Received: 28 February 2021 | Revised: 26 January 2022 | Accepted: 27 January 2022

DOI: 10.1002/iroh.202102088

RESEARCH PAPER

International Review of Hydrobiology

Using the River Ecosystem Service Index to evaluate "Free Moving Rivers" restoration measures: A case study on the Ammer river (Bavaria)

Isabell Becker | Gregory Egger | Lars Gerstner | John Ethan Householder | Christian Damm

Department of Wetland Ecology, Institute of Geography and Geoecology, Karlsruhe Institute of Technology (KIT), Rastatt, Germany

Correspondence

Isabell Becker, Department of Wetland Ecology, Institute of Geography and Geoecology, Karlsruhe Institute of Technology (KIT), Josefstraße 1, 76437 Rastatt, Germany.
Email: isabell.becker@kit.edu

Handling Editor: Christiane Schulz–Zunkel

Funding information

Deutsche Bundesstiftung Umwelt, Grant/Award Number: 32894/01

Abstract

Restoring natural fluvial dynamics is fundamental for sustaining biodiversity and functional integrity of river and floodplain ecosystems. In Central Europe, however, pervasive river regulation and bank protection have greatly impaired ecosystem functioning and many water bodies fail to achieve a good ecological status within the European Water Framework Directive. The "Free Moving Rivers" approach seeks to restore the ecological integrity of rivers and floodplains by creating appropriate conditions for natural fluvial dynamics. Principal goals of the approach include removing artificial constraints on river processes and expanding the river corridor to restore natural river habitats and structures. Lacking, however, are complementary tools that evaluate and predict changes to ecosystem services (ESSs) after implementation. Here, we describe a case study of the Ammer river in Bavaria, Germany, to (i) calculate the extent of the "Free Moving Rivers" corridor, and (ii) assess changes to ESSs of a proposed river restoration measure under two alternative land-use scenarios. To do this, we apply the River Ecosystem Service Index (RESI), whereby individual ESSs are assessed in a spatially explicit way. We show how a proposed implementation of the "Free Moving Rivers" approach enhances three investigated ESSs: flood retention, sediment balance and habitat provision. We conclude that RESI is a potentially useful tool with wide applicability for restoration planning that synthesises floodplain complexity in such a way that facilitates decision making.

KEYWORDS

ecosystem services, river corridor, river development, river restoration measure, self-dynamic

1 | INTRODUCTION

Natural rivers and floodplains are valuable landscape components that provide various benefits for human well-being and ecological functioning (Fischer et al., 2019; Robinson et al., 2002; Schneider et al., 2018; Scholz et al., 2012; Ward et al., 1999). Due to their geomorphic diversity, their varied hydrological conditions, high rates of sediment and biomass turnover, and high productivity, they provide a multitude of ecological functions. These result in numerous ecosystem services (ESSs), such as the provision of food, clean water, fuel, the regulation of flood and drought, the reduction of excess nutrients, the provision of habitats with a high level of biodiversity, cultural identification and cultural assets, like, recreational hiking, fishing and natural experience (Costanza et al., 1997; Feld et al., 2011; Millennium Ecosystem Assessment (MA), 2005; Tockner & Stanford, 2002). Despite their great ecological value and the ESSs they provide, the functional integrity of many European river landscapes is impaired (Schinegger et al., 2012), with 62% having moderate to poor ecological status (Grizzetti et al., 2017). In Germany, about two-thirds of the former river floodplain areas are separated from their river channels and only 9% are classified as near-natural (Bundesministerium für Umwelt Naturschutz und nukleare Sicherheit [BMU] & Bundesamt für Naturschutz [BfN], 2021). A principal reason for the poor ecological status of European river landscapes is the reduction of fluvial dynamics caused by hydraulic-engineering measures, such as channelisation, bank protection, damming, straightening of river courses, the building of levees and intensive land-use adjacent to rivers (Brunotte et al., 2009; Feld et al., 2011; Schneider et al., 2018; Tockner et al., 2010).

Because of a strong correspondence between fluvial dynamics and the provision of ESSs, modern concepts of sustainable floodplain restoration are often based on providing space for re-establishing natural fluvial processes (Biron et al., 2014; Buffin-Bélanger et al., 2015; Piégay et al., 2005; Ward et al., 2001; Wohl et al., 2005). Enlarged floodplain corridors, for example, not only provide natural flood retention areas addressing increased flood risk in particular concerning climate change (Lobanova et al., 2018), but also sustain a natural mosaic of habitats for floodplain-specific biota (Scholz et al., 2012; Ward et al., 1999). Re-establishing fluvial dynamics therefore directly addresses ongoing biodiversity and climate crises, as well as regional governance objectives (e.g., Natura 2000) and sustainable water usage and management (e.g., Water Framework Directive [WFD]; Biron et al., 2014; Piégay et al., 2005).

The French "Espace de Liberté" approach (Freedom Space for Rivers) was the first in Europe to use characteristics of historical river mobility as a basis for recovering fluvial dynamics (Malavoi et al., 1998). Within newly expanded corridors, morphodynamic river processes are allowed to proceed with minimal constraints (Charrier, 2012; Sauvade et al., 2015). The German "Free Moving Rivers" approach ("Freier Pendelraum für Fließgewässer") is also based on this idea, seeking to provide a minimum space for ecologically functioning rivers and floodplains to re-establish important ESSs with positive effects for humans and biodiversity alike (Egger et al., 2020). Implementation requires an appropriately defined river corridor without settlements close to the river and the absence or removal of artificial structures that constrain lateral river movement. A natural or largely unaltered flow regime allowing natural erosive processes is also essential (Egger et al., 2020). Bank protection measures remain only near essential infrastructure, such as bridge pillars. Further protection measures are only necessary if the river channel approaches the boundary of the "Free Moving Rivers" corridor. Agricultural areas inside the corridor can remain in use until the lateral river migration makes it infeasible (Deutsche Vereinigung für Wasserwirtschaft Abwasser und Abfall e. V. (DWA), 2010), although reducing land-use intensity allowing riparian forest succession within river corridors are also primary goals.

Restorations of formerly altered river sections are likely to increase native biodiversity (Kail et al., 2015; Meli et al., 2014; Schindler et al., 2016; Tomscha et al., 2021), add to the multifunctionality of river systems, and thus increase ESS supply (Funk et al., 2021; Meli et al., 2014; Schindler et al., 2014). The environmental and biological complexity of river and floodplain ecosystems and their multifunctionality thus require multidisciplinary assessments that not only quantify positive and negative effects of restoration measures, but also synthesise these in such a way that facilitates decision making (Funk et al., 2021). The River Ecosystem Service Index (RESI) provides a spatially explicit tool for this multiperspective analysis (Pusch, 2016; Podschun, Albert, et al., 2018; Podschun, Thiele, et al., 2018). The index evaluates restoration measures on rivers and floodplains using existing data or, alternatively, is based on assumptions of future conditions (Stammel et al., 2021). Thus, it can be useful in establishing benchmarks for evaluating project goals and successes, as well as for comparing changes to ecosystems services under different hypothetical scenarios (Fischer et al., 2019). Furthermore, effects on ESSs can be illustrated in an easily understandable and spatially explicit format that enhances communication with public authorities and local stakeholders (Podschun, Thiele, et al., 2018).

Here, we apply the RESI approach to a proposed restoration measure according to the "Free Moving Rivers" concept on the Ammer river in Bavaria, Germany, and assess the changes to ESSs under different scenarios. The Ammer provides excellent opportunities for implementation of the "Free Moving Rivers" approach. Its floodplains are subject to intense agricultural use and natural geomorphologic features and riparian habitats are limited to a small river corridor. Erosion and sedimentation processes are largely impeded by protection structures for river training consisting of dykes, groynes, pavement or riprap in cut banks, and an elevated agricultural road on the left river bank. Local initiatives for floodplain enlargement and restoration have already been considered in recent years, particularly after the 1999 Pentecost flood, during which the Ammer overflowed the left-bank dykes downstream of Peißenberg. This led to the construction of a new dyke further away from the river and expanded the potential area for natural fluvial processes. This area is the focus of our study (Figure 1; Rempe, 2018). While the acquisition of sufficient land areas for the dynamic development of rivers is often a principal bottleneck (Damm et al., 2011), this section of the Ammer river between 137.8 and 139.2 km is already under consideration for restoration measures. Furthermore, water bodies and riparian forests in the study area are property of the local water authority of Weilheim. Land ownership obstacles (compensatory payments or property adjustments for privately owned property) are therefore considerably reduced.

We assessed the space requirements for restoration measures and resulting changes to ESSs on the lower Ammer river by answering the following questions:

(i) What is the minimum space required to implement the "Free Moving Rivers" approach in the study area on the lower Ammer river?
(ii) How will ESS provision change after implementing the proposed "Free Moving Rivers" restoration measures?

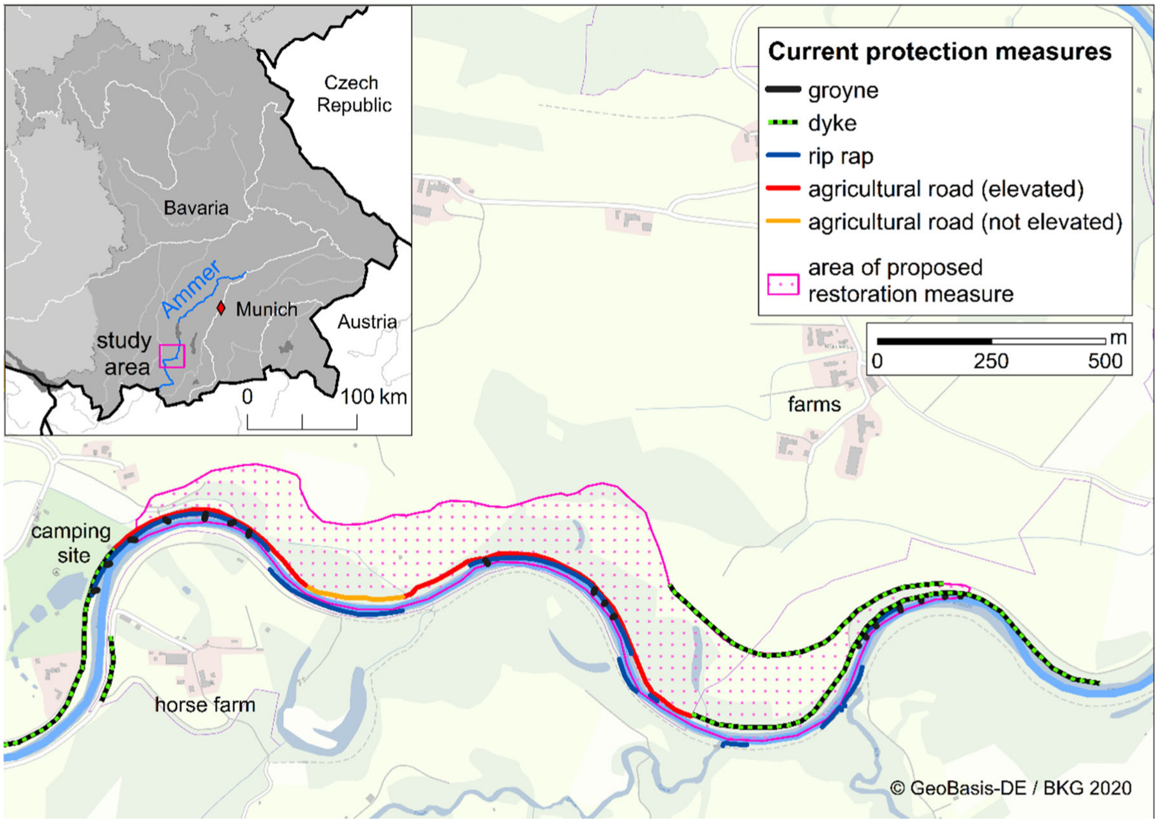

FIGURE 1 Proposed restoration area with current bank fixations and protection structures on the Ammer river upstream of Ammersee lake

2 | METHODS

2.1 | Study area

The Ammer river originates in the Northern limestone Alps in Bavaria close to the Austrian border and flows into the Ammersee lake (Ringler et al., 2000). The study area is located upstream of the Ammersee, and downstream from Peißenberg (Figure 1). River regulation structures built during the 1920s were designed to increase flood protection, expand the area for agricultural use and provide jobs (Heinrich, 2017; Weilheim Water Authority of Weilheim [WWA], 2003). As a consequence, river meanders were cut off and the river course was shortened from 94 to 82 km (Weilheim Water Authority of Weilheim [WWA], 2003). Rectification was accompanied by dyke building, which reduced the active floodplain and eliminated ecologically valuable riparian habitats (Weilheim Water Authority of Weilheim [WWA], 2003). Thus, characteristic structures of pre-Alpine rivers such as gravel bars and undercut slopes nearly disappeared, and 80% of the river is currently heavily modified (Environment Agency of Bavaria [LfU], 2017).

The Ammer river has a typical nival flow regime. Mean annual discharge at the gauging station of Peißenberg is 8.9 m^3/s. Due to snowmelt and high summer rainfall, most flood events occur in early summer with mean annual floods of 95 m^3/s and a mean high water of 121 m^3/s (maximum 365 m^3/s). Mean low water discharge is 2.8 m^3/s (minimum 0.8 m^3/s) (GKD (Hydraulic Services) Bavaria, 2020; Ringler et al., 2000). Annual precipitation at the study site totals 956 mm and the mean temperature is 8.5°C (Climate-Data, 2020).

2.2 | Calculation of the "Free Moving Rivers" corridor

The "Free Moving Rivers" approach (Egger et al., 2020) determines an appropriate width of a river corridor sufficient for the development of habitat diversity and geomorphological features. This corridor is based on geomorphological and hydrological variables of the given river type. River type is initially classified according to the scheme of Pottgießer and Sommerhäuser (2008) which takes into account the geographic location of the river, hydromorphological, biological and physicochemical parameters. Each river type is associated with a set of factors which, when multiplied by the current river width, estimate a potential natural river bed width (current river width multiplied by 3), a minimum river corridor (potential natural river bed multiplied by 3) and maximum river corridor (potential natural river bed multiplied by 10). These are meant to be added as lateral buffers to each side of the river (Dahm et al., 2014). The corridor is later modified to exclude man-made structures which must not be flooded, such as cities or buildings. In our study area (Figure 1) we calculated the "Free Moving Rivers" corridor for a river section of the Ammer downstream of Peißenberg where slope and discharge volume remain approximately constant.

2.3 | Calculation of the RESI

In the RESI approach the capacity of floodplains to provide provisioning, regulating and cultural ESSs is assessed on an expert-defined, five-point ordinal scale for each ESS (Podschun, Albert, et al., 2018). A variety of ESSs, based on the international CICES classification (Haines-Young & Potschin, 2013), can be selected depending on the focus of the study (Stammel et al., 2021). All assessments are calculated for standardised segments in the morphological floodplain on both sides of the river. These segments are oriented perpendicular to the river channel and separated into river, active floodplain (flooded area during a 100-year flood) and inactive floodplain (areas of morphological floodplain that is separated from the river dynamics by regulation structures) compartments (Figure 2; Brunotte et al., 2009; Fischer et al., 2019). Given the wide variety of ESSs, RESI uses various index-based methods to quantitatively assess the provision of the respective ESS, which can include both monetary and nonmonetary values. Each partial index is based on publicly available spatial data using relatively simple algorithms.

In this study, the values of three regulative ESSs (flood retention, sediment balance and habitat provision) were calculated under both current conditions and those expected after implementation of proposed restoration measures for 100 m floodplain segments along the river section. Regulative ESSs are relevant for humans in terms of energy, water and mass balances, can mitigate and regulate global climate and extreme events (Millennium Ecosystem Assessment (MA), 2005; Podschun, Albert, et al., 2018) and were rated as significant by public authority representatives in a stakeholder survey (Podschun, Albert, et al., 2018). In the study area regulative effects are the most important regarding flood protection for the settlements near the Ammer. Furthermore, regulative ESSs are fundamental for achieving the objectives of European regulations, like, the WFD (Podschun, Albert, et al., 2018). Additionally, habitat provision promotes the aims of the Natura 2000 Directive (Fischer et al., 2019); the Ammer river and surrounding riparian forests are part of the Site of Community Importance (SCI) "Ammer vom Alpenrand bis zum NSG 'Vogelfreistätte Ammersee-Südufer'" (site code 8331-302).

Flood retention judges the natural capability of floodplains to reduce peak flow discharge and is a function of retention volume and the systematic mapping of river and floodplain structure (Podschun, Albert, et al., 2018). Retention volume is the ratio of active and morphological floodplain volumes, and thus the per cent of the morphological floodplain that can be flooded. Structural parameters describing the riverbed, riverbank and floodplain are taken from the Bavarian river structure data (Environment Agency of Bavaria [LfU], 2017). Both values are transformed to an ordinal scale based on predefined thresholds and averaged to the flood retention RESI value ranging from 1 (no or only minor loss of active floodplain volume) to 5 (serious loss of active floodplain volume) with higher values indicating better flood retention capacity.

Sediment balance refers to the capacity of rivers to transport sediment and suspended material, and is linked to erosion and sedimentation processes (Podschun, Albert, et al., 2018). The sediment transport capacity of rivers is reduced by structures that impede sediment flow such as reservoirs, dams, weirs, sills or ramps as well as by structures that inhibit erosive processes, such as bank protections. The calculation is based on the river bed assessment of the Bavarian river structure data (Environment Agency of Bavaria [LfU], 2017). These are manually altered according to assumed changes of restoration measures using expert-defined improvements due to the removed structures. An evaluation of the effect of these regulations for each river segment is converted into five classes ranging between class 5, with a mostly unimpeded sediment balance, and class 1, with a highly disturbed sediment balance (Podschun, Albert, et al., 2018).

Habitat provision assesses structural and functional habitat quality for floodplain-specific biota (Fischer et al., 2019). In contrast to flood retention and sediment balance where assessments are performed on the whole morphological floodplain, habitat provision is calculated only in the proposed restoration area allowing for the representation of single habitats that would otherwise not be represented by the area-averaged assessment. Current habitat types were classified according to the biotope assessment of Bavaria (Environment Agency of Bavaria [LfU], 2020) and the land-use model of the Federal Agency for Cartography and

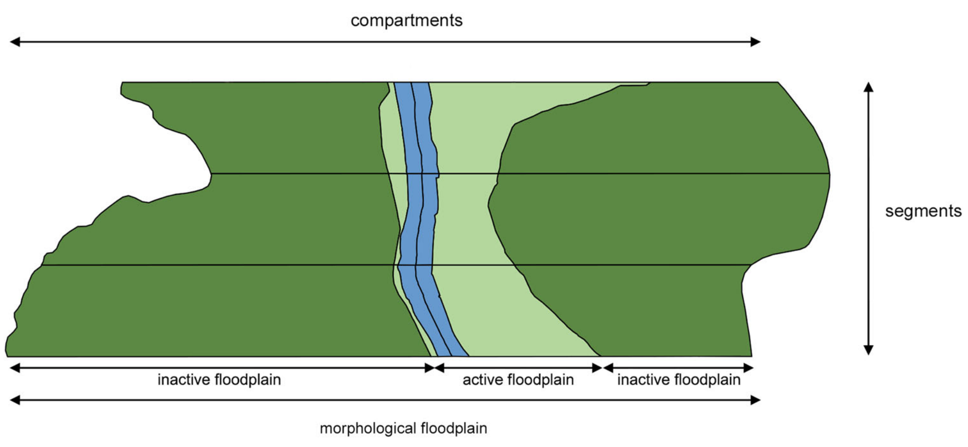

FIGURE 2 Schematic figure of morphological floodplain for calculating RESI at river sections (modified after Lotti, 2018). RESI, River Ecosystem Service Index

Geodesy (LBM-DE2018, BKG) which were revised by ground-truthing during field investigations. The study area is mostly covered by grassland (about 14 ha) and riparian forests (11 ha). Several water bodies such as abandoned meanders and lateral tributaries lie in the area (almost 1 ha in total). Biotope types are assigned an expert-defined habitat value (1–5) defined in the RESI manual and based on land-use and floodplain uniqueness. This value is reduced if the habitat is affected by artificially caused impounded water or is located in the inactive floodplain and increased by good conservation status of Natura 2000 habitat types (Podschun, Albert, et al., 2018). This results in an ordinal scaled assessment between class 5 which describes areas with a very high importance for habitat provision and class 1 with very low importance (Podschun, Albert, et al., 2018).

2.4 | Development of scenarios

We assessed the current conditions (status quo) in the study area and tracked changes of the three ESSs with RESI by the restoration measure under altered flooding, morphodynamics and habitats.

For implementing the proposed "Free Moving Rivers" restoration measure, 745 m of the dyke and 1.5 km of other protection measures and the agricultural road would have to be removed between the camping site on the west and the new dyke in the east, and 2260 m of dykes would have to be overhauled whereon the agricultural road would be relocated (Figure 3). The former elevated road would have to be lowered by about 60 cm to match the elevation level of the surrounding area (determined by additional cross-section measurements of Guzelj et al., 2020) to increase flood frequency. Therefore, river dynamics would be re-established on 28 ha of the Ammer floodplain.

Removed bank protection and lowered banks are assumed to result in higher flood frequency and duration and a more natural sediment balance (Figure 4). On the basis of additional cross-section measurements by Guzelj et al. (2020), calculations revealed an increase in flood frequency from about every 45 years to about every 2 years by lowering the agricultural road along the river banks. The more frequent floods combined with reduced land-use intensity are expected to result in enhanced habitat provision. For the assessment of the habitat provision, two scenarios with different land cover and land-use intensities were developed considering the site conditions in the area of the restoration measure based on experts' estimations. For scenario I "grassland extensification," we assume transformation of 8.6 ha of intensively used grassland into wet *Cnidium dubium* floodplain meadows, including possibilities for endangered floodplain species recovery (Figure 5 left). In scenario II "riparian reforestation," an additional 2.6 ha of riparian forest succession on existing grassland and 0.3 ha on existing deciduous forest are added to scenario I (Figure 6 left).

3 | RESULTS

3.1 | Dimension of the "Free Moving Rivers" corridor

The lower Ammer river is classified as a small river of the upper moraine in the Alpine foreland (river type 3.2 according to Pottgiesser & Sommerhäuser, 2008). The current modified river bed width of 25 m results in a potential natural river bed width of 75 m, a "Free Moving River" minimum corridor of 225 m and a maximum corridor of 750 m (according to Dahm et al., 2014).

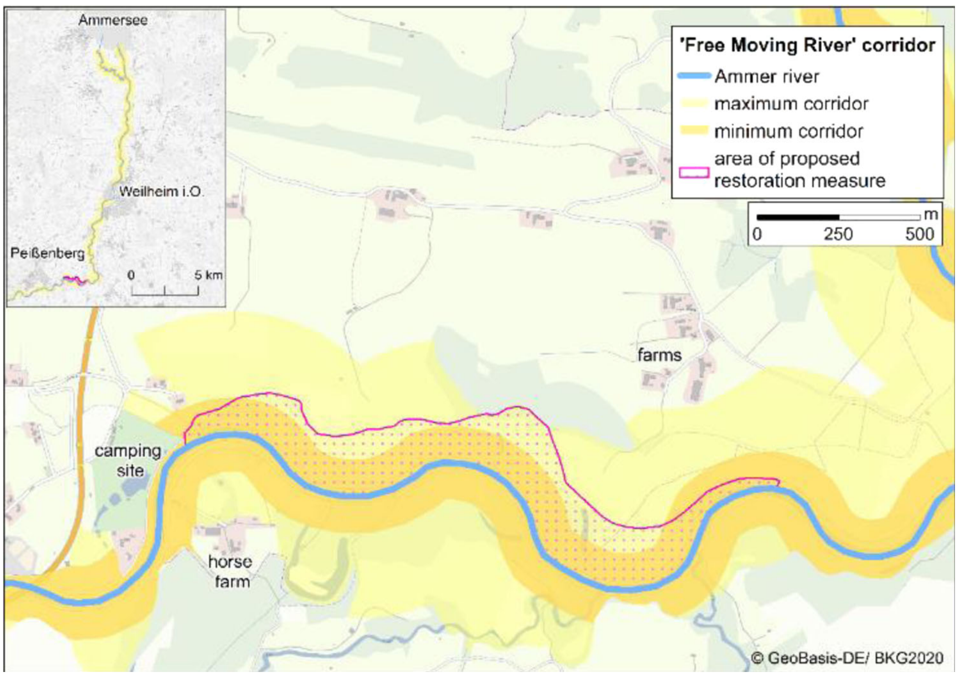

FIGURE 3 Minimum and maximum "Free Moving Rivers" corridor according to the approach of the German Federal Environment Agency (Dahm et al., 2014) for the area of the proposed restoration measure

Constraints that narrow the river corridor in the study area are the cities of Peißenberg and Weilheim and to a smaller extent roads and settlements (Figure 3 inset). The proposed restoration measure is located between the minimum and maximum river corridor (Figure 3).

3.2 | RESI assessment

Results of RESI evaluation indicate weak to strong enhancements for the three ESSs assessed through the restoration measure.

3.3 | Flood retention

Using the ratio between active and inactive floodplain, the RESI flood retention index of the status quo reveals settled areas with high floodplain losses (low RESI values) but also areas in the centre with preserved inundation capacity and therefore higher RESI values (Figure S1 left, see Supporting Information). In the proposed restoration area one segment improves from moderate to low loss (Figure S1 right, see Supporting Information).

3.4 | Sediment balance

In the status quo, anthropogenic impacts on the sediment balance by technical structures are mainly low to moderate with two very low segments at the eastern end of the section (Figure 4 left). The proposed removal of the bank fixations enhances the parameter "bank protection" in the assessment data of river structure (Environment Agency of Bavaria [LfU], 2017), thus leading to an upgrade of many segments in the restoration area mainly by one RESI-class (Figure 4 right).

3.5 | Habitat provision

In the status quo, areas close to the river are covered by riparian forest whereas areas distant to the river are dominated by grassland (Figure 5 left). The habitat provision index is in most cases moderate to high in the status quo. For water bodies and riparian forests it is high to very high (Figure 5 right).

For the grassland scenario, increased flooding and reduced land-use intensity in grassland areas are assumed (Figure 6 left). The habitat provision index therefore increases in many compartments (Figure 6 right).

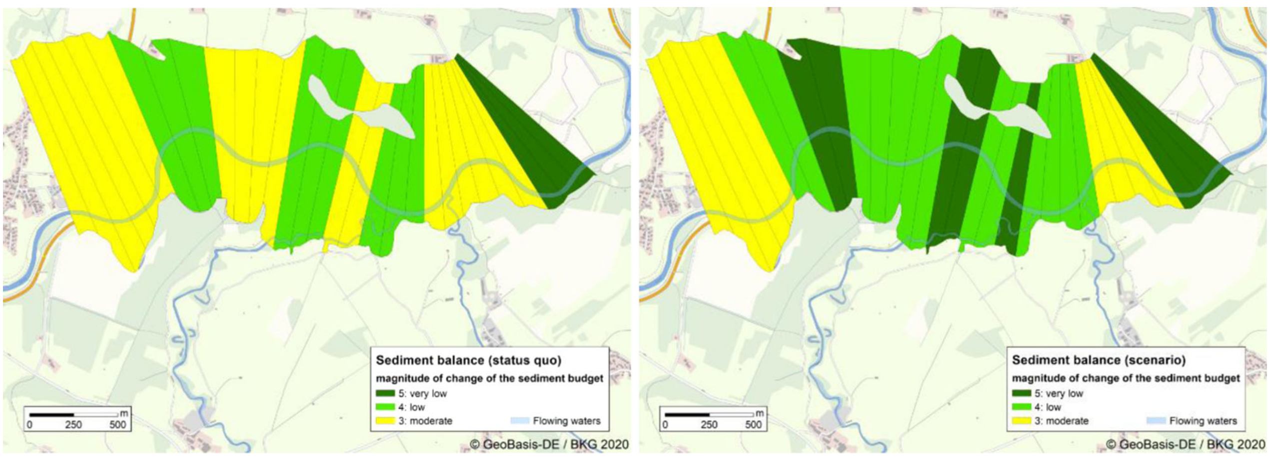

FIGURE 4 RESI assessment of the sediment balance in the restoration measure in the status quo (left) and as expected after implementing a 'Free Moving Rivers' corridor (scenario I and II, right)

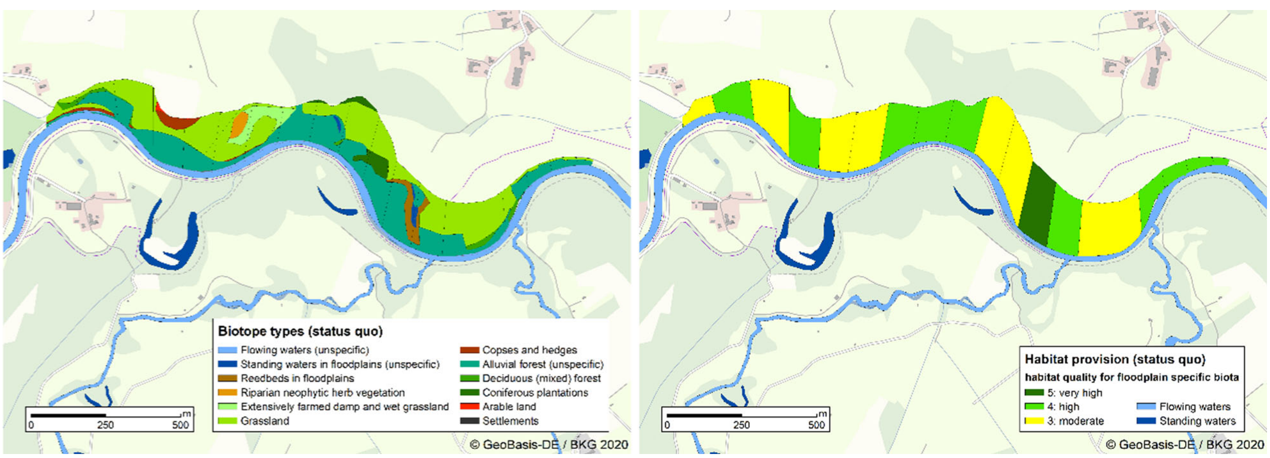

FIGURE 5 Biotope types (left) and habitat provision index (right) in the status quo

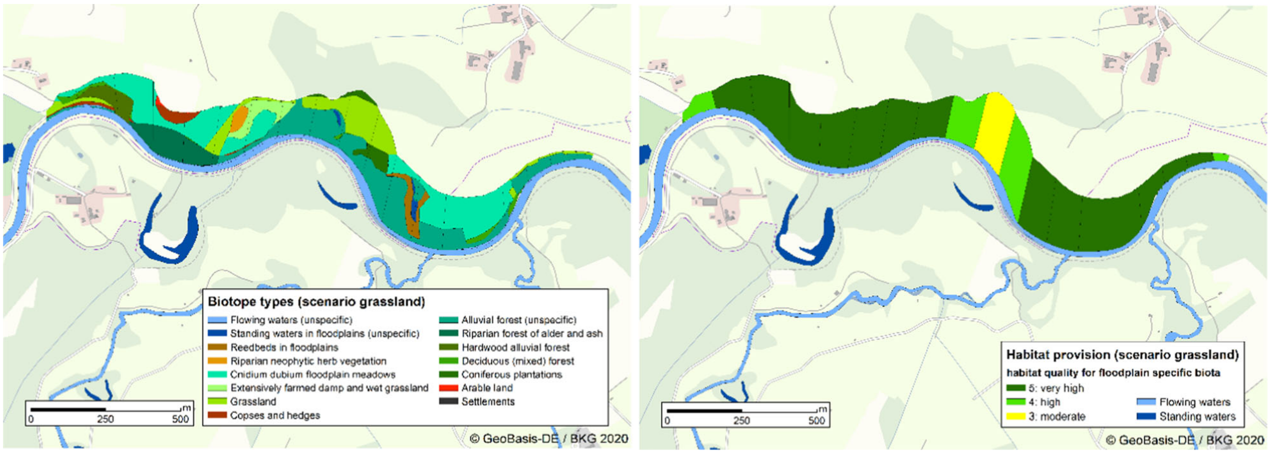

FIGURE 6 Biotope types (left) and habitat provision index (right) with reduced land use intensity for the scenario I 'grassland extensification'

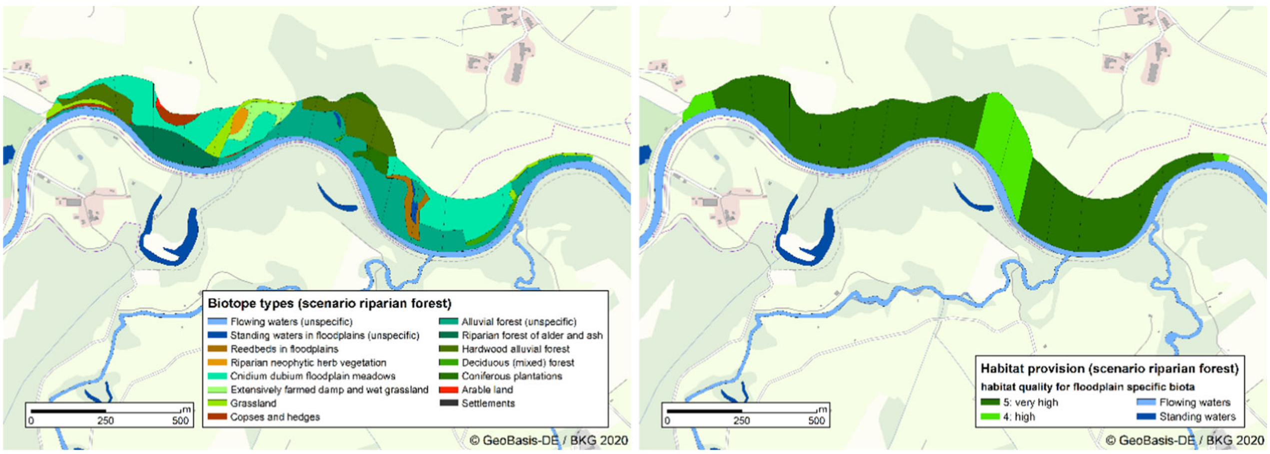

FIGURE 7 Biotope types (left) and habitat provision index (right) for the scenario II "riparian reforestation"

In the riparian reforestation scenario, further reduction of land-use intensity and succession areas for riparian forest are expected to result in more natural biotope types of floodplains (Figure 7 left). In this scenario, every compartment has a high to very high habitat provision index (Figure 7 right).

4 | DISCUSSION

In the study area on the lower Ammer river, the calculated "Free Moving Rivers" width is consistent with the corridor delimited by the newly constructed but unfinished dyke. This supports the idea that the implementation of the proposed restoration measures may be successful in reinitiating natural river processes. The RESI tool can be used to demonstrate changes of ESS provision in this area expected after implementation of the proposed restoration measure.

After implementation, forest and grassland adjacent to the Ammer should receive slightly more flooding (shown by additional measurements of Guzelj et al., 2020). This would help re-establishing the riparian character of the forest stands, which are currently disconnected of disturbances resulting from fluvial dynamics, groundwater-dependent forests dominated by bird cherry, alder and ash (Pruno-Fraxinetum Oberd 1953; Egger et al., 2020), quite different from the potential natural vegetation comprised of grey alder forests (Suck & Bushart, 2012). Despite increasing frequency and duration of floods in the restoration area, RESI flood retention only increased in one segment relative to the status quo (Figure 8). This can be explained by the simplified flood retention algorithm of RESI which uses active floodplain volume defined as flooded areas during a 100-year flood as the main factor. Since the agricultural road reduces small floods but does not prevent flooding during high flood events, the area is already in its status quo considered as an active floodplain and the removal of bank fixations has almost no effect in the RESI assessment of this parameter.

In contrast, habitat provision improves in both scenarios, relative to the status quo (Figure 8). Because of increased flooding and reduced intensity of land use, high-value habitats are expected to develop to increasingly natural floodplain conditions. The highest

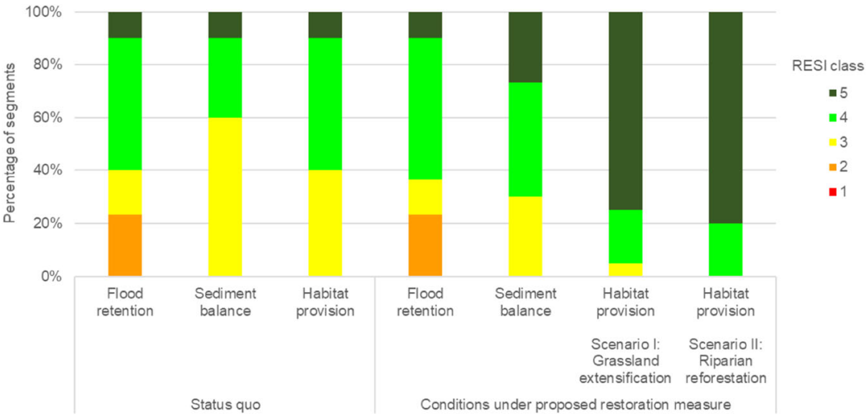

FIGURE 8 Calculations of three ESSs with RESI in status quo and two scenarios for the proposed restoration measure

assessment ratings are predicted to occur in the riparian forest scenario. Since riparian forests are rare habitats in Germany (Bundesministerium für Umwelt Naturschutz und nukleare Sicherheit [BMU] & Bundesamt für Naturschutz [BfN], 2021) and are protected by European (Natura 2000; The Habitats Directive and the Birds Directive) and German (Federal Nature Conservation Act) law, their development is a prior goal. These measures are in line with the river development plan of the Bavarian State for the Ammer which also targets the enlargement of riparian forest areas (Frey et al., 2006).

By removing bank protections, it is expected that a morphological balance of erosion and sedimentation processes can be reestablished for the most part of the river section resulting in a more natural sediment balance (Figure 8). Only a small amount of segments with persisting bank protections at the camping site upstream of the actual restoration measure area and where the relocated dyke approaches the Ammer bank at the end of the study area retain moderate RESI values. In all other segments, sediment balance of river banks and adjacent floodplain areas will change due to the relocation of the agricultural road and reactivation of river banks that enables bank erosion. Enabling self-dynamic river development with the "Free Moving Rivers" approach would reinstall fluvial dynamics, create structural diversity and provide germination sites for rare characteristic species of Alpine rivers (Müller et al., 2019).

Altogether, RESI results on the lower Ammer river show improvements in ESSs intended by the proposed restoration measure in comparison to current conditions. The Ammer river provides further options for the implementation of the "Free Moving Rivers" approach, such as downstream of Weilheim where other restoration measures on the river bed have been implemented in past years (Müller, 2017) and on a straightened section close to the mouth into the Ammersee lake (Egger et al., 2020). However, fundamental changes in site conditions of rivers always have to be considered when planning to implement "Free Moving Rivers" corridors. Human impacts can lead to profound changes that may alter entire river types (Gregory, 2006). As shown for the Ammer downstream of the proposed restoration measure, shortening of the river course and regulation measures lead to incision of the river bed turning a former multichannel river into a single thread river type (Guzelj et al., 2020). In this case, providing space for the river is not likely to re-establish its historical river type. Consequently, restoration objectives have to be adapted accordingly and changed river types have to be considered in calculations (Shields et al., 2003) making feasibility studies generally necessary before implementation of river revitalisation projects (Stammel et al., 2021).

Possible limitations of restoration measures are shown by a meta-analysis of studies on different riparian ecosystems which revealed lower biodiversity and ESSs in restored than in pristine sites (Meli et al., 2014; for different ecosystems see also Benayas et al., 2009). Nevertheless, removing structures that reduce natural river processes in formerly altered areas enhances rivers' ability to provide ESSs (Dehnhardt, 2002; Scholz et al., 2012). Restoration measures often increase the multifunctionality of sites by enhancing the provision of various ESSs. For example, Funk et al. (2021) found the removal of embankments and connection of side channels on a Danube river section resulting in an increase in habitat availability and nutrient retention. Dyke relocations lead to an increase in many wetland ESSs, such as recreational opportunities, water availability and food supply or nutrient and water quality regulation (Hornung et al., 2019; Schindler et al., 2014). Together with reduced maintenance costs for bank protection this can lead to economic benefits, even if decreases in agricultural or forest productivity are included (Buffin-Bélanger et al., 2015; Grossmann et al., 2010). For example, Buffin-Bélanger et al. (2015) quantified ESSs and costs of implemented river corridors for three rivers in Quebec over a 50-year period, finding that monetary and societal benefits increased 1–5-fold over costs.

In this paper, the RESI approach was used on a limited set of ESSs considered important for the Ammer case study. It could have been expanded by adding other ESSs. Customising the set of evaluated ESSs is indeed one of the assets of the RESI method (Stammel et al., 2021). Cultural ESSs could have been added, with other studies revealing a decrease by reduced length of roads resulting in smaller areas with recreational functions (Vallecillo et al., 2019; Woolsey et al., 2007) which might also be the case by the restoration measure in the study area. However, reduced impact of tourists may also reduce physical disturbance of sites or nutrient input (Hornung et al., 2019).

The RESI approach is based on assumed changes in the future development of the site, often relying on expert knowledge that cannot consider all external factors influencing ESSs. This results in some uncertainty concerning the future development of restoration measures. Data quality might sometimes be a limitation to the method, which largely relies on external data. Nevertheless, calculation of the RESI is simple and comprehensible, and the required data are mostly available across Germany. Different restoration measure options can thus be compared and a holistic evaluation of advantages and impacts can be compared, which facilitates communication with stakeholders and authorities to support decision making (Stammel et al., 2021). The RESI can therefore be considered a useful tool to demonstrate changes in ESSs.

5 | CONCLUSION

The dynamic and often unpredictable nature of rivers, as well as a lack of unaltered rivers that serve as natural benchmarks for setting restoration goals makes successful restoration planning a difficult task (Ward et al., 2001). Reinstating more natural fluvial processes of the river is therefore considered a very promising pathway. The "Free Moving Rivers" approach offers a fast, simple and transferable framework for the estimation of the required space of river ecosystems for ecological and regulative processes (Egger et al., 2020). However, for detailed planning of such measures, especially in highly urbanised areas, more comprehensive studies and hydraulic models are needed.

Assessing changes in river ecosystems can be performed by the RESI approach, which offers a standardised assessment method for a larger number of ESSs beyond those tested here. Thus RESI provides a comprehensive tool for the comparison of different measurement options (Podschun, Albert, et al., 2018; Podschun, Thiele, et al., 2018).

ACKNOWLEDGEMENTS

This study was funded by The German Federal Environmental Foundation. Spatial databases were provided by the German Federal Agency for Cartography and Geodesy (GeoBasis-DE/BKG 2020). Open Access funding enabled and organized by Projekt DEAL.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon request.

REFERENCES

Benayas, J. M. R., Newton, A. C., Diaz, A., & Bullock, J. M. (2009). Enhancement of biodiversity and ecosystem services by ecological restoration: a meta-analysis. *Science*, *325*(5944), 1121–1124. http://doi.org/10.1126/science.1172460

Biron, P. M., Buffin-Bélanger, T., Larocque, M., Choné, G., Cloutier, C. A., Ouellet, M. A., Demers, S., Olsen, T., Desfarlais, C., & Eyquem, J. (2014). Freedom space for rivers: A sustainable management approach to enhance river resilience. *Journal of Environmental Management*, *54*(5), 1056–1073.

Brunotte, E., Dister, E., Günther-Diringer, D., Koenzen, U., & Mehl, D. (2009). Flussauen in Deutschland. Erfassung und Bewertung des Auenzustandes. In BfN (Ed.). *Naturschutz und Biologische Vielfalt* 87, Bonn-Bad Godesberg.

Buffin-Bélanger, T., Biron, P. M., Larocque, M., Demers, S., Olsen, T., Choné, G., Ouellet, M.-A., Cloutier, C.-A., Desjarlais, C., & Eyquem, J. (2015). Freedom space for rivers: An economically viable river management concept in a changing climate. *Geomorphology*, *251*, 137–148.

Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU) & Bundesamt für Naturschutz (BfN). (2021). Auenzustandsbericht 2021. Flussauen in Deutschland. Bonn-Bad Godesberg. https://doi.org/10.19217/brs211

Charrier, P. (2012). Flusskorridore in Frankreich. *Konzept*, *Umsetzung*, *Erfahrungen. Auenmagazin*, *03/2012*, 4–9.

Climate-Data. (2020). Climate-Data of Weilheim in upper Bavaria. https://de.climate-data.org/europa/deutschland/bayern/weilheim-in-oberbayern-23046/

Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburgu, K., Naeem, S., O'Neill, R. V., Paruelo, J., Raskin, R. G., Sutton, P., & Van Den Belt, M. (1997). The value of the world's ecosystem services and natural capital. *Nature*, *387*(6630), 253–260.

Dahm, V., Kupilas, B., Rolauffs, P., & Herin, D. (2014). Hydromorphologische Steckbriefe der deutschen Fließgewässertypen. In Umweltbundesamt (Ed.), *Strategien zur Optimierung von Fließgewässer-Renaturierungsmaßnahmen und ihrer Erfolgskontrolle*. Dessau-Roßlau. Texte 43, Appendix 1.

Damm, C., Dister, E., Fahlke, N., Follner, K., König, F., Korte, E., Lehmann, B., Müller, K., Schuler, J., Weber, A., & Wotke, A. (2011). Auenschutz–Hochwasserschutz–Wasserkraftnutzung. In Beispiele für eine ökologisch vorbildliche Praxis, & BfN (Eds.), *Naturschutz und Biologische Vielfalt Heft 112. Bonn-Bad Godesberg. 321 S*.

Dehnhardt, A. (2002). Der ökonomische Wert der Elbauen als Nährstoffsenke: Die indirekte Bewertung ökologischer Leistungen. In A. Dehnhardt, & J. Meyerhoff (Eds.), *Nachhaltige Entwicklung der Stromlandschaft Elbe–Nutzen und Kosten der Wiedergewinnung und Renaturierung von Überschwemmungsauen*. Wissenschaftsverlag Vauk.

Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V. (DWA). (2010). *Merkblatt DWA-M 610. Neue Wege der Gewässerunterhaltung. Pflege und Entwicklung von Fließgewässern*. DWA-Regelwerk.

Egger, G., Juszczyk, I., Gerstner, L., de Oliveira Wittman, A., & Schneider, E. (2020). *Freier Pendelraum für Fließgewässer. Methoden zur Anwendung des Konzeptes an Beispielen in Deutschland* (Final Report of Research Project Funded by the Deutsche Bundesstiftung Umwelt).

Environment Agency of Bavaria (LfU). (2017). *Assessment data of river structure of Ammer river (Gewässerstrukturkartierung Fließgewässer)*. Provided by LfU. https://www.lfu.bayern.de/wasser/gewaesserstrukturkartierung/fliessgewaesser/index.htm

Environment Agency of Bavaria (LfU). (2020). *Biotopkartierung Bayern*. Updated 2020.01.29. Download Service of LfU. https://www.lfu.bayern.de/umweltdaten/geodatendienste/pretty_downloaddienst.htm?dld=biotopkartierung

Federal Agency for Cartography and Geodesy (BKG). (2018). *Land cover model of Germany*. LBM-DE2018.

Feld, C. K., Birk, S., Bradley, D. C., Hering, D., Kail, J., Marzin, A., Melcher, A., Nemitz, D., Pedersen, M. L., Pletterbauer, F., Pont, D., Verdonschot, P. F. M., & Friberg, N. (2011). From natural to degraded rivers and back again: A test of restoration ecology theory and practice. In G. Woodward, *Advances in ecological research* (Vol. 44, pp. 119–209). Academic Press.

Fischer, C., Damm, C., Foeckler, F., Gelhaus, M., Gerstner, L., Harris, R. M. B., Hoffmann, T. G., Iwanowski, J., Kasperidus, H., Mehl, D., Podschun, S. A., Rumm, A., Stammel, B., & Scholz, M. (2019). The 'habitat provision' index for assessing floodplain biodiversity and restoration potentials as an ecosystem service—method and application. *Frontiers in Ecology and Evolution*, *7*(483), 1–16.

Frey, W., Lenhart, B., Fastner, A., & Hofmann, H. (2006). *Gewässerentwicklungsplan Landkreise Weilheim-Schongau und Garmisch-Partenkirchen*. Gewässer I./III. Ordnung - Ammer, Fkm. 116,7 bis 184,2.

Funk, A., Tschikof, M., Grüner, B., Böck, K., Hein, T., & Bondar-Kunze, E. (2021). Analysing the potential to restore the multi-functionality of floodplain systems by considering ecosystem service quality, quantity and trade-offs. *River Research and Applications*, *37*(2), 221–232.

GKD (Hydraulic Services) Bavaria. (2020). *Hauptwerte Abfluss Pegel Peißenberg/Ammer*. https://www.gkd.bayern.de/de/fluesse/abfluss/isar/peissenberg-16612001

Gregory, K. J. (2006). The human role in changing fluvial systems. In L. A. James & W. A. Marcus, *Proceedings of the 37th Binghamton Symposium in Geomorphology*. 79(3-4, 172–191). Elsevier. https://doi.org/10.1016/j.geomorph.2006.06.018

Grizzetti, B., Pistocchi, A., Liquete, C., Udias, A., Bouraoui, F., & Van De Bund, W. (2017). Human pressures and ecological status of European rivers. *Scientific Reports*, *7*(1), 1–11.

Grossmann, M., Hartje, V., & Meyerhoff, J. (2010). Ökonomische Bewertung naturverträglicher Hochwasservorsorge an der Elbe. In BfN (Ed.). *Naturschutz und Biologische Vielfalt* 89, Bonn-Bad Godesberg.

Guzelj, M., Hauer, C., & Egger, G. (2020). The third dimension in river restoration: How anthropogenic disturbance changes boundary conditions for ecological mitigation. *Scientific Reports*, *10*(1), 1–17.

Haines-Young, R., & Potschin, M. B. (2013). Common International Classification of Ecosystem Services (CICES): Consultation on Version 4.3, 2013 ed. EEA Framework Contract No. EEA/IEA/09/003, www.cices.eu

Heinrich, R. (2017). Die unterschiedlichen Charaktere der Ammer. In Landesbund für Vogelschutz (Ed.), *Das Blaue Band. Die Ammergemeinden bandeln an* (pp. 16–21).

Hornung, L. K., Podschun, S. A., & Pusch, M. (2019). Linking ecosystem services and measures in river and floodplain management. *Ecosystems and People*, *15*(1), 214–231.

Kail, J., Brabec, K., Poppe, M., & Januschke, K. (2015). The effect of river restoration on fish, macroinvertebrates and aquatic macrophytes: A meta-analysis. *Ecological Indicators*, *58*, 311–321.

Lobanova, A., Liersch, S., Nunes, J. P., Didovets, I., Stagl, J., Huang, S., Koch, H., delRocío Rivas López, M., Maule, C. F., Hattermann, F., & Krysanova, V. (2018). Hydrological impacts of moderate and high-end climate change across European river basins. *Journal of Hydrology: Regional Studies*, *18*, 15–30.

Lotti, J. (2018). *Application of the River Ecosystem Service Index (RESI) in the Upper Rhine floodplain: Opportunities and limits* [Master Thesis, University of Strasbourg, France and Karlsruhe Institute of Technology, Germany].

Millennium Ecosystem Assessment (MA). (2005). *Ecosystem and human well-being. Wetlands and water. Synthesis*. World Resources Institute.

Malavoi, J.-R., Bravard, J.-P., Piégay, H., Héroin, E., & Ramez, P. (1998). *Guide technique No. 2. Determination de l'espace de liberté des cours d' eau. Méditerranée*. Agence de Bassin Rhône.

Meli, P., Benayas, R., Balvanera, J. M., & Ramos, M. P. (2014). Restoration enhances wetland biodiversity and ecosystem service supply, but results are context-dependent: A meta-analysis. *PLOS ONE*, *9*(4), e93507. https://doi.org/10.1371/journal.pone.0093507

Müller, B. (2017). Die Ammer zwischen Zähmung und Befreiung. In Landesbund für Vogelschutz in Bayern e.V. (LBV) (Ed.), *Das Blaue Band. Die Ammergemeinden bandeln an* (pp. 45–51).

Müller, N., Woellner, R., Wagner, T. C., Reich, M., Behrendt, S., Burkel, L., Neukirchen, M., & Kollmann, J. (2019). Hoffnung für die Populationsentwicklung von Wildflussarten der Alpen? Rückgang und aktuelle Bestandssituation von Zwergrohrkolben (Typha minima), Deutscher Tamariske *(Myricaria germanica)* und Uferreitgras *(Calamagrostis pseudophragmites)* in Bayern. *Berichte der Bayerischen Botanischen Gesellschaft*, *89*, 5–22.

Piégay, H., Darby, S. E., Mosselman, E., & Surian, N. (2005). A review of techniques available for delimiting the erodible river corridor: A sustainable approach to managing bank erosion. *River Research and Applications*, *21*(7), 773–789.

Podschun, S. A., Albert, C., Costea, G., Damm, C., Dehnhardt, A., Fischer, C., Fischer, H., Foeckler, F., Gelhaus, M., Gerstner, L., Hartje, V., Hoffmann, T. G., Hornung, L., Iwanowski, J., Kasperidus, H., Linnemann, K., Mehl, D., Rayanov, M., Ritz, S., … Pusch, M. (2018). RESI - Anwendungshandbuch: Ökosystemleistungen von Flüssen und Auen erfassen und bewerten. *IGB-Berichte*. 31/2018. https://www.resi-project.info/handbuch/

Podschun, S. A., Thiele, J., Dehnhardt, A., Mehl, D., Hoffmann, T. G., Albert, C., von Haaren, C., Deutschmann, K., Fischer, C., Scholz, M., Costea, G., & Pusch, M. (2018). Das Konzept der Ökosystemleistungen - eine Chance für integratives Gewässermanagement. *HyWa*, *62*(6), 453–468.

Pottgiesser, T., & Sommerhäuser, M. (2008). *Begleittext zur Aktualisierung der Steckbriefe der bundesdeutschen Fließgewässertypen (Teil A) und Ergänzung der Steckbriefe der deutschen Fließgewässertypen um typspezifische Referenzbedingungen und Bewertungsverfahren aller Qualitätselemente (Teil B)* (Report of UBA-Project and LAWA-Project O, 8.06).

Pusch, M. (2016). Auen-Quellen vielfältiger Dienstleistungen für den Menschen. *Auenmagazin*, *9*, 4–7.

Rempe, A. (2018). *Wie ein Fluss (fast) wieder jungfräulich wird: Die Renaturierung der Ammer* (1st ed). Bauer, Thalhofen.

Ringler, A., Layritz, M., Vilgertshofer, J., Wimmer, T., & Scheer, C. (2000). *Ökologische Untersuchungen zum Pfingsthochwasser 1999 in Südbayern–Schwerpunkt Ammer-Gebiet. Lebensraum nach dem Hochwasser*. Bayerischen Staatsministeriums für Landesentwicklung und Umweltfragen.

Robinson, C. T., Tockner, K., & Ward, J. V. (2002). The fauna of dynamic riverine landscapes. *Freshwater Biology*, *47*, 661–677.

Sauvade, M. B., Laurent, M. J., Mazeau, L., & Chardon, G. (2015). Schéma d'aménagement et de gestion des eaux du bassin versant Allier aval. Reglement.

Schindler, S., O'Neill, F. H., Biró, M., Damm, C., Gasso, V., Kanka, R., van der Sluis, T., Krug, A., Lauwaars, S. G., Sebesvari, Z., Pusch, M., Baranovsky, B., Ehlert, T., Neukirchen, B., Martin, J. R., Euller, K., Mauerhofer, V., & Wrbka, T. (2016). Multifunctional floodplain management and biodiversity effects: A knowledge synthesis for six European countries. *Biodiversity and Conservation*, *25*(7), 1349–1382.

Schindler, S., Sebesvari, Z., Damm, C., Euller, K., Mauerhofer, V., Schneidergruber, A., Birò, M., Essl, F., Kanka, R., Lauwaars, S. G., Schulz-Zunkel, C., van der Sluis, T., Kropik, M., Gasso, V., Krug, A., Pusch, M. T., Zulka, K. P., Lazowski, W., Hainz-Renetzeder, C., … Wrbka, T. (2014). Multifunctionality of floodplain landscapes: Relating management options to ecosystem services. *Landscape Ecology*, *29*(2), 229–244.

Schinegger, R., Trautwein, C., Melcher, A., & Schmutz, S. (2012). Multiple human pressures and their spatial patterns in European running waters. *Water and Environment Journal*, *26*(2), 261–273.

Schneider, E., Werling, M., Stammel, B., Januschke, K., Ledesma-Krist, G. M., Scholz, M., Hering, D., Gelhaus, M., Dister, E. R., & Egger, G. (2018). Biodiversität der Flussauen Deutschlands. In BfN (Ed.). *Naturschutz und Biologische Vielfalt* 163, Bonn-Bad Godesberg.

Scholz, M., Mehl, D., Schulz-Zunkel, C., Kasperidus, H. D., Born, W., & Henle, K. (2012). Ökosystemfunktionen von Flussauen. Analyse und Bewertung von Hochwasserretention, Nährstoffrückhalt, Kohlenstoffvorrat, Treibhausgasemissionen und Habitatfunktion. In BfN (Ed.). *Naturschutz und Biologische Vielfalt* (Vol. 124, No. 2), Bonn-Bad Godesberg.

Shields, Jr., F. D., Copeland, R. R., Klingeman, P. C., Doyle, M. W., & Simon, A. (2003). Design for stream restoration. *Journal of Hydraulic Engineering*, *129*(8), 575–584.

Stammel, B., Fischer, C., Cyffka, B., Albert, C., Damm, C., Dehnhardt, A., Fischer, H., Foeckler, F., Gerstner, L., Hoffmann, T. G., Iwanowski, J., Kasperidus, H. D., Linnemann, K., Mehl, D., Podschun, S. A., Rayanov, M., Ritz, S., Rumm, A., Scholz, M., … Gelhaus, M. (2021). Assessing land use and flood management impacts on ecosystem services in a river landscape (Upper Danube, Germany). *River Research and Applications*, *37*(2), 209–220.

Suck, R., & Bushart, M. (2012). Potentielle Natürliche Vegetation Bayerns. Erläuterungen zur Übersichtskarte 1: 500 000. In Bayerisches Landesamt für Umwelt (LFU) (Ed.), *UmweltSpezial*.

Tockner, K., Pusch, M., Borchardt, D., & Lorang, M. S. (2010). Multiple stressors in coupled river–floodplain ecosystems. *Freshwater Biology*, *55*, 135–151.

Tockner, K., & Stanford, J. A. (2002). Riverine flood plains: Present state and future trends. *Environmental Conservation*, *29*(3), 308–330.

Tomscha, S. A., Bentley, S., Platzer, E., Jackson, B., de Roiste, M., Hartley, S., Norton, K., & Deslippe, J. R. (2021). Multiple methods confirm wetland restoration improves ecosystem services. *Ecosystems and People*, *17*(1), 25–40.

Vallecillo, S., Notte, L., Zulian, A., Ferrini, G., & Maes, S. J. (2019). Ecosystem services accounts: Valuing the actual flow of nature-based recreation from ecosystems to people. *Ecological Modelling*, *392*, 196–211.

Ward, J. V., Tockner, K., & Schiemer, F. (1999). Biodiversity of floodplain river ecosystems: Ecotones and connectivity. *Regulated Rivers Research & Management*, *15*, 125–139.

Ward, J. V., Tockner, K., Uehlinger, U., & Malard, F. (2001). Understanding natural patterns and processes in river corridors as the basis for effective river restoration. *Regulated Rivers Research & Management*, *17*(4-5), 311–323.

Wohl, E., Angermeier, P. L., Bledsoe, B., Kondolf, G. M., MacDonnell, L., Merritt, D. M., Palmer, M. A., Poff, N. L., & Tarboton, D. (2005). River restoration. *Water Resources Research*, *41*(10), 1–12.

Woolsey, S., Capelli, F., Gonser, T. O. M., Hoehn, E., Hostmann, M., Junker, B., Paetzold, A., Roulier, C., Schweizer, S., Tiegs, S. D., Tockner, K., Weber, C., & Peter, A. (2007). A strategy to assess river restoration success. *Freshwater Biology*, *52*(4), 752–769.

Water Authority of Weilheim (WWA Weilheim). (2003). Die Ammer. Brochure of the Oberland exhibition.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Becker, I., Egger, G., Gerstner, L., Householder, J. E., & Damm, C. (2022). Using the River Ecosystem Service Index to evaluate "Free Moving Rivers" restoration measures: A case study on the Ammer river (Bavaria). *International Review of Hydrobiology*, 1–11. https://doi.org/10.1002/iroh.202102088