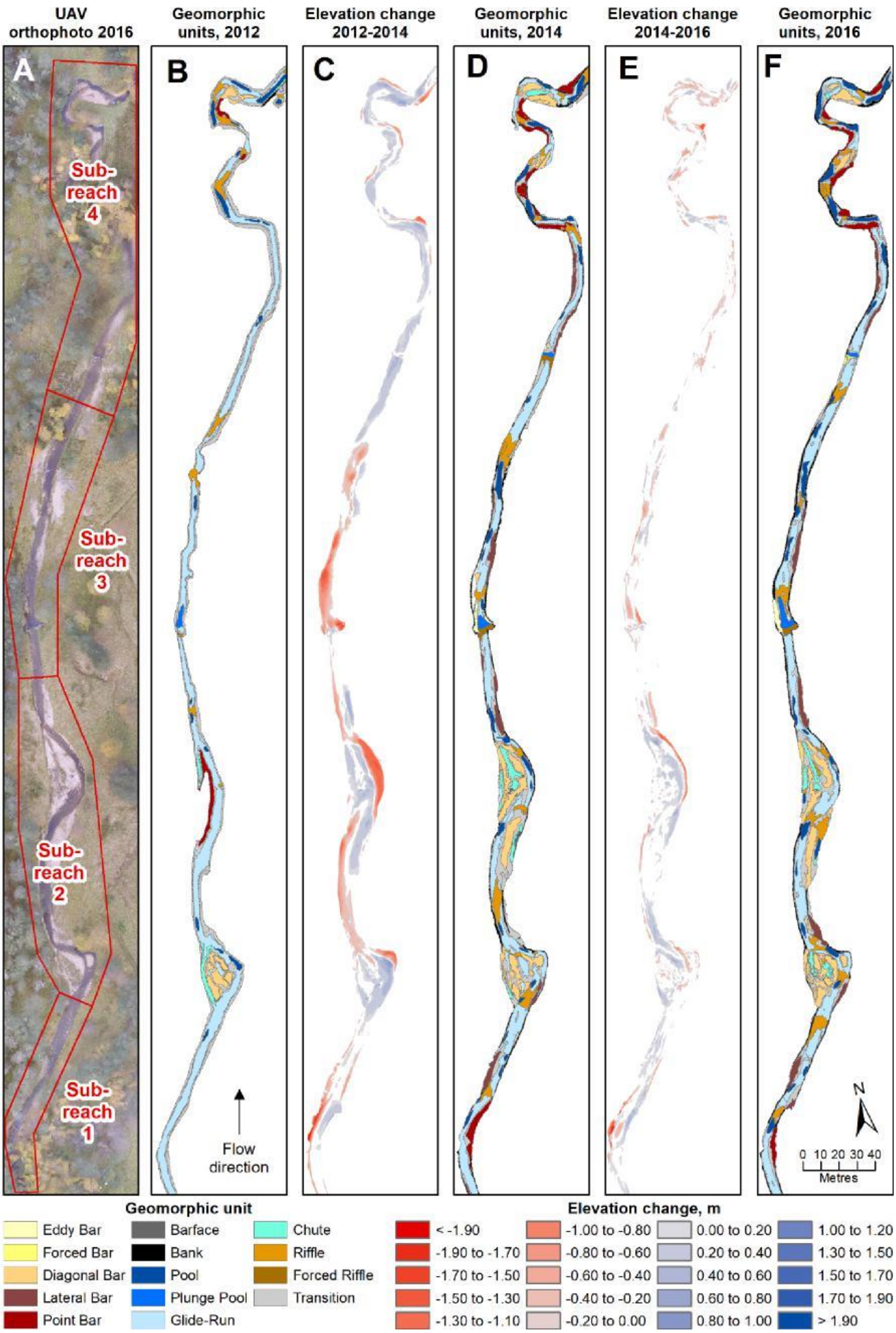

Figure 63: Map showing the diversity of geomorphic units which developed post restoration and the pattern of erosion and deposition post restoration. Image sourced from Williams et al., 2020.

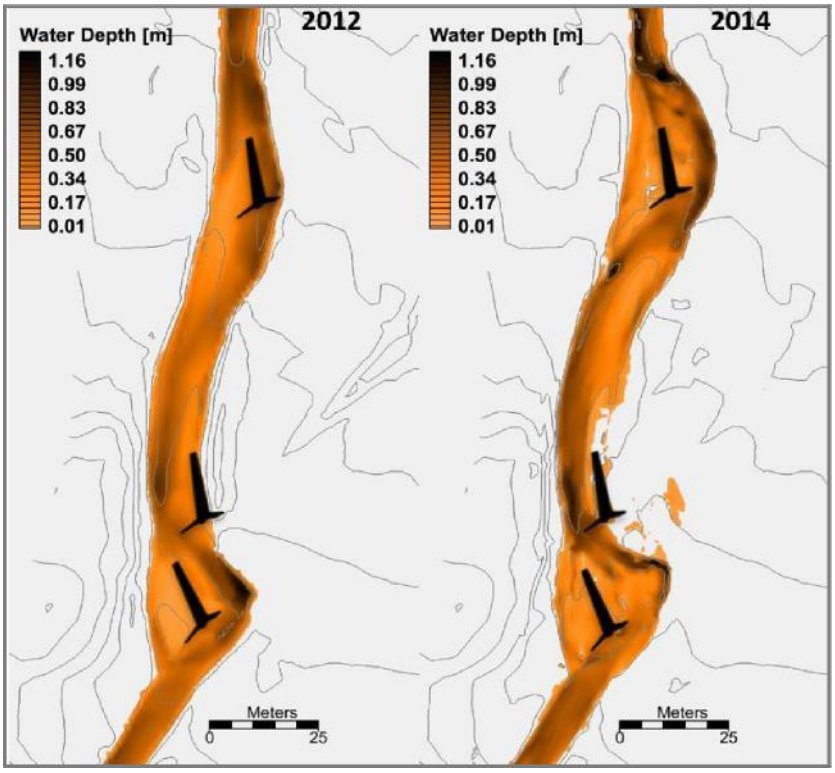

Figure 64: Map showing locations of the wood structures and topographic change that occurred adjacent to the structures. The 2012 image shows the situation immediately after the structures went in and the 2014 is 2 years later. This shows sub-reach 2 as displayed in Figure 55. Sourced from Hamish Moir, cbec eco-engineering.

6.1.5 Pow Burn two-stage channel and ELJ case study

The Pow Burn is located in the South Esk Catchment, in Angus, East Coast of Scotland. This was a straightened, incised channel, with embankments along much of its length, disconnecting the channel from the floodplain. In addition, it could be characterised by poor condition, over simplified habitat. The catchment (Figure 20) and reach scale (Table 21) assessments both indicate its recovery potential falls at the high end of the low category.

Restoration was designed to construct a two-stage channel, which involved lowering sections of floodplain to decrease the effect of the incision on the channel morphology and embankments were removed where present (active intervention). Deflectors were also installed to encourage the river to erode its banks and increase the diversity within the new inset floodplain pockets (ANR). Restoration was delivered in the summers of 2016 and 2017. Much of the land adjacent to Pow Burn is high quality arable and horticulture, meaning that the reference sinuosity was not achievable at this location because the width of land available for the river was less than that required for full recovery. Despite this channel having low recovery potential, it is likely to meet its objectives within a reasonable timeframe (estimated to be 18 – 30 years) as it just has to adjust its planform within the space provided by the inset floodplain, rather than recreate the 'natural' sinuosity of this system.

Table 21: Recovery potential for Pow Burn.

Geomorphic variable	Description	Recovery potential category
Valley Confinement	Low energy unconfined	L
River Type	Low energy active meandering	L
Bed material size	Gravel based, some sand on margins	M
Bar frequency	Few bars – Not many at all but some on the margins or in the middle of the channel	M
Bank grain size	Silt	M
Bank erosion	None – overgrown with vegetation	L
Flow Types	A mix of glides, runs and pools	L
Overall recovery potential – Low but at the high end of low		

Figure 65: The photograph on the left shows the general state of the channel prior to restoration and the photograph on the right shows the 2-stage channel which was installed with the new section of floodplain on the right bank (looking downstream). Deflectors have been installed since this photo was taken which will encourage the river to adjust within this floodplain section.

Pow Burn provides an interesting example as it has combined active intervention and ANR approaches in a low recovery potential reach, as well as experimented with a range of different flow deflector types. Those deflectors that were originally installed were found to be ineffective at eliciting adjustment and recovery at the rates required (Figure 66A). As a result, a range of different deflectors were installed in the autumn of 2017. This included logs of different sizes (Figure 66 B and C), which can effectively divert the flow to the opposite bank, increasing flow velocities and causing erosion. The larger log particularly was seen to cause erosion on the opposite bank almost immediately. Tree hinging was also used, whereby whole trees were bent into the river, whilst secured to their stump. This can provide a relatively quick, easy and secure approach to deflecting flow. Some species of tree such as willow can sprout once hinged, increasing the roughness of the deflector and the longevity of it in the system. Similarly, Figure 66F) shows a willow spilling deflector which will sprout and grow, pushing flow to the opposite bank and increasing erosion. Again, because this will grow, it is likely to have longer residence time in this system, adapting and changing as the river adjusts. Although this type of deflector can be installed in this system due to its low energy, it may be less appropriate in higher energy systems where it may just be easily get washed out during higher flows.

The Pow Burn example, although requiring active intervention to restore improve floodplain connection, highlights how ANR could be delivered on its own (if the channel is not incised) in a reach that is characterised by lower energy and recovery potential. It is likely that recovery will not be rapid, at an estimated 18 – 30 years till full recovery, though given the reach was at the high end of low, the recovery is more likely to be closer to 18 years. However, using ANR to restore rivers over longer time periods means that maintenance (perhaps including replacement or new deflectors) will probably have to be carried out over this time. For example, if the channel migrates away from a deflector, then a new one would have to be installed to ensure the channel will continue to recover. Therefore, whilst ANR approaches can be a good way to restore a river due to their low costs and relatively easy installation, they also require some stewardship and adaptive management based on what is successful within a specific system. This requires that channel recovery is monitored, assessed, and if necessary, new measures installed to ensure that recovery rates do not decrease, so that the river meets its objectives.

Figure 66: Examples of deflectors used in the Pow Burn scheme. A) shows the original deflectors which were installed which were seen to be undersized and not causing the erosion and creating the channel diversity necessary to upgrade morphology. B) shows a larger, rougher wood deflector, C) a log which was installed, D) and E) how live trees can be hinged into the channel and F) a willow spiling deflector designed to narrow the river.

Chapter 7: Conclusion

This report presents an approach which uses both catchment and reach-scale analysis of energy to assess a rivers ability to self-recover. The former provides a coarse resolution overview of the recovery potential through a catchment that can be useful for planning, whilst the latter assesses the geomorphic attributes of a reach and is essential to ground the coarser scale of analysis. This can then inform decisions as to whether active intervention, ANR, natural recovery or a combination of restoration strategies may be appropriate. The key aims of the guidance were;

- To create maps showing the broad-scale distribution of recovery potential and river energy across catchments within Scotland.
- To create a framework which assesses the recovery potential of individual reaches based on geomorphic characteristics.
- To estimate recovery times for reaches of different recovery potential categories, based on the type of pressure on the system and whether passive or active restoration measures were carried out. This could be used to enable the selection of the most suitable approach for a given reach.
- To describe how active intervention, ANR and natural recovery differ as approaches, and define which specific restoration techniques fall into each category and when they are best applied.
- To provide examples of where different restoration approaches have been used on rivers with different recovery potentials, using case studies from Scotland.

This guidance highlights the following key messages;

- Different types of rivers can be characterised by differences in the energy environment, which can be used to understand their potential to recover.
- Passive restoration using ANR measures is unlikely to be appropriate in rivers with a low recovery potential due to the slow rate of adjustment for these systems, and therefore, long recovery times.
- In contrast, ANR measures are likely to be successful in rivers with a high recovery potential, due to their high energy and/or high sediment load.

- For moderate energy rivers the best approach depends on what timescale for recovery is deemed acceptable, as well as the extent and type of pressures on the system.
- In general, Natural Recovery and ANR approaches are cheaper and can be applied over longer lengths of river, making restoration more cost effective and able to be applied at greater scales.
- In some situations, ANR is not going to be appropriate despite the recovery potential of a reach, due to its history and/or current constraints. This includes situations where lateral adjustment is not appropriate such as urban locations, those close to contaminated land and complex scenarios where the channel bed has either eroded or aggraded so that it is disconnected from the floodplain.
- It may be that a combination of approaches may be applied to achieve the best outcome. Restoration approaches don't have to neatly fit into one box, but rather should be applied based on i) the characteristics of the site and ii) existing river recovery, to decide which techniques will more beneficially work with the current trajectory of recovery.

The key is identifying where natural recovery and ANR restoration approaches can be delivered successfully and within acceptable recovery timescales. If the use of this approach can be optimised, then restoration can be carried out over longer reaches of river at a lower cost, maximising the environmental benefit of river restoration. It also allows the river to 'self-heal', rather than the habitats being designed, meaning the river can enhance the existing condition, rather than starting from scratch as in a new, constructed channel. By linking restoration approaches to the specific recovery potential of a reach, we can increase the success of the approach by applying it where it is morphologically appropriate. Having healthy and well-functioning channel and riparian margins is key to protecting and enhancing biodiversity, reducing flood flows by better connecting the river with the floodplain and creating more resilient and sustainable riverscapes.

Finally, future river management needs to look at how space can be provided to support channel processes and additional benefits in the form of channel mobility zones. Restoring riparian corridors and river functioning/health has a multitude of benefits including increased biodiversity, improved flood and drought resilience, reduced excessive channel adjustment and bank erosion, improved water quality and soil retention and increased carbon capture. This approach allows channel recovery and restoration to be viewed, planned and delivered at the catchment/landscape scale, which is needed to yield the benefits necessary to fight the climate and biodiversity crises. Working with the channel's ability to self-heal is key to delivering channel improvements at this scale. Crucially, we need to recognise the role that healthy and sustainable riverscapes play in protecting and allowing healthy and safe communities to flourish downstream.

Chapter 8: References

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Appendix 1: Field Sheets

River Recovery Potential Field Sheets:

Site name:		WB ID:	
Date:		Surveyor:	
Flow conditions:		Weather:	
US grid ref:		DS grid ref:	

Instructions: 1) Fill in the boxes below describing each of the attributes. 2) Circle the recovery potential category judged for each attribute. Recovery potential categories are ***(X)** resilient to change, **(H)** high recovery potential, **(M)** moderate recovery potential, **(L)** low recovery potential and **(A)** anthropogenic influenced.* 3) Transfer recovery potential score to summary table and use this to calculate overall recovery potential.

1. Valley confinement				
(X)	*(H)*	*(M)*	*(L)*	*(A)*
Describe your valley setting:				

2. River Type (Reference – i.e. what it would have been in its natural state)				
(X)	*(H)*	*(M)*	*(L)*	*(A)*
Describe the characteristics of your river type:				

3. Bed Material				
(X)	*(H)*	*(M)*	*(L)*	*(A)*
Describe range of bed material				

4. Bar Frequency				
None due to bedrock (X)	*Many (H)*	*Some or few (M)*	*None (L)*	*None due to anthropogenic (A)*
How frequent are bars within the reach and where are they located?				

5. Bank Grain Size				
(X)	*(H)*	*(M)*	*(L)*	*(A)*
Provide a description of the characteristics of your banks sediment, including how cohesive it is.				

6. Bank erosion					
(X)	*(H)*	*(M)*	*(L)*	*(A)*	
How much bank erosion is there and where is it located? *(If bank protection stopping erosion or livestock causing erosion*					

7. Geomorphic-flow				
(X)	*(H)*	*(M)*	*(L)*	*(A)*
Describe the range of flow types present within your reach?				

River Recovery Summary Table:

Mark the boxes based on the categories circled in the section above:

Geomorphic Variable	**Resilient to change (X)**	**High (H)**	**Moderate (M)**	**Low (L)**	**Anthropogenic influence (A)**
1. Valley confinement					
2. River Type					
3. Bed material size					
4. Bar frequency					
5. Bank grain size					
6. Bank erosion					
7. Geomorphic - flow units					
Total					

Overall Recovery Potential:

Notes on recovery potential categorisation e.g. channel state, dominant processes and recommended restoration approach (active or passive)? Also, constraints to restoration e.g. channel incision, perched channel or nearby potentially vulnerable infrastructure:

Reach-scale recovery potential category Guide:

Print and laminate this and use it to guide your answers in the sheets above.

1. Valley confinement				
(X)	**(H)**	**(M)**	**(L)**	**(A)**
Confined, ‘v’ shaped valley where the channel is confined by a sloping valley 90 – 100% of the time.	Partly confined with narrow floodplain pockets. The floodplain locally widens but the channel remains in contact with the valley margin between 50 – 90% of the time.	Partly confined within wider floodplain pocket, where the channel is in contact with the margin 10 – 50% of the time or moderate gradient unconfined with no confinement but the floodplain has noticeable slope	Low gradient unconfined. This should be flat containing low energy rivers	Valley completely reshaped due to anthropogenic modification
2. River Type (Reference – i.e. what it would have been in its natural state)				
(X)	**(H)**	**(M)**	**(L)**	**(A)**
- Bedrock and cascade - Plane bed - Step-pool	- Wandering - Braided - Plane-riffle - Pool-riffle	- High energy active meandering (cobble bed) - Moderate energy active meandering (cobble/gravel bed)	- Lower energy active meandering (sand/gravel bed) - Passive meandering (sand/silt bed) - Peat	Concrete or blockstone lined channel or equivalent
3. Bed Material				
(X)	**(H)**	**(M)**	**(L)**	**(A)**
Bedrock	Boulders and cobbles	Cobbles and gravels	- Silt and mud - Sand - Fine gravels	- Concrete - Blockstone - Gabions
4. Bar Frequency				
(X)	**(H)**	**(M)**	**(L)**	**(A)**
None - due to high energy, confined planform and bedrock dominance	Many – Bars are very common and reach has a braided, wandering planform	Some – Scattered along the reach, not just outside of bends Few – Small bars, generally inside of bends	None – No bars present within reach, and channel **not** dominated by bedrock	None due to anthropogenic controls on channel processes such as embankments or bank protection
5. Bank Grain Size				
(X)	**(H)**	**(M)**	**(L)**	**(A)**
- Bedrock - Boulder	- Sand - Coarse river sediment in uncohesive matrix	- Silt - Coarse river sediment in cohesive matrix	- Clay - High density tree roots and vegetation (i.e. willow)	- Banks concealed by concrete or blockstone
6. Bank Erosion				
(X)	**(H)**	**(M)**	**(L)**	**(A)**
None due to bedrock or boulder margins	High - Erosion throughout the reach, not just on the outside of bends, but straight sections as well	Moderate – Erosion at expected locations for river type, such as outside of bends	Low – Very little erosion present. Banks stable and held together by cohesive sediment, low energy and/or vegetation	None due to anthropogenic bank protection or excessive caused by livestock poaching
7. Flow Types				
(X)	**(H)**	**(M)**	**(L)**	**(A)**
- Waterfall - Cascade -	- Higher energy riffle - run units Step-pool units - May have a lot of exposed bars (i.e. wandering or braided planform)	- A mix of moderate to low riffle- run- pool and glide units.	- Low energy glides, runs and pools.	- Flume like flow - Stepped due to concrete flow

Appendix 2: Using the rivers recovery potential, what are the times-scales of recovery based on the pressures present in the system?

This section will use the recovery potential categories presented in Chapter 4 to assess how long it is likely to take for reaches to recover from different types of pressures. This is complicated as rivers within each category encompass a range of physical types and the extent and intensity of individual pressures can also differ. In addition, there is a dearth of information in the academic literature on recovery rates. Therefore, the numbers below are a best estimate and in reality, will vary based on the specific attributes of a reach. The analysis of the variables discussed in Section 3 should be used to fine-tune the placement of each reach within the recovery categories.

'Recovery time' represents the time that a type of river would need to alter the morphology so that near-natural river forms and processes were restored to the channel. For example, if a meandering channel had been straightened, it would be deemed recovered when the channel contained the correct geomorphic unit assemblages expected for that river type, with the units displaying good habitat conditions and diversity. This means that the channel may not have reached the same sinuosity as pre straightening, but it will have increased the sinuosity to the point whereby it contains the appropriate habitat. RTC rivers are not included in this analysis, as they are judged as unlikely to have been impacted and to need restoration.

Recovery times will be presented in years, but categorised by multiples of 6 so as to line up with River Basin Management Plan (RBMP) Cycles. Table 22 shows how many years can be associated with the number of RBMP cycles. These were selected as this is the timeframe over which SEPA plans management activities. In addition, because each cycle incorporates a six year period, it provides a certain buffer around the timeframe.

Table 22: Number of RBMP cycles displayed as years.

RBMP cycles	1	2	3	4	5	6	7	8	9	10
Years	6	12	18	24	30	36	42	48	54	60

Restoration strategies have also been separated into three categories as described in full in Section 6. The first is ‘active intervention’. This includes works that actively constructs the morphology of the river, such as digging a new meandering planform, or manually altering floodplain levels to create a two-stage channel. The second category is ‘Assisted Natural Recovery’ (ANR). This refers to restoration that works with the channel in its current location (i.e. land levels are not manually altered), aiming to invigorate processes. For example, this could include removing bank protection or embankments and installing Engineered Log Jams (ELJ) or injecting sediment to kick-start channel adjustment. The final category is natural recovery which refers to the length of time it would take the river to recover if no action was taken. For example, it predicts how long a straightened river with high recovery potential would take until the realignment pressure was removed. This would require anything artificial restricting adjustment such as bank protection or embankments to be assessed to understand if this is likely to be naturally eroded or whether it needs to be manually removed. This is due to the nature of these pressures varying widely, from natural boulders to concrete, necessitating further detail in the assessment.

The pressure categories listed below are those which are used for MImAS (the Morphological Impact Assessment System see Greig et al., 2006). This is because this is how SEPA assesses the morphological impact upon the system and the framework which is used to scope and design restoration schemes. In addition, these are the pressures which are most commonly impacting rivers in Scotland. Not every pressure from MImAS is assessed below. Only, those that are the most common or perceived to have the greatest impact upon whole-scale reach morphology have been included. Pressures that have minor local impacts such as bridge or pipe crossings are not included.

2.1 High impact realignment

High impact realignment (HIR) refers to a river that has been realigned to create a straightened planform, removing and simplifying habitat and fluvial processes. A HIR classification can be applied in reaches where the key features and processes expected in the reference type are largely absent, although there will often be some evidence of these features and processes in poorly or moderately developed form in isolated pockets (Figure 67). In order to achieve ‘recovery’ the channel would have to obtain a sinuosity and the associated bedforms and processes consistent with that river type. This may not be the same sinuosity that was present pre-straightening, but the river has to contain a geomorphic unit assemblage and diversity similar to the one found under reference conditions for that river type. Recovery times are presented in Table 23.

Table 23: Recovery times for rivers that have been straightened and are high impact realigned (HIR) based on a reaches recovery potential and the type of restoration delivered.

Recovery potential	Treatment	Recovery time (years)	Comments
High	*Active intervention*	< 6	Fast recovery based on full remeandering
	Assisted Natural Recovery	6 - 12	This is based on using ELJs and if necessary, gravel injections to kick-start processes. May require pressure removal (i.e. bank protection) if present
	Natural Recovery	6 - 18	Recovery based on if there is nothing impeding adjustment – i.e. bank protection. Depends on the energy and sediment of the reach
Moderate	*Active intervention*	< 6	Fast recovery based on full remeandering
	Assisted Natural Recovery	12 – 18	This is based on using ELJs and, if necessary, gravel injections to kick start processes. May require pressure removal (i.e. bank protection) if present
	Natural Recovery	18 - 42	Time would vary depending on energy of reach
Low	*Active intervention*	6 - 12	Fast recovery based on full remeandering even for low energy
	Assisted Natural Recovery	18 - 30	This is based on using ELJs and if necessary, gravel injections to kick start processes. May require pressure removal (i.e. bank protection) if present
	Natural Recovery	36 +	This could take a very long time if energy is very low, especially for peat systems or those with clay banks

Figure 67: Photographs showing A) a reach that is HIR where key features and processes are largely absent and B) LIR where some of the key features and processes have started to recover, but not as well developed as we would expect in this type of river naturally.

2.2 Low impact realignment

Table 24: Recovery times for rivers that have been straightened and are low impact realigned (LIR) based on a reaches recovery potential and the type of restoration delivered.

Recovery Potential	Treatment	Recovery time (years)	Comments
High	*Active intervention*	< 6	Fast recovery based on remeandering
	Assisted Natural Recovery	6 - 12	This is based on using ELJs and if necessary gravel injections to kick start processes. Time more likely to be 1 than 2
	Natural Recovery	6 – 12	Recovery based on if there is nothing impeding adjustment – i.e. bank protection
Moderate	*Active intervention*	< 6	Fast recovery based on remeandering
	Assisted Natural Recovery	6 - 12	This is based on using ELJs and if necessary gravel injections to kick start processes
	Natural Recovery	12 - 24	Recovery based on if there is nothing impeding adjustment – i.e. bank protection. Should be slightly quicker than for HIR
Low	*Active intervention*	6 - 12	Fast recovery based on remeandering
	Assisted Natural Recovery	12 - 24	This is based on using ELJs and if necessary gravel injections to kick start processes
	Natural Recovery	24 +	Recovery is still very slow. However, if it is quite a diverse LIR then this indicates that it does have the potential to self-recover

Low impact realignment (LIR) indicates that some recovery has taken place and that the river has to do less geomorphic work, in comparison to a river impacted by high impact realignment. This can be defined as a river where 'the key features and processes expected for that reference type are mostly present for the majority of the reach, but are not as well developed as in reference condition' (Figure 67B). Removal of this pressure has the same aim as for HIR, which is that the channel would have to obtain a sinuosity which is appropriate for that river type and contains well developed key features and processes throughout most of the reach. Recovery times are presented in Table 24.

2.3 Culvert

Table 25: Recovery times for rivers that have been culverted based on a reaches recovery potential and the type of restoration delivered.

Recovery Potential	Treatment	Recovery time (years)	Comments
High	*Active intervention*	< 6	The culvert would be removed and the river bed constructed
	Culvert removal followed by Assisted Natural Recovery	6 - 12	This is effectively the same as recovery from HIR, except the channel has to form its own bed post culvert removal.
	Natural Recovery	N/A	If the culvert is not removed, the channel will not recover
Moderate	*Active intervention*	< 6	The culvert would be removed and the river bed constructed
	Culvert removal followed by Assisted Natural Recovery	12 - 18	This is effectively the same as recovery from HIR, except the channel has to form its own bed post culvert removal.
	Natural Recovery	N/A	If the culvert is not removed, the channel will not recover
Low	*Active intervention*	6 - 12	The culvert would be removed and the river bed constructed
	Culvert removal followed by Assisted Natural Recovery	36 +	This is effectively the same as recovery from HIR, except the channel has to form its own bed post culvert removal.
	Natural Recovery	N/A	If the culvert is not removed, the channel will not recover

This looks at the recovery of a watercourse that has been culverted either in a pipe or a box culvert, both open and closed. In order to culvert a watercourse, you would have to straighten it by definition, unless it was a stream in the resilient to change category, which is not included in this analysis. Therefore, this assessment of recovery also considers the works that would need to be carried out to return the river to good condition (i.e. assisted natural recovery would include culvert removal). Recovery times are presented in Table 25.

2.4 Embankments

Recovery times are predicted based on a scenario where the river has the appropriate planform (i.e. sinuosity) but processes are modified due to embankments concentrating the energy in the channel (Table 26). Embankments concentrate flood energy, causing the bed to be scoured resulting in decreased geomorphic unit diversity, simplified in-channel habitats and armoured coarse channel bed. For this scenario, it is assumed that the embankments are located directly on the bank top of both banks and therefore would have the maximum impact on the system. If embankments are set back from the channel or only on one bank, then the recovery time would decrease due to a lower influence upon channel hydraulics.

Active intervention would involve removal or setting back of the embankments to the extent that the impact of the structures on the channel hydraulics was minimal. If the embankments had caused the channel to either build up or cut down, then this would include the work to reconnect the channel with the floodplain (i.e. floodplain lowering if the channel had incised). ANR would involve breaching the embankment or installing measures such as wood to encourage embankment failure. Similar to active intervention, if the channel was incised or aggraded, then ANR would also include the works to bring the channel bed back to appropriate levels. For example, this could include installing engineered wood jams to encourage the channel to build its bed up. Natural Recovery involves an active withdrawal of maintenance, so would include an agreement with the farmer or landowner that they would not maintain their embankments. These embankments would need to be actively assessed as to whether they are likely to fail within the necessary time scales (i.e. flood walls are unlikely to fail due to fluvial processes, whereas smaller grassed features could be eroded by the river) and if needed, more manual work may be needed to breach or remove these pressures.

Recovery would be assessed as complete when the channel had retained the appropriate within-channel bedforms post embankment removal.

Table 26: Recovery times for rivers that have been embanked based on a reach's recovery potential and the type of restoration delivered.

Recovery potential	Treatment	Recovery time (years)	Comments
High	*Active intervention*	< 6	Includes embankment removal or set back plus any land raising or lowering necessary
	Assisted Natural Recovery	6 - 12	Embankment would be breached and if needed ANR measures used to reset bed level
	Natural Recovery	12 - 24	Again, in a high energy system we would expect most embankments to be eroded relatively quickly if maintenance had been stopped. If this is a hard structure (i.e. floodwall) then it may require manual removal
Moderate	*Active intervention*	< 6	Includes embankment removal or set back plus any land raising or lowering necessary
	Assisted Natural Recovery	12 - 18	Embankment would be breached and if needed ANR measures used to reset bed level
	Natural Recovery	18 - 30	Based on the embankments not being maintained. If this is a hard structure (i.e. floodwall) then it may require manual removal
Low	*Active intervention*	6 - 18	Still rapid, but not as quick as for the higher recovery reaches
	Assisted Natural Recovery	18 - 30	Less energy means longer recovery periods even with using tools such as ELJs
	Natural Recovery	36 +	It would take a long time for the channel to adjust and remove the embankments due to the slow rate of lateral migration

2.5 Bank Protection

This looks at the recovery of a river that has bank protection either on both banks or at the points where adjustment would naturally take place. This represents a worst-case scenario, whereby the bank protection is restricting the channel's ability to adjust and recover. There has been no differentiation made between grey and green bank protection here. If intact, either should stop natural lateral adjustment. However, if the site has a softer type of bank protection that is failing, then the recovery times will likely be reduced. The timescales below (see Table 27) also assume that the channel has not been straightened, and that the recovery will involve the channel reforming the habitat that may have become degraded by the presence of the bank protection, rather than requiring wholesale planform adjustment. If a channel has been straightened and has bank protection, then the recovery times should be assessed using the HIR or LIR categories (whichever is relevant) with the assumption that recovery commences once bank protection has been removed either manually or naturally.

Table 27: Recovery times for rivers with bank protection based on a reach's recovery potential and the type of restoration delivered.

Recovery Potential	Treatment	Recovery time (years)	Comments
High	*Assisted Natural Recovery*	< 6	Removal of bank protection
	Natural Recovery	12 - > 60	This depends on the type and condition of the bank protection. It would have to start to fail, before the river would even start to recover. Should be assessed and may need to be removed manually
Moderate	*Assisted Natural Recovery*	< 6	Removal of bank protection
	Natural Recovery	18 - > 60	This depends on the condition of the bank protection. It would have to start to fail, before the river would even start to recover. Should be assessed and may need to be removed manually
Low	*Assisted Natural Recovery*	6 - 12	Removal of bank protection
	Natural Recovery	30 - > 60	This depends on the condition of the bank protection. It would have to start to fail, before the river would even start to recover. Should be assessed and may need to be removed manually, especially in such a low energy system

Active intervention was not assessed for this measure as it was seen as being too similar to Assisted Natural Recovery, and that it would be unlikely that habitat would be manually restored following the removal of bank protection, as the natural recovery is relatively swift. Instead, the ANR category is used to describe the length of time it takes for recovery after the bank protection is manually removed. Natural Recovery refers to a scenario whereby the landowner does not maintain the bank protection, and is therefore a measure of how long it is likely to take to fail (note: this is dealt with differently than for the other pressures). The range of timescales for recovery can be quite large as this process is dependent on the type and condition of bank protection at the time of assessment. For example, gabion baskets fail fairly rapidly in high energy systems, whereas sheet piling can last for extended periods of time. For this reason, when applied in the field, the type and robustness of the bank protection should be assessed, and if it is unlikely to fail, manually removed, even for the natural recovery option. This also recognises that removing bank protection may not be possible in some situations where it is protecting essential infrastructure such as pipelines or train lines.

2.6 Bed reinforcement

This describes a situation where the channel bed had been reinforced, most commonly using large rock, block stone, gabion (or reno) mattresses or concrete. Usually where this has been done, the natural bed load will be transported over these sections more rapidly, leaving a homogeneous bed with little habitat. Usually this type of intervention is only installed locally (i.e. at a bridge crossing) but in some very rare situations it may occur over larger scales, such as for a flood protection scheme. Therefore, for this scenario, the recovery times are calculated using a more local to moderate scale (< 50 m) as opposed to a longer stretch which is very rare, and covered more appropriately in the section about culvert removal (see Table 25).

Active intervention refers to removing the bed protection and introducing the bed material and units needed to create a natural bed. Assisted Natural Recovery refers to a scenario where the protection is removed and the bed is left to restore itself based on the natural sediment load being delivered from upstream. Finally, the Natural Recovery category is more complicated here. This is because in most scenarios bed reinforcement is only installed where it is protecting essential infrastructure such as railway bridges. In these situations it is assumed that they will be maintained, and will last as long as they are maintained. This is reflected in the N/A referred to as the recovery time. In contrast, the faster recovery times in this category refer to situations where no maintenance is carried out and the protection is left to fail. Again, the recovery times will very much depend on the type of protection and the condition it is in at the time of assessment and this information should be used to narrow down where in the recovery time range a site is likely to sit. Therefore, this should be assessed on a site by site basis and if needed manually removed.

Table 28: Recovery times for rivers that have been embanked based on a reaches recovery potential and the type of restoration delivered.

Recovery Potential	Treatment	Recovery time (years)	Comments
High	*Active intervention*	< 6	Removal of bed reinforcement and gravel seeding
	Assisted Natural Recovery	< 6	Removal of bed reinforcement and no other measures
	Natural Recovery	N/A or 12 - > 60	It will not recover until the bed protection is manually removed or fails. Depends on the type of protection
Moderate	*Active intervention*	< 6	Removal of bed reinforcement and gravel seeding
	Assisted Natural Recovery	< 6	Removal of bed reinforcement and no other measures
	Natural Recovery	N/A or 18 > 60	It will not recover until the bed protection is removed or fails. Depends on the type of protection
Low	*Active intervention*	6 - 12	Removal of bed reinforcement and gravel seeding
	Assisted Natural Recovery	12 - 18	Removal of bed reinforcement and no other measures
	Natural Recovery	N/A or 30 > 60	It will not recover until the bed protection is removed or fails. Depends on the type of protection

2.7 A combination of pressures

In real world situations, it is uncommon that each of these pressures exist in isolation. In reality, rivers commonly have a mix of overlapping pressures. Where this occurs, recovery for either the dominant pressure or the pressure which is having the greatest impact on the system should be assessed. For example, HIR has a greater impact on the morphology of a river than bank protection. However, the presence of bank protection can severely impact the rate of recovery. Therefore, the HIR recovery times should be considered as a better indicator of recovery, but only once bank protection has been removed. Thus, every reach should be assessed based on the combination of pressures present, considering which ones have the greatest impact on morphology and which require the greatest recovery times.

The best restoration strategy is one that considers the specific character of a reach (energy and sediment load), the distribution and type of pressures, and an assessment of existing recovery. The more site and reach-specific an assessment can be made, the more useful the output will be at designing an effective restoration strategy. For example, if some recovery has taken place (in a LIR reach) then it would be useful to assess when the reach was originally modified (i.e. straightened), if maintenance has been carried out to maintain that realignment, and how long it has taken to improve its condition once any maintenance was stopped. This will help improve the accuracy of prediction of future recovery. Similar streams in neighbouring catchments or adjacent reaches can also be used as proxies to predict recovery, if the characteristics of the reach are similar. It should be noted the recovery times predicted above are only a guide and the more site-specific information can be used, the better the predictions of recovery times will be.