

Assessing ecosystem services across scales to support nature-based solutions in river floodplains: a review of non-monetary tools

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Abstract

Floodplains are dynamic ecosystems that provide a multitude of ecosystem services (ES), yet they have historically been managed primarily for a limited set of human benefits, often at the expense of biodiversity and multi-functionality. This review synthesises current knowledge in ES and the multi-functionality of floodplains. It further highlights the potential of Nature-based Solutions (NbS) to restore and enhance floodplain multi-functionality and ES through ecologically sound and socially inclusive approaches. Focusing on non-monetary ES assessment tools, such as the RESI and IDES frameworks, the study synthesises lessons from three European case studies (Danube River Basin, River Nebel in Germany and Koviljsko-Petrovaradinski Rit in Serbia). These case studies demonstrate the application of ES indices at basin, regional and local scales for prioritisation, restoration evaluation and stakeholder-informed decision-making. We further discuss trade-offs and synergies amongst ES and highlight participatory approaches that integrate stakeholder perspectives in NbS design and implementation. This review underscores the importance of multi-scale assessments in implementing sustainable floodplain management strategies and supports decision-makers in applying NbS for resilient landscapes that balance ecological, social and economic benefits.

Highlights

- Floodplain restorations are Nature-based solutions enhancing many ecosystem services;
- Non-monetary assessments of ES allow for consistent evaluation of multi-functionality across scales;
- Case studies reveal trade-offs between regulating and provisioning ES, emphasising the need for integrated floodplain management;
- Integration of stakeholders into Nature-based solution planning will increase their acceptance and maximise the benefit for nature and society;



Academic editor: Katrina Marsden

Received: 4 February 2025

Accepted: 13 September 2025

Published: 25 February 2026

ZooBank: <https://zoobank.org/F887F983-BFF3-4D45-9087-1BC1BC1BB64A>

F887F983-BFF3-4D45-9087-

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Citation: Stammel B, Jähnig SC, Mehl D, Pusch M, Srđević Z, Tschikof M, Wulf S, Scholz M (2026) Assessing ecosystem services across scales to support nature-based solutions in river floodplains: a review of non-monetary tools. In: Kaden US, Schmid S, Wulf S, Marsden K, Klusmann C, Bonn A, Tockner K, Scholz M (Eds) *Wetlands in a Changing Climate: Restoring Coasts and Floodplains*. *Nature Conservation* 62: 95–119. <https://doi.org/10.3897/natureconservation.62.148716>

- ES mapping and multi-functionality metrics at multiple scales offer strategic tools for implementing EU biodiversity and climate strategies, including the 2024 Nature Restoration Law.

Key words: Ecosystem services, integrative management, multi-functionality

Introduction

For the last 200 years, the management of rivers and floodplains has been aiming at maximising a small number of selected human benefits: rivers have been straightened, embanked and impounded to support navigation or the use of hydropower; floodplains have been converted into farmland and separated from their rivers by dykes aiming to protect not only settlements and urban infrastructure, but also arable land from flooding (Diaz-Redondo et al. 2017; Stammel et al. 2018). However, the transformation of floodplains by establishing intense human land uses has deteriorated enormously the availability and quality of its unique habitats and related ecosystem services which provide benefits to people (Globevnik et al. 2020). Acceleration of river discharge and lack of space for water retention have increased flood peak height and, hence, flood risks along downstream river sections (Disse and Engel 2001). On top of this, we are observing and predicting an increased occurrence of extreme events, such as floods and droughts with potentially catastrophic consequences for both nature and people (Blöschl et al. 2020; EEA 2021a). Further impacts of climate change are adding to a multitude of emerging challenges in environmental management, such as eutrophication, greenhouse gas emissions, biodiversity loss, simplification of food webs and dwindling provision of ecosystem functions and services in general (Kaden et al. 2023a; see Kaden et al. 2026)). These numerous challenges in environmental management referring to the same floodplain areas call for a paradigm shift towards multi-functionality as a key principle in the valuation, management and development of riverine landscapes instead of the historical focus on single objectives (Schindler et al. 2014, 2016).

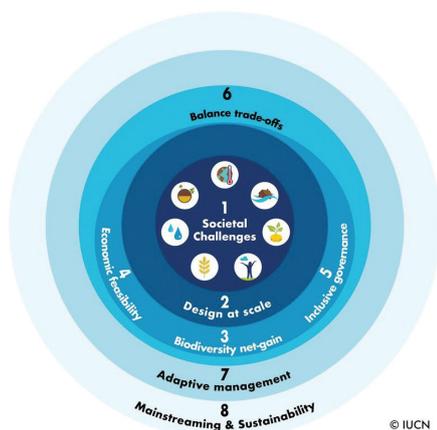
Targeting multiple goals in floodplain management simultaneously requires a shift from the current sectoral, primarily single-purpose technical approaches towards a more integrative management strategy for these complex riverine wetland ecosystems (Stäps et al. 2022). The new integrative strategy should encompass the ecological, economic and social interactions and synergies inherent to the system, while also considering all relevant interests and demands. Ecosystem services (ES) are emblematic of all these interests (Podschun et al. 2018b; Stammel et al. 2020; Jähnig et al. 2022; Cid et al. 2022). If it is feasible to assess all ES in floodplains in a comparable manner, this would provide the basis for informed decision-making regarding the most suitable management measure such as Nature-based solutions (NbS – see Box 1). NbS utilise natural processes to address key societal challenges. They have emerged as a promising approach to restore and enhance floodplain ecosystem functions while providing multiple socio-economic benefits. If implemented according to the definition of NbS (UNEA-5 2022), NbS projects are especially suitable to tackle trade-offs and harness synergies in multi-functional landscapes, resulting in the provision of a wide range of ES as co-benefits (Kozban et al. 2023).

Box 1. Nature-based Solutions: Definition and criteria.

Nature-based solutions (NbS) are defined by the United Nations Environment Assembly (UNEA) as “actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits” (UNEA-5 2022).

In recent years, the NbS concept has received increasing attention in the international policy, research and finance arena, especially as a sustainable and cost-effective approach for climate change mitigation and adaptation (Kozban et al. 2023). However, the NbS approach is not limited to tackling climate change - initiatives can also focus on, for example, food and water security, disaster risk reduction or other societal challenges. The Kunming-Montreal Global Biodiversity Framework, negotiated under the Convention on Biological Diversity (CBD), explicitly calls for the implementation of NbS in two of its global targets for 2030 and the EU Water Resilience Strategy aims to significantly scale-up investment in NbS. By definition, NbS are activities that generate ecosystem services (ES). Yet, while both the NbS and ES concept are primarily anthropocentric, i.e. focusing on benefits that humans derive from nature, it should be noted that NbS must generate biodiversity benefits as well.

The International Union for Conservation of Nature (IUCN) has developed a Global Standard for NbS, providing a user-friendly framework for their verification, design and scaling up (IUCN 2020). It provides a set of eight interconnected criteria (see Box figure) to ensure that NbS projects are, for example, ecologically sound, socially inclusive and acceptable and economically viable. Moreover, it promotes a participatory governance that ensures the inclusion of local communities and other stakeholders in the implementation process. The standard aims to increase the scale of application and impact of the NbS approach, while preventing negative outcomes or misuse of the concept. It offers guidance to practitioners, funding agencies, policy-makers, private sector representatives and other stakeholders, helping to ensure that NbS implementation and related investments adhere to meaningful social and ecological safeguards.



However, evaluating the multiple ES of floodplains, their trade-offs and synergies represent a scientific challenge (Perosa et al. 2021). To identify and design the most suitable NbS project and support the decision-making on it, a variety of ES evaluation methods has been developed (see Neugarten et al. (2018) for an overview). Although monetary assessments are widely recognised in economics and policy-making (see Macháč et al. 2026), they are limited to those ES with clear market values or measurable willingness to pay. Furthermore, monetary values often vary considerably across regions and periods, reflecting differing socio-economic contexts (Chan et al. 2012; Perosa et al. 2021). Non-monetary approaches, in contrast, can be applied to all ES and can give a quantitative and comparable value for holistic decision-making (Podschn et al. 2018b). This paper does not generate new empirical data; instead, we aimed to scientifically bring together experts from different European countries in this field and review their data and experiences to identify common themes. This review aims to synthesise existing knowledge on the conceptual framework from literature and to review and evaluate the applications of non-monetary ES assessment methods for river floodplains on different scales (basin-wide, regional and local). By analysing three case studies (the international Danube River Basin, the Nebel River in Germany and the Koviljsko-Petrovaradinski Rit Nature Reserve in Serbia), we showcase the applicability and benefits of such an ES evaluation approach for different purposes (prioritisation of measures, evaluation of implemented NbS, decision-making of future NbS) and discuss key lessons learned to increase the multi-functionality of floodplain NbS.

Conceptual Framework

Ecosystem services in river floodplains

Currently, the standard for ES categorisation at the European level is given by the Common International Classification of ES (CICES, Haines-Young (2023)), which divides ES into the three main categories Provisioning, Regulation and Maintenance and Cultural ES (Table 1).

Table 1. Examples of the numerous ES in Europe's floodplains.

Provisioning ES	Regulation & Maintenance ES	Cultural ES
Drinking water	Flood regulation	Landscape aesthetic quality
Fisheries, wild herbs and wild animals	Drought regulation	Natural heritage
Arable crop production	Retention of nutrients (N, P)	Opportunities for non-water-related activities
Plant biomass for agricultural use (e.g. fodder)	Local temperature regulation / cooling	Water-related activities
Plant material for construction (e.g. timber, reeds)	Sediment regulation	Knowledge systems
Plant material for energy (e.g. timber, corn)	Habitat provision / Maintaining habitats	Cultural heritage
Water for use (e.g. irrigation, cooling)	Soil formation in floodplains	
	Greenhouse gas regulation and carbon sequestration	

Source: Podschun et al. (2018b), Fischer-Bedtke et al. (2020), Kaiser et al. (2020), Riis et al. (2020), Jähnig et al. (2022), Stäps et al. (2022).

Due to their heterogeneity of waterbodies, sediment types, as well as spatial and temporal variability of water flow, floodplains exhibit more complex ecological processes, structures and functions as compared to purely terrestrial or aquatic systems (Pusch et al. 1998). Peculiarities in floodplains are the continuous water availability, the fertile soils induced by nutrient and sediment depositions during flooding events, a vivid relief and a shifting mosaic of different habitats supporting high biodiversity. Hence, floodplains may not only provide ES that are similarly available in terrestrial parts of a river catchment (i.e. provision of arable crops or fodder, cultural or natural heritage, recreation, pure air), but, additionally, a number of specific ES related to their dynamic aquatic and semi-aquatic features. As a consequence, floodplains represent hotspots of regulating ES (i.e. nutrient retention, flood risk reduction, cooling effect, carbon sequestration, sediment regulation) (see Zak et al. 2026; Ludewig et al. 2026) and additionally provide a number of specific provisioning and cultural ES that only can be provided in wetlands (i.e. water-related recreational activities, provision of fish for food, drinking water) (see Wantzen and Cao 2026). Thus, ES in floodplains can be divided into floodplain-specific ES, floodplain high-performing ES and common ES (Stammel et al. 2025). The provision of the first two ES types highly depends on the pulsing hydrology of the river and is, therefore, higher in intact or restored floodplains than in degraded ones (Scholz et al. 2012; Natho et al. 2013; Schulz-Zunkel et al. 2021; Kaden et al. 2023b).

Advancing ecosystem services in floodplains with Nature-based solutions

A wide range of practical approaches is used to implement NbS as sustainable and cost-effective solutions for the long-term management of multi-functional

river and floodplain systems, improving the green and blue infrastructure. It is important that the remaining functional rivers and their floodplains are protected so that they can provide their ecosystem services, such as habitat provision, water retention or natural purification functions as nature-based solutions. If rivers and wetlands are already impaired by intensive land use or watercourse development, various measures are necessary to restore these riverine landscapes.

Many of these measures (see Table 2) involve initial technical interventions (e.g. opening dykes, closing drainage ditches, removal of embankment, reconstructing meandering river arms), which are aiming to re-establish basic functions of a natural floodplain ecosystem. These measures that re-establish the natural hydro-morphological dynamics and the four-dimensional connectivity (longitudinal, lateral, vertical and temporal) between river and floodplain are effective and self-sustaining. Particularly effective measures include the removal of dams and barriers with accompanying morphological adaptation measures and river channel widening (Breznikar and Mehl 2024). Smaller measures like retaining dead wood in the river also lead to greater habitat and flow diversity, thus improving the typical morphodynamics. Re-establishing lateral and longitudinal connectivity forms the foundation for a wide variety of natural functions and processes within river corridors, which collectively determine the resilience of this ecosystem. The wide range of these NbS, regardless if conservation management, technical or passive restoration measures, as well as the ecological management and extensive use of floodplains, are highly effective in enhancing a wide range of ES (Schindler et al. 2014; Hornung et al. 2019; Kaiser et al. 2020; Wulf 2021; Pusch et al. 2024). Beside the partly negative effect on yields of arable field, ES such as providing clear drinking water, as well as fish and game, retention of nutrients, flood and droughts or sedimentation, maintenance of habitats for endangered species, as well as provision of recreation in urban and rural areas, were mainly positively affected by the measures (Table 2). Additionally, their implementation can also contribute to the reduction of greenhouse gas emissions (especially methane and nitrous oxide) and thus to climate protection (mitigation potential). In some cases, a combination of different types of hybrid measures can be most beneficial (e.g. establishing an extensive management of floodplain meadows after enlarging their area through dyke relocation). Depending on the restoration measures, the performance of ES after the restoration can differ from “high” to “site specific”, which means, only in specific situations, the ES provision will increase. However, also, negative effects by the restoration on specific ES are possible, for example, arable crops and plant biomass which might not be produced anymore after the implementation of restoration measures due to the new hydrological situation (Table 2).

Non-monetary ES Assessment Methods in floodplains

Validated multiple ES indices and mapping of multi-functionality

A large variety of methods to evaluate ES has been developed. Neugarten et al. (2018) and the ValuES project (<http://www.aboutvalues.net/>) provide a comprehensive overview of different ES evaluation tools and a valuable guide to selecting a method. In contrast, the number of methods which simultaneously and uniformly assess all occurring ES specifically in floodplains is very scattered. As

Table 2. Overview of exemplary river and floodplain management and restoration measures representing nature-based solutions and their performance of key ES after restoration. Performance is illustrated with the color in the cells: dark blue – high, light blue – site specific, rose – negative performance. White cells represent irrelevant measures to the specific ES.

Measures	Qualitative description of measures	Ecosystem Services								
		Provisioning			Regulation & Maintenance				Cultural	
		Drinking water	Fisheries, pasture, wild herbs and animals	Arable crops and plant biomass	Nutrient retention	Sediment regulation	Flood regulation	Maintaining habitats	Greenhouse gas regulation and carbon sequestration	Nature-related activities
Protection of naturally functioning river and floodplain systems	Supporting the continued functioning of river and floodplain sections that are in good condition and still provide various ES	Dark blue	Dark blue	Dark blue	Dark blue	Dark blue	Dark blue	Dark blue	Dark blue	Dark blue
Dyke relocation	Enlarging the possibly inundated floodplain area; main purpose is mitigating flood risk and lowering the flood height	Dark blue	Dark blue	Light blue	Dark blue	Dark blue	Dark blue	Dark blue	Dark blue	Dark blue
Removal of embankments and re-meandering	Restoration of dynamic river by enabling lateral erosion, entraining sediments (equilibrium), mitigating river incision and supporting re-meandering	Dark blue	Dark blue	Light blue	Dark blue	Dark blue	Dark blue	Dark blue	Light blue	Dark blue
Reconnection of oxbow lakes and flood channels	(Re-)connection of cut-off former river channels and oxbows in the floodplain	Dark blue	Dark blue	Light blue	Dark blue	Dark blue	Dark blue	Dark blue	Dark blue	Dark blue
Ecological management/restoration of polder areas	Controlled flood detention polders for targeted cut-off of flood waves; preferential land use: forests or extensive grasslands	Light blue	Dark blue	Rose	Dark blue	White	Dark blue	Dark blue	Light blue	Light blue
Restoration and extensive land use (grassland and forests)	Promote the re-establishment of extensive alluvial meadows and pastures as well as new floodplain forests	Light blue	Dark blue	Light blue	Dark blue	Dark blue	Dark blue	Dark blue	Dark blue	Dark blue
Removal of weirs	Re-establishing the full longitudinal and lateral connectivity of a river	White	Dark blue	Light blue	Dark blue	Dark blue	Dark blue	Dark blue	Light blue	Dark blue
River wood	Increase structural diversity by keeping and adding dead wood	White	Dark blue	White	Dark blue	Dark blue	White	Dark blue	Light blue	Dark blue
Stoppage of drainage	Removal or closure of drainage ditches and pipes in the floodplain	Light blue	Dark blue	Rose	Light blue	White	Light blue	Dark blue	Light blue	Dark blue
River channel widening	Widening of artificially narrowed rivers, creation of a new ones, thus increasing floodplain size and decreasing river incision	Light blue	Dark blue	Rose	Dark blue	Dark blue	Dark blue	White	Light blue	Light blue

Summarised from the following sources: <https://www.nwrm.eu/catalogue-nwrm/benefit-tables>, Blackwell and Maltby (2006), Schindler et al. (2014), EEA (2020) and adjusted according to expert judgements of the authors.

a non-monetary, quantitative assessment approach, the RESI (river ecosystem service index, Podschun et al. (2018b); Pusch et al. (2018); Fischer-Bedtke et al. (2020)) has been developed in Germany aiming to map 18 different provisioning, regulation and maintenance and cultural ES of complex riverine landscapes. Subsequently, this RESI approach has been extended and internationally adopted to the Danube River Basin by the IDES project. Nowadays, the IDES approach provides assessment schemes for 26 ES listed in Table 1 (Stäps et al. 2022). Stäps et al. (2022) provide factsheets on the assessment method and the required data for each ES. IDES has either used the RESI indicator approach (Podschun et al. 2018b), which requires detailed data about soil parameters, topography, habitat

types etc. or the simpler capacity matrix approach which was developed by Burkhard et al. (2009) not only for floodplains, but terrestrial landscapes in general and translates land-cover/land-use types into ES values (Stoll et al. 2015). Consistent in both approaches is the classification of the assessment results for each ES performance in an easily intelligible 5-level scale (1–5) comparable with other operational 5-level assessment frameworks, for example, the EU WFD. The results of single areas can be spatially aggregated and mapped for single floodplain segments of 1 to 10 km width in order to visualise assessment results. This approach enables comparisons of the ES amongst each other, but also amongst several floodplain sections and management scenarios.

The resulting information on the provision of multiple ES can be integrated into one single metric, generally referred to as ES multi-functionality indices. Commonly, such indices comprise metrics of alpha diversity (e.g. Shannon, Simpson), beta diversity (i.e. dissimilarities between sites) (Hölting et al. 2019), the sum or mean ES provision (e.g. Funk et al. (2019); Podschun et al. (2018b); Stammel et al. (2025)), threshold-based approaches (e.g. Byrnes et al. (2014) Tschikof et al. (2024)) or the proximity-to-target-value method (Rodríguez-Loainaz et al. 2015). One threshold-based approach is the MuFu (Tschikof et al. 2024), which expresses the ratio between high-valued and low-valued ES. They have been used to identify hot spots of ES capacities and to prioritise areas where ES provision needs to be improved.

Potential Applications of Mapping ES multi-functionality across different scales

Quantifying and mapping the performance of multiple ES provides essential information on the state of floodplains. It can be used to compare different areas and time periods and correlate the evaluation scores with pressures as potential drivers for the provision of ES. The result can identify the best management option, elaborate management goals, identify potential restoration sites, assess restoration success and inform policy-makers, managers and local communities (Maes et al. 2012; Funk et al. 2019; Gilby et al. 2020; Sendek et al. 2021). Thus, the data-based ES assessment of multi-functionality patterns represents an objective tool to support the strategic planning of NbS in floodplains at the basin or regional level, helping to mainstream ES into policy- and decision-making (Maes et al. 2012). Further, it guides integrative planning in floodplains at the local level, enabling decision-makers to include multiple interests to co-design appropriate solutions with stakeholders (Vizi et al. 2023; Tschikof et al. 2024; Ilić et al. 2024).

The spatial level at which the assessment is conducted depends on the type of planning, the spatial assessment unit and the level of accuracy or abstraction of the measures to be taken. On the basin level, at which large assessment units must be used, such an approach mainly addresses ES capacities and human pressures that are relevant at large scales and often linked with the transport of substances along river networks (e.g. nutrient regulation and pollution), very mobile organisms (e.g. habitat for migratory fish and its hydro-morphological alterations) or climatic effects (e.g. greenhouse gas regulation and land-use change). Such extensive ES mapping has been challenging in the past, as it requires standardised or at least harmonised ES evaluations to achieve an unbiased, data-driven and comprehensive overview (Polasky et al. 2015), but recent regulatory and technological developments open new potentials (e.g. EU reporting, open data,

earth observation). At the regional scale, in contrast, due to more precise data and smaller spatial units, concrete evaluations can be used to assess both the current state and either past implementations or future activities. Finally, at the most precise, local scale, the specific interests of stakeholders and the local peculiarities must be considered to identify those NbS that maximise the benefits for the local society. Here, also very localised or subjective ES can be captured, such as the perceived recreational value of a site (e.g. Wulf (2021)) or the cultivation of a specific food item. At the local level, it is thus possible to complement the data-based ES assessment by investigating the use and valuation of the different ES by local stakeholders, as well as their opinions about their relative availability.

Although ES multi-functionality indices visualise the “bigger picture”, they lack specificity about the composition of ES and their actual use and valuation, which differs widely throughout floodplains and societies. Local participatory approaches can complement this issue and are suitable for assessing the effects of NbS, because concrete interventions must be customised to the local conditions and social demands (Tschikof et al. 2024).

Case study application

To showcase the variety of potential applications, we choose three implementations of ES assessment conducted by the authors at different scales (large river basin, entire smaller river, local scale) and for different purposes (prioritisation, evaluation of implemented NbS, decision-making of future NbS). For each case study which is described in more detail in research papers, we briefly describe the investigation area and the assessment methods, the results and their discussion.

The large scale: identifying patterns and prioritising actions in the Danube River Basin

Investigation site and methods

In the large floodplains of the Danube River Basin, the world’s most international river basin with an area of 817,000 km², seven regulating, four provisioning and three cultural ES were selected and evaluated using the IDES approach (Stäps et al. 2022) to correlate them with indicators of human pressures. The 5-level scoring approach used for ES evaluations provided internationally harmonised results, which is especially important in a region where the heterogeneous data availabilities and policies (national vs. EU and non-EU) have always complicated transboundary assessments. Along the rivers Danube, Tisza, Sava and Yantra, ES multi-functionality was assessed by applying the multi-functionality index MuFu (threshold 4) which relates ES values smaller than 4 to those with values with 4 or 5 (Tschikof et al. 2024). Further, eight indicators of human pressures that have been commonly reported in the Basin, were quantified in a standardised way (0–1) and summed to estimate the magnitude of multiple pressures (Fig. 1).

Key findings

Generally, the degree of ES multi-functionality responded inversely to the multiple pressures in rivers and floodplains. Land-use intensity, impoundments and

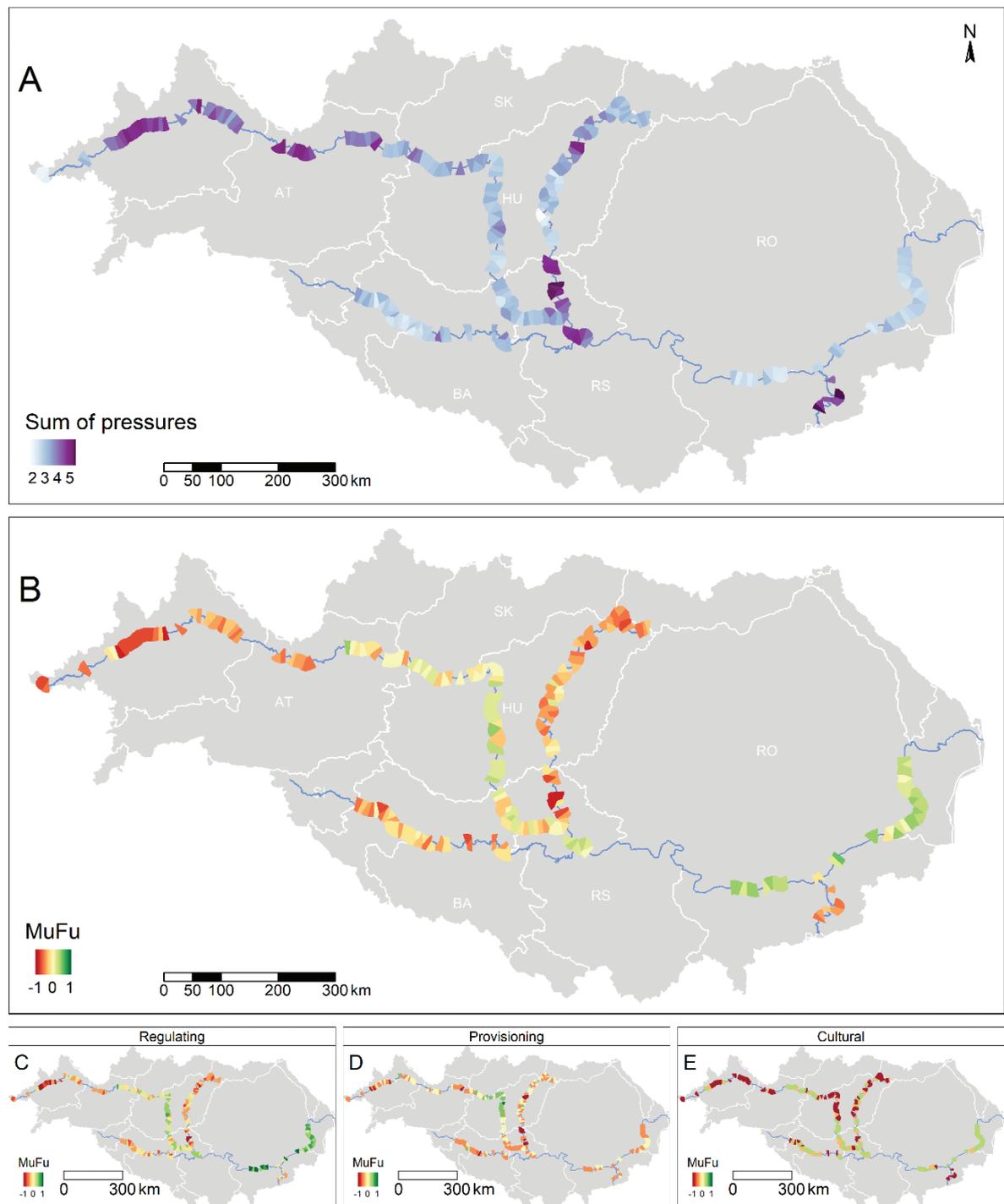


Figure 1. Distribution of indicators of human pressures (A) and ES capacities (B) in 10-km wide segments of large active floodplains of the Danube River Basin. The threshold-based multi-functionality index MuFu ranges between -1 (only low-scored ES < 4) and 1 (exclusively high-scored ES ≥ 4). It is shown both for the total set of ES ($n = 14$) and individually for regulating (C) ($n = 7$), provisioning (D) ($n = 4$) and cultural ES (E) ($n = 3$). The following pressure indicators were considered in A): land use intensity, floodplain loss, low/no nature protection status, river morphological alterations, impoundments/backwater, river total nitrogen concentration, river total phosphorus concentration and landscape simplicity. The following ES were considered in B–E): nitrogen removal, phosphorus retention, greenhouse gas regulation, flood mitigation, low-flow regulation, sediment transport regulation, habitat provision, firewood and timber production, arable crop production, grassland production, water provision, landscape aesthetics, knowledge systems, cultural heritage and diversity. Adapted from Tschikof et al. (2024).

morphological alterations showed the most significant impact on the availability of assessed ES, but the strength of the correlation varied regionally. On the other hand, nutrient pollution of the river has been substantially reduced since 1990 (Kovacs and Zavadsky 2021) and did not significantly impair multi-functionality in our study (Tschikof et al. 2024). The former floodplains, behind dykes and disconnected from direct flooding dynamics, facilitate a more intensive land use resulting in lower capacities to provide a variety of regulating ES (Stammel et al. 2018; Stammel et al. 2025).

Lessons learned

Our findings showed that floodplains along the lower and middle Danube exhibited the greatest levels of ES multi-functionality (i.e. high-scored ES dominate) which clearly calls there for prioritising conservation measures to preserve the extraordinary benefits to nature and society. The upper to middle Danube and Sava Rivers exhibit medium levels of ES multi-functionality (i.e. high and low-scored ES in balance), where prioritising locally-tailored NbS can promote those ES with high human demand (see chapter “Integrating the local view”). Such measures include lateral floodplain reconnections or land-use changes, amongst others (Table 2). In contrast, in major parts of the rivers Yantra, Tisza and the upper Danube, pressure mitigation measures would appropriately support the many low-scored ES and the low levels of multi-functionality. For example, the level of human pressures could be effectively lowered by halting or reversing morphological alterations along the upper Danube and lower Tisza (cf. Hein et al. (2016)), and by reducing nutrient emissions in the eutrophic River Yantra. This prioritisation for conservation, restoration and mitigation measures, based on multi-functionality, revealed similar patterns compared to previous studies on the Danube River (Funk et al. 2019). Furthermore, synergies amongst ES could increase the success of measures by promoting win-win situations (e.g. positive correlations between flood retention and nutrient retention), while also potential trade-offs can be identified at an early stage (e.g. negative correlations between habitat provision and crop production) (Tschikof et al. 2024). The novel ES multi-functionality metric MuFu hence represents a suitable tool to quantify the multi-functionality of river and floodplain management in planning tools, such as the future Danube River Basin and Flood Risk Management Plans (ICPDR 2021a; ICPDR 2021b) and, thus, facilitates complex decision-making processes there, as well as in other river basins. Combining the knowledge on the basin scale with local participatory methods (see the local case study in Serbia) will further help to draw better-informed conclusions for more sustainable floodplain management in the 21st century.

Managing an entire river: River Nebel in northern Germany – demonstrating the co-benefits of river and floodplain restoration

Investigation site

Nowadays, the more than 60 km long lowland River Nebel in Germany, which flows into the Baltic Sea via the River Warnow, has a very high nature conservation and ecological value, featuring its glacial moraine breakthrough valley

section and its vast floodplains, characterised by grasslands and peatlands. In several sections of the river, however, its ecological status had been severely impacted by hydraulic engineering and intensive agricultural use in the 20th century. From 1990 to 2016, extensive efforts have been undertaken to restore around 22 km of the River Nebel and its floodplain at a cost of more than €7 million (Mehl et al. 2018, Fig. 3). These restoration initiatives have addressed societal challenges by NbS and have led to notable improvements in the ecological status of the entire river (Mehl et al. 2018, 2020).

Methods

Aiming to evaluate restoration success, seven regulation and maintenance ES (greenhouse gas retention/carbon sequestration, flood regulation, drought regulation, sediment regulation, floodplain soil formation, cooling effects and habitat provision) were assessed with the RESI Index (Podschn et al 2018a, b; Mehl et al. 2018, 2020) both for the status before and after the restoration, using a combination of current survey data and data from the early 1990s (before restoration). Four cultural ES (landscape aesthetic quality, natural and cultural heritage, opportunities for non-water-related activities, as well as for water-related activities) were evaluated only for the situation after restoration. Where appropriate, monetary values were additionally assigned to regulation and maintenance services (Mehl et al. 2018).

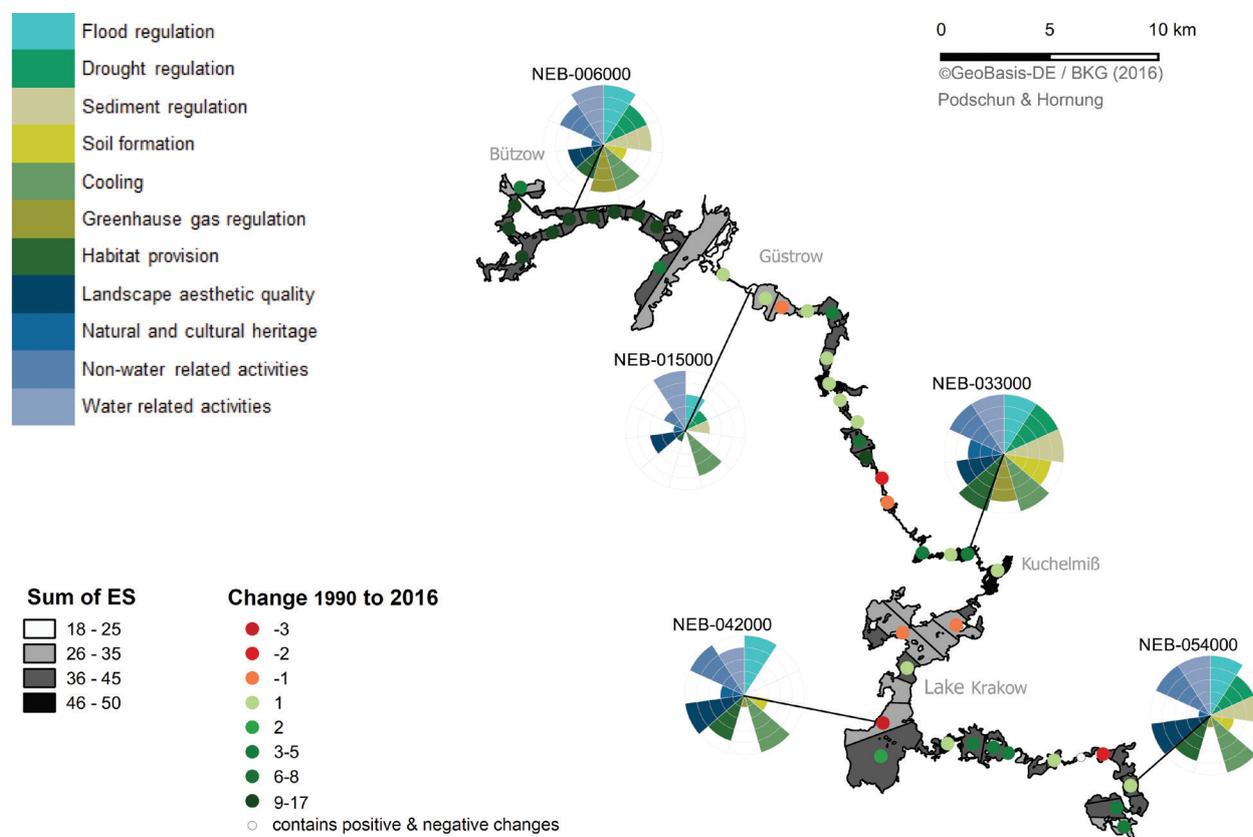


Figure 2. Assessment of 11 ES for selected floodplain segments in 2016 and their change compared to 1990 (before restoration) for the entire River Nebel (Germany) (adapted from Podschn et al. (2018b)).



Figure 3. River Nebel in Mecklenburg below the Village of Hoppenrade, during (2005) and after restoration (2017) (Source: Institut biota GmbH, K. Lüdecke).

Key findings

Overall, restoration measures implemented between 1990 and 2016 have achieved improvements in a number of analysed ES with the RESI-method (Mehl et al. 2018, 2020). Specifically, 35 out of 43 1-km floodplain segments show increases in the performance of ES, with the sum of seven evaluated regulating ES increasing by up to 17 points (Fig. 2). Only seven segments showed a negative tendency (decrease: 1–3 points), mainly because of increasing greenhouse gas emissions from peatland areas, caused by local decreases in water levels that occurred independently from the river restoration project due to climate change effects as well as sedimentation processes. The increases in the performance of ES flood regulation, drought regulation, sediment regulation, habitat provision and partly of carbon sequestration, in contrast, are direct outcomes of the implemented measures. These effects result from the restoration of the river and reactivation of the former floodplain to an active floodplain, the removal of weirs and the resulting impoundment and from the conversion of the formerly intensively used farmland into typical wetland habitats. Regarding the evaluation of cultural ES, the opportunities for water-related and non-water related activities, as well as landscape aesthetics, also received rather high scores for the post-restoration state.

These results show that the benefits for people and the environment of combined river and floodplain restoration measures are much broader than would be revealed by only considering classic parameters of ecological status. A more precise, quantitative evaluation of selected ES revealed the following values:

- A nearly 20% reduction of greenhouse gas emissions from formerly intensively used peatland soils (approximately 9,000 tons per year of CO₂ equivalents, equating to a damage reduction of around €720,000 in 2010 to €2,282,085 in 2023 per year), based on the damage cost approach according to the German Federal Environment Agency's methodological convention (reference year 2014: €80 t⁻¹ CO₂ according to Schwermer et al. (2014) and 2023 €254 t⁻¹ CO₂ according to UBA (2024)).

- An increase in flood retention area of approximately 17% (equivalent to about 119,000 cubic metres of water or a monetary flood risk mitigation of approximately €174 million; the costs were estimated as replacement costs, with current costs of €25 m⁻³ as of 2018, which corresponds to the average value for earthworks, soil transport, planning and investigation from implemented regional projects).
- A more than 12% increase in the cooling capacity of waterbodies and soils (1,815 Gigawatt-hours per year).

Lessons learned

Hence, the River Nebel represents an example for successfully implemented NbS. Results show using the RESI-Index enables assessment of changes in individual ES in comparisons before-and-after measure implementation, despite the different databases for 1990 and 2016. However, it must be noted that no provisioning services were considered in this study. In some cases, the restoration of the Nebel floodplains has severely restricted the previous grassland use. However, recent developments in land-use forms, such as paludiculture, certainly offer the opportunity to utilise formerly drained wetland soils in an economically viable way (Närmann et al. 2021), but should also include nature conservation goals. The results of the floodplain restoration also show the high importance of the ES carbon sequestration in this peatland floodplain, which should be adequately rewarded. Depending on which damage cost approach is used for greenhouse gases, the investment of approx. €7 million in restoration will be amortised in 4 to 10 years.

Integrating the local view: Special Nature Reserve Koviljsko-Petrovaradinski Rit in Serbia - determining the potential of floodplains by scenario assessment

Investigation site

The local scale showcase Koviljsko-Petrovaradinski Rit (KPR) is located on both banks of the Danube River, near Novi Sad, the capital of Vojvodina Province in Serbia (Fig. 4). Spanning an area of 5,886 ha and stretching 22 km in length, the Reserve is home to more than 447,000 inhabitants.

The area represents a structurally diverse and compact complex of marshes and forest ecosystems within the floodplain of the Danube River and is one of the most important protected areas in Serbia along the floodplains of the rivers Danube, Tisza and Sava (Puzović et al. 2015). The ecological assets of the area include:

- a well-preserved and diverse range of orographic and hydrographic marshland features (e.g. islands, backwaters, ponds, swamps, channels, oxbow lakes);
- a huge diversity of habitats (39 habitat types prioritised for conservation);
- species-rich native floodplain plant communities (forests, wet meadows, reeds, rushes) and the presence of rare and endangered animal and plant species.

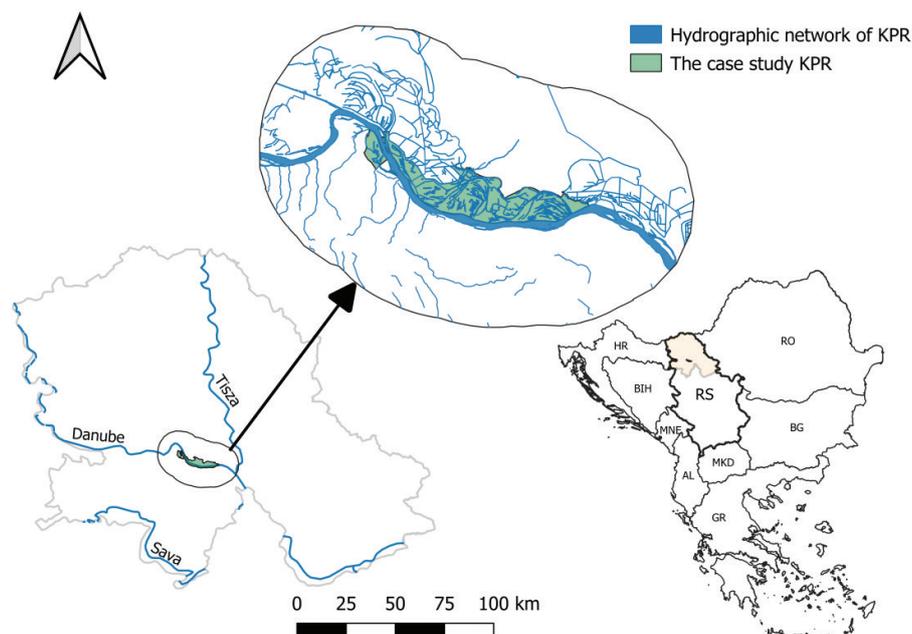


Figure 4. Location of the Koviljsko-Petrovaradinski Rit (KPR) (Ždero et al. 2024).

Forests cover 69% of the area, complemented by large meadows and pastures (15%), as well as waterbodies (8%) (VojvodinaŠume 2021). In addition to its natural values, KPR holds significant socio-economic, cultural and historical importance, providing numerous ES, such as habitat provision, plant material for construction, drinking water, flood regulation, retention of nutrients, landscape aesthetic quality, opportunities for non-water-related activities and cultural heritage.

The status of the wetland habitats (riparian areas, oxbows, backwaters, wet meadows, marshes) and the hydrological regime have significantly deteriorated over the past 30 years due to siltation and aggradation caused by both natural processes and anthropogenic activities (forestry, pollution from the surrounding arable land, flood protection measures). Intensive land use led to habitat degradation and fragmentation, while river regulation and flood protection measures have disrupted the natural flood dynamics. This disruption has altered water flow through the marshes, ponds, channels and former side arms and their exchange with the river, reducing open water surfaces and water quality. Consequently, the area has experienced vegetation succession, transforming aquatic and semi-aquatic vegetation into shrubs and forests, leading to the loss of natural habitats for many important aquatic species and subspecies vital for biodiversity conservation.

Methods

In the KPR, the same ES were assessed as for the entire Danube Basin (see above), but with a more detailed scale to describe the area's status quo. Additionally, two workshops were held with over 40 stakeholders representing various interests relevant to the KPR (Stäps et al. 2022; Tschikof et al. 2024). These workshops, designed as co-learning and co-creation processes, introduced stakeholders to the ES concept and collaboratively identified the ten most important ES in KPR, the five most important pressures and the five most effective

measures to mitigate these pressures. Using a fuzzy cognitive model (Gray et al. 2013) to map the causal relationships amongst identified ES, pressures and measures, stakeholders were asked to identify the combination of measures to increase the ES performance at KPR. Several scenarios were developed jointly: the status quo, an ideal scenario (i.e. all pressures minimised) and an optimal scenario (i.e. an agreed and realistic level of pressure reduction) (Ilić et al. 2024).

Key findings

Additionally, the impact of restoration activities on relative ES values for all three scenarios was analysed. Fig. 5 illustrates the supporting effects of restoration activities on four ES with the highest relative value change provided by KPR: plant biomass production (grassland), water-related activities, flood risk regulation and habitat provisioning. These ES were selected because of the highest change in their relative value across different scenarios.

Lessons learned

The results confirm a low availability of the four investigated ES in the status quo due to the current major deficits in the wetland habitat status (riparian areas, oxbows, backwaters, wet meadows, marshes) and the altered hydrological regime. In the ideal scenario, all ES are improved to good or very good conditions, but this scenario does not account for the varying needs and rights of the local residents and stakeholders. The optimal scenario, in contrast, co-designed during the workshops reflecting all stakeholders' interests, still improves all ES.

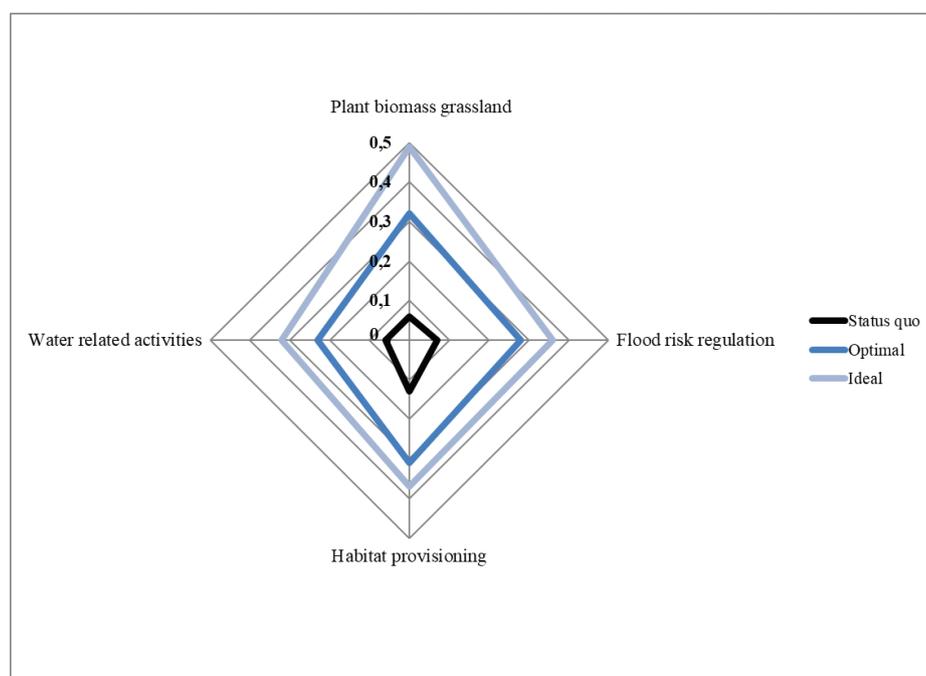


Figure 5. Distribution of the relative values of the four ES for the status quo, the “optimal” and “ideal” scenarios as agreed amongst the stakeholders, in case of applied restoration activities. Values 0–0.5 show the relative value of the floodplain’s potential to provide given ES under the selected scenarios.

This scenario clearly demonstrates the importance of implementing balanced restoration activities and highlights the positive and synergetic effects of reducing human pressures alongside restoration efforts on improving ES availability at KPR. Implementing the ES approach when co-operating and co-designing management options with stakeholders thus leads to more effective decision-making and improved (or even optimised) management strategy for KPR.

The presented case study clearly illustrates that implementing NbS can provide significant benefits both for the local community and the natural environment of KPR. This approach is also reflected in the KPR Management Plan 2022–2031 (VojvodinaŠume 2021), which includes various revitalisation and restoration measures. Since funding often presents a bottleneck for the implementation of such measures, the science-based results of the case study, which are well-suited for communication with stakeholders, can help attract potential investors.

Synthesis and discussion

Historic human alterations of river-floodplain ecosystems have been motivated by several societal sectors and economic interests, including agriculture, urban development, traffic infrastructure construction, flood protection or navigation. Thus, ecological and sustainable floodplain management is often conflicting and competing with strong economic interests. The resulting deficit in many ES may often not be adequately addressed through action options available in water management (such as the Water Framework Directive) or nature protection (such as the Birds and Habitats Directives), only. Additionally, the willingness of land owners to provide land for purposes of river restoration or rewetting formerly drained landscapes is often small (Serra-Llobet et al. 2022). Therefore, the early involvement of all relevant stakeholders, especially land owners and land users, is crucial for the successful implementation of any floodplain project (Wulf 2021; Ilić et al. 2024; Tschikof et al. 2024). Implementing multi-functional green-blue infrastructure and NbS to reconcile water management objectives with diverse sustainable socio-economic activities may potentially resolve these conflicts (Rozkošný et al. 2014; Faivre et al. 2017; Kooijman et al. 2021). The actual selection of the NbS measure type most suitable for a given river or floodplain will depend on the project's scale and objectives as well as the socio-economical, ecological and hydrogeomorphological context of the site and its catchment. Additionally, shown ES assessment approaches may support identifying win-win scenarios avoiding trade-offs which may also reduce the impacts of climate change (EEA 2021b; Seddon 2022). In that context, the EU Nature Restoration Law adopted in 2024 holds much potential to restore biodiversity and ES, thus overcoming some of the problems associated with the implementation of yet established EU legislation, strategies and policies, which, for example, focuses on more sectoral objectives, evaluations and implementation schedules (Hering et al. 2023). It should be noted that, besides the restoration of degraded ecosystems, the conservation of existing, still naturally functioning river and floodplain systems should be given priority wherever possible.

Case studies provided in this article showcase a functional approach that employs multiple quantitative ES assessments to integrate diverse interests

through a multi-dimensional perspective, which can be applied across various scales and planning levels. Our evaluation of ES at the Danube River Basin scale, utilising EU-wide available data, identified deficiencies in ES provision for the floodplains of the Upper Danube, the Tisza or the Yantra Rivers and trade-offs between provisioning ES and regulation and maintenance ES. Identified areas with low ES availability may be selected for the implementation of NbS aiming at the mitigation of existing pressures, whereas areas with high ES assessment scores necessitate protection from potential new human impacts. Other large-scale prioritisation approaches, such as those following the probability of restoration success and the availability of remaining semi-natural areas, may complement this multi-functionality approach (Funk et al. 2019; Domisch et al. 2019). These results can pinpoint geographical restoration focuses on both basin and national levels. At the regional level, we showcased the positive effect of restoration on regulating ES provision by comparing before and after restoration using historical data. Regarding the costs of the restoration of the River Nebel and its floodplains, it can clearly be demonstrated that the costs were amortised after a few years by the reduction in flood risk and CO₂ emissions.

Conducting a standardised ES assessment during the elaboration of regional management plans will enhance integrative and inclusive decision-making processes and, hence, support sustainable NbS implementation. Such status quo and scenarios evaluation of ES provides a scientific decision-support tool for prioritising integrative management options, including conservation, restoration and mitigation at either the basin or the regional scale. Training water managers and planners to organise ES-based, integrative and transparent decision-making processes will foster the development of multi-purpose and sustainable solutions (Serra-Llobet et al. 2022; Vizi et al. 2023), thus facilitating NbS implementation. At the local scale, as we have seen along the Danube, the ES approach facilitates stakeholder integration in planning processes, promoting mutual understanding and appreciation of diverse perspectives and enabling the joint development of site-specific integrative concepts (Ilić et al. 2024). The balance of stakeholder interests and restoration goals may differ amongst countries and landscapes, while the ES approach respects the unique characteristics and constraints of each site, allowing stakeholders to prioritise the most critical ES within their planning areas.

The NbS approach aiming at enhancing ecosystem functions and ES even in highly degraded river landscapes contrasts with traditional restoration methods focusing solely on habitat structures and biota (Cohen-Shacham et al. 2019). However, the NbS approach better represents the nexus between ecosystems and societal systems, introducing options for self-regulatory processes that align natural and human-used systems with common management goals. Societies and communities that are informed about ES deficits can respond to this by mitigating pressures, adapting management measures and implementing NbS to improve the provision of ES. The effectiveness of NbS may be augmented by an adaptive management, based on the regular assessment of a range of ES along with social (stakeholder participation) and economic (new 'green' economic opportunities) indicators (EEA 2021b; Hudson et al. 2023). Balancing the benefits for the majority of society and fostering the greatest synergies between sectors, rather than only catering to short-term benefits for a certain sector/economy, remains the challenge to be solved.

Conclusions and recommendations

Introducing a cross-cutting ES assessment approach to water and floodplain management may provide a valuable database for the spatial planning of management measures and land-use modes that support the multi-functionality of floodplains. Facilitating the implementation of NbS for the benefit of nature and people at the different planning levels will support planners and decision-makers to: (1) cope with growing challenges in environmental management, such as water crises, climate change, biodiversity loss; (2) maximise the benefits of river and floodplain restoration and management beyond flood protection and optimisation of agricultural use; (3) develop future-orientated floodplain action plans at the basin and national level; (4) co-design tailor-made NbS with stakeholders for Europe's threatened floodplains and beyond; (5) demonstrate the synergies and trade-offs of the different sectoral regulatory frameworks and management scenarios and (6) exploit possibilities for economic ES utilisation to mobilise public and private capital for NbS (see also Birk et al. 2026).

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

No use of AI was reported.

Funding

BS, SCJ, MP, ZS, MT and MS acknowledge funding through the European Union's Horizon Europe Research and Innovation Programme (DANUBE4all, grant agreement no. 101093985, Restore4Life grant agreement no. 101112736, SpongeBoost grant agreement no 101112906 and MERLIN grant Agreement no. 101036337). Supported by the Federal Agency for Nature Conservation (BfN) with funds from the Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (BMUKN) (Project No. 3521830200).

Author contributions

B. Stammel: Conceptualisation, Methodology, Formal analysis, Resources, Writing - Original draft, Writing - Review and Editing, Visualisation, Funding Acquisition; S. C. Jähnig: Writing - review and editing; D. Mehl, Z. Srđević, M. Tschikof: Methodology, Formal analysis, Investigation, Resources, Data Curation, Writing - Original draft, Writing - Review and Editing, Visualisation; M. Pusch: Writing - Original draft, Writing - Review and Editing, Funding Acquisition; S. Wulf: Writing - Original draft, Writing - Review and Editing; M. Scholz: Conceptualisation, Methodology, Writing - Original draft, Writing - Review and Editing, Funding Acquisition.

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Data availability

All of the data that support the findings of this study are available in the main text.

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