Review Article

How strong is the evidence – based on macroinvertebrate community responses - that river restoration works?

Ahmed Faraj Ali **Al-Zankana**[ab*], Tom **Matheson**[ab], David Malcolm **Harper**[acd]

[a] University of Leicester, Department of Biology, University Road, Leicester LE1 7RH, UK.

[b] University of Leicester, Department of Neuroscience, Psychology & Behaviour, University Road, Leicester LE1 7RH, UK.

[c] University of Leicester, School of Geography and Environment, University Road, Leicester LE1 7RH, UK.

[d] Freshwater Biological Association, Far Sawrey, Cumbria LA22 0LP, UK.

* Corresponding author at: University of Leicester, Department of Neuroscience, Psychology & Behaviour, University Road, Leicester LE1 7RH, UK.

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Abstract

We reviewed river rehabilitation studies published from 1984 to 2019 to identify factors that might limit effective rehabilitation. This encompasses 89 papers that reported outcomes of 379 independent projects. We found that methods used to evaluate the outcomes of rehabilitation projects may have failed to properly assess the outcomes, which has led to a poor diagnosis of both the "problem" and the effectiveness of any "solution". We identified four methodological limitations that have often precluded the rigorous assessment of the effectiveness of stream rehabilitation:

(1) The most comprehensive Before-After-Control-Impact (BACI) study design was not common practice.

(2) Most studies sampled rivers for only one season following rehabilitation, and therefore could not account for seasonal or annual variations that could affect macroinvertebrate community composition.

(3) Multi-habitat sampling – to comprehensively represent macroinvertebrate communities in study reaches – was rarely applied.

(4) The most commonly employed indicators of rehabilitation success were macroinvertebrate taxa richness and diversity, even though these measures may fail to identify other consequential changes in ecosystem structure and function. Ecosystem functional indicators such as macroinvertebrate Functional Feeding Group (FFG) and Ephemeroptera-Plecoptera-Trichoptera (EPT) richness, diversity, density, biomass and secondary production often had better responses, but were rarely assessed.

Future rehabilitation projects and monitoring of their outcomes should aim to rehabilitate ecosystem functions, not solely structures. BACI monitoring design and multi-habitat sampling at in-stream biotope level are required to detect physical and biological changes that may otherwise go unnoticed. The presence of upstream population sources can facilitate biotic recolonisation and decrease the post-project time frame of recovery.

Key Words: Biodiversity; Channel Reconfiguration; Hydromorphology; Large Woody Debris; Rehabilitation; Stream.

1. Introduction

Physical degradation of aquatic habitats is a serious threat to biodiversity, and freshwater organisms are disproportionally threatened with extinction as compared with terrestrial organisms (Pacini et al., 2013). Ecological restoration has received increasing interest and funding, because degradation of aquatic ecosystems has intensified in recent decades. Restoration has now become a widely accepted objective in developed nations, with an increasing number of restoration projects being implemented. In parallel, a number of meta-analyses have attempted to synthesise general trends in river restoration science. Despite this, it is still unclear how effective restoration measures really are, especially in terms of restoring macroinvertebrate community composition, structure and function.

The assumption that physical rehabilitation (which generally means increase of habitat heterogeneity) leads to increases in biodiversity and population density underlies most rehabilitation projects (Lepori et al., 2006; Miller et al., 2010; Roni et al., 2006). This assumption is sometimes called the “field of dreams” hypothesis (i.e. if you build it, they will come), which has been the core paradigm in most projects (Palmer et al., 1997). This idea is founded on the observed positive relationship between greater (natural) river bed physical diversity and taxon richness (Hutchinson, 1959). In-stream mechanisms thought to underpin this relationship include increased space, food, and refugia (Gurnell et al., 1995; Palmer et al., 2010).

If we are to understand and develop effective rehabilitation measures we must evaluating the success of river rehabilitation projects, learn lessons from the successes and failures, and share these experiences (Addy et al., 2016). Macroinvertebrates are at middle trophic levels within freshwater food webs and can offer valuable information for indicating the trends of biological changes. Altering the amount of available colonisation area by rehabilitation affects macroinvertebrates more than fishes, as the former typically move less (Gore et al., 1998).

Understanding the effectiveness of river rehabilitation techniques is critical for directing the planning and design of future rehabilitation projects (Roni and Quimby, 2005). The need for effective monitoring to achieve this has been acknowledged (Roni and Beechie, 2013), but such monitoring and evaluation is still rare (Bernhardt et al., 2005; Kail et al., 2015; Palmer et al., 2010; Wolter et al., 2013). Most river rehabilitation schemes fail to assess outcomes and effectiveness (Cowx et al., 2013), or use inadequate statistical designs, or inappropriate biological methods, which hamper rehabilitation ecologists’ ability to detect changes (Friberg et al., 2016). Despite the increasing number of rehabilitation interventions and an increased social drive to identify effective solutions that have economic benefits (Everard, 2012; Reichert et al., 2015; Smith et al., 2014), evidence for strong and long-term positive ecological effects of hydromorphological rehabilitation – particularly on macroinvertebrates - is generally limited (Feld et al., 2011; Friberg et al., 2014; Palmer et al., 2010), with a few notable exceptions (Kail et al., 2015; Miller et al., 2010). This partly reflects the lack of robust scientific assessments of rehabilitation measures (Verdonschot et al., 2015). The conflicting results of post-restoration monitoring studies, together with the relative infancy of stream rehabilitation science (Palmer et al., 2014) indicate the urgent need for more and better studies to address the links between hydromorphological rehabilitation and changes in stream biota (Louhi et al., 2011; Wolter et al., 2013).

Several meta-analyses over the past decade have tried to synthesise general trends in river rehabilitation science (e.g. Bernhardt et al., 2005; Feld et al., 2011; Kail et al., 2015; Miller et al., 2010; Palmer et al., 2014; Palmer et al., 2010; Roni et al., 2008; Thompson, 2015; Wolter et al., 2013) (Table 1), but their outcomes are inconsistent, and there is no general agreement about the effectiveness of hydromorphological rehabilitation approaches on macroinvertebrate communities. The limitations of these reviews, however – including which macroinvertebrate metrics were evaluated – have not previously been examined. It appears that insufficient objective data were often a barrier to determining the ecological effectiveness of rehabilitation projects. For example, Bernhardt et al. (2005) found, using the National River Restoration Science Synthesis (NRRSS) database, that only 10% of approximately 37,000 rehabilitation projects (in the USA) had any kind of pre- or post-rehabilitation monitoring. Thompson (2015) reviewed data in the National River Restoration Inventory (NRRI) of the UK and RESTORE of Europe, and found that the main aim of 91% of the 649 projects for which information was available was ecological rehabilitation; but 70% of projects provided no ecological monitoring information. Only 0.7% had used a rigorous (Before-After-Control-Impact, BACI) study design to demonstrate that ecological changes in the rehabilitated site were not due simply to natural variation. Cashman et al. (2018) accessed the NRRI during March 2018 for LWD rehabilitation project. From 912 individual LWD rehabilitation projects, details on monitoring approaches were entered as open text in the NRRI for only 276. In these studies, post rehabilitation monitoring was limited, and mostly restricted to photographic records. Macroinvertebrates were used as a monitoring approach in only 20 projects.

Most of the reviews examined the available literature qualitatively (e.g. Bernhardt et al., 2005; Feld et al., 2011; Palmer et al., 2010; Wolter et al., 2013), at least where rehabilitation projects had been monitored at all; or assessed changes in aquatic community diversity or species richness without quantifying overall ecological outcomes. Other reviews have focused solely on macroinvertebrate community structural variables such as diversity or species richness (e.g. Miller et al., 2010), without an explicit evaluation of whether those structural metrics provide relevant measures of rehabilitation success. A further limitation was the lack of robustness in the case-studies reviewed by Miller et al. (2010), including low quantity and poor quality of published data. The review by Palmer et al. (2014) depended on published data that had not used multi-habitat sampling, and where samples had been collected from riffle habitats only (e.g. Mackie et al., 2013; McClurg et al., 2007; Orzetti et al., 2010; Petty et al., 2013; Scrimgeour et al., 2013; Selvakumar et al., 2010).

The latest quantitative meta-analysis review (Kail et al., 2015), revealed that macroinvertebrate abundance/biomass metrics were more positively affected by in-stream rehabilitation than were richness/diversity metrics, but this conclusion depended on a limited number of case studies (23 published papers covering 32 case studies). These included studies that assessed rehabilitation effects on only one group of invertebrates – for example Chironomidae: (e.g. Spänhoff et al., 2006) – or that assessed the effects of riffle installation with invertebrate samples collected only from the riffle habitat, which is not representative of all study reaches (e.g. Ebrahimnezhad and Harper, 1997). For quantitative analysis, this latter review combined species richness and diversity as one response variable, and abundance and biomass as another. Only three case studies assessed macroinvertebrate biomass.

These ambiguous and limited results, together with increasing calls for appropriate evaluation of rehabilitation projects, require a broader understanding to identify appropriate measures of rehabilitation success, and a detailed review of available evaluations. Only with this in hand will it be possible to design future studies capable of detecting ecological changes.

The aims of the present analysis are to: (1) update available knowledge on the effects of different types of river rehabilitation on habitat heterogeneity at the reach-level; (2) examine whether these approaches have had an overall positive effect on macroinvertebrate community function and structure as a reliable means of assessing success in enhancing macroinvertebrate communities; and (3) to develop a broad understanding of the pitfalls and areas where progress may be made.

We have asked the following questions:

(1) To what extent has proper quantitative evaluation been done, in particular using BACI study designs?

(2) How have macroinvertebrate samples been collected? For example, has a multi-habitat sampling protocol been applied?

To what extent have measures of macroinvertebrate density, biomass, productivity, and functional traits been recorded as examples of processes of the ecosystem, in addition to its structure? Did functional or structural macroinvertebrate metrics show better responses?

Table 1. Meta-analyses reviewing the effects of hydromorphological rehabilitation processes on macroinvertebrate communities.

Bernhardt et al. (2005)	Synthesised information on more than 37,000 projects in the NRRSS database, but there were insufficient objective data to determine the ecological effectiveness of the projects.
Roni et al. (2008)	Reviewed 32 studies that examined responses of macroinvertebrates to in-stream rehabilitation processes. The results were highly variable and the information provided by the reviewed literature was limited so that they were unable to arrive at a firm conclusion.
Miller et al. (2010)	Analysed 24 published studies of 89 rehabilitation projects across the world that were carried out between 1984 and 2009. They showed that increasing habitat heterogeneity may enhance benthic macroinvertebrate species richness but not diversity. Addition of large woody debris (LWD) produced the greatest changes in richness, while changes to density were negligible.
Palmer et al. (2010)	The findings did not support the previous reviews; physical habitat heterogeneities were enhanced successfully, but only 2 out of 78 reviewed projects showed a significant increase in taxa richness to make rehabilitated reaches more similar to reference reaches.
Feld et al. (2011)	Reviewed available literature on the effect of river rehabilitation projects on fish, invertebrates, macrophytes, phytobenthos and algae. Adding LWD increased macroinvertebrate community abundances and species richness in some projects.
Wolter et al. (2013)	Highlighted the need to collect new field data addressing the links between stream hydromorphology and aquatic biota.
Palmer et al. (2014)	Compiled information on 47 published studies that depended on macroinvertebrate metrics. They found that the rehabilitation effects were disappointing. Measurable improvements were variable by rehabilitation methods and monitoring techniques. Biodiversity recovery was rare - only 16% of the most common type of projects (entire channel hydromorphological rehabilitation or in-stream hydromorphological rehabilitation) resulted in any improvements in biodiversity (e.g. Shannon index). The taxon richness of biotic communities (riparian vegetation, macroinvertebrate and fish assemblages) had improved as the result of these projects, but they concluded that taxon richness is not a particularly informative indicator of successful projects; and improvements of taxon richness found post-rehabilitation were not characteristic of the reference site or the desired state of the stream.
Thompson (2015)	Reviewed 649 projects for which information was available in the NRRI and RESTORE databases, finding that 70% of projects provided no ecological monitoring information. Only 0.7% had used a BACI study design to demonstrate that ecological changes in the rehabilitated sites were not due to natural variation.
Kail et al. (2015)	Reviewed 23 published papers (covering 32 case studies) and found a high variability but an overall positive effect of rehabilitation on macroinvertebrates. In-stream rehabilitation more effectively increasing macroinvertebrate abundance and/or biomass than richness and/or diversity.

2. Methods

We conducted an extensive review of peer-reviewed literature and readily available grey literature such as dissertations, theses, and case study reports. The search was not restricted to particular journals. Web of Science, Google Scholar, and SCOPUS were searched using the following keywords: (Restore* OR rehabilit* OR enhance* OR mitigate* OR reconfigurat* OR re-meander*) AND (aquatic habitat* OR reach* OR channel* OR stream* OR river*) AND (heterogeneity* OR LWD* OR habitat* OR instream*) AND (macroinvertebrate* OR invertebrate*). The British Library eTheses Online (EThOS) database was searches using the terms "Restoration and macroinvertebrates", "rehabilitation and macroinvertebrates", "re-meandering and macroinvertebrates", "stream restoration", "river restoration", "stream rehabilitation", "river rehabilitation", "heterogeneity and macroinvertebrates", "habitat and macroinvertebrates", "LWD and macroinvertebrates", "boulder addition and macroinvertebrates", or "channel reconfiguration and macroinvertebrates". These searches were conducted in March and April 2016 and updated on October 1st 2019. Each paper was examined to determine whether the study included an evaluation of stream physical rehabilitation activity using macroinvertebrate community structure and function. Four criteria determined inclusion. (1) The paper must have evaluated a physical rehabilitation project designed to enhance habitat heterogeneity, involving one or more rehabilitation measures such as channel reconfiguration, meandering, addition of artificial substrates like boulders or riffles, addition of large woody debris (LWD), modification of channel connectivity and/or re-vegetation of the riparian zone. (2) The paper must have quantified macroinvertebrate community responses such as community composition, density, richness, diversity, biomass, productivity, and/or functional feeding group structure, richness, and/or diversity. (3) Macroinvertebrate responses must have been quantified at the reach-scale, not within a single habitat (e.g. macroinvertebrate density recorded on only marginal plants or only on gravels, with no information about the rest of the stream). (4) The study must have included a Before-After (BA), a Control-Impact (CI), or a Before-After, Control-Impact (BACI) design.

Some papers were eliminated based on their abstract; all other papers were read in full. We also searched for related literature cited in every paper, including former meta-analyses.

Eighty nine papers published between 1984 and 2019, which together reported the outcomes of 379 independent projects met the criteria for inclusion (Table 2). This included 28 of 32 case studies published by Kail et al. (2015). Some projects were reported by more than one study; if so, the outcomes have been combined. For example, Sundermann et al. (2011), Haase et al. (2013) and Lorenz et al. (2018) reported the impact on macroinvertebrate communities of hydrological rehabilitation of 24 rivers in Germany. Bushaw-Newton et al. (2002) and Thomson et al. (2005) both reported on the effects of dam removal on downstream macroinvertebrate assemblages in a Pennsylvania stream. Thompson (2015) and Thompson et al. (2017) reported the impact of LWD instaltion on macroinvertebrate communities in five lowland streams in the UK.

Each project was placed into one category depending on how it was implemented (using the categories of Palmer et al. (2014)). Categories were:

(1) Entire-channel hydromorphological rehabilitation.
(2) In-stream hydromorphological rehabilitation.
(3) Longitudinal and lateral channel connectivity rehabilitation.
(4) Riparian rehabilitation.

Entire channel hydromorphological rehabilitation projects involved reconfiguring the channel completely, such as by re-meandering, widening, or enhancing channel lateral connectivity by raising/lowering the channel bed to create floodplains; and often incorporated the addition of in-stream structures such as boulders, large woody debris or gravel. In-stream hydromorphological rehabilitation projects were less intensive; they changed in-stream structure without major channel manipulation, such as by creating artificial riffles, decreasing bank erosion, or adding large woody debris.

Lateral connectivity rehabilitation projects involved channel-floodplain reconnection, and longitudinal connectivity projects aimed to enhance the channel longitudinal connectivity by removing small dams and weirs. Riparian rehabilitation projects involved revegetation of channel banks by planting native vegetation, removing non-native vegetation or preventing grazing.

3. Results

3.1. Geographic distribution of the rehabilitation projects

The geographic distribution of rehabilitation projects showed that, despite the global literature search, most projects originated from European countries (61%), followed by USA (30%) and Australia (5%), while the remaining 4% of projects were in Canada (4 projects), New Zealand (7 projects), and Asia (3 projects) (Figure 1A).

3.2. Rehabilitation techniques applied

More than half (54%) of the projects used entire-channel hydromorphological rehabilitation (Figure 1B), and often incorporated the addition of in-stream structures such as artificial riffles, boulders or large woody debris. In-stream hydromorphological restoration without major channel reconfiguration, such as creating artificial riffles, adding large woody debris or boulders was the second most commonly used method (36% of projects). Projects that improved channel-floodplain or longitudinal connectivity by removing small dams and boulders comprised only 6% of the projects. Riparian rehabilitation solely through replanting of river banks by native vegetation, fencing of banks to prevent grazing of animals, or removal of non-native vegetation, made up 4% of projects (Figure 1B).

3.3. Project ages at the time of evaluation

The ages of projects at the time of post-project monitoring differed greatly (Table 2). Hydromorphological and biological monitoring were performed one to three years following rehabilitation in most of the studies. A few studies monitored projects for up to 10 years (e.g. Haase et al., 2013; Jähnig et al., 2010; Lorenz et al., 2009; Martín et al., 2018; Smith and Chadwick, 2014; Stranko et al., 2012; White et al., 2017), or even 20 years (e.g. Laasonen et al., 1998; Louhi et al., 2011; Northington et al., 2011; Roni et al., 2006; Winking, 2015).

3.4. Applied study designs

299 projects (79%) used a Control-Impact (CI) design (Figure 1C) (also known as "space-for-time substitution design"), where a degraded reach within the same or an adjacent river system, and most often upstream of the rehabilitated section, was used as a control. Control reaches were usually selected to best represent the conditions of the rehabilitated reach prior to the rehabilitation process (e.g. Dolph et al., 2015; Friberg et al., 2013; Haase et al., 2013; Verdonschot et al., 2015). A second, but semi-natural, control reach (sometimes called a reference reach) was also used in some studies to permit further comparison of the direction of changes in both the rehabilitated and degraded reaches (e.g. Ernst et al., 2012; Friberg et al., 1998; Laasonen et al., 1998; Muotka et al., 2002; Pedersen et al., 2014; Winking, 2015). The most comprehensive approach used was a Before-After-Control-Impact (BACI) design. In this design, hydromorphological and biological data of pre- and post-rehabilitation processes for both impact (rehabilitated) and nearby control reaches are compared. BACI design was used in 66 projects (17%) (e.g. Al-Zankana, 2018; Friberg et al., 1998; Paillex et al., 2015; Renöfält et al., 2013; Rios-Touma et al., 2015; Thompson, 2015).

The last and least common approach was a simpler Before-After (BA) design, which was used in 14 projects (4%). Some studies used this design to track the recovery of physical and biological features of rehabilitated reaches to pre-rehabilitation levels and/or assess improvements after rehabilitation (e.g. Jungwirth et al., 1993; Wu et al., 2013). 17% of reviewed projects used a second, but semi-natural, control reach as the target state for macroinvertebrate community rehabilitation (e.g. Laasonen et al., 1998; Louhi et al., 2011; Muotka et al., 2002; Stranko et al., 2012; Winking, 2015).

3.5. Biotic sample collection protocols

Most of the evaluation studies sampled only riffle or riffle-pool habitats, which do not cover all available in-stream biotopes. Few studies applied more comprehensive multi-habitat sampling, which more accurately reflects the proportions of microhabitat types (in-stream biotopes) that comprise ≥5% cover (e.g. Al-Zankana, 2018; Haase et al., 2013; Jähnig et al., 2010; Louhi et al., 2011; Pedersen et al., 2007; Winking, 2015).

Most of the published papers that examined the largest number of independent rehabilitation projects (e.g. 5 projects assessed by Thompson (2015) to up to 26 projects assessed by Jähnig et al. (2010)) compared post-rehabilitation samples with samples from their control reaches based on only one sampling visit per project (Haase et al., 2013; Harrison et al., 2004; Jähnig et al., 2010; Stranko et al., 2012; Thompson, 2015; Tullos et al., 2009; Verdonschot et al., 2015; Winking, 2015). Only two studies sampled rivers before and after rehabilitation for multiple years (Louhi et al., 2011; Paillex et al., 2015), and for at least 2 seasons of each year to account for seasonal variation that could affect macroinvertebrate community composition.

3.6. Macroinvertebrate metrics used for monitoring outcomes of restoration

The most common macroinvertebrate metrics used to quantitatively evaluate project outcomes as measured by macroinvertebrate community structure and function (Figure 1D) were:

Taxon richness (27% of the projects),
Density (individuals·m^{-2}) (23% of the projects),
Diversity (18% of the projects), and
Functional Feeding Groups (FFG% and/or FFG richness) (13% of the projects).

Ephemeroptera-Plecoptera-Trichoptera (EPT) % and/or EPT richness was used in 6% of the projects, and invertebrate Biological Index (BI) in 4% of the projects. Macroinvertebrate biomass (energy or mgDryMass·m^{-2}) was used in 3% of projects, and secondary productivity (energy or mgDM·m^{-2}·year^{-1}) in 1% of the projects. Macroinvertebrate taxa evenness was used in 1% of projects. Other macroinvertebrate metrics including community composition 'Bray-Curtis similarity index', macroinvertebrate functional response group, the Proportion of Sediment-sensitive Invertebrates (PSI), and the Quantitative Macroinvertebrate Community Index (QMCI), were used in only 4% of the projects.

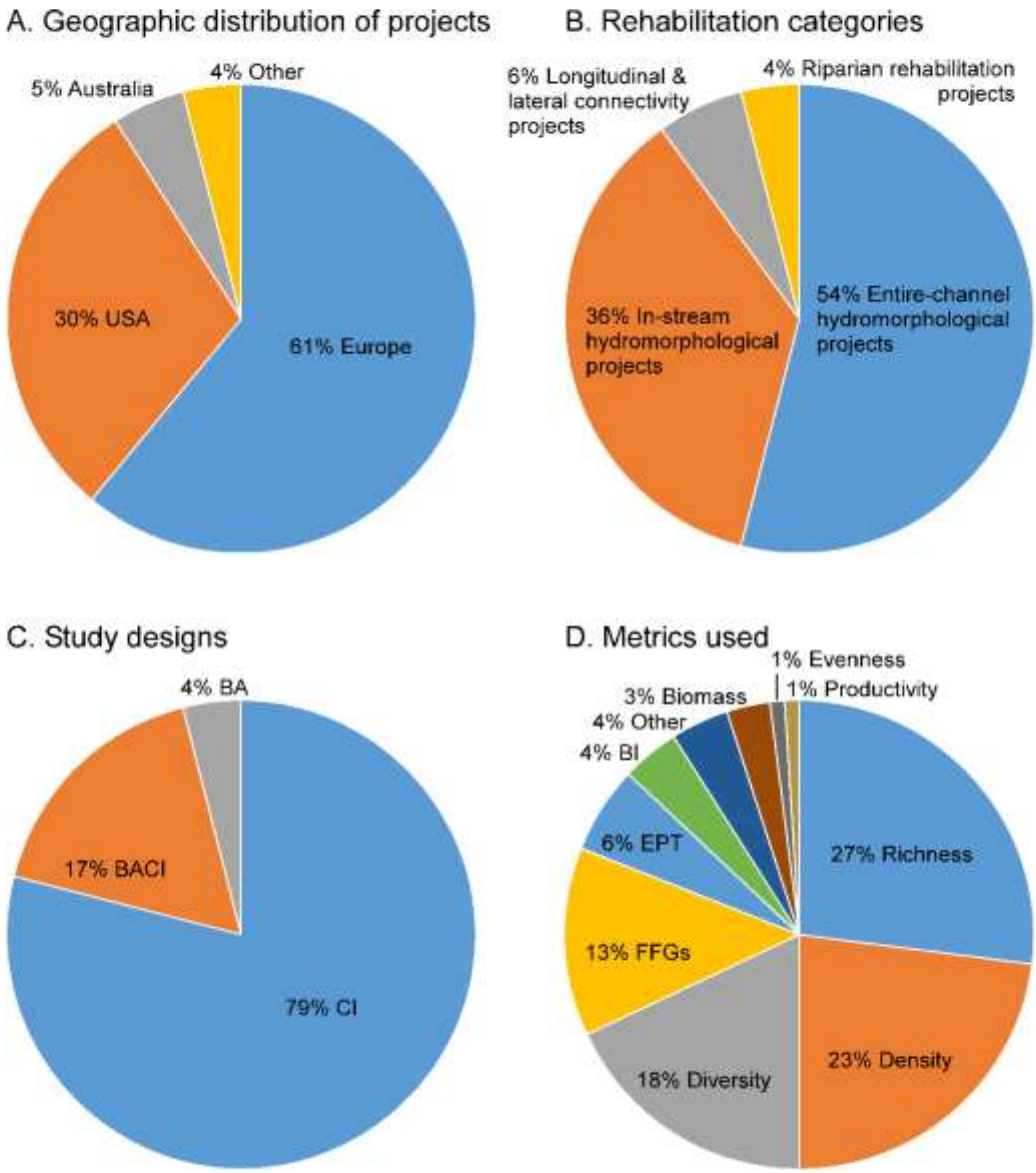

Figure 1. Summary of geographic distribution of rehabilitation projects, most common rehabilitation methods, study designs and most common macroinvertebrate metrics used to quantify the outcomes of rehabilitation for 359 independent rehabilitation projects. Projects were assigned into four groups according to the geographic distribution (A). 'Other' countries include Canada, New Zealand, China, and Japan. Each project's method of rehabilitation was placed into one of four broad categories (B). Study designs used for monitoring the physical and biological outcomes of rehabilitation processes (C) were: Before-After-Control-Impact (BACI), Before-After (BA), and Control-Impact (CI). D. Macroinvertebrate metrics used to quantitatively evaluate project outcomes. FFGs, Functional Feeding Groups; EPT, Ephemeroptera-Plecoptera-Trichoptera; BI, Biological Index. Note that multiple metrics could be listed for the same restoration project.

3.7. Quantifying overall success rates of rehabilitation projects

In what follows, we summarise the success rates of rehabilitation projects categorised into the four main hydromorphological rehabilitation techniques described above. Success was defined as a significant enhancement of a macroinvertebrate metric. The number of projects which monitored each metric are summarised in Table 3, permitting an estimate of the success rate for each separately.

3.7.1. Entire-channel hydromorphological rehabilitation projects

Holistic rehabilitation of streams by re-meandering the straightened and simplified channels, creating artificial riffle-pool sequences, removing bank fixation, widening of the water course, and reconnecting the floodplain resultated in obvious improvements in both channel morphology and physical habitat complexity (e.g. Biggs et al., 1998; Friberg et al., 1998; Friberg et al., 1994; Januschke et al., 2014; Moerke et al., 2004; Purcell et al., 2002). Despite this, the effects on macroinvertebrate communities were limited (Table 2). Only 10-12% of entire-channel hydromorphological rehabilitation projects reported significant increases in macroinvertebrate density, taxon richness, or diversity (Table 3). The effects on functional metrics such as FFG and EPT richness and composition were not much greater, with only 11 – 16% of projects showing significant enhancement. Other rarely used metrics such as Proportion of Sediment-sensitive Invertebrates (PSI), Bray-Curtis Similarity Index and Regional Invertebrate Biotic Index (BI) showed better enhancements.

3.7.2. In-stream hydromorphological rehabilitation projects

The physical diversity of reaches rehabilitated using in-stream hydromorphological methods was generally enhanced in comparison with their nearby physically damaged sites and/or with their pre-rehabilitation status. Only a few projects were not successful (e.g. Leal, 2012; McManamay et al., 2013; Sudduth and Meyer, 2006; Thompson, 2015). The biotic effectiveness of the in-stream rehabilitation measures applied was, however, quite limited (Table 2). The effects on macroinvertebrate richness and diversity were no different to those of entire-channel hydromorphological rehabilitation projects (Table 3). 16% of projects reported increased macroinvertebrate taxon richness, 6% reported increased diversity, and 50% reported increased evenness (however of only four studies in the latter case). Macroinvertebrate total density increased in 22% of projects, biomass in 54%, FFG in 21%, EPT in 27% and productivity in 71% (however of only seven studies in the latter case). These increases mainly arose from projects that added large woody debris to the watercourse.

3.7.3. Longitudinal and lateral connectivity projects

A limited number of studies about rehabilitation of connectivity (5 published papers covering 3 longitudinal and 20 lateral connectivity projects) showed that macroinvertebrate density increased in 87% of cases, and taxa richness in 91% of cases. The overall outcomes of the 3 longitudinal connectivity projects were negative for the macroinvertebrate community downstream of the removed impoundment, but positive for the community in the upstream reach (Table 3). This is because removal of dams enhanced upstream current velocity and sediment transportation.

3.7.4. Riparian rehabilitation projects

Six published papers compared physical and biological structure in 15 independent riparian rehabilitation projects. The physical variables that showed the largest changes, and affected the macroinvertebrate communities most following riparian buffer rehabilitation, were fine sediment reduction, water temperature reduction, and supplied organic matter increase. Macroinvertebrate community structure showed statistically significant enhancement in some studies (Table 3). For example, taxon richness increased significantly in 18% of projects (Jowett et al., 2009; Wu et al., 2013), while total biomass (Wu et al., 2013), EPT richness, EPT density and BI (Jowett et al., 2009; Quinn et al., 2009) showed improvements in a higher proportion of studies – but the small number of studies means that these high values should be interpreted with caution.

4. Discussion

Rehabilitation projects should aim to significantly enhance in-stream biotope diversity relevant for macroinvertebrate communities. In-stream biotopes are distinct ecological units; each providing a unique physical and biological environment, and supporting a characteristic assemblage of macroinvertebrates (Kemp et al., 1999). They have also been described as the "interface between organisms and the physical processes of the river" (Harper and Everard, 1998). Gravel and cobble biotopes provide important refuges for invertebrates during floods (Matthaei and Townsend, 2000), are more stable, and support higher numbers of macroinvertebrate taxa (including Ephemeroptera, Plecoptera, Trichoptera) than sandy biotopes (Maxted et al., 2003; Pan et al., 2012; Quinn and Hickey, 1990; Timm, 2003). Refugia are spatially discrete patches within the channel bed substratum where hydraulic forces and shear stresses are lower, relative to the surrounding area (Lancaster et al., 2006). The occurence of invertebrates in refugia during disturbances increases the chance of survival and allows redistribution and collonisation post-disturbance (Hart and Finelli, 1999; Lancaster and Belyea, 1997). Riffles have often been percieved as homogenous geomorphological units (Grant et al., 1990). High diversity of aquatic macroinvertebrates has been found in riffles, and high numbers (e.g. oligochaetes and chironomid larvae) in organic-rich sediments, reflecting the feeding modes of different taxa and their processing of different carbon sources. Benke (1984) found that woody materials were heavily colonised, with higher taxa diversity than sand or mud. Retention and accumulation of leaf-letter by woody materials also supported higher biomass and secondary productivity of macroinvertebrates (Entrekin et al., 2009). Such patterns of macroinvertebrate distribution and abundance related to in-stream patches (Beauger et al., 2006; Bostelmann, 2003; Reice, 1980) highlight the value of heterogeneity for macroinvertebrate communities (Buss et al., 2004).

Macroinvertebrate species often have specific in-stream biotope requirements that change during their life. All these habitats must be present and of sufficient quality to guarantee recolonisation and the development of sustainable populations (Verdonschot et al., 2015). Failure of rehabilitation projects to enhance physical and hydrological heterogeneity was regarded as the main factor explaining lack of effects on macroinvertebrate community in 48 projects (13% of reviewed projects) (e.g. Leal, 2012; Selvakumar et al., 2010; Tullos et al., 2009; Verdonschot et al., 2015; Violin et al., 2011). For example, Verdonschot et al. (2015) found that the 'missing effect' of 19 rehabilitation projects in 10 European countries assessed on macroinvertebrate richness and diversity measures might be due to failure of the rehabilitation measure. They found that rehabilitation by remeandering and/or widening increased 'visually appealing' macrohabitats, but had no significant effect on in-stream biotope diversity relevant for macroinvertebrate communities.

Rehabilitation techniques were very diverse, and many techniques were used together. Entire-channel rehabilitation projects such as re-meandering and adding coarse substrates (artificial riffles) led to immediate rehabilitation of some features of natural stream channel morphology (e.g. Al-Zankana, 2018; Biggs et al., 1998; Friberg et al., 1994) and enhanced structural heterogeneity (e.g. Harrison et al., 2004). Removal of bank fixation, widening of the water course, and floodplain connection, led to more diverse substrate composition and floodplain habitat heterogeneity (e.g. Januschke et al., 2014).

In-stream rehabilitation projects, especially those using large woody debris installation techniques, were more effective for enhancing macroinvertebrate community assemblages, especially density, biomass, functional feeding groups (FFGs) and Ephemeroptera-Plecoptera-

Trichoptera (EPT), compared to other rehabilitation techniques (e.g. Al-Zankana, 2018; Entrekin et al., 2009; Lester et al., 2007; Pretty and Dobson, 2004; Smock et al., 1989; Wallace et al., 1995).

Enhancing longitudinal connectivity by removing small dams and weirs had initially adverse effects on macroinvertebrate density due to the mobilisation of fine sediments from the upstream stagnant section, so full beneficial effects occurred only after the fine sediments had been transported farther downstream, which seemed to take decades (Thomson et al., 2005). Bushaw-Newton et al. (2002) found that sediment transport increased downstream of removed dams, while the upstream channel form changed and upstream benthic biota assemblages shifted from lentic to lotic taxa and mean number of EPT nearly tripled within one year of the dam removal. Maloney et al. (2008) found that within two years of dam removal, relative abundance of EPT taxa increased upstream due to increased flow and substrate particle size. Spatial and temporal aspects of dam removal are therefore very important and need a more cautious approach than other rehabilitation methods. The deposition of fine sediment on courser substrate downstream of the removed impoundment could limit the availability of courser substrate preferred by EPT and by fish for spawning. Paillex et al. (2015) studied the effects of floodplain connectivity on abundance and richness of aquatic macroinvertebrates by reconnecting 18 lateral floodplain channels to the Rhone River main channel. They found a significant increase in channel lateral connectivity two years after the rehabilitation, and the abundance and richness of benthic biota assemblages shifted from lentic to lotic taxa.

Riparian rehabilitation through re-vegetation is reported to have enhanced channel physical habitat diversity and in-stream substrate heterogeneity (Thompson and Parkinson, 2011), alleviated water pollution (Wu et al., 2013), decreased water temperature (Becker and Robson, 2009; Quinn et al., 2009), increased bank stability (Selvakumar et al., 2010), and increased availability of terrestrial food (Thompson and Parkinson, 2011). The highest diversity of macroinvertebrates was found in areas where riparian rehabilitation and opening of side channels was conducted (Nordhov and Paulsen, 2016).

It is essential to address the potential impact of confounding factors such as land use, erosion, high levels of heavy metals and nutrient pollution, at the larger catchment scale. Catchment scale pressures that were not mitigated by in-stream rehabilitation impeded recovery of stream macroinvertebrate taxa richness and diversity in 55 projects (15% of reviewed projects) (e.g.

Harrison et al., 2004; Larson et al., 2001; Louhi et al., 2011; McManamay et al., 2013; Roni et al., 2006).

Well designed monitoring (e.g. using the most comprehensive Before-After-Control-Impact (BACI) designs) is required to detect any physical and biological changes that may otherwise go unnoticed – but BACI study designs were not common practice. Effective monitoring of rehabilitation projects requires two distinct evaluations (Barmuta, 2002). First, rehabilitated reaches should be compared to their pre-rehabilitation conditions to assess whether the rehabilitation affected the response variables of interest. Second, rehabilitated reaches should be compared to target conditions to assess whether the rehabilitation achieved its purpose. The dearth of pre-rehabilitation data has pushed researchers to use a surrogate methodology - so-called Control-Impact (CI) study designs – used in 79% of monitored rehabilitation projects. This can be misleading (Miller et al., 2010) and "renders [supposed] impacts on macroinvertebrates questionable" (Feld et al., 2011). This limited approach might confound responses to rehabilitation with differences between macroinvertebrate communities (Laasonen et al., 1998; Negishi and Richardson, 2003), because macroinvertebrate community metrics vary naturally at small spatial scales for reasons unrelated to rehabilitation activities (Miller et al., 2010; Negishi and Richardson, 2003). A BACI study design was used in 66 rehabilitation projects (17% of reviewed projects). 77% of those with BACI design and 2 years' sampling showed significant improvements in macroinvertebrate metrics (e.g. Al-Zankana, 2018; Friberg et al., 1994; Herbst and Kane, 2009; Rios-Touma et al., 2015).

Biotic samples should be collected in a representative way from all available in-stream biotopes: sampling of only gravel or riffle areas is generally insufficient to capture important changes. Multi-habitat sampling protocols were rarely applied (e.g. Al-Zankana, 2018; Haase et al., 2013; Jähnig et al., 2010; Louhi et al., 2011; Pedersen et al., 2007; Winking, 2015). Improvements in macroinvertebrate community diversity were recorded by comprehensive studies (e.g. Al-Zankana, 2018; Pedersen et al., 2007; Winking, 2015). Studies using more rigorous evaluations (multi-habitat sampling of macroinvertebrates) were more likely to detect significant increases in taxa richness or diversity in the 26 studies used by Palmer et al. (2010), Miller et al. (2010) and Rubin et al. (2017). Examining the functional and structural properties of taxa across distinct biotopes was found to provide a greater understanding of biotic responses to river rehabilitation works (Al-Zankana, 2018; White et al., 2017). Such information can guide more effective rehabilitation and management strategies.

Partitioning the effects of rehabilitation outcomes from other sources of variance – especially seasonal and inter-annual variation – was not possible, as many projects evaluated restoration by sampling only once (either during spring or summer). Surprisingly, 111 independent rehabilitation projects (29% of reviewed projects) were evaluated by sampling only once and without incorporating undisturbed control reaches (Haase et al., 2013; Harrison et al., 2004; Jähnig et al., 2010; Thompson, 2015; Tullos et al., 2009; Verdonschot et al., 2015). All but five of these used CI designs (the other five (Thompson, 2015) used BACI). None of the 111 projects recorded any significant improvements in the macroinvertebrate communities within the restored reaches. These results may be misleading because biotic communities usually follow a cyclical pattern. For example, distinct seasonal trends in macroinvertebrate density and biomass were recorded in woody debris dams by Smock et al. (1989). If the post-rehabilitation evaluation is conducted during a peak or lull in the cycle, misleading results may be obtained (Leal, 2012).

It is critical to incorporate undisturbed (semi-natural) reaches in the study design as target states of rehabilitation, so that it is possible to track the direction of macroinvertebrate community structure and function changes.

Using a broader range of macroinvertebrate metrics as response variables (and not simply relying on taxa richness or diversity) will improve our understanding of the relationships between created habitat heterogeneity and changes of macroinvertebrate community composition, structure and function (e.g. functional traits, FFGs%, FFGs diversity, EPT%, EPT diversity, EPT density, EPT biomass and annual production). Despite calls to use a broader range of macroinvertebrate metrics (including both structural and functional measures) to understand ecological effects of stream rehabilitation outcomes (Dolph et al., 2015; Feld et al., 2011; Muhar et al., 2016; Palmer et al., 2005), most studies used only a limited range of measures. Macroinvertebrate taxa richness and diversity have commonly been used as monitoring metrics, even though these may fail to identify other consequential changes in ecosystem structure and function. Functional metrics such as FFG abundance%, FFG biomass%, EPT abundance%, EPT biomass% and secondary productivity showed better responses, especially for in-stream hydromorphological rehabilitation projects. These significant improvements were observed mostly with increasing amounts of large woody debris, which led to collection of organic matter and increased food availability (e.g. Al-Zankana, 2018; Dolph et al., 2015; Entrekin et al., 2009; Smock et al., 1989; Wallace et al., 1995). Only seven projects used macroinvertebrate productivity as a functional metric (Al-Zankana, 2018; Dolph et al., 2015; Entrekin et al., 2009; Wallace et al., 1995), but in five cases (71%) these projects reported significant increases. These rarely-examined functional properties of macroinvertebrate communities would provide more ecological information about the ecosystem responses to rehabilitation activities, and could pinpoint project limitations.

The time frame for biotic responses and the recolonisation of macroinvertebrate communities depends on the availability of source populations of colonists upstream of rehabilitated reaches. Post rehabilitation monitoring has shown that one year is insufficient for macroinvertebrate communities to respond where there is a lack of diversity (a source population) in adjacent reaches from which to recruit (Esdar, 2019; Nordhov and Paulsen, 2016). Other projects found positive responses within a year, suggesting the presence of source populations of colonists upstream of the rehabilitated reach (e.g. Al-Zankana, 2018; Neale and Moffett, 2016). In some cases, macroinvertebrate recovery was also limited by declining habitat quality over time due to erosion, barriers to dispersal (e.g. Wallace, 1990), and pollutant input, all of which may have affected sensitive taxa and delayed community recolonisation (Palmer et al., 2010).

5. Conclusions

This review has a number of important implications for the planning and management of future stream hydromorphological rehabilitation projects and the monitoring of their success.

First, rehabilitation projects should significantly enhance in-stream biotope diversity relevant for macroinvertebrate communities. LWD installation was more effective for enhancing macroinvertebrate community assemblages than the other applied rehabilitation techniques. Spatial and temporal aspects of dam removal are very important and need a more cautious approach than other rehabilitation methods. The deposition of fine sediment on coarser substrate downstream of the removed impoundment could limit the availability of corrser substrate preferred by EPT and by fish for spawning.

Second, it is essential to address the potential impact of confounding factors including land-use, erosion and nutrient pollution at the larger catchment scale. Catchment scale pressures that were not mitigated by in-stream rehabilitation impeded recovery of stream macroinvertebrate taxa richness and diversity.

Third, well designed monitoring (e.g. using rigorous BACI designs) is required to detect physical and biological changes that may otherwise go unnoticed. Macroinvertebrate samples should be collected in a representative way from all available in-stream biotopes (at multi-habitat level): sampling of only gravel or riffle areas is generally insufficient to capture important changes. It is important to incorporate undisturbed (semi-natural) reaches in the study design as target states of rehabilitation, so that it is possible to track the direction of macroinvertebrate community structure and function changes.

Fourth, the time frame for biotic response and recolonisation of macroinvertebrate communities depends on the availability of source populations of colonists upstream of the rehabilitated reach. One year was insufficient for macroinvertebrate communities to respond in many cases, due to lack of a source population in adjacent reaches from which to recruit.

Fifth, using a broader range of macroinvertebrate metrics as response variables (and not simply relying on taxa richness or diversity) will improve our understanding of the relationships between created habitat heterogeneity and changes of macroinvertebrate community composition, structure and function (e.g. functional traits, FFG%, FFG diversity, EPT%, EPT diversity, and their density, biomass and annual production).

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Table 2. Summary of published studies of the effects of rehabilitation projects on habitat heterogeneity and macroinvertebrate community structure and function. Project age indicates the age of each project in years at the time of monitoring. Study designs: Control-Impact (CI), Before-After (BA), Before-After-Control-Impact (BACI).

Reference Location (No. of Projects)	Rehabilitation technique	Study design (project age)	Key Finding
Edwards et al. (1984) Ohio, USA (1)	Artificial riffle and pool construction	CI (6)	Different depths and velocities were provided. Significant difference in family richness was recorded; macroinvertebrate abundance and family richness were higher in natural and rehabilitated (artificial riffles and pools) versus channelised area.
Smock et al. (1989) Virginia, USA (2)	Woody material addition	CI (1)	Macroinvertebrate abundance and biomass increased with increasing amount of woody material, leading to collection of organic matter and increased food availability. Contribution of shredder feeding group to biomass increased with increasing abundance of dams.
Jungwirth et al. (1993) Lower Austria (1)	Channel reconfiguration	BA (3)	Project increased spatial variance in depths and velocities to provide a wider range of substrate types. Significant increase in macroinvertebrate species richness recorded, while biomass decreased.
Tikkanen et al. (1994) Finland (1)	Boulder addition	BA (1)	Slight increase in bed roughness and mean particle size. Slight decrease in abundance immediately after rehabilitation, no measurable effect on species richness.
Friberg et al. (1994) Denmark (1)	Re-meandering	BACI (2)	Proposed that density and diversity increased after two years of re-meandering, recovery of biota community after rehabilitation process needs one to two years
Wallace et al. (1995) North Carolina, USA (1)	Woody material added downstream of three riffles	BA (4)	At LWD addition sites, stream depth and organic matter increased, current velocity decreased, sand and silt covered the cobble substratum. Macroinvertebrate abundance, biomass, and secondary production increased significantly after rehabilitation. Abundance, biomass, and secondary production of scrapers and filterers decreased, while collectors and predators increased, no change in overall shredder biomass.
Hilderbrand et al. (1997) West Virginia, USA (2)	Addition of woody material to compare systematic or random placement of pieces	BA (2)	Systematic placement had a lower effect on erosion and score rates than random placement. No changes in macroinvertebrate total abundance. Some functional groups increased with the pool areas.
Biggs et al. (1998) Denmark (1), UK (1)	Re-meandering, addition of gravel and cobble	CI (1)	Dramatic increase in channel meandering and substrate heterogeneity. Non-significant increase in macroinvertebrate species richness or abundance.
Friberg et al. (1998) Denmark (1)	Channel reconfiguration, re-meandering, addition of gravel and rock	BACI (6)	Immediate rehabilitation of natural stream channel morphology observed. Non-significant increase in macroinvertebrate species richness or abundance.
Laasonen et al. (1998) Finland (9)	Addition of boulders, and flow deflectors; excavation and channel enlargement	CI (<1-16)	Bed roughness higher in rehabilitated than unrehabilitated reach, more different depths and flows present in rehabilitated reach. No difference in macroinvertebrate richness or abundance between rehabilitated and channelised sections.
Gørtz (1998)	Addition of gravel and	CI	Resulted in deeper and narrower stream with a

Denmark (1)	boulders	(4)	higher flow velocity near the bottom and a coarser substrate. Macroinvertebrate abundance increased and became similar to the natural reach, with no change in diversity
Gerhard and Reich (2000) Germany (2)	Addition of woody material	CI (4)	Rehabilitated reaches had more functional habitat patches per metre than unrehabilitated. Macroinvertebrate abundance, species richness and diversity increased in Joseklein stream, with no increase in Lude stream.
Larson et al. (2001) Washington, USA (6)	Addition of woody material	CI (2-10)	Channel complexity significantly increased. No change in macroinvertebrate IBI.
Muotka and Laasonen (2002) Finland (4)	Addition of boulder weir and deflector	BACI (3)	Substrate heterogeneity increased, retention efficiency was higher in rehabilitated than channelised, but lower than in natural streams. Only algae-feeding invertebrate shredder density increased.
Purcell et al. (2002) California, USA (1)	Channel restructuring, addition of step pools, rocks, riparian revegetation and opening up of a culvert stream	CI (3)	Channel complexity increased by meanders, step pools. Buffer vegetation increased. Macroinvertebrate IBI and taxa richness improved in rehabilitated reach relative to control reach.
Muotka et al. (2002) Finland (3)	Enhancing habitat heterogeneity through addition of boulders, flow deflectors, excavation and channel enlargement	CI (4-8)	Higher leaf retention in natural and 8 year old rehabilitated reach. Algae-feeding scrapers were the only macroinvertebrate group whose density increased significantly after restoration.
Bushaw-Newton et al. (2002) Thomson et al. (2005) Pennsylvania, USA (1)	Dam removal	BACI (1)	Sediment transport downstream caused habitat alteration. Macroinvertebrate assemblage shifted from lentic to lotic taxa. Dam removal caused reduction in the macroinvertebrate density, but the effect was temporary. Changes in macroinvertebrate density and richness were non-significant. Mean number of EPT nearly tripled within one year upstream of the removed dam.
Haapala et al. (2003) Finland (2)	Addition of boulder weir	BA (2)	Channel complexity was higher in rehabilitated reaches. No consistent differences in macroinvertebrate structure between channelised and rehabilitated reaches.
Negishi and Richardson (2003) Canada (1)	Addition of boulder deflector	BACI (1)	Habitat heterogeneity increased in comparison with pre-rehabilitation and the reference reach. Macroinvertebrate abundances increased 280% in the rehabilitated reach and converged with those of the reference reach, Detritivore taxa numerically dominated the macroinvertebrate community.
Pretty and Dobson (2004) UK (3)	Addition of woody material	BA (2)	Log addition enhanced detrital standing stocks. Macroinvertebrate total abundance and taxon richness were significantly increased in the rehabilitated reach, the response was most marked for detritivores.
Harrison et al. (2004) UK (13)	7 projects with riffle construction, and 6 projects with flow deflector	CI (4-9)	Flow and depth heterogeneity increased. Neither artificial riffles nor flow deflectors had any significant impact on macroinvertebrates taxon richness. Macroinvertebrate diversity of rehabilitated reaches related closely to that of non-rehabilitated reaches.

Korsu (2004) Finland (1)	Addition of boulders	BA (<1)	Invertebrates recolonised the rehabilitated reach to pre-project level within 2 weeks of disturbance. Relatively fast recovery of invertebrate can be in winter. Moss biotope (bryophytes) is important for invertebrates as a habitat and refuge.
Moerke et al. (2004) Indiana, USA (2)	Re-meandering, addition of boulders and logs, riffle-pool construction, sediment reduction and riparian re-vegetation	BACI (5)	Habitat improved after one year of rehabilitation, with more pools and less fine sediment. After five year of rehabilitation the density of macroinvertebrates remained higher than unrehabilitated reach, with no increase in diversity.
Lepori et al. (2005) Sweden (7)	Addition of boulders and channel restructuring; removal of bank armoring. Widening	CI (3-8)	Higher habitat heterogeneity in rehabilitated than unrehabilitated reach. No enhancement in macroinvertebrate diversity or richness were observed.
Roni et al. (2006) Oregon, USA (13)	Boulder weir placement, and addition of logs	CI (1-20)	Pool area, number of LWD, boulders, and pools were significantly higher in the rehabilitated site than the control site. No enhancement in abundance, richness, EPT%, FFGs% or IBI were observed.
Lepori et al. (2006) Sweden (3)	Addition of boulders, channel widening.	CI (4-6)	Current velocity decreased, woody material entrapment by introduced boulders, and leaf retention were higher in stream margins. There were no increases in macroinvertebrate biomass or the fraction of secondary production based on detritus.
Rosi-Marshall et al. (2006) Michigan, USA (2)	Enhancing in-stream hydromorphology through under-bank cover and pool-creating structures.	BACI (1)	Channel depth and organic matter retention increased, but macroinvertebrate density, diversity, and FFGs composition did not change.
Sudduth and Meyer (2006) Georgia, USA (4)	Enhancing in-stream hydromorphology through bank stabilisation.	CI (1-9)	Percentage of organic habitat did not change. Macroinvertebrate total abundance, diversity, richness, biomass, FFGs composition, abundance, and biomass enhancements were not significant.
Lester et al. (2007) Australia (8)	Addition of woody material	BACI (1)	Wood increased the storage of organic matter and sediments, and improved bed and bank stability. Macroinvertebrate density and richness increased; treated streams had greater family richness and greater richness of all functional feeding groups. Richness increased in all wood, benthic and edge habitats.
Pedersen et al. (2007) Denmark (1)	Re-meandering and addition of gravel	BACI (1)	Macrophytes recolonised the reach after rehabilitation. Macroinvertebrates total abundance, species richness, EPT% and richness, changes were non-significant. Community diversity increased. Only Heptageniidae abundance increased significantly.
Sarriquet et al. (2007) France (1)	Addition of gravel	CI (3)	There was no change in invertebrate assemblage density or taxonomic richness.
De Vaate et al. (2007) Netherland (3)	Secondary channel construction	CI (3)	Former channel substrate changed from silt to sand, macroinvertebrate species richness increased rapidly following habitat development.
Nakano and Nakamura (2008) Japan (1)	Re-meandering, addition of boulders	CI (2)	There were significant differences in depths, velocities and sediment habitats. Rehabilitated and natural reaches had significantly higher density and taxa richness than the control reach.

Maloney et al. (2008) Illinois, USA (1)	Dam removal	BACI (3)	Habitat improved, flow rate and substrate particle size increased, channel width and depth decreased. There was no change to overall macroinvertebrate assemblage structure. EPT% increased within two years of dam removal.
Becker and Robson (2009) Australia (6)	Willow removal, riparian re-vegetation.	CI (1-8)	Revegetated sites were warmer and had a higher light intensity compared to older revegetated and natural sites. Density and richness of macroinvertebrates did not vary among site types.
Quinn et al. (2009) New Zealand (2)	Riparian re-vegetation with native plants, and exclusion of livestock	BACI (1-6)	After rehabilitation, channel width, water depth and water temperature were reduced, macroinvertebrate density decreased, and EPT richness increased in one reach. EPT density, IBI, and QMCI increased significantly.
Lorenz et al. (2009) German (2)	Re-meandering, floodplain connection, and addition of wood and small cobbles	CI (2-10)	Habitat heterogeneity were significant increased. Number of macroinvertebrate families, taxa and genera were higher in the rehabilitated reaches than the straightened reaches. Macroinvertebrate density were only increased in the river that was rehabilitated 10 years before the study took place.
Tullos et al. (2009) North Carolina, USA (24)	Channel reconfiguration	CI (1- 4)	Habitat features and channel complexity were similar between rehabilitated and control sites. Shannon genus diversity increased in urban streams, with no changes in rural and agricultural streams.
Jowett et al. (2009) New Zealand (2)	Riparian re-vegetation, fencing to exclude livestock.	CI (1-8)	Macroinvertebrate communities, EPT richness, and EPT% become more similar to those of reference sites (native forest) only in one case study.
Herbst and Kane (2009) Sierra Nevada, Spain (1)	Channel reconstruction, addition of rock substrate and erosion control fabric. Willow planting	BACI (2)	Deposition of fine sediments and sand increased at the downstream end of the rehabilitated reach one year after rehabilitation, and it became similar to those of the pre-project by the second year. Macroinvertebrate community and trophic structure increased after rehabilitation: diversity and composition of sensitive taxa (EPT) and shredders increased, while tolerant taxa and filter-feeders decreased.
Selvakumar et al. (2010) Virginia, USA (1)	Bank stabilisation through bioengineering and bank revegetation	BACI (2)	In-stream structures were improved. EPT taxa were enhanced significantly.
Entrekin et al. (2009) Michigan, USA (3)	Addition of woody material	BACI (2)	22% increase of macroinvertebrate biomass and secondary production recorded in one rehabilitated reach, but no significant changes in two other reaches.
Coe et al. (2009) Washington, USA (2)	Addition of woody material	CI (2)	Macroinvertebrate density was significantly higher on woody material than on cobbles. Wood substrate increased the density of invertebrates at reach level.
Chin et al. (2010) Texas, USA (3)	Channel stability increased by construction of riffle and steps, riparian re-vegetation along gradient banks	BA/CI (2)	Measurable changes detected in channel characteristics and habitat condition. Channel cross-section area increased. Significant increase in taxa richness, EPT%, and grazers% were observed.
Jähnig et al. (2010) Austria, Czech republic, Germany, Italy, and Netherlands (26)	Re-meandering, removal of bank fixation, addition of gravel, boulders and woody material	CI (3-12)	Habitat diversity improved in rehabilitated reaches, but there was no significant enhancement in macroinvertebrate density, richness, diversity, or evenness.

Louhi et al. (2011) Finland (6) Finland (15)	Addition of boulder ridges, flow deflectors and woody material	BACI (3) CI (15-17)	Stream habitat diversity increased. Post-rehabilitation macroinvertebrates density and richness decreased. Feeding groups did not show significant response to rehabilitation.
Thompson and Parkinson (2011) Australia (3)	Riparian re-vegetation	CI (15)	Habitat heterogeneity was higher in re-vegetated reaches. There was a clear shift in aquatic invertebrate community structure between non-rehabilitated and re-vegetated reaches across all streams. Dominant taxa found in non-rehabilitated reaches included gastropods, chironomids, oligochaetes and some bivalves which all generally classed as pollutant tolerant taxa.
Testa et al. (2011) Mississippi, USA (1)	Addition of woody material	BACI (2)	Woody substrate tripled after rehabilitation, but there was no significant enhancements in macroinvertebrate density or family richness.
Northington et al. (2011) Virginia, USA (6)	Natural channel design, addition of in-stream structures. Riparian re-vegetation	CI (1-20)	No evidence of any significant effects of rehabilitation on the ecosystem processes.
Selego et al. (2011) Virginia, USA (1)	Addition of logs, and gravel. Riparian re-vegetation	BACI (1)	After rehabilitation, macroinvertebrate community composition, IBI and density became more similar to the reference reach, and collector-filterers and scrapers became most dominant.
Schiff et al. (2011) New York, USA (1)	Re-meandering, addition of boulders and woody material, bank stabilisation through fibre rolls, rock wing deflectors and tree revetments	CI (2-5)	There were small improvements in local habitat, but there were no significant improvements in macroinvertebrate density or richness.
Albertson et al. (2011) California, USA (1)	Channel reconfig-uration, re-meandering, removal of fine sediment and addition of gravel	CI (1)	Macroinvertebrate density and biomass declined after rehabilitation, while richness and evenness of the rehabilitated reach were significantly increased in comparison with the unrehabilitated reach.
Violin et al. (2011) North Carolina, USA (4)	Channel rehabilitation	CI (1-7)	No significant improvement in reach-scale habitat features. Natural reaches had significantly higher taxa richness than degraded and rehabilitated reaches in winter samples. EPT species richness was higher in the natural reach and differed significantly from the degraded and rehabilitated reaches in both winter and summer.
Clark (2011) Australia (1)	Improvement of bank stability, riparian re-vegetation and riffle construction	CI (1)	Macroinvertebrate diversity, richness, abundance and predator% in rehabilitated site were similar to that of reference site, while the environmental variables did not differ significantly between rehabilitated and degraded sites in spring. There were higher numbers of sensitive taxa in the natural sites.
Sundermann et al. (2011) Haase et al. (2013) Lorenz et al. (2018) Germany (24)	Removal of bank fixation, addition of flow deflectors and woody material, creation of a new channel, and connectivity.	CI (1-12) (6-17)	Rehabilitated sections had significantly higher SDI values and higher variance of river width and depth. Macroinvertebrate composition, density, richness, evenness, diversity, dominance and FFGs did not enhance.
Leal (2012) California, USA (1)	Addition of woody material	CI (1)	There was a smaller substrate particle size in the rehabilitated site. No significant difference between

			other habitat features such as canopy cover, algae, tree roots, and emergent vegetation %. Lower invertebrate abundance and diversity was associated with LWD in several months of the first year after rehabilitation. There was no significant improvement of macroinvertebrate density or richness.
Ernst et al. (2012) New York, USA (5)	Natural channel design and restructuring.	CI (1-5)	Bank stability and macroinvertebrate Gatherer% increased significantly. There were no significant enhancement in the rehabilitated reaches macroinvertebrates abundance, richness, EPT richness, Chironomidae%, or any FFGs%.
Stranko et al. (2012) Maryland, USA (15)	Channel reconstruction, tree planting, and removing concrete structures.	CI (5-10)	Macroinvertebrate biotic index, number of genera, intolerant genera, mayfly genera, and stonefly genera were remained similar to those of unrehabilitated reaches.
Extence et al. (2013) UK (2)	Weir removal, channel narrowing, mechanical removal of fine sediment and addition of gravel	BACI (3)	PSI increased at rehabilitated sites as taxa associated with coarse substrate quickly colonised the rehabilitated habitat.
McManamay et al. (2013) North Carolina, USA (2)	Addition of gravel	BACI (1)	Gravel was washed down by water current, the taxonomic composition shifted, but the increased macroinvertebrate richness and density were not sustained, and the response was specific to individual taxa or particular FFG.
Wu et al. (2013) China (1)	Riparian re-vegetation	BA (1)	Vegetation cover area, species richness, and diversity increased after rehabilitation. Macroinvertebrate richness and biomass increased significantly.
Renöfält et al. (2013) Sweden (1)	Dam removal	BACI (3.5)	Sediment deposition increased significantly after removing the dam, macroinvertebrate density slightly decreased, while number of taxa significantly decreased.
Friberg et al. (2013) Denmark (1)	Re-meandering, addition of coarse substrate	CI (19)	No evidence of long-term positive effects of rehabilitation on macroinvertebrate community composition.
Smith and Chadwick (2014) UK (8)	Improvement of flow conditions, re-meandering	CI (2-10)	The rehabilitated reaches macroinvertebrate (litter decomposer) density, richness or biomass were not enhanced. They remained similar to those of the unrehabilitated reaches.
Januschke et al. (2014) Germany (3)	Removal of bank fixation, widening, floodplain connection	CI (7- 9)	Rehabilitated reaches had more diverse substrate composition. Floodplain habitat heterogeneity increased. Macroinvertebrate species composition was more variable over time in rehabilitated than unrehabilitated reaches.
Erwin (2014) Canada (3)	In-stream habitat manipulation, enhancing longitudinal connectivity for fish passage by creating pool-weir and choke-pool structures	BACI (1)	There were no significant changes in macroinvertebrate abundance or diversity.
Pedersen et al. (2014) Denmark (6)	Re-meandering, addition of pebbles and gravel	CI (3)	Gravel substrate was introduced without considering flow or stream power, and did not provide sufficient habitat conditions for macroinvertebrate assemblages. Macroinvertebrate

			density, richness, diversity, evenness, EPT density, and EPT richness were not related significantly to increasing substrate heterogeneity.
Mueller et al. (2014) Germany (6)	Addition of boulders and gravel	BACI (1)	Macroinvertebrate community composition changed after rehabilitation. Overall density, richness, Shannon diversity, evenness, and FFGs did not change.
Koebel et al. (2014) Florida, USA (1)	Restoration of flow and habitat structure	BACI (3)	River habitat significantly changed after flow rehabilitation. Collector-filterer density and biomass increased significantly.
Rios-Touma et al. (2015) Oregon, USA (3)	Re-meandering, addition of boulders and woody material, floodplain reconnection, and riparian re-vegetation	BACI (4)	There were no differences in substrate composition, large wood pieces, and canopy cover after rehabilitation. Macroinvertebrate richness increased significantly after rehabilitation, diversity increased after rehabilitation, but both were still lower than the reference streams. FFGs diversity increased significantly but was still lower than the reference streams.
Paillex et al. (2015) France (20)	Floodplain reconnection	BACI (4)	Lateral connectivity increased significantly, lotic invertebrate density and richness increased after 2 and 4 years of lateral reconnection.
Winking (2015) Germany (13)	Remove of concrete bed, construction of near natural channel and riparian area, wastewater free	CI (1-5/9-20)	Macroinvertebrate community composition of old rehabilitated sites (9-20 years old) was more similar to the reference sites, while the younger sites (1-5) were well separated from the reference sites. The community composition of seven sites connected to the upstream natural site was enhanced and became similar to reference sites, while that of six other sites un-connected with the reference site, remained significantly different from reference sites.
Thompson (2015) Thompson et al. (2017) UK (5)	Addition of woody material	BACI (1)	Installed LWD were not successful in enhancing the reach-scale geomorphology. Macroinvertebrate abundance and biomass were higher within LWD habitat. At reach-scale, biomass was significantly higher in rehabilitated reaches than un-rehabilitated, but density and richness, diversity, and FFGs composition did not differ.
Dolph et al. (2015) Minnesota, USA (3)	Addition of boulders and woody material, riparian re-vegetation	CI (1)	No significant improvement in taxa richness and EPT abundance%. Macroinvertebrate density and number of EPT taxa significantly increased. Biomass doubled in rehabilitated reaches and production was 2 to 3 times higher in rehabilitated reaches. Collector-filterers production were dominant.
Verdonschot et al. (2015) 10 European countries (19)	Channel widening, removal of bank fixation, re-meandering, reconnection of lateral sides, and addition of in-stream structures	CI (3-18)	There were no significant effects on overall macroinvertebrate total richness, diversity, and EPT richness, or diversity. The limited overall effect on macroinvertebrates reflects the limited effect of most rehabilitation measures on biotope composition and diversity.
Neale and Moffett (2016) New Zealand (2)	Daylighting, entire-channel reconfiguration through removal of concrete pipes, addition of boulders, cobbles and LWD.	BACI (1.5)	There was significant increase in EPT richness after daylighting restoration in only one reach. FFGs changed from collector- to grazer-dominant community. Macroinvertebrate community taxonomic composition did not change after daylighting.
Nordhov and Paulsen (2016)	Building a new island, re-opening of side	CI (1)	They stated that, "it is too early to conclude whether the restoration processes have started

Norway (1)	channels, riparian rehabilitation.		among in the macroinvertebrate community and more investigations are needed''. They collected macroinvertebrate samples one year after the rehabilitation process.
White et al. (2017) UK (3)	Creating a multi-channel platform by vegetation islands.	CI (7-16)	Macroinvertebrate community composition (both taxonomic and functional elements) of the rehabilitated reach was still similar to that of the degraded reach (control reach). There were no significant indications of structural or functional turnover of macroinvertebrate communities after the rehabilitation process. There were fewer crustaceans (Asellidae and Gammaridae), which could be attributed to a reduction in the amount of coarse organic particulate matter being retained within mineralogical patches.
Al-Zankana (2018) UK (2)	Meandering, in-stream biotope restoration, gravel installation, LWD installation, riparian revegetation.	BACI (1-2)	In-stream biotope number and diversity were increased in both rehabilitated reaches. Macroinvertebrates community composition (both taxonomic and FFGs) were enhanced to become more similar to those of the non-degraded reaches. There were significant increases in the macroinvertebrate total density, total biomass, taxa richness, diversity and secondary production in the rehabilitated reaches.
Li et al. (2018) China (1)	Creation of instream wetland, groyne, artificial drop and boulder placement	CI (2-6)	Continuous improvement in physical habitat quality led to a significant increase in macroinvertebrate taxa richness, diversity and evenness.
Lium (2018) Norway (2)	Meandering, reducing sedimentation, channel reopening and boulder addition	CI (8)	The project was not successful in enhancing the restored reach's macroinvertebrate diversity.
Martín et al. (2018) Switzerland (1)	Channel widening to improve sediment retention	CI (12)	Despite enhancement of habitat heterogeneity, the restored reach's macroinvertebrate total density and taxa richness were less than those of the degraded reach (control reach).
dos Reis Oliveira et al. (2019) Netherlands (1)	Adding sand and LWD	CI (1)	Initial decreases in macroinvertebrate diversity were observed after sand addition, but this recovered rapidly following stabilisation. Patches recently covered by sand had significantly lower macroinvertebrate diversity and richness.
Esdar (2019) Norway (7)	Channel connectivity and gravel installation.	CI (1)	There were no significant effects of the rehabilitation process on the rehabilitated reach's macroinvertebrate diversity.
Funnell (2019) New Zealand (1)	Channel widening, riparian revegetation and LWD addition	BACI (<1)	Several macroinvertebrate taxa showed predominantly negative effects of increased sedimentation from the mechanical rehabilitation work. Post- rehabilitation data were collected 2 days after the completion of the mechanical restoration to assess short-term impacts of restoration work

Note, FFG, Functional Feeding Group; LWD, Large Woody Debris ; EPT, Ephemeroptera- Plecoptera- Trichoptera; IBI, Index of Biotic Integrity; PSI, Proportion of Sediment-sensitive Invertebrates; QMCI, Quantitative Macroinvertebrate Community Index; CC, Community Composition (using Bray-Curtis Similarity Index); FRG, Functional Response Group; SDI, Spatial Diversity Index.

Table 3. Outcomes of rehabilitation projects as assessed by macroinvertebrate community parameters. Projects were placed into one of four categories according to the rehabilitation methods used. Outcomes are listed as a percent of projects recording significant improvement in macroinvertebrate density (Individual·m^{-2}), taxa richness, diversity, evenness, biomass (energy or mgDM·m^{-2}), functional feeding group FFG%, FFG richness, Ephemeroptera-Plecoptera-Trichoptera (EPT)%, EPT richness, invertebrate Biological Index (BI), secondary productivity (energy or mgDM·m^{-2}·$year^{-1}$), or other parameters (e.g. Proportion of Sediment-sensitive Invertebrates (PSI); Quantitative Macroinvertebrate Community Index (QMCI); macroinvertebrate functional response group ; community composition determined by Bray-Curtis similarity index). Note that many studies assessed more than one outcome measure.

Parameters used to assess success of rehabilitation project	Rehabilitation category							
	Entire-channel hydromorphological		In-stream hydromorphological		Longitudinal and lateral connectivity		Riparian rehabilitation	
	Percentage of projects recording significant improvement	Number of projects	Percentage of projects recording significant improvement	Number of projects	Percentage of projects recording significant improvement	Number of projects	Percentage of projects recording significant improvement	Number of projects
Density	10%	99	22%	125	87%	23	0%	11
Richness	10%	157	16%	114	91%	22	18%	11
Diversity	12%	122	6%	80	0%	1	-	0
Evenness	25%	8	50%	4	-	0	-	0
Biomass	11%	9	54%	24	-	0	25%	4
FFG	16%	76	21%	72	-	0	-	0
EPT	11%	44	22%	27	100%	2	80%	5
BI	20%	20	5%	20	-	0	80%	5
Productivity	100%	1	71%	7	-	0	-	0
Other	36%	25	5%	22	-	0	100%	2

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