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Modelling of potential vegetation identifies diverging expectable outcomes of river floodplain widening

Imelda Somodi[a,*,1], Krisztina Dóra Konrád[a,b,c,2], Dávid Béla Vizi[d,e], Béla Tallósi[f], Andrea Samu[g], Péter Kajner[g], Ákos Bede-Fazekas[a,h,3]

[a] Institute of Ecology and Botany, HUN-REN Centre for Ecological Research, Alkotmány út 2-4., Vácrátót H-2163, Hungary
[b] Department of Plant Systematics, Ecology and Theoretical Biology, Institute of Biology, Faculty of Science, ELTE Eötvös Loránd University, Pázmány Péter sétány 1/C., Budapest H-1117, Hungary
[c] Doctoral School of Biology, Institute of Biology, Faculty of Science, ELTE Eötvös Loránd University, Pázmány Péter sétány 1/C., Budapest H-1117, Hungary
[d] Middle Tisza District Water Directorate, Boldog Sándor István körút 4., Szolnok H-5000, Hungary
[e] University of Public Service, Doctoral School of Military Sciences Ludovika tér 2., Budapest H-1083, Hungary
[f] Hortobágy National Park Directorate, Rezeda utca 20., Szolnok H-5000, Hungary
[g] Nature Conservation Department, WWF Hungary, Álmos vezér útja 69/a, Budapest H-1141, Hungary
[h] Department of Environmental and Landscape Geography, Institute of Geography and Earth Sciences, ELTE Eötvös Loránd University, Pázmány Péter sétány 1/C., Budapest H-1117, Hungary

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ABSTRACT

River re-naturalisations are at the forefront of conservation efforts. The hope is that these interventions will benefit both local ecosystems and facilitate flood mitigation. While hydrological modelling has been a standard procedure in assessing the outcomes of river re-naturalisations, vegetation modelling has not always been performed as part of these assessments. We hypothesised that the use of potential vegetation modelling, i.e. the modelling of self-sustainable vegetation that can survive after the intervention, can provide insight into vegetation outcome of river re-naturalisation and can thus support vegetation restoration and conservation planning. We investigated the utility of potential vegetation modelling under a specific, widespread element of river re-naturalisation: river floodplain widening at three study sites along the Tisza River in Hungary. We applied potential vegetation modelling, in addition to hydrological and groundwater modelling, to assess the expected vegetation outcome of the river floodplain widening. Flood frequency and duration were assessed by the HEC-RAS hydrological model. Based on the output this hydrological model provided, expected values of the water-related explanatory variables (including groundwater level) were calculated. Statistical relationships encompassed by the existing mulitple potential vegetation (MPV) models of Hungary were applied to the environmental variable sets corresponding to conditions before and after floodplain widening (pre- and post-treatment, respectively), including water-related and other explanatory variables. This resulted in predicted potential vegetation distribution for pre-treatment and post-treatment

* Corresponding author at: Alkotmány út 2-4., Vácrátót H-2163, Hungary.
E-mail addresses: somodi.imelda@ecolres.hu (I. Somodi), konrad.krisztina@ecolres.hu (K.D. Konrád), vizi.david.bela@kotivizig.hu (D.B. Vizi), tallosibela@hnp.hu (B. Tallósi), andrea.samu@wwf.hu (A. Samu), peter.kajner@wwf.hu (P. Kajner), bfakos@ecolres.hu (Á. Bede-Fazekas).
[1] 0000-0002-6207-3796
[2] 0000-0002-4414-8766
[3] 0000-0002-2905-338X

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conditions, which were then compared via ordinations and PERMANOVA. At two of the study sites, post-treatment potential vegetation prediction typically showed vegetation types requiring wetter and less saline conditions when compared to the pre-treatment potential vegetation distribution. This pattern corresponds to general expectations given river floodplain widening. However, at one of the sites, the potentiality of saline and non-saline steppe vegetation was actually more pronounced under the expected post-treatment conditions than those before widening. The strengthening of the potentiality of dry vegetation types can be explained by the minor environmental differences related to the microrelief. As the studied sites were all located in the lowlands where geomorphological variation is small, the effect of these minor geomorphological differences on post-treatment potential vegetation would have remained hidden without applying MPV models. In conclusion, scenarios that employ MPV models help predict river restoration outcomes more accurately and can help identify factors that might otherwise be overlooked. Thus, when combined with physical modelling of river flow, their use can aid in the restoration and landscape planning decisions in river re-naturalisation projects.

1. Introduction

Most of the rivers in Europe, and many rivers around the world, have been regulated by embankments and other barriers (Dynesius, Nilsson, 1994; Lehner et al., 2011; Grill et al., 2019). River embankments often leave narrow strips for floodplain vegetation along the river (Meyerhoff, Dehnhardt, 2007; Damm, 2013; Peters et al., 2021). Re-naturalization of river flow is an increasingly used measure thanks to various expected benefits: improved flood control, summer drought mitigation, and improvement of local ecosystems (Zsuffa and Bogardi, 1995; Bednarek, 2001; Wohl et al., 2015). A frequent form of re-naturalisation is the enlargement of the active floodplain by modifying embankments: opening, removing or moving them farther from the river (Vuren et al., 2005; Warner et al., 2012; Van Buuren et al., 2015).

In addition to mitigating floods (Brillinger et al., 2020; Han et al., 2023), such projects are also expected to lead to the increased naturalness of the floodplains (Vuren et al., 2005; Warner et al., 2012, Van Buuren et al., 2015). Typically, an increase in wetland vegetation is one of the primary goals of river re-naturalisation (Meyerhoff, Dehnhardt, 2007; Marttunen et al., 2019; Ioana-Toroimac et al., 2022). Conservation evidence points to natural marshes developing in the majority of river restoration cases (Conservation Evidence database, 2023) However, examples exist that river re-naturalisation does not always yield the expected wetlands (Kail et al., 2015; Ioana-Toroimac et al., 2022).

Vegetation modelling is a tool that can provide substantial assistance to assess the potential results of such interventions and support planning for the eventual outcomes. Vegetation modelling has been incorporated into river restoration outcome estimates as major life forms (i.e. forest/grassland; e.g. Dixon et al., 2016, Vermaat et al., 2021) and as major habitat types (aquatic/mesic/xeric; Bair et al., 2021). However, the need to provide greater detail on expected vegetation types in river re-naturalisation effect predictions has also been called for (Ochs et al., 2020; Del Tánago et al., 2021). Knowledge of the range of vegetation types which can survive under the expected environmental conditions is relevant in various cases. The range of potential vegetation is infromative of the range of possible vegetation outcomes (1) when solely the hydrological intervention is carried out or (2) when vegetation restoration is planned with the motivation to support the development of vegetation types that can survive with no or minimal management. Choosing vegetation types from the range of potential natural vegetation as restoration target helps achieving the ambitious contemporary restoration targets (e.g. European Commission, Directorate-General for Environment, 2022; Fu et al., 2023): if a restored type is self-sustainable, more resources are left to cover larger extents for restoration.

The potential natural vegetation (PNV) concept represents the vegetation that could survive under the environmental conditions of a specific site at a specific time point (Tüxen, 1956; Somodi et al., 2021). PNV only reflects survival chances, thus provides estimation without considering constraints by propagule limiations or successional routes. Thus, PNV characterises the environment from the point of view of vegetation (Somodi et al., 2021). However, PNV is theoretical, hence vegetation types designated as PNV are not necessarily present at the location. PNV can help to assess the self-sustainable vegetation of locations not currently vegetated (e.g. urban area, arable field) or self-sustainable vegetation under different than actual conditions.

Traditionally, PNV estimates were made by individuals with expert knowledge (Tüxen, 1956; Küchler, 1964; Neuhäuslová et al., 2001); however, it is also possible to employ models in PNV estimation (e.g. Tichy, 1999; Somodi et al., 2017; Fischer et al., 2019). PNV models quantify the vegetation-environment relationship and thus are a useful tool in impact assessment, such as studying the potential impact of river re-naturalisation (e.g. Ochs et al., 2020). Somodi et al. (2012) and, (2017) further extended the PNV concept to reflect modern ecological knowledge into a probability distribution of potentially surviving vegetation types at a specific location (multiple potential natural vegetation, MPNV). Thus, the MPNV approach can incorporate several alternative stable states (Baker and Walford, 1995; Petraitis, 2013). This extension of the concept can be particularly useful for restoration planning as it allows for the consideration of multiple self-sustaining vegetation types per location (e.g. Török et al., 2018).

While PNV encompass vegetation capable of survival without human management, the need to assess the self-sustainability of vegetation types in cultural landscapes has also emerged. Thus, the term Potential Replacement Vegetation (PRV; Chytrý 1998) has been introduced to represent those seminatural vegetation types that would be stable in a specific location given human management (e.g. grazing, mowing). As the suitability of floodplains to seminatural vegetation under low-intensity management is also of interest in many cases, we have developed a probabilistic estimation of PNV and PRV together. This combined vegetation potential was termed

MPV after Konrád et al. (2022).

In this paper, we aim to test, if vegetation modelling and particularly modelling a probability distribution of potentially surviving vegetation types (i.e. MPV) can contribute to our understanding of the vegetation consequences of river floodplain widening.

2. Methods

2.1. Study sites

The three sites we studied all lie along the Tisza River in the Middle Tisza Region of the Hungarian Great Plain (Fig. 1). The Tisza River is one of the major rivers in Central Europe. It is the largest tributary of the Danube River, and the second-longest river in Hungary after the Danube (Borsos and Sendzimir, 2018). It originates in the Ukrainian Carpathian Mountains and flows a total of 966 km, 597 km through the Hungarian Great Plain. Geomorphologically, this region is characterized by a flat landscape. Originally, the riverine landscape of the middle Tisza region was shaped by the river's dynamics. The meandering river often changed course, leaving channel belts and oxbow lakes behind. However, the river has been highly regulated since the middle of the 19th century. Concurrently, the mainstream of the Tisza was shortened by ca. 30% (Tockner et al., 2021). The main objectives of this regulation have been to control the water level, ensure ship navigation, and prevent inland floods. As a result of this regulation, the width of the active floodplain has been reduced significantly. However, still natural material lines the riverbed, the embankments are constructed from soil and are covered with herbaceous vegetation. (Semi)natural vegetation is present along the riverbed up to the embankment. Natural vegetation in the Middle Tisza region is primarily composed of floodplain forests, wetlands, grasslands and steppe forests. However, the region has been severely transformed by agricultural use, thus natural vegetation is confined to small areas. Currently, willow-poplar gallery forests line the riverbeds often in a narrow strip within the embankments. Hardwood gallery forests (dominated

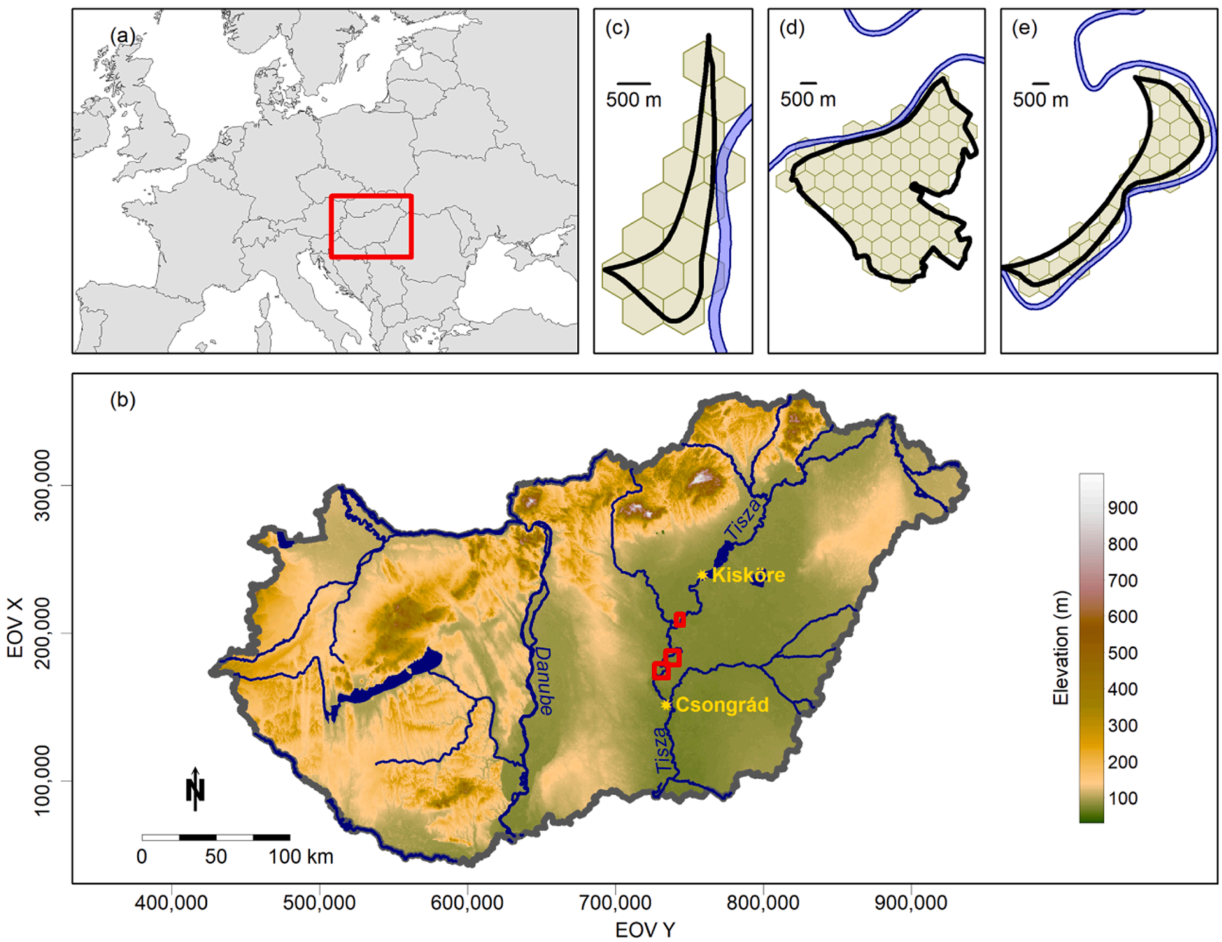

Fig. 1. Location of Hungary within Europe (a) and of the study sites within Hungary (b). The colouring corresponds to elevation. Hydrological modelling was applied to the section of Tisza between the towns of Kisköre and Csongrád, which are shown on the map with asterisks. Maps of the study sites (Fokorúpuszta, Tiszaföldvár, and Tiszakécske), are shown in subfigures (c), (d), (e), respectively. The outline is drawn around the floodplain area to be added to the active floodplain. The hexagonal grid served as spatial units of the analyses.

by *Quercus robur*, *Fraxinus angustifolia*, and *Ulmus laevis* together) are present where the width of the active floodplain allows or sometimes outsides as remnants (Bölöni et al., 2008). The most common wetlands are reed (*Phragmites australis*) communities and sedge meadows (with *Carex riparia* and *C. acutiformis*), which can be present both inside the active floodplain and behind the embankments depending on local water conditions (Molnár et al., 2008).

The drawbacks of the narrow active floodplain along the Tisza have been recognised (Lóczy et al., 2009, Kiss et al., 2021). Therefore, the Middle Tisza Water Directorate made plans to widen the active floodplain by embankment removal and/or relocation at three different sites. This plan provided opportunity for the joint modelling of hydrological consequences and vegetation outcome of river floodplain widenings.

The three study sites involved in the research were at Fokorúpuszta (which is part of the town of Besenyszög), Tiszaföldvár, and

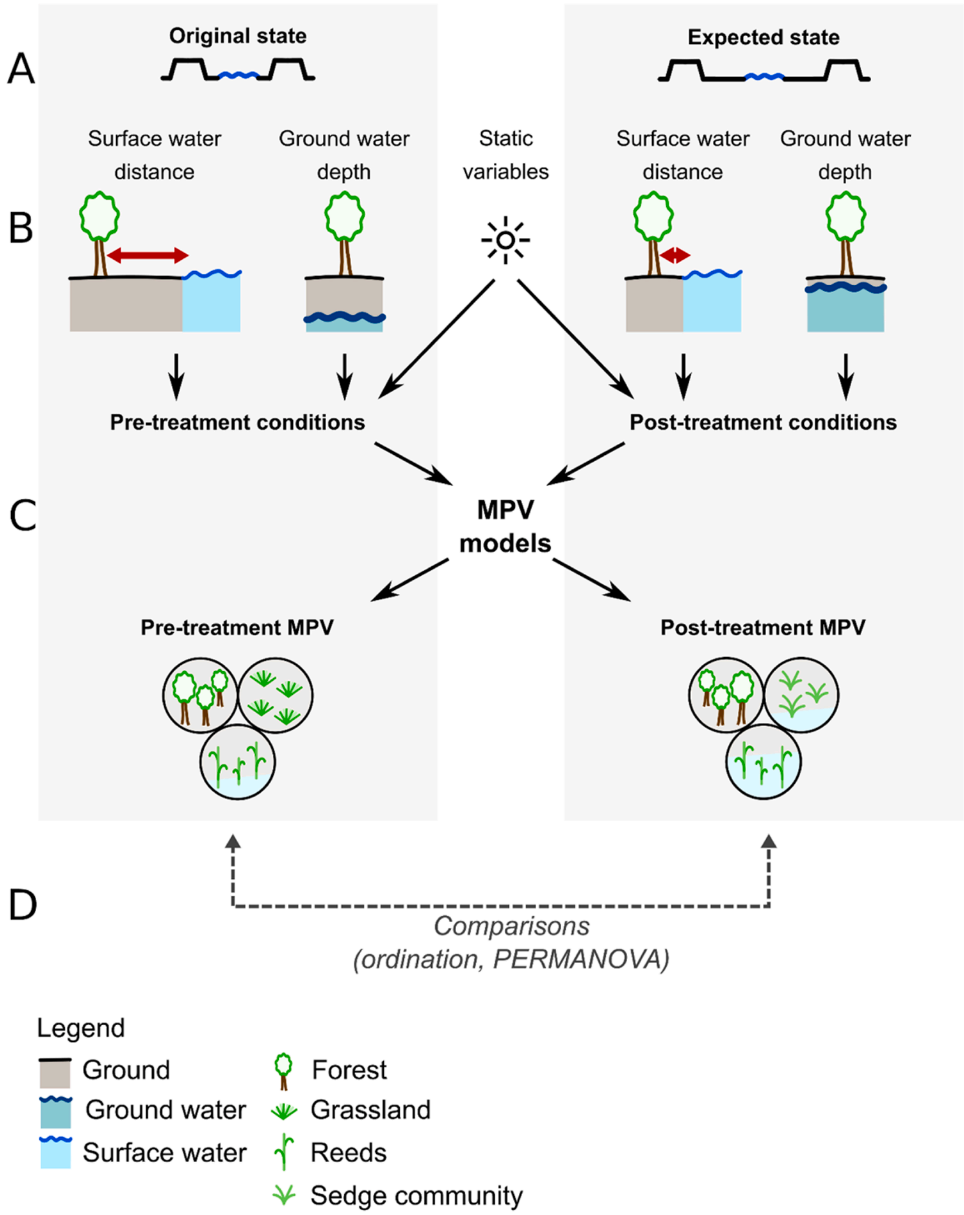

Fig. 2. Modelling workflow of the study. We compared vegetation predictions for two states of the study sites situated along the Tisza river. The regulated, original state (pre-treatment) and an expected state that would result from river floodplain widening (post-treatment). The modelling steps are the following: A) Hydrological modelling of the water conditions. B) assessment of values of water-related variables before and after widening. This includes the assessment of distance from the water body and distance to groundwater from the surface before and after the widening. C) Application of MPV models to the environmental conditions in both states. D) Comparison of vegetation conditions and identification of expected changes under the planned river floodplain widening interventions. Pictograms of vegetation types demonstrate that MPV represents potential vegetation as a distribution and this distribution is expected to change with the hydrological interventions.

Tiszakécske (Fig. 1).

At each site, the goal of the planned hydrological intervention reflected in the hydrological models was the widening of the active floodplain. In each case, this was modelled according to general practice: opening the current embankment towards additional areas along the river. In two cases (Fokorúpuszta, Tiszakécske), the modelled river floodplain widening includes the establishment of embankments farther from the river than the previous ones were situated. The outline of the study sites reflects these new embankments. At Tiszaföldvár, the presence of a natural bench (elevation) in the terrain at the outer edge of the study site would act as a natural embankment after opening the original one. For each site, we designate the original state as "pre-treatment" and the modelled outcome of hydrological interventions as "post-treatment" state further on.

The river floodplain widening has already been carried out at Fokorúpuszta. However, the time elapsed since the completion of the project has not been sufficient for the vegetation to stabilise and to serve as a possible mean of validation. In Fokorúpuszta, the pre-treatment condition was characterised by flat terrain with mostly dry channel beds leading occasional excess water to the Tisza. Along the channels, large swaths were covered with successional communities: bush and small fragments of willow-poplar gallery forest. These were mostly eliminated during the floodplain widening. In the post-treatment phase so far, ruderal vegetation has developed, and this is expected to undergo further succession.

At the Tiszakécske site, the embankments run very close to the river. A strip of willow-poplar forests occupies the space between the embankment and the riverbed. Outside the embankment, agricultural land dominates the landscape with occasional wetland (mostly reeds) patches interspersed.

In Tiszaföldvár, the embankment also runs close to the river, and thus current wetlands are confined to a strip along the river. The remainder of the currently non-flooded area harbours saline steppes as actual vegetation. There are parts of the planned floodplain that are currently used as agricultural land, but saline grasslands are also present in great diversity and in good natural condition. These have been designated as part of a protected area.

2.2. Modelling workflow

Assessment of vegetation outcome of river floodplain widening was accomplished by a workflow consisting of four stages (Fig. 2). A) Applying a hydrodynamic model to assess river dynamics, B) assessing values of water-related variables including distance to river and groundwater depth model, C) applying the MPV models to the pre-treatment and post-treatment environmental conditions represented by the updated variables, D) comparison of pre- and post-treatment potential vegetation by ordination and PERMANOVA.

2.3. Hydrodynamic modelling

Hydrodynamic modelling was applied to assess the impact of river floodplain widening on the hydrology of the river (e.g. flood peak reduction, changes in run-off conditions). We applied the HEC-RAS modelling software of the Hydrologic Engineering Center (HEC) of the US Army Corps of Engineers. The program has been used successfully for one- and two-dimensional modelling in the United States of America for all major rivers (Brunner, 2016). It has also been used for the Tisza River in Hungary already (Vizi et al., 2018).

The model was calibrated based on the highest ever observed flood in 2000 on an approximately 156 km long river section of the Tisza from Kisköre (402 river km) to Csongrád (246 river km). Flow discharge measurements for the 2000 flood were available at Kisköre and at a middle part of the modelled river section: Szolnok (337,5 river km). The 2000 flood event corresponds to a flood event with 100-year return, thus the observations corresponding to that event supplied the parameters for a 100-year return period flood. Floods with shorter return period received parameters adjusted to the expected lower severity as deduced from this major flood event. Parametrisation was carried out relying on the current active floodplain with the original embankments, as the actual flood event only affected that area. For each study site, the opening of the current embankment on 50 m length was modelled together with the placement of new embankments at the farther edge of the study sites (in Tiszaföldvár, this coincides with the natural bench, so would not need actual embankment to be built). The 50 m opening was chosen to reflect the actual practice of river floodplain widenings in the region, so as to make the vegetation outcome assessment relevant to conservation applications. The expected severity of floods was modelled at three levels: corresponding to floods returning every 2, 5, and 10 years (HQ2, HQ5, and HQ10, respectively).

We had used data from two water gauge stations to assess the precision of the model outcomes: Martfű, and Tiszaug. These are close to the Tiszaföldvár and Tiszakécske study sites, respectively. The average difference between the computed and the observed data was 0–10 cm at each control point, which indicates acceptable model accuracy.

The roughness of the newly widened floodplain in the model was set identical to the present after the following considerations. In the current active floodplain, the vegetation is already quite dense but also may be subject to change (Vizi and Právetz, 2020). In our case, hydrodynamic models also have to account for the full range of possibly self-sustainable vegetation types represented by MPV. Therefore, instead of trying to adjust to vegetation expectations not informed by MPV yet (as it cannot be available before the hydrological modelling), we relied on roughness represented by the current land cover. Current land use is most intensive in Tiszakécske outside the river embankment, while elsewhere the landscape structure (i.e. forested/non-forested, density) was not very different from the structure of spontaneously developing vegetation. To assess the importance of this difference, we also calculated the models using a scenario of natural vegetation development for Tiszakécske. The difference regarding river dynamics was negligible, which supported our decision to work uniformly with roughness corresponding to existing land cover. The roughness factor assigned to land use categories was determined on the basis of the prescriptions of the Hungarian standard, as well as on the basis of values applied by HEC-RAS and proposed by Chow (1959).

2.4. MPV models

The analysis relies on the pre-treatment and post-treatment, i.e. current and expected potential vegetation distribution of the sites. Potential natural vegetation (PNV) distribution was modelled in the multiple potential natural vegetation (MPNV) framework (Somodi et al., 2017; Somodi et al. 2024). Potential replacement vegetation (PRV) was modelled in the same way as PNV and the two were unified as the multiple potential vegetation estimate ('MPV', sensu Konrád et al., 2022). Accordingly, the MPV of Hungary incorporates 39 vegetation types as PNV and 8 vegetation types as PRV. 19 vegetation types of these were identified as potentially present either in the pre-treatment or post-treatment situations within the study areas (Table S1.1).

MPV models were trained in previous research (Somodi et al., 2017, Somodi et al. under review). In that process, presence/absence data of vegetation types were derived from the Hungarian Actual Habitat Database (MÉTA; www.novenyzetiterkep.hu/english/node/70; Molnár et al., 2007; Horváth et al., 2008). The database was compiled as a result of an exhaustive field survey of the (semi)natural vegetation of Hungary between 2003 and 2006. It contains vegetation data in a ca. 700 m hexagonal grid covering the country (hereinafter: MÉTA grid). The same grid was used throughout vegetation modelling and in the current study. Explanatory variables for the MPV models were calculated from datasets on soil (Pásztor et al., 2015), hydrology, topography (USGS, 2004) and climate. All the non-climatic explanatory variables were aggregated or extracted to the centre of hexagons of the MÉTA grid. Climate data for the model training represent the period between 1971 and 2000. These were acquired from the CarpatClim-Hu database (Szalai et al., 2013) in daily temporal and 0.1° (approx. 10 km) horizontal resolution. After aggregating the climate data to monthly variables averaged over the 30-year period, they were statistically downscaled to the resolution of the MÉTA grid through regression kriging. This yielded 68 candidate explanatory variables for the MPV model. This initial set of explanatory variables was limited to ensure maximum pairwise Pearson correlation of 0.7, Variance Inflation Factor (VIF) of 10, and condition number (CN) of 20 (Dormann et al., 2013). Table 1 summarises the 21 explanatory variables resulting from this process.

MPV models were trained at the resolution of the MÉTA grid for the complete area of Hungary, and they were done so separately for each of the vegetation types. Boosted Regression Trees (BRT; a.k.a. Gradient Boosting Model, GBM; Friedman et al., 2000; Friedman, 2002; Schapire, 2003) approach was used to construct the models following the optimization process described by Elith et al. (2008). BRT is reported to be a robust and flexible modelling approach with outstanding predictive power (Elith et al., 2006; Bühlmann and Hothorn, 2007; Velásquez-Tibatá et al. 2016). Before training the models, MÉTA hexagons without any recognisable (semi)natural vegetation were removed. Then, the remaining data (36.46% of the country) were divided into equal-sized training and evaluation sets by random sampling with prevalence stratification. This was done in order to evaluate the performance of the model in predictions to the pre-treatment period.

Model performance was assessed on the evaluation dataset based on a widely applied (Mouton et al., 2010; Kaymak et al., 2012) goodness-of-fit measure, the Area Under the ROC Curve (AUC; Hanley and McNeil, 1982). AUC is between 0 and 1, where 1 indicates the perfect fit. The AUC of the individual models of the 19 vegetation types were within the range of 0.811–0.991 with a mean value of 0.940. The models performed excellently according to AUC (Swets, 1988).

The models predicted the probability of occurrence per vegetation type. The predictions were within the interval [0,1]. These raw probability values, however, are not directly comparable across vegetation types. In order to ensure comparability, raw predicted data interpreted on ratio scale were rescaled to a five-level ordinal scale (Somodi et al., 2017). Since the rescaling procedure was performed

Table 1
The 21 environmental variables used as input to the MPV models. The right column indicates those variables, which were recalculated for the post-treatment conditions due to floodplain widening influencing their values.

Environmental predictor	Potentially affected by river regulation modification
Isothermality (ratio of mean diurnal range and temperature annual range)	
Maximum temperature of warmest month	
Minimum temperature of the coldest month	
Precipitation of wettest quarter	
Precipitation of driest quarter	
Presence of carbonate bedrock within a hexagon	
Presence of volcanic acidic bedrock within a hexagon	
Presence of volcanic neutral bedrock within a hexagon	
Presence of volcanic alkaline bedrock within a hexagon	
Presence of siliciclastic sedimentary and pyroclastic bedrock within a hexagon	
Maximum of sand fraction ratio of the top (0–30 cm) soil layer within a hexagon	
Mean organic matter content within a hexagon	
Mean depth of groundwater level within a hexagon	×
Maximum of rooting depth within a hexagon	
Distance of the hexagon centroid to the closest river	×
Distance of the hexagon centroid to the closest stream	
Distance of the hexagon centroid to the closest canal	
Distance of the hexagon centroid to the closest lake	
Distance of the hexagon centroid to the closest non-built (natural) water body of any type (lake, river, stream)	×
Distance of the hexagon centroid to the closest water body of any type (lake, river, stream, canal)	×
Standard deviation of the Topographic Position Index (TPI) within a hexagon	

for each vegetation type separately, different thresholds were calculated for the rescaling of the vegetation types based on the presence/absence data. The interpretation of the values of the resulting ordinal scale is the following:

0 and 1: not potential;
2: fairly potential;
3: likely potential;
4: surely potential.

A decision has to be made in the case of each study and for each application at which level to consider certain vegetation as fully potential. For the current research, we merged ranks 0 and 1 to represent lack of potentiality according to our experience with MPV estimations (Török et al., 2018; Konrád et al., 2022; Konrád et al., 2023). Thus, these are designated as rank 1 further on.

2.5. Modified environmental characteristics of the prediction area

The planned and correspondingly modelled river floodplain widening would affect the potential vegetation by changing the water availability. Four of the 21 predictors used by our MPV models are potentially modified by water availability (Table 1).

As no hydrological model output was available that would directly specify post-treatment groundwater levels, we estimated these using correlative models for each site (Fig. 2B). In our MPV models, groundwater levels were represented by mean depth of ground water level within one hexagon, thus we aimed at updating this variable for post-treatment conditions so that the MPV predictions can be calculated for those conditions as well. We trained BRT models on a broader area surrounding the sites being studied so as to ensure sufficient input data to parametrise the models yielding groundwater levels. Because this model is highly empirical, it might reflect site-specific relationships.

We applied the following calculation steps:

1. Selection of all the hexagons per site of which more than half the area was covered by flood parameter estimates. These were used as training areas in the subsequent correlative models.
2. Flood duration and water depth corresponding to 2-, 5- and 10-year recurrent floods (HQ2, HQ5, HQ10 respectively) in the pre-treatment phase were extracted from the hydrological models to serve as covariates;
3. The known groundwater depth of the training hexagons in the pre-treatment phase was used as response variable. Flood duration and water depth of HQ2, HQ5 and HQ10 flood events were used as covariates. A BRT model was trained with 2000 trees of three levels, 0.00001 learning rate, normal distribution and 50% bag fraction to identify the relationship between the groundwater level and the covariates;
4. Relying on the trained BRT models and the post-treatment values of the covariates, expected post-treatment groundwater levels were predicted. This prediction was applied for all of the hexagons within the area of future active floodplain for each of the three sites. Pre-treatment and post-treatment groundwater values are presented in Supplementary Material S2.

   The previously trained (Somodi et al., 2017) MPV models were applied both to the pre- and post-treatment environmental conditions (Fig. 2C). MPV distribution was estimated for 14, 69, and 29 spatial units in Fokorúpuszta, Tiszaföldvár and Tiszakécske respectively (Fig. 1). These encompass the planned and existing floodplain together at each site.
5. Comparisons of pre- and post-treatment MPV

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To assess the effect of the treatment, statistical analyses were performed (Fig. 2D). First, in order to get a general overview, principal coordinate analysis (PCoA, Gower, 1966; 'vegan' package, Oksanen et al., 2019) was conducted for the MPV of all study sites. As the MPV prediction is measured on ordinal scale and therefore was rich in ties, the distance matrix required for PCoA was calculated based on Kendall's τ_B correlation coefficient transformed to the 0–1 range using the following formula (Eq. 1.) as in Konrád et al. (2022):

$$d = \sqrt[2]{0.5 - 0.5 * \tau_B} \quad (1)$$

Results of the PCoA were visualised on an ordination plot with each site colour-coded. To conduct a deeper assessment, we also conducted PCoA analysis for each location separately. Groupings according to two binary variables, i.e. treatment (pre/post-treatment) and side of the embankment (flooded/non-flooded) were projected onto ordination plots. If the embankment crossed a hexagon, side was assigned according to which side covered the larger area within the hexagon. The non-flooded side as a category was only present in the pre-treatment setting as embankments were scheduled to be removed or to be shifted to the farther edge of the study sites as treatment. Finally, the effect of groupings, i.e. treatment & side of the embankment, was tested using PERMANOVA ('vegan' package, Oksanen et al., 2019) per location. If explanatory variables (treatment, side of embankment) of PERMANOVA were significant, the separation of the groups formed by the combination of the two factors was tested using pairwise post-hoc test ('pairwiseAdonis', Martinez Arbizu, 2017) with p-value adjustment according to Holm (1979).

All analyses were done using R statistical software (R Core Team, 2020). Predictors were calculated using 'dismo' (Hijmans et al., 2020), 'exactextractr' (Baston, 2020), 'gbm' (Greenwell et al., 2020), 'gstat' (Pebesma, 2004; Gräler et al., 2016), 'raster' (Hijmans, 2020), 'sf' (Pebesma, 2018) and 'usdm' (Naimi et al., 2014). Spatial visualisation and GIS analyses were done using packages 'concaveman' (Gombin et al., 2020), 'ggplot2' (Wickham, 2009), 'raster' (Hijmans, 2020), 'scatterpie' (Yu, 2019), 'sf' (Pebesma, 2018) and 'sp' (Pebesma and Bivand, 2005; Bivand et al., 2013), 'vegan' (Oksanen et al., 2019).

3. Results

The most apparent predicted changes in the potential distribution of vegetation types (Supplementary Material S3, S4) varied from site to site in response to the planned river floodplain widening. As identified by applying MPV models to pre-treatment conditions, pre-treatment potential vegetation was mainly characterised by herbaceous wetland types (e.g. reeds) and willow-poplar forests at Fokorúpuszta. These vegetation types were also coinciding with the patches of vegetation that existed there. However, there was also potential for grassland vegetation for the most part divided equally between saline and non-saline grassland vegetation. Even steppe forests were present in the MPV distribution, i.e. there were locations within the study area, where they could have survived under the pre-treatment conditions(Fig. S4.1). Dry grasslands and steppe forests were, however, not actually present. The potentiality for dry grasslands and steppe forests (e.g. H5a, M3) was predicted to possess the same potentiality rank after floodplain widening, while the potentiality of wet habitats, particularly that of willow-poplar gallery forests (J3_J4), wet meadows (D34) and sedge communities (B5) increased. In Tiszaföldvár, the actual wetland vegetation along the current riverbed coincides with the pre-treatment potential. Additionally, the models also predicted potential for wetlands in the northeastern area on the non-flooded side of the embankments in place of current arable fields before floodplain widening already (Fig. S4.2). Compared to these pre-treatment conditions, changes in response to river floodplain widening are expected to be more intensive close to the river according to model outcomes. Farther from the river, the existing saline character is expected to change little, even though the area would receive floods with river floodplain widening. However, as we near the river, models predict changes that reduce the potential of saline habitats (F1a, F2, F4, M3), parallel to the increase in the potentiality of willow-poplar gallery forests (J3_J4) and tall herb vegetation (D6). In the area closest to the river, the model also predicts wet meadows (D34) and hardwood gallery forests (J6) for the post-treatment conditions.

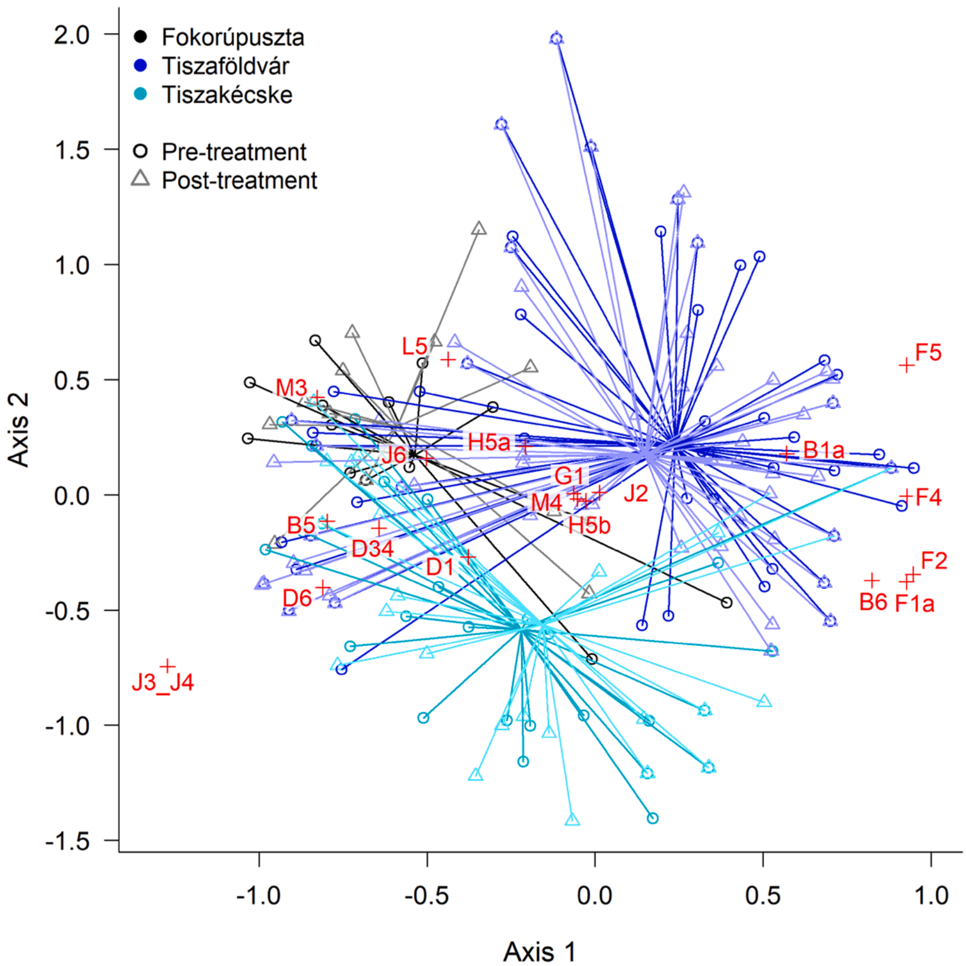

Fig. 3. PCoA of spatial units (hexagons) of all sites. The first axis corresponds to increasing salinity along increasing values. Each site is individually colour-coded. Pre-and post-treatment is primarily distinguished by the shape of the symbol: circles correspond to pre-treatment, triangles to post-treatment. However, post-treatment symbols also receive a lighter version of the site colour. Lines are drawn between the group centroids and the specific sample unit using the colour corresponding to the site. One group corresponds to one site in one state, i.e. pre- or post-treatment. For vegetation type names see Table S1.1.

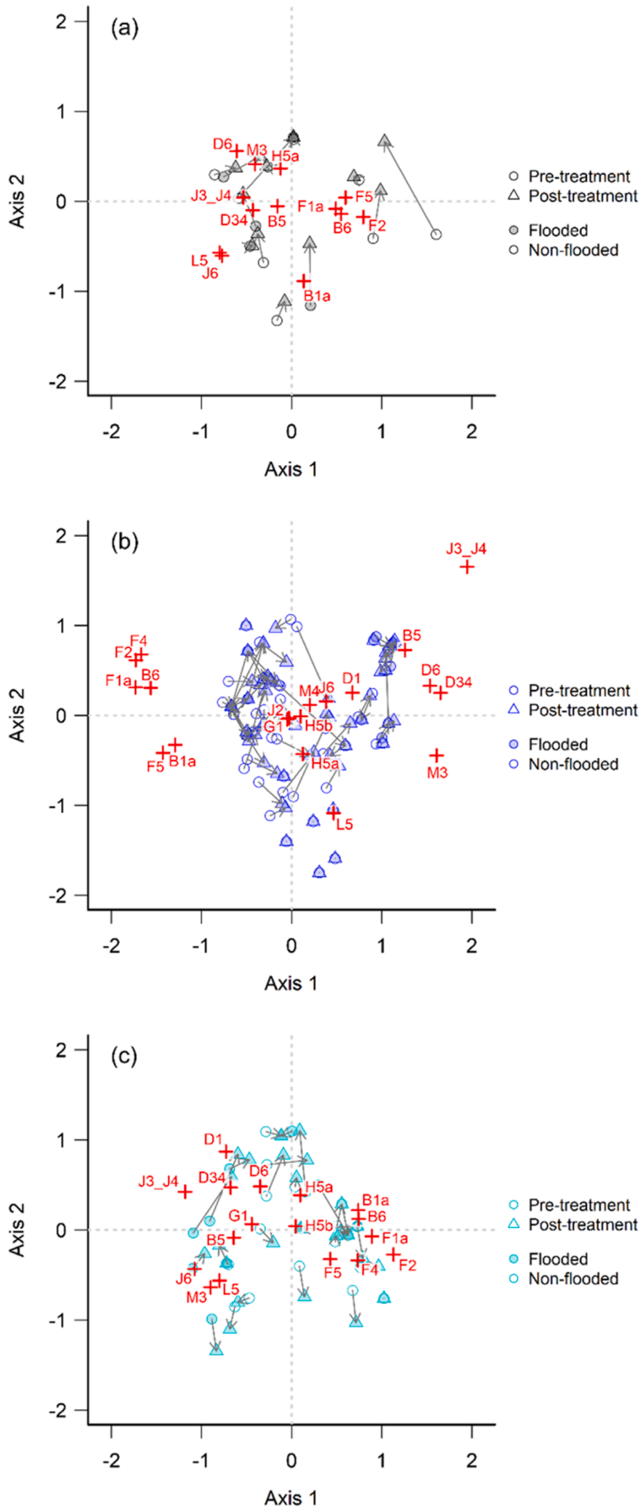

Fig. 4. PCoA of individual sites. (a) Fokorúpuszta, (b) Tiszaföldvár, (c) Tiszakécske. Arrows point towards the position of the same hexagon in the altered conditions. Full circles depict flooded, open circles non-flooded embankment side. Site colouring is retained for comparability with Fig. 3. For vegetation type codes see Table S1.1.

At Tiszakécske, pre-treatment potential vegetation is identified by the model as a mixture of wetland and dry vegetation, including forests and herbaceous types as well as saline and non-saline types (Fig. S4.3). However, the potentiality of willow-poplar forests is predicted to decrease here with the treatment even for most of the hexagons closest to the river. At the same time, the potentiality of dry and saline grasslands (H5a and F4-F5 respectively) is predicted to increase.

PCoA analysis helped identify the tendencies in different hexagons and display them in one picture. In the joint analysis of the sites, the first two axes explained 42% and 9% of variance, respectively. Thus, the first axis appears to have an important role in distinguishing between the sites. Considering the position of potentially surviving habitats in the ordination space (Fig. 3), this axis stretches from the group of wet or mesic meadows and forests (D34, B5, J3_4) to the groups of saline grasslands (F1a, F2, F3, F5) complemented by reeds (B1a) that also tolerates saline conditions well. Also, the shift in conditions along this axis is most expressed. However, the direction of shift of group centroids differs for different sites. Fokorúpuszta and Tiszaföldvár shift away from the saline conditions, while Tiszakécske shifts towards them.

PCoAs performed separately for the individual sites provided further detail on the direction and nature of the expected changes (Fig. 4.). The first two axes explained at least 48% of the variance for each of the sites. Additionally, a pronounced decrease in the explained variance appeared after the first two axes. Thus, we interpreted these two axes in accordance with existing recommendations (Podani, 2000, Bakker, 2023).

For Fokorúpuszta, the PERMANOVA analysis did not reveal significant divergence. One of the reasons might be the relatively small sample size ($n = 14$). Another reason, however, could be that the terrain at this site is even, thus pre- and post-treatment conditions might naturally be closer to each other than in the case of the other sites. However, the individual PCoA of Fokorúpuszta (Fig. 4a) still reveals discernible trends. The explained variances of the first two axes are 32% and 18%. The first axis can be linked with the same gradient as in the case of the joint ordination of sites. Additionally, axis 2 appears to represent a tolerance gradient to permanent wet conditions for the non-saline habitats. Closed hardwood forests (L5, J6) appear at the bottom, while willow-poplar gallery forests (J3_J4) appear in the middle and mesic to wet meadows appear at the top. Arrows are typically aligned with axis 2, showing a shift towards more flood-tolerant habitats. The appearance of reeds (B1a) at the bottom appears to contradict this interpretation. The most probable reason for this placement is that the willow-poplar forests are expected to replace them. The shifts shown by the arrows are consistent at this site. The hexagons originally flooded and not flooded are both expected to undergo similar changes.

The PERMANOVA analysis showed significant divergence at the other two sites, with both explanatory variables significantly contributing to the differences (Supplementary Material S5). At these two sites, post hoc tests underlined the differences between the flooded and non-flooded sides of the embankments and their response to floodplain widening (Table 2, Table 3).

According to the post hoc tests, the nature of changes after an expected floodplain widening differed for both individual ordinations. For both sites, there is a significant difference between the MPV composition of the two sides of the embankment given the pre-treatment condition (pre-treatment flooded vs non-flooded) and the expected MPV composition of flooded sites before and after the intervention. In the case of Tiszaföldvár, the difference between pre-treatment non-flooded hexagons that would become part of the active floodplain from post-treatment flooded ones was marginally significant also.

The ordination helps to identify the nature of the expected changes: the first two axes explained 47% and 10% of the variance for Tiszaföldvár. The first axis was again the salinity gradient, the shift away from saline habitats is more typical, but arrows are longer along the other axis, i.e. changes are expected along that gradient rather. Predicted shifts appear in both directions along axis 2. For hexagons already charcterised by saline habitats in the pre-treatment phase this shift appears towards drier variant, while for hexagons characterised by non-saline habitats (also closer to the river, see Fig. S4.2) this shift appears towards wetter habitats.

In the ordination of Tiszakécske the first axis explained 37%, and the second 11% of variation. The first axis shows the same gradient as elsewhere: a salinity gradient. Changes are expected along this gradient as the joint ordination also showed. Thus the post-treatment MPV distribution contains more saline habitats after river floodplain widening. However, the individual ordination makes another tendency is also apparent. Many of the arrows also show an expected change along the second axis. The second axis here corresponds to a wetness gradient. For both saline and non-saline habitats, regularly flooded habitats, or those tolerating standing water, are at the top of the chart (wetlands /D1, D6/, willow-poplar gallery forests /J3_J4/ and saline marshes /B6/, respectively;), while habitats without long-term standing water tolerance are at the bottom (mesic forests /M3, L5/ and saline steppes respectively /F2, F4, F5/). Thus, the direrer vegetation types take a higher share in the MPV composition of individual hexagons after river floodplain widening.

4. Discussion

As opposed to the cases listed in Conservation Evidence (Conservation Evidence database, 2023), the MPV modelling revealed that not all of the sites can be expected to be suitable for wetland vegetation after river floodplain widening. On the one hand, different sites

Table 2
Results of the post hoc tests following the PERMANOVA for the Tiszaföldvár site. “pretr.” refers to pre-treatment conditions, “posttr.” refers to post-treatment state.

	Df	Sum of Squares	R^2	F	adj. p-value
pretr. flooded vs. pretr. non-flooded	1	0.297	0.22	18.359	0.003
pretr. flooded vs. posttr. flooded	1	0.205	0.13	11.125	0.003
pretr. non-flooded vs. posttr. flooded	1	0.052	0.02	2.797	0.085

Table 3
Results of the post hoc tests following the PERMANOVA for the Tiszakécske site. "pretr." refers to pre-treatment conditions, "posttr." refers to post-treatment state.

	Df	Sum of Squares	R^2	F	adj. p-value
pretr. flooded vs. pretr. non-flooded	1	0.103	0.270	9.980	0.003
pretr. flooded vs. posttr. flooded	1	0.067	0.144	5.727	0.008
pretr. non-flooded vs. posttr. flooded	1	0.014	0.024	1.228	0.291

showed different reactions along the salinity axis in response to the intervention. On the other hand, there was even an example of the site potential becoming more favourable for dry vegetation than wetlands.

In general, the most striking consequence of removing or shifting the embankment farther from the river is the recurrent incidence of flooding within the new floodplain (Janssen et al., 2021; Schindler et al., 2022). It is expected that this flooding will alter soil conditions and also wash out salts even if present in the soil of the specific region. Inland saline habitats are often characterised by standng water during colder periods of the year (Boros et al., 2023; Bölöni et al., 2011). Standing water can appear on the surface or as elevated groundwater. Thus, recurrent floods would prevent their development. Indeed, as expected, two of the sites displayed an expected shift away from the saline conditions given floodplain widening, in both the joint and individual ordinations. There was, however, variation in how these two sites reacted. At one of the sites, Fokorúpuszta, the expected changes follow the intuitive and general pattern (Conservation Evidence database, 2023): the potential vegetation of the whole area would become wetter and more flood-tolerant under floodplain widening. E.g. willow-poplar forests would become more potential. In the larger study area, Tiszaföldvár, changes in response to a floodplain widening are predicted to diverge according to spatial position as the PERMANOVA and the maps of MPV distribution revealed. Furthermore, the ordinations show that the potential vegetation of one group of hexagons would become wetter and more flood-tolerant, while the dry saline character would be preserved in the MPV of the other group of hexagons. Interpreting this pattern based on the three sources together, we can identify that floodplain widening would affect the hexagons closer to the river more towards becoming suitable for wetland vegeation. At the same time, few floods would reach the farther parts of the new active floodplain, which thus would develop differently. Considering that the area farther from the river harbors protected saline grasslands, it is a conservation benefit that their potential would not be decreased by their inclusion into the active floodplain.

As opposed to the differences between pre-treatment and post-treatment MPVs of Fokorúpuszta and Tiszaföldvár that align well with expectations, unexpected patterns are predicted for Tiszakécske.

First, as the individual ordination of the spatial units at Tiszakécske shows, the complete area is expected to move towards drier MPV composition given floodplain widening. Furthermore, the difference of pre- and post-treatment MPV is signficant exactly for those hexagons that represent the active floodplain in the pre-treatment condition. Considering that these hexagons are part of the floodplain both in the pre-treatment and post-treatment scenario it is an unexpected pattern.

Second, considering the expected outwashing of salts by floods, the most unexpected change that would occur, is the increase in the potentiality of saline vegetation. Indeed, there have been warnings that the outcome of river re-naturalisation can be variable (Hein et al., 2016; Kail et al., 2015; Whipple and Viers, 2021). However, it is noteworthy that in our case all sites are situated within the same biogeographic region, along the same river and at similar topographic situations. Besides the variation itself, it is particularly unexpected, that the resulting conditions may favour even drier and more saline habitats than did the starting conditions. However, our case is actually similar to that of Janssen et al. (2021), who also perceived that river embankment can hold up water in a lowland setting and thus sustain wetter vegetation on the non-flooded side than normally would be expected after embankment removal. Saline soil conditions are widespread along the Tisza river (Sahbeni and Székely, 2022), thus it is reasonable that the reduction in water availability would shift the environment towards saline habitats and/or towards other dry grasslands. River floodplain widening would alter the water flow and would allow all water to run down to the river from the new active floodplain. This change in hydrography is then reflected in the expected change of the vegetation potential as well. This topography is, however, far from apparent. The Tisza River flows through the Great Hungarian Plain without much apparent topographic variation (Sahbeni and Székely, 2022). The river bank at this location can be considered "steep" only in comparison to the otherwise flat landscape. Thus, if flood and vegetation modelling were not done in conjunction with one another, it would be difficult — if not impossible — to predict the overall effect of floodplain widening here. Our findings are in concert with the literature on the subject, which also stresses that the environmental background, including topography, is strongly determinative of the outcome (e.g. Ochs et al., 2020; Theodoropoulos et al., 2020). Our three sites are all situated in the middle segment of the river and are relatively close to each other. We know that minor topographic variation can have significant effects in lowlands (Rabl et al., 2020; Deák et al., 2021; Dítě et al., 2021), but without close examination and modelling, one might not expect such great differences in the outcome of a floodplain widening. A key issue is that minor topographic features act in concert with other environmental factors. Thus, potential vegetation modelling can be of particular help, because it examines the landscape not from a human point of view, but through the "eye" of the vegetation. That is, it explores the environmental combinations that impact vegetation suitability (Somodi et al., 2021). This also reinforces the findinds of the significance of vegetation modelling in assessing river re-naturalisation outcomes (dos Reis Oliveira et al., 2020, Ochs et al., 2020).

Nowadays, river restoration is highly encouraged. At the same time, it requires a sacrifice on the part of those who use the land along the rivers (Garcia et al., 2020; Johnson et al., 2020; Han et al., 2023). In Hungary, river floodplain widening typically requires the forfeit of fertile agricultural land. Therefore, negotiations towards river floodplain widening involve local stakeholders (Hein et al., 2016). Due to some of the effects of climate change that have already been acknowledged by the stakeholders, negotiations are slowly becoming easier (similarly to Bogdan et al., 2022). However, if the outcome of the restoration wildly differs from what the public expects (e.g. salinization instead of wetland development) a negative perception of the restoration process may arise, and this could hamper negotiations later on. Knowledge of potential vegetation can help avoid this in two ways: if financial/resource constraints limit the extent of floodplain restoration, such projects can be focused on an area where commonly expected vegetation types, typically wetlands are most likely to flourish. If the target locations are constrained by the demands and expectations of property owners, expectations regarding the floodplain widening can be fine-tuned to produce the desired outcome, e.g. by stressing the desirability of saline habitat restoration (e.g. Lubińska-Mielińska et al., 2022), as well as that of the rich avifauna to be expected on occasionally flooded saline habitats (Zadereev et al., 2020; McDonald et al., 2022). In addition to the advantages that the knowledge of potential vegetation offers in and of itself, multiple potential vegetation assessment further facilitates planning by providing a probability distribution of potential vegetation types (Somodi et al., 2017). This then allows for adaptation to societal and/or technical constraints within the given range of sustainable vegetation (Török et al., 2018).

5. Conclusion

The use of MPV modelling shed light on the variability of expected outcomes of river floodplain widening regarding vegetation. These outcomes included the potentiality for vegetation types that are not typically considered when contemplating river floodplain widening. Consequently, the application of MPV proved valuable in identifying areas along the river that are likely to support specific types of vegetation. This also means avoiding failure to meet restoration and conservation targets due to unexpected course of vegetation development. On the other hand, if the river fragment to be widened is predetermined, adding MPV modelling to hydrological modelling can assist forming expectations regarding the vegetation outcome. This can facilitate sustainable active restoration as well, by directing restoration efforts towards vegetation types that can be self-sustainable at the newly widened river floodplain.

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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. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2024.e02859.

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