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Research article

Cross-scale and integrative prioritization of multi-functionality in large river floodplains

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ABSTRACT

Floodplains provide an extraordinary quantity and quality of ecosystem services (ES) but are among the most threatened ecosystems worldwide. The uses and transformations of floodplains differ widely within and between regions. In recent decades, the diverse pressures and requirements for flood protection, drinking water resource protection, biodiversity, and adaptation to climate change have shown that multi-functional floodplain management is necessary. Such an integrative approach has been hampered by the various interests of different sectors of society, as represented by multiple stakeholders and legal principles. We present an innovative framework for integrated floodplain management building up on ES multi-functionality and stakeholder involvement, forming a scientifically based decision-support to prioritize adaptive management measures responding at the basin and local scales. To demonstrate its potential and limitations, we applied this cross-scaled approach in the world's most international and culturally diverse basin, the Danube River Basin in Europe. We conducted large-scale evaluations of anthropogenic pressures and ES capacities on the one hand and participatory modelling of the local socio-ecohydrological systems on the other hand. Based on our assessments of 14 ES and 8 pressures, we recommend conservation measures along the lower and middle Danube, restoration measures along the upper-middle Danube and Sava, and mitigation measures in wide parts of the Yantra, Tisza and upper Danube rivers. In three case study areas across the basin, stakeholder perceptions were generally in line with the large-scale evaluations on ES and pressures. The positive outcomes of jointly modelled local measures and large-scale synergistic ES relationships suggest that multi-functionality can be enhanced across scales. Trade-offs were mainly present with terrestrial provisioning ES at the basin scale and locally with recreational activities. Utilizing the commonalities between top-down prioritizations and bottom-up participatory approaches and learning from their discrepancies could make ecosystem-based management more effective and inclusive.

1. Introduction

Floodplains are socio-ecohydrological systems that provide essential ecosystem services (ES) to society. Their unique location between aquatic and terrestrial spheres and spatio-temporal heterogeneity result in an exceptionally high degree of multi-functionality, i.e. the supply of ES relative to their human demand (Manning et al., 2018; Schindler et al., 2014). Floodplains are hotspots of biodiversity (Schindler et al., 2016; Stanford et al., 2005), nutrient turnover (McClain et al., 2003) and productivity (Tockner and Stanford, 2002). They represent valuable

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sponges in a river landscape during stormwater and drought periods (Jakubínský et al., 2021; Vári et al., 2022), are dynamic areas of sediment deposition and erosion (Wohl, 2021), and act as sinks and sources of greenhouse gases (Schindlbacher et al., 2022; Zehetner et al., 2009). However, human colonialization and the need for food, security, energy, materials, and transport have severely transformed rivers and their floodplains worldwide (Hein et al., 2021; Tockner et al., 2010), controlling their ecosystem functions (Brauns et al., 2022; Moi et al., 2022) and services (Rillig et al., 2023). Europe's floodplains along large rivers have suffered from past land reclamations for agricultural and urban uses, which resulted in areal losses between 70% and 100% (Globevnik et al., 2020). Nowadays, the remaining floodplain habitats suffer from ecological simplification (Peipoch et al., 2015) and only 17% are in a good conservation status, according to the reporting under the EU Habitats Directive (EEA, 2020). In Europe's heavily industrialized Danube River Basin (DRB), the most reported significant pressures are nutrient pollution, hydro-morphological alterations for navigation, hydropower, flood protection, and invasive alien species (Habersack et al., 2016; Hein et al., 2016; ICPDR, 2021). Those pressures have also drastically altered the quantity and quality of ES (Culhane et al., 2019), but this impact has been investigated only in a few cases so far (e.g. Funk et al., 2021; Perosa et al., 2021).

The concept of ES multi-functionality addresses the need to manage landscapes in such a way that they can provide multiple ES simultaneously (Manning et al., 2018). In recent decades, requirements to protect against natural disasters, provide clean water resources, preserve biodiversity, and adapt to climate change have fueled interest in multi-functional floodplain management. However, such an integrative approach has been hampered by the various and often conflicting interests of different sectors of society (Schindler et al., 2016). The ES concept helps to bridge social and natural dimensions by describing the various benefits humans obtain from ecosystems. An ecosystem-based management through enhancing the ES provision has therefore become a popular paradigm for environmental management (Langhans et al., 2019). It has already been partly adopted in a few policies (e.g. the EU Biodiversity strategy) and continues to gain significance (Bouwma et al., 2018) but still struggles to address the challenges faced by complex systems, including floodplains (Erős et al., 2019). The broad geographic and cultural diversity in the DRB further complicates the planning and implementation of various measures in this region. To reveal causal relationships and the systems' behavior to changes, the ES concept can be integrated into the Drivers-Pressures-State-Impact-Response (DPSIR) framework (Kelble et al., 2013). Hence, quantifying and mapping the provision of multiple ES and the pressures acting on them provides essential information on the response needed to elaborate management goals, identify potential restoration sites, assess restoration success, and inform policy-makers, managers, and local communities (Funk et al., 2019; Gilby et al., 2020; Maes et al., 2012; Sendek et al., 2021). On a large scale, multi-functionality indices using standardized ES assessments have proved useful in prioritizing floodplains for general management options (Hölting et al., 2019b; Schindler et al., 2014). However, the indices lack concreteness about the composition of ES and their actual use, which differs widely throughout floodplains. Therefore, participatory methods with local stakeholders are essential to understand ES's benefits to society, identify management options, and analyse their impact accordingly (Gray et al., 2015).

We hypothesize that strategic and ecosystem-based floodplain management should consider both, large-scale and data-based prioritizations as well as local societal needs. This would open up the possibility of combining the advantages of a top-down approach at the landscape level and those of a bottom-up approach for planning implementations on-site. However, to our knowledge, neither a standardized evaluation of floodplain ES nor a combination of multi-functionality indices and participatory methods have been explored in the DRB. In this study, we present a cross-scaled DPSIR approach that considers anthropogenic pressures and ES at a large scale, as well as local perceptions of stakeholders. Our objectives were to (1) map the presence of multiple pressures and ES in active floodplains to prioritize areas for general management options in the DRB (conservation, restoration, mitigation), (2) locally compare and validate the importance of pressures and ES uses through stakeholder workshops in 3 case study areas to (3) eventually derive tailored management recommendations and assess their potential impact on ES in co-created implementation scenarios.

2. Methods

2.1. A cross-scale floodplain management concept

To foster strategic and integrative floodplain management, we applied a cross-scale DPSIR approach in the DRB. We developed a management concept that builds on the evaluation of the multi-functionality of floodplains, considering both large-scale status assessments and local stakeholder involvement (Fig. 1). To address the elements of the DPSIR framework, we selected dominant *pressures*, ES as *state*, their relationships as *impact* and management measures as *response*. We did not explicitly assess the underlying *drivers,* which are reflected by the resulting pressures. Whereas the data-based evaluation at the basin scale operates top-down aiming at harmonizing ES indicators across administrative borders, participatory methods operate bottom-up aiming at capturing the diversity of human uses and subjective valuations. We compared both assessments to highlight their commonalities and discrepancies and to reveal the geographical and cultural differences of the investigated areas.

2.2. Study area

2.2.1. Large-scale: Danube River Basin

The DRB drains to the Black Sea. With over 800,000 km^2 in 19 countries, it is the second largest river basin in Europe and the most international basin in the world. We investigated large river-floodplain systems along the Danube River (divided into upper, middle, and lower Danube) and its tributaries Tisza, Sava, and Yantra. These tributaries were selected because they span across large parts of the basin, cover a wide range of river sizes (mean discharges at the river mouth: Yantra 22 $m^3\ s^{-1}$, Tisza 789 $m^3\ s^{-1}$, Sava 946 $m^3\ s^{-1}$, Danube 6219 $m^3\ s^{-1}$), and still have extensive active floodplains. We delineated rivers and active floodplains following the methods of Tschikof et al. (2022) and Eder et al. (2022) and demonstrated the massive floodplain loss by visualizing the former floodplain extent (EEA, 2018b) (Fig. 2). Large active floodplains were defined as riparian areas wider than the main river stem and larger than 500 ha, which are inundated in a flooding event with a recurrence interval of up to 100 years. In most cases, this delineation of the former floodplains was determined by the presence of dykes. The resulting river stretches with large active floodplains (3842 km^2) were divided into 253 equidistant segments by creating Voronoi polygons around points every 10 km along the river course in esri ArcGIS Pro (version 2.9).

2.2.2. Local scale: case study areas

The local case studies were conducted in three active floodplain sections across the DRB (Fig. 2), differing greatly in their geography, nature protection statuses, human uses, and socio-economical settings and, hence, the representations of stakeholders involved.

2.2.2.1. Donau-Auen national park, Austria. This case study area (96 km^2) is located between the capital cities Vienna and Bratislava. It is the longest free-flowing section of the Austrian upper Danube (36 km, mean discharge (MQ) = 1930 $m^3\ s^{-1}$), having the hydrological and ecological character of an alpine river. It is the largest ecologically relatively intact natural riverine environment of its kind in Central Europe and a national park under international protection (Natura 2000 site, IUCN category 2)

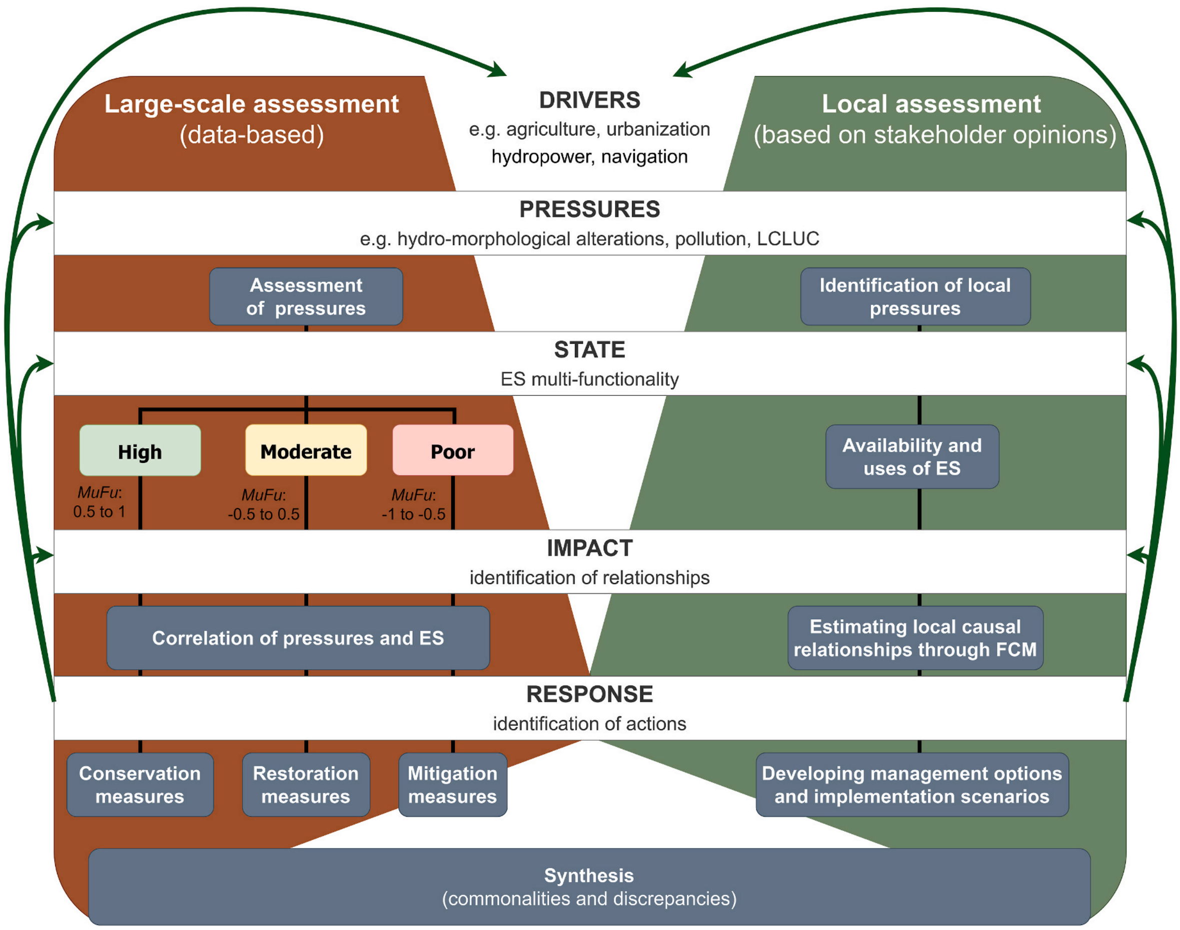

Fig. 1. Flowchart of the cross-scaled DPSIR framework applied in the Danube River Basin. Responses are realized locally but can affect the state of floodplains on a larger scale (green arrows). The assessments at the two scales, based on data and stakeholder opinions, are compared to generate new insights for integrated management (ES = ecosystem services, FCM = fuzzy cognitive mapping, LCLUC = land cover and land use change, *MuFu* = the multi-functionality index in equation (2)). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

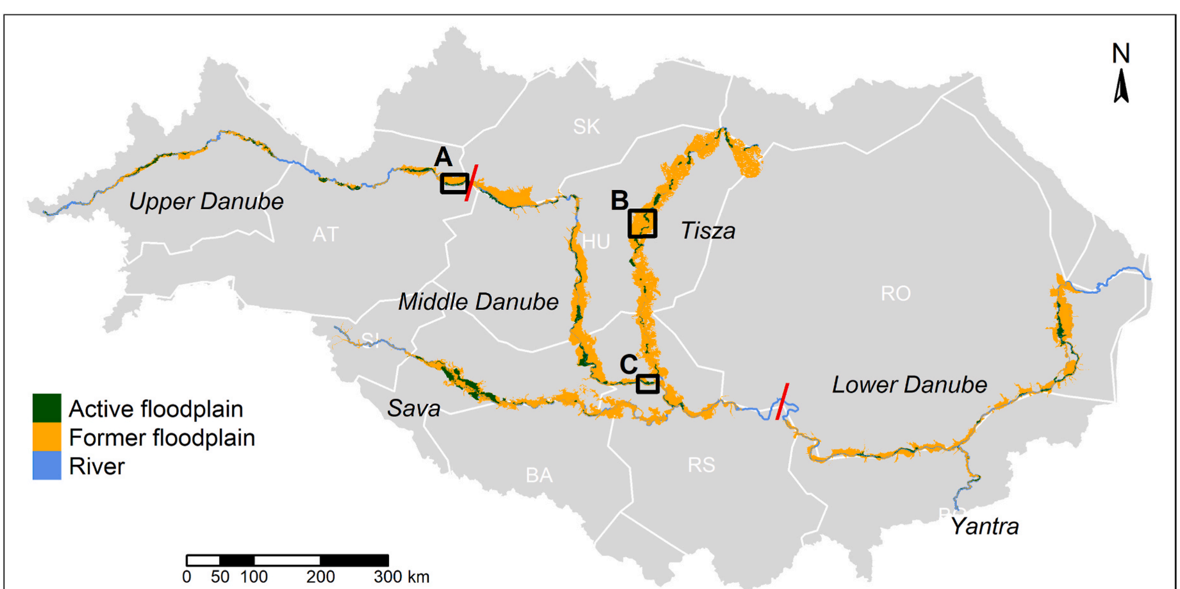

Fig. 2. Studied active floodplains (green) along the Danube, Tisza, Sava and Yantra rivers. The black boxes indicate the location of the case study areas Donau-Auen national park in Austria (A), the floodplain between Kisköre and Szolnok in Hungary (B), and the special nature reserve Koviljsko-petrovaradinski rit in Serbia (C). Red lines indicate the borders between the upper, middle, and lower Danube. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

in the Danube Network of Protected Areas. This section of the Danube River hosts an enormous variety of habitats and is a refuge for many endangered plant and animal species, but it also represents an important waterway for transporting goods and passengers. The proximity to the two capitals makes the national park an attractive destination for recreation and tourism and a site of intensive research (Arnberger et al., 2021). The national park is exposed to hydro-morphological pressures caused by river regulation and hydropower, as well as recreational overuse and invasive alien species. Under consideration of navigation purposes, there have been recent advances in enhancing the impaired hydrological connectivity, reducing riverbed incision, and thus, improving the ecological state. Progressive side-channel reconnections, removal of rip-raps, and integrated river engineering measures have been conducted and accompanied by scientific monitoring since 1996 and are ongoing (Tögel and Baumgartner, 2016). The participating stakeholders represented the conservation, fisheries, environmental management, tourism, and administrative sectors, including the National Park Authority and the National Waterway Authority in charge of implementing the restoration measures (Table SI2).

2.2.2.2. Floodplain between kisköre and szolnok, Hungary. This case study area (92 km^2) is located in the middle of the Great Hungarian Plain along the Tisza River downstream of the Tisza reservoir lake (MQ = 532 m^{3}s^{-1}). Most of this section (74 km^2) is used for agriculture. The remaining wetlands of this river section are uniquely valuable ecosystems and their aesthetics are valued by the local communities, although only a few areas are still in their natural or near-natural state. Protected floodplain areas provide habitats for endangered species and help to retain water during flood peaks, reducing flood damage by storing surplus water. The 'Tisza blooming', the mass emergence and mating of the Tisza mayflies (*Palingenia longicauda*), which experienced a dramatic range loss (Bálint et al., 2012), is a unique event and a popular tourist attraction. In this area, the spatial and temporal distributions of precipitation are highly variable, resulting in alternating flood and drought events. Since the 1930s, the extent of forest and bushland has increased and the extreme conditions and human afforestation favored non-native species. This growing land cover type increased the hydrological roughness and formed a run-off barrier for floods, increasing sediment deposits and flood levels. The case study area contains 4 restoration activities of which dyke relocations are planned to mitigate the problem (Vizi and Právetz, 2020). Stakeholder representation covered the private and education sectors, water utilities, the local national park, and the regional water directorate in charge of the restoration activities (Table SI2).

2.2.2.3. Special nature reserve koviljsko-petrovaradinski rit, Serbia. This case study area (83 km^2) is located along the Danube River (MQ = 2110 m^{3}s^{-1}) downstream of Novi Sad (river km 1225–1250). It contains a linear bog complex representing an ecological corridor, most notably for amphibians and birds during their seasonal migrations. The area is divided into forest areas (69%), meadows and pastures (15%), as well as water bodies (8%) (PCVŠ, 2021). Its significant value for safeguarding biodiversity led to its designation as an Important Bird and Biodiversity Area (IBA), Important Plant Area (IPA), and Ramsar site. Besides, this floodplain is part of the Danube Network of Protected Areas and the EMERALD Network. The area offers a wide variety of ES to the local communities (INCP, 2015) and is used for forestry, hunting, traditional fishing, and cattle breeding. Settlements and monuments of cultural and historical significance in a stunning landscape make the site an attractive tourist destination. The participating stakeholders represented the sectors of conservation, water management, forestry, agriculture, tourism, education, aquaculture, husbandry, citizen associations, and national and regional administration, all of which have a stake in the decision-making processes (Table SI2).

2.3. Evaluation of multiple pressures and ecosystem services in floodplains

2.3.1. Large-scale assessments

We used indicator values of eight reported pressures on floodplains in the DRB (Habersack et al., 2016; e.g. Hein et al., 2016; ICPDR, 2021; Peipoch et al., 2015) and rescaled them between 0 (minimum value) and 1 (maximum value) using the linear min-max transformation,

$$X_{scaled} = \frac{x_i - x_{min}}{x_{max} - x_{min}} \quad (1)$$

where X_{scaled} is the rescaled pressure indicator, x_i is the value of the pressure within each segment i, and $x_{\min}$ and $x_{\max}$ are the minimum and maximum indicator values for the entire data set. The pressures and the original range of their indicator values are given in Table 1. We then summed the eight rescaled pressures per 10-km segment to estimate the magnitude of multiple pressures in each segment.

We adapted an indicator-based approach after Podschun et al. (2018) and Stäps (2022) to assess eight ES using best-available data. We extended the assessments with models for timber and firewood production (Santoro et al., 2021), water provision (E-Hype model, van Gils et al., 2020), and expert opinions on the capacity of land cover types to provide cultural ES (Stoll et al., 2015) (Table 2). The resulting 14 ES are in line with important river-floodplain ES identified by Petsch et al. (2023). All ES were evaluated in the river-floodplain segments and scored from 1 (no or low ES provision) to 5 (high ES provision) using either ordinal assessment classes or quintiles on indicator values (Fig. SI1). A detailed description of the evaluation methods and data used is described in the SI, chapter 1. Even though ES scores and pressures were partly obtained with the same indicators, we applied Spearman rank-correlations per segment to reveal spatial co-occurrences including synergies (positive relations) and trade-offs (negative relations) in the corrplot R-package. We considered significant correlations ($p < 0.05$) for further discussions.

A multi-functionality index *MuFu,* based on the ideas of Byrnes et al.

Table 1
Selected pressure indicators within active floodplain segments, their units, and value ranges.

Pressure indicator	Abbr.	Unit	Value range in the study area	Data source
Land use intensity	LI	% of urban and arable land	0–94	EEA (2018a)
Floodplain loss	FL	% loss of connected floodplain areas (share of former floodplain in the morphological floodplain)	15–100	EEA (2018b), Eder et al. (2022)
Low/no nature protection status	PS	% of non-protected areas	0–100	Areal share without a Natura 2000 or a similar protection status outside the EU
River morphological alterations	MA	Ordinal evaluations according to the WFD	2–5	ICPDR (2015)
Impoundments/ Backwater	IM	Binary (absence, presence)	0, 1	ICPDR (2015)
River total nitrogen concentration	NC	mg l^{-1}	1.5–5.1	ICPDR (2021)
River total phosphorus concentration	PC	mg l^{-1}	0.04–0.4	ICPDR (2021)
Landscape simplicity	LS	Patch density in ha ha^{-1}	107–1	EEA (2018b), R-package: landscapemetrics

Table 2
Selection of ES evaluated at a large scale based on empirical data, models and expert opinions. On this large scale, the ES capacity was considered. The used methods, data and models are listed in the supplementary information, chapter 1. The compartment (Comp.) refers to the river (R), floodplain (F), or both.

Category	ES capacity	Abbr.	Indicator description	Unit	Comp.
Regulating	Nitrogen removal	RN	Dissolved nitrogen (NO_3) permanently eliminated by denitrification	kg NO_3 ha^{-1} yr^{-1}	R + F
	Phosphorus retention	RP	Particulate total phosphorus (TP) retained by deposition and trapping	kg TP ha^{-1} yr^{-1}	R + F
	Greenhouse gas regulation	RG	Inverse of the net emission (emissions – sequestration) of CO_2, CH_4, and N_2O (as CO_2 equivalents)	kg CO_2 eq. ha^{-1} yr^{-1}	F
	Flood mitigation	RF	Reduction of the flood discharge and lowering of the flood peak in the floodplain	ordinal	R + F
	Low-flow regulation	RL	Maintenance of the hydrological low flow	ordinal	R + F
	Sediment transport regulation	RS	Evaluation of the internal sediment balance of the river	ordinal	R
	Habitat provision	RH	Habitat quality in the river and floodplain (area-weighted mean score of river and floodplain)	ordinal	R + F
Provisioning	Firewood and timber production	PF	Mean above-ground forest biomass	t ha^{-1}	F
	Arable crop production	PA	Yield potential based on land use, soil types, and flood-induced loss	ordinal	F
	Grassland production	PG	Yield potential based on land use, soil types, and flood-induced loss	ordinal	F
	Water provision	PW	Annual river discharge	m^3 yr^{-1}	R
Cultural	Landscape aesthetics	CL	Expert judgment	ordinal	R + F
	Knowledge systems	CK	Expert judgment	ordinal	R + F
	Cultural heritage and diversity	CH	Expert judgment	ordinal	R + F

(2014), Schindler et al. (2014), and Podschun et al. (2018) was used to assess the overall status of the floodplains in the basin.

$$MuFu = \frac{1}{N}\sum_{i=1}^{N}(n(ES_i \geq y) - n(ES_i < y)) \quad (2)$$

Where N is the number of ES, ES_i is the score of individual ES, n is the number of ES falling below or above a threshold score y. We set $y = 4$, which represents the level "good" at the 5-level score or the 60th percentile which is in the range of thresholds used in other studies (e.g. Byrnes et al., 2014; Stürck and Verburg, 2017; van der Plas et al., 2016). *MuFu* ranges between −1 (all ES scores <4) and 1 (all ES scores ≥4). At *MuFu* = 0, higher and lower-scored ES are in balance. *MuFu* was calculated using all 14 ES (Fig. 3 B), and separately for the categories of regulating, provisioning and cultural ES (Fig. 3C–E). To maximize the ES in the evaluated study areas, we recommend general management actions based on the *MuFu* index values. In areas with high index values (0.5–1), we propose conservation measures to sustain the high multi-functionality of the floodplain, at low values (−1 to −0.5) measures that mitigate pressures on multi-functionality, and at intermediate values (−0.5 to 0.5) tailored management actions that depend on the local composition of ES and pressures (Fig. 1). We tested the impact of the pressures on *MuFu* using a multiple linear regression (MLR, R-package: stats). Pressures and *MuFu* in the six river sections were compared with a Kruskal-Wallis test following a Dunn's test.

2.3.2. Local assessments

In the three case study areas, we quantified the use of ES and modelled their changes due to pressures and management measures in collaboration with local stakeholders. The composition and number of represented sectors differed between the areas, depending on the site characteristics and the level of stakeholder commitment (Table SI2). Firstly, via questionnaires, the stakeholders were individually asked to identify and rate elements (5-level scale) from an extensive list of ES (n = 27), their influencing pressures (n = 28) and appropriate management measures (n = 21), and to add relevant elements, if not included in the list. For each case study area, we then selected the most voted and top-rated ES (n ≥ 10, depending on ties), pressures (n ≥ 5), and measures (n ≥ 5). Secondly, in workshops, the stakeholders jointly created fuzzy cognitive maps (FCM) with the selected elements following a DPSIR approach using the Mental Modeler software (Gray et al., 2013; mentalmodeler.com). Starting from the ES, the stakeholders openly discussed the perceived impact of pressures on ES and the impact of the management measures on the pressures. The agreements and compromises from the discussions were mapped by hierarchically connecting the previously selected elements and weighting the connections between −1 (strong negative impact) and 1 (strong positive impact). Like this, the most important causal relationships of the socio-ecohydrological systems were collectively identified (Fig. SI2). Thirdly, we moderated an open dialogue of the stakeholders' opinions on a realistic degree of implementation of measures to converge to an "agreed management scenario". These agreed influences of the envisaged measures were again quantified between −1 and 1 (implementation leads to a substantial reduction vs. increase in pressures). Finally, we used this information to semi-quantitatively model the system's response to the measures in Mental Modeler's scenario interface, using a sigmoid transfer function. The outcomes were eventually plotted as relative changes in pressures and ES provision per case study area.

3. Results

3.1. Large-scale assessments of multiple pressures and ES

According to our analyses, 84% of the large active floodplains have been lost in the DRB, and 30% of the remaining ones have an agricultural and urban land cover of more than 25%. A quarter of the analyzed river segments were in a poor to bad morphological state and more than half could be classified as eutrophic according to Savic et al. (2022) (TN > 1.5 mg N l^{-1} and TP > 0.075 mg P l^{-1}). The presence of multiple pressures was highest along the Yantra and the upper Danube, significantly exceeding all other river sections ($p_{adj} < 0.01$) (Fig. 3A). The Tisza and the middle Danube followed, with pronounced pressure levels at the Tisza reservoir lake and around the confluence of the Danube and Tisza. In contrast, the lower Danube, the Sava, and parts of the middle Danube and Tisza were impacted by considerably fewer pressures.

The degree of multi-functionality generally showed an inverse trend to multiple pressures ($R^2 = 0.45$, MLR, Table SI1) with the strongest impacts of land use intensity ($t = -9.5$, $p < 0.001$), impoundments (t =

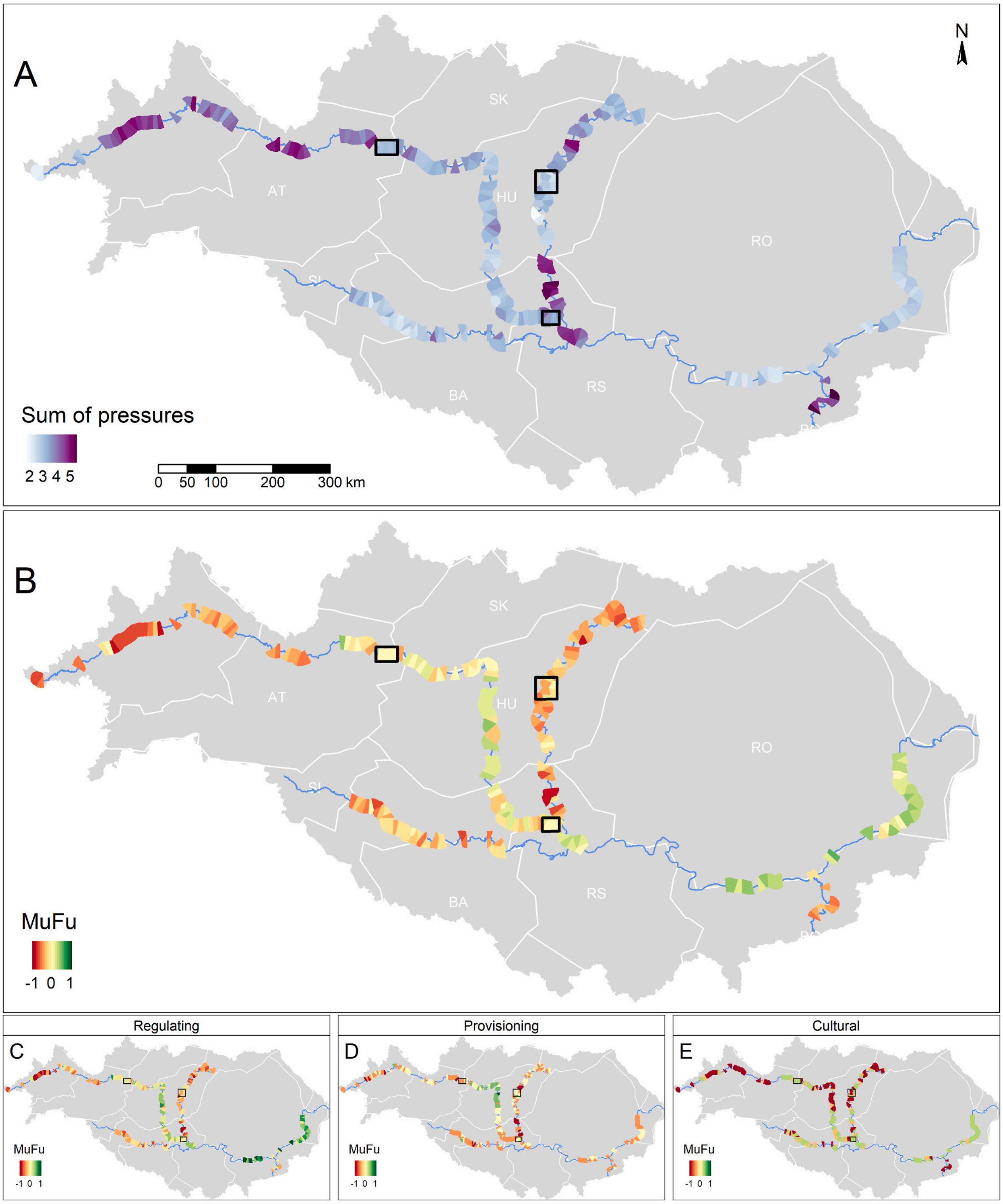

Fig. 3. Distribution of multiple pressures (A) and ES (B) in large active floodplains. The multi-functionality index *MuFu* is shown for the total set of ES (n = 14) and individually for regulating (C) (n = 7), provisioning (D) (n = 4) and cultural ES (E) (n = 3). Black boxes indicate the locations of the case study areas. Due to the small spatial extent of active floodplains, we created a buffer to enlarge and map the segments.

−3.5, $p < 0.001$), and morphological alterations ($t = -2.6$, $p < 0.01$). However, this pattern was not equally pronounced everywhere. For example, the floodplain section downstream of the confluence of Danube and Tisza still showed a high *MuFu* despite being exposed to multiple pressures (Fig. 3B). In contrast, the extensive floodplain areas along the Sava showed reduced exposure to pressures but only low to moderate *MuFu* index. This pattern was mainly caused by low-scored provisioning and regulating ES (Fig. 3C and D). Consequently, the *MuFu* indices of the lower and middle Danube significantly exceeded those of all other river sections ($p_{adj} < 0.01$). Based on our concept, we generally recommend conservation measures mainly along the lower and middle Danube (Fig. 3B, green segments), restoration measures along the upper-middle Danube and Sava (Fig. 3B, yellow segments), and mitigation measures in wide values parts of the Yantra, Tisza and upper Danube rivers (Fig. 3B, red segments).

Land use intensity showed negative correlations with all ES except for arable crop and grassland production (Fig. 4 A). Landscape simplicity, on the other hand, did not distinguish between the quality of landcover types and, hence, did not compromise multi-functionality. The degree of floodplain loss had only moderately negative impacts

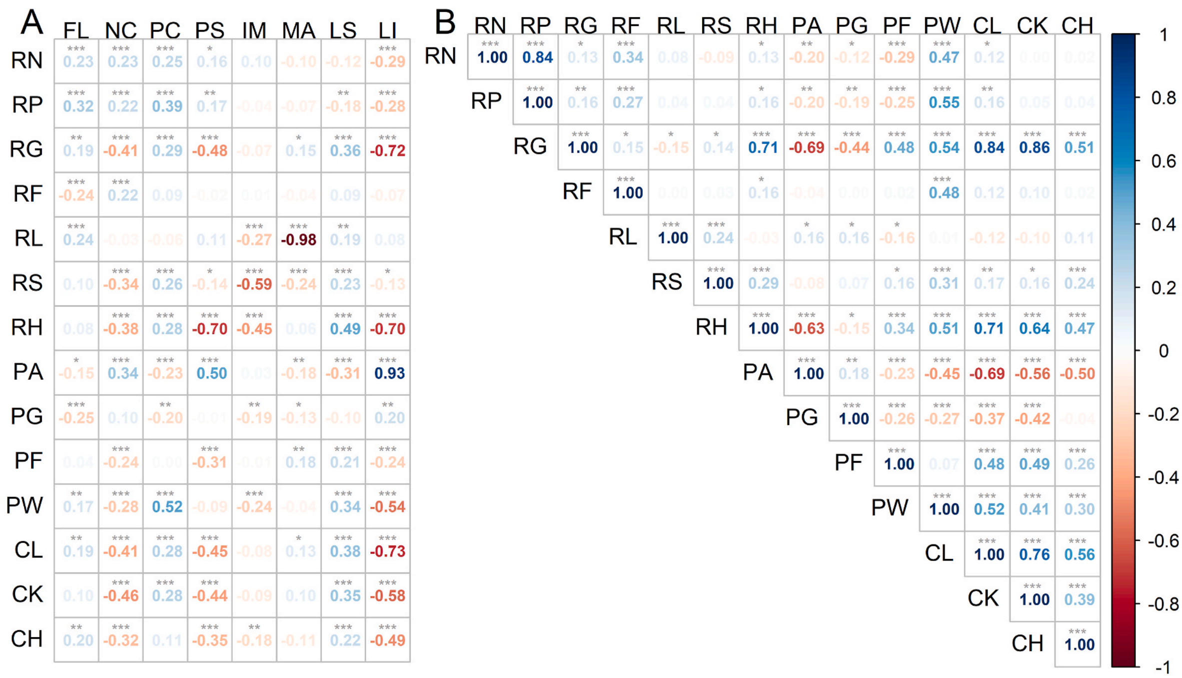

Fig. 4. Spearman rank correlations (ρ) between rescaled pressures and ES scores (A) and synergies and trade-offs between ES scores (B) at the basin scale. Significance levels of the pairwise correlations are indicated by asterisks *** ($p < 0.001$), ** ($p < 0.01$), * ($p < 0.05$). (*Ecosystem services*: RN = Nitrogen removal, RP = Phosphorus retention, RG = Greenhouse gas regulation, RF = Flood mitigation, RL = Low-flow regulation, RS = Sediment transport regulation; RH = Habitat provision, PF = Firewood and Timber production, PA = Arable crop production, PG = Grassland production, PW = Water provision, CL = Landscape aesthetics, CK = Knowledge systems, CH = Cultural heritage and diversity. Pressures: LI = Land use intensity, FL = Floodplain loss, PS = Low/no nature protection status, MA = River morphological alterations, IM = Impoundments/Backwater, NC = River total nitrogen concentration, PC = River total phosphorus concentration; LS = Landscape simplicity).

on the ES of active floodplains. However, we were not able to evaluate the loss or change in ES compositions outside the active floodplains. Higher nutrient concentrations also resulted in higher nutrient retention rates in floodplains. Nitrogen concentration and low protection status negatively affected greenhouse gas regulation and habitat provision. Synergistic relationships among ES dominated over trade-offs (Fig. 4 B). The strongest synergies were observed between ES controlled by natural land cover types (habitat provision, greenhouse gas regulation, landscape aesthetics, knowledge systems). Flood mitigation correlated with the fewest ES, but only positively (water and habitat provision, nutrient retention, and greenhouse gas regulation). Generally, trade-offs occurred between terrestrial provisioning ES and most other ES.

3.2. Local stakeholder workshops in case study areas

The stakeholder perceptions showed significant differences in selecting locally relevant ES and pressures in the case study areas. Whereas hydro-morphological pressures like hydropower, river regulation, and human infrastructures were frequently mentioned in Austria, natural disasters like floods, droughts, and storm events were mentioned in Hungary, and pollution through wastewater and pesticides in Serbia, respectively (Fig. 5). Additionally, invasive alien species and land conversion were top-ranked in two study areas. Similarly, the importance and uses of ES ranged from predominately regulating ES in the Austrian, provisioning ES in the Hungarian, and cultural ES in the Serbian study area (Fig. 6). The proposed measures to counteract pressures and support multi-functionality also differed accordingly. Most commonly, the stakeholders prioritized floodplain restoration measures, reduction of agricultural pollution, combating invasive alien species, and improving environmental education and awareness (Table 3). Their influence in the agreed scenarios, i.e. the consensus of the stakeholders on a realistic level of implementation of the measures, differed between sites. Whereas the Hungarian stakeholders were optimistic about the

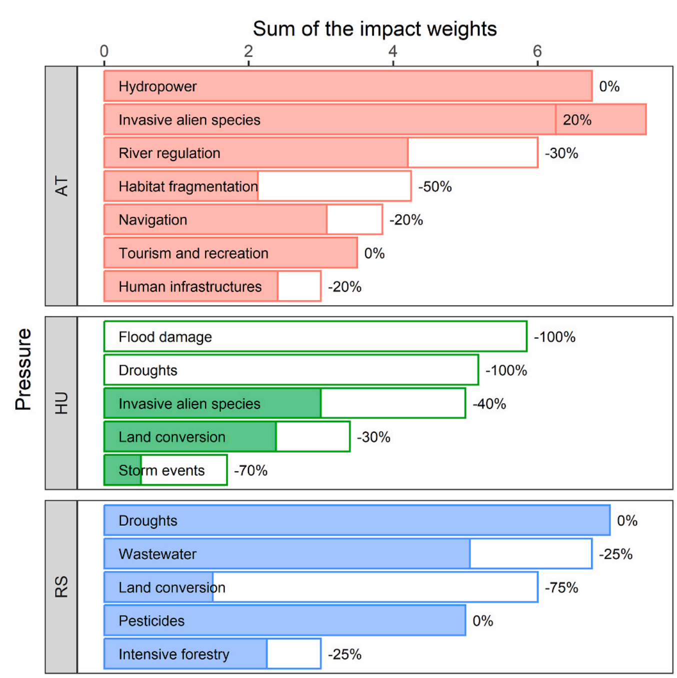

Fig. 5. Sum of the impact weights (−1 to +1) of pressures on all ES extracted from the fuzzy cognitive maps for the three case studies in Austria (AT), Hungary (HU) and Serbia (RS). The current state is indicated by empty bars. The relative changes in the agreed scenarios are given as a percentage and indicated by the filled bars.

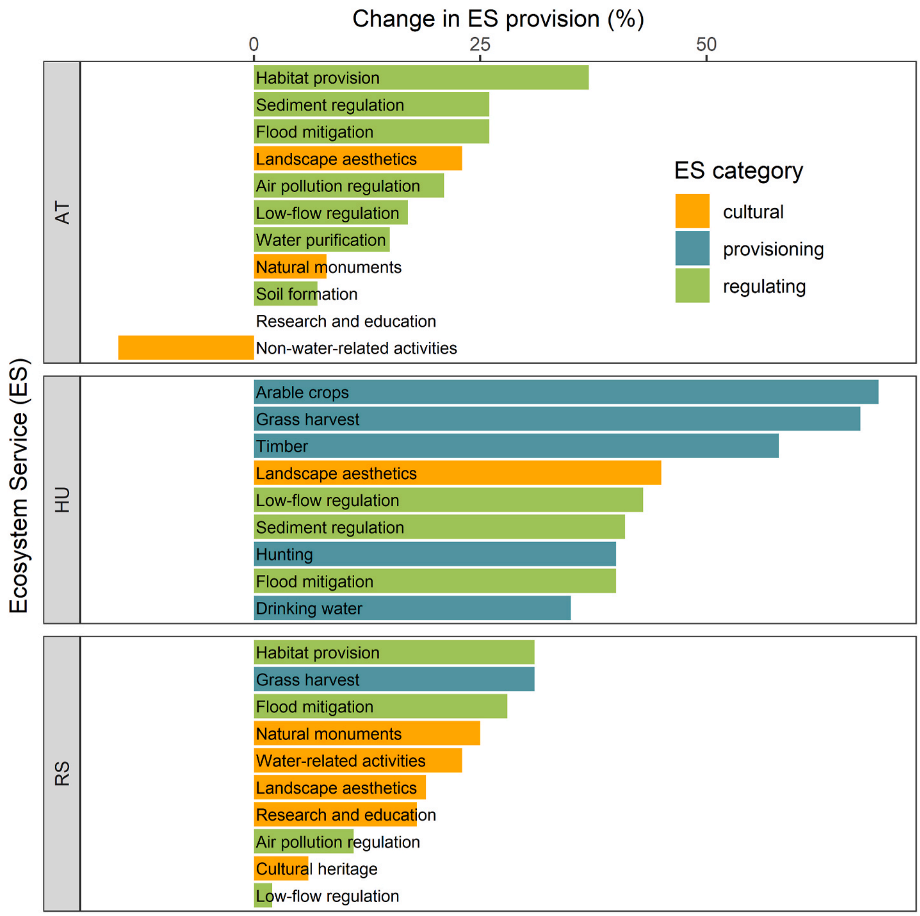

Fig. 6. Relative changes of ES provision in the agreed implementation scenarios compared to the current state were extracted from the fuzzy cognitive maps for the three case studies in Austria (AT), Hungary (HU) and Serbia (RS). ES, selected by the stakeholders, are differentiated into the three categories: cultural, provisioning, and regulating ES.

Table 3
The selected management measures most highly rated by the stakeholders to mitigate the dominant pressures on ES in the case study areas.

Austria	Hungary	Serbia
Floodplain restoration (lateral reconnections, removal of embankments)	Floodplain restoration	Streamlining decision making
Improved bedload management	Dyke relocation	Environmental education and awareness
Environmental education and awareness	Reduction of agricultural pollution	Reduction of agricultural pollution
Restoration of the natural flow regime	Prevention of invasive species	Promoting autochthonous plants
Habitat improvement	Water retention measures	Creation of flood retention areas
Restoration of the longitudinal connectivity		

efficiency of the measures to reduce or even eliminate the prevailing pressures, the Austrian and Serbian stakeholders were concerned about the extent to which pressures could be mitigated. The Austrians even assumed an increase in invasive species despite the measures (Fig. 5). Overall, the impacts of these scenarios on the ES were generally positive throughout the case study areas, thus increasing multi-functionality. The only trade-off was found with land-based recreational activities in the Austrian national park, where restoration measures render the area less accessible to people (Fig. 6).

4. Discussion

4.1. *Pressures on the floodplains' multi-functionality and their recognition across scales*

In accordance with a Europe-wide assessment by Hölting et al., 2019b, we found that, with a few regional exceptions, multiple pressures and a high land use intensity in particular impair multi-functionality. On the other hand, nutrient pollution has been substantially reduced since the previous DRB management plans (2009 and 2015) and did not significantly impair multi-functionality. Intensive land use within riparian land and hydro-morphological alterations of rivers are more persistent pressures and the leading cause of lateral disconnection and floodplain loss (ICPDR, 2021). Lateral connectivity is an essential property of floodplains (Funk et al., 2023), critically affecting their spatio-temporal complexity and multi-functionality (Sendek et al., 2021). It controls nutrients (Natho et al., 2020) and water retention, sediment deposition and remobilization (Kretz et al., 2021), and the dispersal of organisms but can jeopardize provisioning ES like crop production. With our methods, we were not able to clearly illustrate the impact of floodplain loss and other pressures outside active floodplains on their ES and habitat quality (Fig. 4). This common study limitation was also critically pointed out by Erős et al. (2019) who recommended to include extensive landscape-level or historical assessments of riverscapes to allow the development of more informed floodplain conservation and management decisions. However, other studies in the DRB demonstrated the effects of floodplain loss and the potential for reconnections using a comparable ES evaluation methodology. For example, Stammel et al., 2021 showed that the structural alterations in the vast former floodplains towards more intensive land use were responsible for a decline in multi-functionality. Tschikof et al. (2022) showed that reconnecting parts of the former floodplains through dyke allocations can significantly enhance the nitrogen retention capacity in the DRB. Similar effects were observed in large North American floodplains using a different method (Jacobson et al., 2022).

Likewise, the loss of active floodplain sections was high in the three case study areas, accounting between 18% and 99%. Other dominant pressures detected on the large scale (rescaled pressure indicator >0.5) were morphological alterations and landscape simplification in Austria, a high land use intensity and a low nature protection status in Hungary, and morphological alterations, impoundments, increased phosphorus concentrations (>0.1 mg l^{-1}) and landscape simplification in Serbia. The Austrian stakeholders well recognized the hydro-morphological issues and measures were stated accordingly. Also, the Hungarian stakeholders recognized the high degree of arable land in their area but perceived natural disasters as a greater pressure on the highly valued provisioning ES. Serbian stakeholders mentioned land conversion and intensive forestry contributing to landscape simplification, and nutrient pollution but did not consider the present hydro-morphological alterations important. Conversely, several remaining local pressures, like intensive alien species or tourism and recreational overuse, could not be mapped in the entire DRB.

4.2. Methodological challenges and learning opportunities in cross-scale ES evaluations

In recent years, the research on multiple ES, ES bundles, and multi-functionality has enormously increased but the ES selection and evaluation methods differ widely throughout studies with varying objectives and scales (Hölting et al., 2019; Manning et al., 2018). To date, no standards on ES-related practices (terminology, data, methods, format) exist albeit having a great potential to further mainstream ES in particular use contexts (Polasky et al., 2015). This renders a comparison of ES extremely difficult. For example, we used areal rates (kg ha^{-1} yr^{-1}) to define nutrient retention, also used in recent large-scale assessments (e.g. Kaden et al., 2023). If we had expressed it as the share of retained river load (%), another commonly used indicator (Jacobson et al., 2022; Podschun et al., 2018), nutrient retention would have been strongly controlled by discharge (Gordon et al., 2020). Considering our wide range of discharges and nutrient loads (e.g. 138–222 735 tons NO_3 per year), this would have resulted in a completely different spatial pattern of the same ES. In some cases, however, different evaluation methods obtained similar outcomes. In our study, we included land cover/land use types to assess habitat provision in the floodplains (Scholz et al., 2012). Land use types have been proven to be indicative of biodiversity, habitat provision, and many other ES (Burkhard et al., 2009; Felipe-Lucia and Comín, 2015). Even though we evaluated the habitat quality using this relatively simple approach, we found clear spatial co-occurrences with the more sophisticated Bayesian distribution models for protected species by Funk et al. (2019). The same study also concluded a similar pattern of multi-functionality increasing along the Danube River course, even though the set of ES and their evaluation methods differed completely. A more explicit definition on what ES and ecosystem-based management are would facilitate their implementation in practice at EU and national levels (O'Hagan, 2020). Our harmonized ES evaluation method using freely available EU data and a simple 5-level scale can support this endeavor for European rivers and floodplains.

Furthermore, we observed that ES evaluations on the large and local scale were generally in agreement, suggesting a certain robustness of our methods and results. The ES capacity for landscape aesthetics, habitat provision, sediment regulation, knowledge systems, cultural heritage, timber/firewood, and arable crop production scored levels of 3–5 in the areas where they were considered most important. However, we found mismatches for low-flow regulation in Austria (score: 1) and Serbia (score: 2), flood mitigation in Hungary (score 2–3), and water purification in Austria (score: 2–3) (Fig. SI1). Many cultural ES like recreation were much more noticeable by people and connected to their specific locations (Tew et al., 2019) but have yet to be evaluated on a large scale. In contrast, greenhouse gas regulation was an important ES on the large scale but was instead "invisible" to stakeholders at local scales. Such discrepancies are equally important as they highlight that ES are provided at different scales and that there are regional differences in the peoples' valuations of their provision and demand. After creating the fuzzy cognitive maps in our workshops, we presented regional maps of our data-based ES evaluations to the stakeholders (Fig. SI3) to put their own area into a larger perspective, enhance discussions and create new insights (van Berkel and Verburg, 2012). On the other hand, supra-regional management can highly benefit from local knowledge (McElwee et al., 2020) by identifying gaps and opportunities for science-based decision support (Bouska et al., 2016). Thus, a mutual learning process takes place. However, we were unable to incorporate stakeholder feedback again into our large-scale evaluations but strongly recommend that its potential be considered in future assessments. Mapping the pressures in river basins that actually affect people and their environments, like recreational overuse or invasive species, could help to coordinate relevant research and management efforts better. The active participation of stakeholders in river basin management has been frequently mentioned to promote ecological and social sustainability, but effective engagement at this level is still lacking (Euler and Heldt, 2018; Lim et al., 2022). Jähnig et al. (2022) and von Haaren and Albert (2011) showed examples and highlighted specific factors to better integrate the ES concept in environmental planning and river basin management. Factors include common ES indicators, standards for data collection, methods for scenario-based assessments examining ES interactions, a stronger inclusion of participatory tools and (big) digital data, and stronger methodological cooperation among sectors overall; all of which we have incorporated to the best of our knowledge and within the scope of our possibilities.

4.3. Scale-dependent considerations of management objectives to improve multi-functionality

The dominating positive correlations among regulating and cultural ES indicate that the multi-functionality can generally be increased in the DRB (Fig. 4). Synergistic effects resulting in win-win situations support the resilience of floodplains in a changing climate (Capon et al., 2013) and can create opportunities to better integrate the goals of the water framework, the habitats and the floods directives (ICPDR, 2021; Weigelhofer et al., 2020). Similar to other studies, we found a positive effect of a good habitat conservation status on regulating or cultural ES that conflict with crop or grassland production (Funk et al., 2019; Grizzetti et al., 2019; Maes et al., 2012b). Because such trade-offs are typical, all ES can never be maximized simultaneously (Manning et al., 2018), which is also reflected by our maximum *MuFu* value of 0.57 (theoretical maximum = 1). The sites with a high level of multi-functionality clustered at the lower and middle Danube reaches and most of them were part of the EU Natura 2000 network of protected areas. When spatially prioritizing areas for further nature conservation actions, it is recommended to consider the connectivity between similar scored segments (Erős et al., 2018) and the ES provision of different habitat types (Erős et al., 2019). Areas with a moderate multi-functionality, including the three case study areas, dominated in the DRB and are proposed for locally tailored restoration or rehabilitation measures. In contrast, we recommend setting mitigation measures for the prevailing dominant pressures in areas with a heavily impaired multi-functionality. This is, for example, a reduction of morphological alterations along the upper Danube (cf. Hein et al., 2016) or a reduction of nutrient pollution in the Yantra River. Besides the similar results based on multi-functionality, Funk et al. (2019) also used prioritizations based on reversibility and the availability of remaining semi-natural areas for restoration. Such decisions are relevant in the landscape context and are commonly made top-down.

In the study areas, we classified the overall multi-functionality as moderate (Austria, Serbia) to moderately low (Hungary) (Fig. 3 B). Whereas the Austrian case showed the highest capacities for regulating ES, Hungary showed the highest values for provisioning ES and Serbia for cultural ES (Fig. 3C–E). Therefore, the decision of which ES to support with which measures remains to be made on-site together with stakeholders. Eventually, only measures with high acceptance among land owners and users can be successful. Stakeholders anticipated predominantly positive outcomes in our three case study scenarios (Fig. 6). Even in the Hungarian case, they expected an increase in multi-functionality and no trade-offs between provisioning ES and dyke relocations, floodplain restorations, and a reduction of agricultural pollution. Only in the Austrian case, a pronounced trade-off between regulating and recreational ES was detected. The necessary reduction of the path network would inhibit the possibility to explore the site by walking or bicycle. As tourism is not expected to decrease in the future (Fig. 5), this issue needs to be picked up by management to be communicated to the wider population and further offer alternatives to relocate the ongoing recreational pressure. Nevertheless, the measures presumably enhance multi-functionality due to improving the habitat provision for rheophilic communities, nutrient retention, and the opportunity to experience the aesthetics of a natural riverine landscape (Funk et al., 2021). In the Serbian case, there is a significant potential for the development of ecotourism and, consequently, the development of rural communities located along the borders of the study area. However, there needs to be more communication among essential stakeholders, i.e. public, private, and civil sectors, and better coordination between different sectors. Implementation of measures such as streamlining decision-making and environmental education and awareness would help bridge these gaps and improve multi-functionality.

4.4. Importance of stakeholder compositions for decision-making

The perceived impacts of measures on ES in the fuzzy cognitive maps scenarios were largely supported by other expert opinions (Hornung et al., 2019). Still, any participatory model remains a mirror of the involved opinions and their relative weights, which highly depend on the stakeholders' type and composition. For example, the management and administrative sectors dominated in the Austrian case, while in Hungary, the private sector was mainly present (Table SI2). A higher level of background knowledge might be one reason, why Austrian stakeholders estimated lower and more realistic impacts of the measures in the implementation scenario. Because of these issues related to stakeholder compositions, some study designs prefer separate models of homogeneous stakeholder groups or individuals. This helps to visualize diverging perspectives and provides a deeper insight into the uncertainty of complex socio-environmental problems (e.g. Hölting et al., 2020). We, however, aimed at capturing one aggregated belief to streamline the social learning and decision-making process. Therefore, we sought an open dialogue and distilled a consensus of the discussions. Ultimately, the choice between individual or group-level maps rests on the research context (Gray et al., 2014). Nonetheless, involving all affected parties (decision-makers and those interested in the decisions) at an early stage, managing their power to contribute knowledge equally, and matching it to the scales and issues under consideration can help to improve the outcomes of any decision-making processes (Reed et al., 2018).

5. Conclusion

In this study, we provided the first Danube-wide overview of the multi-functionality of floodplains and presented the potential of a cross-scale approach to aid strategic and integrated floodplain management. Utilizing the synergies and acknowledging the discrepancies between top-down prioritization and bottom-up participatory management approaches could make ecosystem-based management more effective and inclusive. Our two diverging goals to (1) harmonize evaluations at a large scale and (2) locally capture causal relationships of river-floodplain systems created some unavoidable mismatches. Still, we juxtaposed selected aspects to reveal the benefits and limitations of a cross-scale approach. We found general agreements between data-driven assessments and local knowledge but also viewed their discrepancies as an opportunity for social learning. Based on our experiences, we recommend that future assessments strengthen an iterative exchange between scales and approaches to move forward in the decision-support process collaboratively. Our approach can be easily applied in most European river basins or be adapted to other basins. For that to happen, we advocate for a standardization of objective and spatially explicit ES assessments in floodplains of other river basins, acknowledging the human perspective on individual ES, particularly cultural ES. We are aware that any floodplain management practices aiming at conservation, restoration, production, or recreation will alter the supply of ES. The prevailing synergies between regulating and cultural ES in the DRB are promising to promote win-win situations in future floodplain management. Even in case study areas where the conflicting provisioning ES were more relevant, we could identify suitable scenarios promoting multi-functionality locally. Further, we would like to direct future research to the lesser-known relationships with ES multi-functionality, including pressures acting on the basin or continental scale (e.g. land use or climate change, floodplain or connectivity loss) and those that concern residents (e.g. the local impact of aquatic and terrestrial invasive species). Extending the spatial and thematic coverage of systematic assessments and the number of participatory case studies might better elucidate how sustainable management in areas with an exceptionally high or low multi-functionality could look like.

CRediT authorship contribution statement

Martin Tschikof: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Barbara Stammel:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Gabriele Weigelhofer:** Writing – review & editing, Supervision, Conceptualization. **Elisabeth Bondar-Kunze:** Writing – review & editing, Funding acquisition, Conceptualization. **Gabriela Costea:** Writing – review & editing, Resources, Formal analysis. **Martin Pusch:** Writing – review & editing, Methodology, Conceptualization. **Zorica Srdević:** Writing – review & editing, Resources, Methodology, Formal analysis. **Pavel Benka:** Writing – review & editing, Resources, Methodology, Formal analysis. **David Bela Vizi:** Writing – review & editing, Methodology, Formal analysis. **Tim Borgs:** Writing – review & editing, Methodology, Formal analysis. **Thomas Hein:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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