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Identification of conservation and restoration priority areas in the Danube River based on the multi-functionality of river-floodplain systems

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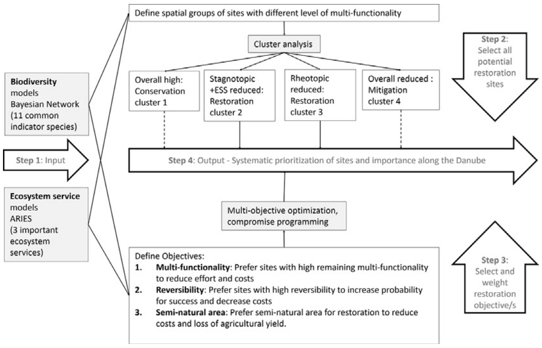
HIGHLIGHTS

- Large river-floodplains are multi-functional hotspots altered by multiple pressures.
- Restoring and conserving floodplains requires systematic planning.
- We prioritize reaches based on multi-functionality, reversibility and costs.
- Our framework can serve as a planning tool for conservation and restoration.

GRAPHICAL ABSTRACT



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ABSTRACT

Large river-floodplain systems are hotspots of biodiversity and ecosystem services but are also used for multiple human activities, making them one of the most threatened ecosystems worldwide. There is wide evidence that reconnecting river channels with their floodplains is an effective measure to increase their multi-functionality, i.e., ecological integrity, habitats for multiple species and the multiple functions and services of river-floodplain systems, although, the selection of promising sites for restoration projects can be a demanding task. In the case of the Danube River in Europe, planning and implementation of restoration projects is substantially hampered by the complexity and heterogeneity of the environmental problems, lack of data and strong differences in socio-economic conditions as well as inconsistencies in legislation related to river management. We take a quantitative approach based on best-available data to assess biodiversity using selected species and three ecosystem services (flood regulation, crop pollination, and recreation), focused on the navigable main stem of the Danube River and its floodplains. We spatially prioritize river-floodplain segments for conservation and restoration based on (1) multi-functionality related to biodiversity and ecosystem services, (2) availability of remaining

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semi-natural areas and (3) reversibility as it relates to multiple human activities (e.g. flood protection, hydropower and navigation). Our approach can thus serve as a strategic planning tool for the Danube and provide a method for similar analyses in other large river-floodplain systems.

1. Introduction

River-floodplain systems are among the most endangered ecosystems worldwide, with up to 90% of floodplains in Europe and North America strongly impaired by human activity (Tockner and Stanford, 2002). Loss of riparian and floodplain area due to agricultural encroachment or urbanization, often accompanied by pollution, are seen as the most relevant threats to their biodiversity and ecosystem services both worldwide (Vörösmarty et al., 2010) and in Europe (Schindler et al., 2014, 2016). The alteration of hydromorphological conditions due to conventional engineering works for hydropower generation, flood protection and infrastructure are additional pressures on remaining riverine habitats and biodiversity (Habersack et al., 2016).

Large river-floodplain systems are hotspots of global biodiversity (Shiel et al., 1998; Tockner and Stanford, 2002), and multiple regulating, provisioning and cultural ecosystem services (Tockner and Stanford, 2002; Tomscha et al., 2017). In addition, jointly conserving and restoring river and floodplain systems' flood retention capacity, biodiversity, and the ecological status of adjacent water bodies has become a priority in environmental and water policy in Europe (EU Flood Risk Directive, EU Biodiversity Strategy to 2020, EU Water Framework Directive respectively). Floodplains are also a key element of the EU Green Infrastructure Strategy (Schindler et al., 2014), where green infrastructure is defined as ‘a network of natural and semi-natural areas that deliver a wide range of ecosystem services,’ i.e., systems with high multi-functionality including provision of habitats, flood regulation or clean water (Garmendia et al., 2016; Schindler et al., 2014). Overall, natural ecosystems in general (Benayas et al., 2009; Bullock et al., 2011) and specifically floodplains (Schindler et al., 2014, 2016) show a high multi-functionality related to biodiversity and ecosystem services and well-directed ecological restoration efforts have the potential to simultaneously increase both.

Widespread evidence already shows that restoration of lateral hydrological connectivity (including removal, slotting or lowering of dykes and levees or reconnection of sidearms) can effectively reduce hydro-morphological pressures and restore multi-functionality of river-floodplain systems (Mueller et al., 2017; Paillex et al., 2009; Reckendorfer et al., 2006; Rumm et al., 2018; Schindler, et al., 2016; Straatsma et al., 2017). This includes the abandonment of intensively used agricultural land in floodplains and their conversion into natural habitats, which is widely practiced in forest restoration (Benayas et al., 2008), and is an important intervention to increase river-floodplain system multi-functionality (Schindler et al., 2014). Human stressors related to engineered structures (e.g., hydropower dams, flood regulation levees, and navigation infrastructure) restrict the potential for floodplain restoration by controlling flow and restricting natural geomorphic processes, including channel migration (Schiemer et al., 1999; Tockner et al., 1998). The selection of sites for successful conservation and restoration can thus be challenging as the knowledge required to disentangle these multiple stressors is still incomplete (Feld et al., 2016), particularly in large-river systems (De Leeuw et al., 2007). Contributing to the challenge, quantitative ecological data on floodplains are often scarce and heterogeneous, as many of the ecological status indices under the Water Framework Directive focus on the river's main stem and do not require sampling of its floodplains (Funk et al., 2017). Where it does exist, floodplain monitoring and reporting under EU Habitats and Birds Directives does not follow harmonized or optimized monitoring approaches (Borre et al., 2011; EEA, 2015a; Tsiripidis et al., 2018). In light of such data gaps, local expert knowledge is gaining importance in conservation biology and is believed to increase the quality of models for decision making (Balram et al., 2004; Drescher et al., 2013; Martin et al., 2012; Kuhnert et al., 2010).

Environmental management challenges are particularly acute for the Danube River, the longest and most international river in the EU. In the Danube's current state, deficits in the system's ecology are evident across the entire navigable stretch of the river, with a failure to achieve good ecological status or potential as defined by the Water Framework Directive (ICPDR, 2016). However, few countries within the Danube watershed have implemented or planned restoration through the year 2021. Danube watershed countries have also unevenly reported on floodplains of basin-wide importance having restoration potential (ICPDR, 2016). High restoration costs (Ebert et al., 2009), strong differences in socio-economic conditions (Domisch et al., this issue), inconsistencies in legislation among the different Danube watershed countries and the complexity of the environmental problems and the heterogeneity of drivers and pressures may hamper strategic planning and joint management efforts (Hein et al., 2016, 2018). For example, data from past restoration projects in Romania have shown that compensation costs to farmers (in terms of lost agricultural yield) can be higher than the restoration costs itself (Schwarz, 2010). By contrast, for river-floodplain areas impacted by multiple drivers, i.e., hydropower, navigation and flood regulation that have high restoration constraints (Hein et al., 2018), restoration costs can be expected to be even higher, as adaptive management may be required, which can extend over multiple decades. A more strategic and harmonized approach is required for conservation and restoration planning at the scale of large catchments (Hein et al., 2018; Seliger et al., 2016), which combines multiple data sources, including local expert knowledge as a source of best-available information and evidence (Gilliland and Laffoley, 2008). Such an approach also provides information that can enable synergies between multiple EU policies and targets towards ecosystem-based management approaches. Therefore, the core task of this study is to prioritize river-floodplain reaches of the navigable Danube for restoration and conservation by optimizing for highest multi-functionality at lowest cost and risk in failing this target. We do so by combining quantitative data for key biodiversity indicators generated using Bayesian networks and modelled ecosystem services data generated using the Artificial Intelligence for Ecosystem Services (ARIES, Villa et al., 2014) modelling platform. Finally, we applied trade-off analysis to support the identification of important areas with biodiversity and ecosystem services conservation and restoration potential, based on multi-functionality goals, reversibility, and restoration costs.

2. Methods

2.1. Study system

The Danube River Basin is the most international river basin in the world, and is shared by >80 million people from 19 countries. The Danube (Fig. 1) connects with 27 large and over 300 small tributaries on its way from the Black Forest to the Black Sea, with a catchment size of approximately 800,000 km^2. Accordingly, a huge variety of human activities and related pressures affect this area. The extent of floodplains in the Danube River Basin has been reduced by 68% (Hein et al., 2016).

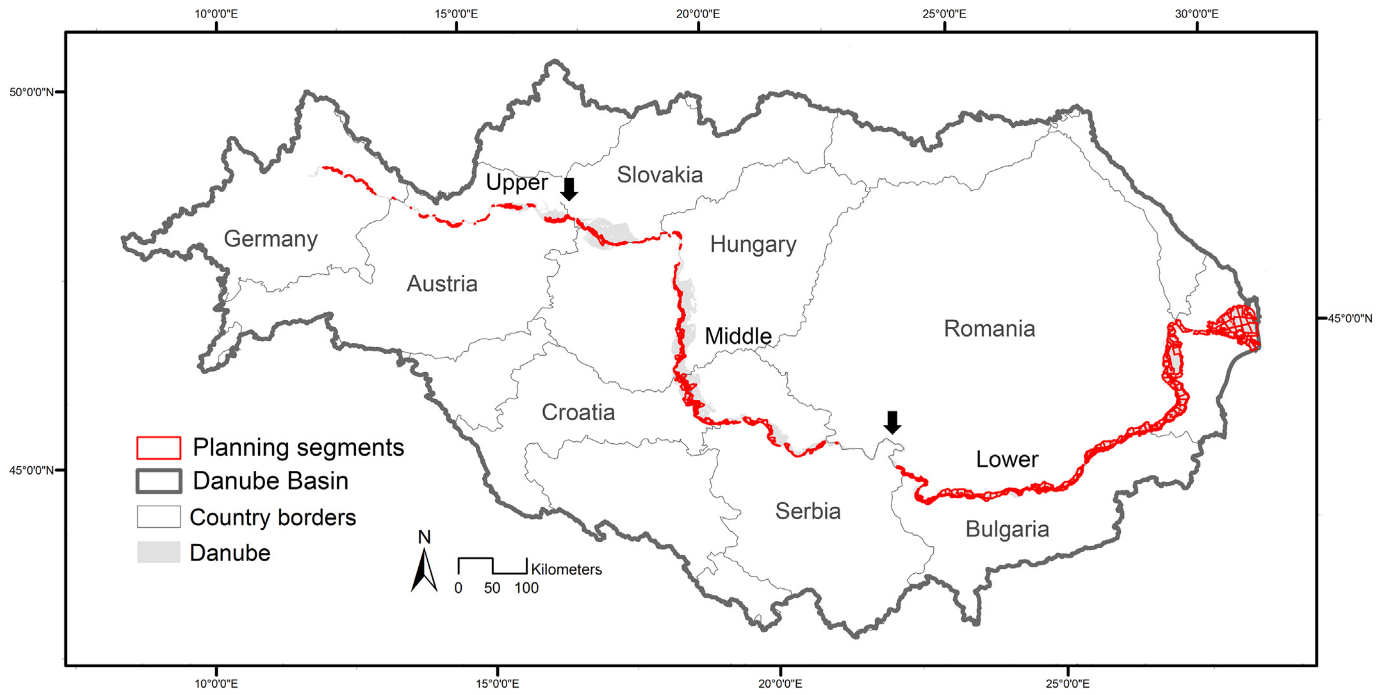

Fig. 1. Study area map showing the river-floodplain system, divided into segments based on the stretches from hydro-morphological assessment (Schwarz, 2014) along the navigable stretch of the Danube. Arrows mark borders between the three Danube Regions: Upper Danube: Germany and Austria, Middle Danube: Slovakia, Hungary, Croatia and Serbia; Lower Danube: Romania, Bulgaria and Ukraine. Gaps (grey) along the Danube show river sections where no floodplains occur due to natural causes (narrow valleys) or their complete loss from urbanization.

These floodplain losses have mainly been caused by the ongoing conversion of active floodplain and wetland areas into intensively used agricultural polders. The integrity of remaining floodplains is further threatened by hydrological disconnection due to river engineering works that provide flood control, navigation and hydropower generation (Hein et al., 2016, 2018; ICPDR, 2016).

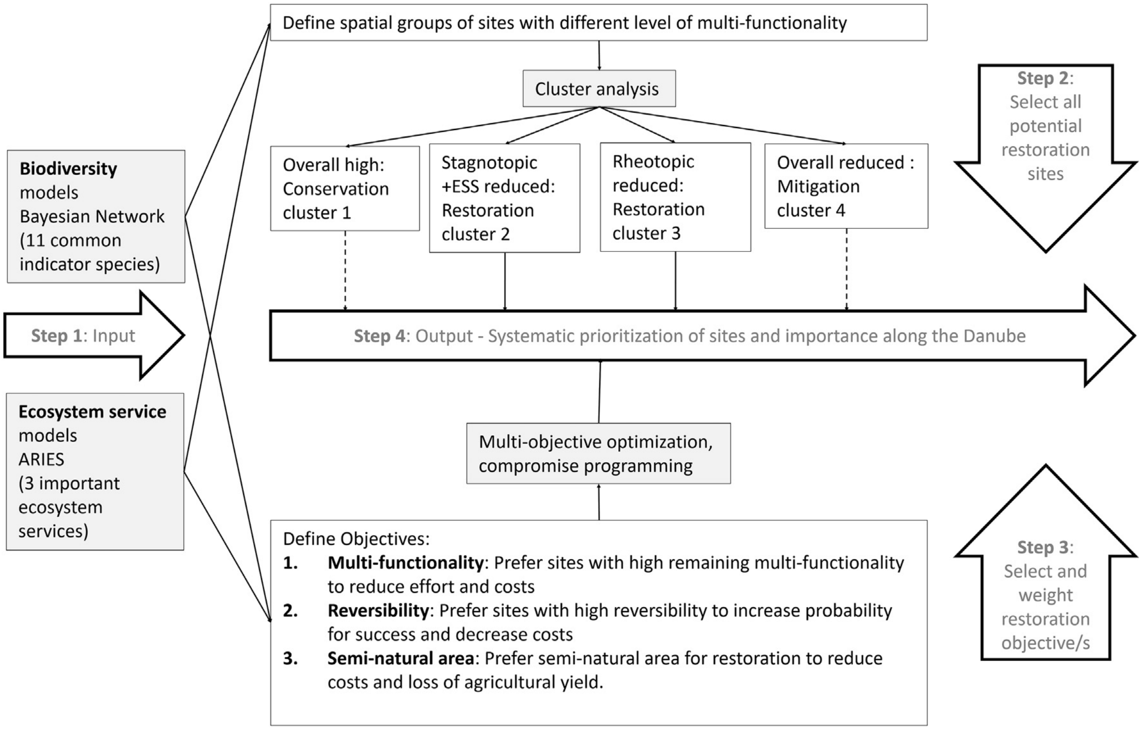

Fig. 2. Framework used for the prioritization of the river-floodplain system for conservation and restoration along the Danube. Work can be divided into four steps: Step 1: Modelling biodiversity and ecosystem service indicators as input for the optimization framework. Step 2: Clustering sites with different level of multi-functionality to select sites with conservation, restoration and reduced restoration potential (mitigation sites). Step 3: Defining and weighting objectives for restoration within scenarios and using compromise programming, to select sites with lowest distance to those objectives using a multi-objective optimization approach. Finally, in step 4, output from steps 2 and 3 is combined and results are compared along the Danube. Dashed arrows show potential additional analysis options.

2.2. Analysis framework

Our systematic prioritization approach can be divided into four steps (Fig. 2). In the first step, we generated initial input by modelling multiple indicator species to quantify biodiversity using Bayesian Networks and use the ARIES platform to quantify essential ecosystem services. In a second step, we systematically classified sites for conservation, restoration and those with a reduced restoration potential (mitigation sites) based on the remaining level of multi-functionality using cluster analysis. In a third step, we applied multi-objective optimization to support the identification of sites with the highest biodiversity and ecosystem service restoration potential for seven contrasting scenarios, based on the combinations of three main objectives relevant for restoration planning of large river-floodplain systems. These criteria include: (i) the actual level of *multi-functionality* to prioritize sites with high remaining value to reduce effort and costs, (ii) *reversibility*, expressed as the potential to successfully restore multi-functionality related to multiple drivers, and (iii) the availability of remaining *semi-natural area* versus agricultural land, which reduces restoration costs and losses of agricultural yield. In a final step, we combined multiple outputs from steps 2 and 3 to compare the importance of different conservation and restoration scenarios along the Danube and conducted a gap analysis.

2.3. Model input development (step 1)

2.3.1. Biodiversity models – Bayesian Networks

We used Bayesian network models to quantify biodiversity along the Danube. Models are based on open-access data quantifying drivers, pressures and biodiversity status in the system (Table 1). Land use was quantified using Copernicus land use/land cover data obtained from the European riparian zones dataset developed by the local component of Copernicus Land Monitoring Services (land.copernicus.eu, resolution of 20 m, 2011–2013, EEA, 2015b). Riparian zone extents were laterally delineated using the Potential Riparian Zones dataset (EEA, 2015b). For navigation, we included information on "critical locations" which are river stretches where the recommended fairway depth (depth of the channel that is required for navigation) of 2.5 m at Low Navigable Water Level (LNWL) was not achieved (Fairway and Danube, 2014; Fairway, 2016). We also incorporated information on navigation class according to the "Classification of European Inland Waterways" created by the European Conference of Ministers of Transport, which relates to the carriage of intermodal containers in convoys of barges (Economic Commission for Europe, 2012). Reservoir length (Table 1) of hydropower plants is also incorporated in the model. It was collected during the hydro-morphological assessment for the Joint Danube Survey 2 of the ICPDR (https://danubis.icpdr.org/). Further, to quantify hydro-morphological pressure, an assessment of hydro-morphological alterations is available for the navigable stretch of the Danube River. This was conducted in 2013 by integrating information on engineering structures and floodplains with adjacent land use, navigation, hydrological and morphological background data, using consistently collected field reports along the whole navigable stretch of the Danube River and following the European-wide guiding standard (CEN standard) supporting Water Framework Directive approaches (ICPDR, 2015; Schwarz, 2014). It consists of a semi-quantitative assessment based on 10 km river reaches, and includes ten assessment parameters of which six (Table 1) are included in our modelling approach. Finally, conservation status and population size of widely distributed protected species are included as biodiversity indicators. Natura 2000 sites information is collected from local experts and synthesized in a pan-European database by the European Environment Agency (EEA) (https://www.eea.europa.eu/data-and-maps/data/natura-9, database information from 2016 was used, Appendix, Fig. A.1). This European dataset is already widely used for conservation and management planning (e.g., Cortina and Boggia, 2014; Hermoso et al., 2018). We extracted information on the conservation status or population size of protected species collected for Habitats and Birds Directive for 121 sites along the navigable stretch of the Danube River. We included only widely distributed species with adequate representation in the database (represented in at least 60% of the sites situated along the Danube) to guarantee broad representativeness along the whole study area and statistical confidence. Large-scale studies provide wide evidence that common species are in general good indicators for biodiversity including the richness of rare species (Lennon et al., 2004; Mazaris et al., 2010; Pearman and Weber, 2007) and also ecosystem service delivery (Winfree et al., 2015). Additionally only species sensitive to hydro-morphological pressure variables (significant correlation, see Appendix, Table A.1) were selected for the modelling approach (Table 1).We also tested protected riparian and aquatic habitats data collected for Habitats and Birds Directive, but found no significant correlations with hydro-morphological pressure variables (Appendix, Table A.1). However, several of the included animal species are also indicative for naturalness of the terrestrial habitat and floodplain forests (Table 1). Overall, using this selection strategy, we can included eleven species from a variety of taxonomic groups (fish, amphibian, birds and mammals) and functional ranges (Table 1).

We split all geographical and associated tabular data and compiled them in ArcGIS 10.3 at the spatial scale of the hydro-morphological assessment (10 km river reaches see Schwarz, 2014, Fig. 1). We used these data for analysis of the relationships within and between multiple drivers and pressure ($N = 395$) and at the spatial scale of the Natura 2000 sites for the analysis of the relationships within and between pressure and biodiversity status variables (for N see Table 1).

We use Bayesian Networks for the analysis of biodiversity indicators, as they are highly suitable for the analysis of discrete data, they provide a visual depiction of the causal linkages between multiple environmental drivers, pressures and states, making it easy to interpret multiple interactions between variables included in the models (Death et al., 2015; Friedman et al., 1999; Milns et al., 2010; Mori and Saitoh, 2014). They explicitly account for uncertainty (Uusitalo, 2007) and can be used with small and incomplete datasets. We conducted Bayesian Network analyses using a completely data-driven approach within the R package "bnlearn" (Scutari, 2010). In a first step we analysed the causal relationships between multiple drivers and pressures (comprehensive driver-pressure dataset), creating a causal driver-pressure network. In a second step we linked the status indicators into this driver-pressure

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Notes to Table 1:

[1] Vines et al., 2003.
[2] Gollmann et al., 1988.
[3] Ficetola and De Bernardi, 2004.
[4] Kolozsvary and Swihart, 1999.
[5] Schiemer and Waidbacher, 1998.
[6] Guti, 1996.
[7] Schiemer and Spindler, 1989.
[8] Kottelat and Freyhof, 2007.
[9] Prenda et al., 2001.
[10] Drozd et al., 2009.
[11] Oldham et al., 2000.
[12] Probst and Gaborik, 2011.
[13] Heneberg, 2013.

network based on the pressure-biodiversity status dataset and created driver-pressure-biodiversity status networks for each of the 11 conservation target species focusing on each network's predictive performance. Finally, we evaluated the predictive performance of all networks using cross validation and fit the final Bayesian Networks based on the available datasets.

The causal structure of the driver-pressure network was learned using a score-based structural learning algorithm. We selected this method as our data set is relatively small and constraint-based algorithms are known to require very large datasets to obtain adequate performance. We use a bootstrapping approach to estimate the importance of the possible links in the network and give a certainty value to

Table 1
Data description and classes/discretization for drivers (D), pressures (P) and biodiversity status (S) indicator variables used in Bayesian Network models.

Code	Description of indicator	Discretisation	Network (N - size of dataset)
Driver			
urban	Percentage of the potential floodplain area covered by urban structures	1/2/3/4: ≤1/1-3.8/3.8-10.4/>10.4 % coverage in the potential floodplain area	D-P and D-P-S
agriculture	Percentage of the potential floodplain area covered by agricultural land	1/2/3/4: <6.6/6.6-22.6/22.6-44.7/>44.7 % coverage in the potential floodplain area	D-P and D-P-S
navigation1	Navigation class according to the “Classification of European Inland Waterways”	2/3/4/5: navigation class VIa, VIb, VIc, VII	D-P and D-P-S
navigation2	Critical locations for inland navigation where the fairway depth of 2.5 m at Low Navigable Water Level was not achieved	0/1: river stretch contains critical locations or not	D-P and D-P-S
hydropower	River stretch is situated within the reservoir area upstream of a hydropower plant	0/1: river stretch is situated within reservoir area or not	D-P and D-P-S
Pressure			
bankstabilization	Extent of reach affected by artificial bank material (% of bank length)	1/2/3/4/5: high/good/moderate/poor/bad (see Schwarz, 2014)	D-P and D-P-S
planform	Planform of the River channel The planform describes the view of a river from above, showing for example the sidearms of a braided river.	2/3/4: good/moderate/poor or bad (see Schwarz, 2014)	D-P and D-P-S
erosiondeposition	Erosion/deposition character	1/3/5: high/moderate/bad (see Schwarz, 2014)	D-P and D-P-S
engineeringstructures	Impacts of artificial in-channel structures within the reach (impoundments, groynes)	1/3/5: high/moderate/bad (see Schwarz, 2014)	D-P and D-P-S
flooding	Degree of lateral connectivity of the river and the floodplain (Extent of floodplain not allowed to flood regularly, owing to engineering)	2/3/4/5: good/moderate/poor/bad (see Schwarz, 2014)	D-P and D-P-S
connectivity	Degree of lateral movement of the river channel	2/3/4/5: good/moderate/poor/bad (see Schwarz, 2014)	D-P and D-P-S
Biodiversity state			
Bombina	Conservation status of *Bombina sp.* (amphibian) Indicator for fish-free seasonal, pond like, sun-exposed waterbodies[1,2] and the availability of natural terrestrial habitats (woodland)[3,4]	1/2/3: excellent/good/average or reduced conservation status according to EU Habitats Directive	D-P-S (62)
Gym_bal	Conservation status of *Gymnocephalus baloni* (fish) Rheophilic species inhabiting the main stem and connected sidearms of large rivers[5], serving as an indicator for lateral connectivity as it migrates from main stems to river backwaters to spawn.[8]	1/2/3: excellent/good/average or reduced conservation status according to EU Habitats Directive	D-P-S (43)
Gym_sch	Conservation status of *Gymnocephalus schraetzer* (fish) Rheophilic species that serves as an indicator for the status of the main stem of large rivers[5,8]. It prefers sandy and muddy substrate[5]and spawns on gravel in inshore zones of the river[5]	1/2/3: excellent/good/average or reduced conservation status according to EU Habitats Directive	D-P-S (45)
Lutra	Conservation status of *Lutra lutra* (mammal) The species is a good indicator for overall natural habitat conditions including high natural bank vegetation, low human disturbance and surrounding natural forests.[9]	1/2/3: excellent/good/average or reduced conservation status according to EU Habitats Directive	D-P-S (53)
Misgurnus	Conservation status of *Misgurnus fossilis* (fish) Stagnophilic species that prefers stagnant sidearms with soft and muddy substrate and high macrophyte cover, spawning in dense flooded vegetation. The species is an indicator for the availability of natural stagnantbackwaters.[10]	1/2/3: excellent/good/average or reduced conservation status according to EU Habitats Directive	D-P-S (42)
Rhodeus	Conservation status of *Rhodeus amarus* (fish) Stagnophilic species[5] serving as an indicator for isolated to partially connected backwaters and their connectance[6,7]	1/2/3: excellent/good/average or reduced conservation status according to EU Habitats Directive	D-P-S (48)
Triturus	Conservation status of *Triturus dobrogicus* (amphibian) Indicator for temporary, macrophyte-rich, sun-exposed water bodies[11] and the availability of natural terrestrial habitats (woodland)[3,4]	1/2/3: excellent/good/average or reduced conservation status according to EU Habitats Directive	D-P-S (46)
Zin_str	Conservation status of *Zingel streber* (fish) Rheophilic species serving as an indicator for the status of the main stem of small to large rivers[5,8]. It prefers gravel substrate[5] and fast-flowing water[8], spawning in inshore zones of the river on gravel[5]	1/2/3: excellent/good/average or reduced conservation status according to EU Habitats Directive	D-P-S (41)
Zin_zin	Conservation status of *Zingel zingel* (fish) Rheophilic species inhabiting the main stem of large rivers[5,8], spawning on sand often in connected sidearms**5**It is an indicator for the status of the main stem of large rivers and availability of connected side-arms.	1/2/3: excellent/good/average or reduced conservation status according to EU Habitats Directive	D-P-S (46)
Haliaeetus	Population of *Haliaeetus albicilla* (bird) The species requires large open-water bodies for feeding near tall forest stands, mainly floodplain forest, which it uses for nesting. It is indicative of large undisturbed wetlands and floodplain forest as is it sensitive to disturbance.[12]	1/2/3: >3/1-3/<1 individuals per stretch	D-P-S (39)
Alcedo	Population of *Alcedo atthis* (bird) The species nests in vertical river banks, making it an indicator for active erosion and natural substrate along river banks[13]	1/2/3: >9/4-9/<4 individuals per stretch	D-P-S (32)

potential arcs and nodes using the approach of Friedman et al. (1999). Therefore, we used a BDe (Bayesian Dirichlet equivalent) score with a uniform prior distribution and equivalent sample size of five. This search procedure is used in hill-climbing search with random restarts. We conducted 1000 non-parametric bootstraps in the procedure using the “boot.strength” function from the package “bnlearn” for R (Scutari, 2010), which calculates the probability of each arc in the network based on its empirical frequency over a set of networks learned from bootstrap samples. Model averaging was used to build a driver-pressure network containing only the relevant arcs using the “averaged.network” function. Direction of arcs was restricted to go from drivers to pressures. Finally the procedure was repeated for all pressure and biodiversity status datasets for each species to determine most probable arcs between pressures and the respective species data.

The resulting structure of the driver-pressure network and pressure-biodiversity status networks were integrated into driver-pressure-biodiversity Bayesian networks for each species.

All driver-pressure-biodiversity status networks were validated with 10-fold cross-validation using driver-pressure-biodiversity data within the “bn.cv” function. Data were split into10 subsamples; for each subset a Bayesian Network is fitted on the other k - 1 subsets and posterior classification error is calculated for that subset (percent error is then computed, including all relevant nodes in the network). We ran cross-validation 50 times to get a representative value for the models' predictive performance. As final models, we retained the model structure with the best predictive performance for each species. Those were informed using the function “bn.fit” from the same R package. The network structure and conditional probability tables (CPTs, probabilities of the outcome for each possible combination of input values) related to drivers and pressures were thus informed by driver-pressure data, and CPTs related to species status variables were informed by pressure-biodiversity status data (see Pollino et al., 2007).

Final Bayesian Networks were used to estimate conditional probabilities (CP, probabilities predicted from the variables in the network) for each status class for all river segments. For the aggregation of the calculated probabilities into one status index (SI) per species, we used the following formula (compare Cortina and Boggia, 2014):

$$\begin{aligned}\mathrm{SI} = {} & \mathrm{CP}(\text{"excellent conservation status"}) * 2.\\ & + \mathrm{CP}(\text{"good conservation status"}) * 1\end{aligned}$$

2.3.2. Ecosystem service modelling and aggregation

To represent a range of different ecosystem services, we included one of the most important provisioning, cultural and regulating ecosystem services for river-floodplain systems respectively, following the Common International Classification of Ecosystem Services (Haines-Young and Potschin, 2012): pollination, recreation, and flood regulation. Pollination is a further essential ecosystem service in the agricultural-dominated landscape, as it increases the yield and quality of 70% of globally important crops (Klein et al., 2007). Riparian areas and lake and river boundaries represent especially important nesting and foraging sites for many native pollinators given the abundance of floral resources they provide and their proximity to water bodies, making them important ovipositing sites (Resh and Cardé, 2009). Areas with low human influence, and specifically water bodies, exert a strong attraction for recreational purposes (Paracchini et al., 2014). Flood regulation is an important ecosystem service of floodplain systems, and direct links to the restoration of river and floodplain systems' flood retention capacity (Heintz et al., 2012).

The ARIES platform was used for assessing those three ecosystem services. ARIES is an open-source technology capable of selecting and running models to quantify and map all aspects of ecosystem service provision, including their biophysical generation, flow and extraction by sinks and beneficiaries (Villa et al., 2014).

The ARIES pollination model first calculates pollination supply, the suitability of the environment to support wild insect pollinators based on nesting suitability and floral availability (Zulian et al., 2014; Lonsdorf et al., 2009). The model also accounts for the positive effect of water bodies (streams and lakes) on the probability of pollinator presence based on inverse weighted distance, as well as the effect of ambient temperature and solar radiation on pollinator activity (Corbet et al., 1993). We estimated pollination demand based on the weighted sum of crop pollination dependencies (Klein et al., 2007), multiplied by their production for 55 crop types requiring insect pollination to increase their production (Monfreda et al., 2008).

The recreation model is inspired by the ESTIMAP model of nature-based outdoor recreation developed by Paracchini et al. (2014). Recreation supply is calculated as an additive function of naturalness based on land cover type and the Euclidean distance to nature-based factors of attractiveness (e.g., distance to protected areas, water bodies, or mountain peaks). Recreation demand takes into account the likelihood of taking a day trip to a certain location and the population defining the “catchment area” of that location.

The flood regulation model identifies areas providing greater flood regulation as those with higher flood hazard probability (based on topographic wetness index (Kirkby and Beven, 1979), mean annual precipitation, and mean temperature of the wettest season) and water retention by soils and vegetation, based on the Curve Number (CN) method (Chapman, 1985; Ferrer-Juliá, 2003). Demand for flood regulation is calculated using population density and flood hazard probability data.

A full description of all ecosystem service models and data sources can be found in this issue (Martínez-López et al., 2019a).

Finally, data for ecosystem services were normalized (from 0 to 1) and aggregated as the mean value across the potential area remaining for restoration for each river-floodplain segment using ArcGIS10.3.

2.4. Define clusters of multi-functionality (step 2)

We used cluster analysis to identify groups of river-floodplain reaches with homogenous sets of species (SI per species) and levels of ecosystem service provision (mean per segment). We identified and analysed clusters in the data using K-means cluster analysis (Raudsepp-Hearne et al., 2010), using Scree plots to determine an appropriate number of clusters. To stabilize the clusters, we set the number of iterations in the K-means procedure at 100 to ensure a global minimum of variance. Then, we mapped the clusters in ArcGIS10.3 (ESRI) to visualize their spatial pattern.

2.5. Restoration objectives and multi-objective optimization (step 3)

Next, we applied compromise programming, a multi-objective optimization approach (Malczewski, 1999), to identify the most relevant areas for biodiversity and ecosystem service restoration within different compromise scenarios related to three river-floodplain restoration objectives:

(1) Multi-functionality (e.g., Schindler et al., 2014, 2016): Natural floodplains provide habitat for various aquatic species and provide multiple ecosystem services. Restoration aims to re-establish these multiple functions. Sites with high remaining multi-functionality are priorities for restoration, as their protection will have lower effort and costs than areas requiring active restoration. We calculated multi-functionality by summing the aggregated species SI predicted and mean modelled ecosystem service provision per reach.

(2) Reversibility (e.g., Schiemer et al., 1999; Tockner et al., 1998): River-floodplain systems are impacted by a multitude of human activities that constrain their reversibility to natural conditions. This impact and interaction of multiple drivers affects the

potential to restore multi-functionality. Sites with high reversibility are priorities for restoration, as they are likely to have lower costs and greater probability of success than sites with low reversibility. We calculated reversibility by summing the aggregated species SI predicted based on drivers only.

(3) Semi-natural area (e.g., Benayas et al., 2009; Schindler et al., 2014): River-floodplain restoration is often restricted by the availability of natural and semi-natural areas that remain in the floodplain. Abandonment of agricultural polders for restoration and conversion into naturally vegetated land is associated with costs for purchase or future compensation to farmers and may decrease an area's agricultural yield. Semi-natural areas are priorities for restoration, in order to reduce costs and loss of agricultural yield. We calculated semi-natural area as the percentage of land in semi-natural conditions (excluding agricultural areas) from the total area that is directly adjacent to the river and therefore potentially available for restoration (excluding any type of urbanised area or infrastructure), using ArcGIS 10.3 (Fig. 2).

We used these three criteria within compromise programming methodology (Malczewski, 1999) to analyse the best compromise solution for spatial prioritization of restoration. The method is based on the distance from an ideal point (a theoretical optimal point, e.g., 100% multi-functionality or 100% semi-natural area), which is calculated as:

$$D_s = \left\{ \sum_{j=1}^{n} W_j \times \left[\frac{v_{ip,j} - v_{ns,j}}{v_{ip,j} - v_{nip,j}} \right]^m \right\}^{1/m}$$

where Ds is the distance from ideal point in scenario s; n is the number of criteria (j); $v_{ip,j}$ is the ideal value for the j_{th} criterion, $v_{ns,j}$ is the actual value of the j_{th} criterion in scenario s, $v_{nip,j}$is the negative-ideal (worst possible) value for the j_{th} criterion and m is the metric which is used in the analysis. Metric parameter m can be quantified from 1 to ∞, ranging from a total compensatory to total non-compensatory approach, respectively. We used a metric value $m = 2$, which is equivalent to the Euclidean distance and represents a partial compensatory methodology.

We compared seven weighted compromise scenarios (Table 2), ranging from a scenario with river river-floodplain reaches only prioritized based on the availability of semi-natural areas to one with river-floodplain reaches prioritized based on the reversibility to natural conditions only, and analysing different compromises sequentially including all three criteria (multi-functionality, reversibility and semi-natural area).

2.6. Comparison of restoration scenarios and gap analysis (step 4)

To show the importance of the different compromise scenarios along the Danube, we summarized results for the Upper, Middle and Lower section of the Danube. We conducted a gap analysis to compare proposed clusters for conservation, restoration and mitigation with existing conservation sites. To do this, we overlaid polygons representing the boundaries of Natura 2000 sites with river segments identified for conservation, restoration, and mitigation in our analysis. We conducted this overlay in ArcGIS and calculated the percentage match of the existing and calculated areas.

3. Results

3.1. Model input development (step 1)

The architecture of the final driver-pressure Bayesian network (Fig. 3) shows multiple links between the different drivers and pressures. The impact of hydropower reservoirs (hydropower) has multiple links in the network. In reservoirs (variable hydropower), the waterway has less critical locations (variable navigation2) and a higher navigation class (variable navigation1). In reservoirs (variable hydropower) main stem and banks are altered by engineering structures (variables engineeringstructures and bankstabilization) and the planform of the river (variable planform) is significantly altered. Hydropower plants (hydropower) further strongly alter the erosion/deposition pattern (variable erosiondeposition) of the river. Close to urban areas and infrastructure (variable urban) the river is significantly impacted by bankstabilization (variable bankstabilization) measures. Engineering works in the main stem (variable engineeringstructures) and along the banks (variable bankstabilization) related to navigation (variable navigation1, 2) significantly alters the planform of the river (variable planform) as well as erosion/deposition pattern (variable erosiondeposition). Disconnection of floodplains (variable connectivity) is impacted by bankstabilization measures (variable bankstabilization) as well as flood regulation measures (variable flood) and is linked to all drivers in the model including agriculture in the riparian area (variable agriculture).

Looking at the other final Bayesian networks, including biodiversity status, it is evident that the architecture (Table 3, Appendix, Fig. A.2) and conditional probabilities (Appendix, Table A.2) vary across species indicators. Typical floodplain species (e.g., *Rhodeus amarus*, *Misgurnus fossilis*) showed stronger relationships to floodplain connectivity than typical river species (e.g., *Gymnocephalus schraetzer*, *Zingel streber*), which showed higher predictive performance in networks that included only variables related to the main stem of the river. As shown by the architecture of the different networks, changes in those variables that are directly or closely linked to the species node have the highest impact on the predicted probabilities per species. Conversely, nodes that are more distant have lower impact (Appendix, Table A.2).

Ten-fold cross validation (Table 3) of final driver-pressure-biodiversity status models shows good to moderate performance across species (Table 3), with comparable performance to similar studies (Death et al., 2015).

3.2. Define clusters of multi-functionality (step 2)

The cluster analysis identified four clusters with different levels of multi-functionality among reaches of the Danube River (Fig. 4). Cluster 1 identifies the most intact river-floodplain reaches, which shared high multi-functionality across species and ecosystem services. Therefore, this cluster can be defined as having the highest conservation potential. Flood regulation is the only ecosystem service with reduced provision in cluster one, as many reaches in this cluster are situated along the Lower Danube, where most of the floodplain area is used for agriculture, which have relatively low flood regulation capacity compared to forested riparian areas. Clusters 2 and 3 show bundles of river-floodplain reaches with either high remaining potential for only the rheotopic/river community, amphibians and recreation, or high remaining potential for the stagnotopic/floodplain community and all three ecosystem services, respectively (Fig. 4). These two clusters are therefore defined as having restoration potential of varying types. For cluster 2, this would entail restoration of stagnant water bodies and riparian habitats for stagnophilic species and ecosystem service supply, including abandonment of agricultural polders, while cluster 3would require restoration of the dynamic water bodies including reconnection of sidearms or removal of artificial bank material. Cluster 4 has reduced biodiversity potential across all species but high potential, with restoration, for increased flood regulation. We define this cluster as having potential for mitigation measures related to flood regulation. Most of the sites in this class have high hydromorphological constraints (e.g., river embankments, dykes or levees) due to navigation, hydropower and urbanization but remaining floodplain areas, often covered by floodplain forests, have high remaining flood regulation capacity or also capacity to maintain habitat for particular indicator species if considered for restoration.

3.3. Restoration objectives and multi-objective optimization (step 3)

The input variables related to the three objectives for the multi-objective optimization approach—multi-functionality, reversibility and semi-natural area—show clear patterns along the Danube. Areas with high remaining multi-functionality (Fig. 5a), having lowest distance to the ideal point, are mainly found along the Lower Danube followed by the Middle and Upper Danube. Near-natural area is found in large areas along the Upper and Middle Danube, but limited extents are found along the Lower Danube, and show a relatively low distance to the ideal point of 100% coverage with semi-natural area (Fig. 5b). Stretches with high reversibility are mainly found in the Lower Danube and a few sites in the Middle Danube (Fig. 5c). Accordingly, compromise programming results (Appendix, Fig. A.3) for the seven scenarios show a clear trade-off between the availability of semi-natural land for restoration and reversibility for restoration related to multiple drivers for the multi-functionality cluster described in step 4. The three criteria also show clear differences in the total distance to target. Coverage of semi-natural area ranges from 0 to 100% along the Danube, whereas distance to target related to multi-functionality and reversibility is never lower than 25%. This reflects the high level of alteration along the Danube, where even sites with the most natural conditions do not currently achieve full multi-functionality.

3.4. Comparison of restoration scenarios and gap analysis (step 4)

The seven compromise scenarios enable the systematic identification of the most promising areas for restoration, which can include the three criteria independently or in combination with different weightings (Table 2). Together with the cluster analysis results, segments of clusters 2 (rheotopic/river and recreation) and 3 (stagnotopic/floodplain species and multiple ecosystem services) with restoration potential are systematically prioritized (Appendix, Fig. A.3). As an example of the application of the approach, we compared results across regions (Fig. 6a). Along the Upper Danube, segments with restoration potential (clusters 2 and 3) are generally scarce, and the reversibility criterion further reduces the number of segments that are prioritized for restoration. Based on the semi-natural area criterion, many of the reaches with restoration potential along the Middle Danube have the lowest distance to the target, whereas based on reversibility alone potential reaches along the Lower Danube have lowest distance to target. Across the different compromise scenarios, the trend changes continuously by region, being most balanced across the Middle and Lower Danube for scenario 4. There are also numerous sites that are prioritized in the Middle and Lower Danube region that have relatively low distance to target across all scenarios.

Additionally we compared the compromise programming results across all scenarios for the two restoration clusters—clusters 2 and 3 (Fig. 6b). In the scenario that optimizes for semi-natural area only and the compromises 1 to 3, river segments of cluster 2 are scarcely represented. From compromise 4 to the scenario that optimizes for reversibility only, cluster 2 sites are represented more in greater balance with those selected in cluster 3.

Our gap analysis showed that already a very high proportion (about 80%) of the area in clusters 1 and 3 is already part of the Natura 2000 protected area network. Our high multi-functionality/conservation cluster and high multi-functionality/high restoration potential for stagnotopic species and ecosystem services cluster are already widely protected in Natura 2000 sites. Many of the river-floodplain systems identified in this cluster are part of well-known national parks like Nationalpark Donauauen in the Upper Danube, Kopački rit in the Middle Danube or Persina in the Lower Danube. For both clusters 2 and 4, about 50% of their area is protected under Natura 2000. River segments of these clusters have relatively high coverage of agricultural land, which in many cases is excluded from protected areas.

Table 2
Weights for the compromise programming of the different scenarios.

Scenario	Multi-functionality	Semi-natural area	Reversibility
Seminatural	0	1	0
Compromise 1	0.5	0.5	0
Compromise 2	0.4	0.4	0.2
Compromise 3	0.33	0.33	0.33
Compromise 4	0.4	0.2	0.4
Compromise 5	0.5	0	0.5
Reversibility	0	0	1

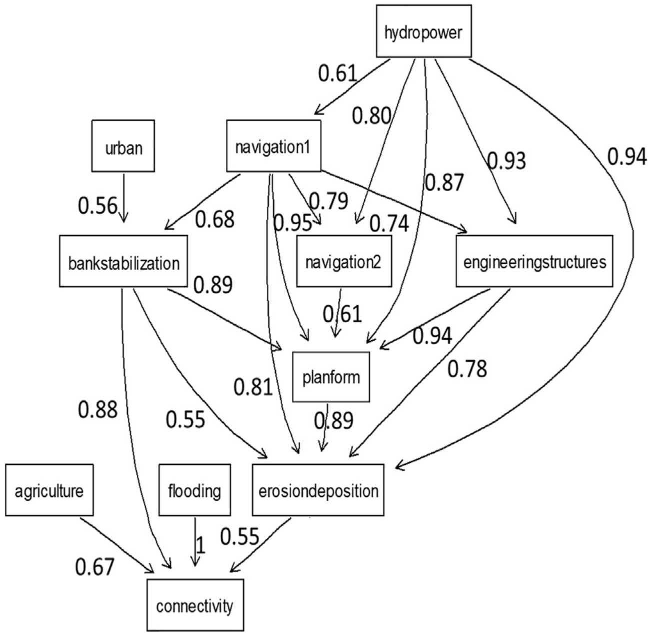

Fig. 3. Driver-Pressure Bayesian network, results from boosting the causal structure of the network. Numbers are the calculated probabilities of arcs. For description of codes, see Table 1.

4. Discussion

4.1. Strength of biodiversity models

Our approach of learning Bayesian networks for driver and pressure data to identify their structure successfully depicts multiple causal relationships in ways that generally agree with existing knowledge, demonstrating model sensitivity and validity as follows. For example, hydropower supports the navigability of the river, as in the deep and relatively wide reservoir reaches, no obstacles to navigation are present (Habersack et al., 2016). In these reservoirs, associated engineering structures significantly alter the system, substantially altering patterns of erosion and deposition as well as river planform (Graf, 2006; Habersack et al., 2016; Hein et al., 2016). Floodplain agriculture combined with related flood-protection measures (creation of agricultural polders) has led to a substantial reduction in floodplain areas hydrologically connected to the river (Hein et al., 2016; ICPDR, 2016).

Local expert judgment compiled within the database of the Natura 2000 network of protected areas proved to be a highly relevant source to predict habitat availability for multiple species across taxonomic and functional groups; this is critical in evaluating the multi-functionality of remaining river-floodplain systems. This matches the findings of other studies, as this dataset is already widely used for conservation and management planning (e.g., Cortina and Boggia, 2014; Hermoso et al., 2018). The results of our models matched basic knowledge on the habitat preferences of the selected species. These ranged from stagnophilic and rheophilic fish species (Schiemer and Waidbacher, 1998), to species dependent on active erosion like the European

Table 3
Structure and cross-validation results of the final selected Bayesian Networks for the conservation status of protected species (see also Appendix, Fig. A.2 for network structure).

Species code	Link to driver-pressure network	Included in network	Mean posterior classification error from 10-fold cross-validation
Alcedo	Erosion/deposition	All drivers and pressures	0.32 (±0.072)
Bombina	Erosion/deposition	All drivers and pressures	0.26 (±0.047)
Gym_bal	Erosion/deposition	All drivers and pressures	0.23 (±0.057)
Gym_sch	Erosion/deposition	Excluding agriculture, connectivity and flood	0.27 (±0.055)
Haliaeetus	Connectivity	All drivers and pressures	0.24 (±0.072)
Lutra	Erosion/deposition	All drivers and pressures	0.30 (±0.048)
Misgurnus	Connectivity	All drivers and pressures	0.25 (±0.056)
Rhodeus	Connectivity	All drivers and pressures	0.21 (±0.069)
Triturus	Erosion/deposition	All drivers and pressures	0.25 (±0.058)
Zin_str	Erosion/deposition	Excluding agriculture, connectivity and flood	0.21 (±0.075)
Zin_zin	Erosion/deposition	Excluding agriculture, connectivity and flood	0.29 (±0.057)

kingfisher (*Alcedo atthis*), which uses vertical river banks created by natural erosion (Heneberg, 2013) to amphibians, for whom active erosion increases the availability of small sun-exposed waterbodies preferred as spawning habitat (Tockner et al., 2003). We have also included species indicative for the status of riparian habitats like amphibians and the white-tailed eagle (*Haeliaeetus albicilla*, Table 1). However, not directly including riparian species as indicators may underestimate the biodiversity of the riparian habitats.

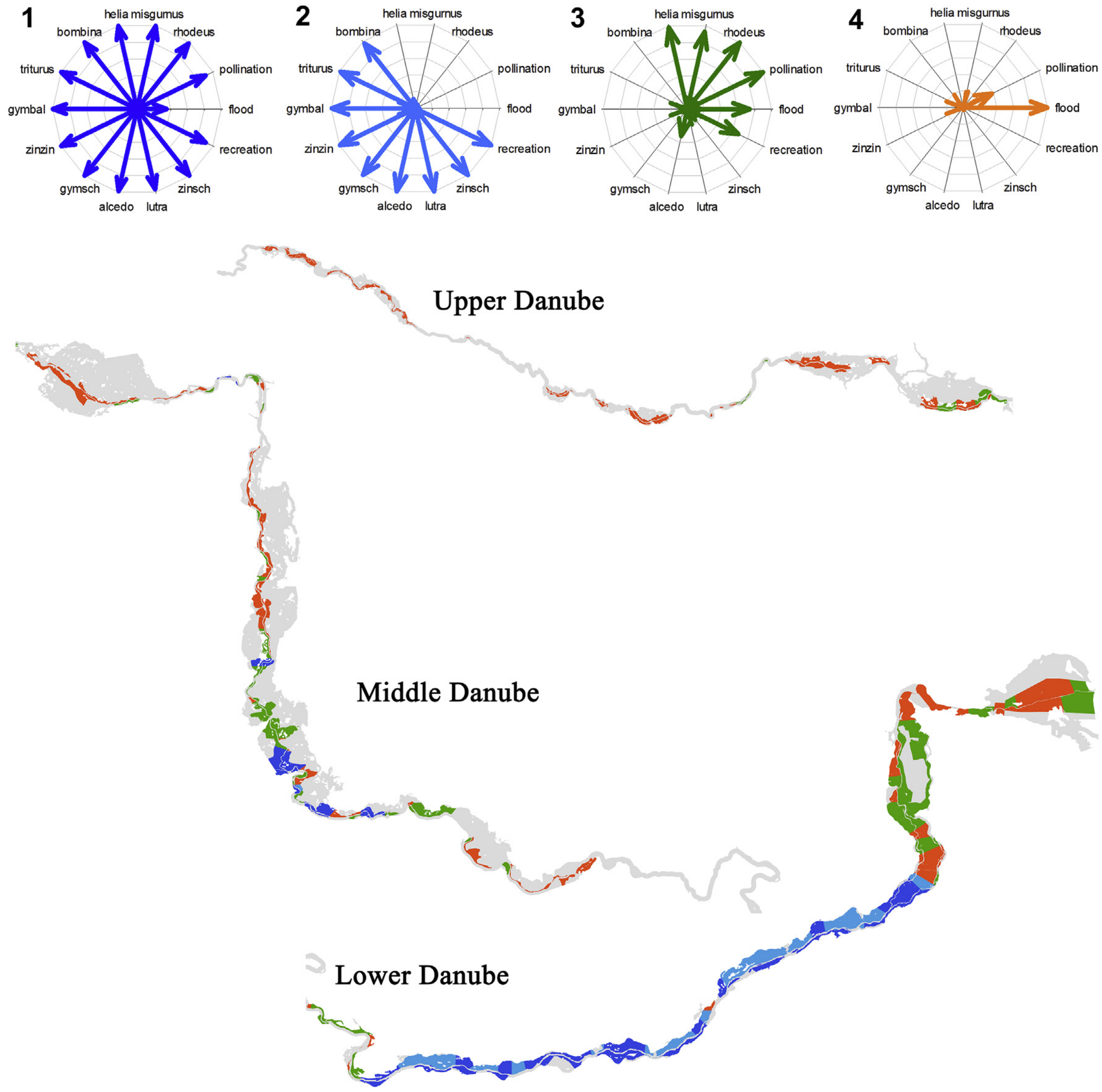

Fig. 4. Cluster analysis results, showing four relevant clusters related to species and ecosystem service values. Arrow lengths represent the relative value across the clusters, i.e., the longer the arrow, the higher the potential of species habitats and ecosystem services in the respective cluster. Colors of arrow plots correspond to the colors on the map. Dark blue/cluster 1: multi-functional cluster; light blue/cluster; light blue/cluster 2: rheophilic/river and recreation cluster; green/cluster 3: stagnophilic/floodplain species and multiple ecosystem service cluster; orange/cluster 4: reduced multi-functionality with remaining high flood regulation potential cluster. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Our approach, based on multiple aquatic species with contrasting habitat requirements and selected important ecosystem services, enables the identification of river reaches that show a high degree of multi-functionality. The recorded high overlap between areas important for biodiversity and ecosystem service is consistent with other studies (Egoh et al., 2011; Maes et al., 2012) pointing to the close relationship between biodiversity and ecosystem services, which is often greater in natural systems (Chan et al., 2011; Schneiders et al., 2012). However, others have found less spatial overlap between biodiversity and ecosystem services (Egoh et al., 2014), pointing to the importance of approaches that analyse for their congruence like our clustering approach (Bai et al., 2011).

Sites with high restoration potential were effectively selected, and were grouped into two clusters. One has deficits mainly for the rheotopic community, and requires restoration of natural dynamics through reconnection of sidearms or removal of artificial bank material. The other shows deficits for the stagnotopic community and ecosystem services and requires restoration of stagnant water bodies and riparian habitats, including abandonment of agricultural polders. This cluster aligned with the findings of Schindler et al. (2014), who identified that the abandonment of agricultural area could lead to high-level restoration of ecosystem services. By contrast, floodplain reconnection has high potential for biodiversity restoration (Mueller et al., 2017; Paillex et al., 2009, 2015; Reckendorfer et al., 2006; Rumm et al., 2018; Straatsma et al., 2017), its effect on ecosystem services can expected to be positive but lower (Schindler et al., 2014).

Lastly one cluster bundled sites with reduced biodiversity potential across all species but high potential, with restoration, for increased flood regulation. We thus define this cluster as having potential for mitigation measures related to flood regulation. But there is also capacity to maintain habitat for particular indicator species. Even heavily degraded floodplain system can have high value or restoration potential for a specific, mostly stagnotopic, community (Funk et al., 2009; Schiemer et al., 1999). It would also be possible to prioritize segments for mitigation measures by focusing on this cluster using the same three criteria (i.e., multi-functionality, reversibility and semi-natural area).

4.2. Multi-objective optimization

The two main causes of deterioration of the hydro-morphological conditions of river-floodplain systems, and therefore main targets for restoration, are the loss of floodplain area caused by agricultural polders and hydrological disconnection of remaining floodplains due to river engineering works. These issues are directly addressed by our approach via the semi-natural area and the reversibility criterion, respectively. Therefore, our prioritization method selects river reaches where floodplain restoration can minimize loss of agricultural land and those where hydrological connectivity between river and floodplain could be restored with the least effort and risk of failure.

For our approach, compromise programming is more advantageous than spatial conservation planning tools like Marxan, which are widely used for conservation planning (Reyers et al., 2012; Vallecillo et al.,

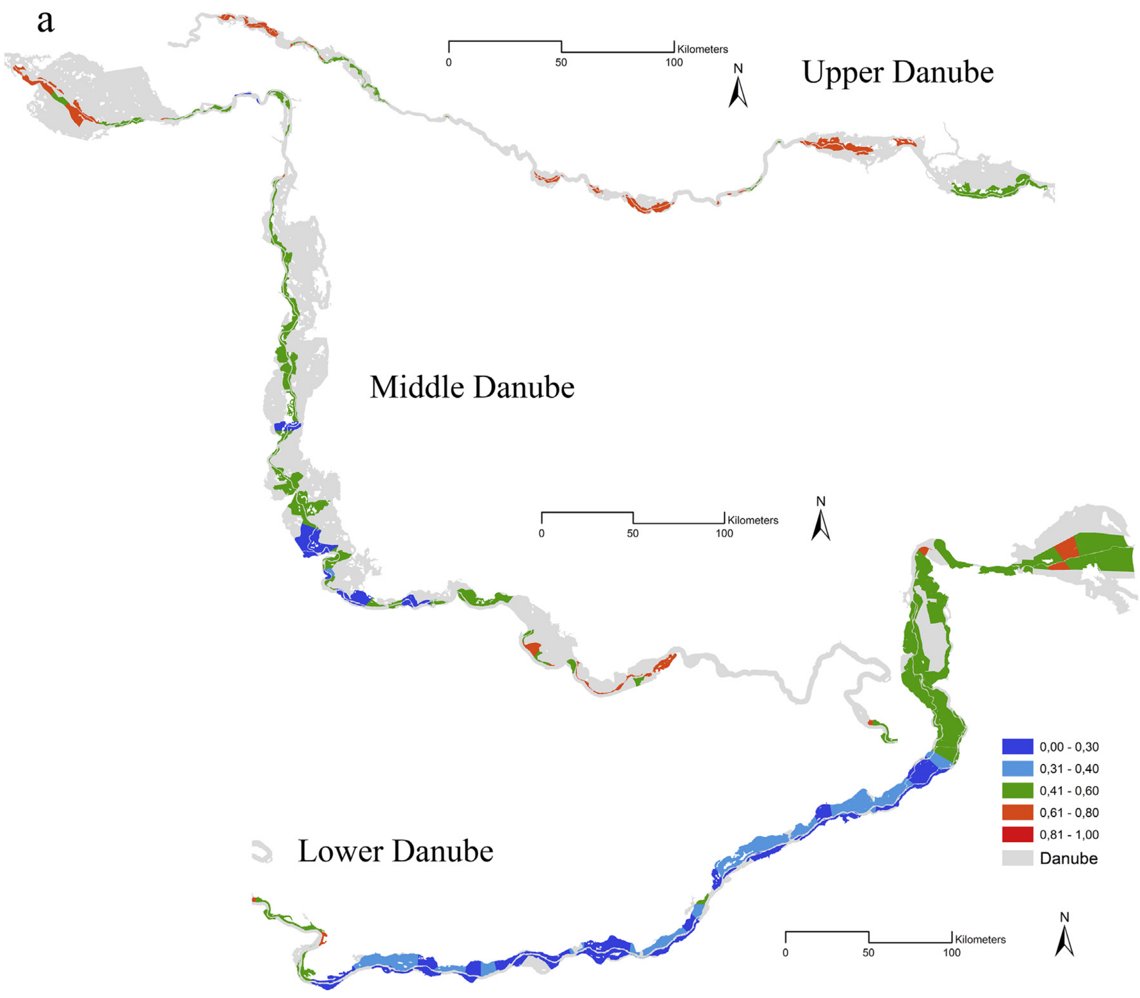

Fig. 5. Input variables for the multi-objective optimization approach using compromise programming. Values are expressed as distance from ideal point ranging from blue (relative close to ideal conditions, with high priority for conservation and restoration) to red (highest distance to ideal conditions, with low priority for restoration). (a) Multi-functionality, (b) Reversibility, (c) Semi-natural area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

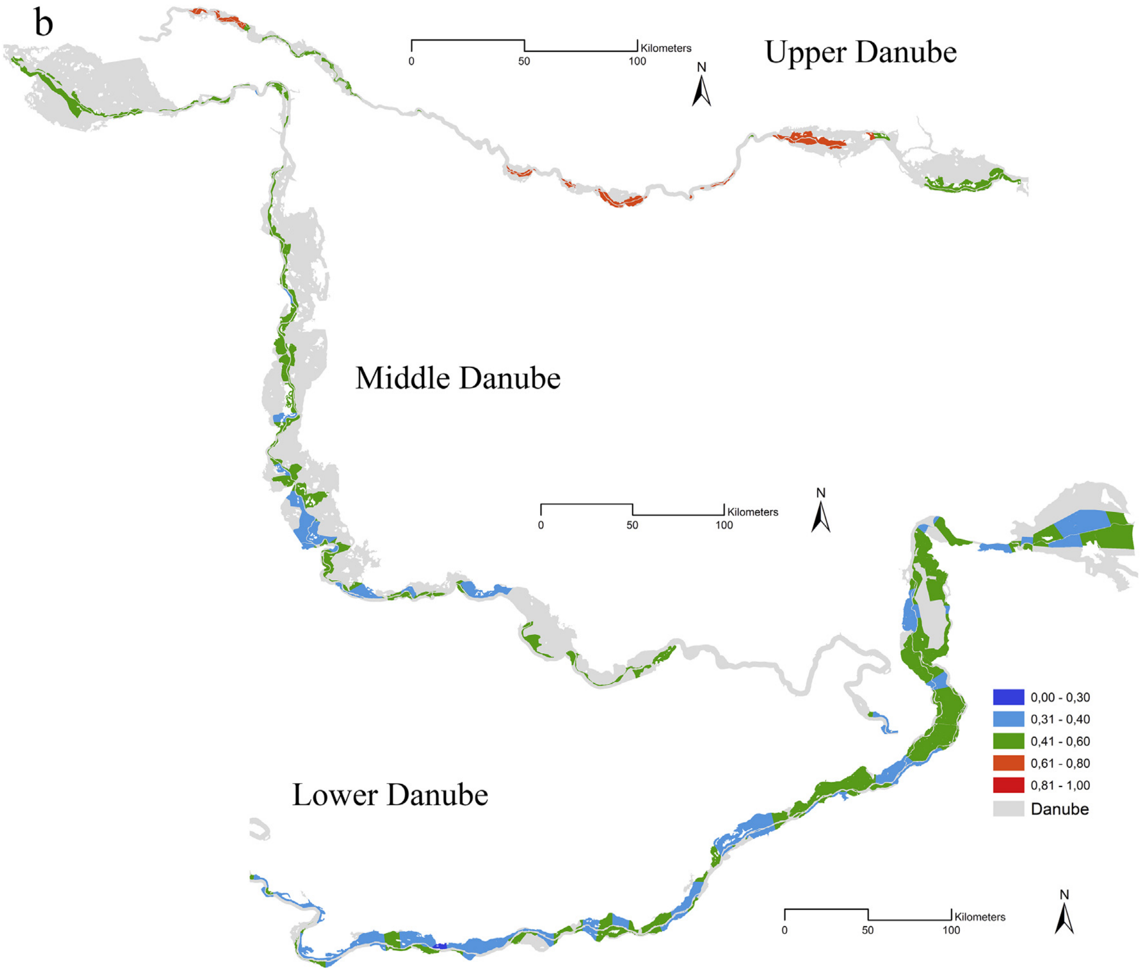

Fig. 5 (*continued*).

2018; Domisch et al., submitted, this issue). Compromise programming is a multi-objective optimization tool (e.g. Sacchelli et al., 2013), which enables the systematic optimization of different restoration strategies, which are not considered in Marxan (Dujardin and Chadès, 2018). Additionally, when the focus is on selecting for multi-functional sites, a hotspot method, i.e., using summed and merged indices, might be favoured since sites selected by Marxan are not necessarily those that contain high levels of both multiple biodiversity components and ecosystem services (Schröter and Remme, 2016). Hotspot approaches comparable to ours have already been used for diverse purposes including planning of green infrastructure networks (Liquete et al., 2015) and site prioritization for ecological restoration (Comín et al., 2018).

4.3. Relevance for the Danube River floodplains

Our gap analysis showed that most of the sites we are prioritizing for conservation are already part of Natura 2000 sites (80% of the area). Sites with a high multi-functionality related to the stagnotopic community and ecosystem services are already widely part of Natura 2000 sites, indicating the effectiveness of Natura 2000's site selection along the Danube. Sites with a high coverage of agricultural area and high multi-functionality related to the rheophilic community are less protected (50% of the area) under the Habitats and Birds Directive. However, these sites are important for restoration, and their nomination for Natura 2000 status and subsequent restoration planning should be considered in order to preserve the Danube's full suite of biodiversity and ecosystem services.

In relation to restoration plans included in the Danube River Basin Management Plan (ICPDR, 2016), some high-priority sites that we identified have high priorities across the different scenarios and are already designated as sites with high restoration potential (e.g., “Incinta Bistret Nedeia Jiu” or “Dabulen Potelu Corabia” in Romania). We also identified sites where restoration is already planned and ongoing (“Donau-Auen National Park” in Austria https://www.danubegis.org/), and others in areas where no sites are yet designated, e.g., along the Hungarian Danube.

4.4. Analysis framework

Our approach supports the systematic prioritization of conservation and restoration of ecosystem services and biodiversity along one of Europe's largest rivers—the Danube—based on a framework including modelling, cluster analysis, and multi-objective optimization. By prioritizing sites with greater probability of restoration success at lower cost across the entire Danube River ecosystem, our approach may foster transboundary coordination and cooperation as it is independent from administrative and political boundaries and thus offers potential for better cost-effectiveness in achieving large scale conservation and ecosystem service targets (Bladt et al., 2009; Egoh et al., 2014).

By considering the multi-functionality of river-floodplain systems plus the cumulative impacts of multiple important human activities including agriculture, navigation and hydropower, the approach also has potential to foster conservation and restoration planning across multiple policies. This includes measures to be proposed under the Water Framework Directive for European rivers to reach prescribed “good

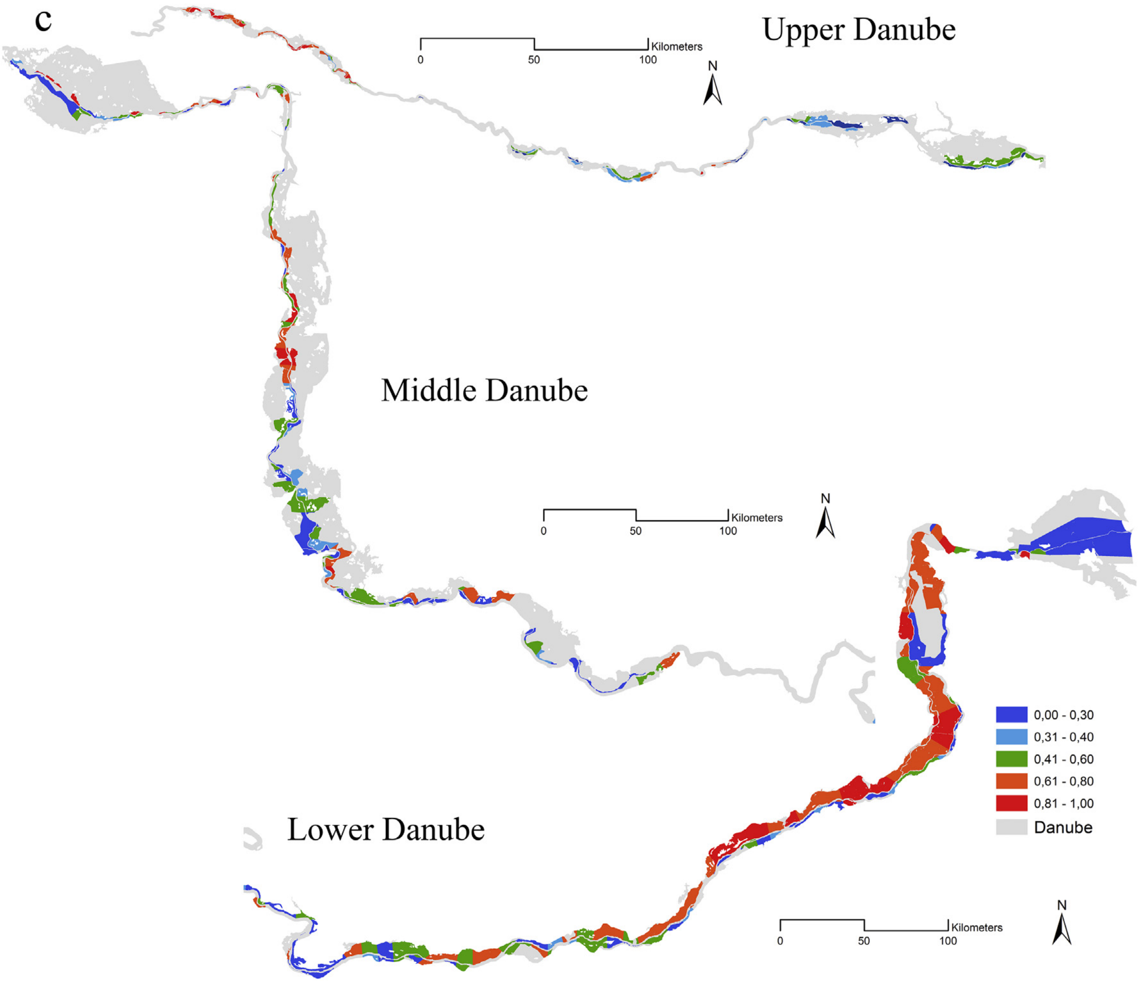

Fig. 5 (*continued*).

ecological status." A prioritization approach is also necessary for the Natura 2000 network along the Danube River (Hermoso et al., 2018). In this sense, restoration prioritization can guide the selection of sites for restoration project funding e.g., under the EU LIFE+ programme (http://ec.europa.eu/environment/life/funding/lifeplus.htm), and thus also support the implementation of the EU Biodiversity Strategy (Cortina and Boggia, 2014; Hermoso et al., 2018). Local restoration of lateral connectivity in river-floodplain systems is a pre-requisite for attaining effective environmental flows (e-flow) at catchment scale (another Water Framework Directive goal, EC, 2015), through hydrological restoration and restoration of sediment supply and transport (Hayes et al., 2018, Opperman et al., 2010). Direct accounting for catchment-scale impacts on hydrology and erosion and deposition related to sediment transport was not possible within our approach because of lack of sufficient knowledge and availability of indicators (Habersack et al., 2016).Generally, however, floodplains restored to an ecologically dynamic state are more resilient to external perturbation (Palmer et al., 2005).

Furthermore, enhancing ecosystem services has become a top priority in environmental policy in Europe that is connected to flood regulation (EU Flood Risk Directive), the EU Green Infrastructure Strategy, and the EU Biodiversity Strategy, which aim to maintain and enhance ecosystems and their services by establishing green infrastructure and restoring at least 15% of degraded ecosystems (Schindler et al., 2014).

Based on varying socio-economic or political conditions for the different scenarios, our results can guide restoration proposals for different regions, but can also guide country-level or even water body-level (as defined under Water Framework Directive) prioritization within the Danube watershed, as it is possible to combine different compromise scenarios spatially within this very flexible approach. Our approach also makes it possible to weight criteria differently across space, depending on political or socio-economic zoning (Malczewski, 1999).

5. Conclusions

Our approach of coupling predictive models with spatial prioritization is a promising tool with high potential to support catchment-scale management decisions. As the method is very flexible and the criteria we use (multi-functionality, reversibility and availability of semi-natural land for restoration) are broadly applicable, we believe that our approach is transferable to other river-floodplain systems with comparable management challenges. To make the approach operational, participatory processes involving decision makers across the catchment, member state and local levels would be a further important step (Martínez-López et al., 2019b; Schwarz, 2010). Although open-access data and expert judgment proved to give sufficient information within our approach, detailed field data would be highly relevant for the validation of our results. Finally, as the loss of aquatic habitat from disconnection of river-floodplain systems is a continuing process (Habersack et al., 2016), rapid decision tools that build upon best-available data and information are required in management planning. Such approaches would ideally follow a precautionary approach, where a lack of full scientific certainty is not viewed as a reason for postponing decisions (De Santo, 2017), as no action is clearly leading to a

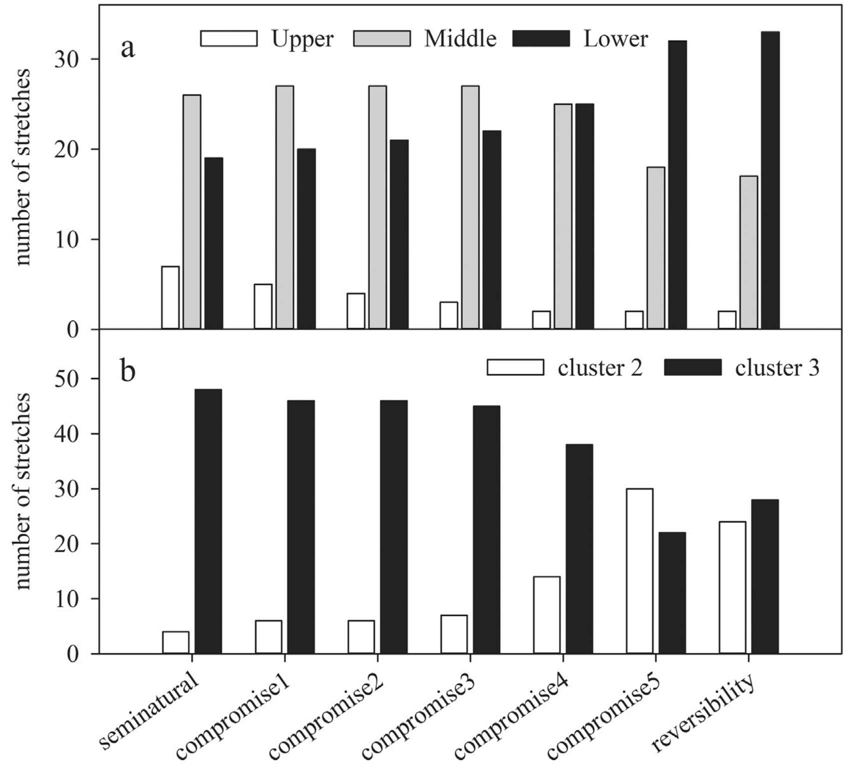

Fig. 6. Example for the prioritization of river-floodplain segments for restoration, comparing (a) Upper, Middle and Lower regions of the Danube and (b) for the two restoration clusters, clusters 2 and 3 (see Fig. 4). For this example the 15%restoration target (target 2) of the EU Biodiversity Strategy to 2020 was applied. The most promising 15% of segments with restoration potential (clusters 2 and 3) are counted per scenario, as calculated using compromise programming.

progressive deterioration of aquatic habitats, biodiversity, ecosystem services and functions of the system.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.10.322.

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