Environment Agency

Improving river habitats to support wildlife during high and low flows – what works in which rivers

Chief Scientist's Group report

March 2024

Version: SC230009/R1

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Published by:

Environment Agency
Horizon House, Deanery Road,
Bristol BS1 5AH

www.gov.uk/environment-agency

Further copies of this report are available from our publications catalogue: www.gov.uk/government/publications or our National Customer Contact Centre: 03708 506 506

Email: research@environment-agency.gov.uk

Author(s):
Seb Bentley, Judy, England, Andrew Griffiths, Matt Hemsworth, George Heritage, Luke Hussey, Dave Mould, Rob Williamson.

Keywords:
River restoration, ecological and geomorphological resilience, hydraulic modelling,

Research contractors:
Dave Mould, Luke Hussey, Andrew Griffiths, Matt Hemsworth JBA, Salts Mill, Victoria Road, Saltaire. 01274 714 269.

Seb Bentley, George Heritage, Rob Williamson, Dynamic Rivers, 07722060056

Environment Agency’s Project Managers:
Judy England and Duncan Wheeler

Project number:
SC230009

Citation:
Environment Agency (2023) River Restoration to increase ecological resilience – what works in which rivers. Environment Agency, Bristol.

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Dr Robert Bradburne
Chief Scientist

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Acknowledgements

We would like to thank the following for allowing their projects to be used as case studies: Royal Society for the Protection of Birds (RSPB), National Trust, Wild Trout Trust, Stoke County Council.

Executive summary

The large number of modified water courses and the anticipated changes in flow regime due to climate change are driving work to increase the geomorphological and ecological resilience of English rivers. River Restoration schemes are increasing in number and aspiration in terms of the types and scale of improvements delivered. This report includes a literature review and summary of recent case studies to update evidence for what interventions work best in particular situations now and in the future.

Earlier work in 2014 described the evidence to support appropriate restoration measures (dependent on river type and local setting) to improve river habitats during low flows. Evidence was presented in a matrix that summarised available measures and the likelihood to which they will improve geomorphological and ecological resilience at low flows for a given river type, with a level of confidence based on available evidence. Practitioners can use the matrix to make a high-level assessment of what measures or combination of measures may improve their system and to access literature and case studies.

The update described in this report involved a review of 69 papers, most published since 2014. As a result, the matrix was extended to include measures reported since 2014, a new river type of 'urban artificial' and considered the suitable of the measure in providing resilience at high flows. The expert judgement of the project team was used to complete the new sections of the matrix as to whether the measure was likely to increase ecological resilience during flow extremes (high, medium and low possibility and inappropriate). Evidence from the literature review was used to apply a level of confidence to the expert opinion of the whole matrix. Reviewed papers provided limited information about the geomorphological setting of schemes. In many cases, it was not possible to clearly identify the river type and/or restoration measure, which restricted the amount of information which could be transferred to the matrix. Gaps in the matrix remain.

To address some of these gaps a two-dimensional (2D) modelling exercise was conducted on 10 new case studies focussed on generating insights for high energy and chalk environments, as well as schemes designed using a process-based approach, which allows natural processes to create habitats, for example by leaving space for adjustments. Ecological and geomorphological resilience is quantified by the variety and type of available habitats at different flows. Ecological resilience was considered to be greater if slower flowing habitats were present to provide shelter during high flows and flowing water habitats were present during low flows. The results provided evidence that reconnecting channel and floodplain (via a range of approaches) increased wetted area, often even at very low flows and slower flowing areas at high flows. In more constrained sites (either by land-use or urbanisation) improvements in resilience were also observed such as creating flow refuges, using a different range of techniques.

Gaps in the matrix remain with some measures having no evidence and some river types having little evidence (there appears to be a bias towards lower energy single thread channels in the literature). The evidence underpinning the matrix, could potentially be improved by reviewing other river restoration assessments such as reports from work undertaken by consultants and Rivers Trusts which are not often reported in the scientific literature or the targeting of monitoring and appraisal to address the gaps.

The river restoration measures to improve geomorphological and ecological resilience in a changing climate should be considered in a catchment context and work with natural processes to promote success. Larger-scale benefits may be achieved by taking a wider system view making space for channel migration, floodplain reconnection, wider hydrological functioning and allowing natural recovery over a larger area.

1. Introduction

1.1. Introduction

Over half of England's watercourses have been subject to deliberate physical modification for a range of reasons and sometimes over very long time periods. This modification affects natural physical processes, the habitats created and the ecosystems they support (Environment Agency, 2021). This change in channel shape alters the habitat composition at low and high flows, including the presence of refuges (flowing water conditions at low flows and slower flowing areas at high flows) that aid survival during these extreme events. Such extreme events are likely to increase under climate change (Watts, 2015).

In 2014 the Environment Agency undertook a study to aid understanding of how restoration measures can improve river habitats during low flows (Environment Agency, 2014). The study built an evidence base identifying the most appropriate restoration measures (dependent on river type and local setting) to improve river habitats during low flows. The study addressed the lack of effective appraisal of river restoration measures as assessment was both patchy and, in many cases, unscientific (lacking details such as objective setting, survey design, data quality and statistical analysis see, for example: Palmer et al. 2005, Environment Agency 2008, Vaughan et al. 2009, Feld et al. 2011). The 2014 study aimed to help practitioners design suitable schemes by linking restoration measures, river type and restoring natural processes to improve ecological resilience. The main output from the study was a matrix summarising evidence of measure effectiveness for a range of river types aiming to guide practitioners in selecting appropriate restoration measures. The matrix also highlighted areas with limited insights. Details of the river types used in the matrix are presented in the Appendix.

This study is an update of the 2014 investigation. The update is required given the rapid developments in restoration approaches with process-based projects beginning to supersede those that aimed towards an historic reference state. For example, river restoration approaches are extending beyond re-meandering in favour of system dynamism which aims for a natural self-sustaining process of habitat creation and evolution. This report is a review and update of the evidence base and further addresses gaps in scientific knowledge and information by providing new evidence of the impact of restoration measures considered useful in adapting to a changing climate.

1.2. Context

Climate change is expected to alter flow patterns in English rivers. Analysing seasonal mean flow changes for two future time slices (2020 to 2050 and 2050 to 2080), Kay (2021) found large decreases in summer flows across the England (median ~45%) but possible increases in winter flows (median ~9%) especially in the north and west. These results mean that the applicability and performance of restoration measures need to be considered against these potential changes in flows and resilience to larger floods. In turn the impact on the habitat suitability and availability for freshwater organisms at both low and high flows needs to be considered.

Both droughts and high flows are natural disturbances in river systems that influence community structure, alter species composition, abundance and richness, and can promote diversity (Poff et al 1997). Droughts and dry periods reduce the volume of available water, resulting in a loss of horizontal, longitudinal and vertical connectivity between the water body and its surroundings. Initially, wetted habitat is lost when the river becomes disconnected from its riparian zone but, as the drought progresses, longitudinal river connectivity may also be lost (Boulton, 2003).

Peak flood flows can cause substantial physical disturbance to river biota (e.g. Lake, 2000 Dunbar et al. 2010), although the threshold flows at which this occurs is uncertain (Death, 2008). The impact of flooding in a given watercourse will be dependent on the species composition and any physical modification that the watercourse has been subjected to (a function of the stability of the habitats, and the velocities in the channel) (Dunbar et al. 2010).

The presence of refuges can mitigate the impacts of extreme events. For example, during low flows fish and mobile invertebrates may migrate to deeper areas where velocities are maintained (Jones et al., 2015). Recovery following a low flow event will depend on its duration and intensity, and the ability of biota to persist within the refuges and/or recolonise (Boulton, 2003). Similarly, during flood conditions when river systems experience the greatest velocities, fish and invertebrates can actively avoid being washed away by using refuges such as backwaters, sheltered margins or the riverbed (Lancaster and Hildrew, 1993).

Morphologically more diverse sites, with little or no habitat modification, provide refuges and resilience during low flows – through a range of flow environments, deeper pools and boulders/logs/plants. Conversely, modified river channels have more homogenous habitats with few refuges, which exacerbates the impacts of low flows on biota (Environment Agency 2013a, Dunbar et al. 2010, Jones et al., 2015). Similarly, morphologically diverse sites are more likely to provide refuge for aquatic organisms in higher flow events, compared to homogenous channels where the risk of washout is higher (Dunbar et al. 2010, Jones et al., 2015). As result morphological restoration (appropriate to the river type in question) can be a successful adaptation measure to increase resilience to extreme events.

1.3. Project aims

Building on the 2014 project, this study updates and further develops the evidence around measures that can be applied to enhance physical habitats during low and high flow conditions, but also to ensure they are effective and sustainable at bank full flows when geomorphic processes are likely to be most active. Specific objectives were to:

1) Identify further (to the 2014 study) any additional measures that create a range of refuge for freshwater organisms during low and high flows.
2) Identify any further river types which should be included in the matrix.
3) Illustrate the potential habitat benefits at low and high flows of selected interventions through the examination of 10 case studies.
4) Update the matrix guide to selecting restoration measures to help target where restoration measures are likely to be most ecologically effective.

1.4. Report structure

Section 2 presents a summary of the literature review.

Section 3 summarises the results of the ten case study assessments.

Section 4 presents the revised guide to selecting restoration measures, which identifies measures likely to improve low and high flow conditions in a range of river situations.

Section 5 presents the conclusions.

This report is accompanied by an annex detailing the 10 case studies.

2. Literature Review

2.1. Introduction

The review examined 69 published journal articles focussing on the appraisal of river restoration schemes. Each was categorized based on the river type, location, impacts on river habitat at high and low flows and ecological response. The key findings of the literature review are presented in this report, a fuller review is available on request via research@environment-agency.gov.uk. It was beyond the scope of the project to carry out a full systematic evidence review of all available sources.

2.2. Overview of the literature

2.2.1. Contextual analysis

In total, thirteen countries reported restoration scheme monitoring and evaluation, of the literature reviewed, with studies from Europe and North America dominating. The UK, Germany, USA and Canada appear to have the most extensive monitoring programmes based on reporting levels. Restoration reach length appears clustered below five km with the majority covering reach lengths less than two km and ten shorter than 0.5 km. Longer reaches were reported but these tended to be an amalgamation of multiple shorter reaches. In total, 20 restoration measures were described with the majority offering the addition of wood (e.g. Stewart et al. 2006, Harvey et al. 2017, Addy and Wilkinson, 2019, Al-Zankana et al. 2020, 2021), riffle creation (e.g. Favata et al. 2018, Papangelakis and Macvicar 2020, Baho et al. 2021), re-meandering (e.g. Seer et al. 2020, Szymanska et al. 2020) and riparian planting (e.g. Boudell et al. 2015, Feld et al. 2018, Janssen et al. 2019). Newer techniques such as beaver reintroduction (Law, et al. 2017, Puttock et al. 2017) and 'stage-zero'[1] (Powers et al. 2018) schemes were represented but in low numbers. Semi-engineering approaches, such as the use of flow deflectors (e.g.

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[1] Stage Zero is a condition in which a river and its floodplain have been undisturbed for a period of time allowing the system to adjust to prevailing flow, sediment, and biological processes. Such systems characteristically develop as a dynamic river corridor comprising of areas of patchy wetland connected by a highly diverse network of river channels.

The philosophy of Stage Zero restoration is to work with natural processes to rehabilitate modified and degraded rivers and floodplains, encouraging the watercourse to redevelop as a diverse, feature rich dynamic system fully connected to its floodplain. This may involve complete infilling of the current degraded channel or selective intervention to rejuvenate river and valley bottom morphology and dynamics. A more detailed description may be found in Cluer and Thorne (2014).

Szymanska et al. 2020) and grade control structures (Salant et al. 2012), remain in use. Low activity single thread channels continue to dominate the river types being restored (e.g. Mouton et al. 2011, Thompson et al. 2017, Addy and Wilkinson, 2019) with varying levels of sinuosity reported. Interestingly wetland fen (Law et al. 2017), wandering (Fuller et al. 2018, Schwindt et al. 2019) and anastomosing (a low energy multi-threaded river, Powers et al. 2018) systems were occasionally reported on. Often, however, the channel type was not described, which limits the confidence with which the findings could be transposed to the matrix.

System modifications being addressed through restoration were largely interventions to increase flow conveyance through widening (e.g. Harvey et al. 2017), deepening (e.g. Hockendorff et al. 2017) and straightening (e.g. Knott et al. 2018,) and to protect banks from erosion (e.g. Pander et al. 2019). Wood loss (Marttila et al. 2015, Harvey et al. 2017, Livers et al. 2017, Hockendorff et al. 2017) and vegetative assemblage changes (e.g. Modiba et al. 2017, Feld et al. 2018, Janssen et al. 2019) were also reported on. A large number of sand-dominated channels were assessed (e.g. Favata et al. 2018, Oliveira et al. 2019), possibly reflecting the general lowland nature of the majority of restored channels with gravel based systems also strongly represented (e.g. Tetu et al. 2016, Bauer et al. 2018, Fuller et al. 2018). Higher energy systems with coarser (cobble/boulder) substrates were unreported and many papers failed to comment on bed substrate. The reported monitoring period appears highly variable ranging from a single year through to longer than 10 years. This statistic is also poorly reported.

2.2.2. Key Findings

The influence of flow on morphologic and ecologic function and the role of morphology in influencing hydrology and ecosystems has been mentioned in several papers (e.g. Pedersen et al. 2014, Favata et al. 2018, Feld et al. 2018), as has the appropriate integration of a wider understanding of catchment processes (Newson, 2002). This suggests a move away from single feature or single species focussed restoration approaches towards a process-based restoration / naturalisation approach, but data and evidence remain scarce and variable in quality. To make evidence more interpretable and applicable, a more systematic morphologic unit scale assessment of scheme performance is needed that uses a consistent physical, hydrological and ecological framework to describe and evaluate restoration measures at various scales and across a wider range of river environments (Heritage et al. 2009). The following sections outline the main conclusions from the literature review that has been undertaken.

In general restoration efforts remain biased towards lowland single thread systems. Process based restoration schemes which consider wider catchment are often much more resilient and sustainable than passive restorations schemes (Fuller et al. 2018). Natural regeneration (‘passive’ restoration) schemes are often slower to show ecological improvement (Atkinson and Bonser 2020).

If a single feature restoration approach is used or if the scheme is misaligned with system processes, any ecological gains can be lost due to the vulnerability of the restoration measure to high flows (Salant et al. 2012). Single measure schemes are not recommended, and a process-based approach is likely to develop a more robust, self-sustaining system (Harrison et al. 2004, Fuller et al. 2018).

2.2.3. Overview of specific measures

The introduction of large wood encourages both erosion and deposition (Harvey et al. 2017). Greater response is seen with more varied structures (Wohl et al. 2015) and those occupying a greater proportion of the cross-section area of the channel (Harvey et al. 2017) – this was reported on in the previous study (Environment Agency 2018) so adds confidence to the impacts of this approach. Large wood has also resulted in an increase in invertebrate numbers (Al-Zankana 2020, 2021) with engineered deflectors resulting in a marginal improvement in salmonid numbers (Stewart et al. 2006).

New gravel bar creation shows only limited stability and are vulnerable to high flows after construction, it is likely that newer sediment is more mobile than that seen in naturally formed bar units (Bauer et al. 2018). This should be considered during design. It was also noted that new gravel bars were favoured by colonisation of pioneer plant species (Bauer et al. 2018, Staentzel et al. 2018).

Fischer et al. 2018 reported that reactivation of floodplain features showed best development where water inundation was infrequent. Oxbows were given as an example in this instance. This contrasts with other studies (Modrak et al. 2018, Januschke et al. 2019) that suggest that floodplain geomorphic response is strongly linked to the discharge regime with more frequent flooding promoting change. Backwaters performed well with improved macrophyte, invertebrate and juvenile fish numbers (Fisher et al. 2018, Staentzel et al. 2018,). More widespread wetting of the floodplain also generated improvements with waterlogged, ungrazed floodplain areas showing species improvement (Law et al. 2019). Recurring floods were also shown to favour niche development (Modrak et al. 2018).

Invertebrate numbers are adversely impacted by maintenance, with vegetation cutting resulting in a significant decline in ecological status (Baattrup-Pedersen et al. 2018), as marginal vegetation is vital for invertebrates and juvenile fish (Mouton et al. 2011). Riparian planting acts to buffer delivery of silt, Nitrogen and Phosphorous to channels, improving overall water quality (Chua et al. 2019).

2.2.4. Geomorphological-ecological linkage

Having confidence in the link between ecological response to geomorphological change is confounded by a number of factors. Ecological success can be limited by the small size of any restoration scheme, adverse catchment conditions and wider influences (Manfrin et al. 2018, Baho et al. 2021). Limited colonisation populations can also limit response (Lorenz et al. 2018). There is often a time lag between the restoration and ecological response, which will be complex, and often beyond the monitoring period of a particular project (Boudell et al. 2015, Law et al. 2017).

Some studies found that sediment diversity correlated well with species diversity (Pedsrsen et al. 2014), although other studies were less conclusive with regards to this correlation (e.g. Jahnig et al. 2010) - micro-habitat variation is thought to be key to ecological response (Al-Zankana 2020, 2021). The literature reviewed also suggested that morphological diversity following restoration is not initially correlated with ecological diversity (Lorenz et al. 2018), though this may reflect the time lag between the geomorphological and ecological response (Lorenz et al. 2018, Baho et al. 2021).

2.2.5. Commentary on the literature

It is clear from this review of the recent research papers linked to river restoration appraisal have significant weakness with regard to adequately assessing the geomorphological setting of schemes or their overall functionality. Similarly, many are generalist, drawing overarching conclusions and making broad statements regarding restoration success with little local context. As such there is considerable variation in the conclusions drawn. The bias towards lowland single thread systems and the continued significant presence of structural, semi-engineered approaches to restoration is also presently failing to reflect the more recent attempts to integrate process understanding into geomorphological restoration and naturalisation. There is a general lack of detail in the literature with regards to information about the river type and restoration scheme, as well as a lack of monitoring, which makes it difficult understand the context of the results and so apply the lessons learnt elsewhere.

2.2.6. New measures identified

From the literature review, six new river restoration measures were identified that were not explicitly represented in the previous matrix version. These have been listed in Table 1 below, along with a brief description of each measure and the potential benefits.

Restoration Measure	Description	Potential hydromoprhological and ecological benefits	References
Bankside and Riparian planting	Planting trees or other larger vegetation either along the bank edge of a watercourse or within the riparian zone.	• Over time provides a source of large wood for wood feature formation in the channel as part of natural processes; • Provision of cover and shade to the watercourse; • Improved bankside stability, particularly where more than a single line of trees can be planted; • Interception of surface water runoff and associated water quality benefits.	Thompson et al. 2017 Kujanova et al. 2018 Knott et al. 2018 Boudell et al. 2015
Beaver reintroduction	The reintroduction of beavers to a river system.	• Beavers can generate highly diverse wetland areas; • Beavers can create improved floodplain connectivity through wood feature creation.	Law et al. 2017 Puttock et al. 2017
Stage Zero	Infilling a river channel to allow flow to spread widely across a floodplain area and to develop over time – a 'system reset'.	• Improved floodplain connectivity can result in the creation of diverse wetland and hydraulic habitats; • Encourages natural processes; • Can be useful in Natural Flood Management.	Powers et al. 2018
Backwater Creation	Creation of a backwater linked to the main river channel.	• Backwaters provide refuge for fish during higher flows; • Backwaters often exploit palaeo-channels and can be created alongside wider wetland creation; • They provide hydraulic habitat diversity at low and high flows.	Martilla et al. 2015
Multi-thread channel	Creation of more than one channel as part of a river restoration scheme.	• Numerous river types would naturally be multi-thread systems, therefore this often works with natural processes associated to the river type; • Hydraulic habitat diversity is significantly increased; • Sustainable sediment transport processes are allowed to operate.	Livers et al. 2017
Bed ploughing	Mechanical disruption to the river bed that is armoured and/or choked with fine sediments.	• Disruption to an armoured bed can reinstate sediment transport processes and habitat creation.	Janssen et al. 2019

Table 1. Additional measures found within the literature review

Case studies

2.3. Choice of case studies

The selection of the ten case studies was informed by the evidence gaps and the new restoration techniques identified within the literature review (Table 2). The case studies were selected to help address evidence gaps in the matrix (including the addition river types and measures identified in the literature review). They also needed sufficient available channel geometry and flow data to enable modelling of the effects under different flow regimes.

Table 2. Table summarising the rationale for case study choice

Site	Restoration measure	Rationale
Grisedale	Riffle-rapids, point bars, bank lowering	Introduction of in-channel features and bank lowering to reconnect the floodplain and palaeo channels in a high energy environment.
Scarrow	Riffle introduction, wetland creation, anastomosing sections	Riffles were used to raise local water levels to reconnect the floodplain alongside wetland and anastomosing channel creation in a lower energy environment.
Long Preston	Berm creation Bifurcating channel Backwater reconnection, setting back embankments – floodplain reconnection	Models a longer reach than the other examples on a larger river. A range of in-channel and floodplain measures used.
Aller at Selworthy	Stage zero	Recently completed Stage zero study on an active single thread river type. Detailed 2D modelling undertaken in the design phase
Fowlea Brook	Remeandering Gravel addition/bed reprofiling Channel narrowing	Constrained urban/artificial watercourse. Starts to build evidence base for new river type in matrix. Variety of restoration measures employed.
Dunston Beck	Riffle creation, floodplain lowering, wetland creation, bifurcation, channel realignment and	Introduction of riffles alongside floodplain lowering and channel realignment to provide floodplain reconnection and wetland creation. Riffles provided significant hydraulic habitat improvements,

	remeandering, pond creation	reinstating natural process leading to some lateral adjustment.
River Witham at Manthorpe	Riffle and gravel bar feature creation alongside embankment removal and floodplain lowering.	Introduction of riffles alongside embankment removal and floodplain lowering to provide floodplain reconnection and wetland creation. Riffles provided significant hydraulic habitat improvements in this chalk system.
Hartsop Hall	Flood embankment setting back, multi-channel creation, floodplain reconnection, riffle-rapids, channel widening	Flood embankment setting back and channel widening allowed a multi-thread river reach to be created. Improved floodplain connectivity was created downstream where riffles were created and a section of bank lowered, this is creating improved wetland.
Geltsdale	Floodplain reconnection through chute channel creation and blocking, channel realignment and bifurcation	The floodplain was reconnected at Geltsdale through blocking of the existing straight channel and creation of a chute channel to direct flow into the floodplain. A new meandered and bifurcated channel was created at the downstream end to provide improved hydromorphology and floodplain reconnection compared to the previous straight channel.
Goldrill Beck	New channel creation, channel bifurcation, floodplain reconnection, anastomosed channels and riffle-rapid creation	The previous Goldrill Beck channel was perched and straight, the channel was realigned into the valley bottom as part of the restoration scheme to provide improved floodplain connectivity. The channel was also bifurcated to provide hydraulic habitat diversity and woodland anastomosed development was encouraged at the downstream end of the scheme. Riffle-rapid features were added to the new channel as new morphological features to further improve connectivity to the floodplain.

2.4. Modelling Approach

The modelling approach is summarised in this section, with a more detailed methodology in in the accompanying report of the case studies.

2.4.1. Hydraulic habitat modelling

The assignment of different hydraulic ranges to define physical habitats (biotopes) is a widely accepted approach to assessment (see, for example, Kemp et al.

2000, Harvey et al. 2008, Harvey and Clifford 2008, Heritage et al. 2009). Mapping of the biotopes allows quantification of habitat area, diversity and patchiness – all of which are important aspects of defining ecological quality, diversity and resilience.

The hydraulic biotopes are defined by the variation of the Froude number (the ratio of inertial to accelerational forces; see Gordon et al. 1994), which has been found to be a reliable hydraulic variable to distinguish between different biotopes (see, for example, Wadeson 1994, Kemp et al. 2000, Heritage et al. 2009) – Figure 1.

Hydraulic habitat mapping was performed using a simulation of low flow and bankfull conditions using a 2-dimensional fixed bed hydrodynamic model. The performance of the restoration measures in terms of hydraulic and ecological resilience was made using three flows that could be expected to occur relatively frequently:

- Q95 – Flows exceeded 95% of the time - representing a summer flow, identifying hydraulic biotopes and habitat conditions at low flows (including low flow refuges)
- Q10 – Flows exceeded 10% of the time - representing a winter flow, identifying hydraulic biotopes and habitat conditions during moderately high flows (including high flow refuges)
- QMed – the median annual flood, identifying hydraulic biotopes and refuge availability during a flood which would occur relatively frequently.

The habitat maps were used to identify the presence and coverage of faster flowing areas during low flow conditions (low flow refuges) and slower flowing or slack areas during higher (bankfull) flows (high flow refuges). For each case study, a comparison of the reach where the morphological measure had been applied was made to either pre-restoration conditions or a nearby degraded section. This gave an indication of how the biotope habitat composition had changed as a result of the scheme.

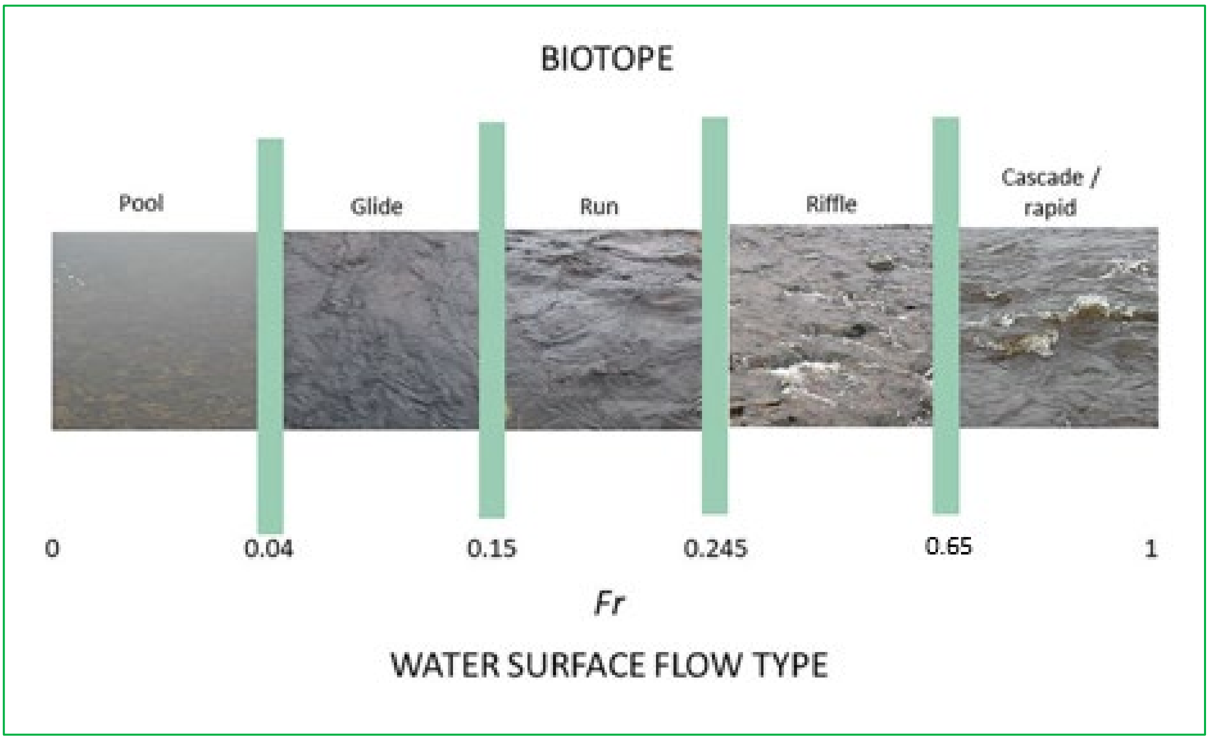

Figure 1. Hydraulic biotope thresholds used

2.4.2. Shear stress

Bed load movement and sediment transport is a function of shear stress. When the drag force of flowing water against a particle is greater than the gravitational force holding it in place it begins to move. Shear stress was calculated and plotted for the QMed scenario for each of the case studies, therefore, this analysis provides an understanding of the geomorphological resilience of the measures in high flow events.

2.4.3. Fish habitat suitability

Where the modelling, restoration measure and data was appropriate, a fuzzy logic habitat model (JHAB) was used to assess habitat suitability for fish (see accompanying report of the case studies). This approach was used to review the habitat suitability for different life stages of fish species of interest (depends on the fish expected to be present in the river) and refuge at high flows.

The modelling provided a spatial assessment of the channel through the calculation of a Habitat Suitability Index (HSI) for each flow and species/life stage of interest. This was used to assess:

- quantity of available habitat – Total Habitat Suitability Index (THSI)
- quality of the habitat – Habitat Quality Index (HQI)

2.4.4. Vegetation classification

For a selection of the case studies that involved changes to the floodplain, the habitat, composition was classified and mapped to demonstrate the changes and likely development linked to the proposed restoration scheme.

2.5. Case studies overview

This section presents the 10 case studies which were investigated as part of this project, the modelling and analysis methods employed and provides a summary of the results at each of the sites. The case study sites covered a range of river types and restoration measures including new approaches identified in the literature review (Figure 2).

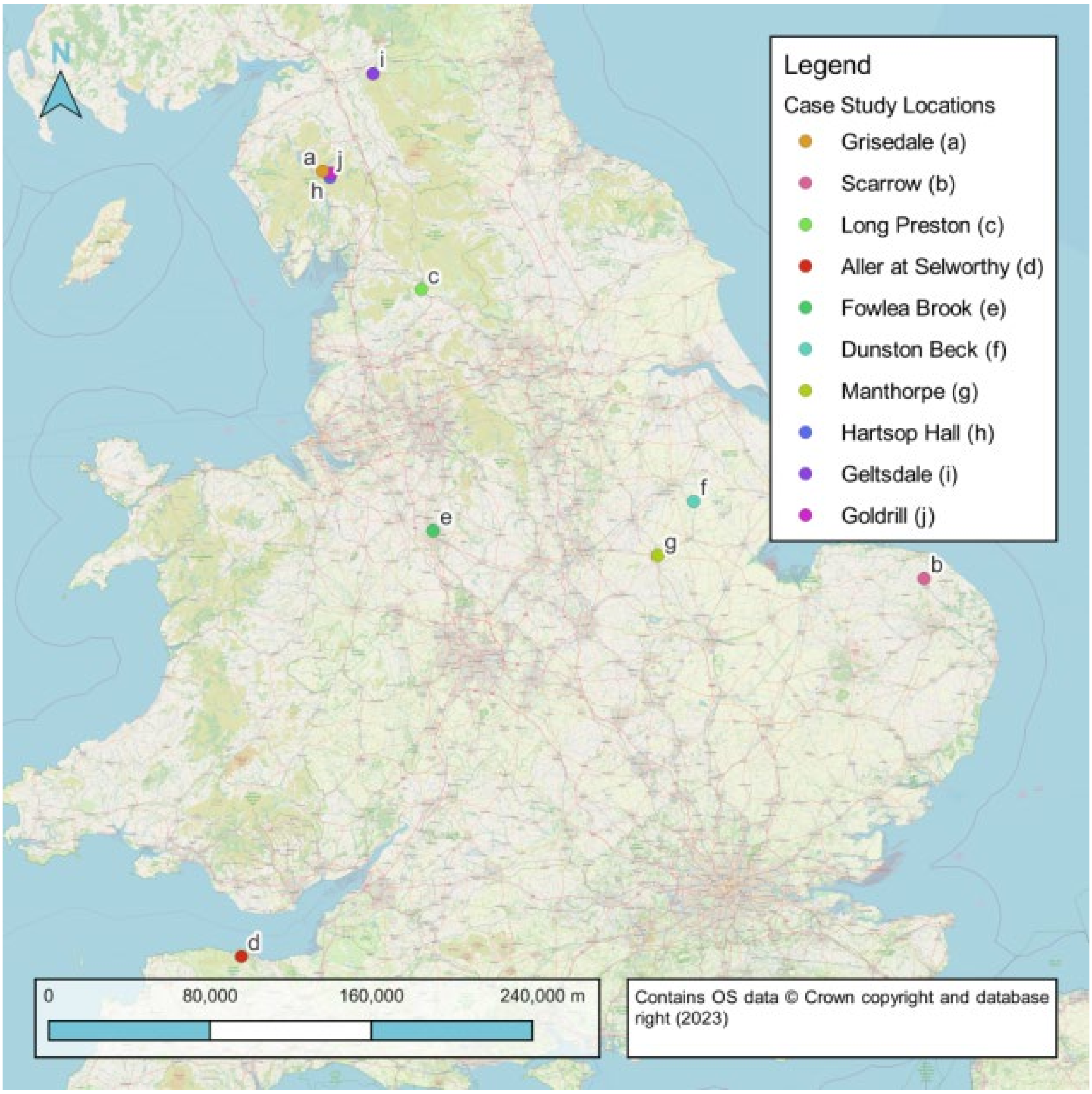

Figure 2. Case study locations

The model results suggests that all of the schemes were likely to deliver some improvements in the resilience of the ecological and geomorphological system. The most striking results were from schemes which led to the large-scale reconnection of the floodplain, for example at Goldrill and Selworthy. This led to large increases in wetted area, a reduction in energy in the system and a prevalence of lower energy biotopes such as pool and glide. Smaller (but nevertheless important) improvements to resilience were identified at more constrained sites (such as Fowlea and Long Preston). Each are constrained in a different way, Long Preston by existing land use, and Fowlea by urban development. Overall, the schemes were able to demonstrate improvements in the geomorphological and ecological resilience at both high and low flows. An overview of the case studies is presented here with further information about the river characteristics, restoration measures and the modelled assessments detailed in an annex to this main report.

Grisedale (a)

River type: active single thread and wandering.

Restoration action: installation of riffle-rapids and point bars and bank lowering.

Impacts: increasing floodplain connectivity with increased floodplain activation observed during higher Q10 and flood flows with much of this water occupying newly created depressions in the floodplain. The increased floodplain connectivity is shown to increase the proportion of lower energy pool and glide biotopes. In-channel shear stresses remain similar however lower shear stresses are observed in floodplain areas.

Scarrow (b)

River type: passive single thread.

Restoration action: riffle introduction, wetland creation and the creation of anastomosing sections.

Impacts: The restoration techniques implemented at the study site have had a generally positive effect on floodplain connection and fish habitat. The greatest improvement is observed at Q10 flows, with floodplain reconnection and fish habitat increasing across all life stages.

Long Preston (c)

River type: active single thread.

Restoration action: backwater creation, multi-thread channel creation and setting back embankments.

Impacts: the restoration techniques implemented in the study area have brought about a modest improvement in floodplain connection – however, this improvement is largely confined to Q10 flows. Little change is observed during Q95 and 1 in 2 year event flows. Similarly, only subtle changes in biotope types are observed during the Q10 and Q95 flows where, the riffle biotope increases, offset against a decrease in run biotope. For the 1 in 2 year event, biotope type remained largely the same, post restoration. No change in shear stress was observed.

Aller at Selworthy (d)

River type: active single thread.

Restoration action: Stage zero.

Impacts: a large increase in floodplain connectivity was observed. The majority of the additional flows on the floodplain are pool and glide biotopes at all flows, with an increase in riffle and rapid biotopes at higher flows. Lower shear stresses were observed on the floodplain post restoration compared to those within the channel pre-restoration. A large increase in fish habitat availability was shown across all modelled flows (all life stages of Brown trout) in addition to large increases in refuge habitat at higher flows.

Fowlea Brook (e)

River type: urban/artificial.

Restoration action: remeandering, gravel addition/bed reprofiling and channel narrowing.

Impacts: increases morphological variability and sediment dynamics in the new channel. Clear areas of erosion and deposition are developed. There is much greater evidence of erosional processes post change whilst the channel-floodplain connectivity was maintained. The largest changes in flow biotopes and fish habitat were observed at Q10. At Q95 the fish habitat modelling suggests the restoration has mixed results depending on the life stage of interest.

Dunston Beck (f)

River type: passive single thread.

Restoration action: riffle creation, floodplain lowering, wetland creation, bifurcation, channel realignment, remeandering and pond creation.

Impacts: The increase in overall wetted area under low and winter flows shown by the modelling undertaken demonstrates the increased resilience to low flows created as a result of the restoration scheme. There is also an overall improvement in biotope diversity under summer and winter flows when compared to pre-restoration conditions, with more characteristic riffles and pools being created as a result of the scheme under summer flows, as well as an increase in overall wetted area. Floodplain habitat creation and likely development is also predicted to be diverse as a result of the new hydrological regime created. Wet grassland and fen mire could develop across the reconnected floodplain areas, however this development is reliant on a suitable grazing regime at the site. Projects involving system naturalisation aim to rejuvenate processes as well as physical form, as such dynamic change must be anticipated and subsequent management of the system must be cognisant of this fact by for example setting back stock fencing to allow space for the channel as it migrates.

Manthorpe (g)

River type: passive single thread.

Restoration action: riffle and gravel bar feature creation alongside embankment removal and floodplain lowering.

Impacts: The increase in overall wetted area under low and winter flows shown by the modelling undertaken demonstrates the increased resilience to low flows created as a result of the restoration scheme. There is also an overall improvement in biotope diversity under summer flows when compared to baseline conditions, with more characteristic riffle biotopes created by the introduced features, as well as an increase in overall wetted area. Floodplain habitat creation and likely development is also predicted to be diverse due to the change in hydrological patterns. A variety of fen mire, wet grassland and swamp type habitat is likely to develop over time in response to the improved connectivity to the floodplain and raising of groundwater level.

Hartsop Hall (h)

River type: active single thread/wandering.

Restoration action: flood embankment setting back, multi-channel creation, floodplain reconnection, riffle-rapids and channel widening.

Impacts: a significant increase in overall wetted area under low flows (Q95 and Q10) shown by the modelling undertaken demonstrates the increased resilience to low flows created as a result of the restoration scheme and associated restoration measures. This is mainly a result of the channel widening undertaken and the improved floodplain connectivity created at the downstream end of the reach. There is also an overall improvement in biotope diversity under summer and winter flows when compared to baseline conditions.

Geltsdale (i)

River type: active single thread.

Restoration action: floodplain reconnection through chute channel creation and blocking, channel realignment and bifurcation.

Impacts: an increase in overall wetted area under low flows is shown by the modelling undertaken for Q95 summer flows, with a greater increase seen under Q10 winter flows, compared to baseline as a result of the restoration scheme and associated restoration measures. There is also an overall improvement in biotope diversity under summer and winter flows when compared to baseline conditions, mainly as a result of the new channels and significantly improved floodplain connectivity to wetland features.

Goldrill Beck (j)

River type: active single thread/wandering.

Restoration action: new channel creation, channel bifurcation, floodplain reconnection, anastomosed channels and riffle-rapid creation.

Impacts: a significant increase in overall wetted area under low flows shown by the modelling undertaken demonstrates the increased resilience to low flows created as a result of the restoration scheme and associated restoration measures. There is also an overall improvement in biotope diversity under summer and winter flows when compared to baseline conditions. Floodplain habitat creation and likely development is also predicted to be diverse as a result of the new hydrological regime created.

3. Guide to selecting restoration measures

This section presents a matrix (Table 3) to help target restoration measures to river types where they are most likely to lead to increased ecological resilience to extreme flows. The matrix is a version of the guide developed within Environment Agency (2016) updated with the literature review presented in section 2 and the 10 case studies. The matrix is intended to be an easily digestible and usable summary of the available evidence, allowing practitioners to identify suitable measures, whilst signposting to further information and evidence.

3.1. Amendments to matrix

Two amendments have been to the guide produced in 2016, with the inclusion of an additional river type and additional success factor.

3.1.1. High flow refuge

The 2014 study had a focus on low flow habitat in particular. Climate change will increase the severity of both low and high flow events (Kay, 2021). With increased frequency and magnitude of higher flows, the importance of refuge for aquatic organisms in our river systems is increasingly important. Many of the restoration measures assessed in the 2014 study (e.g. improving floodplain connectivity) and some of the new measures identified for this study (e.g Stage Zero, Backwater creation) are intended, in part to provide refuge at higher flows. Including this additional success factor in the matrix, will help practitioners better understand the potential impact of their scheme on high flow refuge.

3.1.2. Additional river type

The 2014 study identified several typical UK river types. This latest study has identified urban / artificial rivers as an additional river type. Urban rivers can be defined as significantly modified resulting in a deviation away from their expected classification outside of the urban environment. Common modifications to urban rivers include culverting, bed and bank protection, straightening and widening. The combination of several modifications often removes common morphological features (such as active erosion zones or depositional areas) because the rivers form and function is heavily influenced by modification (past and present).

3.2. Limitations

The following limitations should be noted when using the matrix.

- As highlighted in Section 2, although best efforts were made to identify and review the most appropriate papers, it did not constitute a full systematic review of river restoration literature.
- The evidence base from published literature used to update the matrix is often lacking detail to understand the particular river type being described and analysed. Those papers included in the matrix provide site specific results with clarity on river type and restoration measures.
- Grey literature often provides a better understanding of river type and restoration measures utilised. This could be work undertaken by Rivers Trusts or Consultants. It was not possible to review this evidence to include in the matrix as part of this project.

3.3. Matrix

The matrix provides a 'traffic light' system for determining the level to which each morphological measure is likely to improve geomorphological and ecological resilience. Measures identified as 'green' are likely to be the most appropriate to the river type and to have the greatest positive impact on improving resilience. 'Yellow' implies a moderate impact and 'red' those considered to have a low impact – though they may, in some circumstances, still be appropriate for the river type. The matrix also highlights those measures that are not appropriate for the particular river type as they are considered not to work with the natural geomorphic processes associated with that particular river type and are unlikely to be sustainable (grey shading).

As in the 2014 study, the colour coding is based on expert opinion – JBA and Dynamic Rivers staff, the project board, case studies and the literature review. The matrix combines both the 2014 study, and the literature review and case studies undertaken for the current project.

In addition to the colour coding, the matrix also indicates the level of confidence in the evidence:

- 'H' indicates 2 or more case studies with measured benefits
- 'M' indicates that the literature reviewed shows some measured benefit
- 'L' indicates that the published/grey literature reviewed shows the measure may provide some benefits but lacks conclusive monitoring data or evidence is contradictory

The numbers beneath the letters 'H', 'M' and 'L' in the matrix indicate the source from the literature review on which the indicated assessment is based. For clarity the sources from the 2104 study and the sources from the current study are presented in separate tables (Table 4 presents the 2014 study and Table 5 presents the evidence from the current study).

Table 4. Evidence from 2014 study

Ref. no	Source	Ref. no	Source
1	Abbe and Montgomery 1996	**26**	JBA 2012-14b*
2	Archer and Newson 2002	**27**	JBA 2014a*
3	Besacier-Monbertrand et al. 2012	**28**	JBA 2014b*
4	Buchanan et al. 2012	**29**	JBA 2014c*
5	Buijse et al. 2002	**30**	Kennedy et al. 2014
6	Clilverd et al. 2013	**31**	Kondolf 2006
7	Davidson and Eaton 2013	**32**	Kristensen et al. 2011
8	Downs and Thorne 2000	**33**	Kristensen et al. 2013
9	Downward and Skinner 2005	**34**	Kristensen et al. 2014
10	Endreny and Soulman 2011	**35**	Large and Petts 1996
11	Environment Agency 2005*	**36**	Luderitz et al. 2011
12	Feld et al. 2011	**37**	Müller et al. 2014
13	Florsheim and Mount 2002	**38**	Newson 2002
14	Gumiero et al. 2013	**39**	Pander et al. 2015
15	Hammersmark et al. 2008	**40**	Pedersen et al. 2007
16	Harper et al. 1998	**41**	Pedersen et al. 2009
17	Holden 2009	**42**	Pulg et al. 2013
18	Jeffries et al. 2003	**43**	RRC 1999
19	JBA 2011*	**44**	Ribble Rivers Trust 2012
20	JBA 2012a*	**45**	Rohde et al. 2005
21	JBA 2012b*	**46**	Schirmer et al. 2014
22	JBA 2012c*	**47**	Schwartz et al. 2014
23	JBA 2012d*	**48**	Sear and Newson 2004
24	JBA 2012-13*	**49**	Sear et al. 2010
25	JBA 2012-14a*	**50**	Van Zyll De Jong et al. 1997

Notes: See References for details of these sources.
* Unpublished

Table 5. Evidence from current study

Ref. no	Source	Ref. no	Source
51	Case study – Grisedale (a)	62	Al-Zankana et al. 2021
52	Case Study – Scarrow (b)	63	Puttock et al 2017
53	Case study – Long Preston (c)	64	Birnie-Gauvin et al. 2018
54	Case Study – Aller at Selworthy (d)	65	Favata et al. 2018
55	Case Study – Fowlea Brook (e)	66	Harvey et al. 2017
56	Case Study – Dunston Beck (f)	67	Janssen et al. 2019
57	Case Study – Manthorpe (g)	68	Oliveira et al. 2019
58	Case Study – Hartsop Hall (h)	69	Parker et al 2017
59	Case Study – Geltsdale (i)	70	Powers et al. 2018
60	Case Study – Goldrill (g)	71	Seer et al 2018
61	Addy and Wilkinson 2019	72	Thompson et al. 2017

The matrix summarising the evidence is presented in this section. An excel spreadsheet version is available on request via research@environment-agency.gov.uk.

Key:

	High possibility of either enhancing riparian habitat, leading to a more heterogeneous channel bed morphology or creating a range of refugia for freshwater organisms
	Moderate possibility of either enhancing riparian habitat, leading to a more heterogeneous channel bed morphology or creating a range of refugia for freshwater organisms
	Low possibility of either enhancing riparian habitat, leading to a more heterogeneous channel bed morphology or creating a range of refugia for freshwater organisms
	Inappropriate restoration measure for the river type

	RESTORATION MEASURE							
RIVER TYPE	**Grip blocking**	**Planting native trees**	**Fine sediment measures**	**Floodplain connectivity**	**Assisted natural recovery**	**Moving whole planform**	**Re-me&ering, palaeo channel / oxbow reconnection**	**Bank reprofiling**
Bedrock	Likely to be found in upl& areas; fish species of interest – salmonids, probably brown trout							
Low flow hydromorphic impact		**L** 2			**L** 38			
Low flow ecology impact		**L** 2			**L** 38			
Bankfull flow hydromorphic impact		**L** 2			**L** 38			
High flow ecological impact								
Step-pool	Likely to be found in upl& areas; fish species of interest – salmonids, probably brown trout & bullheads.							
Low flow hydromorphic impact		**L** 2			**L** 38			
Low flow ecology impact		**L** 2			**L** 38			
Bankfull flow hydromorphic impact		**L** 2			**L** 38			
High flow ecological impact								
Plane-bed	Likely to contain salmonids (including brown trout, & possibly salmon), also coarse fish such as grayling, chub & dace							
Low flow hydromorphic impact					**L** 38			
Low flow ecology impact					**L** 38			
Bankfull flow hydromorphic impact					**L** 38			
High flow ecological impact								
Wandering								
Low flow hydromorphic impact				**L** 14, 20,51	**M** 27, 38		**L** 36	**L** 29
Low flow ecology impact				**L** 14, 20,51	**L** 27, 38		**L** 36	**L** 20
Bankfull flow hydromorphic impact				**H** 14, 15, 20, 27,51	**M** 27, 38		**L** 36	**L** 20
High flow ecological impact				**L** 51				
Active single thread	Likely to contain a wide range of salmonid & coarse fish – including grayling, barbel & roach, & in lowl& reaches, bream & carp							
Low flow hydromorphic impact	**L** 17, 44	**M** 25, 49	**L** 12	**L** 14, 35,51	**L** 38	**L** 43	**M** 24, 32, 36,53,61	**L** 8
Low flow ecology impact	**L** 17, 44	**M** 25, 50	**L** 12	**L** 14, 35,51	**L** 38	**L** 43	**M** 24, 32, 36,53,61	**L** 8
Bankfull flow hydromorphic impact	**L** 17, 44	**M** 25, 49	**L** 12	**H** 5, 14, 35,51,53	**L** 38	**L** 43	**M** 24, 32, 36,61	**L** 8
High flow ecological impact				**L** 51,				
Passive single thread	Likely to contain a wide range of salmonid & coarse fish – including grayling, barbel & roach, & in very lowl& reaches, bream & carp							
Low flow hydromorphic impact			**L** 12	**M** 14,52,56,57,58,59,60	**L** 38	**L** 34, 40, 56	**L** 28, 32	**L** 67
Low flow ecology impact			**L** 12	**M** 14,52,56, 57,58,59,60	**L** 38	**L** 40, 56	**L** 28, 32	
Bankfull flow hydromorphic impact			**L** 12	**M** 14, 52,56,57,58,59,60	**L** 38	**L** 34, 40, 56	**L** 28, 32, 71	
High flow ecological impact				**M** 52,56,57,58,59,60		**L** 56	**L** 71	
Lowland anastomosed	Likely to contain a wide range of salmonid & coarse fish – including grayling, barbel & roach, & in very lowl& reaches, bream & carp							
Low flow hydromorphic impact		**M** 25, 49		**L** 13, 14	**L** 38		**L** 31, 39	
Low flow ecology impact		**M** 25, 50		**L** 13, 14	**L** 38		**L** 31, 39	
Bankfull flow hydromorphic impact		**M** 25, 49		**H** 3, 5, 13, 14	**L** 38		**L** 31, 39	
High flow ecological impact								
Urban/artificial	Various, depending on location & river type							
Low flow hydromorphic impact							**L** 55	
Low flow ecology impact								
Bankfull flow hydromorphic impact							**L** 55	
High flow ecological impact								

	RESTORATION MEASURE							
RIVER TYPE	**Channel widening**	**Channel narrowing**	**Gravel addition / bed reprofiling**	**Deculverting**	**Barrier removal**	**Barrier management**	**Berm creation**	**Large Wood Material and flow deflectors**
Bedrock	Likely to be found in upl& areas; fish species of interest – salmonids, probably brown trout							
Low flow hydromorphic impact					**L** 9			
Low flow ecology impact					**L** 9			
Bankfull flow hydromorphic impact					**L** 9			
High flow ecological impact								
Step-pool								
Low flow hydromorphic impact					**L** 9			**L** 10
Low flow ecology impact					**L** 9			**L** 10
Bankfull flow hydromorphic impact					**L** 9			**L** 10
High flow ecological impact								
Plane-bed	Likely to contain salmonids (including brown trout, & possibly salmon), also coarse fish such as grayling, chub & dace							
Low flow hydromorphic impact					**L** 9			
Low flow ecology impact					**L** 9			
Bankfull flow hydromorphic impact					**L** 9			
High flow ecological impact								
Wandering								
Low flow hydromorphic impact	**L** 45		**L** 15,51		**L** 9			L **4**
Low flow ecology impact	**L** 45		**L** 15,51		**L** 9			
Bankfull flow hydromorphic impact	**L** 45		**L** 15,51		**L** 9			**L** 4
High flow ecological impact			**L** 51					
Active single thread	Likely to contain a wide range of salmonid & coarse fish – including grayling, barbel & roach, & in lowl& reaches, bream & carp							
Low flow hydromorphic impact	**M** 19, 45		**L** 12, 32, 37, 41, 48,51		**L** 9	**L** 12		**M** 1, 16, 26, 49, 50
Low flow ecology impact	**L** 19, 45		**L** 12, 32, 37, 41, 48,51		**L** 9	**L** 12		**L** 1, 49, 50
Bankfull flow hydromorphic impact	**M** 19, 45		**L** 12, 32, 37, 41, 48,51		**L** 9	**L** 12		**H** 1, 8, 16, 26, 49, 50
High flow ecological impact			**L** 51					
Passive single thread	Likely to contain a wide range of salmonid & coarse fish – including grayling, barbel & roach, & in very lowl& reaches, bream & carp							
Low flow hydromorphic impact	**L** 58	**L** 22	**H** 12, 16, 32, 37, 41, 42,		**M** 9, 21, 22	**L** 12	**L** 21	**M** 23, 26, 30,62, 66,69
Low flow ecology impact	**L** 58	**L** 22	**H** 12, 16, 32, 37, 41, 42,		**M** 9, 21, 22,64	**L** 12	**L** 21	**M** 30, 62,66,68, 72
Bankfull flow hydromorphic impact	**L** 58	**L** 22	**H** 12, 16, 32, 37, 41, 42,		**M** 9, 21, 22	**L** 12	**L** 21	**M** 23, 26, 30,62
High flow ecological impact	**L** 58							
Lowland anastomosed	Likely to contain a wide range of salmonid & coarse fish – including grayling, barbel & roach, & in very lowl& reaches, bream & carp							
Low flow hydromorphic impact	**L** 9, 45		**L** 41		**L** 9			**M** 16, 26, 49
Low flow ecology impact	**L** 9, 45		**L** 41		**L** 9			**L** 49
Bankfull flow hydromorphic impact	**L** 9, 45		**L** 41		**L** 9			**M** 16, 26, 49
High flow ecological impact								
Urban/artificial	Various, depending on location & river type							
Low flow hydromorphic impact		**L** 55	**L** 55					
Low flow ecology impact								
Bankfull flow hydromorphic impact		**L** 55	**L** 55					
High flow ecological impact								

	RESTORATION MEASURE							
RIVER TYPE	Boulder clusters	Reinstatement of rapids	Bankside and riparian planting	Beaver Reintroduction	Stage zero	Backwater creation	Multi thread channel creation	Bed ploughing (unlocking an armoured bed)
Bedrock	Likely to be found in upl& areas; fish species of interest – salmonids, probably brown trout							
Low flow hydromorphic impact								
Low flow ecology impact								
Bankfull flow hydromorphic impact								
High flow ecological impact								
Step-pool								
Low flow hydromorphic impact								
Low flow ecology impact								
Bankfull flow hydromorphic impact								
High flow ecological impact								
Plane-bed	Likely to contain salmonids (including brown trout, & possibly salmon), also coarse fish such as grayling, chub & dace							
Low flow hydromorphic impact								
Low flow ecology impact								
Bankfull flow hydromorphic impact								
High flow ecological impact								
Wandering								
Low flow hydromorphic impact								
Low flow ecology impact								
Bankfull flow hydromorphic impact								
High flow ecological impact								
Active single thread	Likely to contain a wide range of salmonid & coarse fish – including grayling, barbel & roach, & in lowl& reaches, bream & carp							
Low flow hydromorphic impact	**L** 37, 50			**M** 63	**M** 54		**M** 53, 59, 60	
Low flow ecology impact	**L** 37, 50				**M** 54		**M** 53,59,60	
Bankfull flow hydromorphic impact	**L** 37, 50			**M** 63	**M** 54		**M** 59,60	
High flow ecological impact					**M** 54		**M** 59,60	
Passive single thread	Likely to contain a wide range of salmonid & coarse fish – including grayling, barbel & roach, & in very lowl& reaches, bream & carp							
Low flow hydromorphic impact	**L** 37						**M** 52,56,58	**L** 67
Low flow ecology impact	**L** 37		**L** 65				**M** 52,56,58	
Bankfull flow hydromorphic impact	**L** 37						**M** 52,56,58	
High flow ecological impact							**M** 52,56,58	
Lowland anastomosed	Likely to contain a wide range of salmonid & coarse fish – including grayling, barbel & roach, & in very lowl& reaches, bream & carp							
Low flow hydromorphic impact					**M** 70			
Low flow ecology impact								
Bankfull flow hydromorphic impact								
High flow ecological impact								
Urban/artificial	Various, depending on location & river type							
Low flow hydromorphic impact								
Low flow ecology impact								
Bankfull flow hydromorphic impact								
High flow ecological impact								

4. Conclusions

4.1. Driver

The hydrological conditions within England's rivers are likely to become more extreme in future years both in terms of the scale and duration of droughts and the frequency and magnitude of higher flows. Therefore, any scheme which is aiming to restore or improve a river, should look to maximise the geomorphological and ecological resilience which the scheme would bring.

4.2. Guide

This project further built upon a matrix (initially developed in 2014) which provides a summary of which river and floodplain restoration measures provide benefits in different river types. The colour coding system developed for the 2014 study could be used 'at a glance' by practitioners to provide initial guidance on the suitability of potential measures at their site. The matrix is also underpinned by a wide ranging (although not systematic and exhaustive) literature review and case studies from both the initial 2014 study and the current study. The underpinning research and information is clearly communicated in the matrix and associated references, allowing readers to delve more deeply into the evidence base for a given measure.

4.3. Literature review

The literature review looked at papers from around the world for a range of river types. The aim of the review was to identify site specific sites, with clearly defined river types and restoration measures which could be transposed into the matrix. In many cases, despite the scheme providing valuable information around the improvements offered by a given measure, that evidence could not be transferred to the matrix. The papers displayed significant weakness with regard to adequately assessing the geomorphological setting of schemes or their overall functionality. This restricted the amount of detail which could be added to the matrix.

The most common restoration measures reported in the scientific literature were localised semi-engineering approaches such as deflectors, with the river types dominated by passive single thread systems (although in several cases the river type was not clearly defined in the literature). There was a general lack of higher energy systems with a coarser substrate and this gap was filled with a number of case studies looking at energetic upland systems.

The influence of flow on morphologic and ecologic function and the role of morphology in influencing hydrology and ecology has been mentioned in several papers as has the appropriate integration of a wider understanding of catchment processes. This chimes with the move away in recent years from single-feature or single species restoration approaches towards a process-based restoration / naturalisation approach, but data and evidence remain scarce and variable in quality. This gap has been addressed in this project by selecting case studies which are based on a process-based restoration and include the implementation of a range of restoration measures.

The literature review identified that a further river type – urban/artificial should be added to the matrix, as this results in a deviation away from their expected classification outside of the urban environment. Given the likely increases in flows for high flows under climate change it is also of importance to maximise the resilience of aquatic organisms under high flows as well (the previous 2014 study focussed on the resilience of aquatic organisms at low flows only).

4.4. Case Studies

The case studies were selected to fill in some of the gaps identified in the literature review by including sites in very high energy environments and a chalk stream (Whitham at Manthorpe). The selection of the case studies also favoured those which were designed as a process-based restoration rather than single measure/species schemes.

At each of the sites, the restoration measures were modelled pre and post-change using a fixed bed 2D hydraulic model. To maximise confidence in the modelling, a variety of data sources was used to create the pre and post change DTM, included using Environment Agency LIDAR, detailed pre-change survey, post-change drone survey and detailed design modelling depending on availability. The best available data was used at each of the sites.

The model results show that all of the schemes led to some improvement in the resilience of the ecological and geomorphological system at both low and high flows. The most striking results were from schemes which led to the large-scale reconnection of the floodplain, for example at Goldrill and Selworthy. This led to large increases in wetted area, a reduction in energy in the system and a prevalence of lower energy biotopes such as pool and glide.

Smaller (but nevertheless important) improvements to resilience were identified at more constrained sites (such as Fowlea and Long Preston). Each are constrained in a different way, Long Preston by existing land use, and Fowlea by urban pressures. The schemes were able to demonstrate improvements in the geomorphological and ecological resilience at both high and low flows.

There are a number of limitations to the modelling undertaken, not least in that the post- change modelling is a snapshot of the conditions on the day of the survey (or the final design). The modelling approach chosen does not have a mobile bed, and so the post-change results are a snapshot of that moment. For the schemes with the greatest predicted improvement, it would be valuable to repeat the drone surveys before the next update of this matrix, to better understand the evolution of these measures over the short to medium term.

Modelling the potential effects of restoration activities is a valuable tool to anticipate scales of likely change. Post restoration monitoring should also be considered as this will allow system response to be understood, helping inform future scheme design. This is particularly important when using naturalisation techniques such as stage zero where change is anticipated but remains difficult to predict due to a lack of data rich example schemes.

4.5. Further development

The matrix initially developed in 2014 has been updated with the evidence collected from both the literature review and case studies. The matrix provides a functional first look up for practitioners wanting to understand the potential effectiveness of measures on their river. It also encourages practitioners to think about the river and catchment on a process basis rather than thinking about a single measure or species. The matrix is underpinned by the case studies and literature review which are clearly signposted.

Further depth could be brought to the matrix by integrating other sources of river restoration case studies such as the EU RESTORE project River Wiki (www.restorerivers.eu/wiki/index.php?title=Main_Page). In this Wiki, the depth of the information provided is often not as detailed as that in scientific literature, but it provides a likely source of information to bolster the evidence in the matrix, with the potential to reduce the bias away from passive single thread systems.

Better use in the future could be made of grey literature from Consultants and Rivers Trusts, as numerous schemes have been constructed across the country without the results being disseminated in academic literature. Whilst there is often a paucity of monitoring on many of these schemes, valuable evidence and modelled assessments could be included in the matrix (along with suitable caveats). Again, this could be very useful to help build evidence in the less studied river types and restoration measures.

Many restoration schemes are not robustly monitored or appraised following construction. The literature review noted that there was often a delay or a disconnect between the construction of the scheme and ecological improvements being observed, and that there was sometimes not a correlation between geomorphological complexity and ecological response due to many confounding factors. Detailed appraisal of 'flag ship' schemes in particular would help to build the evidence base further and improve confidence in the effectiveness and appropriateness of different restoration measures.

4.6. Concluding comments

The review of evidence of the effectiveness of river restoration measures in improving geomorphological and ecological resilience highlighted the need to understand the catchment context of the restoration location and to work with natural processes to promote success.

Larger scale benefits may be achieved by taking a wider system view of restoration rather than more localised engineering interventions such as making space for channel migration and flood water storage. Auditing the amount and condition of habitat in catchments could inform whether approaches such as riparian fencing or flood plain reconnection might allow more natural recovery over a larger area. Whereas, restoration schemes are often limited to short channel reaches. Following such an eco-morphological catchment-based approach for future restoration planning and monitoring could help increase catchment resilience in a changing climate.

References

ABBE, T.B. AND MONTGOMERY, D.R., 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regulated Rivers: Research and Management, 12 (2-3), 201-221.

ADDY, S. AND WILKINSON, M.E., 2019. Geomorphic and retention responses following the restoration of a sand-gravel bed stream. Ecological Engineering, 130, 131-146.

AL-ZANKANA, A., MATHESON, T. AND HARPER, D., 2021. Adding large woody material into a headwater stream has immediate benefits for macroinvertebrate community structure and function. Aquatic Conservation: Marine and Freshwater Ecosystems, 31 (4), 930-947.

ARCHER, D. AND NEWSON, M., 2002. The use of indices of flow variability in assessing the hydrological and instream habitat impacts of upland afforestation and drainage. Journal of Hydrology, 268 (1-4), 244-258.

ARMSTRONG, J.D., KEMP, P.S., KENNEDY, G.J.A., LADLE, M. AND MILNER, A.J. 2003. Habitat requirements of Atlantic salmon and brown trout in rivers and streams. Fisheries Research, 62 (2), 143-170.

ATKINSON, C.L., JULIAN, J.P. AND VAUGHN, C.C., 2014 Species and function lost: Role of drought in structuring stream communities. Biological Conservation, 176, 30-38

BESACIER-MONBERTRAND, A.-L., PAILLEX, A., AND CASTELLA, 2012. Short-term impacts of lateral hydrological connectivity restoration on aquatic macroinvertebrates. River Restoration and Applications, 30 (5), 557-570.

BIRNIE-GAUVIN, K., CANDEE, M.M., BAKTOFT, H., LARSEN, M.H, KOED, A. AND AARESTRUP, K., 2018. River connectivity reestablished: Effects and implications of six weir removals on brown trout smolt migration. River Research and Applications, 34 (6), 548-554.

BUCHANAN, B.P., WALTER, M.T., NAGLE, G.N. AND SCHNEIDER, R.L., 2012. Monitoring and assessment of a river restoration project in central New York. River Research and Applications, 28 (2), 216-233.

BUIJSE, A.D., COOPS, H., STARAS, M., JANS, L.H., VAN GEEST, G.J., GRIFT, R.E., IBELINGS, B.W., OOSTERBERG, W. AND ROOZEN, F.C.J.M., 2002. Restoration strategies for river floodplains along large lowland rivers in Europe. Freshwater Biology, 47 (4), 889-907.

CLILVERD, H.M., THOMPSON, J.R., HEPPELL, C.M., SAYER, C.D. AND AXMACHER, J.C., 2013. River-floodplain hydrology of an embanked lowland

Chalk river and initial response to embankment removal. Hydrological Sciences Journal*,* 58 (3), 627-650.

CLOUGH, S.C, AND TURNPENNY, A.W.H., 2001. *Swimming speeds in fish: Phase 1.* R&D Technical Report W2-0.26/TR1. Bristol: Environment Agency.

CLUER, B. AND THORNE, C.R., 2014. A stream evolution model integrating habitat and ecosystem benefits. River Research and Applications, 30(2), 135 – 154.

DAVIDSON, S.L. AND EATON, B.C., 2013. Modelling channel morphodynamic response to variations in large wood: implications for stream rehabilitation in degraded watersheds. Geomorphology, 202, 59–73.

DEATH, R.G.. 2008. Aquatic Insects: challenges to populations. Ch 6: The effects of floods on aquatic invertebrate communities. Wallingford UK: CABI. 103-121.

DE CRISPIN DE BILLY, V. AND USSEGLIO-POLATERA, P., 2002. Traits of brown trout prey in relation to habitat characteristics and benthic invertebrate communities. Journal of Fish Biology, 60 (3), 687-714.

DOWNS, P.W. AND THORNE, C.R., 2000. Rehabilitation of a lowland river: reconciling flood defence with habitat diversity and geomorphological sustainability. Journal of Environmental Management, 58 (4), 249-268.

DOWNWARD, S. AND SKINNER, K., 2005. Working rivers: the geomorphological legacy of English freshwater mills. Area, 37 (2), 138-147.

DUNBAR, M.J., PEDERSEN, M.L., CADMAN, D., EXTENCE, C., WADDINGHAM, J., CHADD, R. AND LARSEN, S.E., 2010. River discharge and local-scale physical habitat influence macroinvertebrate LIFE scores. Freshwater Biology, 55 (1), 226-242.

DURISCH-KAISER, E., 2014. Morphological, hydrological, biogeochemical and ecological changes and challenges in river restoration – the Thur River case study. *H*ydrology and Earth System Sciences, 18, 2449-2462.

ENDRENY, T.A. AND SOULMAN, M.M., 2011. Hydraulic analysis of river training cross-vanes as part of post-restoration monitoring. Hydrology and Earth System Sciences, 15 (7), 2119–2126.

ENVIRONMENT AGENCY, 2005. Gravel reworking to restore a low flow channel. River Darent, Hawley Manor, Kent. Unpublished report.

ENVIRONMENT AGENCY, 2008. Overview of river restoration science and practice: managing hydromorphological pressures in rivers: Stage 1 science and practice. Unpublished report.

ENVIRONMENT AGENCY, 2013a. Managing water resource pressures. Implementing hydro-morphological measures. Position statement on implementing hydromorphological rehabilitation measures where water resource pressures are identified as a reason for failure. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2013b. Weir removal, lowering and modification: a review of best practice. Report SC070024. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2013c. Migration and seasonal habitat requirements of UK freshwater fish species. Unpublished internal report.

ENVIRONMENT AGENCY, 2014. Restoration measures to improve river habitats during low flows. Report SC120050/R. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2017. Physical modifications: challenges for the water environment.

FELD, C.K., BIRK, S., BRADLEY, D.C., HERING, D., KAIL, J., MARZIN, A., MELCHER, A., NEMITZ, D., PEDERSEN, M.L., PLETTERBAUER, F., PONT, D., VERDONSCHOT, P.F.M. AND FRIBERG, N., 2011. Chapter Three – From natural to degraded rivers and back again: a test of restoration ecology theory and practice. In Advances in Ecological Research, Volume 44 (ed. G. Woodward), pp. 119-209. Waltham, MA: Academic Press.

FAVATA, C.A., MAIA, A., PANT, M., NEPAL, V. AND COLOMBO, R.E., 2018. Fish assemblage change following the structural restoration of a degraded stream. River Research and Applications, 34 (8), 927-936.

FLORSHEIM, J.L. AND MOUNT, J.F. 2002. Restoration of floodplain topography by sand-splay complex formation in response to intentional levee breaches, Lower Cosumnes River, California. Geomorphology, 44 (1), 67-94.

GILVEAR, D.J., SPRAY, C.J. AND CASAS-MULET, R., 2013. River rehabilitation for the delivery of multiple services at the river network scale. Journal of Environmental Management, 126, 30-43.

GORDON, N.D., MCMAHON, T.A. AND FINLAYSON, B.L., 1994. Stream Hydrology: An Introduction for Ecologists. Chichester: Wiley.

GUMIERO, B., MANT, J. HEIN, T., ELSO, J. AND BOZ, B., 2013. Linking the restoration of rivers and riparian zones/wetlands in Europe: Sharing knowledge through case studies. Ecological Engineering, 56, 36-50.

HAMMERSMARK, C.T., RAINS, M.C. AND MOUNT, J.F., 2008. Quantifying the hydrological effects of stream restoration in a montane meadow, northern California, USA. River Research and Applications, 24 (6), 735-753.

HARPER, D., EBRAHIMNEZHAD, E. AND COT, F.C.I., 1998. Artificial riffles in river rehabilitation: setting the goals and measuring the successes. Aquatic Conservation: Marine and Freshwater Ecosystems, 8 (1), 5-16.

HARVEY, G.L. AND CLIFFORD, N.J., 2008. Distribution of biologically functional habitats within a lowland river. Aquatic Ecosystem Health and Management, 11 (4), 465-473.

HARVEY, G.L., CLIFFORD, N.J. AND GURNELL, A.M., 2008. Towards an ecologically meaningful classification of the flow biotope for river inventory, rehabilitation, design and appraisal purposes. Journal of Environmental Management, 88 (4), 638-650.

HARVEY, G.L., HENSHAW, A.J., PARKER, C. AND SAYER, C.D. 2017., Re-introduction of structurally complex wood jams promotes channel and habitat recovery from overwidening: Implications for river conservation. Aquatic Conservation: Marine and Freshwater Ecosystems, 28 (2), 395-407.

HEGGENES, J, 1989. Physical habitat selection by brown trout (Salmo trutta) in riverine systems. Nordic Journal of Freshwater Research, 64, 64-90.

HERITAGE, G.L., MILAN, D.J., AND ENTWISTLE, N., 2009. An investigation of the role of geomorphology in influencing biotope distribution. In Ecohydrology of Surface and Groundwater Dependent Systems: Concepts, Methods and Recent Developments (ed. M. Thoms, K. Heal, E. Bogh, A. Chambel and V. Smakthin), Proceedings of JS.1 at the Joint IAHS and IAH Convention, Hyderabad, India, September 2009, IAHS Publication 328, pp. 68-76. Wallingford: IAHS Press.

HOLDEN, J., 2009. A grip-blocking overview [online]. Upland Hydrology Group paper, School of Geography, University of Leeds.

JANSSEN, P., PIEGAY, H., PONT, B. AND EVETTE, A. 2019. How maintenance and restoration measures mediate the response of riparian plant functional composition to environmental gradients on channel margins: Insights from a highly degraded large river. Science of The Total Environment, 656, 1312-1325.

JEFFRIES, R., DARBY, S.E., AND SEAR, D.A., 2003. The influence of vegetation and organic debris on flood-plain sediment dynamics: case study of a low-order stream in the New Forest, Hampshire. Geomorphology, 51 (1-3), 61-80.

JBA CONSULTING & DYNAMIC RIVERS, 2023a. Unpublished modelling undertaken for this project.

JBA CONSULTING & DYNAMIC RIVERS, 2023b. Unpublished modelling undertaken for this project.

JBA CONSULTING & DYNAMIC RIVERS, 2023c. Unpublished modelling undertaken for this project.

JBA CONSULTING & DYNAMIC RIVERS, 2023d. Unpublished modelling undertaken for this project.

JBA CONSULTING & DYNAMIC RIVERS, 2023e. Unpublished modelling undertaken for this project.

JBA CONSULTING & DYNAMIC RIVERS, 2023f. Unpublished modelling undertaken for this project.

JBA CONSULTING & DYNAMIC RIVERS, 2023g. Unpublished modelling undertaken for this project.

JBA CONSULTING & DYNAMIC RIVERS, 2023h. Unpublished modelling undertaken for this project.

JBA CONSULTING & DYNAMIC RIVERS, 2023i. Unpublished modelling undertaken for this project.

JBA CONSULTING & DYNAMIC RIVERS, 2023j. Unpublished modelling undertaken for this project.

JBA CONSULTING, 2011. Croxall Lakes channel widening assessment. Unpublished report.

JBA CONSULTING, 2012a. River restoration plan development for the River Ribble Long Preston Deeps SSSI. Unpublished report.

JBA CONSULTING, 2012b. Flood and restoration management plan for the Pent Stream. Unpublished report for the Environment Agency.

JBA CONSULTING, 2012c. Flood and restoration management plan for the Pent Stream. Unpublished report for the Environment Agency.

JBA CONSULTING, 2012d. River Nar hydromorphological assessment for proposed river restoration measures. Unpublished report.

JBA CONSULTING, 2012-13. River restoration design for reconnection of a palaeochannel on the River Ecclesbourne, Duffield. Unpublished.

JBA CONSULTING, 2012-14a. Unpublished audits of New Forest rivers and streams.

JBA CONSULTING, 2012-14b. Restoration plan development for 50+ SSSI sites within the New Forest.

JBA CONSULTING, 2014a. Unpublished audits of New Forest rivers and streams.

JBA CONSULTING, 2014b. Unpublished modelling undertaken for this project.

JBA CONSULTING, 2014c. Unpublished modelling undertaken for this project.

JONES, I., ABRAHAMS, C., BROWN, L., DALE, K., EDWARDS, F., JEFFRIES, M., KLAAR, M., LEDGER, M., MAY, L., MILNER, A. AND MURPHY, J., 2013. The impact of extreme events on freshwater ecosystems. London: The British Ecological Society.

KAY, A.L. 2021. Simulation of river flow in Britain under climate change: Baseline performance and future seasonal changes. Hydrological Processes. 35 pg 1- 10.

KEMP, J.L., HARPER, D.M. AND CROSA, G.A., 2000. The habitat-scale of ecohydraulics of rivers. Ecological Engineering, 16 (1), 17-29.

KENNEDY, R.J., JOHNSTON, P. AND ALLEN, M., 2014. Assessment of a catchment- wide salmon habitat rehabilitation scheme on a drained river system in Northern Ireland. Fisheries Management and Ecology, 21 (4), 275-287.

KONDOLF, G.M., 2006. River restoration and meanders. Ecology and Society, 11 (2), 42.

KRISTENSEN, E.A., BAATTRUP-PEDERSEN, A. AND THODSEN, H., 2011. An evaluation of restoration practises in lowland streams: Has physical integrity been re- created? Ecological Engineering, 37 (11), 1654-1660.

KRISTENSEN, P.B., KRISTENSEN, E.A., RIIS, T., BAISNER, A.J., LARSEN, S.E., VERDONSCHOT, P.F.M. AND BAATTRUP-PEDERSEN, A., 2013. Riparian forest as a management tool for moderating future thermal conditions of lowland temperate streams, Hydrology and Earth System Sciences Discussions, 10, 6081-6106.

KRISTENSEN, E.A., KRONVANG, B., WIBERG-LARSEN, P., THODSEN, H., NIELSEN, C., AMOR, E., FRIBERG, N. PEDERSEN, M.L. AND BAATTRUP-

PEDERSEN, A., 2014. 10 years after the largest river restoration project in Northern Europe: hydromorphological changes on multiple scales in River Skjern. Ecological Engineering, 66, 141-149.

LAKE, P.S., 2000., Disturbance, patchiness and diversity in streams. Journal of the North American Benthodological Society, 19(4), 573-592.

LANCASTER, J. AND HILDREW, A.G., 1993. Flow refuge and the microdistribution of lotic macroinvertebrates. Journal of the North American Benthological Society, 12 (4), 385-393.

LARGE, A.R. AND PETTS, G.E., 1996. Historical channel-floodplain dynamics along the River Trent. Applied Geography,16 (3), 191-209.

LUDERITZ, V., SPEIERL, T., LANGHEINRICH, U., VOLKL, W. AND GERSBERG, R.M., 2011. Restoration of the Upper Main and Rodach rivers – The success and its measurement. Ecological Engineering, 37 (12), 2044-2055.

MANN, R.H.K., 1995. Natural factors influencing recruitment success in coarse fish populations. In The Ecological Basis for River Management (ed. D.M. Harper and A.J.D. Ferguson), pp. 339-348. Chichester: John Wiley.

MÜLLER, M. PANDER, J. AND GEIST, J., 2014. The ecological value of stream restoration measures: an evaluation on ecosystem and target species scales. Ecological Engineering, 62, 29-139.

NEWSON, M.D., 2002. Geomorphological concepts and tools for sustainable river ecosystem management. Aquatic Conservation: Marine and Freshwater Ecosystems, 12 (4), 365-379.

PALMER, M.A., BERNHARDT, E.S., ALLAN, J.D., LAKE, P.S., ALEXANDER, G., BROOKS, S., CARR, J., CLAYTON, S., DAHM, C.N., SHAH, J.F., GALAT, D.L., LOSS, S.G., GOODWIN, P., HART, D.D., HASSETT, B., JENKINSON, R., KONDOLF, G.M., LAVE, R., MEYER, J.L., O'DONNELL, T.K., PAGANO, L. AND SUDDUTH, E., 2005. Standards for ecologically successful river restoration. Journal of Applied Ecology, 42 (2), 208-217.

OLIVEIRA, P.C.D.R., KRAAK, M.H.S., VERDONSCHOT, P.F.M. AND VERDONSCHOT, R.C.M., 2019. Lowland stream restoration by sand addition: Impact, recovery, and beneficial effects on benthic invertebrates. River Research and Applications, 35 (7), 1023-1033.

PANDER, J. MÜLLER, M. AND GEIST, J., 2015. Succession of fish diversity after reconnecting a large floodplain to the upper Danube River. Ecological Engineering, 75, 41-50.

PARKER, C., HENSHAW, A.J., HARVEY, G.L. AND SAYER, C.D., 2017. Reintroduced large wood modifies fine sediment transport and storage in a lowland river channel. Earth Surface Processes and Landforms, 42 (11), 1693-1703.

PEDERSEN, M.L., FRIBERG, N., SKRIVER, J., BAATTRUP-PEDERSEN, A. AND LARSEN, S.E., 2007. Restoration of Skjern River and its Valley – short-term effects on river habitats, macrophytes and macroinvertebrates. Ecological Engineering, 30 (1), 145-156.

PEDERSEN, M.L., KRISTENSEN, E.A., KRONVANG, B. AND THODSEN, H., 2009. Ecological effects of re-introduction of salmonid spawning gravel in lowland Danish streams. River Research and Applications, 25 (5), 626-638.

POWERS, P.D., HELSTAB, M. AND NIEZGODA, S.L., 2018. A process-based approach to restoring depositional river valleys to Stage 0, an anastomosing channel network. River Research and Applications, 35 (1), 3-13.

PULG, U., BARLAUP, B. T., STERNECKER, K., TREPL, L. AND UNFER, G. 2013, Restoration of spawning habitats of brown trout (Salmo trutta) in a regulated chalk stream. River Research and Applications, 29 (2), 172-182.

PUTTOCK, A., GRAHAM, H.A., CUNLIFFE, A.M., ELLIOTT, M AND BRAZIER, R.E., 2017. Eurasian beaver activity increases water storage, attenuates flow and mitigates diffuse pollution from intensively-managed grasslands. Science of the Total Environment, 576, 430-443.

RRC, 1999. River Cole, restored 1995/6. Cranfield, Bedfordshire: River Restoration Centre. Available from: http://www.therrc.co.uk/projects/cole_brochure.pdf

RIBBLE RIVERS TRUST, 2012. Cam and Gayle Beck restoration trial. Final report 2011/12. Clitheroe, Lancashire: Ribble Rivers Trust.

ROHDE, S., SCHÜTZ, M., KIENAST, F. AND ENGLMAIER, P., 2005. River widening: an approach to restoring riparian habitats and plant species. River Research and Applications, 21 (10), 1075-1094.

SCHIRMER, M., LUSTER, J., LINDE, N., PERONA, P., MITCHELL, E.A.D., BARRY, D.A., HOLLENDER, J., CIRPKA, O.A., SCHNEIDER, P., VOGT, T., RADNY, D. AND SCHWARTZ, J.S., NEFF, K.J., DWORAK, F.J. AND WOOCKMAN, R.R., 2014. Restoring riffle-pool structure in an incised, straightened urban stream channel using an ecohydraulic modelling approach. Ecological Engineering, 78, 112-126.

SEAR, D.A. AND NEWSON, M.D., 2004. The hydraulic impact and performance of a lowland rehabilitation scheme based on pool–riffle installation: the River Waveney, Scole, Suffolk, UK. River Research and Applications, 20 (7), 847-863.

SEAR, D.A., MILLINGTON, C.E., KITTS, D.R. AND JEFFRIES, R., 2010. Logjam controls on channel: floodplain interactions in wooded catchments and their role in the formation of multi-channel patterns. Geomorphology, 116 (3-4), 305-319.

SEER, F.K., BRUNKE, M. AND SCHRAUTZER, J., 2018. Mesoscale river restoration enhances the diversity of floodplain vegetation. River Research and Applications. 34 (8), 1012-1023.

THOMPSON, M.S.A., BROOKS, S.J., SAYER, C.D., WOODWARD, G., AXMACHER, J.C., PERKINS, D.M. AND GRAY, C., 2017. Large woody debris “rewilding” rapidly restores biodiversity in riverine food webs. Journal of Applied Ecology, 55 (2), 895-904.

VAN ZYLL DE JONG, M.C., COWX, I.G. AND SCRUTON, D.A., 1997. An evaluation of instream habitat restoration techniques on salmonid populations in a Newfoundland stream. Regulated Rivers: Research and Management, 13, 603-614.

VAUGHAN, I.P., DIAMOND, M., GURNELL, A.M., HALL, K.A., JENKINS, A., MILNER, N.J., NAYLOR, L.A., SEAR, D.A., WOODWARD, G. AND ORMEROD, S.J., 2009. Integrating ecology with hydromorphology: a priority for river science and management. Aquatic Conservation, Marine and Freshwater Ecosystems, 19 (1), 113-125.

VERDONSCHOT, P.F.M. AND FRIBERG, N., 2011. Chapter Three – From natural to degraded rivers and back again: a test of restoration ecology theory and practice. In Advances in Ecological Research, Volume 44 (ed. G. Woodward), 119-209. Waltham, MA: Academic Press.

WADESON, R.A., 1994. A geomorphological approach to the identification and classification of instream flow environments. Southern African Journal of Aquatic Science, 20 (1), 38-61.

WATTS, G., BATTARBEE, R.W., BLOOMFIELD, J.P., CROSSMAN, J., DACCACHE, A., DURANCE, I., ELLIOTT, J.A., GARNER, G., HANNAFORD, J., HANNAH, D.M. AND HESS, T., 2015. Climate change and water in the UK–past changes and future prospects. Progress in Physical Geography, 39(1), 6-28.

List of abbreviations

DEM	Digital Elevation Model
DTM	Digital Terrain Model
EA	Environment Agency
FEH	Flood Estimation Handbook
GEP	Good Ecological Potential
GES	Good Ecological Status
JBA	Jeremy Benn and Associates Limited
LIDAR	Light Detection and Ranging
LWD	Large Woody Debris
m	Metres
m^2	Square metre
m^3/s	Cubic metres per second
masl	Metres above sea level
Nm^{-2}	Newton per square metre
SSSI	Site of Special Scientific Interest
WFD	Water Framework Directive

Appendix River types

A 1 River typology

It is important to understand the river type before considering the type of restoration measure to apply as different river types have varying flow and sediment characteristics and some are more energetic than others. Having this understanding means that selected measures can be aligned to natural processes characteristic of each river type and are more likely to be effective.

When assessing a river type, it is important to understand whether the river is currently managed such that it appears to be a specific river type and whether under natural conditions (that is, unconstrained or restored) it would take another form. For example, a river may appear to be relatively passive due to protected banks or inline structures which, if removed, could introduce more active sediment transport processes and flows.

Most rivers change throughout their course exhibiting characteristics of the different river types at certain points. This change may be a smooth transition or a sudden change between types. Expert geomorphological assessment is recommended to identify river type, when considering restoration potential or the application of a specific measure. This geomorphological assessment can include a review of dominant in-channel processes, such as stream power within the catchment context, which can be used to understand likely trajectories of change and the likely success of any restoration measures or combination of measures. Poor identification of dominant river processes may lead to the selection of restoration measures that are unsuitable and ineffective, or could lead to further deterioration of the watercourse.

This study uses a modified version of the river classification developed by Montgomery and Buffington (1997) as a loose framework. Although this is a North American classification system, it was seen to correspond to the range of river types in the UK. It categorises rivers into the eight types presented here and was used to indicate where natural processes may not sustain the measure in some locations.

A2 Bedrock

A significant coverage of bedrock within the channel and the floodplain indicates a very robust and stable river type. They are most common in upland areas and contain very little stored sediment on the channel bed, aside from temporary stores of fine sediment deposited in pools that are flushed through during high flow events. The channel gradient is likely to be steep and they often exist in confined valleys (v-shaped valleys), giving energetic flow conditions able to transport large amounts of sediment. River Dee at Linn O' Dee (Figure A.1) River Calder upstream of Todmorden Example rivers:, River Teme at Felind.

Figure A.1 Example bedrock river type: River Dee at Linn O' Dee

A2 Step-pool

This river type is generally formed by boulder groups/cluster or bedrock layers forming steps separated by pools, providing stable/robust channel conditions. The pools may contain finer sediments (fines and gravels) due to the low energy conditions created by the backwater effects of the steps, but these may be transported downstream during elevated flow conditions. The channel gradient is likely to be steep and the river usually flows through a confined valley (v-shaped valley), giving energetic flow conditions able to transport large amounts of sediment. They are often found in upland areas, similar to bedrock rivers. Only larger material is generally stored on the channel bed, apart from small deposits of finer material in the pools. shows an example of a step- pool river type and lists other river examples. Example rivers: tributary of River Dee west of Braemar (Figure A.2), River Wharfe at Outershaw, Jumble Hole Clough adjacent to Jumble Hole Road at Hebden Bridge.

Figure A.2 Example step-pool river type: tributary of River Dee west of Braemar

A3 Plane bed

The channel bed of plane bed rivers is generally dominated by cobbles and gravels; significant depositional features are absent, with a monotonous riffle/run biotope dominating with few/no deeper pool areas. They generally have a moderate gradient and either have restricted connectivity to the floodplain or exist within confined or partly confined valleys. Sediment transport capacity is therefore relatively high in most cases and lateral activity is often restricted by stable banks, limiting the potential for depositional feature growth. There is generally little fine sediment infilling of the channel bed as a result of the moderately energetic flow conditions. The hydromorphological characteristics of plane bed rivers (high width to depth ratio, shallow flow depth, riffle flow type, few sediment features/stores, gravel/cobble bed) mean that, under natural conditions, the channel bed is likely to be relatively uniform.

This means that the restoration objective for a river/reach of this type should not be to increase heterogeneity, but to ensure restoration encourages development of the morphological features and processes described. Plane bed characteristics can also be artificially created as a result of past modification or straightening of a river (particularly in urban areas) and therefore it is important to understand historic change to the system before classifying a river that displays plane bed characteristics. Example rivers: River Calder between Todmorden and Hebden Bridge, (Figure A.3), River Blackwater at Perthshire, Walsden Water at Todmorden.

Figure A.3 Example plane bed river type: River Calder between Todmorden and Hebden Bridge.

A4 Wandering

Wandering river types are often found in moderate gradient systems where sediment loads are high with an extended/wide valley floor. They often display some braided and active single thread channel characteristics, but are highly responsive and dynamic rivers that can change significantly following one high flow event. Lateral movement can be significant where banks are weak and riparian vegetation is sparse, resulting in channel switching as it migrates across the valley floor over time. Depositional gravel features are often large (assisted by reasonable floodplain connectivity that allows deposition of sediment at higher flows) within this river type as a result of the high sediment loads and capacity for lateral movement. Many rivers of this type been heavily managed with walls and gravel removal, meaning that this river type is rarer than would be expected naturally. Example rivers: River Wharfe downstream of Buckden (Figure A.4), River Wooler at Wooler.

Figure A.4 Example wandering river type: River Wharfe downstream of Buckden

A5 Active single thread

Active single thread rivers are generally lowland river types with a relatively low gradient. Sediment loads are moderate and lateral movement can be moderate (depending on bank cohesivity and the condition of the riparian corridor). Depositional features are small to moderate in size (restricted by sediment loads and lower levels of lateral erosion compared to wandering river types), usually found in unconfined or partly confined valleys with floodplains present, and are generally composed of gravels and finer sediment. Energy levels are lower compared with wandering systems but are able to erode, transport and deposit during channel forming flows. Example river: River Medlock at Clayton Vale (Figure A.5).

Figure A.5 Example active single thread river type: River Medlock at Clayton Vale

A6 Passive single thread

Passive single thread rivers are generally found in lowland areas with a low gradient. Sediment loads (particularly gravels) are lower and bed material is generally dominated by finer sediment (for example, sands and silts). Depositional (gravel) features are uncommon or poorly developed if present. The banks of the channel are often cohesive restricting lateral movement. Therefore, any available energy is often focused on the channel bed, leading to incised, deep channels with a poor connection to the floodplain. Bank protection may be artificially creating passive conditions by restricting lateral movement potential. Example river: River Swift at Rugby (Figure A.6).

Figure A.6 Example passive single thread river type: River Swift at Rugby

A7 Lowland anastomosed

Lowland anastomosed rivers are found in lowland areas with low gradients. They develop a multi-thread channel network through stable islands, bars and berms and as a result of the formation and movement of LWD jams. Floodplain connectivity is good and different channels are activated at different flow levels, spreading flow energy over a wide area, creating stable channel conditions. Bed material is generally composed of fine sediment with some gravel exposed in locally energetic areas. Wet woodland often thrives in the riparian zone of this channel type due to the well-connected floodplain and the woodland often provides the lateral stability required for the functioning of this river type. Example river: River Trent at Croxall Lakes.

Figure A.7 Example lowland anastomosed river type: River Trent at Croxall Lakes (© Google Earth, GetMapping 2014)

A8 Urban rivers

Urban rivers are watercourses within an urban setting that exhibit modifications in channel structure, flow regime, water quality, and surrounding land use due to human activities and urbanisation processes. These alterations distinguish them from other river types and present unique challenges for management and conservation. Example rivers: River Crane, London, most rivers in urban areas.

Figure A.8 Example urban river type: River Crane, London

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