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ORIGINAL PAPER

Floodplains along the Danube River evaluated with the Floodplain Evaluation Matrix (FEM) determining their importance for flood protection, ecology, and socio-economics

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Abstract

This study presents a method to investigate the influence of active floodplains on flood protection, ecology, and socio-economics. We used and further developed the Floodplain Evaluation Matrix (FEM) to systematically assess the Danube River, known as the most international river worldwide. The study also aims to develop a method applicable to other large rivers, taking into account different data availability and research objectives. Hydrological, hydraulic, ecological, and socio-economic parameters were assessed to address the multiple functions and services of floodplains. The evaluation showed that some active floodplains significantly reduce the impact of a 100-year flood event, with relative flood peak reductions by up to 17% and decelerating the flood wave by up to 41.5 h. While other floodplains may not have a noticeable impact on hydrological or hydraulic parameters, they play a crucial role in preserving biodiversity by providing essential habitats for protected species. We introduced an approach to assess whether a floodplain should be preserved and to categorize the restoration demand as low, medium, or high. Our findings indicate a universal need for preservation and restoration measures across all floodplains, with 81% demonstrating a high or medium demand for restoration. Preservation and restoration of floodplains are integral parts of achieving more sustainable floodplain management for each river. Applying the FEM to other large rivers could create a basis for sustainable decision-making, increase awareness of the multiple benefits of floodplains, and foster the implementation of preservation and restoration measures.

Keywords Floodplain management · Preservation · Restoration · Flood risk management · Hydrodynamic modelling

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1 Introduction

Floodplains are fundamental parts of natural river systems (Funk et al. 2019; Knox et al. 2022; Meli et al. 2014) and provide vital ecosystem services (Costanza et al. 1997; Petsch et al. 2023; Wantzen et al. 2016). When a floodplain is degraded, interrupted, or impaired, valuable and crucial ecosystems that are home to a large number of both aquatic and terrestrial species are lost (Costanza et al. 1997). Floodplains are, therefore, often referred to as biodiversity hotspots (Schindler et al. 2016). At multiple scales, biochemical processes in floodplains are dynamically intertwined and controlled by multidimensional interactions of flow, nutrients, and sediments (Gordon et al. 2020; Robinson et al. 2002; Schindler et al. 2014; Villa and Bernal 2018). Moreover, the public has long since discovered floodplains for recreational purposes and has begun to acknowledge their cultural value (Petsch et al. 2023; Stammel et al. 2021).

Intact floodplains rely on hydraulic connectivity and overbank flows due to flood events. Despite the essential importance of floodplains for natural flood retention and flood risk mitigation (Opperman et al. 2009; Schober et al. 2020; Serra-Llobet et al. 2022) floodplains have been impaired since the beginning of civilization, resulting in the loss or degradation of about 90% of former floodplains in North America and Europe. A new global data set reveals a floodplain loss of ~600,000 km^2 between 1992 and 2019 (Rajib et al. 2023). At our study site, the Danube, a recent study (Eder et al. 2022a, b) and earlier reports (Hein et al. 2016; Schwarz 2010) confirmed a loss of 79% of former floodplains.

The consequences of the steady decrease in floodplains are evident on several levels. From an ecological point of view, the loss of floodplains or their isolation from the river results in the disappearance or severe degradation of the habitats for flora and fauna that live in them (Di Baldassarre et al. 2013, 2018; Opperman et al. 2009). The decline in floodplains, however, also leads to a significant increase in flood peaks and an acceleration of flood runoff (Habersack et al. 2015; Helton et al. 2014; Kundzewicz and Menzel 2005). In the Danube River, flood wave travel time has been significantly reduced compared to the nineteenth century (Blöschl et al. 2013).

The loss of floodplains is discussed as a key reason for the increase in extreme flood events on rivers. Due to changing climatic conditions, conventional flood protection, such as structural measures, could fail more frequently in the future, putting the area behind the protective structures, which is characterized by a high level of development and thus vulnerability, at risk (Di Baldassarre et al. 2018; Jüpner 2018; Ludy and Kondolf 2012; Schober et al. 2013).

Despite efforts to promote floodplain preservation and restoration, many floodplains are under pressure due to economic development (Steffen et al. 2007; Vörösmarty et al. 2010) and remain ecologically impaired or disconnected. The prevailing economic pressure, societal changes, opposed interest, and human-related impacts on our ecosystem pose a great challenge to floodplain preservation, restoration, and sustainable river management (Auerswald et al. 2019; Hein et al. 2016; Klijn et al. 2018).

In order to overcome barriers, facilitate conservation progress, and find win–win solutions among stakeholders, the floodplain evaluation matrix (FEM) is used as an approach to systematically quantify the influence of floodplains on flood risk reduction, ecology, and socio-economics. Floodplain evaluation is an integral part of flood risk analysis and aims to understand the characteristics, features, and dynamics of a floodplain by studying the topography, hydrology, geomorphology, vegetation, land use, and other factors. The field of flood risk analysis and assessment has seen a substantial increase in publications over the past decade, indicating the ongoing need for further research (Díez-Herrero and Garrote 2020). Numerous studies (Cammerer and Thieken 2013; De Bruijn et al. 2008; Eder et al. 2022a, b; Elmer et al. 2012; Hall et al. 2005; Klijn et al. 2015; Kundzewicz et al. 2014; Linde et al. 2011; Winsemius et al. 2016) systematically address future developments, including population growth, increasing urbanization, and the potential impacts of climate change on flood discharge, in order to evaluate future flood risks. Floodplain evaluation studies (Abell et al. 2023; Karpack et al. 2020; Lininger and Polvi 2020; Rohde et al. 2006; Schober et al. 2020) often deal with human modifications to floodplains, their effects, and floodplain restoration. Following the objective that restoration should be attempted at the watershed scale (Bernhardt and Palmer 2011; Wohl et al. 2005), we aim to demonstrate the advantages of a comprehensive transdisciplinary floodplain assessment capable of delivering basin-wide water management information, resulting in recommendations for floodplain preservation and restoration. The evaluation of floodplains with a set of parameters can show the importance of the floodplains, leading to more preservation and restoration efforts. We further developed the FEM to address the outlined research questions at any river system:

- Why are active floodplains important from a perspective of flood protection, ecology, and socio-economics?
- How is the value of active floodplains distributed within a large river system, and what factors influence this distribution?
- Is the Floodplain Evaluation Matrix suitable and applicable to determine the importance of floodplains for an entire large river?
- Can the Floodplain Evaluation Matrix provide a basis for future floodplain management and promote floodplain preservation and restoration?

The method was first applied to the Danube River, known as the most international river worldwide. The application was done within the EU-funded "Danube Floodplain" project (https://www.interreg-danube.eu/approved-projects/danube-floodplain#! accessed on 12 November 2024) that aimed at enhancing international water management and flood risk prevention, focusing on floodplain management. A consortium of representatives from national water agencies, universities, research institutes and NGOs along the Danube River worked together in this project to develop and apply the methods presented in this paper.

2 Material and methods

2.1 Study area—Danube River

The Danube River Basin has an area of 800.000 km^2 and forms the second largest catchment in Europe. Located in the centre and the southeast of Europe, it includes territories of 19 riparian countries. It is regarded as the most international river basin in the world. A population of about 80 million people lives along the Danube and its tributaries (ICPDR 2011, 2015). The Danube River originates in the Black Forest Mountains in Germany and discharges into the Black Sea, covering a distance of 2857 km. The mean annual discharge of the Danube at the mouth is 6486 m^{3}s^{-1} (Sommerwerk et al. 2009). The basin is divided into three sub-regions (Upper, Middle, and Lower Danube) corresponding to a characteristic gradient and landscape features from source to delta. Rapid currents occur in the upper catchment, and alpine tributaries dominate the flow and sediment characteristics. In the middle and lower sub-regions, the Danube flows predominantly in a lowland landscape. The transport capacity has dropped after passing the Hungarian Gates Gorge, creating a series of riparian plains and islands. Downstream the confluence of the tributaries Drava, Tisza, and Sava it has gained size, and the flow rate has almost tripled. About 80 km upstream of the Black Sea, the Danube River splits up into three branches, forming a delta of about 6500 km^2 (ICPDR 2011).

2.2 Floodplain Evaluation Matrix (FEM)

The Floodplain Evaluation Matrix (FEM), developed by Habersack et al. (2015), is a holistic floodplain evaluation method that uses hydrological, hydraulic, ecological and socio-economy parameters to assess the multiple functions of a floodplain. The method's concept and framework were presented in Habersack et al. (2015). Schober et al. (2013) and Habersack & Schober (2020) applied the method to rivers reaches in Austria (Danube, Raab, and Inn) to evaluate the role of floodplains in reducing flood hazards using hydrological and hydraulic parameters. The FEM has a flexible design and can be adapted to research questions and project needs. Eder et al. (2022a, b) expanded the method for a future-oriented flood risk management and considered land use developments and climate-related changes in flood discharges.

We further developed and adapted the FEM in this study to apply the method to an entire large river for the first time, leading to a comprehensive and systematic evaluation of floodplains. Since the Danube River is an international river, we had to adapt the method to the data availability in each country and find parameters that were accepted and could be applied by the representatives of the different states. The adaptations were necessary to develop a schematic approach of the FEM that allows an application at any river according to the data availability and research objectives. We also introduced the novel concepts of "need for preservation" and "restoration demand", offering recommendations for floodplain preservation and restoration through commonly agreed parameters and thresholds established in collaboration with representatives from national water agencies, universities, research institutes, and NGOs from ten countries. The developed method consists of four consecutive steps, each of which is described in the following paragraphs. Figure 1 illustrates the developed approach in a flow chart.

2.2.1 Step I: data acquisition and analysis

The first step is a comprehensive acquisition and analysis of diverse data sets. The data basis is individual for each river. As subsequent steps rely on the availability and quality of the data, this step is crucial.

Hydrological and hydraulic data such as observed flood waves, measured water levels, and hydraulic models are necessary to calculate the mandatory parameter of the FEM (relative peak reduction, flood wave translation, and water level change). Furthermore, depending on the research objectives, additional data sets such as geospatial, ecological, and other relevant data may be gathered during this stage.

Fig. 1 Flow chart of the floodplain evaluation matrix (FEM). In step I., different data sets are collected and analyzed. The next two main steps (II. and III.) represent essential tasks leading to the first two FEM outputs: delineated floodplains and selected FEM parameters. In step IV, the first three tasks (1., 2., 3.) are mandatory, while all other tasks are optional, dependent on research questions or goals. In this study, all options were applied and led to results/outputs (1., 2., 3a., 3b., 3c., 4). The available data and selected tasks for this study are highlighted by the dotted rectangle, while optional data and tasks are presented in italics

2.2.2 Step II: delineating floodplains

The second step is a task to delineate floodplains based on available data and the chosen approach. Various methods exist in the literature for identifying active floodplains, including the consideration of inundation areas from flood events with specific recurrence intervals, examination of recent alluvial deposits, or utilizing ecological approaches to identify areas colonized by organisms adapted to flooding (Nanson and Croke 1992; Schwarz 2010; Tockner and Stanford 2002). The FEM provides the user the flexibility to select from these diverse methods found in the literature or use delineated floodplains from previous studies. The key requirement is to generate floodplains with clearly defined starting and ending points as the output of the delineation process.

2.2.3 Step III: selecting FEM parameters

The selection of FEM parameters depends on data availability and research goals. The mandatory FEM parameters are the relative peak reduction, flood wave translation, and water level change. This step provides the flexibility to include any additional parameter deemed necessary or valuable for addressing specific research questions. The chosen parameters are the output of this step. In Sects. 2.3.1–2.3.4, the mandatory FEM parameters are described along with additional ones.

2.2.4 Step IV: FEM application

In this step, hydrological and hydraulic scenarios are defined, the selected parameters are calculated, and optional tasks are performed based on the set research goals.

The first task is to define hydrological and hydraulic scenarios. It is mandatory to use a HQ_{100} at each floodplain, derived from observed data. Furthermore, it is advisable to include both steep and flat flood waves to assess the floodplain's sensitivity to varying hydrological conditions. Other hydrological scenarios can include flood waves with shorter or longer recurrence intervals, such as HQ_{30} and HQ_{1000}, or consider the impact of increased flood peaks due to climate change. All other hydrological scenarios, such as mean or bankfull discharge, can be defined in this step as well if they are necessary for the selected parameters.

When considering hydraulic scenarios, two are mandatory: simulating the entire existing floodplain with the current dyke heights and a pure river channel model, in which the floodplains are disconnected by dykes with unlimited height. Additionally, further scenarios may involve gradual reductions of the floodplain and adjustments in dyke heights, ranging from 25 to 75%.

The next task is to calculate the selected parameter by performing the necessary numerical simulations using the defined scenarios, the available models, and the chosen approaches. Afterwards, thresholds for different performance classes can be established to evaluate the performance of a floodplain for a certain parameter. This can involve defining various performance classes and implementing a point system, such as high (5 points), medium (3 points), or low (1 point). These performance classes can then be used to assess the "need for preservation" and determine the "restoration demand." For instance, one approach could be to decide whether a floodplain should be preserved based on whether it achieves a high-performance rating (5 points) for at least one parameter in the evaluation, indicating a "need for preservation." Following this, the "restoration demand" can be determined by categorizing floodplains into low, medium, or high restoration demand groups based on the total points received during the application of the FEM.

The last optional task consists of analyzing and comparing the results of floodplains in different river reaches or the entire basin to get an overview of the importance of the floodplains in different reaches.

The following outputs can be obtained if all optional tasks are applied:

1. Evaluated floodplains.
2. Performance classes for floodplains.
3. Ranked floodplains.
    a. Based on points.

b. Floodplains that need to be preserved
c. Restoration demand of floodplains.

4. Basin-wide analysis of floodplains

2.3 Floodplain Evaluation Matrix (FEM) parameters

2.3.1 Hydrological parameters

Hydraulic models are used to determine hydrological parameters by computing the flood wave transformation between in- and output hydrograph for each floodplain. Since the design discharge for flood protection measures mostly corresponds to a 100-year return period (HQ_{100}—medium frequency), it is necessary in the FEM to calculate the retention effects of each floodplain for such an event. Therefore, all input hydrographs had to have a peak discharge at the beginning of the floodplain that corresponded to a HQ_{100}. In general, the hydraulic models should be split into smaller models to represent a single floodplain with an in- and outflow section. This ensures that the peak of the inflow hydrograph corresponds to the HQ_{100} discharge and that only the effects of that floodplain are investigated.

2.3.1.1 Relative flood peak reduction—ΔQ_{rel} This parameter considers the effect of a floodplain on the peak of a flood wave. The difference between the peak of an in- and output hydrograph at the beginning, respectively at the end of a floodplain, results in the peak reduction ΔQ_{tot} ($m^3\ s^{-1}$) for the investigated floodplain. However, it is necessary to calculate the retention effect of the river channel to show only the effect of the floodplain on peak reduction. For calculating the peak reduction ΔQ_{RC} ($m^3\ s^{-1}$) of the river channel, "river channel" models, where the floodplains are disconnected from the river, are used. The floodplains can be disabled, or hypothetical dykes could be implemented that cannot be overtopped to simulate the loss of the floodplain areas. The same input hydrograph is used as for the calculation of ΔQ_{tot}. In Fig. 2, the in- and output hydrographs for the river channel model (ΔQ_{RC}, Δt_{RC}) and the hydraulically active floodplain (ΔQ_{tot}, Δt_{tot}) are visible. It is

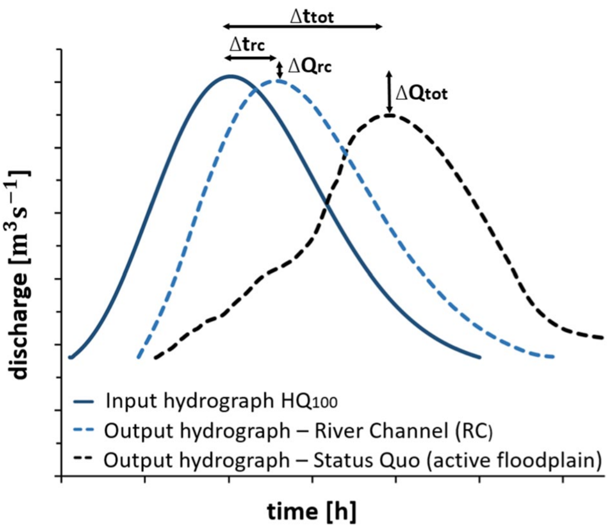


Fig. 2 The input hydrograph is the same for the river channel model and the current case where the floodplain is active. The blue-dotted line shows the output hydrograph for the river channel model. The black-dotted line represents the output hydrograph for the model where the floodplain is connected to the river. ΔQ_{tot}—flood peak reduction total (m^3s^{-1}); ΔQ_{RC}—flood peak reduction river channel model (m^3s^{-1}); Δt_{tot}—flood wave translation total (h); Δt_{RC}- flood wave translation river channel model (h)

shown that the retention effect of the floodplain is significant. In the absence of inundation areas, the peak reduction for the entire river reach would be close to zero. The flood wave translation would be reduced as well.

ΔQ_{RC} has to be subtracted from ΔQ_{tot} to demonstrate only the effect of the floodplain on the peak reduction ΔQ:

$$\Delta Q = \Delta Q_{tot} - \Delta Q_{RC} \left(m^3\ s^{-1} \right) \tag{1}$$

The relative peak reduction ΔQ_{rel} (%) is computed to allow a comparison of the peak reduction effect in different river reaches (Eq. 2). Q_{max} is the highest discharge value of the input flood wave, and $Q_{bankfull}$ is the discharge where the river starts overtopping its bank. To calculate the relative peak reduction ΔQ_{rel}, $Q_{bankfull}$ is subtracted from Q_{max} because the floodplain is not active until $Q_{bankfull}$ is reached.

$$\Delta Q_{rel} = \Delta Q / \left(Q_{max} - \Delta Q_{bankfull} \right) \times 100(\%) \tag{2}$$

2.3.1.2 Flood wave translation—Δt The flood wave translation is the second parameter required to investigate the process of wave attenuation and shows the deceleration of the flood wave through the floodplain. It is determined in a similar way as the peak reduction, by calculating the time difference Δt (h) between the occurrence of the out-/input hydrograph peak (see Fig. 2). The same hydrographs are used as for calculating the peak reduction. For demonstrating only the flood wave translation due to the floodplain, the following equation is used:

$$\Delta t = \Delta t_{tot} - \Delta t_{RC}(h) \tag{3}$$

2.3.2 Hydraulic parameter

2.3.2.1 Water level change—Δh The hydraulic models were also used to illustrate the effects of a total loss of a floodplain on the water levels. The "river channel", is a case where the river is fully embanked and completely disconnected from the floodplain used to determine the water levels without the effects of the floodplain (h_{RC}) for a HQ_{100}. The same hydraulic models and input hydrographs that were employed to calculate ΔQ_{tot} and Δt_{tot} are used to determine the water levels with the connected floodplain (h_{tot}). The water levels h_{tot} and h_{RC} are observed at a defined cross-section in the middle of the river channel, and the mean value is determined to calculate the water level change Δh (cm) by subtracting h_{RC} from h_{tot} (see Eq. 4). This yields the water level increase due to the floodplain loss.

$$\Delta h = \Delta h_{tot} - \Delta h_{RC}(cm) \tag{4}$$

2.3.3 Ecological parameters

2.3.3.1 Existence of protected species This parameter is used to assess the number of protected plant and animal species in a floodplain according to different sources such as the Natura 2000, Emerald Network, national databases, or other studies.

2.3.3.2 Connectivity of floodplain water bodies Longitudinal, lateral, and vertical connectivity is crucial for the functionality of riverine ecosystems. However, given the complexity of the assessment in all three directions and the project goals, a simplified method was chosen to apply this parameter to all floodplains along the Danube. Therefore, only lateral connectivity, which refers to the connection of the river channel and the floodplain, was investigated. The parameter was determined considering three scenarios:

1. Mean water level
2. Bankfull flow
3. Above bankfull flow

The connectivity is determined using the same hydraulic models as for calculating the hydrological parameters. Only the input hydrographs have to be changed according to the investigated scenario (mean water level, bankfull, above bankfull). The inundation areas of each scenario are used to determine the lateral connectivity of water bodies (e.g., side branches, oxbows) in the floodplain. First, the discharge has to be found where the floodplain water bodies are connected (flooded). The next step is to determine the "natural (historical)" status of the water bodies on the floodplains. For this, historical river maps prior to major river regulation activities or written historical documents are used. A possible source of historical maps is the website (https://static-cdn.mapire.eu/en/ accessed on 20 January 2024) from the company Arcanum. There are four possible outcomes when comparing the current and historical status:

1. No "natural" (historical) water bodies on the floodplain.
2. Existing water bodies on the active floodplain in the current and historical condition.
3. On the historical "natural" (historical) water bodies exist, but in the current floodplain, no water bodies are left due to human activity (e.g., dykes, etc.).
4. On historical maps, "natural" (historical) water bodies exist that are also still present on the current floodplain but have been cut off by human structures.

The river type must also be considered to evaluate the lateral connectivity. For example, the connectivity naturally starts at bankfull discharge in case of a meandering river system. If this is the case, the floodplain receives a high performance (5 points) in the FEM, and no further steps are needed. Historically braided or anastomosing river types receive a high performance when the side channels are already connected below mean discharge. The detailed scenarios for the FEM are listed below:

1. Water bodies connected up to mean water level/No "natural" (historical) water bodies on the floodplain/meandering river systems connected above bankfull discharge (high performance—5 points).

2. Water bodies connected at mean water level up to bankfull discharge (medium performance—3 points).
3. Water bodies not connected above bankfull discharge/On the historical maps "natural" (historical) water bodies exist, but at the current floodplain no water bodies are left (low performance—1 point).

If a human structure cuts off parts of the existing floodplain water bodies (e.g., a dyke), the determined performance is downgraded to the next class because we recognize this as negative for the connectivity. For example, floodplain water bodies are connected up to mean flow, leading to high performance in the FEM. However, by checking the historical maps or a DEM, it was discovered that the existing water bodies have been cut off, resulting in a downgrade to the medium performance class.

2.3.4 Socio-economical parameters

2.3.4.1 Potentially affected buildings This parameter determines the number of buildings on each floodplain and divides it by the total area of the floodplain to allow a comparison between them. Aerial photographs, high-resolution satellite imagery, or cadastral information can be used to determine the number. Cadastral information is more accurate than satellite-based detection, but their public access is often difficult or non-existent. If access to these datasets is available, they should be preferred since they are more accurate. The determination of the number of buildings on each floodplain is carried out with the help of GIS software such as ArcGIS or QGIS.

2.3.4.2 Land use Land use adapted to potential flooding minimizes the socio-economical vulnerability of a floodplain. Hence, less vulnerable land uses on the floodplain such as forests or natural grasslands receive high performance, while highly vulnerable land uses such as settlements get a low performance. The CORINE land cover data set (https://land.copernicus.eu/pan-european/corine-land-cover/clc2018 accessed on 20 January 2024) from the Copernicus database summarizes land cover into five categories: "Artificial surfaces", "Agricultural areas", "Forest and semi- natural areas", "Wetlands", and "Water bodies", and can be used to analyse the current land use of each floodplain in a GIS. Each land use class was assigned to one of three performances (low, medium, high) based on the vulnerability against flooding (see Table 6—Appendix). For example, land use urban fabric units or industrial units are highly vulnerable against flooding, resulting in low performance (1 point) in the FEM. The different land uses are combined proportional to their areas to one evaluation value for the whole floodplain by multiplying all highly vulnerable areas by 1, the area of medium vulnerability thereby 3 and the low vulnerability areas with 5. The respective results are summed up and then divided by the sum of the total floodplain area, resulting in a weighted FEM-value for the floodplain.

2.4 Thresholds for FEM parameters

Generally, the thresholds can be defined individually for each river, taking into account specific characteristics of the river and its floodplains (e.g., basin size, river type). The thresholds for the hydrological and hydraulic parameters can be defined based on the previous FEM studies (Habersack et al. 2008; Schober et al. 2013, 2020) and may incorporate findings from studies on preparation time for population and emergency forces (Friso et al. 2008), as well as on damage functions based on water levels (de Moel AND Aerts 2011). All thresholds should be discussed and defined within an expert consortium that can consists of local and regional experts who possess comprehensive knowledge about the river's characteristics, hydrology, geomorphology, ecology, and socio-economic dynamics. By bringing together this multidisciplinary expertise, the consortium can collaboratively define thresholds and develop strategies tailored to the specific needs and challenges of the river under investigation.

2.5 Recommendations for preservation and restoration

Providing recommendations for floodplain preservation and restoration based on a multicriteria approach is desirable for effective floodplain management. Giving preservation recommendations derived from such methodology could assist stakeholders and decision-makers in prioritizing floodplain preservation efforts. Assessing a floodplain's restoration demand offers insights into its current status and the extent of human interventions. Typically, higher restoration demand indicates increased human development on the floodplain and greater deviation from its natural state.

3 FEM application at the Danube River

This section presents the application of the FEM at the Danube River, beginning with an overview of each step outlined in 2.2.1–2.2.4. Subsequently, it provides a basin-wide overview of the calculated FEM parameters and their performance allowing a comparison across three distinct river sections. Finally, the number of floodplains that should be preserved based on our results and the distribution of restoration demand along the Danube River are presented.

3.1 Step I: data acquisition and analysis

Following the research goals, hydrological, hydraulic, ecological, geospatial, and other data were collected and analyzed. An overview and a more detailed description of all used data is presented in Table 4 (see Appendix).

3.2 Step II: Delineating floodplains

Numerous approaches have been documented in literature to delineate active floodplains. These include analyzing inundation areas corresponding to flood events with defined recurrence intervals, studying recent alluvial deposits, or employing ecological methods to identify zones inhabited by organisms adapted to flood conditions. We used the 50 active floodplains (> 500 ha) that Eder et al. (2022b) identified in their study based on hydraulic data. We also used their naming convention for floodplains, including country code (DE = Germany, AT = Austria, SK = Slovakia, HU = Hungary, HR = Croatia, RS = Serbia, BG = Bulgaria, RO = Romania), followed by the river code (DU = Danube River), and the floodplain type (AFP = active floodplain). The fourth and last part is the sequential number within the country in flow direction of the river. If a floodplain crosses international borders, each nation is listed in the code, starting with the one upstream.

3.3 Step III: selecting FEM parameters

At the Danube River, we started with parameters that were investigated in previous studies on floodplain evaluation (Habersack et al. 2008, 2015; Schober et al. 2013) to have a data basis and comparative values. As described in Sect. 2.2.3, the mandatory FEM parameters are the relative peak reduction, flood wave translation, and water level change. Besides that, each partner of the "Danube Floodplain" project could suggest new parameters for one of the four categories of interest (Hydrology, Hydraulic, Ecology, Socio-Economics) that met our requirements. First, the parameter should be applicable in each country (data availability), and partners from each country should be able to apply the parameter using a description. In the end the project team selected the parameters considering the parameter's application and informative value. Table 1 shows the selected FEM parameters for the application at the Danube River.

3.4 Step IV: FEM application

First, we defined our hydrological and hydraulic scenarios. Since the applied method requires that the peak discharge at the beginning of the floodplain corresponds to a HQ_{100}, we used the shape of one of the two major flood events in the years 2006 and 2013, depending on which flood event was closest to a HQ_{100} in the respective floodplain. Table 5 (see Appendix) details which flood event was chosen in each country. In some cases, up- or downscaling of the flood wave was required to reach the exact HQ_{100} discharge at the beginning of the floodplain. The mean and the bankfull discharges were required to determine the ecological parameter "connectivity of floodplain water bodies".

We applied the two mandatory hydraulic scenarios by simulating the entire existing floodplain with current dyke heights and the river channel model (i.e., disconnected floodplains by unlimited dyke heights along the river channel).

Calibrated 1D and 2D hydraulic models were used to perform numerical simulations to determine hydrological, hydraulic, and ecological parameters, with the national hydrological agencies providing the necessary discharges and flood waves. In Table 5 (see Appendix), all the models used and the discharges for the parameters are presented for each country. Generally, hydraulic models were divided into smaller segments to represent individual floodplains, each featuring an inlet and outlet section. This approach ensures that the peak

Table 1 Overview of the selected FEM parameters. The hydrological and hydraulic parameters are mandatory in the FEM

Hydrology	Hydraulics	Ecology	Socio-Economics
Relative peak reduction (%)	Water level (m)	Existence of protected species (−)	Potentially affected buildings (n/km^2)
Flood wave translation (h)		Connectivity of protected species (−)	Land use (−)

of the inflow hydrograph aligns with the HQ_{100} discharge, enabling focused investigation solely on the effects of that specific floodplain. In our study, all countries except Hungary, used this approach. Due to practical reasons, the Hungarian team selected a different modelling approach and used a continuous hydraulic model to calculate the hydrological and hydraulic parameters for the Hungarian floodplains. Therefore, also a continuous model was used for the river channel with disconnected floodplains, and they calculated the impact on the water level with this model.

We calculated our defined FEM parameters with the described methods from Sect. 2.3.1–2.3.4 and the results are presented in the following Sect. 3.5.

At the Danube River, thresholds were defined for each parameter, categorizing performance levels as high (5 points), medium (3 points), or low (1 point). The thresholds and the point system for the hydrological and hydraulic parameters were defined based on previous FEM studies (Habersack et al. 2008; Schober et al. 2013, 2020) and consider studies on preparation time for population and emergency forces (Friso et al. 2008) as well as on damage functions based on water levels (de Moel and Aerts 2011). All thresholds were discussed and defined in several meetings within the expert consortium of the "Danube Floodplain" project. These thresholds were determined through testing with Danube River data, and variations were applied considering the input of all involved representatives from national water agencies, universities, research institutes and NGOs along the Danube River. This collaborative effort resulted in, for example, two key thresholds for the "protected species" parameter. One for "need for preservation" and another for "restoration demand", because only one protected species could lead to the need for preserving the floodplain, but clearly, there is a high restoration demand if only one protected species is present. To determine "the need for preservation", a floodplain is considered low-performing if no protected species are present, medium-performing if 1–20 species are present, and high-performing if more than 20 protected species exist. For the "restoration demand", floodplain performance is categorized as low if less than 40 protected species are present, medium if the count is between 40 and 100, and high if it exceeds 100. In Table 2, all thresholds for the chosen FEM parameters are presented. For the connectivity parameter, no thresholds are defined because the described methodology for applying this parameter leads directly to one of the three performance classes.

We developed a two-step approach to provide recommendations for the preservation and restoration of floodplains based on the FEM results. First, we assessed the "need for preservation" to determine whether a floodplain should be preserved. Following that, we evaluated the "restoration demand". The higher the restoration demand, the more human interventions (e.g., land developments) have occurred on the floodplain and the further the floodplains are away from a natural state. A floodplain must be preserved if at least one parameter of the minimum set is rated with a high performance (5 points). After that, the restoration demand is defined. Using the parameters and their ratings, each floodplain is assigned to one of three groups (low, medium, and high restoration demand). The floodplains were assigned to one of these groups using the total number of points they received in the FEM. For the first time, the "restoration demand" of a floodplain was determined using the FEM. The thresholds were established by the expert consortium of the "Danube Floodplain" project. The consortium consisted of stakeholders and decision-makers who regularly met to discuss different suggestions and variations of the thresholds to define the final thresholds for the project and this paper. Establishing the thresholds through an expert consortium ensures that it is based on the collective expertise and input of relevant decision-makers and stakeholders,

Table 2 Thresholds for all FEM parameters

Ranking	Hydrology		Hydraulic	Ecology			Socio-Economics	
Performance classes (points)	Peak reduction(%)	Flood wave translation (h)	Water level change (cm)	Connectivity (-)	Protected species (-)		Affected buildings (n/km2)	Land use (-)
Low performance (1)	> 1	< 1	< 10	1	0	< 40	> 5	< 2
Medium performance (3)	1–2	1–5	10–50	31–20	40–100	1–5		2–4
High performance (5)	< 2	> 5	> 50	5	> 20	> 100	< 1	> 4

Blue indicates high performance (5 points), green indicates medium (3 points), and orange indicates low performance (1 point)

Table 3 Used thresholds for the floodplains to determine their "restoration demand"

Ranking		
Restoration demand	Rule	Min sum points
High demand	All below 23 points	< 23
Medium demand	max 2 × Medium (3) and 2 × Low (1) or 3 × Low (1)	23–26
Low demand	max 2 × Medium (3) and 1 × Low (1)	≥ 27

Light green color indicates low, yellow medium and red high demand for restoration

considering the diverse perspectives and needs of the stakeholders involved. The following thresholds are intended to serve as a starting point for further discussion, as new results may require adjustments to be made to the system.

The sum of the points received can be maximum 35 (seven minimum parameters × 5 points each) and has to be ≥ 27 to result in a low demand for restoration. Floodplains with total points between 26 and 23 are considered to have medium restoration demand. All floodplains with < 23 points show a high demand for restoration (Table 3).

3.5 Basin-wide analysis

This section presents a basin-wide overview of the calculated FEM parameters and their performance allowing a comparison across the Upper, Middle, and Lower Danube. This allows to identify potential differences between the three sections.

Sixteen active floodplains with an average size of 50 km^2 were identified and evaluated using the FEM at the Upper Danube. Ten are located in Germany, two in Baden-Wuerttemberg that were not evaluated in the scope of this project and eight in Bavaria. The remaining six active floodplains are in Austria and at the Austrian-Slovakian section (see Fig. 7—Appendix). Twenty-four active floodplains with an average size of 54 km^2 were identified and evaluated using the FEM at the Middle Danube. Five are located in the Hungarian-Slovakian section, eight in Hungary, one in the Croatian-Hungarian section, five in the Serbian-Croatian section, and five in Serbia (see Fig. 8—Appendix). Ten active floodplains with an average size of 78 km^2 were identified and evaluated using the FEM at the Lower Danube. Six are located in the transboundary section of Bulgaria and Romania. Four active floodplains are found in Romania (see Fig. 9—Appendix).

The table of the final FEM, covering all sections, is provided in Table 7 (see Appendix), offering an overview of all results at a glance. Since this work builds on the "Danube Floodplain" project, the results and further outputs are accessible to the public through the spatial database "Danube Floodplain GIS" (http://earth.geo.u-szeged.hu/dfgis/ accessed on 20 January 2024).

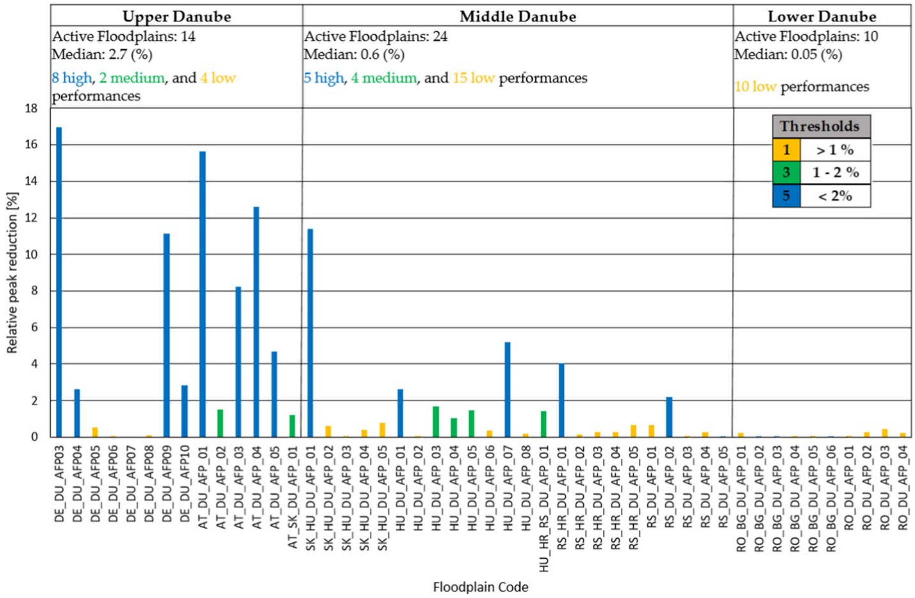


Fig. 3 Relative flood peak reduction for all active floodplains along the Danube River. Blue color indicates high, green medium and orange low performance in the Floodplain Evaluation Matrix (FEM) based on the defined thresholds. Insert shows the thresholds for the presented parameter

3.5.1 Relative flood peak reduction

Figure 3 shows the relative flood peak reduction results for all active floodplains along the Danube River. The calculated values range from 0 to 17%. Thirteen floodplains exhibit high performance ($\Delta Qrel > 2\%$), six medium performance (1–2%), and the remaining 29 floodplains a low performance. 62% (eight) of the floodplains with a high performance and one-third (two) of the floodplains with a medium performance are found in the Upper Danube section. All floodplains at the Lower Danube display a low performance.

3.5.2 Flood wave translation

Due to the flow processes in the floodplains, the flood wave is decelerated in a range of 0.25–41.5 h. Twenty-eight floodplains show a medium (1–5 h), fourteen a high (> 5 h), and six a low (< 1 h) performance for the "flood wave translation" parameter. Six high-performing (> 5 h) floodplains are distributed in both the Upper (around 43% of the floodplains in this section) and Middle Danube (25% of the floodplains in this section). In the Lower Danube only medium (eight floodplains) and high (two floodplains) performances can be found. The median in the upper section is 5 h, in the middle section 2.75 h, and in the lower Section 2 h.

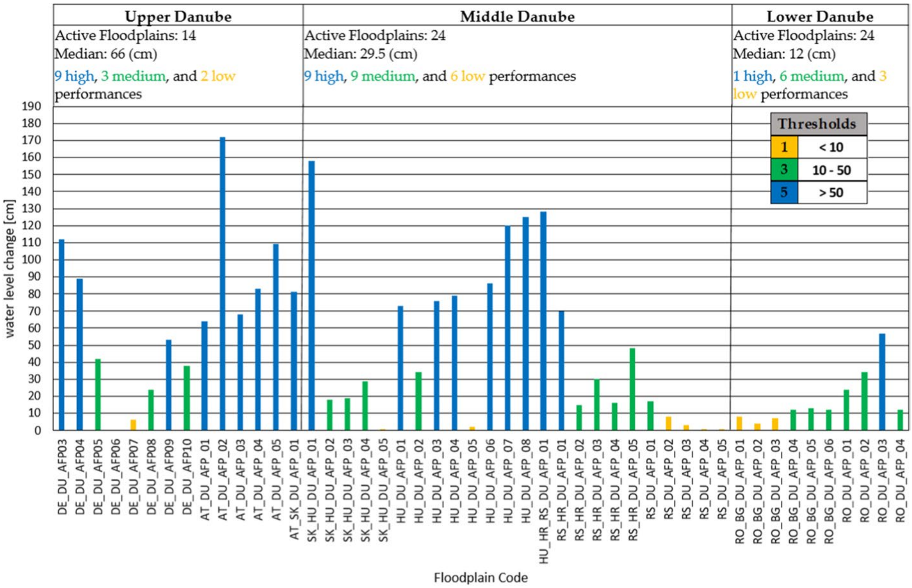


Fig. 4 Water level change for all active floodplains along the Danube River. Blue color indicates high, green medium and orange low performance in the Floodplain Evaluation Matrix (FEM) based on the defined thresholds. Insert shows the thresholds for the parameter shown

3.5.3 Water level change

Figure 4 shows all water level changes observed in the river channel if the active floodplains were disconnected from the river. In nineteen cases, the water level would rise at least 50 cm (= high performance). Nine each are located in the Upper (64% of the floodplains in this section) and Middle Danube (around 38% of the floodplains in this section). Only one floodplain in the Lower Danube reached the highest performance class. The median in the upper section is 66 cm, in the middle section 29.5 cm, and in the lower section 12 cm.

3.5.4 Connectivity of flood water bodies

From an ecological perspective, the lateral connectivity between the river channel and floodplain is impaired by human interventions in all active floodplains along the Danube River, leading to no high performance. At the Upper Danube, only one floodplain received a medium performance. All the other twelve showed a low performance. The middle section presented a more balanced picture, with ten low and fourteen medium performances. All floodplains at the Lower Danube received a medium rating for the connectivity parameter.

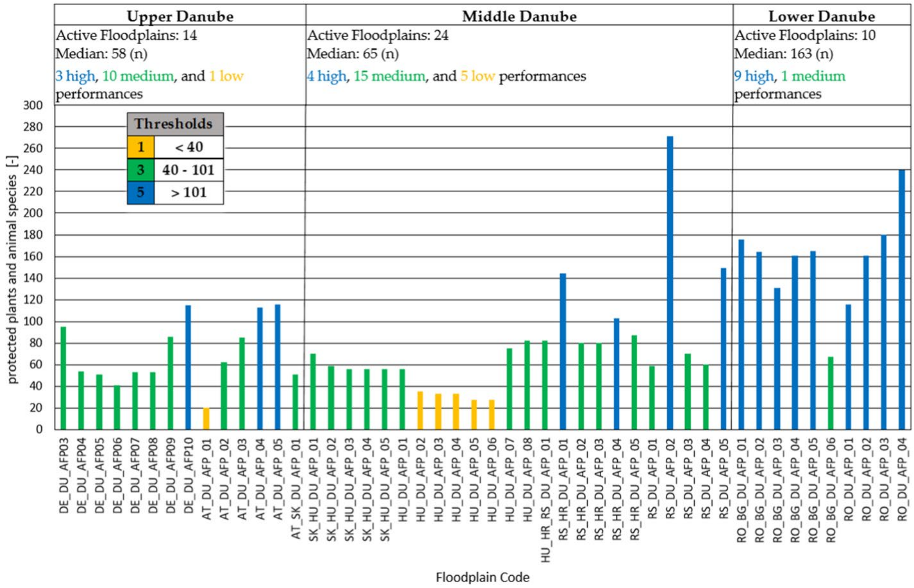


Fig. 5 Existence of protected plant and animal species at all active floodplains along the Danube River. Blue color indicates high, green medium and orange low performance in the floodplain evaluation matrix (FEM) based on the defined thresholds. Insert shows the thresholds for the "restoration demand "

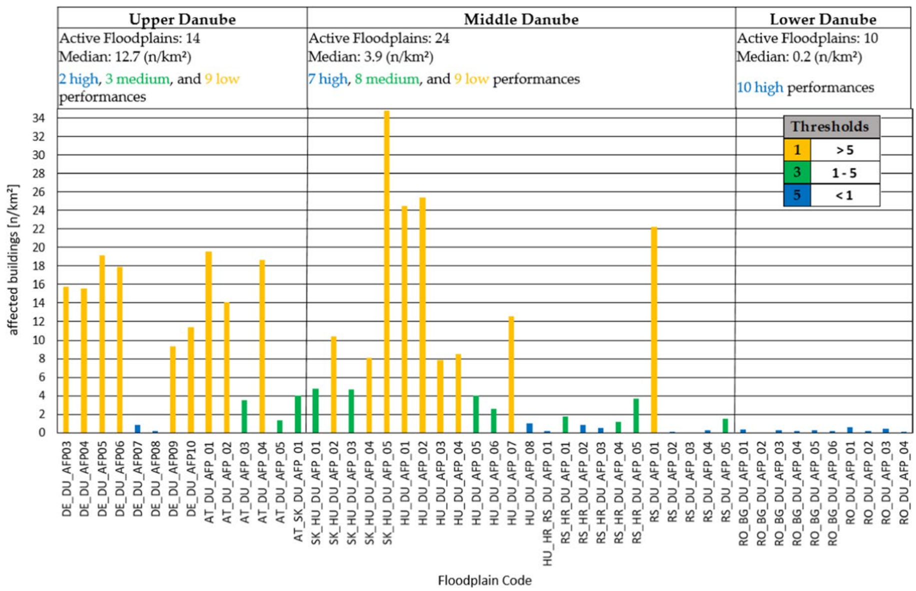


Fig. 6 Affected buildings per km^2 at all active floodplains along the Danube River. Blue color indicates high, green medium and orange low performance in the floodplain evaluation matrix (FEM) based on the defined thresholds. Insert shows the thresholds for the shown parameter

3.5.5 Protected species

For the protected species parameter, two thresholds were defined by the expert consortium (see 3.4). In this subsection, we use the “restoration demand” thresholds to assess the different performances. The number of protected species per floodplain is notably highest at the Lower Danube (see Fig. 5). On the majority of the floodplains at the Lower Danube (nine out of ten), more than 100 protected species (= high performance) can be found, resulting in a median of 162. In the upper and middle sections of the Danube, the median is 58 and 65, respectively, with three and four floodplains in the highest performance class.

3.5.6 Affected buildings per area

At all floodplains along the Lower Danube, less than one building per km^2 (= high performance) can be found (see Fig. 6). At the Middle Danube, the highest value of around 35 buildings per km^2 is observed, but the median of this section lies at around four buildings/km^2 and is thus significantly lower than at the Upper Danube, which yields about 13 buildings/km^2. In the middle section, nine floodplains are in the lowest performance class, eight in the middle class, and nine in the highest class. At the Upper Danube, nine floodplains are also in the lowest class, and only two floodplains are in the highest. The remaining three floodplains have a medium performance.

3.5.7 Land use

Evaluating land use and linking it to vulnerability enables the determination of the floodplain’s suitability for flooding. The analyses reveal a distinct pattern in each section. In the Upper Danube River, eleven floodplains exhibit medium vulnerability to flooding based on the land uses, resulting in a corresponding medium performance. Only on three floodplains, the vulnerability is low (= high performance). In the middle section, the majority (twenty-one out of twenty-four floodplains) showcase a low vulnerability, aligning with high overall performance; the other three demonstrate a medium performance. The vulnerability of floodplains in terms of land use is uniformly low in the Lower Danube, translating to only high performances across this entire section.

3.6 “Need for preservation” and “restoration demand”

A primary objective of the “Danube Floodplain” project was to identify floodplains that should be preserved and restored. To address this goal, we further developed the FEM by incorporating the “need for preservation” and the “restoration demand”. Detailed discussions of this novel approach are provided in the Sects. Based on the developed approach and evaluated parameters, we determined that all active floodplains along the Danube River should be preserved, since at least one parameter received the highest-ranking class in each floodplain. Furthermore, our analysis revealed that 50% (24) of the active floodplains showed a high restoration demand, 31% (15) a medium, and only 19% (9) a low restoration demand (see Table 7–Appendix). Notably, all floodplains with a high restoration demand are concentrated in the Upper or Middle Danube regions.

Along the Lower Danube, eight floodplains exhibit a medium restoration demand, while two exhibit a low restoration demand.

4 Discussion

Our developed and applied method evaluates floodplains along an entire large river, providing an overview of their importance based on various parameters. While the method leads to recommendations for preservation and restoration, it is essential to recognize and address certain inherent limitations and uncertainties associated with our approaches. Hence, we start the discussion by thoroughly examining the identified limitations (see Sect. 4.1) to properly address and acknowledge them before discussing our findings in the following subsections.

4.1 Limitations

4.1.1 Hydrological and hydraulic parameters

Using hydraulic models to calculate hydrological and hydraulic parameters entails certain uncertainties and limitations, which are well-known through several studies with such models (Aronica et al. 1998; Hall et al. 2005; Pappenberger et al. 2005; Tritthart and Gutknecht 2007). In our case, this starts with the input flood waves. We used the shape of flood waves that were measured at the closest gauging station next to the investigated floodplain. The form and volume of a flood wave can vary significantly depending on the flood event and its origins. For example, flood waves can be shallower or steeper than those we used. Overall, the rainfall-runoff pattern is very complex and individual for each river and event (Haider 2014). Schober et al. (2013) showed that, in general, steep flood waves with shorter duration are attenuated stronger. Our calculated hydrological parameters only represent the results for one particular flood event. To compare the parameters, we ensured that the input hydrograph for each floodplain corresponded to a HQ_{100}, which is a value where statistical inferences play a role since these extreme values are extrapolated from historical data. Other sources for uncertainties include terrain representation and roughness parameterization in the hydraulic models. Each country used available calibrated and validated models to calculate the parameters and reduce uncertainties. All countries, with the exception of Austria, utilized 1D models to compute the parameters. While 2D models are generally considered to be the preferred method for calculating these parameters (Connell et al. 2001), it is also possible to obtain acceptable results using 1D models (Ferstl 2020; Schober et al. 2013). Schober et al. (2013) and Ferstl (2020) showed that with suitable databases (measured hydrographs of flood events) and expertise, 1D models can accurately simulate the observed reduction in flood peak and translation of flood wave. In the study by Ferstl (2020), the deviation between measured and simulated flood peak reduction was approximately 3%.

In our study, the hydraulic models should be split into smaller models to represent a single floodplain with an in- and outflow section. As described in Sect. 2.3.2, the Hungarian modelling approach was different for practical reasons. They used a continuous hydraulic model to calculate the parameters. As long as the hydrograph at the beginning of each floodplain corresponds to a HQ_{100} this approach has no effects on the hydrological parameter. In the case of the hydraulic parameter, it is different since the water level change becomes larger when using a continuous model for each floodplain. Hence, the results of the hydraulic parameter for the Hungarian floodplains should not be compared with results from other countries.

4.1.2 Ecological parameters

The two ecological parameters that we applied to the entire river also have certain limitations. First, all the uncertainties mentioned in the previous Sect. 4.1.1 regarding hydraulic models play a role for the "connectivity" parameter as well since such models were used for this parameter too. Another limitation is that few temporal changes in lateral connectivity were considered, as it was determined by a hydraulic model using only three different steady discharges. However, as the catchment of the Danube River is greatly influenced by climate change and hit by serious droughts and floods, applying only three steady discharges might provide only a rough snapshot of the lateral connectivity. Moreover, we did not evaluate longitudinal and vertical connectivity, though they play an essential role in habitat continuity and species migration. Undoubtedly, all three types of connectivity are important, but one goal of this study was to develop a method that could be applied along an entire river and be transferable to other rivers. Therefore, data sources and parameters were chosen, which are easier to access and apply. Since the applied FEM has a flexible design, other analyses that consider all three types of connectivity could be applied at other case studies if the data availability is given. Some ideas about the other directions of connectivity can be found in Woolsey et al. (2007), or Fryirs et al. (2007).

For the number of protected species, we had to rely on the database of Natura2000. However, its applied methodology differs among the countries (Hošek and Dusek 2016). All plant and animal species were considered to be of equal value so as not to favor any of the protected species. In addition, the occurring number of each protected species was not considered in the method. Here one could still improve the applied approach.

Additionally, invasive species are increasingly important elements of riparian ecosystems. However, in this study, their number and abundance were not evaluated due to a lack of information.

4.1.3 Socio-economical parameters

The evaluated socio-economical parameters were: "affected buildings" and "land use". The land use is derived from the CORINE LU/LC data set for 2018. This data set is extracted from high-resolution satellite imagery and is uniform for all of Europe. The geometric accuracy is better than 100 m, and the thematic accuracy is better than 85%. The smallest size of the land use units in the database is 25 ha (Büttner et al. 2021). On the scale of the floodplains, errors due to misclassification or the geometry are smaller and averaged out. The FEM ranking of each class is fixed and has been applied uniformly to all floodplains. Therefore, inconsistencies are minimized.

The data sets applied to derive the "affected buildings" parameters are more diverse. For some floodplains, buildings were counted based on visual interpretation on aerial photographs, sometimes (restricted) cadastral information was used, and there were also countries where high-resolution satellite imagery formed the base data set. The spatial resolution of the base data influences the identifiable buildings. Cadastral information is more accurate than satellite-based detection. Also, the methodology in different floodplains may differ slightly. In some cases, each individual building was counted based on remote sensing data, while in the case of cadastral data, the function of the buildings was taken into account, which could reduce the number of identified buildings. For the purpose of this study, it is acceptable to use both approaches, as the goal was to obtain a rough estimate of affected buildings. The quality of the visual identification of buildings may also vary according to the experience of the human interpreter (Lillesand et al. 2015).

4.1.4 Thresholds for FEM parameters

Due to the research objectives, we introduced thresholds for each parameter to determine three different performance classes, subsequently defining the "need for preservation" and the "restoration demand". These thresholds were established based on empirical data from previous studies (e.g., flood peak reduction) but also used values from flood risk analyses that showed, for example, that damages are higher when the water depth exceeds 50 cm (de Moel and Aerts 2011) or emergency forces can prepare the public much better if they have more time (Friso et al. 2008). To determine the thresholds, various options for the Danube River were tested in a thorough process and a consortium of experts from various organizations, including national water authorities, universities and non-governmental organizations, was consulted. This collaborative effort resulted in thresholds specific to the Danube River that should not be seen as fixed values but rather as a basis for further floodplain analyses. Generally, the thresholds need to be individually defined for each river, taking into account river-specific characteristics (e.g., river type, basin size). This approach allows the consideration of the unique features of each river system during the definition of the thresholds.

4.2 Application of the FEM at the Danube River

The evaluation of the active floodplains along the Danube River with the FEM showed that the floodplains are important for flood protection, ecology, and socio-economy. Some floodplains are more relevant for flood protection, and others fulfil more ecological or socio-economic functions and services.

As the results for the hydrological parameter "relative flood peak reduction" demonstrated, most floodplains (62%) at the Upper Danube significantly reduce the flood peak by more than 2% of a HQ_{100} flood peak. At the Lower Danube, no floodplain was able to reduce the peak by this amount. We identified following reasons for that. First, dykes of hydropower plants in the upper reaches lead to later flooding of the floodplains, as already shown by Schober et al. (2013) at the Austrian Danube, where at some floodplains, the dykes are overtopped at discharges around a HQ_5. Previous studies (Haider 2014; Schober et al. 2013; Skublics et al. 2016) showed that if the bankfull discharge is higher or later in the rising limb of the flood wave, the peak reduction will be larger as when the floodplain is flooded already at the beginning of the rise. Secondly, at the Lower Danube, the percentage of the former floodplains is smaller than along the Upper Danube (Eder et al. 2022b). Thirdly, the flood waves in mountainous regions such as the Upper Danube are generally steeper than the flood waves in lowland rivers. In the lower section, the Danube is such a lowland river. Studies from Haider (1995) or Schober et al. (2013) demonstrated that the flood peak reduction for steep flood waves with shorter duration is stronger. The investigations of Schober et al. (2013) have shown that the peak reduction for every floodplain in Austria is stronger for a steeper flood wave. In contrast, the flood wave translation can also be higher for flatter flood waves. In our study, we see barely significant differences between the performances in the three Danube sections for the “flood wave translation” parameter.

The results of the hydraulic parameter “water level change” showed some differences between the sections. The loss of the floodplain would lead in the upper section in 64% of cases to an increase of the water level by at least 50 cm. At the Middle Danube, 38%, and at the Lower Danube, only 10%. One reason for that might be that a higher percentage of the former floodplains is preserved in the upper section Eder et al. (2022b) and disconnecting these areas from the river would lead to the higher water levels in the river channel.

In contrast to the hydraulic parameter and the relative flood peak reduction, the ecological parameter “protected species” showed a different picture. At the Lower Danube, the floodplains have the best values (most protected species) from an ecological perspective. In the upper section, a higher percentage of former floodplains is preserved, but as the "land use" parameter also showed, land use in the active floodplains has changed significantly and most of the natural properties were lost. Agricultural and urban uses are much higher in the upper section, and this, of course, subsequently reduces the potential habitats for various species and increases the vulnerability against flooding. Floodplains are used for agriculture, especially in mountainous areas (Upper Danube) with limited space. There are barely any agricultural uses on the active floodplains along the Lower Danube. Flood characteristics of the lower section might also play a role in that since floodplains at the Lower Danube can be flooded for several weeks due to lower flood dynamics (Nagy and Kiss 2016; Varadi and Goncz 1999).

Urban usage is also highest in the upper section and is reflected in the parameter “affected buildings”. The median of the Upper Danube is with 13 buildings/km^2 significantly higher than in the middle section (four buildings/km^2). Floodplains are attractive for agricultural and settlement development due to their topographic characteristics, fertility, and water availability (Schober et al. 2013). The limited space for urban development in the mountainous countries of the Upper Danube promotes more urban developments in the narrow valley bottoms along the rivers (Schober et al. 2020) than at the Lower Danube, where less than one building per km^2 could be found on the active floodplains.

The assessment of the ecological parameter “connectivity of floodplain water bodies” showed the effects of the massive floodplain loss occurred at the Danube River, which was demonstrated in previous studies (Eder et al. 2022b; Schwarz 2010). No active floodplain has kept their natural (historical) lateral connectivity. One reason for this is that all floodplains lost their former extent due to human interferences, morphological changes, etc. Very often dykes cut off parts of the former floodplains, and in our applied method, as soon as dykes disconnect the former floodplain, a high performance (= natural (historical) status) is impossible. In the upper sections, most of the floodplains (thirteen out of fourteen) showed even a low performance (= poor lateral connectivity). Some floodplains are only connected to the river when the discharge corresponds to a HQ_5, due to the dykes of hydropower plants (Schober et al. 2013). In the Middle and Lower Danube, the active floodplains have mostly a medium performance.

In this study, we introduced the “need for preservation” to provide floodplain managers and decision-makers with a basis for deciding whether a floodplain should be preserved. The expert consortium of the project determined that all functions and services provided by the floodplain should be treated equally. After exploring various approaches, the consortium reached the conclusion that as soon as one parameter was evaluated with a high performance, the floodplain must be preserved, irrespective if the parameter is an ecological or a hydrological one.

The “restoration demand” was introduced to assess the current status of the floodplains with the FEM. Humans use and modify floodplains for many purposes (agricultural usage, urban development, leisure activities, etc.), affecting and changing their natural functions and services (Rajib et al. 2021; Schindler et al. 2014; Tockner and Stanford 2002). Restoration measures such as reconnecting side channels are considered valid solutions to restore the lost ecological and flood protection functions and services (Sanon et al. 2012; Serra-Llobet et al. 2022; Stammel et al. 2021). In our assessment with the FEM, we identified the most natural floodplains in the basin to perform best. Therefore, their “restoration demand” was evaluated as low, although this should not imply that no measures are needed to improve their performance. It only indicates that compared with the other floodplains, these are the closest to their natural state. In our evaluation, all relatively well-preserved floodplains received at least 27 points. Hence, this value was considered a suitable threshold, and all floodplains that reached at least 27 points were considered as having a low “restoration demand”. Floodplains where humans significantly altered the natural functions, services, and former extent of the floodplain reached not more than 23 points in our assessment. Therefore, all floodplains that scored less than 23 points were evaluated with high “restoration demand”. The floodplains that reached between 23 and 27 points received a medium demand for restoration. Since this study is the first one that evaluates the floodplains of an entire large river using the FEM, these presented thresholds should be seen and used as a starting point for later studies on other floodplains. These thresholds are flexible and could be changed based on the results of further studies.

4.3 Future usage of the floodplain evaluation matrix

As the vulnerability and limitations of structural flood protection measures have been clearly demonstrated during major flood events (de Kok and Grossmann 2010; Hutton et al. 2019; Jüpner 2018; Kundzewicz and Menzel 2005), floodplain preservation and restoration have become essential elements of European environmental and water policies (EC: European Commission 2000, 2007, 2009), as they provide functions and services related to flood defence and ecology. Nevertheless, floodplains are still under pressure due to societal changes such as economic development, urbanization, population growth, etc. (Steffen et al. 2007; Vörösmarty et al. 2010). In Europe, more than 1000 km^2 are sealed each year, although the EU-goal is to achieve a “no net land take” by 2050 (European Parliament and Council, 2013). The previous land consumption has left its mark, especially on river floodplains. 90% of former floodplains have been lost or are negatively impacted by human activities in Europe and North America (Tockner and Stanford 2002). Floodplain evaluation using the FEM provides decision-makers and stakeholders with a basis for floodplain management decisions by demonstrating the importance and impact of floodplains on flood protection, ecology, and socio-economy. The results of the FEM can contribute to strengthening the preservation and restoration efforts by underlying the importance and effects of the floodplains. The FEM results are also presented in the latest version of the Danube River Basin (ICPDR: International Commission for the Protection of the Danube River 2021b) and Flood Risk Management Plan (ICPDR: International Commission for the Protection of the Danube River 2021a), leading to the conclusions that all active floodplains must be preserved and a concrete large-scale restoration program is needed to restore floodplains as much as possible. Evaluating and collecting information about other floodplains along other large rivers (e.g., Nile, Mississippi) is desirable and would support floodplain managers in the preservation and restoration of floodplains. Admittedly, fully implementing the FEM is a time-consuming process. Therefore, we developed a QGIS plugin to accelerate and simplify the evaluation procedure by delineating floodplains, calculating specific FEM parameters, storing the results, and generating factsheets for each floodplain. More information on the current version of this FEM-Tool is available at https://www.interreg-danube.eu/uploads/media/approved_project_output/0001/49/976f5f357d4013348ba4aa13cc79aa42e7912c43.pdf accessed on 17 January 2024.

5 Conclusions

This study aimed to develop a method to determine the effects of active floodplains on flood protection, ecology, and socio-economics at different river systems. To achieve this, we used and further developed the floodplain evaluation matrix (FEM) (Habersack et al. 2015; Habersack & Schober 2020) to allow an application to the Danube River. The challenge of our study was to develop a method applicable in all countries, respecting the different data availability, and replicable at other large rivers. At the same time, we considered floodplains' multiple functions and services by assessing hydrological, hydraulic, ecological, and socio-economic parameters. The active floodplains exhibited a range of flood mitigation benefits, including significant reductions in flood peak (up to 17%), deceleration of flood wave progression (up to 41.5 h), and lower water levels (up to 174 cm) during a HQ_{100} event. Meanwhile, other floodplains may not have a noticeable impact on flood events but play a crucial role in preserving biodiversity by providing essential habitats for protected species.

Besides evaluating the effects of floodplains, a task was to identify floodplains where preservation and restoration efforts should be taken based on the FEM. Hence, the "need for preservation" and the "restoration demand" were introduced and assessed, showing that all active floodplains should be preserved and that all floodplains need restoration measures since their natural functions and services were compromised. 81% of the floodplains demonstrated a high or medium demand for restoration, emphasizing the urgency of intervention.

The results of the FEM not only highlight the diverse benefits of floodplains but also underline the need for actions, particularly in preservation and restoration efforts. Presenting the results could convince planners and funders to strengthen their support for the preservation and restoration of floodplains, leading to implementation of preservation and restoration measures as demanded in water and environmental policy plans such as the EU Floods Directive (2007/60/EC) (EC: European Commission 2007) and EU Biodiversity Strategy for 2030 (EC: European Commission 2020).

Appendix

See Tables 4, 5, 6 and 7, and Figs. 7, 8 and 9.

Table 4 Overview of all data sources used for FEM application identifying the active, former, and potential floodplains alongat the Danube River

Data	Source Name	Description	Countries
Hydraulic and Hydrological	Hydraulic models	Calibrated 1D and 2D hydraulic models were used to calculate hydrological, hydraulic, and ecological parameters. In Table A2, all used models are shown in more detail	DE, AT, SK, HU, HR, RS, BG, RO
	Hydrological data	Flood waves from different flood events (2006 and 2013) along the Danube River and various discharges (mean, bankfull, HQ_{100} → see Table A2) were used to determine the hydrological, hydraulic, and ecological parameters	DE, AT, SK, HU, HR, RS, BG, RO
Ecological	Natura 2000 database	A database that includes information about the occurrence of protected plant and animal species and their habitats at Natura 2000 sites. The data can be downloaded via the Natura 2000 Viewer[1], which is an online tool presenting all Natura 2000 sites	DE, AT, SK, HU, HR, BG, RO
	EMERALD network	A network of areas of special conservation interest listing protected plants and animal species and habitats that are part of the Convention on the Conservation of European Wildlife and Natural Habitats	RS
	Studies	Available studies (Simić, 2017) in the floodplains and available data from the Institute for Nature Conservation of Serbia Information system if no data from the EMERALD network was available	RS
Geospatial	Land cover data set	The CORINE LU/LC data set[2] for 2018 from the Copernicus database summarizes land cover into five categories: “Artificial surfaces”, “Agricultural areas”, “Forest and semi-natural areas”, “Wetlands”, and “Water bodies”	DE, AT, SK, HU, HR, RS, BG, RO
	Cadastral information	High-resolution, high-accuracy cadastral scale databases, usually with official status, were used to extract building information in vector format	DE, HU, RS, BG
	Aerial photographs	High-resolution, high-accuracy digital (ortho)photographs of different sources were used to extract buildings by visual interpretation	RO
	Satellite images	Google Earth, OpenStreetMap, World Imagery, etc. were used for high-resolution satellite images	DE, AT, SK, HU, HR, RS, BG, RO

Table 4 (continued)

Data	Source Name	Description	Countries
Other	Danube floodplains	Previously delineated active floodplains presented in Eder, identified in the scope of the "Danube Floodplain[3]" project and available on the "Danube Floodplain GIS[4]", are used as a basis for the active floodplains in the present study	DE, AT, SK, HU, HR, RS, BG, RO
	Dykes	The project "Danube FLOODRISK[5]" provides information about dykes along the entire Danube River. This data can be requested from the International Commission for the Protection of the Danube River (ICPDR)	DE, AT, SK, HU, HR, RS, BG, RO

[1]https://natura2000.eea.europa.eu/ accessed on 12 February 2024; [2]https://land.copernicus.eu/paneuropean/corine-land-cover/clc2018 accessed on 12 February 2024;

[3]https://www.interreg-danube.eu/approved-projects/danube-floodplain#! accessed on 12 February 2024;

[4]http://earth.geo.u-szeged.hu/dfgis/ accessed on 12 February 2024; [5]https://environmentalrisks.danube-region.eu/projects/danube-floodrisk/ accessed on 12 February 2024

Country code: DE = Germany, AT = Austria, SK = Slovakia, HU = Hungary, HR = Croatia, RS = Serbia, BG = Bulgaria, RO = Romania

Table 5 Overview of the hydraulic models and hydrological data used

Country	Germany	Austria	Slovakia	Hungary	Croatia	Serbia	Bulgaria	Romania
Software	SOBEK 1D	Hydro_AS-2D	HEC-RAS 1D	HEC-RAS 1D	HEC-RAS 1D	HEC-RAS 1D	HEC-RAS 1D	HEC-RAS 1D
Creator of hydraulic model	Hydrotec Ingenieurgesellschaft (Aachen)	werner consult, Geoconsult, riocom	BME, modified by ÉDUVIZIG	BME, modified by ÉDUVIZIG	Jaroslav Černi Water Institute	Jaroslav Černi Water Institute	National Administration "Apele Romane" and National Institut of Hydrology and Water Management	National Administration "Apele Romane" and National Institut of Hydrology and Water Management
Year of creation	Setup: 2011; Main Update: 2018	2010–2012	2014	2014	2015	2015	2019–2020	2019–2020
Owner	Federal Institute of Hydrology (BfG)	Upper and Lower Austria ÉDUVIZIG	ÉDUVIZIG	Jaroslav Černi Water Institute	Jaroslav Černi Water Institute	National Administration "Apele Romane" and National Institut of Hydrology and Water Management	National Administration "Apele Romane" and National Institut of Hydrology and Water Management	
Calibration	Calibration: flood events 2002 and 2005; Validation: flood event 1999	flood 2002	flood event 2013	flood event 2013	flood events 1994, 2006, 2010	flood events 1994, 2006, 2010	flood event 2006, 2010, 2013	flood event 2006, 2010, 2013
Model boundaries (river-km)	2587–2201	2162–1872	1849–1699	1699–1380	1432–1275	1432–943	860–395	860–172
Input hydrograph for FEM	flood event 2013	flood event 2013	flood event 2013	flood event 2013	flood event 2006	flood event 2006	flood event 2006	flood event 2006
HQ100 discharges (m3/s)	1250–8800	8920–11200	8450–10390	8450–10390	8900–11317	8900–15400	2460–16600	2460–16600
Bankfull discharges (m3/s) 540–1150	5522–7602	2940–5322	2940–5322	3890–4830	3890–6400	4100–9800	4100–9800	

Table 5 (continued)

Country	Germany	Austria	Slovakia	Hungary	Croatia	Serbia	Bulgaria	Romania
Mean discharges (m3/s)	124–1420	1450–2068	2068–2241	2021–2285	3170–5800	3170–5800	5474–6088	5474–6088

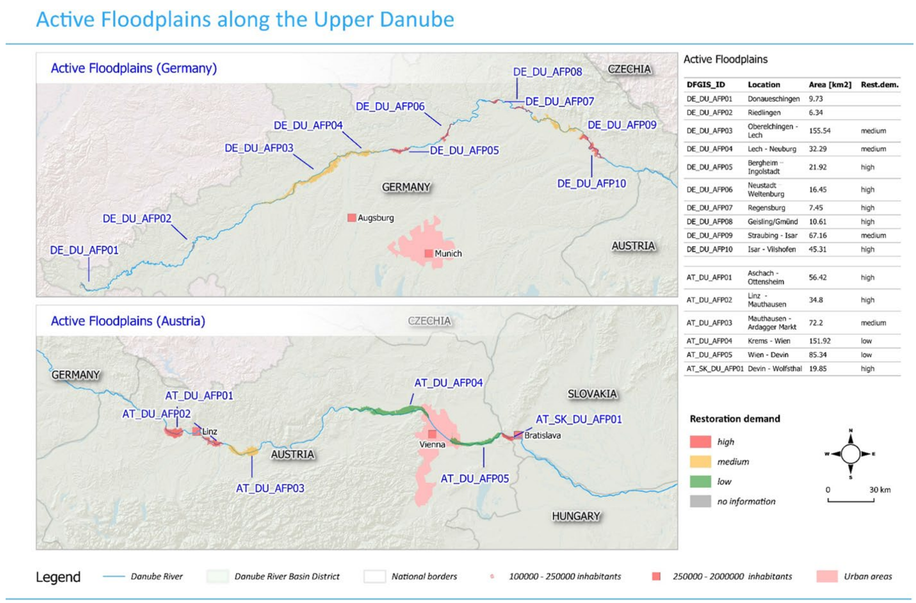
Table 6 Land use types of the Corine Land Cover data set with corresponding FEM-evaluation (1 = low, 3 = medium, 5 = high performance) based on the vulnerability against flooding

CLC_CODE	LABEL3	FEM-evaluation
111	Continuous urban fabric	1
112	Discontinuous urban fabric	1
121	Industrial or commercial units	1
122	Road and rail networks and associated land	1
123	Port areas	1
124	Airports	1
131	Mineral extraction sites	1
132	Dump sites	1
133	Construction sites	1
141	Green urban areas	1
142	Sport and leisure facilities	1
211	Non-irrigated arable land	3
212	Permanently irrigated land	3
213	Rice fields	3
221	Vineyards	3
222	Fruit trees and berry plantations	3
223	Olive groves	3
231	Pastures	3
241	Annual crops associated with permanent crops	3
242	Complex cultivation patterns	3
243	Land principally occupied by agriculture, with significant areas of natural vegetation	3
244	Agro-forestry areas	3
311	Broad-leaved forest	5
312	Coniferous forest	5
313	Mixed forest	5
321	Natural grasslands	5
322	Moors and heathland	5
323	Sclerophyllous vegetation	5
324	Transitional woodland-shrub	5
331	Beaches, dunes, sands	3
332	Bare rocks	5
333	Sparsely vegetated areas	5
334	Burnt areas	3
335	Glaciers and perpetual snow	not relevant
411	Inland marshes	5
412	Peat bogs	5
421	Salt marshes	not relevant
422	Salines	not relevant
423	Intertidal flats	5
511	Water courses	5
512	Water bodies	5
521	Coastal lagoons	5
522	Estuaries	5
523	Sea and ocean	5

Table 7 Overview of the results for the FEM-parameters incl. ranking (need for preservation + restoration demand) for all active floodplains along the Danube River.

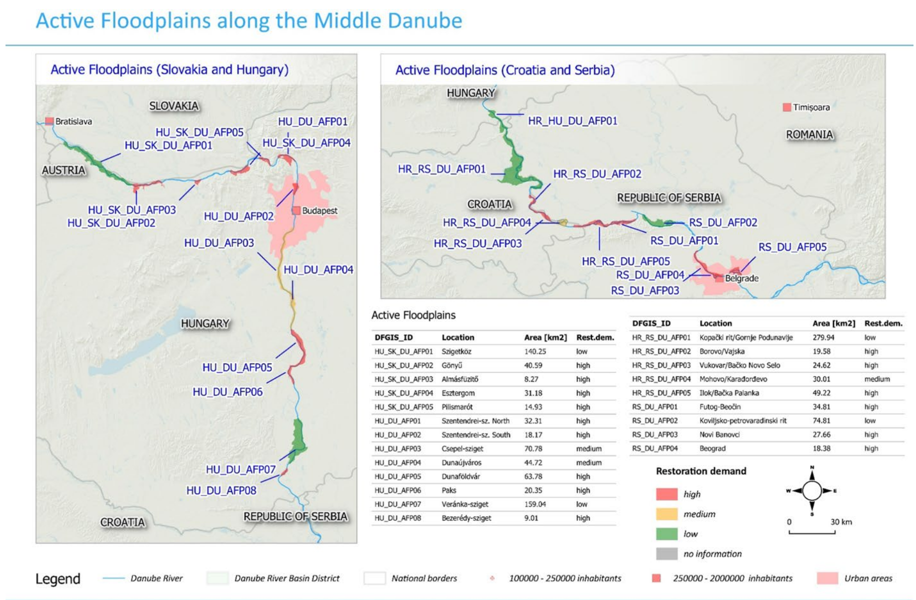
River section	Floodplain	Hydrology		Hydraulics	Ecology			Socio-Economics		Ranking	
		peak reduction (%)	flood wave translation (h)	water level change (cm)	connectivity (-)	protected species (-)		affected buildings (n/km²)	land use (-)	Restoration demand (low, medium, high)	Need for preservation
Upper Danube	DE_DU_AFP_01										
	DE_DU_AFP_02										
	DE_DU_AFP_03	**16.98**	16.5	112	1	95	95	15.76	3.63	medium (23)	yes
	DE_DU_AFP_04	2.63	9.5	89	1	54	54	15.58	3.92	medium (23)	yes
	DE_DU_AFP_05	0.53	3	42	1	51	51	19.16	4.57	high (17)	yes
	DE_DU_AFP_06	0.07	1	0	1	41	41	17.93	3.40	high (13)	yes
	DE_DU_AFP_07	0.00	1.25	6	1	53	53	0.81	3.65	high (17)	yes
	DE_DU_AFP_08	0.08	0.25	24	1	53	53	**0.19**	3.64	high (17)	yes
	DE_DU_AFP_09	11.13	6.75	53	1	86	86	9.32	3.61	medium (23)	yes
	DE_DU_AFP_10	2.83	5	38	1	115	115	11.39	3.52	high (21)	yes
	AT_DU_AFP_01	15.64	5.5	64	1	20	20	19.58	3.40	high (21)	yes
	AT_DU_AFP_02	1.52	2.5	**172**	1	62	62	14.04	3.76	high (21)	yes
	AT_DU_AFP_03	8.24	5.5	68	1	85	85	3.52	3.81	medium (25)	yes
	AT_DU_AFP_04	12.60	**20.5**	83	1	113	113	18.63	4.68	low (27)	yes
	AT_DU_AFP_05	4.68	5	109	**3**	**116**	**116**	1.38	**4.74**	low (29)	yes
	AT_SK_DU_AFP_01	1.21	4	81	1	51	51	3.98	3.56	high (21)	yes
Middle Danube	HU_SK_DU_AFP_01	**11.40**	7	**158**	**3**	70	70	4.79	4.88	low (29)	yes
	HU_SK_DU_AFP_02	0.60	2	18	1	59	59	10.42	4.21	high (17)	yes
	HU_SK_DU_AFP_03	0.06	0	19	1	56	56	4.71	3.57	high (15)	yes
	HU_SK_DU_AFP_04	0.39	2	29	**3**	56	56	8.08	3.74	high (17)	yes
	HU_SK_DU_AFP_05	0.79	0.4	1	1	56	56	34.77	4.08	high (13)	yes
	HU_DU_AFP_01	2.61	0	73	1	56	56	24.48	3.88	high (19)	yes
	HU_DU_AFP_02	0.05	3	34	**3**	35	35	25.37	4.25	high (17)	yes
	HU_DU_AFP_03	1.69	6	76	**3**	33	33	7.85	4.23	medium (23)	yes
	HU_DU_AFP_04	1.03	7	79	**3**	33	33	8.52	4.42	medium (23)	yes
	HU_DU_AFP_05	1.49	1	2	**3**	27	27	4.01	4.05	high (19)	yes
	HU_DU_AFP_06	0.34	0.5	86	**3**	27	27	2.61	4.69	high (19)	yes
	HU_DU_AFP_07	5.22	7	120	**3**	75	75	12.62	4.42	low (27)	yes
	HU_DU_AFP_08	0.20	0	125	**3**	82	82	0.99	4.95	high (22)	yes
	HU_HR_DU_AFP_01	1.41	5	128	**3**	82	82	0.14	4.91	low (27)	yes
	RS_HR_DU_AFP_01	4.04	**41.5**	70	1	144	144	1.78	4.90	low (29)	yes
	RS_HR_DU_AFP_02	0.14	2	15	1	80	80	0.87	4.80	high (21)	yes
	RS_HR_DU_AFP_03	0.25	2.5	30	1	80	80	0.53	**4.97**	high (21)	yes
	RS_HR_DU_AFP_04	0.28	2.5	16	**3**	103	103	1.20	4.96	medium (23)	yes
	RS_HR_DU_AFP_05	0.68	5	48	1	87	87	3.70	4.82	high (19)	yes
	RS_DU_AFP_01	0.66	3	17	1	59	59	22.20	4.62	high (17)	yes
	RS_DU_AFP_02	2.21	7.5	8	1	**271**	**271**	0.13	4.95	low (27)	yes
	RS_DU_AFP_03	0.02	4	3	**3**	70	70	**0.00**	**4.97**	high (21)	yes
	RS_DU_AFP_04	0.27	3	1	**3**	60	60	0.27	4.79	high (21)	yes
	RS_DU_AFP_05	0.01	2.5	1	**3**	149	149	1.53	4.71	high (21)	yes
Lower Danube	RO_BG_DU_AFP_01	0.22	1	8	**3**	176	176	0.38	4.82	medium (23)	yes
	RO_BG_DU_AFP_02	0.01	2	4	**3**	164	164	**0.00**	4.94	medium (23)	yes
	RO_BG_DU_AFP_03	0.01	2	7	**3**	131	131	0.24	4.31	medium (23)	yes
	RO_BG_DU_AFP_04	0.06	4	12	**3**	161	161	0.21	4.40	medium (25)	yes
	RO_BG_DU_AFP_05	0.03	2	13	**3**	165	165	0.28	4.62	medium (25)	yes
	RO_BG_DU_AFP_06	0.01	2	12	**3**	67	67	0.15	4.65	medium (25)	yes
	RO_DU_AFP_01	0.02	1	24	**3**	116	116	0.56	**4.98**	medium (25)	yes
	RO_DU_AFP_02	0.27	5	34	**3**	161	161	0.14	4.97	medium (25)	yes
	RO_DU_AFP_03	**0.44**	11	**57**	**3**	180	180	0.45	4.87	low (29)	yes
	RO_DU_AFP_04	0.23	**39**	12	**3**	**240**	**240**	0.13	4.95	low (27)	yes
FEM-rating	performance	Thresholds	Thresholds	Thresholds	Thresholds	Thresholds		Thresholds	Thresholds	Thresholds	Thresholds
	low	<1	<1	<10	1	0	<40	>5	<2	≥ 27	at least one high performance
	medium	1-2	1-5	10-50	3	1-20	41-100	1-5	2-4	23-26	
	high	>2	>5	>50	5	>20	>100	<1	>4	<23	no high performance

Blue color indicates high, green medium and orange low. performance. Light green color indicates low, yellow medium and red high demand for restoration



DFGIS_ID	Location	Area [km2]	Rest.dem.
DE_DU_AFP01	Donaueschingen	9.73	
DE_DU_AFP02	Riedlingen	6.34	
DE_DU_AFP03	Oberelchingen - Lech	155.54	medium
DE_DU_AFP04	Lech - Neuburg	32.29	medium
DE_DU_AFP05	Bergheim - Ingolstadt	21.92	high
DE_DU_AFP06	Neustadt - Weltenburg	16.45	high
DE_DU_AFP07	Regensburg	7.45	high
DE_DU_AFP08	Geisling/Gmünd	10.61	high
DE_DU_AFP09	Straubing - Isar	67.16	medium
DE_DU_AFP10	Isar - Vilshofen	45.31	high
AT_DU_AFP01	Aschach - Ottensheim	56.42	high
AT_DU_AFP02	Linz - Mauthausen	34.8	high
AT_DU_AFP03	Mauthausen - Ardagger Markt	72.2	medium
AT_DU_AFP04	Krems - Wien	151.92	low
AT_DU_AFP05	Wien - Devin	85.34	low
AT_SK_DU_AFP01	Devin - Wolfsthal	19.85	high

Fig. 7 All active floodplains along the Upper Danube and their restoration demand



DFGIS_ID	Location	Area [km2]	Rest.dem.
HU_SK_DU_AFP01	Szigetköz	140.25	low
HU_SK_DU_AFP02	Gönyű	40.59	high
HU_SK_DU_AFP03	Almásfüzitő	8.27	high
HU_SK_DU_AFP04	Esztergom	31.18	high
HU_SK_DU_AFP05	Pilismarót	14.93	high
HU_DU_AFP01	Szentendrei-sz. North	32.31	high
HU_DU_AFP02	Szentendrei-sz. South	18.17	high
HU_DU_AFP03	Csepel-sziget	70.78	medium
HU_DU_AFP04	Dunaújváros	44.72	medium
HU_DU_AFP05	Dunaföldvár	63.78	high
HU_DU_AFP06	Paks	20.35	high
HU_DU_AFP07	Veránka-sziget	159.04	low
HU_DU_AFP08	Bezerédy-sziget	9.01	high

DFGIS_ID	Location	Area [km2]	Rest.dem.
HR_RS_DU_AFP01	Kopački rit/Gornje Podunavlje	279.94	low
HR_RS_DU_AFP02	Borovo/Vajska	19.58	high
HR_RS_DU_AFP03	Vukovar/Bačko Novo Selo	24.62	high
HR_RS_DU_AFP04	Mohovo/Karađorđevo	30.01	medium
HR_RS_DU_AFP05	Ilok/Bačka Palanka	49.22	high
RS_DU_AFP01	Futog-Beočin	34.81	high
RS_DU_AFP02	Koviljsko-petrovaradinski rit	74.81	low
RS_DU_AFP03	Novi Banovci	27.66	high
RS_DU_AFP04	Beograd	18.38	high

Fig. 8 All active floodplains along the Middle Danube and their restoration demand. Left: active floodplains in Slovakia and Hungary. Right top: active floodplains in Hungary, Croatia, and Serbia

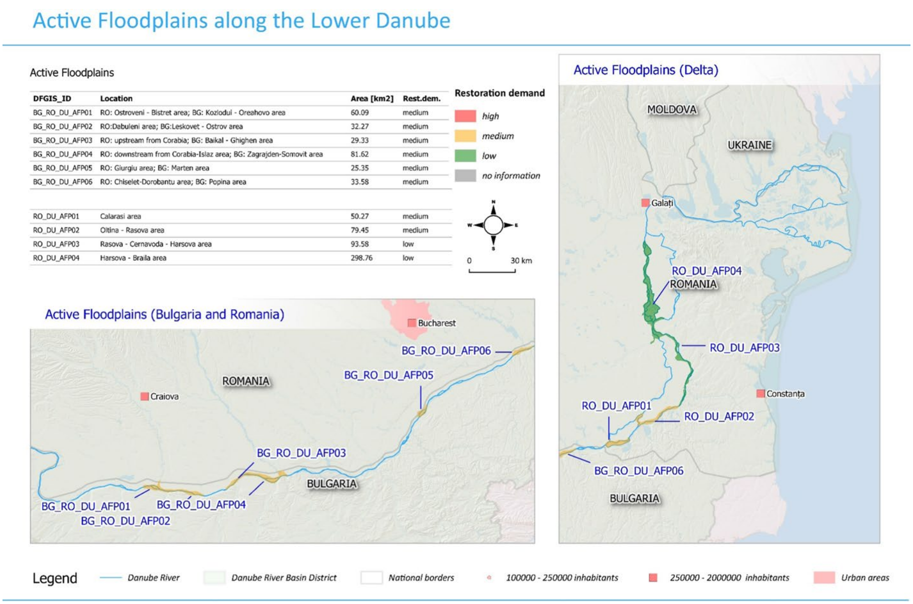


Fig. 9 All active floodplains along the Lower Danube and their restoration demand

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Data availability The identified active, former, and potential floodplains can be found in the "Danube Floodplain GIS" (http://earth.geo.u-szeged.hu/dfgis/ accessed on 12 February 2024) which is a spatial database, created in the scope of the "Danube Floodplain" project and showing the FEM results on floodplain factsheets.

Declarations

Conflicts of interest The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

Abell JM, Pingram MA, Özkundakci D, David BO, Scarsbrook M, Wilding T, Williams A, Noble M, Brasington J, Perrie A (2023) Large floodplain river restoration in New Zealand: synthesis and critical evaluation to inform restoration planning and research. Reg Environ Change 23(1):18

Aronica G, Hankin B, Beven K (1998) Uncertainty and equifinality in calibrating distributed roughness coefficients in a flood propagation model with limited data. Adv Water Resour 22(4):349–365. https://doi.org/10.1016/S0309-1708(98)00017-7

Auerswald K, Moyle P, Seibert SP, Geist J (2019) HESS Opinions: socio-economic and ecological trade-offs of flood management—benefits of a transdisciplinary approach. Hydrol Earth Syst Sci 23(2):1035–1044. https://doi.org/10.5194/hess-23-1035-2019

Bernhardt ES, Palmer MA (2011) River restoration: The fuzzy logic of repairing reaches to reverse catchment scale degradation. Ecol Appl 21(6):1926–1931. https://doi.org/10.1890/10-1574.1

Blöschl G, Nester T, Komma J, Parajka J, Perdigão RAP (2013) The June 2013 flood in the Upper Danube Basin, and comparisons with the 2002, 1954 and 1899 floods. Hydrol Earth Syst Sci 17(12):5197–5212. https://doi.org/10.5194/hess-17-5197-2013

Büttner G, Kosztra B, Maucha G, Pataki R, Kleeschulte S, Hazeu G, Vittek M, Schröder C, Littkopf A (2021) Copernicus land monitoring service. CORINE Land Cover. User Manual. European Environment Agency (EEA). https://land.copernicus.eu/user-corner/technical-library/clc-product-user-manual

Cammerer H, Thieken AH (2013) Historical development and future outlook of the flood damage potential of residential areas in the Alpine Lech Valley (Austria) between 1971 and 2030. Reg Environ Change 13(5):999–1012. https://doi.org/10.1007/s10113-013-0407-9

Connell RJ, Painter DJ, Beffa C (2001) Two-dimensional flood plain flow. II: Model validation. J Hydrol Eng 6(5):406–415. https://doi.org/10.1061/(ASCE)1084-0699(2001)6:5(406)

Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M (1997) The value of the world's ecosystem services and natural capital. Nature 387(6630):6630. https://doi.org/10.1038/387253a0

De Bruijn K, Klijn F, McGahey C, Mens M, Wolfert H (2008) Long-term strategies for flood risk management: scenario definition and strategic alternative design. CRC Press, Boca Raton

de Kok J-L, Grossmann M (2010) Large-scale assessment of flood risk and the effects of mitigation measures along the Elbe River. Nat Hazards 52(1):143–166. https://doi.org/10.1007/s11069-009-9363-6

de Moel H, Aerts JCJH (2011) Effect of uncertainty in land use, damage models and inundation depth on flood damage estimates. Nat Hazards 58(1):407–425. https://doi.org/10.1007/s11069-010-9675-6

Di Baldassarre G, Viglione A, Carr G, Kuil L, Salinas JL, Blöschl G (2013) Socio-hydrology: conceptualising human-flood interactions. Hydrol Earth Syst Sci 17(8):3295–3303. https://doi.org/10.5194/hess-17-3295-2013

Di Baldassarre G, Kreibich H, Vorogushyn S, Aerts J, Arnbjerg-Nielsen K, Barendrecht M, Bates P, Borga M, Botzen W, Bubeck P, De Marchi B, Llasat C, Mazzoleni M, Molinari D, Mondino E, Mård J, Petrucci O, Scolobig A, Viglione A, Ward PJ (2018) Hess Opinions: an interdisciplinary research agenda to explore the unintended consequences of structural flood protection. Hydrol Earth Syst Sci 22(11):5629–5637. https://doi.org/10.5194/hess-22-5629-2018

Díez-Herrero A, Garrote J (2020) Flood risk analysis and assessment, applications and uncertainties: a bibliometric review. Water. https://doi.org/10.3390/w12072050

EC: European Commission (2000) Directive (2000/60/EC) for establishing a framework for Community action in the field of water policy (water framework direction)

EC: European Commission (2007) Directive (2007/60/EC) on the assessment and management of flood risks. European Parliament Council

EC: European Commission (2009) Directive (2009/147/EC) on the conservation of wild birds. vol 20. http://data.europa.eu/eli/dir/2009/147/oj/eng

EC: European Commission (2020) EU Biodiversity Strategy for 2030—bringing nature back into our lives

Eder M, Löschner L, Herrnegger M, Hogl K, Nordbeck R, Scherhaufer P, Schober B, Seher W, Wesemann J, Zahnt N, Habersack H (2022a) RegioFEM—applying a floodplain evaluation method to support a future-oriented flood risk management (Part II). J Flood Risk Manag 15(1):e12758. https://doi.org/10.1111/jfr3.12758

Eder M, Perosa F, Hohensinner S, Tritthart M, Scheuer S, Gelhaus M, Cyffka B, Kiss T, Van Leeuwen B, Tobak Z, Sipos G, Csikós N, Smetanová A, Bokal S, Samu A, Gruber T, Gălie A-C, Moldoveanu M, Mazilu P, Habersack H (2022) How can we identify active, former, and potential floodplains? Methods and lessons learned from the Danube River. Water. https://doi.org/10.3390/w14152295

Elmer F, Hoymann J, Düthmann D, Vorogushyn S, Kreibich H (2012) Drivers of flood risk change in residential areas. Nat Hazards Earth Syst Sci 12(5):1641–1657. https://doi.org/10.5194/nhess-12-1641-2012

European Parliament and Council (2013) Decision No 1386/2013/EU of the European Parliament and of the Council of 20 November 2013 on a General Union Environment Action Programme to 2020 'Living well, within the limits of our planet.' Off J Eur Union 354:171–200

Ferstl L (2020) Bewertung von Überflutungsflächen an der niederösterreichischen Donau anhand der Floodplain Evaluation Matrix—Vergleich von 1D/2D-Modellen [Master Thesis]. Universität für Bodenkultur

Friso K, Banninga J, van Zuilekom K (2008) FLORIS-modelling and analyses of evacuation. Goudappel Coffeng, University of Twente, Deventer

Fryirs KA, Brierley GJ, Preston NJ, Kasai M (2007) Buffers, barriers and blankets: the (dis)connectivity of catchment-scale sediment cascades. CATENA 70(1):49–67. https://doi.org/10.1016/j.catena.2006.07.007

Funk A, Martínez-López J, Borgwardt F, Trauner D, Bagstad KJ, Balbi S, Magrach A, Villa F, Hein T (2019) Identification of conservation and restoration priority areas in the Danube River based on the multi-functionality of river-floodplain systems. Sci Total Environ 654:763–777. https://doi.org/10.1016/j.scitotenv.2018.10.322

Gordon BA, Dorothy O, Lenhart CF (2020) Nutrient retention in ecologically functional floodplains: a review. Water 12(10):10. https://doi.org/10.3390/w12102762

Habersack H, Schober B (2020) Floodplain evaluation matrix FEM: a multiparameter assessment methodology. J Flood Risk Manag 13(3):e12614. https://doi.org/10.1111/jfr3.12614

Habersack H, Hauer C, Schober B, Dister E, Quick I, Harms O, Wintz M, Piquette E, Schwarz U (2008) Flood risk reduction by PReserving and restOring river FLOODPLAINs—PRO_FLOODPLAIN. In: Samuels P, Huntington S, Allsop W, Harrop J (eds) Flood risk management: research and practice, 1st edn. CRC Press, Boca Raton, pp 733–743

Habersack H, Schober B, Hauer C (2015) Floodplain evaluation matrix (FEM): an interdisciplinary method for evaluating river floodplains in the context of integrated flood risk management. Nat Hazards 75(1):5–32. https://doi.org/10.1007/s11069-013-0842-4

Haider S (2014) Retention in unseren Flüssen. Oesterr Wasser Abfallwirtsch 66(1):59–66. https://doi.org/10.1007/s00506-013-0128-9

Haider, S (1995) Der Beitrag von Vorlandueberflutungen zur Verformung von Hochwasserwellen.

Hall JW, Sayers PB, Dawson RJ (2005) National-scale assessment of current and future flood risk in England and wales. Nat Hazards 36(1):147–164. https://doi.org/10.1007/s11069-004-4546-7

Hein T, Schwarz U, Habersack H, Nichersu I, Preiner S, Willby N, Weigelhofer G (2016) Current status and restoration options for floodplains along the Danube River. Sci Total Environ 543:778–790. https://doi.org/10.1016/j.scitotenv.2015.09.073

Helton AM, Poole GC, Payn RA, Izurieta C, Stanford JA (2014) Relative influences of the river channel, floodplain surface, and alluvial aquifer on simulated hydrologic residence time in a montane river floodplain. Geomorphology 205:17–26. https://doi.org/10.1016/j.geomorph.2012.01.004

Hošek M, Dusek J (2016). Methodological guidelines for natura 2000 sites selection (Proposed Sites of Community Importance) in Serbia. https://doi.org/10.13140/RG.2.2.31479.47524

Hutton NS, Tobin GA, Montz BE (2019) The levee effect revisited: Processes and policies enabling development in Yuba County, California. J Flood Risk Manag 12(3):e12469. https://doi.org/10.1111/jfr3.12469

ICPDR. (2011). The Danube River basin—facts and figures. https://www.icpdr.org/flowpaper/app/services/view.php?doc=icpdr_facts_figures.pdf&format=pdf&page=page&subfolder=default/files/nodes/documents/

ICPDR (2015) The Danube River basin district management plan—part a—basin-wide overview. ICPDR—International Commission for the Protection of the Danube River, p 192

ICPDR: International Commission for the Protection of the Danube River (2021a) Danube Flood Risk Management Plan—Update 2021. ICPDR – International Commission for the Protection of the Danube River, p 174

ICPDR: International Commission for the Protection of the Danube River (2021b) Danube River Basin Management Plan—Update 2021. ICPDR – International Commission for the Protection of the Danube River, p 290

Jüpner R (2018) Coping with extremes—experiences from event management during the recent Elbe flood disaster in 2013. J Flood Risk Manag 11(1):15–21. https://doi.org/10.1111/jfr3.12286

Karpack MN, Morrison RR, McManamay RA (2020) Quantitative assessment of floodplain functionality using an index of integrity. Ecol Ind 111:106051. https://doi.org/10.1016/j.ecolind.2019.106051

Klijn F, Kreibich H, de Moel H, Penning-Rowsell E (2015) Adaptive flood risk management planning based on a comprehensive flood risk conceptualisation. Mitig Adapt Strat Glob Change 20(6):845–864. https://doi.org/10.1007/s11027-015-9638-z

Klijn F, Asselman N, Wagenaar D (2018) Room for rivers: risk reduction by enhancing the flood conveyance capacity of the Netherlands' large rivers. Geosciences 8(6):224. https://doi.org/10.3390/geosciences8060224

Knox RL, Wohl EE, Morrison RR (2022) Levees don't protect, they disconnect: a critical review of how artificial levees impact floodplain functions. Sci Total Environ 837:155773. https://doi.org/10.1016/j.scitotenv.2022.155773

Kundzewicz ZW, Menzel L (2005) Natural flood reduction strategies—a challenge. Int J River Basin Manag 3(2):125–131. https://doi.org/10.1080/15715124.2005.9635252

Kundzewicz ZW, Kanae S, Seneviratne SI, Handmer J, Nicholls N, Peduzzi P, Mechler R, Bouwer LM, Arnell N, Mach K, Muir-Wood R, Brakenridge GR, Kron W, Benito G, Honda Y, Takahashi K, Sherstyukov B (2014) Flood risk and climate change: global and regional perspectives. Hydrol Sci J 59(1):1–28. https://doi.org/10.1080/02626667.2013.857411

Lillesand T, Kiefer RW, Chipman J (2015) Remote sensing and image interpretation. Wiley, London

Lininger KB, Polvi LE (2020) Evaluating floodplain organic carbon across a gradient of human alteration in the boreal zone. Geomorphology 370:107390. https://doi.org/10.1016/j.geomorph.2020.107390

Ludy J, Kondolf GM (2012) Flood risk perception in lands "protected" by 100-year levees. Nat Hazards 61(2):829–842. https://doi.org/10.1007/s11069-011-0072-6

Meli P, Rey Benayas JM, Balvanera P, Martínez Ramos M (2014) Restoration enhances wetland biodiversity and ecosystem service supply, but results are context-dependent: a meta-analysis. PLoS ONE 9(4):e93507. https://doi.org/10.1371/journal.pone.0093507

Nagy J, Kiss T (2016) Hydrological and morphological changes of the lower Danube near Mohács. Hung J Environ Geogr 9(1–2):1–6. https://doi.org/10.1515/jengeo-2016-0001

Nanson GC, Croke JC (1992) A genetic classification of floodplains. Geomorphology 4:459–486

Opperman J, Galloway GE, Fargione J, Mount JF, Richter BD, Secchi S (2009) Sustainable floodplains through large-scale reconnection to rivers. Science 326(5959):1487–1488. https://doi.org/10.1126/science.1178256

Pappenberger F, Beven K, Horritt M, Blazkova S (2005) Uncertainty in the calibration of effective roughness parameters in HEC-RAS using inundation and downstream level observations. J Hydrol 302(1):46–69. https://doi.org/10.1016/j.jhydrol.2004.06.036

Petsch DK, Cionek VDM, Thomaz SM, dos Santos NCL (2023) Ecosystem services provided by river-floodplain ecosystems. Hydrobiologia 850(12):2563–2584. https://doi.org/10.1007/s10750-022-04916-7

Rajib A, Zheng Q, Golden HE, Wu Q, Lane CR, Christensen JR, Morrison RR, Annis A, Nardi F (2021) The changing face of floodplains in the Mississippi River Basin detected by a 60-year land use change dataset. Sci Data 8(1):1–11. https://doi.org/10.1038/s41597-021-01048-w

Rajib A, Zheng Q, Lane CR, Golden HE, Christensen JR, Isibor II, Johnson K (2023) Human alterations of the global floodplains 1992–2019. Sci Data 10(1):1. https://doi.org/10.1038/s41597-023-02382-x

Robinson CT, Tockner K, Ward JV (2002) The fauna of dynamic riverine landscapes. Freshw Biol 47(4):661–677. https://doi.org/10.1046/j.1365-2427.2002.00921.x

Rohde S, Hostmann M, Peter A, Ewald K (2006) Room for rivers: an integrative search strategy for floodplain restoration. Landsc Urban Plan 78(1–2):50–70

Sanon S, Hein T, Douven W, Winkler P (2012) Quantifying ecosystem service trade-offs: the case of an urban floodplain in Vienna, Austria. J Environ Manage 111:159–172. https://doi.org/10.1016/j.jenvman.2012.06.008

Schindler S, Sebesvari Z, Damm C, Euller K, Mauerhofer V, Schneidergruber A, Biró M, Essl F, Kanka R, Lauwaars SG, Schulz-Zunkel C, van der Sluis T, Kropik M, Gasso V, Krug A, Pusch MT, Zulka KP, Lazowski

W, Hainz-Renetzeder C, Wrbka T (2014) Multifunctionality of floodplain landscapes: relating management options to ecosystem services. Landsc Ecol 29(2):229–244. https://doi.org/10.1007/s10980-014-9989-y

Schindler S, O'Neill FH, Biró M, Damm C, Gasso V, Kanka R, van der Sluis T, Krug A, Lauwaars SG, Sebesvari Z, Pusch M, Baranovsky B, Ehlert T, Neukirchen B, Martin JR, Euller K, Mauerhofer V, Wrbka T (2016) Multifunctional floodplain management and biodiversity effects: a knowledge synthesis for six European countries. Biodivers Conserv 25(7):1349–1382. https://doi.org/10.1007/s10531-016-1129-3

Schober B, Hauer C, Habersack H (2013) A novel assessment of the role of Danube floodplains in flood hazard reduction (FEM method). Nat Hazards 75(1):33–50. https://doi.org/10.1007/s11069-013-0880-y

Schober B, Hauer C, Habersack H (2020) Floodplain losses and increasing flood risk in the context of recent historic land use changes and settlement developments: Austrian case studies. J Flood Risk Manag 13(3):e12610. https://doi.org/10.1111/jfr3.12610

Schwarz U (2010) Assessment of the restoration potential along the Danube and main tributaries. For WWF International Danube-Carpathian Programme, Vienna, p 58

Serra-Llobet A, Jähnig SC, Geist J, Kondolf GM, Damm C, Scholz M, Lund J, Opperman JJ, Yarnell SM, Pawley A, Shader E, Cain J, Zingraff-Hamed A, Grantham TE, Eisenstein W, Schmitt R (2022) Restoring rivers and floodplains for habitat and flood risk reduction: experiences in multi-benefit floodplain management from California and Germany. Front Environ Sci. https://doi.org/10.3389/fenvs.2021.778568

Simić D (2017) Sastav faune ptica spomenika prirode 'Lesni profil Kapela u Batajnici'—The composition of the bird fauna of the Natural Monument 'Lesni profil Kapela u Batajnici'.

Skublics D, Blöschl G, Rutschmann P (2016) Effect of river training on flood retention of the Bavarian Danube. J Hydrol Hydromech 64(4):349–356. https://doi.org/10.1515/johh-2016-0035

Sommerwerk N, Baumgartner C, Bloesch J, Hein T, Ostojic A, Paunovic M, Schneider-Jacoby M, Silber R, Tockner K (2009) The Danube river basin. In: Tockner K, Uehlinger U, Robinson CT (eds) Rivers of Europe. Elsevier, Amsterdam, pp 59–112. https://doi.org/10.1016/B978-0-12-369449-2.00003-5

Stammel B, Fischer C, Cyffka B, Albert C, Damm C, Dehnhardt A, Fischer H, Foeckler F, Gerstner L, Hoffmann TG, Iwanowski J, Kasperidus HD, Linnemann K, Mehl D, Podschun SA, Rayanov M, Ritz S, Rumm A, Scholz M, Gelhaus M (2021) Assessing land use and flood management impacts on ecosystem services in a river landscape (Upper Danube, Germany). River Res Appl 37(2):209–220. https://doi.org/10.1002/rra.3669

Steffen W, Crutzen PJ, McNeill JR (2007) The anthropocene: are humans now overwhelming the great forces of nature? Ambio 36(8):614–621

te Linde AH, Bubeck P, Dekkers JEC, de Moel H, Aerts JCJH (2011) Future flood risk estimates along the river Rhine. Nat Hazards Earth Syst Sci 11(2):459–473. https://doi.org/10.5194/nhess-11-459-2011

Tockner K, Stanford JA (2002) Riverine flood plains: present state and future trends. Environ Conserv 29(3):308–330. https://doi.org/10.1017/S037689290200022X

Tritthart M, Gutknecht D (2007) 3-D computation of flood processes in sharp river bends. Proc Instit Civil Eng Water Manag 160(4):233–247. https://doi.org/10.1680/wama.2007.160.4.233

Varadi J, Goncz B (1999) Flood protection in Hungary. Seminar on Flood Prevention and Protection

Villa JA, Bernal B (2018) Carbon sequestration in wetlands, from science to practice: an overview of the biogeochemical process, measurement methods, and policy framework. Ecol Eng 114:115–128. https://doi.org/10.1016/j.ecoleng.2017.06.037

Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, Glidden S, Bunn SE, Sullivan CA, Liermann CR, Davies PM (2010) Global threats to human water security and river biodiversity. Nature 467(7315):555–561. https://doi.org/10.1038/nature09440

Wantzen KM, Ballouche A, Longuet I, Bao I, Bocoum H, Cissé L, Chauhan M, Girard P, Gopal B, Kane A, Marchese MR, Nautiyal P, Teixeira P, Zalewski M (2016) River Culture: an eco-social approach to mitigate the biological and cultural diversity crisis in riverscapes. Ecohydrol Hydrobiol 16(1):7–18. https://doi.org/10.1016/j.ecohyd.2015.12.003

Winsemius HC, Aerts JCJH, van Beek LPH, Bierkens MFP, Bouwman A, Jongman B, Kwadijk JCJ, Ligtvoet W, Lucas PL, van Vuuren DP, Ward PJ (2016) Global drivers of future river flood risk. Nat Clim Chang 6(4):381–385. https://doi.org/10.1038/nclimate2893

Wohl E, Angermeier PL, Bledsoe B, Kondolf GM, MacDonnell L, Merritt DM, Palmer MA, Poff NL, Tarboton D (2005) River restoration. Water Resour Res. https://doi.org/10.1029/2005WR003985

Woolsey S, Capelli F, Gonser T, Hoehn E, Hostmann M, Junker B, Paetzold A, Roulier C, Schweizer S, Tiega SD, Tockner K, Weber C, Peter A (2007) A strategy to assess river restoration success. Freshw Biol 52(4):752–769. https://doi.org/10.1111/j.1365-2427.2007.01740.x

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