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RESEARCH PAPER

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Effective restoration measures in river‐floodplain ecosystems: Lessons learned from the 'Wilde Mulde' project

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Abstract

Over the last 40 years, a growing number of restoration projects have been implemented to improve the ecological conditions of highly degraded rivers and their floodplains. Despite considerable investment in these projects, information is still limited about the effectiveness and the success of such river restoration measures, mainly due to a lack of standardised and interdisciplinary assessment approaches. During the project 'Wilde Mulde—Restoration of a dynamic riverine landscape in Central Germany', we implemented hydromorphological restoration measures (installation of large wood, removal of rip-rap, reconnection of a former river side-arm) along a lowland river in Central Germany. We carried out intensive scientific monitoring of biodiversity, hydromorphology, ecosystem functions and services, as well as socio-economic aspects. A Before/After-Control/Impact (BACI) design was used to identify the spatial and temporal effects of the restoration measures and to distinguish them from changes caused by background variation. For this, we used a comprehensive set of indicators, including abiotic (flow velocity, diversity of riverbed topography, and flow resistance), biological (ecosystem respiration, macro-invertebrates, fish, carabids, vegetation, and birds) and socio-economic (acceptance and public awareness) indicators as well as the ecosystem service indicator aesthetic quality of the landscape. To meet the inherent challenges of such a large-scale field experiment, like unpredictable environmental conditions, we used an experimental approach that allowed us to demonstrate a measurable success of the implemented restoration measures. The majority of the abiotic and some of the biological and socio-economic indicators at the restored sites approached values of a natural reference site while already deviating from values of a nonnatural reference site two years after restoration. In addition to the applied interdisciplinary approach, multiple scales of field investigations and data analyses are essential as key components for evaluating successful river and floodplain restoration projects.

KEYWORDS
floodplain, indicators, restoration, river, Wilde Mulde

1 | INTRODUCTION

Dynamic rivers and their floodplains are among the most species-rich environments, providing a range of unique and essential ecosystem functions and services (Tockner & Stanford, 2002). A diverse hydromorphological template and a dynamic hydrological connectivity between rivers and their adjacent floodplains are key drivers for conserving and enhancing biodiversity and ecosystem services in riverine landscapes (Tockner & Stanford, 2002). When considering the restoration of rivers and fluvial systems, ecological restoration should be seen as those efforts that help with the recovery of a degraded, damaged, or destroyed ecosystem (SER, 2021) and as the efforts that return ecosystems to their original, undisturbed state (Bradshaw, 1996; Roni et al., 2005). This suggests that restoration is not simply the opposite of degradation (Moerke et al., 2004). Restoration reinstates essential key processes and improves the degraded state of a habitat. It aims at eliminating the causes of degradation (e.g., flow regulation, reduced habitat diversity, and reduced connectivity) rather than merely addressing the symptoms (e.g., reduced fish density) in an impaired system (Woolsey et al., 2005). Rivers are strongly impacted by various human activities, which often lead to severe degradation (e.g., EEA, 2016; Jungwirth et al., 2002). Thus, river restoration primarily addresses the impacts from anthropogenic hydromorphological stressors (e.g., flow regulation, damming, channelisation, diking, dredging) while implementing measures to mitigate these impacts (e.g., dam removal, remeandering, the reconnection of backwaters). In Europe, most floodplains are degraded (Schindler et al., 2016). It is often the lateral connectivity that is disrupted, accelerating both the disconnection of secondary channels and the drying out of floodplains (Hein et al., 2016; Paillex et al., 2009). This negatively affects the dynamic links between various water bodies of the floodplain and the main river channel (Amoros & Bornette, 2002), leading to permanent alterations in freshwater biodiversity (Tockner & Stanford, 2002) and ecosystem functioning (Funk et al., 2019). Restoration measures are therefore required to reverse these negative trends and restore habitat diversity in the long run (Amoros, 2001; Pander et al., 2018). Incentivised by the EU Water Framework Directive and the required river basin management plans, there has been a growing interest in restoration programmes and restoration ecology over recent decades (Paillex et al., 2009). Although a wide range of river restoration techniques has been implemented over the past 100 years, floodplain restoration has become more important in recent decades (Morandi et al., 2017; Roni et al., 2019) with few exceptions, of course, such as the restoration along the Old Rhine River (Schmitt et al., 2019). Most restoration projects in floodplains are still performed on a relatively small scale and are restricted to single measures, such as removing a few hundred metres of riverbank stabilisation. Nowadays, however, there are also massive engineering projects with various restoration measures, including the relocation of roads, levees, and infrastructure for 5–20 km of the river (Roni et al., 2019). With recent political attempts by the European Biodiversity Strategy (COM, 2020) to encourage restoration along European rivers, it is imperative to develop consistent approaches when monitoring restoration effects. The development of this kind of consistent approach can benefit from a scientifically sound evaluation of the effectiveness and success of restoration projects. Only a few projects included a scientific monitoring scheme, revealing that many restoration measures did not have the expected effect on biodiversity and indicating that local restoration measures could even fail (Kail & Wolter, 2010). While there is a need for appropriate monitoring systems, it is just as urgent to develop standardised and interdisciplinary evaluation approaches to record the effectiveness and success of restoration measures in a statistically sound manner (e.g., Feld et al., 2011; Jähnig et al., 2011; Morandi et al., 2017; Palmer et al., 2005). Much of this discrepancy can be attributed to our current lack of understanding of drivers and their multiple effects and interactions in complex systems such as floodplains, and the effectiveness of responses (e.g., Haase et al., 2013; Kail et al., 2015; Palmer et al., 2010). Restoration ecology is still largely based on the hypothesis that habitat heterogeneity is a main driver of biodiversity (e.g., Feld et al., 2011; Oliveira et al., 2020; Roni et al., 2019), while integrative approaches that consider interactions of stressors and their biological effects are still rare (e.g., Feld et al., 2011; Oliveira et al., 2020). Therefore, the relationships among biological, geomorphological, and hydromorphological diversity remain poorly understood due to the lack of data collected on the relevant spatial and temporal scales (e.g., Vaughan et al., 2009) and the missing of long-term restoration monitoring (e.g., Hering et al., 2013). One such gap is the link between the endpoint of restoration (e.g., the restoration target) and its difference to the ecological status before degradation. Another is the time scale required for an ecosystem to recover from degradation (Feld et al., 2011). To address some of these challenges, several studies have described the Before/After-Control/Impact (BACI) design as suitable because it monitors both temporal and spatial variations in impact assessments (e.g., Fisher et al., 2019; Haase et al., 2013; Mahlum et al., 2018; Oliveira et al., 2020). However, several evaluation programmes suffer from the lack of such a statistically sound design, making it often impossible to distinguish restoration success from background variation, which occurs irrespective of restoration. Furthermore, few studies evaluate the provision of ecosystem services as another possible parameter to describe the success of river restoration measures (Schindler et al., 2014; Schirmer et al., 2014). Within the 'Wilde Mulde' project, we aimed to implement an interdisciplinary approach that integrated several indicators, that is, abiotic (flow v elocity, diversity of riverbed topography, and flow resistance), biological (ecosystem respiration, macroinvertebrates, fish, carabids, vegetation, and birds), and socio-economic (acceptance and public awareness) indicators, as well as the ecosystem service indicator aesthetic quality of the landscape. We aggregated those indicators from a range of individually measured indicators to comprehensively monitor the effects of two different restoration measures (installation of large wood [LW], removal of rip-rap [RR]). We measured the postrestoration effects for the installation of LW compared to a control site without LW and the postrestoration effects for the removal of RR compared to two reference conditions: a stabilised (RR) and a non-stabilised riverbank (natural riverbank). The latter is not very often the case, given how rare natural, undisturbed stretches of rivers are and therefore represents a special quality of the 'Wilde Mulde' project.

2 | THE 'WILDE MULDE' PROJECT

2.1 | Study area

The study area encompasses a 24-river kilometre section (between 51°52′05.0″ N 12°14′56.9″ E and 51°43′18.0" N 12°17′35.7″ E) of the Mulde River, a lowland tributary of the Elbe River in Germany. It is part of the UNESCO Biosphere Reserve River Landscape Elbe (Figure 1), and large sections of the river course and floodplain areas have been protected as part of the nature reserve "Untere Mulde" since 1961.

The entire study area is part of the Natura 2000 site "Untere Muldeaue" (DE 4239-302) and includes many listed habitat types according to Annex 1 of the EU-Habitat Directive, including rivers with submerged floating vegetation (number [nb.] 3260), dynamic riverbanks (nb. 3270), softwood (willow), alluvial forests (nb. 91E0), and hardwood riparian mixed forests (nb. 91F0). Moreover, the study area is also part of the UNESCO World Heritage Site "Dessau-Wörlitzer Gartenreich" (summarised by Schulz-Zunkel et al., 2017). The Mulde River is classified as a lowland stream with a mean annual discharge of 66.7 $m^3 s^{-1}$. It shows a pronounced hydrologic variability ranging from a mean low discharge of 17.9 $m^3 s^{-1}$ to a mean high discharge of 450 $m^3 s^{-1}$ (LHW, 1995–2017, averaged discharges at the gauging station Priorau, 51°73′ 19.8" N, 12°29′44.1" E). Over the project period, discharge dynamics were characterised by one bankfull event and two events with slightly higher water levels (2017 [bankfull]: 352 m³ s^{-1}, 2019: 286 m³ s^{-1}, 2020: 184 m³ s^{-1}, maximum measured discharges at the gauging station Priorau, 51°73′19.8″ N, 12°29′44.1″ E) and almost three dry years with the lowest discharge values ever recorded for that area (2018: 9.55 m³ s^{-1}, 2019: 11.4 m³ s^{-1}, 2020: 10.1 m³ s^{-1}, minimum measured discharge at the gauging station Priorau) (Figure 2).

FIGURE 1 The Mulde River catchment and the location of the project area in Germany

Habitat types found in the Mulde floodplains are a mosaic of oxbow lakes, grasslands with flood channels, remnants of hardwood floodplain forests, as well as arable land (Brunotte et al., 2009). However, in spite of a high-quality natural environment in some parts of the Lower Mulde, the river floodplain lacks natural hydromorphological dynamics in many river sections (Puhlman & Rast, 1997). It is exposed to riverbed erosion, mainly caused by several weirs and in particular due to the Mulde reservoir (all upstream of the study area), which retains large amounts of river sediment (Junge, 2015). Structural measures, such as riverbank stabilisation, accelerate the deepening of the river even more. The resulting lowered stream water level has had a negative impact on the groundwater level in the floodplain, leading to a faster ageing of the wetlands and oxbow lakes. Large wood is scarce in the Lower Mulde, mainly due to deforested riverbanks, and in many places, lateral side erosion is prevented by riverbank protection using rip-rap (Schulz-Zunkel et al., 2017). The entire catchment area of the Mulde (approx. 7000 km²) is heavily polluted with contaminants from the activities of former mining and chemical industries (e.g., Greif, 2015; Klemm et al., 2005). Until the 1990s, the Mulde, along with its tributary Spittelwasser, were among the most polluted river systems in Europe (e.g., Feldmann et al., 1997; Jacobs et al., 2015). Despite the significant improvement in water quality, inorganic and organic pollutants can still be detected in the riverbed sediment and floodplain soils (e.g., Junge et al., 2020). Therefore, potential remobilisation through restoration measures had to be examined in detail during the project.

2.2 | Restoration measures and expected outcomes

The project 'Wilde Mulde' aimed to sustainably promote the natural riverbed dynamics of the Lower Mulde by implementing defined restoration measures to restore hydromorphological processes in the river and to improve the hydrological connectivity of the river with its

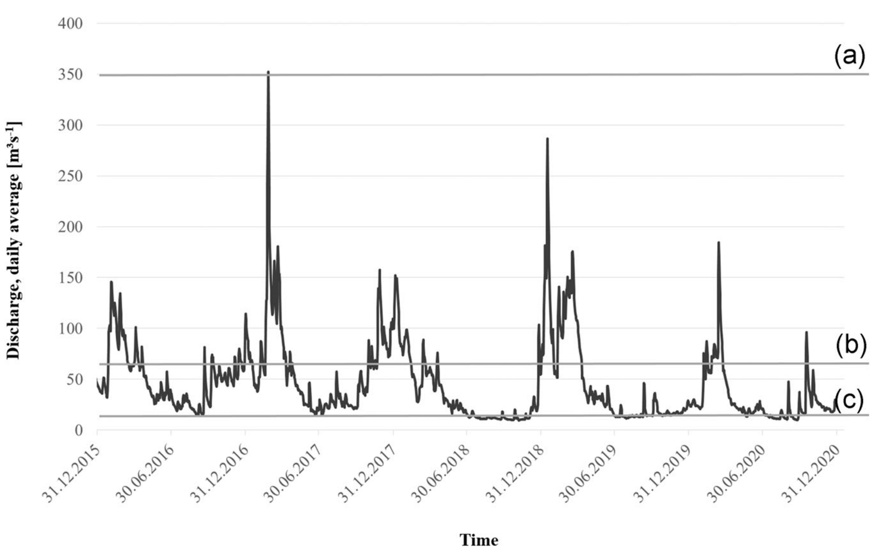

FIGURE 2 Discharge dynamics during the project period (December 2015– December 2020) and mean discharge dynamics as 20-year averages at the gauging station Priorau, 51°73′19.8″N, 12°29′44.1″E. (*Source*: LHW, 1995–2017). (a) bankfull >350 m³ s^{-1}, (b) mean discharge = 66.7 m³ s^{-1}, and (c) mean low discharge = 17.9 m³ s^{-1}

adjacent floodplains. As a result of these measures, we expected new pioneer sites to be created where species and biological communities could find suitable habitats that are considered particularly endangered at the national and the European level. Three restoration measures were implemented to achieve these goals (Figure 3 and Table S1).

2.2.1 | Installation of large wood

Large wood (LW) is underrepresented in German rivers. It modulates its hydromorphology, increases lateral connectivity, and creates new habitats for aquatic and riverine flora and fauna (e.g., Anlanger et al., 2022; Pilotto et al., 2014). A total of six felled trees (with an average length of 20 m) were installed in the Lower Mulde River. Each location represented a relatively uniform, poorly structured riverbed. Two trees were installed in October 2017, and four more trees in September 2018. Hybrid poplars (rather than indigenous oak or elm trees) from the surrounding area were felled and used. The trees were permanently fixed to the riverbed by chaining each individual tree to six concrete blocks to prevent dislocation during floods or thick ice. Immediately after the installation of LW, we expected the resulting turbulent flows to alter the local streamflow conditions and thus reshape the riverbed in the direct vicinity and leeward of the LW. One site was purposely chosen next to a pedestrian bridge to enable interested people passing by to observe the morphological development and biological effects on birds and fish.

2.2.2 | Removal of rip-rap

A cut bank with a length of about 500 m stabilised by rip-rap (RR) was restored. This was done by removing an approx. 1 m thick

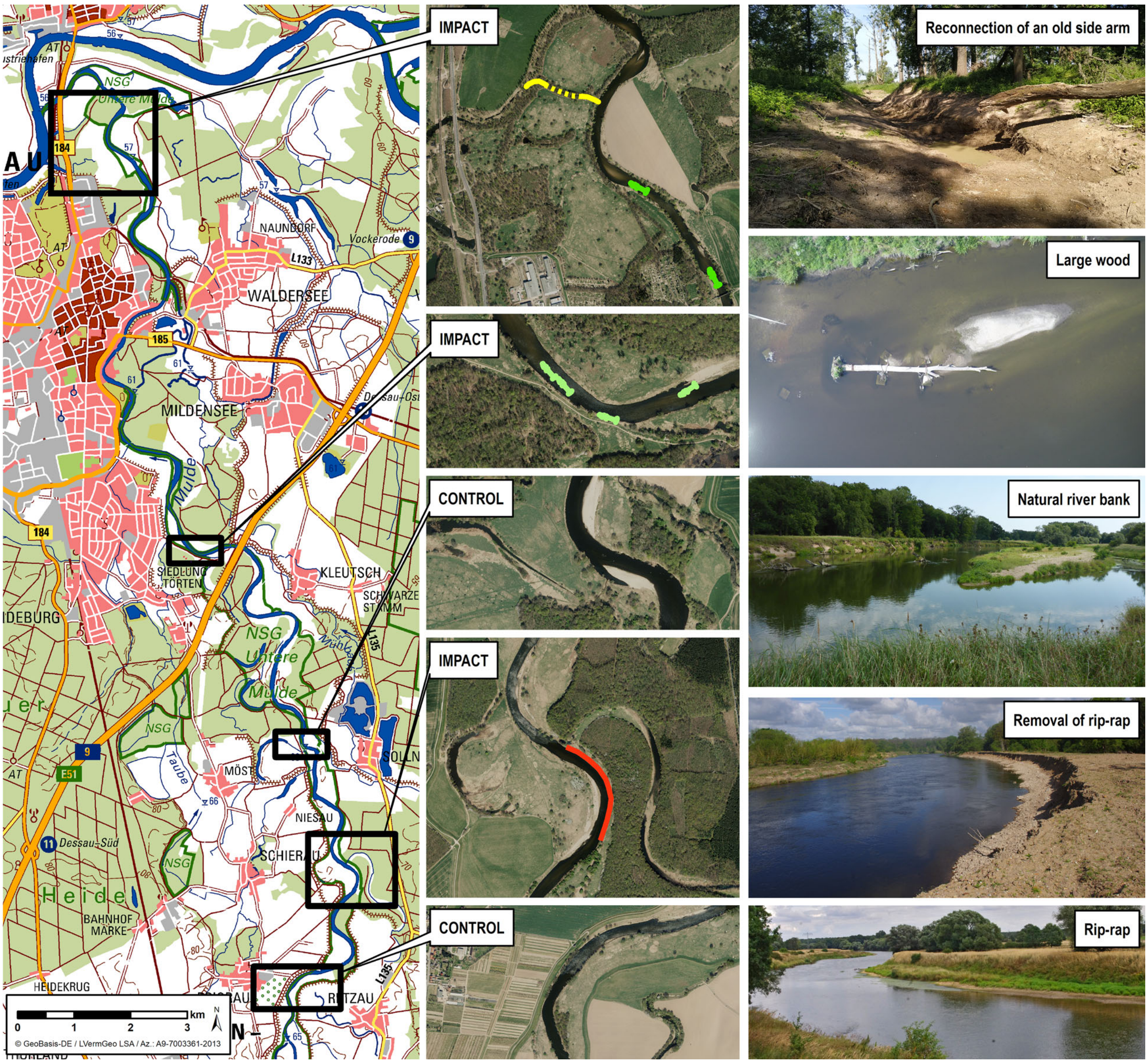

FIGURE 3 Overview of the project area 'Wilde Mulde', the study sites and the restoration measures implemented (yellow line: reconnection of a former river side-arm; light green lines: installation of large wood; red line: removal of rip-rap)

revetment of porphyry stones built in 1989 as part of a maintenance stabilisation measure. The restoration of this cut bank was to enable the formation of steep slope cut banks typical for dynamic rivers. Moreover, gravel bars on the opposite side or downstream (slip-off slopes) should then form due to the mobilisation of sediment from new erosion. We expected both the cut banks and the slip-off slopes to provide valuable habitats for riverine birds, such as the Common Kingfisher *(Alcedo atthis)*, the Sand Martin *(Riparia riparia)*, the Little Ringed Plover *(Charadrius dubius)*, and the Common Sandpiper *(Actitis hypoleucos)* among others. We also expected this restored river section to meander once again. In other, non-stabilised sections, the Mulde River had shown meandering movements of 40 m within 15 years. However, the expected meandering movements are difficult to predict as this process largely depends on the dimensions of the river channel planform (e.g., the curvature and the width of the meander bend), the soil type, as well as LW in the proximity of the cut banks and, most importantly, on the number and duration of bankfull and overbank discharges in the respective sections. In any case, we expected a significant local improvement in hydromorphology and natural river dynamics, as well as a substantial increase in lateral riverbank erosion. Ideally, this would be accompanied by the undercutting of trees close to the riverbank (along the cut bank between 25 and 45 m until the forest), ensuring a naturally increased amount of LW in the river. Improved lateral erosion can increase the sediment input associated with natural LW input, which may positively affect processes such as aquatic-terrestrial connectivity between the river and its adjacent floodplains (e.g., Paetzold & Tockner, 2005; Ward, 1989). This improvement in river dynamics should result in new structures and create a more diverse riverbed topography ranging from deep to shallow waters, gravel bars, and slip-off slopes, as well as new potential sites for softwood riparian mixed forests.

2.2.3 | Reconnection of a former river side-arm

Only a few of the former river side-arms or oxbow lakes in the floodplain are still connected to the river during flood events. This has resulted in the drying out of these floodplain structures. With the reconnection of a former river side-arm to the Lower Mulde River, this process could be slowed down, and characteristic dynamics be initiated, and thus, we expected that an important floodplain habitat could be restored. The former river side-arm was reconnected to the Mulde River at mean discharge (66.9 $m^3 s^{-1}$, LHW, 1995–2017, gauging station Priorau). Due to its location close to the Elbe River, the side-arm now directly connects the Mulde to the Elbe. This connection favours a more varied confluence of the mouth of the Mulde River and forms an ecologically valuable side-arm with regular interaction between both rivers and their floodplains. Furthermore, we expected that after the flooding of this almost 2 km long flood channel system, temporary ponds would remain in the connected side-arm throughout the year, thus providing valuable habitats for amphibians and dragonflies, for example.

2.3 | Study design

The assessment of the implemented restoration measures followed the BACI design (before vs. after, control vs. impact; here, the impact is one of our restoration measures) (Smith, 2002; Stewart-Oaten & Bence, 2001). A full BACI design was implemented for the restoration measures installation of large wood (LW) and removal of rip-rap (RR). For LW, the control site was a defined river section without LW, whereas the impact site was where the LW was installed. Changes deviating from the conditions of the control site were defined as a restoration success. For RR, we designated two types of control sites: a stabilised river bank and a non-stabilised riverbank (natural riverbank). Thus, we had the unique opportunity to include a natural reference site in this project. The success of this restoration measure was defined as any change that led to an approximation of the natural condition of the river bank at the reference site. We defined abiotic, biological, and socio-economic indicators and the ecosystem service indicator aesthetic quality of the landscape that can be used to determine changes due to the restoration measures. For each of these indicators, we assessed the effect of the restoration measures installation of LW and removal of RR at two different spatial scales and various strata. Local-scale effects were measured at single strata directly affected by the impact (river, cut bank). Reach-scale effects were measured for RR only, referring to effects measured at several strata (cut bank, slip-off slope, river) integrated for the whole meander curve (see red line in Figure 2b and Table 1). The used monitoring design for the investigated indicators was based on sampling plots (selected according to a raster-based, stratified random design) and for some species groups on transects reflecting hydrological gradients (Figure S1). We conducted repeated sampling before the treatment. For all indicators, at least one complete data set was available after the treatment (Table 1).

2.4 | Data analysis

We investigated the effect of the restoration measures on several abiotic, biological, and socio-economic indicators as well as on the ecosystem service indicator aesthetic quality of the landscape (Tables 1 and 2). As abiotic indicators, we selected the riverbed topography and the composition of the bed material to quantify morphological changes, as well as water depth, flow velocity, and turbulence to document the development of hydraulic and hydromorphological diversity. As biological indicators, we selected ecosystem respiration and different organism groups (macroinvertebrates, fish, dragonflies, carabids, vegetation, and birds) that were shown to be sensitive to hydrological changes. Their positive responses to restoration have been frequently reported (Pilotto et al., 2019). As socio-economic indicators, we selected acceptance, minimising conflicts, and public awareness. These indicators reflect whether residents and other stakeholders were involved in the implementation and if their involvement was beneficial, for example, if it increased knowledge. For the biological indicators, we used several individual indicators

TABLE 1 Overview of indicators for assessing the effects of the restoration measures

Indicators	**Impact**-sites								**Control**-sites							
	Removal of rip-rap (RR)				**Large wood[1] (LW)**				**Rip-rap[2] (RR)**				**Natural riverbank[3]**			
	Riv	CuBa	SoS	FP	Riv	CuBa	SoS	FP	Riv	CuBa	SoS	FP	Riv	CuBa	SoS	FP
Abiotic indicators																
Mean flow velocity					x[4]											
Flow diversity	x	x	x		x				x	x	x		x	x	x	
Diversity of river bed topography	x	x	x		x	x	x		x	x	x		x	x	x	
Sediment diversity	x	x	x		x	x	x		x	x	x		x	x	x	
Reducing flow resistance					x[4]											
Hydromorphological diversity	x	x	x		x	x	x		x	x	x		x	x	x	
Biological indicators																
Ecosystem (metabolism) respiration	x	x	x		CI[5]				x	x	x		x	x	x	
Benthic food web	x	x	x						x	x	x		x	x	x	
Macroinvertebrates	x	x	x		CI[5]				x	x	x		x	x	x	
Fish	x	x	x		x	x	x		x	x	x		x	x	x	
Macrophytes	x								x				x			
Dragonflies		x	x							x	x			x	x	
Carabids		x	x							x	x			x	x	
Vegetation		x	x	x						x	x	x		x	x	x
Birds		x	x	x						x	x	x		x	x	x
Socio-economic indicators																
Public awareness	[BA]				CI[6]											
Minimizing conflicts	[BA]				CI[6]											
Acceptance	[BA]				CI[6]											
Ecosystem services																
Provision of habitats	[x]				[x]				[x]				[x]			
Retention of nutrients	[x]				[x]				[x]				[x]			
Retention of sediments	[x]				[x]				[x]				[x]			
Landscape aesthetic quality	x				CI[6]				CI[7]				CI[7]			

Note: All indicators were collected according to a full BACI design (x). Exceptions are marked in the table as BA, CI. Grey fields mean: no data collected for these strata: Riv = river, CuBa = cut bank, SoS = slip-off slope, FP = floodplain. The following numbers give further specifications: 1, Installation of large wood at two sites; 2, Rip-rap at two sites; 3, Natural riverbank at two sites; 4, Measured in the laboratory; 5, Control site for the local assessment 'large wood installation' is a river section close to the impact but without large wood; 6, National level (German wide) versus local level (project area); 7, Control sites for 'landscape aesthetic quality' are two natural riverbanks. In brackets [] means that work is in progress.

(abundance, taxonomic and functional diversity, indicator and keystone species, age structure, and ß-diversity) for each organism group (Table S2). To test for an effect of the restoration measures on the abiotic, biological, and socio-economic indicators and their individual metrics, we applied separate Generalised Linear Models (GLM) with the same basic structure. In each GLM, we included two main effects: a Before–After (BA) and a Control–Impact (CI) effect, as well as the interaction term between the BA- and CI-terms (BACI; Fisher et al., 2019). Depending on the study design (Table 1), the effects of restoration were assessed using one of the three model terms (BA, CI, BACI; Table 2) by significance level ($p < 0.05$). Individual indicators were assigned to the various composite indicators. The overall effect of a composite indicator was evaluated based on the range of the effects that were assessed for the individual indicators. If either positive or negative effects were found for all individual indicators of a composite indicator, then the overall effect of the composite indicator was rated as positive or negative (respectively). If both positive and negative effects were found for an individual indicator, then the overall effect of the composite indicator was rated as ambiguous. If there were no significant effects for any of the individual indicators assigned to a composite indicator, its overall effect was rated as zero. A positive effect means that the indicator became more similar to the natural conditions, while a negative effect means that the indicator became less similar to natural conditions. For abiotic indicators, we could not

TABLE 2 Changes in the investigated abiotic, biological, and socio-economic indicators and the ecosystem service indicator aesthetic quality of the landscape after implementing the restoration measures installation of large wood (LW) and removal of rip-rap (RR) on different spatial scales (local-scale$_{ls}$ refers to effects measured for individual strata that were directly affected by the impact [river, cut bank], reach-scale$_{rs}$ effects were measured for RR only, referring to effects measured for several strata [cut bank, slip-off slope, river] integrated for the whole meander curve)

	Large wood (LW)			Removal of rip-rap (RR)					
	local-scale (LW_{ls})			local-scale (RR_{ls})			reach-scale (RR_{rs})		
	BACI	BA	CI	BACI	BA	CI	BACI	BA	CI
Abiotic indicators									
Mean flow velocity	↗[1]								
Flow diversity	↗[1]				↗[2]				↗[2]
Reducing riverbed deepening	↗			↗			↗		
Diversity of river bed topography	↗			↗			0		
Sediment diversity		↗↘				↗↘			↗↘
Flow resistance	↗								
Biological indicators									
Ecosystem (metabolism) respiration			0	0			0		
Macroinvertebrates			0	0			0		
Fish			↗				↗↘		
Dragonflies				0			0		
Carabids				0↗			0		
Vegetation				0↗			0		
Birds				↗					
Socio-economic indicators									
Acceptance			↗					↗	
Minimizing conflicts			↗					↗	
Public awareness			↗					↗↘	
Ecosystem services									
Landscape aesthetic quality			↗↘						↗

Note: 0, no effect; ↗, positive effect towards natural conditions; ↗↘, ambiguous effect; black arrows show effects based on statistical evidence, grey arrows show tendencies; effects that were not investigated are shown with light grey highlighted fields; [1]results based on laboratory experiments, [2]results based on field survey from 2020 only.

apply the GLM-model. Nevertheless, to achieve comparability with the statistics used for the other indicators, the mean values and standard deviations of the measured abiotic indicators were analysed to show trends of change. For the socio-economic indicators, we used rating scale statements in multiple questionnaire surveys. For LW, we phrased seven different statements on possible positive effects, dangers, and the approval and rejection of such a measure. These statements were included in a national online survey (Gapinski et al., 2020) and local online and face-to-face surveys. Because the local surveys were conducted after the restoration measure was implemented, a before-after effect was estimated by comparing the national sample (without environmental education offerings) and the local samples (after environmental education was provided). The mean values of both samples were compared with the non-parametric Wilcoxon rank-sum test. For RR, only an after-implementation survey with a small sample was carried out. These nonrepresentative results could only be compared with verbal and written statements from the early project phase before implementing the restoration measures, which tended to be characterised by rejection and misunderstandings. Thus, the results only represent a tendency. The visual attractiveness of the sites, which is summarised under the ecosystem service indicator landscape aesthetic quality, was also queried for LW using ranking statements in the online surveys (national/local corresponds to control-impact). Photo-based questions from the local online and face-to-face surveys were used for RR. Participants subjectively rated various sites with fixed and natural river banks in terms of their visual attractiveness.

3 | RESULTS

We assessed the responses of 12 indicators for LW and 14 indicators for RR, and the indicator for the ecosystem service aesthetic quality of the landscape for both (Table 2). The impact assessment for some socio-economic indicators and three more ecosystem services (Table 1) are not yet finalised. LW mainly caused local-scale effects on the single strata (here: river), and we observed significant positive effects for fish, acceptance, minimising conflicts, and public awareness, whereas no effects were found for ecosystem respiration as well as macroinvertebrates. RR caused effects on the local scale (RR_{ls}), namely for the strata river, cut bank, and partly slip-off slope, as well as on the reach-scale (RR_{rs}), in other words, on the entire meander curve (see red line in Figure 2b). For RR_{ls}, we observed significant positive effects for birds, zero to positive effects for carabids and vegetation, but no effects for ecosystem respiration, macroinvertebrates, and dragonflies. For RR_{rs}, we saw a significant positive effect for the aesthetic quality of the landscape, ambiguous effects for fish, and no effects for ecosystem respiration, macroinvertebrates, dragonflies, carabids, and vegetation. For all abiotic indicators and both measures, only trends for effects were observed. However, the preliminary analysis of the abiotic data showed that both restoration measures initiated changes towards natural conditions. In fact, only the effect of sediment heterogeneity was ambiguous in terms of the bimodality of the river bed material. The sediment was very clearly dominated by coarse sand and medium gravel, while fine gravel was much less present. We also only observed tendencies for the investigated socio-economic indicators for RR_{rs}. For all indicators, but especially those with ambiguous and zero to positive results, a closer look is needed at the single indicators considered for the overall assessment (Table S2). Only one or two individual indicators could be assigned to the composite indicator's macroinvertebrates and fish for LW and birds for RR_{ls}. For the composite indicator's vegetation and carabids for RR_{ls}, individual indicators showed such different responses that no clear overall assessment was possible.

4 | DISCUSSION

There is a consensus on the importance of river and floodplain restoration, but it is still debated as to what constitutes a successful restoration project in detail. Several authors have addressed this issue over the years and established different criteria and standards for measuring the effectiveness of successful river and floodplain restoration from an ecological perspective. The studies range from more general ones, describing the success of restoration measures (Kondolf, 1995; Palmer et al., 2005; Woolsey et al. 2007; Jähnig et al., 2011) to studies that focused on the analysis of indicators and statistical evaluations (Vermaat et al., 2016; Weiwei et al., 2019). Nowadays, studies also try to consider the concept of ecosystem services and integrate the different requirements of the conservation objectives set out in the legislation (Schindler et al., 2016; Weigelhofer et al., 2020). However, the ongoing loss of biodiversity in rivers and their floodplains has not yet been stopped (EEA, 2020). The first step towards mitigation was made when the European Biodiversity Strategy (COM, 2020) set the goal that by 2030, European rivers should become free-flowing again over a length of at least 25,000 km. Therefore, we need to be able to effectively demonstrate a reversal of biodiversity loss (Mace et al., 2018) and legitimately show the success of urgently needed restoration measures. In this respect, the 'Wilde Mulde' project aimed to implement a comprehensive and interdisciplinary approach. This project was unique due to its close cooperation between on-ground implementation and scientific evaluation throughout the project lifetime. We implemented three restoration measures over the five-year duration of the project, accompanied by intensive stakeholder participation and scientific monitoring for all measures with regard to their ecological impact. We can therefore ascertain that with this project, we almost had an ideal situation that satisfied stakeholder needs (stakeholder success) and improved scientific understanding and the practical aspects of river and floodplain restoration (learning success), enabling the project to be successful both from an ecological and a societal perspective in the way that Palmer et al. (2005) described. In terms of our definition of ecological success for the implemented restoration measures (RR: towards the reference site natural riverbank and LW: changes deviating from the conditions of the control site) that were carried out using the BACI design, we observed a success for LW regarding mean flow velocity, flow diversity, reduced riverbed deepening, diversity of riverbed topography, flow resistance and for RR_{ls} regarding carabids, vegetation, and birds. Overall, we saw no response of aquatic biota (macroinvertebrates including dragonflies) to either of the two restoration measures. We attribute this variation to small-scale hydromorphological heterogeneity, which causes greater structural effects within rather than between different sites and comparably stronger responses of terrestrial than for aquatic biota (Pilotto et al., 2019). However, almost all of the abiotic as well as the socio-economic indicators showed mainly positive responses to both restoration measures, independent from scales. This allows us to make an overarching statement about the effects of the restoration measures, which are not only limited to the ecological effects. Nevertheless, the question about the success or the effectiveness of the restoration measures is limited to short-term responses rather than long-term ones since (i) we only recorded data for a maximum of two years after implementing the measures, so we were only able to detect short-term responses, (ii) restored habitats were still strongly influenced by the construction work itself, and (iii) two consecutive years with very low water levels (Figure 2) significantly slowed down the progress of the restoration measures towards natural conditions because higher water levels are crucial for triggering the expected geomorphic dynamics. These uncertainties clearly illustrate the difficulty in assessing the success and effectiveness of both measures. Therefore, we hypothesise that positive short-term effects will probably become more prominent over time.

However, we strongly recommend further analysis and surveys to better describe the various responses of the investigated indicators. Moreover, the landscape context and the entire catchment's impact play an essential role in the success of the restoration measures. Thus, without detailed knowledge about, for example, erosion and sedimentation processes, suitable source populations and stepping stones for the reintroduction of various species typical for riverine floodplain systems, it is difficult to interpret the early effects of restoration and assess any long-term trends (e.g., Stammel et al., 2012). For example, specialist species are still missing in the vegetation (Seele-Dilbat et al., 2022), clearly indicating the need to include information about their distribution throughout the entire catchment area. Furthermore, for some species groups, such as dragonflies (family: Gomphidae), the ecological status was already considered to be good before the restoration measures were implemented. Some indicators measured may also reveal that there are no species pools available from which species may quickly migrate to the restored river sections. This, in turn, shows the already strong anthropogenic influence on the project area, which is still comparatively close to nature (Puhlman & Rast, 1997). To further evaluate the effects of the restoration measures, continued observation of the single abiotic (e.g., dynamic water level changes, riverbank relocation, riverbed development) and biological indicators (e.g., species abundance and diversity) is needed. Moreover, a long-term monitoring or at least a further evaluation phase is necessary to finally determine whether the implemented restoration measures are sustainable and whether the abiotic, biological, and socio-economic indicators are approaching natural conditions. In addition, longer-term evaluations are also necessary to assess ecosystem services to gain valid conclusions (MEA, 2005). In any case, the results from projects such as the 'Wilde Mulde' contribute to our understanding of drivers and their multiple effects and interactions in riverine landscapes (e.g., Anlanger et al., 2022; Gapinski et al., 2022; Kretz et al., 2021; Schnauder et al., 2021; Seele-Dilbat et al. 2022; Sprössig et al., 2022). During the scientific monitoring, we measured many indicators that contain proxies for immediate success, such as flow diversity and the diversity of riverbed topography and those that attracted keystone species such as fishes and birds. In contrast, others such as macroinvertebrates and dragonflies, as well as vegetation and carabids, need more time. Thus, we expect the latter to follow the short-term indicators with a time lag. For potential upcoming projects, we have made all the data available in a database (BEXIS 2.14.3; https://bexis.ufz.de:4434/ddm/Home/index). This will facilitate quantifying long-term effects and the interactions of stressors and their biological effects (e.g., Feld et al., 2011; Oliveira et al., 2020).

5 | CONCLUSIONS

The success and effectiveness of restoration projects in riverine landscapes face several challenges. With the project 'Wilde Mulde', we have learned that (i) a close collaboration between practice and science, (ii) constant communication with a broad range of stakeholders, and (iii) finding pragmatic solutions are essential for the acceptance and ultimately the successful implementation of restoration measures in the field. However, evidence of the success and effectiveness of restoration measures in terms of changes in abiotic, biological, and socio-economic indicators, as well as ecosystem services, ideally towards natural conditions, depends on many factors in the project and also on the catchment area. This clearly emphasises the importance of interdisciplinary approaches and considering multiple scales for field surveys and data analysis as key components for successful river and floodplain restoration projects. Still, the need for long-term interdisciplinary monitoring and evaluation of restoration measures is crucial to detect the full effect of restoration measures on both ecological and socio-economic parameters.

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DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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SUPPORTING INFORMATION

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