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Synthesis report on science-based needs for action

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Executive Summary

The consortium of the *lifelineMDD* project has conducted eight scientific studies focused on the river corridor of the Mura, Drava and Danube, within the UNESCO 5-country biosphere reserve Mura-Drava-Danube (TBR MDD). The studies focused on biotic factors (fish, birds) and abiotic framework conditions (sediment, hydromorphology, including modifications by training structures, climate change, hydropeaking) and aimed to create the scientific basis that helps recognise and prioritise restoration needs. In this two and a half year's interdisciplinary process, scientists and stakeholders from across the TBR MDD came together to discuss, share data and information that enable decision makers and water- as well as protected area managers better understand the ecological corridor as a whole and thereby support long-term planning of management and restoration works. Project partners conducting the research have reached out to science and education institutions, local stakeholders such as individual scientists or NGOs and national or regional authorities for water management and nature protection for scientific data, previous research and literature. A series of workshops involving the extended project team, including essential stakeholders took place, and the first ever TBR MDD-level scientific conference brought those involved together.

The present study is a summary and synthesis of this process and of all eight studies' results. It presents, for the first time on the TBR MDD level, combined maps of biotic and abiotic data, as well as parallel interpretation of results from all studies, in an attempt to underline priority conservation and restoration actions as indicated by the reality on the field. It does not explain in detail each study's methods; however, a short summary table is included in the Annex, and each study is publicly available for those wanting to dive in. The synthesis maps rely on data from the bird census (at the basis of the bird study) and the data collected on training structures and historical development of the rivers. Due to different constraints mainly related to time and budget, the data depth of the other studies does not allow for the same geographical analysis. Nevertheless, as it can be seen by the structure of each study and the cross-references included, an exchange of information, methods, contents and preliminary, as well as final results among the research teams took place. The present report therefore additionally attempts a qualitative synthesis interpretation of the results of each study, with an eye on the aims of conservation and restoration.

The main findings of the different studies have one common denominator: the recognition of the TBR MDD as a highly valuable ecological corridor and safe haven for many species, and the main conclusion, from all different perspectives and factors, that restoration of the rivers is a must to counteract the negative effects of the different threats such as the various effects of hydropower dams upstream of the free-flowing stretch of the rivers and of the general channelization and floodplain reduction historically and at present, as well as of sediment extraction. Such effects are primarily sediment deficit and riverbed incision and, as direct effects, further disconnection of the floodplains and loss of habitats and aquatic and terrestrial or bird species. Following key numbers summarise the status of the TBR MDD:

- During fish sampling 53 species of fish could be found with electrofishing and eDNA sampling throughout the Mura, Drava, Danube, and Danube backwaters, which is a considerable diversity attributed to the river stretches' longitudinal connectivity and the existence of valuable habitats throughout the TBR MDD.
- The study that looked at the effects of hydropeaking within the TBR MDD, with a focus on the effects by the last hydropower plant on the Drava (Donja Dubrava) has shown that the demand-driven operation affects the river ecosystem as far as 100 rkm downstream of the dam.
- The field survey for river birds (2021 and repeated 2022) along the Mura, Drava and Danube has re-confirmed the international protected area's importance as an ecological corridor for birds as well. For example, between 7.000-10.000 pairs of Sand martins and 200-450 pairs of Bee-eaters, both indicators species for intact river habitats, have been counted. Additionally, the bird census' results also showed a higher presence and nesting activity of such birds along the more natural or near-natural stretches of the rivers, which confirms the need for restoration in order to improve bird habitats within the Natura 2000 areas.
- The study of the river training structures along the Mura, Drava and Danube has shown that one single 5 rkm segment on the lower Drava contains no regulation works (<1 km) while the most impacted 10 km segment of the Danube contains up to 14.4 km of structures (counting both banks together). This confirms that, in spite of the near-natural appearance of some of the river stretches, past and current regulation has been extensive. The comparison with the known historical state has shown an area loss of the main channel of 42%, of the side channels of up to 92%, and of gravel and sand bars of 84%, which are considerable losses in retention area and potential habitats.
- The study of sediment balance and transport within the TBR MDD has shown an overall total riverbed incision over the past few decades since major regulation works on all but three of the 25 measurement points; its value moving between 0.01 and 2.5 meters. Overall, the study recognizes very high sediment deficits (e.g. 45,000 m3 per annum on the Mura's Austrian-Slovenian section), which, however, can be reduced by widening the main river channel and increasing its sinuosity – both of these targets are reachable through restoration. The project's pilot restoration at Hrastje Mota was projected to potentially contribute with 30,000 m^3 of sediments through bank erosion. The sediment study has clearly identified the Slovenian-Austrian section of the Mura as a high-priority for restoration. Due to the high incision, the riverbed here threatens to lose the gravel, and to eventually break through into finer sediment, which would be hard to restore based on ecologically oriented methods.
- The climate change and hydrological studies have both predicted swift and strong changes to occur soon in the area: in general, there will be a warming and a shift in precipitation patterns. Compared to the 1976-2005 reference period, summer months are projected to be 10% drier and winter months up to 20% wetter by the end of the century, with a particularly pronounced summer runoff decrease by the end of the century.

- Data showing bird breeding site density per river segments overlapped with indicators of hydromorphological state has shown that about 21% of the Mura's length in the TBR MDD, about 16% of the Drava's and about 23% of the Danube's is in the comparatively highest class, meaning potentially suitable from a hydromorphological point of view as bird breeding habitat, and thereby also of the highest ecological value.

The collected knowledge, data and the scientist teams' recommendations are compiled into a set of proposed action. This breaks down the overall term "restoration" into manageable steps, suggested for implementation by the TBR MDD management and by different stakeholders directly involved and of pivotal importance for the biosphere reserve implementation, such as water management authorities and bodies responsible for management of protected areas.

The study is built up corresponding to its combining and synthesising nature. Chapter 1 briefly presents the international context of the studies and places it within the different available frameworks, then taking each study and summarising its setting, previous data availability in the specific field and, most importantly, their results. Chapter 2 explains the method used for the synthesis and joint analysis of the collected biotic and abiotic data which is presented in detail and interpreted in chapter 3. Chapter 4 lists all data uncertainties and further research needed. The core conclusion of the report is found in chapter 5, summarised in the form of a set of actions proposed for implementation based on the eight studies' results, along with a summary of the argumentation line behind each action.

1. Introduction

The present synthesis report compiles the key findings of all scientific studies (seven studies) conducted in the frame of the project lifelineMDD, for establishing the scientific knowledge base. The aim is to draw conclusions on priorities for protection and restoration of the TBR MDD. For this purpose, we firstly overlay biotic and abiotic data where data depth allows for it in search of causality relations and scientific basis for points of actions. Secondly, we review the challenges detected and solutions recommended within the studies on bio-indicators for ecological connectivity and on abiotic framework conditions.

Following studies have been elaborated within the lifelineMDD project and can be consulted individually. The list below also shows each study's short name, which is used within the report for future referencing.

- Fish population status report (incl. Annex) (referred to in this report as "fish study")
- River birds breeding report ("bird study")
- River training structures and historical mapping within the Mura-Drava-Danube TBD ("river training structures study"/"RTS study", including the "historical mapping")
- Sediment mobilisation study report ("sediment mobilisation study")
- Sediment balance and transport study ("sediment study")
- Climate change study report, including Hydrological study ("climate change and hydrology studies")
- Study on Hydropeaking on the Drava ("hydropeaking study")

The report then highlights those proposed actions that contribute to multiple aims and have a high synergy effect. The synthesis report also aims to define priority river stretches for restoration by overlaying the geographic results of different studies. Finally, the synthesis report is also an important input for the TBR MDD River Restoration Strategy for which it serves as a scientific basis and call for action.

The above-listed studies serve as good tools and knowledge collections for reaching the proposed aim, as the selected biotic elements and abiotic factors in focus have an indicator function for the ecological status of rivers. Fish populations and river birds serve as indicator species groups to assess the ecological functionality of the river corridor in all connectivity dimensions (as e.g. in the WFD criteria or according to the FFH and Birds Directives). This also shows the need to analyse jointly the situation of bio-indicators with that of abiotic framework conditions, to provide clear guidance on the need for action. Therefore, complementary to the biotic indicators, a set of abiotic framework conditions that are suitable for describing the health status of a river (sediment transport, degree of regulation of the rivers) or expected to influence the health of the river in the future (climate change and hydrology), have been investigated.

1.1. Background

The area analysed and targeted by the present study (hereinafter called "target area") comprises all river stretches of the 5-country Biosphere Reserve Mura-Drava-Danube (TBR MDD), shared between Austria, Slovenia, Hungary, Croatia and Serbia. Spanning across these five countries, the lower courses of the Drava and Mura Rivers and the related sections of the Danube are among Europe's ecologically most important riverine areas. The three rivers form a 700 kilometres long "green belt", connecting almost 1.000.000 hectares of highly valuable natural and cultural landscapes, including a chain of 13 individual protected areas and 3.000 km² of Natura 2000 sites. This is the reason why, in 2009, the Prime Ministers of Croatia and Hungary signed a joint agreement to establish the Mura-Drava-Danube Transboundary Biosphere Reserve across both countries. Two years later, in 2011, Austria, Serbia and Slovenia joined this initiative. Together with Croatia and Hungary, the five respective ministers of environment agreed to establish the world´s first five-country Biosphere reserve and Europe´s largest river protected area. One-step at a time, the TBR MDD became reality: Hungary and Croatia (2012), Serbia (2017), Slovenia (2018) and Austria (2019) achieved UNESCO designation. The pentalateral designation was submitted in 2020 and designation finally achieved in September 2021.

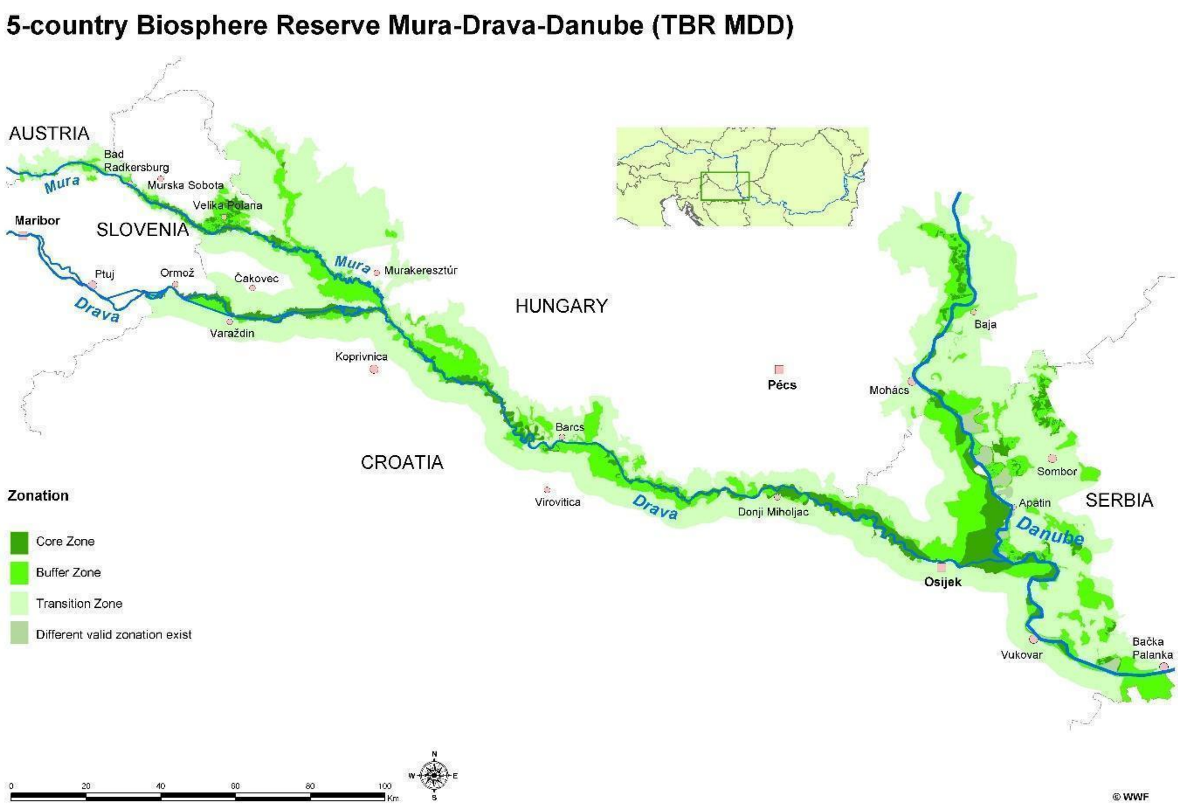


Figure 1: Map of the 5-country Biosphere Reserve Mura-Drava-Danube (TBR MDD)

The preparation process of the TBR MDD nomination has implied an intensive transboundary and transdisciplinary cooperation between protected areas, nature protection in general, water management, but involved also other sectors that are users of the rivers or their floodplain, such as local and regional governments, land use planning and tourism. The Mura-Drava-Danube Transboundary Cooperation Programme (2018, coop MDD) was elaborated within this process. It has defined the Guidelines for a dynamic river corridor, as well as a set of actions in the Transboundary Action Plan, all of which, when implemented, contribute to the successful implementation of the TRB MDD. These strategic planning documents have provided the TBR MDD-specific framework and basis for the present synthesis. The present synthesis report, as well as the set of studies conducted within the frame of the project, constitute implementation steps of the Biosphere Reserve, and of e.g. Objective 1.4. of the Guidelines along with sub-objectives 1.4.a-1.4.c (experts and scientists working cross-border on relevant research) of the Action Plan's Action 6 (Joint monitoring), as well as complementary steps within Actions 12 (TBR MDD Symposium) and 24 (Development of a joint river restoration plan for the TBR MDD).

The five-country Biosphere Reserve Mura-Drava-Danube constitutes a part of the Danube River basin, involving five of the seventeen Danube countries. Basin-level transboundary cooperation for water management is an element implied by the Water Framework Directive of the EU (WFD), having set the framework for river- and flood risk management planning at the basin level, thus making transboundary alignment for basins shared across borders inevitable. On a national and EU level, the individual River Basin Management Plans (RBMP) set the framework for the development and management of rivers and their floodplains. Flood Risk Management Plans (FRMP) are also under development as required per Floods Directive, in order to identify and manage areas that are under high risk from floods. From an ecological point of view, the EU Directives for FFH and Birds set the rules and framework. The biosphere reserve's management body is not a river basin management commission appointed to fulfil any EU states' WFD-related obligations, however, the nomination of the TBR MDD and the implementation of the biosphere reserve's goals across this pentalateral river system contribute to achieving the good ecological status of the rivers and, thereby, implicitly, to achieving the goals of the WFD. The approach proposed within the lifelineMDD project of data collection about and analysis of the status quo of the rivers, to define the need for action including, but not restricted to restoration and protection of the rivers, also fits in well with the EU's proposed Nature Restoration Law (EC, 2022).

Modern river management must consider not only economic, but also ecological and social aspects. This requires cooperation and communication in river management beyond administrative boundaries. In future, rivers are to be managed on basin level, including participation of stakeholders and the general public. It is also easier to achieve sustainable solutions that are widely accepted and feasible in the river basin, by making use of synergies, particularly in the areas of flood protection, aquatic ecology and local recreation. A variety of strategies and tools have been developed in order to incorporate these different aspects. For example, the River Basin and Risk Management Concept ("GE-RM") in Austria is created primarily for water bodies and catchment areas with a need for action regarding flood risk management and river basin management. Apart from the flood hazard, the ecological status, land use, spatial planning, third party rights etc. are considered. Another example is given by the WWF River Development Plan ("Flussentwicklungsplan", FEP) as an integrative planning instrument that shows the current status of the most important river functions in Austrian river basins in a 6-digit number combination and gives implications on a possible development. The FEP combines current data, guidelines and strategies in the river basin and generates added value from them. The lifelineMDD partnership acknowledges these existing ideas. In an effort to take first steps in a similar direction, a strategic integrated approach in river restoration based on scientific studies and a cross-sectoral learning process was developed.

1.2. Status of knowledge regarding biotic & abiotic parameters in the TBR MDD

The present synthesis summarises and combines the findings of the scientific studies conducted within the project lifelineMDD during 2020-2022, a first-time effort to analyse biotic and abiotic elements within the 5-country biosphere reserve Mura-Drava-Danube, building on existing data and previous studies. In the 19th and 20th century, when the demands for agricultural land, infrastructure and settlements increased and flood protection gained importance, the Mura, Drava and Danube rivers underwent systematic channelization. The river course was partially straightened and the flow was constrained into a narrow channel between protected riverbanks (Habersack & Piegay, 2007). The construction of river channelization structures like groynes, embankments and dykes led to the loss of floodplains or natural terraces, and shortened the river length by cutting off meanders and straightening the riverbed. Two key elements of natural dynamic river ecosystems are a balanced sediment regime and a dynamic riverbed. In natural rivers, gravel and sand is repeatedly mobilised at varying time-scales and is transported along the entire river. In channelized rivers, transport capacity is increased beyond the supply from upstream. Instream reservoirs for hydropower plants often significantly decrease the amount of sediment available for downstream river sections, or at least change the natural seasonal cycles and processes. The incision is further accelerated by influences that decrease sediment supply from upstream. The missing sediment is the result of a disturbed sediment connectivity caused by e.g. check dams or dredging. Changes in river basin habitats - both retrospective and predictive - are directly linked to the spread of numerous endangered species and habitats. Therefore, specific indicator species and habitats were selected as examples and their current distribution and population sizes were set in relation to the development of habitat areas in the river basin.

The collection of studies has had the aim to establish the knowledge base regarding vertical, lateral and longitudinal connectivity within the MDD bio-corridor, as basis for the TBR MDD River Restoration Strategy, which references this present compilation. Studies on bio-indicators birds and fish indicate the functionality of the existing habitats and dynamic processes related to connectivity: fish need diverse in-stream habitat conditions for all life stages of the occurring fish coenosis and longitudinal as well as lateral connectivity to reach spawning sites. River birds breed on gravel bars and steep banks created by longitudinal sediment flow and lateral dynamics. Studies on abiotic framework conditions have assessed the processes and dynamics strongly influencing habitat quality and connectivity in the river corridor: the sediment study shows stretches of sediment deficit/surplus, sedimentation and erosion trends, and reasons for sediment imbalance. Modelling climate change effects has shown how climate change alters connectivity (e.g. through different hydrological seasons) and biodiversity within TBR MDD. Mapping of river training structures, in the present, as well as put into a historical context, shows the status quo of structures altering hydromorphology in the whole TBR MDD.

All studies have formulated, to the extent possible, conclusions and action recommendations based on sound science, which have been jointly reviewed by the partnership to compile the most synergetic and beneficial recommended measures that serve as a basis for action recommendations and the commitment called "River Restoration Strategy".

We do not present in this synthesis document each study's methodology in details. Below, you will find a brief summary of each of the studies' main findings. Annex 1 of this study contains the explanation of the river sections used in each of the studies and referenced in the result summary, while Annex 2 lists the main outputs from each study, and gives a very brief summary of the data collection and analysis methods applied in the study to obtain those results. Each study is publicly available on the project lifelineMDD website and can be consulted to obtain a deeper understanding of the sources and methods applied to produce the data that is used for the present synthesis. Chapter 3 explains the theoretical framework and the method of compiling and synthesising all study results to obtain the overlay maps and quantitative synthesis conclusions.

1.2.1. Fish population status report

Over 60 fish species are known to colonise the Mura, Drava and Danube, including a high share of protected species. During a sampling survey in 2021, covering nine sampling sections[1] in Mura and Drava 53 species were recorded with electrofishing and eDNA sampling methods. A major reason why there are many fish species with healthy, self-reproducing populations (see fish abundance and biomass indicators in Figure 2) is that

[1] For an explanation of the river sections used in this study, see Annex A3.

the Mura and Drava rivers are freely migratable throughout this river corridor (~300km). Another important reason is the still existing hydro-morphological dynamics and the resulting habitat diversity, which is unique for rivers of this dimension in Europe.

The focus of the investigations was on the longitudinal gradient of the fish community in Mura and Drava as well as the lateral gradient in the Danube's backwaters. Rheophilic fish account for a much higher community share in the Mura compared to the Drava. The residual flow stretch in the Drava (SR) shows a higher share of rheophilic fish compared to the other Drava sections below the hydropower plant.

The most abundant species in the Mura and the Drava was the bleak (*Alburnus alburnus*). In terms of fish biomass, the three dominant species were the nase (*Chondrostoma nasus*), followed by barbel (*Barbus barbus*) and chub (*Squalius cephalus*). Additionally, the highly endangered cactus roach (*Rutilus virgo*) had significant shares within the rheophilic guild along the Mura and Drava sections.

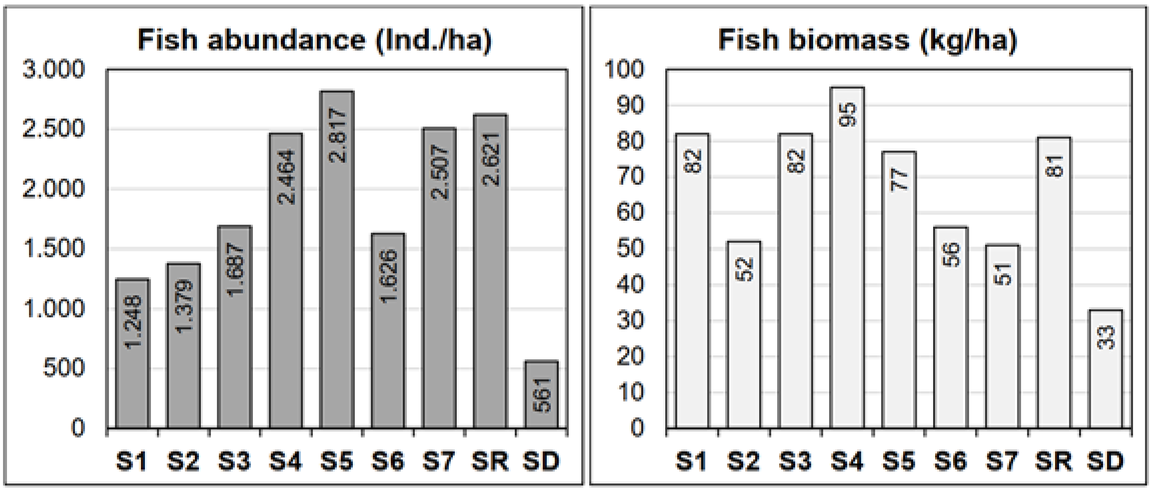


Figure 2: Standardized fish abundance (ind/ha) and fish biomass (kg/ha) per sampling section.

In the surveyed Danube section, the fish communities with bleak and roach (*Rutilus rutilus*) as common species in both pilot areas correspond to the character of the floodplain in the lowlands. Inside the Special Nature Reserve (SNR) "Gornje Podunavlje" the only natural connection to the Danube is located at the Sakajtaš site, however, it is dependent on high floods. Bajski Kanal and Mrtva Baračka are completely separated from the Danube and the water level there is regulated by human activities. The SNR "Karađorđevo" was generally richer in fish biomass with numerous autochthonous and endangered species. All sites within SNR "Karađorđevo" are exposed to tidal waves. Lovrenac and Lovrenac-Račva, the localities that are the furthest from the Danube, are least exposed to water renewal. These are eutrophic, swampy backwaters, and may be completely silted up in the near future due to the accumulation of fine sediments. The Lovrenac Canal is also the location where the Serbian partnership implemented a pilot restoration activity, restoring the canal through sediment dredging, to prolong the backwater's lifespan and improve its habitat quality.

The presence of hard embankments and morphological regulations has clear negative consequences for the riverine fish community. Based on the data collected it is assumed that the artificial flow fluctuations caused by the HPP Donja Dubrava drastically reduce the amount of fish in sections below the power plant.[2]

The number and density of non-native species occurring in the TBR MDD is increasing with river length. The relative abundances of non-native species are generally much higher in the Danube than in the Drava and Mura. In particular, Ponto-Caspian gobies spreading upstream from the Danube and lower Drava River could cause serious ecological instability or community shifts (see Figure 3).

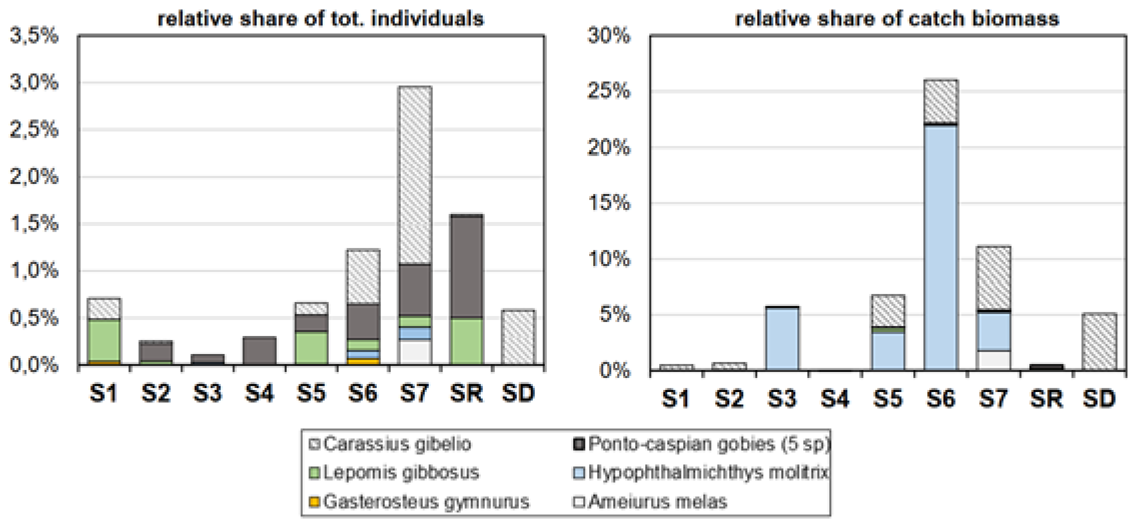


Figure 3: Relative dominance of non-native fish species within the fish community in the sampled sections. Values based on total catch number (Ind.) and total catch biomass (kg). Status of C. gibelio in Europe/MDD-region not fully resolved.

The generally low densities of predatory fish species and the widespread absence of juvenile predators are remarkable, although habitats for reproduction and all age stages are present. This phenomenon indicates high fishing pressure.

1.2.2. River birds breeding report

Breeding birds, which depend on habitats created in highly dynamic riverine ecosystems, such as steep banks, gravel and sand bars, are endangered on the European level, mainly due to habitat loss. In the lifelineMDD Bird study seven river breeding birds were chosen as indicator species and monitored throughout the TBR MDD for the first time based on a harmonised counting method, over two breeding seasons: 2021 and 2022. Four of the

[2] The effects of the hydropower dam on the downstream river are detailed in the Hydropeaking Study

species are gravel/sand bar breeders: Little Tern *Sternula albifrons*, Common Tern *Sterna Hirundo*, Common Sandpiper *Actithis hypoleucos*, Little Ringed Plover *Charadrius dubius* and, three are steep bank breeders: Kingfisher *Alcedo atthis*, Sand Martin *Riparia riparia*, European Bee-Eater *Merops apiaster*. These target indicator species have a complex ecology or special ecological needs; therefore, they indicate the conditions of their habitats well. The species themselves, their distribution (presence or absence), number of their breeding sites and numbers of breeding pairs give us a good insight into the conditions of the rivers Mura, Drava and Danube.

A prolonged period of high-water levels in 2021 adversely affected the nesting birds on the Drava and Danube. Nevertheless, the monitoring continued in 2022 allows for some reliable conclusions. Results (Figure 3) indicate that the lower parts of the Mura (Mura II, Mura III) and the upper parts of the Drava (Drava I, Drava II) are most important for bar-breeding birds in the TBR MDD, whereas the Drava (Drava II, Drava III) and Danube (Danube II) are more important for bank-breeding birds. Common Kingfisher was the most evenly distributed species along the study area; Little and Common Terns were the rarest nesting bird species, recorded only in Drava II section

The bird survey confirmed the national and international importance of the Mura, Drava and Danube River between Ceršak (SLO) and Bačka Palanka (RS) for these targeted species. For instance, 7.000-10.000 pairs of Sand Martins and 200-450 pairs of Bee-eaters are breeding in natural steep banks. Information on the observed birds' occurrence and linear breeding densities along the Mura, Drava and Danube rivers provides valuable clues about the state of the riverine habitats and processes on separate parts of the river channel (see Figure 2). In addition, results show that restoration projects are essential for connectivity, as in the heavily regulated upper reaches of the Mura River, indicator bird species were only recorded in the areas of the lifelineMDD pilot restoration site at Hrastje-Mota or other previous restoration sites on the Austrian riverbank (Gosdorf, Sicheldorf).

According to the analysis of bird breeding data also the most important segments with highest density and/or river breeding bird biodiversity of rivers Mura, Drava and Danube were identified. These have to be priorities in the conservation of natural or near-natural river segments and are as follows:

- **Mura River**:
    - opposite the previous segment, long stretches of upper Mura between Ceršak and Gornja Radgona (rkm 110-145)
    - between Križovec (HR) and Domašinec (HR)/Muraszemenye (HU) (rkm 045-065) and
    - upstream of the Mura-Drava confluence at Legrad (rkm 000-005)
- **Drava river**:
    - between Vízvár/Heresznye (HU) and Križnica (HR) (rkm 175-190)
    - between Legrad and Hlebine (rkm 215-235)

- Drava upstream of Barcs to Gornje Predrijevo upstream of Noskovci (rkm 120-160)
- between Repaš and Čambina (rkm 200-210)
- short stretches downstream of Dubrava lake (rkm 240-250)
- in the area of Trnovec (rkm 290-295);

- **Danube River:**
  - one segment in between Aljmaš and Borovo, upstream of Vukovar (rkm 1340-1380)
  - and short stretches of Danube in the area of Šarengrad-Bačka Palanka (rkm1295-1305)
  - area of Batina/Bezdan (rkm 1420-1430) hold only few characteristic bird species of pristine riverine habitats. Such sections should be considered a priority in planning future river restoration projects.

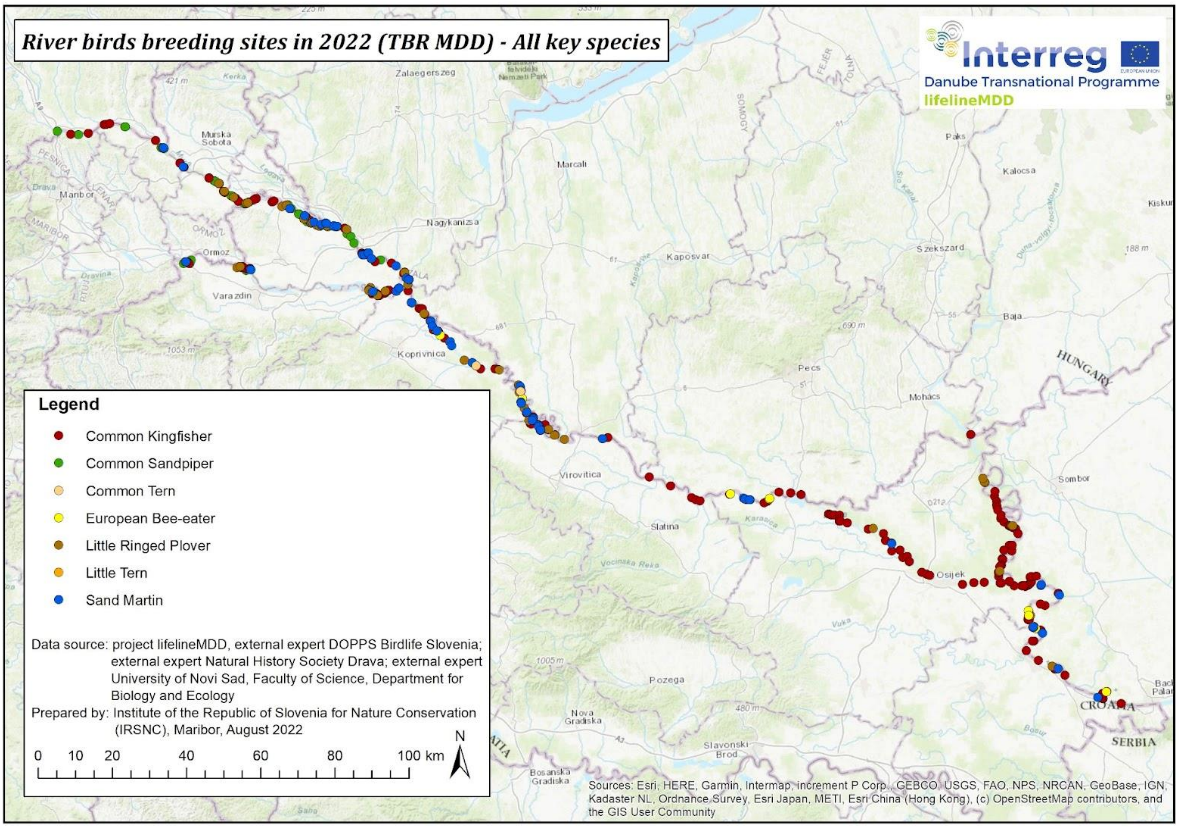


Figure 4: Distribution of seven target bird species (Little Ringed Plover Charadrius dubius, Common Sandpiper Actitis hypoleucos, Common Tern Sterna hirundo, Little Tern Sternula albifrons, European Bee-Eater Merops apiaster, Common Kingfisher Alcedo atthis, Sand Martin Riparia riparia) registered in the Mura, Drava and Danube riverbed between Ceršak (SLO) and Bačka Palanka (RS), based on registrations of presumably nesting individuals during the 2022 censuses

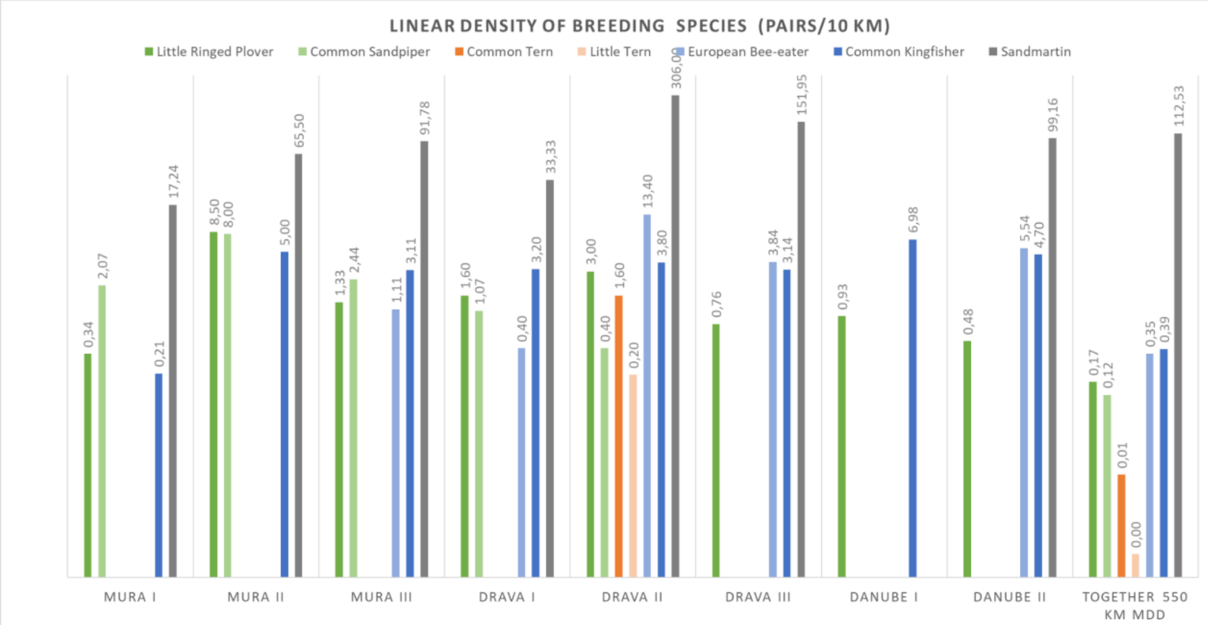


Figure 5: Linear density (pairs per 10 km) of the seven target bird species (Bar-breeders: Little Ringed Plover Charadrius dubius, Common Sandpiper Actitis hypoleucos, Common Tern Sterna hirundo, Little Tern Sternula albifrons & bank-breeders: European Bee-Eater Merops apiaster, Common Kingfisher Alcedo atthis, Sand Martin Riparia Riparia) registered in the Mura, Drava and Danube riverbed between Ceršak (SLO) and Bačka Palanka (RS), based on registrations of presumably nesting individuals during the 2022 censuses. The values of the "y" axis are displayed on a logarithmic scale.

During the bird survey, threats were also identified which mostly included all kinds of anthropogenic activities in the riverbed that clearly took place during or shortly before the breeding season: gravel excavation, off-road driving and prolonged recreational use (i.e. picnic, fireplace, boat stop).

1.2.3. River training structures

The study had aimed to increase the knowledge of river morphology and habitat conditions and to provide the essential fundament for river restoration and management of protected areas in the Transboundary Biosphere Reserve Mura-Drava-Danube (TBR MDD). The main result of the study consists of two major data sets. Firstly, it provides an inventory of river training structures, based on a previous study, updated based on new satellite imaging and field mapping inputs (Figure 6). A mapping of river training structures has existed (status 2012, Schwarz U. 2013), however, this has now been updated to capture deterioration that has occurred since then, as well as structures that have been built in the almost ten years since the previous study. Secondly, it shows, for the first time in this detail and for this area, the historical habitat distribution within the river corridor, in the TBR MDD, which is of major importance as a potential reference state definition and for future restoration activities. For the first time the entire rivers of the TBR MDD, including their banks, and their active and historical floodplains are mapped delivering valuable information for restoration endeavours in the river corridor.

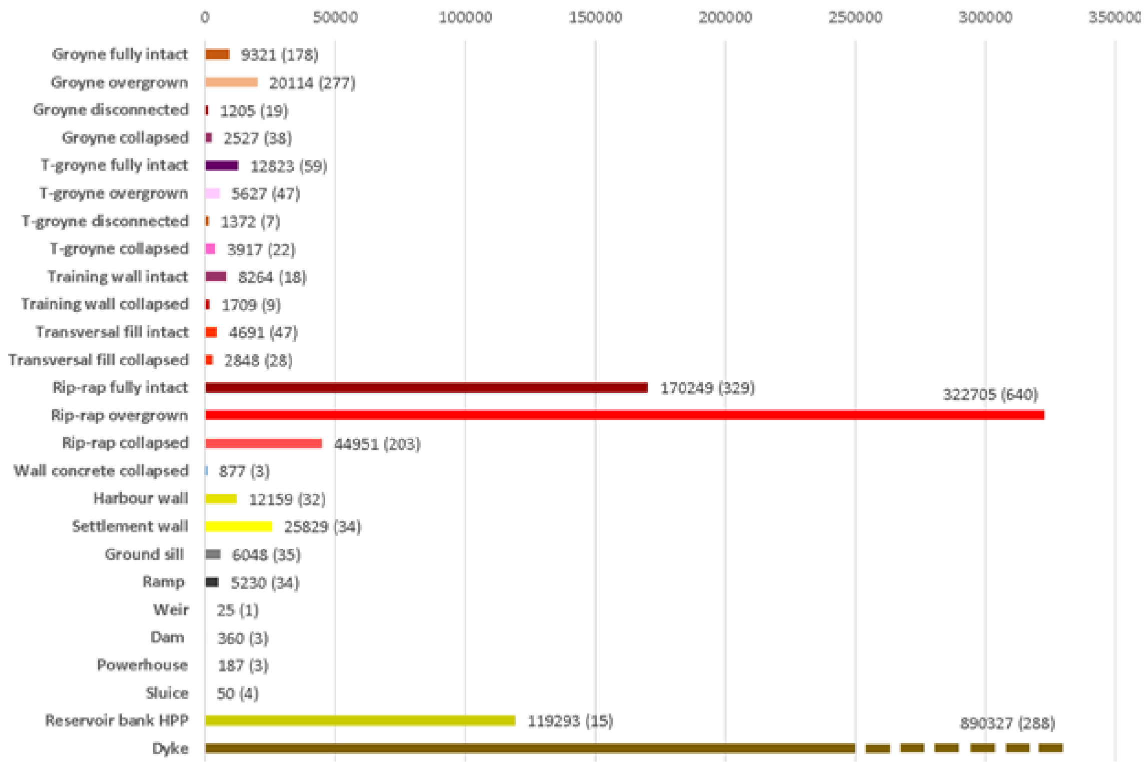


Figure 6: Total distribution of river training structures in the entire MDD TBR (in m).

Shrinkage of the floodplain is well recognizable across the complete TBR MDD: the total sum of the length of flood defence dykes is approximately 890 km, which is more than the entire length of the three rivers. In other words, flood dykes are present at least on one bank at full length. A look at the extent of river regulation (density of training structures per river section) shows that this is quite high: only one single 5 rkm segment on the lower Drava contains no regulation works, two segments some 200 m and all other segments include > 1 km regulation, the most impacted up to 14.4 km (as based on the 10 rkm segments on the Danube counted both banks together; the lengths count all regulation works together, rip-rap, training walls and groynes, but not the flood dykes).

The historical mapping is using to a major extent the Second Austrian Military Survey (~1860) partially complemented by the First Austrian military survey (~1780) as well as additional historic sources for some of the river sections (Austrian State Archive 2021),. When compared to the current (2012) status of the river corridor, this has yielded conclusions regarding the extent of habitat loss. Comparing the major riparian habitats for these two states (historic and present), the loss over time, but also a shift in habitats is obvious (see Figure 7). There has been a loss of 42% in the total area of the main channel surface, including all main side branches and a loss of 92% in the number and area of side channels. The area and number of gravel and sand bars have decreased by 84% and 67% respectively. Looking at the loss of islands including main river channel and floodplain islands on side channel systems (islands must include riparian forest, single gravel and sand bars don't count), the upper courses of Mura and Drava (anabranching system) are strongly affected (See Figure 8).

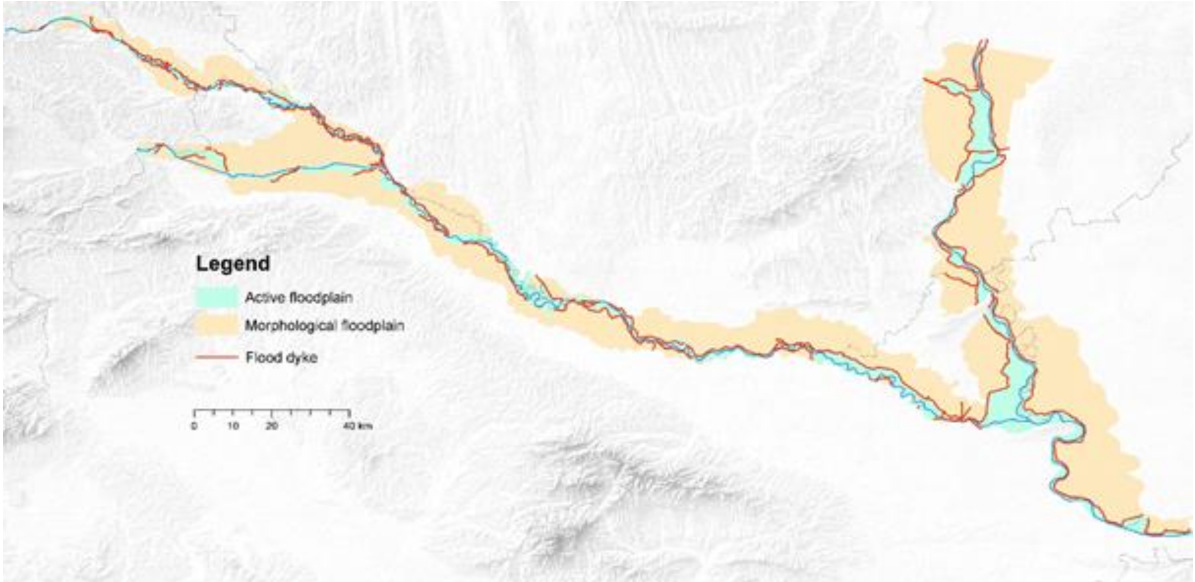


Figure 7: The outline of flood defence (red lines) and the morphological (green) as well as active floodplain (yellow) indicating the considerable loss of floodable area as such but also the remaining spots.

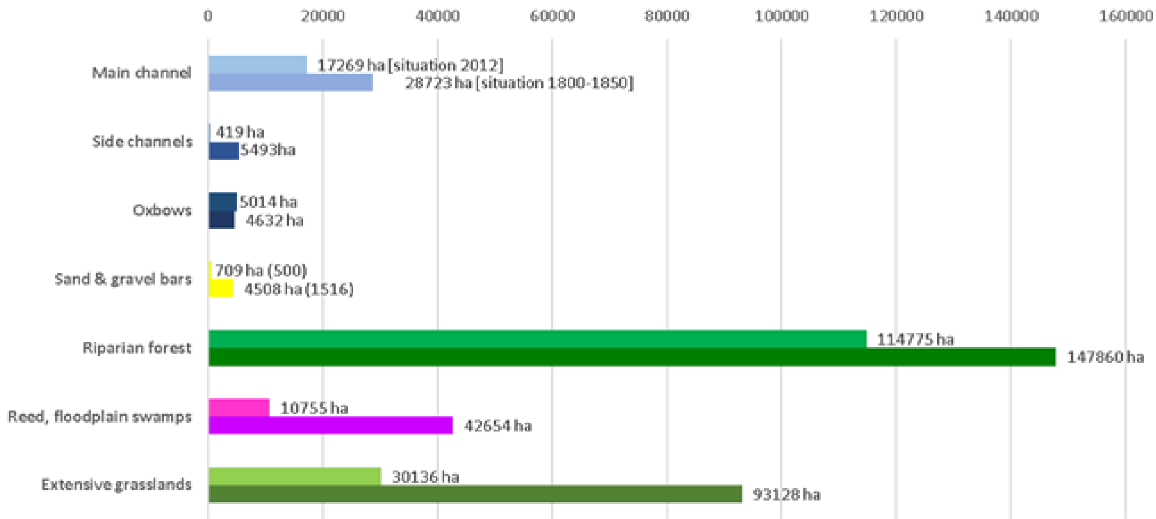


Figure 8: Total project area with river and floodplain habitats (for side channels, oxbows and bars also the number in brackets). The upper bar represents the situation in 2012, the lower bar the situation before major regulation (1800-1850).

The study also concluded that several important meander bends or short anabranching reaches that remain without regulation can serve as reference sites for restoration activities. The GIS data of the habitat mapping based on historical maps may additionally serve for defining reference states. Together with the remaining active floodplains and available lateral space, restoration activities could have success, in particular, if the sediment deficit caused by upstream dams can be reduced or compensated.

1.2.4. Sediment mobilisation study

From January to March 2022, a widening of the Mura river in Hrastje Mota in Slovenia was implemented. The sediment mobilisation study is in close connection with this measure. The expectation was that widening of the Mura channel in combination with rock structures would change the hydraulic conditions in this area. With the progression of lateral erosion, the resulting decreased flow velocities should have positive effects on the stabilisation of the riverbed in this section and further downstream.

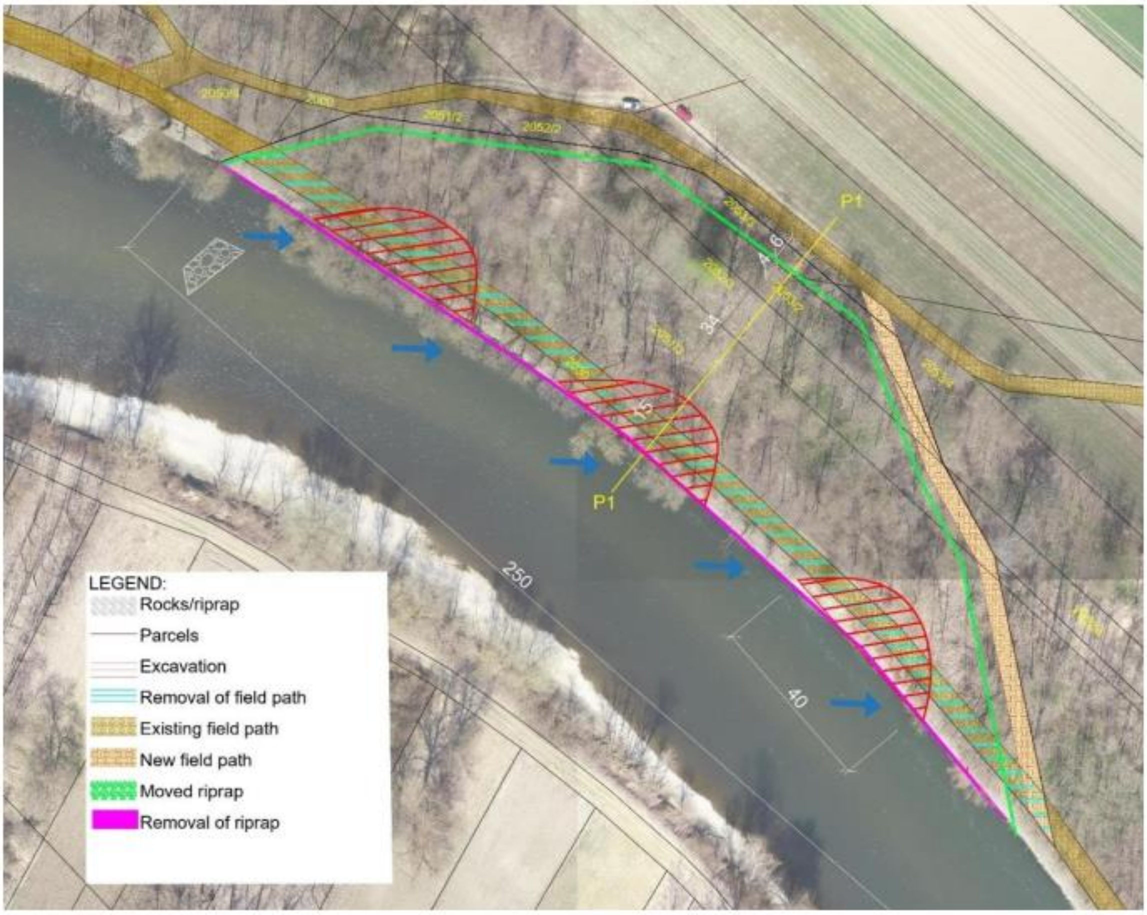


Figure 9: Plan of the restoration measure

With detailed hydraulic analyses, the impact of the planned works was studied. At the inflow into the widened area, the hydraulic conditions were modelled or measured and analysed in detail. Derived results should help to optimise the inflow section. The flow analysis was used for a detailed spatial visualisation of the change in flow velocities (direction and extent) and the change in shear stresses between initial and intermediate conditions. This provided a preliminary assessment of the erosion-prone sections along the excavated coves. A comparison with the final situation proved the effect of the measure concerning the reduction of velocity. Additionally, the influence of lateral erosion on the hydraulic characteristics of the respective Mura section (velocity in the widening area) was analysed and the transport of deposited sediment from the indentations to the riverbed was estimated.

The hydraulic analysis confirmed that the planned measures altered the decisive parameters (velocity, depth, shear stress) as it was aimed. Due to the removal of the bank protection, higher discharges at the exposed bank lead to bank erosion and sediment mobilisation. This provides gravel to the Mura River, mitigates the effects of riverbed deepening and widens the main channel. The implemented measures thus create conditions consistent with the objectives of the lifelineMDD project.

1.2.5. Sediment balance and transport study

In the past, the morphology of the Mura and Drava rivers ranged from predominantly braided, anabranching river systems along the upstream sections to meandering, single-thread main channel with smaller side-channels and typical floodplain waters further downstream and in the Danube section of the TBR MDD (see Figure 10). A peculiarity of this area is that some of the river sections still retained parts of their characteristic morphology and the associated dynamics. The comparison of the more natural historical condition with the current state showed that the original river type has been transformed into a mostly single-threaded channel system with decreased widths and sinuosity. Systematic channelization and sediment retention in the upstream sections started in the 19th century.

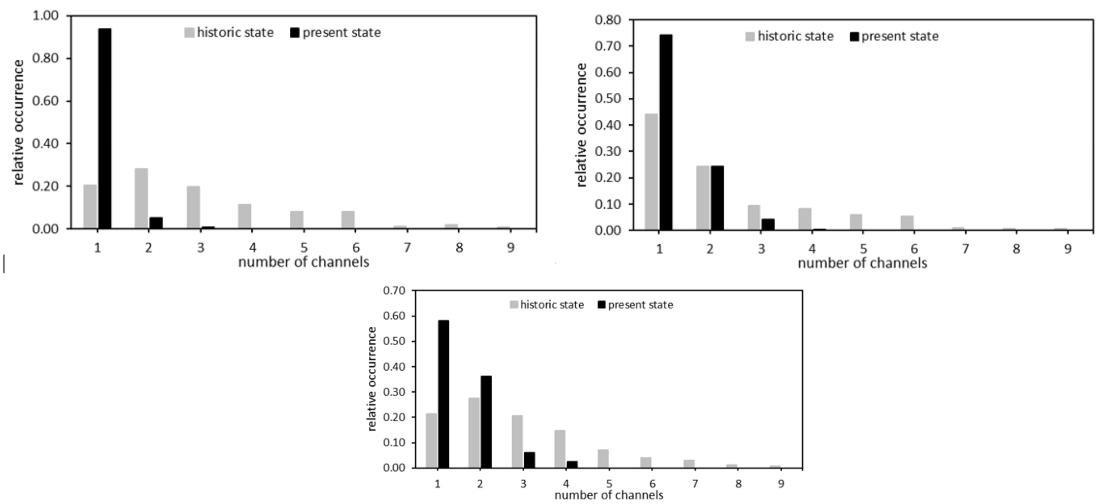


Figure 10: Upper left: Relative occurrence of number of channels along the Mura; Upper Right: Relative occurrence of channel numbers along the Drava; Bottom centre: Relative occurrence of channel numbers along the Danube

The objective of this study was to investigate sediment transport conditions along the TBR MDD river network in order to identify deficiencies, to prioritise sections for restoration and to recommend appropriate restoration measures. The straightening of the Drava and Danube rivers resulted in a reduction in length of 35% and 23%, respectively (see Figure 11). The greater depth of water in the narrowed channel, the increased gradient, and the concentration of flood flows between the dykes increased the capacity for sediment transport. In addition, bank protection impeded lateral dynamics, and the increased uniformity of channel widths reduced bed morphodynamics.

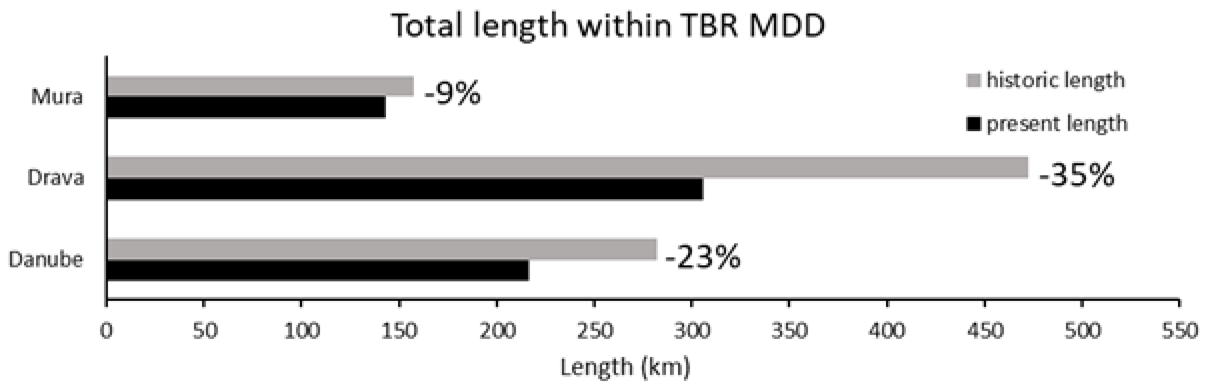


Figure 11: Length of the main channel of the Mura, Drava and Danube as during the second military mapping survey (1810s-1850s, grey) and in 2012 (black).

While transport of sediment increased in the channelized rivers, the supply of sediment has been retained in reservoirs by transverse structures upstream of the TBR MDD for more than a century. Since then, almost no bedload enters the TBR MDD due to the series of hydroelectric power plants upstream. Consequently, the rivers in the TBR MDD incised into their alluvium, while siltation during floods increased the elevation of the floodplain. The deposited sediments behind the protected banks were and still are largely not accessible to the river for erosion. In general, riverbed incision and aggradation of fine sediments led to decoupling of the river and the adjacent floodplains.

The analysis of the low water levels measured at the gauges showed severe incision (see Figure 12).

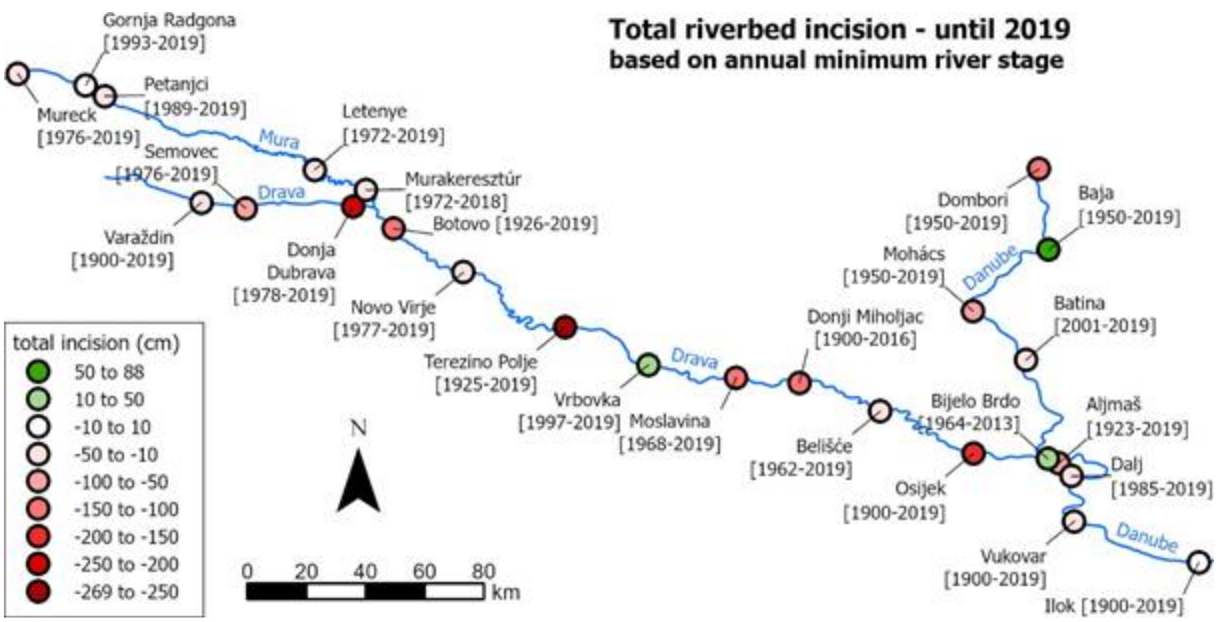


Figure 12: Total incision at gauging station cross sections based on minimum river stage analyses.

The thickness of the gravel layer on the Mura River between Austria and Slovenia is very low and the riverbed is rapidly approaching the underlying tertiary fine material, threatening a riverbed breakthrough. The bedload supply from the erosion of riverbanks upstream is not sustainable without additional sediment supply, and will not last for long. On the Drava River, after the construction of the hydropower plants, suspended sediment transport at Botovo has decreased by 72%, while the reservoirs show massive sedimentation. According to modelling, a gravel volume of about 45,000 m³ per year is necessary to keep the channelized Mura between Austria and Slovenia in a dynamic equilibrium (Klösch *et al.*, 2021). Currently, about 29,000 m³ are eroded from the gravel bed along the border between Austria and Slovenia every year. A widened and more sinuous channel would reduce the required bedload supply to 20,000 m³ per year. For comparison: the implemented pilot site Hrastje Mota may contribute about 30,000 m³ in total through bank erosion (Pomgrad VGP d.d., 2022) and the bank consists partly of fines, which are transported in suspension and hence are not bed forming. Larger measures would strongly decrease the sediment transport capacity while more sediment could be mobilised during construction. In the reach of the larger Drava River at Botovo, where bedload transport of about 50,000 m³ per year was measured (Rákóczi and Szekeres, 2004), again the amount of required bedload supply would be significantly reduced in a widened and more curved channel.

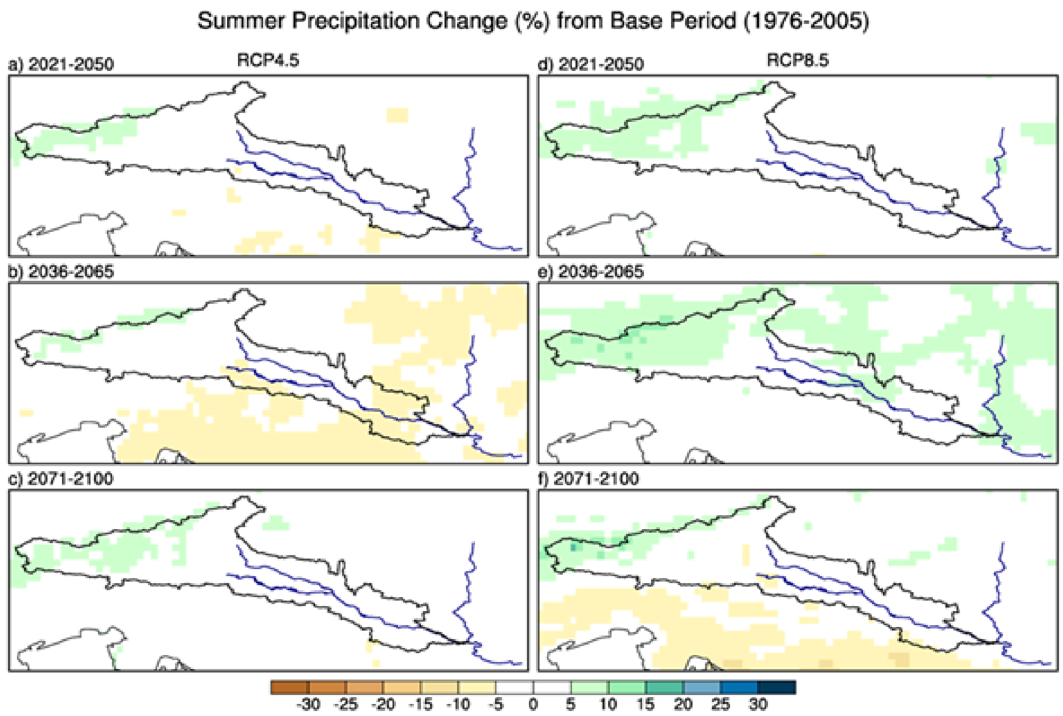
High priority for restoration should be given to the Mura between Austria and Slovenia, where due to the incision the riverbed threatens to lose the gravel and to eventually break through into finer sediment, which would be hard to restore based on ecologically oriented methods. For bedload augmentation, upstream reaches should be preferred. Otherwise, the synthesis map helps to identify reaches with highest restoration needs.

1.2.6. Climate change and Hydrology study

The objective of the study was to predict future climate change signals in terms of temperature and precipitation and climate extremes for two emission scenarios.

In general, there will be a warming and a shift in precipitation patterns. Compared to the 1976-2005 reference period, summer months are projected to be 10% drier and winter months up to 20% wetter by the end of the century (see Figure 13). The decrease in summer runoff is particularly pronounced by the end of the century. An average increase in mean winter temperature (December-February) of up to 2.2°C and 4.2°C, respectively, by 2100 under different scenarios can have huge impacts in areas with snow cover, as the amount of snow in winter is reduced and spring snowmelt consequently begins earlier. This can lead to increased water stress later in the summer months.

(a)



(b)

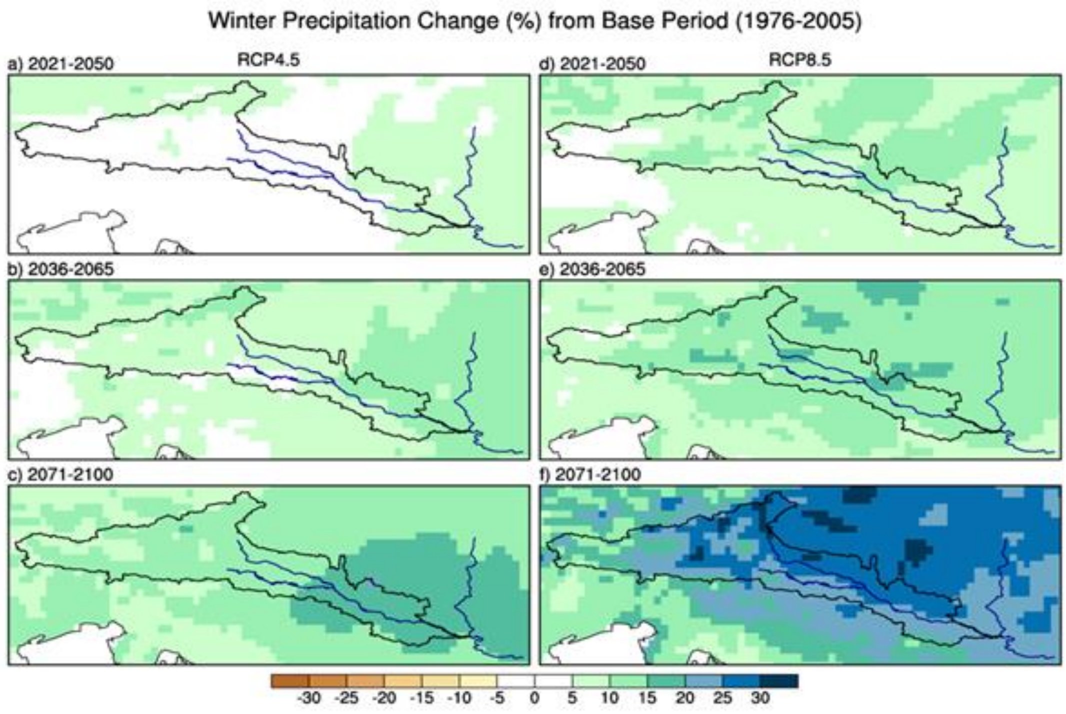


Figure 13: Spatial distribution of summer (a) and winter (b) precipitation changes (in %) from reference period 1976-2005 based on ensemble-mean of five selected models for different future periods (rows) under two emission scenarios (columns)

The decrease in summer runoff reflects the expected increase in evapotranspiration and decrease in precipitation. Higher temperatures and lower precipitation during the extended growing season will affect agriculture and forestry. Artificial irrigation is expected to increase water demand in the study area. Thus, the extension of the growing season can be used for agriculture. A simultaneous decrease in summer runoff and increase in temperature may significantly affect water quality. This could negatively impact the entire ecosystem, and the changes may cause shifts in aquatic and terrestrial species composition.

A quantification of extreme indices shows a steady increase of heat waves and heavy precipitation events until the end of this century (Figure 14). There are increasing trends in summer days and tropical nights. In regions where it is already hotter, this trend is even stronger. Longer hot periods are predicted for these regions in the future. There is evidence that night-time temperatures will warm more than daytime temperatures. This will lead to a sharp decrease in frost and ice days and threaten tourism and winter sports in the region. Precipitation-related indicators predict an increase in heavy precipitation episodes (Figure 15). This usually leads to severe flood events.

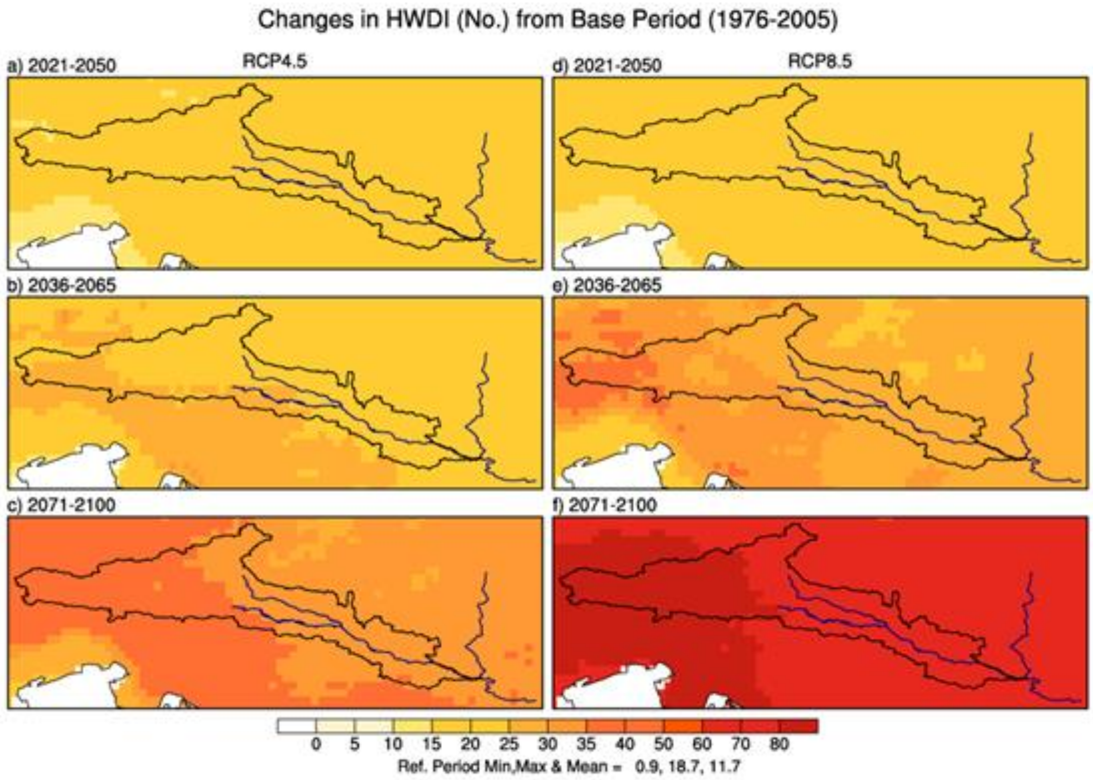


Figure 14: Differences in the heat wave duration index using an ensemble mean of five selected models. The differences are determined through calculating the means of each time-period and comparing them with the mean of the reference period (1976-2005)

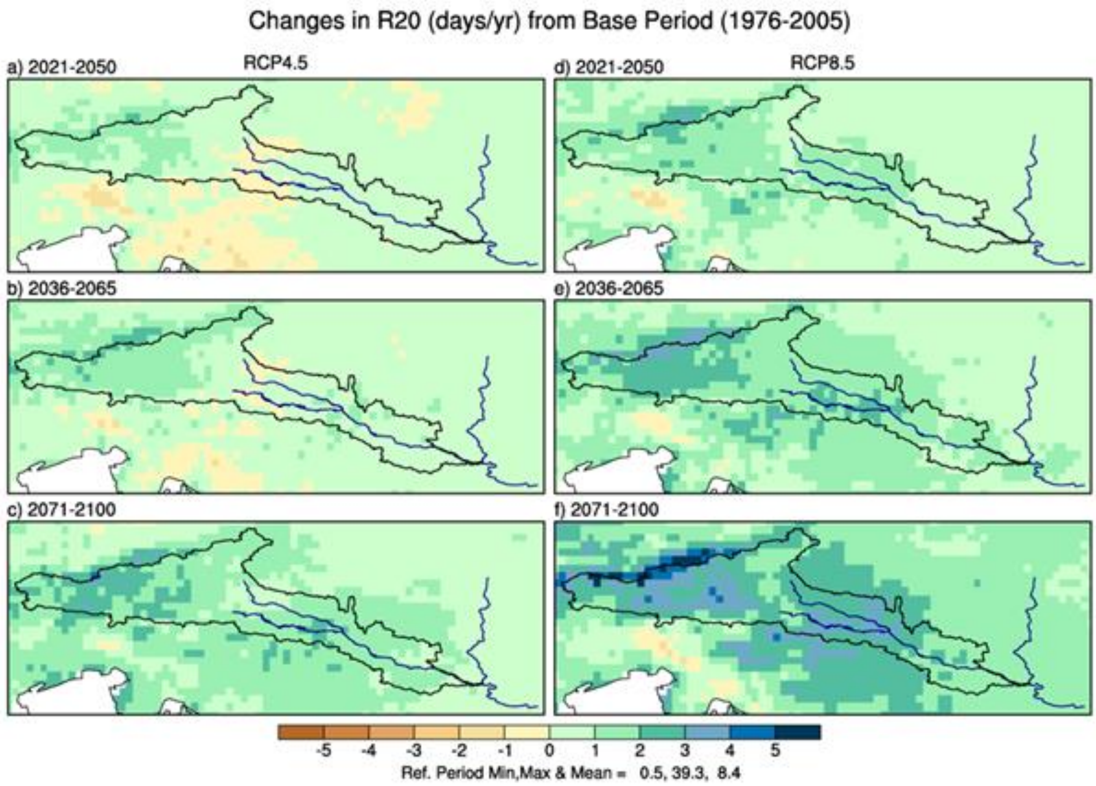
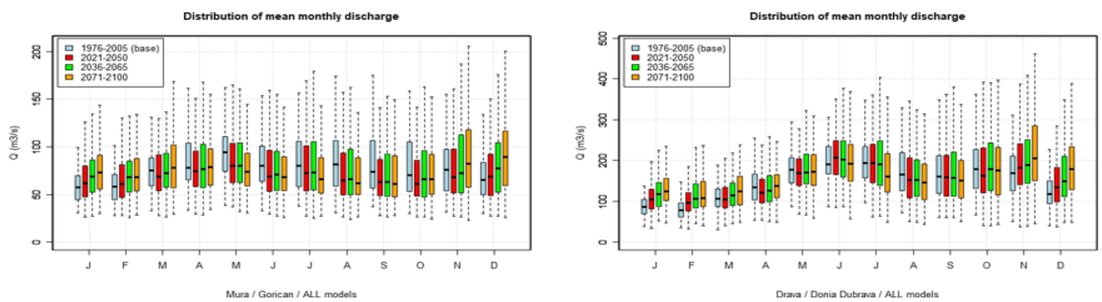


Figure 15: Differences in number of heavy precipitation days i.e., greater than 20mm symbolized by R20, using an ensemble mean of five selected models. The differences are determined through calculating the means of each time-period and comparing them with the mean of the reference period (1976-2005).

A model to simulate hydrological processes and produce hydrological prognosis for quantifying the potential impacts of climate change on the hydrological regime of the Mura and Drava rivers within the TBR MDD was developed. This is one of the most important steps in the development of climate change adaptation recommendations for the TBR MDD and essential for the future development of the basin.

Hydrological analyses (Figure 16) for the Mura and Drava river basins indicate the changes by the end of the next century as described before. The results of the reviewed hydrological climate change studies for the Danube are very similar to the projections for the Mura and Drava.

(a)



(b)

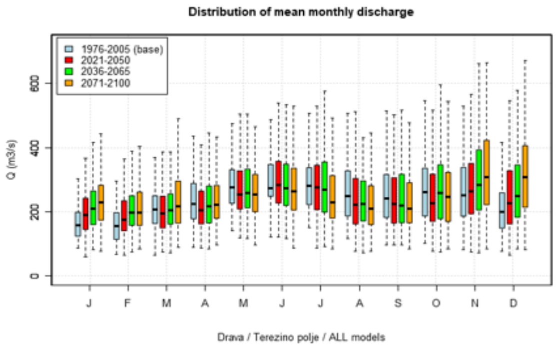


Figure 16: (a)Left: Distribution of mean monthly discharge for all model combinations at Mura/Goričan; Right: Distribution of mean monthly discharge for all model combinations at Drava/Donja Dubrava; (b): Distribution of mean monthly discharge for all model combinations at Drava/Terezino Polje

1.2.7. Hydropeaking study

Having recognised the need for a more in-depth study of the effects of energy-economically optimised operation of hydropower plants early on after the start of the project implementation, the lifelineMDD consortium found the resources to commission the study and it could be completed on time for its results to be included in the present synthesis. The research team took a closer look at the hydrological and potential ecological consequences of hydropower plant operation, based on available data and on the state of scientific knowledge. For doing so, it used data from hydropower plant (HPP) operators and hydrographic services operating on the Drava across Austria, Slovenia and Croatia and analysed the frequency and amplitude of increase and decrease events, with a specific focus on the effects of operating the most downstream HPP. Compared to the other studies, mostly focused on identification and assessment of the current status, it then went one step further, and described possible mitigation measures. These measures therefore go one step further in concreteness compared to the other studies.

Using two different methods for the determination of the presence and extent of hydropeaking[3], the study found several results which are highly significant for further research as well as possible mitigation measures. The amplitude of the power plant operation in Donja Dubrava reaches heights of up to 2 m and even about 100 km downstream of the plant, amplitudes of ca. 0.5 m can still be detected (Table 1). The morphological conditions include a wide discharge profile with shallow gravel banks, which leads to the conclusion that there is a considerable risk of so-called pool-trapping, and also that consequently high predation mortality by e.g. bank related birds may occur. The research team determined the level of hydropeaking that occurs most often, and is therefore the level for which ecological effects should be studied in a targeted way. It also recognised the critical period (1-2 months) of the year during which mitigation measures or a reduced hydropeaking operation could bring the most effects in terms of decreased loss of fish. The potential critical period was recognised based on the evidence from

[3] For details regarding methodology see original study or Annex A2.

literature combined with information related to the presence of fish species on this section of the river. The team working on this study also considered the correlation between results found by the fish study downstream of Donja Dubrava and hydropeaking to be a highly probable reason for the reduced amount of fish in sections below the power plant.

Table 1: Donja Dubrava hydropower plant - summarised results for the scenarios relevant to the ecological assessment.

Station/hydrographs		1	2	3	4
Distance to PP (rkm)		5,4	20,4	47,1	94,3
amplitude increase events	(m^3/s)	250 - 375	225 - 340	175 - 260	225 - 340
	baseflow Q95 (cm)	150 - 210	120 - 180	90 - 130	50 - 70
	baseflow MQ (cm)	110 - 160	80 - 130	70 - 110	30 - 60
max. flow rate increase events	(m^3/s)/h	125 - 250	80 - 150	40 - 80	15 - 40
	baseflow Q95 (cm/min)	1.3 - 2.5	0.8 - 1.5	0.4 - 0.7	0.2 - 0.3
	baseflow MQ (cm/min)	1 - 1.8	0.5 - 1	0.2 - 0.5	0.1 - 0.2
max. flow rate decrease events	(m^3/s)/h	125 - 250	70 - 120	40 - 70	15 - 35
	baseflow Q95 (cm/min)	1.3 - 2.5	0.7 - 1.3	0.3 - 0.7	0.2 - 0.3
	baseflow MQ (cm/min)	1 - 1.8	0.5 - 1	0.2 - 0.5	0.1 - 0.2

(rkm – river kilometer, Q95 – flow value exceeded 95% of time, MQ – mean flow; due to high redundancy, amplitudes only refer to increase events)

The study concluded that the maximum flow rate of decrease events must be limited to 50-60 m^3/s per hour with reference to the Donja Dubrava hydrograph in order to significantly reduce the risk of fish stranding over the first 50 kilometres downstream of the hydropower plant, which could also reduce the stranding risk for benthic invertebrates.

Based on the literature available, consideration for mitigation measures are proposed, which would improve flow by attenuation of the flow rate of downramping events (reduction of the stranding risk), attenuation of the flow rate of up-ramping events (reduction of the drift risk), reduction in amplitude (reduction in hydropeaking-related impacts on habitat alterations), attenuation of the flow rate of up- and down ramping events and reduction in amplitude/reduction in drift and stranding risk and hydropeaking impacts on habitat alteration. Potential direct measures available according to state-of-the-art know-how consist in: operation restriction of a storage hydropower plant (ecologically adapted operation mode), attenuation of hydropeaking waves through a diversion channel, optimised management of existing retention volume or by-pass valves. A combination of several direct and indirect measures may be required to achieve the greatest ecological effect. Some technically available options may not be feasible due to nature protection regulation (e.g, Birds & Habitats Directives) and overall restoration must comply with EU Water Framework Directive requirements. With regard to the overall hydrologically stressed Drava, where hydrological stress should be reduced in general to improve conditions, additionally, the residual flow stretches in Slovenia and Croatia are of particular importance, as they can form "indispensable ecological stepping stones" for the downstream free-flowing sections if the habitat is maintained and improved by ecologically optimized eFlows and hydropeaking is kept away.

2. Methodology

Due to a large amount of data (hundreds of filed samples of bird observations and single river training structure records as well as measurements and historical analysis of cross-sections), "assessment segments" carrying the necessary information and allowing basic overlays and joint analysis were necessary and therefore introduced. The segments' length is 10 rkm for the Danube and 5 rkm for the Drava and Mura rivers (altogether 114 segments, 28 for Mura, 64 for Drava and 22 for Danube). However, data were not collected in sufficient spatial resolution for all studied aspects. In particular, data from fish samples and the data referring to the continuous channel incision and sediment balance have insufficient spatial resolution to be overlaid. Information from these studies were considered for the qualitative assessment.
This chapter will show only the most important findings, without explaining all the parameterisations and without generating overlay assessment tools which could be further developed in future projects. The individual work package reports contain many such details that go beyond the scope of this chapter.

We explain the approach we implemented to compare and combine individual topics and parameters below. To allow a concise and general assessment, all contents were reduced to a three-class assessment. This logic follows the classification generated based on the bird data, aims for compatibility based on the lowest common denominator and reduces complexity.

2.1. Suitability of indicators

The **historical indicators** cover *the reduction of the historical number of channels/side-channels* and *the sinuosity* (reduction of river length, in particular in meandering reaches). Both are variables that indicate river morphology and therefore their change, particularly reduction over time is used as a strong indicator for the degradation of river systems over time (over the last two centuries). Width variability is another important parameter for the hydromorphological state, the analysis of which provided valuable input to the understanding of habitat loss, supporting the two parameters of reduction of side channels and sinuosity. Its interpretation requires some knowledge of the history of river regulation in this area, which explains why partially wider channels are found today than in the past (in particular on the Danube, which had almost two parallel channels downstream of Gemenc /Baja).

There are different possible indicators that can be used to assess the **overall morphological degradation of rivers**. For the anabranching upper river courses of the Drava and the Mura the *change in number of channels* is a better suitable parameter, whereas for the meandering lower course, the *sinuosity* is a much better indicator.

The **current hydromorphological state** is controlled by the *training structure density*, an indicator which includes the total length of all training structures as an integral parameter to describe the current pressure of river regulation, and the subsequent distribution of bar and bank breeding birds. River training structures are all riprap, groynes, transversal fills, guiding walls, harbour and settlement walls, hydropower reservoirs as well as dams, ramps and sills, with exception of lateral flood dykes. The analysis of floodplains and water birds should complement the analysis in the future.

Biotic elements (birds) are represented by the indicator *breeding site density*. This parameter was prepared for the overlay map based on breeding pairs' data of seven indicator bird species, describes the density of the breeding sites found, and can only be used as an indirect indicator for the presence of breeding pairs, without actually describing the density of breeding pairs per se. The categories bank and bar breeders were pulled together into the simplified indicator of bird breeding sites' density in two steps. First, data containing all breeding sites of the bird species nesting on banks (Common and Little Tern *Sterna hirundo and Sternula albifrons,* Little Ringed Plover *Charadrius dubius*, Common Sandpiper *Actitis hypoleucos*) and those of species nesting in steep banks (Sand Martin *Riparia riparia, European* Bee-eater *Merops apiaster*, and European Kingfisher *Alcedo atthis*) were converted into indicators for bank breeding sites and bar breeding sites. Second, the values split into classes were pulled together into the overall indicator bird breeding sites' density.

2.2. Description of classes

Class 1: Best state. Lowest pressure, **smallest change** stretches, based on the assessed parameters. It must be emphasized that the systemic problem of disturbed sediment regime and channel incision, as found in all three rivers, cannot be neglected. There are no stretches free from human alterations, therefore reference conditions are no longer found.

For the assessed biotic data (birds) this first class would indicate **segments with the highest densities of breeding sites**. Those stretches should be subject of preservation and improvements of morphodynamic processes.

Class 2: Middle state. **Moderate to considerable pressure and moderate to considerable changes**; **moderate bird breeding site densities.** Stretches are organised in a broad middle class, representing the majority of assessment segments. This class would include many stretches having to be improved by a wide range of potential restoration measures.

Class 3: Worst state. Highest pressure and highest changes; **lowest bird breeding site density** characterising stretches with the worst impact of river alterations caused by hydropower, river regulation for flood defence and waterway transport. Aside from the upper Drava hydropower reach, all free-flowing reaches still have significant potential for improvements, in particular where those reaches spread across several assessment segments, or in general >10 km length, disturbing the bio-corridor functions within the TBR.

2.3. Assessment

As parameters were collected in different forms/dimensions (percentages of changes for the historical analysis, total length of river training works, bird densities of breeding pairs and breeding sites) the following pragmatic classification was proposed:

Class 1: best segment state

A. For **historical changes** <(-)10% which describe the negative developments as integrative values for the reduction of sinuosity (meanders), the reduction of the number of side-channels as well as the reduction of width variability (the few occurring positive values were included in this best class).

B. For **river training structures** (riprap, groynes, transversal fills, guiding walls, harbour and settlement walls, hydropower reservoirs as well as dams, ramps and sills) the total length of structures are summarised and weighted by the different assessment length (10 rkm for Danube, 5rkm for Drava and Mura). This first class is represented by segments with <1,000 m total length for 5rkm (10% of 10 km left and right bank length together) and <2,000 for 10 rkm segments (10% of 20 km left and right bank).

C. For **birds**, the highest densities of breeding sites based on the field survey (combined data for bar and bank breeder) and subsequent classification are included:

- Bank breeders: Class no. "1" = 15-24 breeding sites identified in AssSeg (assessment segments; 10km, 5km) together in both seasons of field surveys in 2021 and 2022.

- Bar breeders: Class no. "1" = 9-35 breeding sites identified in AssSeg (10km, 5km) together in both seasons of field surveys in 2021 and 2022.

Class 2: middle segment state

A. For the **historical changes** <(-)50%

B. For the **training structures** <5,000 and <10,000 m (the former for 5 rkm length segments; the latter for 10 rkm segments)

C. For **birds**, the second middle class of breeding pair density was applied.

- Bank breeders: Class no. "2" = 4-14 breeding sites and

- Bar breeders: Class no. "2" = 1-8 breeding sites. Breeding sites identified together in both seasons of field surveys in 2021 and 2022.

Class 3: worst segment state

A. All values > (-) 50% changes of values for the historical analysis.

B. All values >5,000 and >10,000 m for the training structures respectively (the former for 5 rkm length segments; the latter for 10 rkm segments)

C. For birds, this class represents the segments with only a few or no records: Bank breeders: Class no. "3" = 0-3 breeding sites and Bar breeders: Class no. "3" = 0 breeding sites. Breeding sites identified together in both seasons of field surveys in 2021 and 2022.

Table 2: Classification of pressures and density of bird breeding sites

Topic/data set	Class 1: Best state	Class 2: Middle state	Class 3: Worst state
River training structures: Pressure from infrastructure	Lowest pressure	Moderate to considerable pressure	Highest pressure
Historical assessment of morphology: changes compared to historical / reference state	Smallest change	Moderate to considerable changes	Highest changes
Birds data: Density of breeding sites	Highest density of breeding sites	Moderate bird breeding site density	Lowest bird breeding site density

For the combination of the parameters and contents, the basic arithmetic mean (no weighting) and a simple classification scheme were applied, which identifies the best and the worst classes and allows a wide room for the intermediate class. We recognise the limitations of such an initial assessment (e.g. for the equal consideration of sinuosity, channel number and width variability, where worse values for sinuosity can be equalized by moderate to considerable values for the other two indicators).

Table 3: Assessment classes for overall analysis

Assessment class	Class value thresholds for arithmetic mean
Class 1	1-1.5
Class 2	1.6-2.5
Class 3	2.6-3

To have a basis for comparison and check of the chosen method, we also looked at a segment class value calculation using a “worst value” assessment (worse assessment beats a better assessment for the other parameter). This was only applied for one analysis (see Figure 1).

Table 4: Classes for the comparison, so-called "worst-value analysis"

Assessment class	Class combinations
Class 1	1 and 1
Class 2	2 and 2
Class 3	1 and 3, 2 and 3, 3 and 3

The application of assessment segments was implemented and applied for the TBR MDD rivers for the first time. Many analysis results underline previous findings and further support and combine the individual studies. Therefore, the analysis of overlay maps should be understood as the first step to further specify and assess river reaches towards a restoration strategy and the selection of type-specific measures. For this particular task, it is necessary to analyse the data based on the eight defined river section types (RST). However, this would require much more detailed analysis and explanation and should be part of the next steps. We must point out that the current analysis is an attempt to generate a first overall picture, keeping in mind all issues and uncertainties which could be considered in the future analysis:

- First, the assessment includes general parameters for all river segments. For the historical analysis the combination of the sinuosity, the loss of side channels and the reduction of width variability was considered, and for the assessment of current pressures from training structures the full set of structures was used. This approach does not take into consideration the eight river section types (see Annex A1) which characterize individual morphological river types as anabranching and meandering stretches, or the size of rivers and usages in general (e.g. considering navigation with its particular low water regulation).
- Second, we must emphasise that the presented results on the "hydropower reach" of the Drava in SI and HR should not be considered in the same manner as all other free-flowing reaches, as the pressures and parameters were mixed for the reservoirs/tailrace canals and the former river bed (residual water stretch). This river stretch must be always treated separately. Further details and limitations regarding individual parameters are discussed in the interpretation in 3.1 and 3.2.
- Third, and last, it is obvious that applying the averaging on a segment basis leads to the disappearance of sharp boundaries. E.g. dams in the middle of a segment or very different river banks, e.g. in Vukovar or Apatin (Danube rkm 1,335 and rkm 1,400 respectively), with one completely altered bank on one, and a still rather intact bank on the other side of the river.

3. Data Overlay: linkage between abiotic and biotic datasets

The aim of this chapter is to overlay the resulting assessment layers for abiotic and biotic parameters for the identification of still rather intact river reaches and river stretches which have been altered most. Finally, it is possible to support the restoration strategy with suggestions for river reaches for restoration based on the scientific findings.

Proposed initial analysis

After exploring various overlays and combinations, we present four analyses in subchapters 3.1- 3.3., before giving the first recommendations in 3.4:

3.1 Presents the linkage of the historical mapping of river morphology and river training structures in two steps.

3.2 Shows the linkage between historical changes (as based on the mean value assessment explained for 3.1) and the current bird breeding site density as combined distribution of bank and bar breeders.

3.3 Indicates the linkage between the current river training structures and bird breeding site density as under 3.2 explained above.

3.1. Linking the historical changes of river morphology and river training structures

Firstly, the overlay considers a "worst value" ('negative') assessment of those changes and pressures which indicate the big picture of general pressures and main stretches of the river system. This overlay using a class determination method that is different from the one described in Table 3 (compare Table 4), yields a 'control' overlay map that shows those areas where human intervention has put some kind of pressure.
Secondly, based on the same datasets, but assessed as mean values according to Table 2 a more differentiated picture of the combined historical changes/current pressures is delivered. This analysis of abiotic alterations and pressures is the base for the overlay maps of abiotic data with bird data as the only bio indicator with sufficient spatial resolution.

As addressed in the introduction, aside from the disturbed sediment balance and subsequent channel incision, which both represent significant pressures for all of the rivers in the TBR, there are further important indicators for the development of these rivers. The general historical development and changes/reduction in sinuosity ("meandering"), the number/loss of side channels as well as the reduction of the width variability were considered. The combination of these parameters with the current state (total length per segment) of river training structures completes the picture of past and current pressures and alterations, giving also a first indication of channel incision. At least for the observed river gauging sites, incision rates of up to several centimetres per year can be proven, but results do not deliver continuous information on channel incision.

Figure 17 combines the historical morphological analysis (integration of reduced sinuosity, loss of side channels and reduced width variability) with the present density of all training structures per segment by using a "worst value" assessment (worse assessment beats a better assessment for the other parameter: see Table 4).

In general, and, as expected, the upper river courses of the Mura and the Drava, but also the Hungarian Danube entirely fall in the worst class, due to intensive river regulation in the past. For the upper Mura for flood defence and land reclamation, for the upper Drava in particular for hydropower. For the Danube a low water regulation for the maintenance of the waterway plays an important role. However, remaining reaches with less historical changes and current pressures can still be found on all rivers, but in particular on the Drava, where the upper part of the "Lower Drava forest reach" between Donji Miholjac and Osijek (ca. rkm 75-25) can be indicated as a less altered reach. This is the general picture, which, however, does not reflect the high ecological values of remaining stretches/segments on all rivers ('ecological stepping stones').

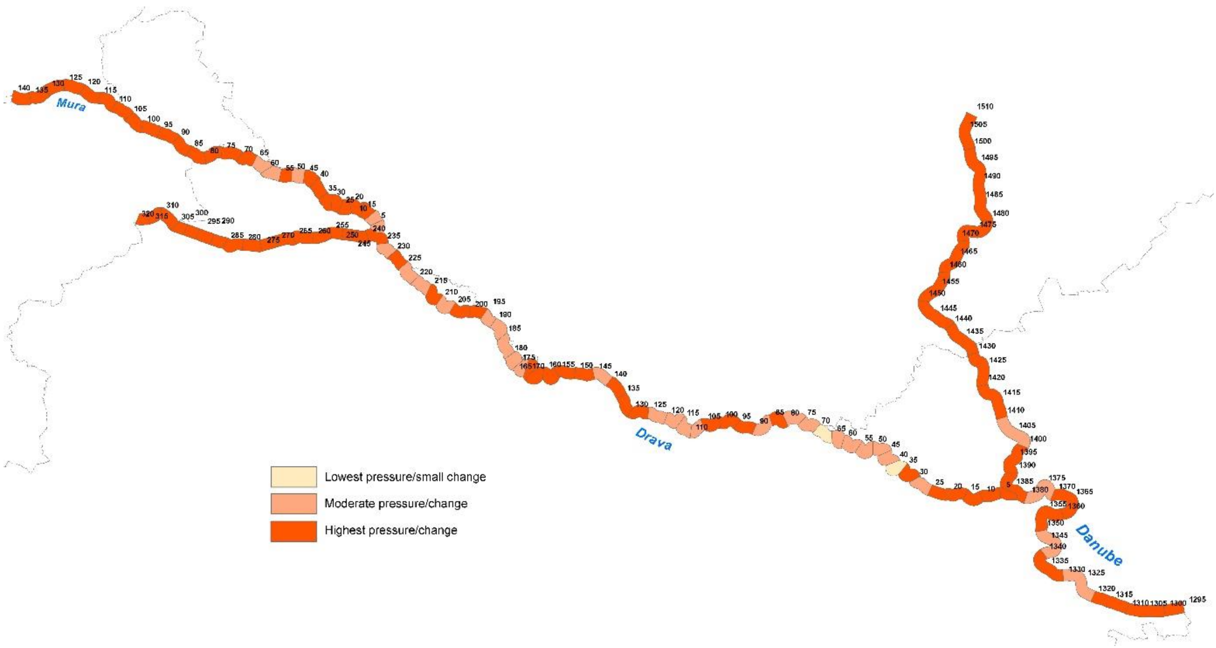


Figure 17: "Worst value" assessment of the combination of historical changes (reduction of sinuosity, number of side channels and width variability) and presence of river training structures.

Coming back to the issue of process-based channel incision, the analysis is limited to the "major" stretches as mentioned above. However, e.g. the observed strong incision around Barcs (Drava rkm 155) on the lower Drava cannot be explained by the analysis and must definitively take into consideration the excessive sediment exploitation from the upstream reach and the overall negative sediment balance.

As opposed to the analysis and map shown in Figure 17, the map in Figure 18 integrates the historical changes with the density of current river training structures, and thereby allows for more differentiation while also underlining the positive aspects, i.e. those segments with fewer/the least alterations. In particular, it delivers shorter stretches for the Drava, with obviously reduced changes/current pressures. However, limitations must be mentioned in the historical assessment for “town reaches” around Barcs, Osijek, Apatin and Vukovar, where the sinuosity (position of main channels) remains “unchanged” and therefore the current state of the river stretches is overestimated. Looking at the historical number of side channels, some segments downstream of Barcs are also misleading, as regulation leads to some additional “islands” on or around training structures and “new” side channels while the possibly less exact, limited historical map material indicates probably fewer side channels in the strongly meandering reach. Those are general issues, which have to be considered in particular for the border reach between Barcs and Donji Miholjac, the entrance of the lowest section of the Croatian Drava.

To highlight some specificities, we can compare these results with the bird map in 4.3 for a specific stretch, e.g the spectacular steep bank at the lower end of the transition of the Drava from an anabranching to a meandering river type at Drava rkm 180-190. While some meanders were cut (even the Bélavár meander reach in the 1980ties), and some training structures were built later on the Croatian side to protect agricultural land and gas fields, this reach still hosts very important riparian habitats.

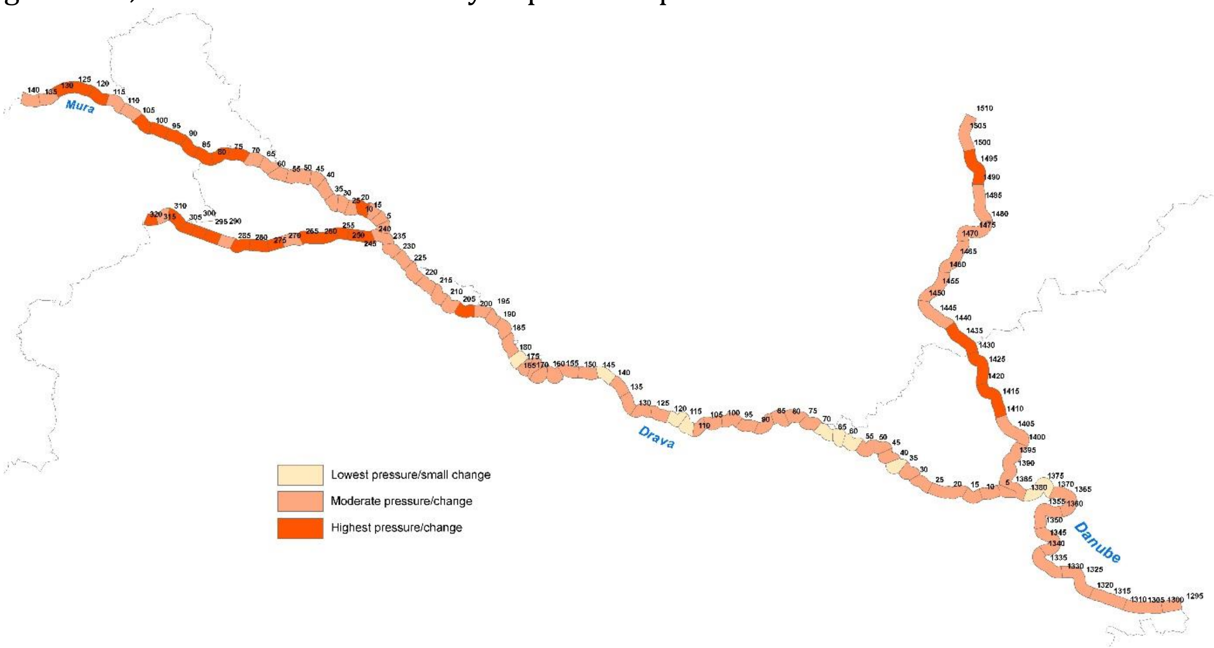


Figure 18: Density of river training structures combined with the historical comparison (reduction of sinuosity, number of side channels and width variability) as integral mean values (mean value calculation explained in Table 3).

3.2. Linking the historical changes of river morphology to the breeding sites of birds

Figure 19 combines the data available for historical loss of river dynamics (reduction of sinuosity, loss of side channels and reduction of width variability) with the distribution of typical birds nesting sites on sediment bars and steep banks. The aim of the analysis is to show the general effects of river channelization over the last 200 years on habitats. The suitability of the rivers as bird habitats is controlled by the indicator bird breeding sites.

River reaches with less historical changes and high densities of breeding pairs (dark colour) can be found for all rivers, namely along lower Mura (HR-HU reach), along several reaches in the anabranching section of Middle Drava and meandering lower Drava as well as along the Danube up- and downstream of the Drava confluence.
Where rivers become strongly altered over time as on the upper Mura, in parts of lower Drava and Danube (light green segments) the reduction of bird breeding density is evident. All morphological parameters, the decrease of sinuosity, the reduction of channels as well as the reduction of width variability can be directly addressed to decreasing habitats (bars and erosion banks).

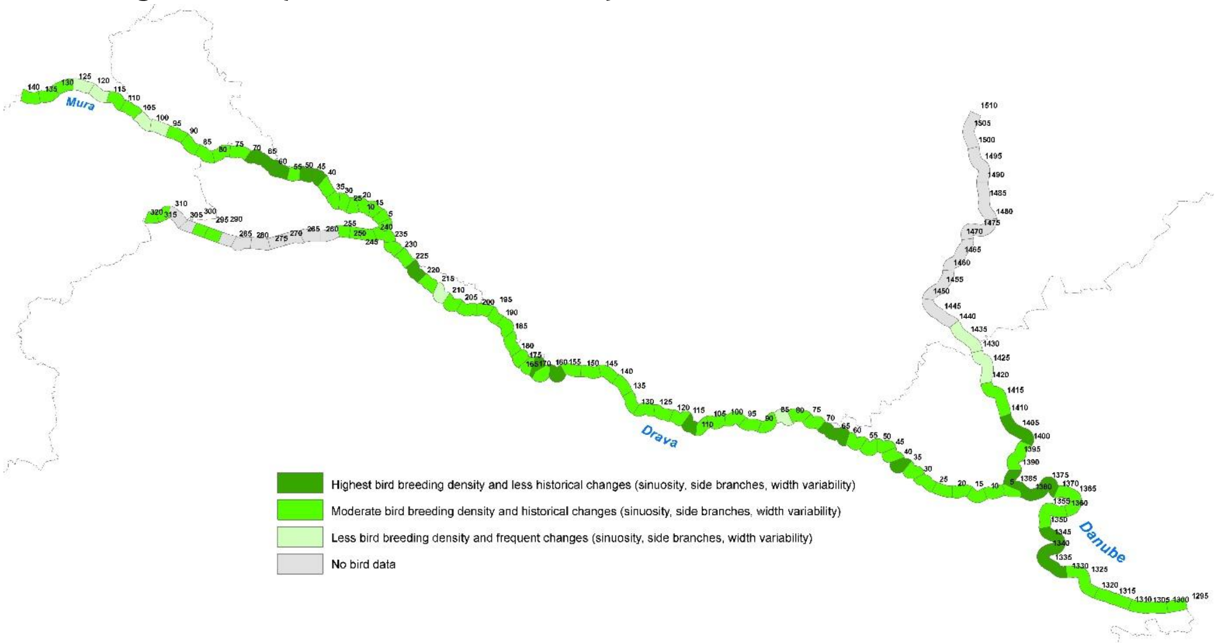


Figure 19: Combination of historical parameters (reduction of sinuosity and number of side channels as well as width variability) with bird densities of breeding pairs (combined data for bar and bank breeders).

3.3. Linking density of river training structures to breeding sites of birds

The training structure density is an integral parameter and describes the current pressure of river regulation and the subsequent distribution of bar and bank breeding birds. The effects or inheritance of the historical changes are recognizable on the long-term development of rivers on the habitats for birds as described in 4.2 and their effects are further reinforced by the current river training structures.

In comparison with the historical morphological changes described in the previous chapter, the role of the present river training structures, i.e. the effect of bank reinforcement on the bird breeding sites, is even stronger. Its analysis indicates the highest influence of a low presence of training structures precisely on the stretches with the highest values for bird distribution, i.e the transition reach from anabranching to meandering conditions on the lower Mura (rkm 40-70), the middle transition reach of the Drava downstream of the Mura confluence (rkm 220-225 and adjacent), the strongly meandering Drava reach upstream of Barcs (rkm 170-190), the lower Drava downstream of the HU-HR border to the highway crossing upstream of Osijek (rkm 35-70 including some segments of the 2nd, middle class), and the Danube reach just downstream of the Drava confluence (rkm 1,335-1,380 including some average segments).

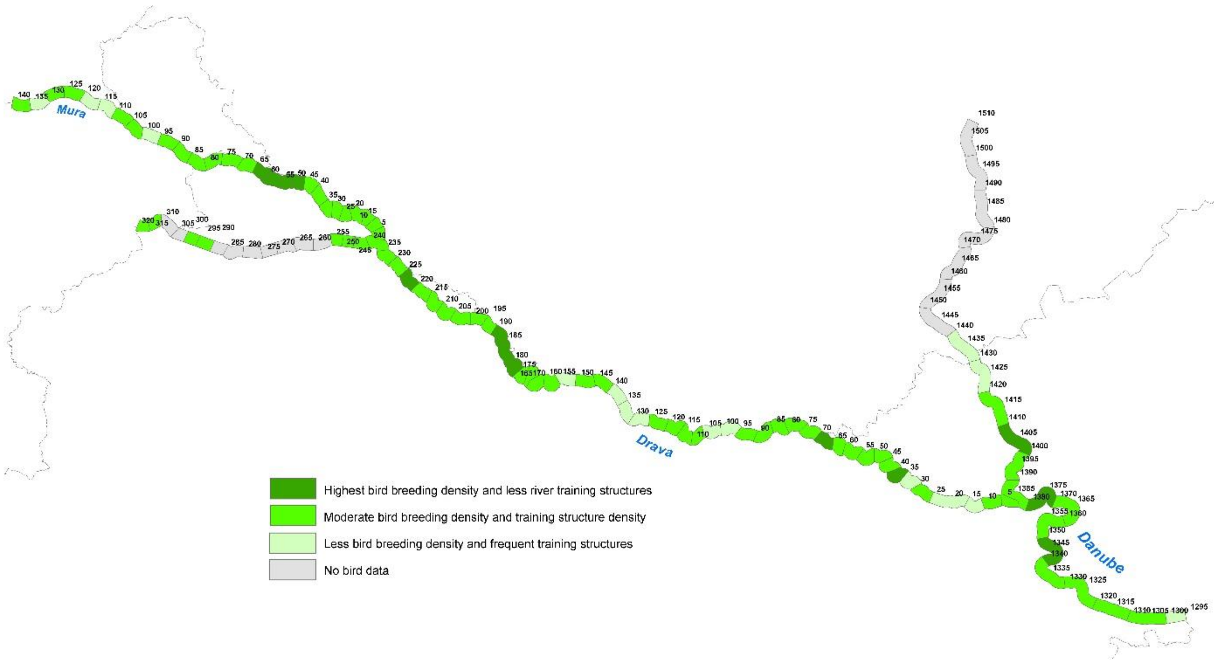


Figure 20: Combination of the density of current river training structures with bird densities of breeding pairs (combined data for bar and bank breeders).

The combination map in Figure 20 complements and partially sharpens the findings of the comparison with the historical morphological changes (Figure 19). Altogether, 21 segments can be identified as having been assigned to the highest class by bird breeding site density/river training structures and/or bird breeding density and historical changes: 30 km for Mura (about 21% of its length in the TBR MDD), 50 km for Drava (~16% of its length in the TBR MDD) and 50 km for Danube (~23% of the river's length in the TBR MDD). This also indicates potential high breeding densities of bank and bar breeder species, both groups of species very sensitive to specific conditions, therefore very strong indicators for the hydromorphological state of the rivers (Figures 17 and 18). Conversely, stretches with a lot of deficits (high presence of training structures) are well visible in the class assignments based by intersecting hydromorphology data with bird breeding sites' data as such on the upper Mura, on the lower Drava downstream of Barcs and around Osijek, as well as on the upper and lower end of the observed Danube reach. Finally, the assessment proves the high ecological values of different stretches on all three rivers and strengthens the importance and connectivity of and within the TBR MDD.

Based on the overlay maps in sub-chapters 3.1 to 3.3 (figures 17 to 20) it is possible to draw some general conclusions towards restoration options and needs:

- The analysis approves the strong correlation of bioindicators such as birds in particular for the morphodynamical processes, i.e. the creation and rejuvenation of most important habitats such as steep erosion banks and gravel and sand bars. Any proposed restoration measure to improve the situation for the aforementioned bird species (bank and bar breeders) should therefore support the increase of morphodynamical processes in the river continuum (discharge regime and sediment continuum).

- The analysis indicates the need to protect and improve the bio corridor as some long gaps and interruptions of missing bird observations and strong river alteration can be noted. This refers not only to the upper reaches of the Mura and the Drava (strong regulation and hydropower), but also to the Danube (waterway), including the Drava reach between the Danube confluence and Osijek (strongly trained for maintenance of the waterway), as well as several reaches on the lower Drava (highway bridge).
- The existing data gives valuable first insights and should be considered for further investigations on the suitability for and pressures on fish (spawning) habitats, their restoration or the assessment of the channel incision and reduction of lateral connectivity/side channels.
- Even though the analysis so far does not consider the river section types (RST), it clearly indicates that a match between restoration activities and the appropriate river section type is required to succeed with measures[4]. The same suitability assessment is suggested for finding the appropriate size and magnitude of restoration measures. Too short and specific measures (e.g. only the reconnection of a single short side channel or oxbow) might result in small, local improvements with a short lifespan.
- The historical development, i.e. the history of regulation should be further assessed for all three rivers individually, to find a roll-back concept to improve the rivers' state step by step.
- The "room for the" rivers concept and the expansion of the current regulation corridor for many stretches should be followed up on consistently. Therefore, floodplain restoration by the targeted repositioning of flood dykes must become a feasible option to increase the lateral shift of the rivers wherever possible. An analysis of this option should include the flood dykes and a floodplain assessment.
- The navigable Danube and Drava downstream of Osijek are facing additional pressures from (low water) river regulation for the waterway, which have to be reduced by state-of-the-art knowledge and measures preventing further construction of grey infrastructure (expanded real-time monitoring of fairway, limited dredging and repositioning of material).

3.4. Qualitative analysis of findings from all studies – linking findings of biotic and abiotic studies

The fish study has indicated that non-native fish species' occurrence may be related to the warming of water temperatures and the related changed riverine habitat conditions, as well as morphological changes. It warns that in particular Ponto-Caspian gobies spreading upstream from the Danube and lower Drava River could cause serious ecological instability or community shifts. Paired with the predicted general warming, it can be

[4] The lifelineMDD project produced a River restoration Toolbox, which offers a practical guide to this type of hands-on decision processes required for restoring any river stretch.

expected that the number and share of non-native fish species may increase, or a change or expansion of geographical range of their occurrence may be observed, if the warming tendency continues.

An improvement of hydromorphology and of the sediment balance would improve spawning conditions for most of the fish species present in the Mura and Drava on these sections. As the age distributions of the fish caught during the fish study has shown, many of the studied sections are missing the kind of habitat variation that is needed by different age groups of fish. As a consequence of indications based on results of the fish ecological study there may be some effect of hydropeaking on the age distribution of fish. For example, the presence of more gravel bars or shallow reaches with gravel underneath have been found to be better suitable habitats for early development stages, thereby also improving reproductive success. On the other hand, improvement of hydromorphology has proven not to be sufficient. Evidence found by the study on the effects of operating the last hydropower dam on the Drava has shown that amplitudes of the power plant operation reaches heights of up to 2 m and even 100 km downstream amplitudes of about half a metre can still be detected.

The relevant literature shows that hydropeaking can lead to stranding and lateral displacement of fish (stranded fish may remain on the substrate and suffocate or they can be entrapped, i.e. isolated in potholes), their drift and downstream displacement or reduced spawning and rearing success. In the hydropeaking section of the Drava, mainly the juveniles of the predominant rheophilic, gravel-spawning cyprinids such as nase, barbel, asp or cactus roach and some others inhabit shallow gravel habitats along the banks. The juveniles of all these rheophilic species are particularly sensitive to power plant-induced water level fluctuations and get potentially affected by stranding and drift displacement.

The riverbed incision measurement map (Figure 10) clearly shows the joint effects of the major channelization (meander cutting and shortening, width reduction, cutting of side channels and hard embankments) and hydropower dams acting as sediment traps upstream. Incision can be measured almost everywhere, on all three rivers, to a different extent. On certain sections, based on the measurements, it does reach alarming extent.

The sediment deficit, as measured e.g. on the Mura in its Austrian-Slovenian border section, is at 45,000 m3 per year. Introduction of this amount of sediment under the current hydromorphological conditions, however, would merely stabilise the riverbed incision at its current level. On the other hand, the hydraulic modelling of part of this section has clearly shown that widening the riverbed and increasing its sinuosity would reduce the required bedload supply to 20,000 m^3 per year, i.e. the sediment deficit can be reduced by improvement of hydromorphology.

All climate change models suggest a warming over the coming decades, with larger warming expected during the winter months, which would have an expected effect on the availability of snow cover, as well as on the timing of the spring snowmelt, which may come earlier. Overall, a warmer and wetter winter is expected. All of this could significantly alter the hydrological cycle of the area. The Drava exhibits a fluvial-glacial hydrological regime, which may shift if glaciers become smaller or melt at different times and rates. The Mura's nivo-pluvial regime means that, under current predictions of changes in weather patterns, its regime will shift as well.

The analysis of quantification of extreme indices shows a consistent increase in heat waves and intense precipitation events by the end of the 21st century. The number of heavy and very heavy precipitation days will increase all across the Mura-Drava-Danube region, except in a few regions where negative change is observed. The hydrologic projections have reinforced these predictions. All models show an evident expected increase in mean annual floods by the end of the 21st century. Such an increase in frequency and intensity of extreme precipitation events is alarming as they are usually followed by heavy flooding events.

A simultaneous decrease in summer runoff and increase in temperature may significantly affect water quality. In turn, longer and more intense low-water periods affect the habitat availability and diversity for fish and, on the long term, could negatively affect the entire ecosystem. The changes may cause shifts in aquatic and terrestrial species composition. For the fish species, this may mean a longitudinal shift along the river continuum, in the stretches preferred by certain species. Species that breed on gravel and sand bars or steep banks breed in the TBR MDD between April and the end of July. As the results of the climate study show, there will be changes in the hydrological regime in the future, as well as more frequent flooding events on an annual basis. If high water levels occur throughout the breeding season (something similar happened during the bird census in 2022 on the Drava and Danube rivers), this can have long-term effects on the populations of these birds as well.

Linking back to the study of historical changes leads us to the recognition that lateral disconnection from floodplains has removed retention areas as well as the chance for water purification through filtering within the floodplains. Shorter and tighter riverbeds, as currently recognized compared to the historical state of the riverbeds, mean faster and shorter flood waves, as floodwater is restricted to moving into one direction.

On the other hand, the warming tendency, as well as the clear indications from both regional climate change models and hydrologic projections that summer runoffs will significantly decrease over longer summer periods invite us to revisit the results of the study on current training structures and historic changes on hydromorphology. Many of those human-induced changes are related to hydropower (less so within the TBR MDD) or, in the lower Drava and the Danube, to navigation. Under conditions of changed hydrological conditions, the sustainability of keeping and maintaining infrastructure modifying hydrology and supporting such uses of water will remain a political and economic decision.

4. Data Gaps and Uncertainties – need for future research

4.1. Biotic elements: fish, river birds

The ecological importance of TBR MDD as a biodiversity hotspot and unique river system was confirmed by the fish study. However, the informative value of a single sampling campaign is limited. Due to the high habitat variability and the seasonal and yearly variability of the fish coenosis as well as imperfect discharge conditions during sampling, targeted and well-planned future investigations are necessary; a combination of eDNA and electrofishing is recommended. In general, fish data were not used for overlay maps within this synthesis, due to the limited data depth: the field study was too limited in time and geography to allow general conclusions to be drawn. Sections must be sampled in greater detail and greater effort to cover the full habitat heterogeneity representatively. Further sampling must cover different seasons and different water levels.

Field analysis has shown that the amount of typical riverine fish in the Drava sections below the hydropower plant seems drastically reduced: fish density and fish biomass were by far the lowest compared to all other sampling sites, and the density of juvenile rheophilic fish was extremely low in this section. Therefore, ecological effects of the HPP Donja Dubrava, especially the hydropeaking effects, the consequences of the migration barrier and the morphological degradations may be the greatest risks for the fish fauna in the Drava and need closer investigation. Intensive studies on the migratory behaviour of e.g. nase, but also further medium distance migrants should be considered. The absence of predatory species is remarkable and could be explained by an intensive fishing pressure. This needs to be investigated further.

The occurrence of non-native fish species in the TBR MDD is considerable, especially in the Danube reach. In particular, the effects of the mass occurrence of the Ponto-Caspian gobies, which are spreading further upstream from the Danube and lower Drava, need to be studied in terms of shifts in fish communities and any associated instability. A longer-term or cross-section investigation of potential changes induced by effects of the climate change on the riverine habitats, and links to (non-native) species distribution could be potentially interesting. Floodplain water bodies should be monitored seasonally and over a longer term to assess connectivity and create a data basis to highlight potential needs of connectivity improvements in the future.

The analysis of floodplain and water birds should complement the analysis in the future, with regular census (at least every 2-3 years). A future census should also include the Hungarian section of the Danube in TBR MDD (rkm 1425-1510), which wasn't surveyed in 2021 and 2022. Follow-up projects should focus on the interplay between particular hydromorphological structures (steep banks, gravel bars, side channels, meander bends) and identification of those abiotic elements that turn certain river stretches into suitable bird breeding habitats, whereas other, of similar parameters, are not deemed suitable by birds.

Consideration of additional factors, such as disturbance or hydrological indicators may be required for a correct causality identification. Overall, long-term bird monitoring across the TBR MDD would be a value added to recognise long-term tendencies and allow for monitoring effects of changes in hydromorphology or other factors. The form of such a study could be that of a survey of the carrying capacity of the TBR MDD for indicator bar breeders and bank breeders (e.g. inventory of the number and size of gravel/sand bars and steep banks in the TBR MDD), if possible every 5-10 years and comparison between years. Considering the indications found that the immediate vicinity of the Mura, Drava and Danube rivers in the TBR MDD, host a significant part of the population of birds an inventory of river bird species on all gravel pits in the immediate vicinity of the Mura, Drava and Danube is recommended. An example is the common tern, which in the past nested on the river course (Kralj et al. 2019) and moved because of the fluctuation of the water lever due to hydropower plants.. A further step is that of a systematic inventory of threats (where & which type of threats) to river breeding birds in the TBR MDD along the entire stretch of rivers Mura, Drava, and Danube, and an assessment of the degree of threats of tourism and recreation to nesting on gravel bars, as well as an analysis of the impacts of invasive species on steep bank breeders.

4.2. Abiotic framework conditions

One source of uncertainty in the hydrologic model developed for the Drava River basin is the reduction in total snow and glacier storage in the basin, which means that the projected increase in low flows is not sustainable. Studies and better data are needed to estimate total snow and glacier storage in the basin.

For more accurate predictions of hydrology, the effects of pressures other than climate change need to be included in the assessment, e.g. land use changes, water use changes, population growth/decline, existing and planned flow control structures, etc.

Measurement of groundwater levels on a longitudinal and lateral gradient across the floodplains of the Mura-Drava-Danube could help quantify effects of riverbed incision, as well as potential positive effects of restorations bringing along riverbed stabilisation.
Apart from the need for measuring groundwater levels, the data collected for the sediment balance and transport study has shown that harmonisation of measurement methods across the TBR MDD gauging stations may be welcome.

The hydropeaking study conducted within the project has relied on data available from hydrographs along the rivers Mura, Drava and Danube. Frequency of measurements varies across the countries, from measurements every 15 minutes to measurements once per hour. At a lower frequency of measurements it may happen that flow fluctuation amplitudes are underestimated, as at higher flow rates of down- or up-ramping events the point of change between trends is missed. An increase of the frequency of measurement data collection at hydrography is therefore desirable.

Considering the results of the hydropeaking study, it is recommended to study the ecological effects of hydropeaking, with a focus on birds and fish, and potentially on further biotic elements as well. Some results presented in the fish study (Rauch, 2022) point at a significant influence of the operation mode of the Donja Dubrava hydropower plant on the fish community in the downstream Drava section. The length frequency distribution of the nase near the power plant shows that, apart from a few juveniles caught in the residual flow stretch, juvenile nase are completely absent. Downstream of Donja Dubrava, nase were only found from lengths of approx. 30 cm on. This is in sharp contrast to all other sections sampled during the study, where juvenile fish dominate in numbers throughout. This result is underlined by the comparison of the mean lengths of individuals along the study area (MDD), where the deviations in the vicinity of Donja Dubrava become obvious (Fig. 23, circled in red).

Hydropeaking operations can strongly influence temperature patterns in the downstream reach (Greimel *et al.* 2018, Hayes *et al*. 2019). However, an analysis of the temperature influence on the Drava by the Donja Dubrava power plant is not possible on the basis of the present data set, since higher resolution data (e.g. quarter-hour values or hourly values) are required for this purpose in order to be able to derive statements in correlation with the discharge data. For a detailed analysis of the consequences of the Donja Dubrava power plant on the river ecology of the Drava, detailed temperature data must be collected. To assess, as well, the hydro-chemical effects of the sediment interruption by the last HPP dam, the establishment of a series of measurements for hydro-chemical changes would also be advisable, since no corresponding data are currently available to discuss potential consequences for the ecology of the affected section.

5. Proposed Actions

Based on the studies summarised here, and based on the synthesised information conveyed by them we formulate several actions for implementation.

01. Keeping migratory routes uninterrupted or reopening them is of primary importance for healthy fish populations.

Both biotic and abiotic studies recognized the longitudinal connectivity of the Mura, Drava, and Danube within the TBR MDD as one of the defining characteristics that allowed for this area to function as an ecological refuge for fish and bird species, but also for the preservation to a good extent of this high value riverine ecosystem. Some fishes migrate over long distances mainly to spawn (e.g. nase, barbel). Therefore, the migration routes for the fish at the hydropower plants within the TBR MDD must be continuous in both directions.

02. Identification and mapping of training structures as potential restoration sites.

River training structures that are old, have collapsed or are in need of maintenance, constitute potential sites for restoration and could be low-hanging fruits for restoring lateral connectivity of the rivers with their floodplains. Identifying and mapping such structures is an essential first step to prepare the implementation of the EU Restoration Law.

03. Identification and definition of historical reference states or stretches that can serve as reference states for restoration.

Historical mapping clearly analyses and illustrates the difference between the historical and current situation, especially in terms of river length, river width, width variability, and active floodplain extent/structure, and can serve as a reference for the general and type-specific restoration framework. Additionally, unregulated meander bends or short anabranching reaches can be used as reference areas for restoration activities. In combination with remaining active floodplains and the available lateral space restoration activities, restoration measures would have a good possibility of success.

04. Choosing the right type of restoration efforts for each type of river stretch.

Depending on the original morphology, restoration should focus on either increasing wetted width (widening/self-dynamic erosion and/or reconnection/creation of side channels) or increasing sinuosity (allowing bank erosion, reconnection of meanders), but both parameters should be considered and artificial constraints removed to allow lateral dynamics. The River Restoration Toolbox elaborated within the lifelineMDD project can be used as a decision making as well as planning support tool to choose the right restoration elements for the identified river stretch.

05. Removal of hard embankment structures/morphological regulation wherever possible.

Old or desolate training structures, such as rip-rap or other hard embankments may no longer be needed to protect human lives or essential infrastructure. Based on the state-of-the-art knowledge in river management, such structures may be removed to restore lateral connectivity and improve retention capacity of the river, as well as hydromorphology. Such restoration contributes to the achievement of restoration goals, while also helping to reach good ecological status of the rivers as required by the EU WFD. Fish, as shown in the fish study, use a wide variety of habitats during their life cycle. Therefore, a corresponding habitat diversity, suitable for all species of the species community, is also essential for a diverse fish fauna. A crucial point for dynamic development of the riverbed is the availability of land, therefore land purchase and compensation mechanisms or measures are of pivotal importance.

06. Restoring river sections with greater curvature and width and making lateral dynamics possible.

Sediment connectivity and morphodynamics in the TBR MDD area are urgent and need to be improved. This is done by creating restored river sections with greater curvature and/or width. Such widening, additionally, requires less sediment supply to maintain and restore bed elevations than channelized river sections. Bank protections need to be removed and levees set back for lateral dynamics due to bank erosion and bar/bank accretion. This will allow more space to be used by the river for morphodynamics. Channel incision should be stopped and a dynamic equilibrium should be based on a moving river bed and not maintained by self-armouring (a coarsening of the bed that can develop when there is an obvious equilibrium due to a sediment deficit) or by artificial transversal structures or natural rocks.

07. Returning sediment that has been removed during the restoration works to the river.

During the implementation of restoration measures, sediment removed during construction works should be returned to the river in order to make the natural morphology self-dynamic and to ensure sediment transport that guarantees continuous morphodynamics. Upstream sections are also expected to have a stabilising effect, while downstream sediment supply may be temporarily reduced which requires special attention. With increasing size of the project, transport capacity decreases, while at the same time the sediment gain increases due to the construction.

08. Sediment supply from upstream.

In addition to restoration activities and lateral mobilisation of sediments, sediment must be supplied upstream in sufficient quantity and composition to compensate for its deficit. Agreements should be worked out with hydropower operators of the hydropower dams upstream of the TBR MDD to search for solutions that enable sediment transport. Artificial supply of sediment should be considered as an option.

09. Collection of flow data at hydrographs on a higher resolution

The hydropeaking study conducted for the Drava River with a focus on the TBR MDD sections of the river was based on data available on a 60-minute resolution of flow rates (for Slovenian and Croatian sections). The literature suggests that calculation with data at such a resolution underestimates the amplitude of strong hydropeaks. Therefore, better data collection is necessary to allow for a correct assessment of the flow fluctuation in hydropeaking.

10. Studying the ecological consequences and exact impacts of hydropeaking below the last hydropower dam.

The fish study has found some results indicating that there may be a potentially significant effect of the last hydropower dam's operation on the fish fauna. The hydropeaking study has found evidence that supports this hypothesis, showing that a flow variation amplitude of up to 2 m is recognisable in the 50 km section downstream of the last HPP, and effects of the hydropower operation are still measurable up to 100 km downstream. For a proper assessment of the ecological impacts of hydropeaking, a targeted study would be necessary. In the hydropeaking section of the Drava, mainly the juveniles of the predominant rheophilic, gravel-spawning cyprinids such as nase, barbel, asp or cactus roach and some others are particularly sensitive to power plant-induced water level fluctuations and get potentially affected by stranding and drift displacement. Thus, a targeted study should focus on these species' populations, as well as on potential further indirect effects (e.g. through the clogging effect on sediments).

11. Elimination or at least mitigation of negative consequences of hydropeaking.

Hydropeaking operations are fatal, especially for the early developmental stages of fishes. High losses of early stages have in any case severe consequences for the entire fish populations of the affected sections. Results of the hydropeaking study may become the basis to start a constructive, solution-oriented process together with the HPP owners to improve conditions for fish within the river.

The hydropeaking study has concluded that the maximum flow rate of decrease events must be limited to 50-60 m^3/s per hour with reference to the Donja Dubrava hydrograph in order to significantly reduce the risk of fish stranding in the first 50 kilometres downstream of the hydropower plant. This could also reduce the stranding risk for benthic invertebrates. Hydropeaking amplitudes must be reduced thereby also reducing the artificially induced water exchange zone, which would likely decrease the associated negative ecological impacts (e.g., entrapment of fish in pools, hydraulic stress to benthic invertebrates).

12. Initiation of a social process to better develop sustainable angling in the TBR MDD.

The composition of species plays an essential role in a functioning river system. Predators at the top of the food chain are of central importance. It seems that pressure from recreational angling could be responsible for the low densities of predatory species.

13. Improving the water renewal in the Danube backwaters.

Serbian backwaters are partially eutrophic, swampy and may be completely silted up in the near future due to the accumulation of sediment. Restoration activities that reconnect the floodplains over the long-term should be considered. Widening would improve water and sediment flow during higher flood waves. Further investigation should determine if excavation of these sites is feasible.

14. Reduction of stressors such as habitat degradation or fragmentation.

Having identified the riverine ecosystem at the core of the TBR MDD as a biodiversity hotspot and safe haven for many species, it is crucial to tackle those stressors which may cause further degradation and that were identified by all of the studies. The main stressors are sediment deficit, current level of hydromorphology modification and fragmentation of high value habitats. On the long-term, sustainable and complex solutions for each of these should be found, as proposed here, relying on restoration.

15. Setting up a monitoring framework for adaptive restoration considering goals of the management against extreme events.

For an efficient and sustainable decision-making process, the assessment and analysis should focus on measures against extreme events due to climate change, including vulnerability to flooding. A monitoring framework has to be designed to enable adaptive management of the restoration trajectory. Cooperative planning with the institutions responsible for management of extreme events should be considered.

16. Improvement of legal protection, resilience, and connectivity of the area.

In general, ecosystems need to adapt to the impacts of climate change. The suggestions for adapting ecosystems to these impacts also apply to rivers, namely improving resilience, connectivity, and legal protection while reducing stressors such as habitat degradation or fragmentation (Palmer et al. 2008). Natural riverine habitat conditions and river dynamics have to be maintained and promoted, according to the principle: Near-natural sections must be protected; degraded river areas must be rehabilitated.

Restoration of river sections, wetlands and floodplains in the TBR MDD region is critical and must be completed to mitigate the negative impacts of current and future climate change, e.g. retaining excess water has great potential to increase flood resilience.

17. Maintenance of habitat heterogeneity and morphological integrity.

Habitat heterogeneity and morphological integrity play an important role and must be maintained. E.g fish species tend to follow their preferred thermal niche in the river network. Therefore, spatial connectivity between different river segments as well as surrounding habitats such as deep pools with high groundwater exchange is of great importance, especially for cold-water taxa (Palmer *et al.* 2008). For water birds, habitat heterogeneity is of great importance as well, as hydromorphologically more intact rivers provide the kind of bank structures suitable for birds' breeding and feeding. At the same time, lateral connectivity of floodplains is crucial for all different species of flora and fauna of such habitats.

18. Repeat climate change simulations for TBR MDD using more precise regional climate models.

Data from the latest generation of global climate model simulations conducted as part of CMIP6 (Coupled Model Intercomparison Project Phase 6) will be available in the coming years. It is strongly recommended that future assessments of climate change projections for the TBR MDD are based on at least 10 of CMIP6-based regional climate model simulations to improve climate change projections, analyses, and assessments.

19. Develop interdisciplinary networks of research to jointly analyse the complex projected effects of climate change on the TBR MDD.

For climate change mitigation and adaptation to be successful in the future, climate change research must be more transdisciplinary and integrative. Through inclusion of conservation and restoration practitioners, researchers, policy and decision makers, NGOs and other stakeholders, all of the impacts can be covered (Pletterbauer et al, 2018). Further improvements to the assessment of the hydrological projections would need to include impacts of pressures other than climate change, such as land use changes, changes in water consumption, population increase/decrease, existing and planned river control structures, etc. Such networks have to be developed among the countries included in the TBR MDD to exchange related data. Research objectives need to be aligned with a long-term policy to create synergies among the various objectives. Interdisciplinary climate change research also needs to feed back into plans for implementing restoration activities, in order to ensure that better restoration effects can be achieved, by accounting for projected external or internal changes in the ways an ecosystem will work.

20. Rethinking of restoration in terms of Nature-based solutions considering expected climate change effects

Considering the projected higher occurrence of extreme flood events, restoration events that reconnect retention areas and improve hydromorphology in a way that slows down flood waves or generally improves hydrological conditions are desired. Efficiency of restoration activities can also be improved if expected climate change effects are considered in the restoration plan design. The interdisciplinary network of research described in Action 19 would provide the scientific input required for informed Nature based solutions.

21. Seeking an understanding and willingness of operators of hydropower plants to agree on operation and cooperation for mutual benefit.

River management and contingency plans are particularly important in the TBR MDD to minimise flood hazards. With a total of 22 hydropower plants operated by different countries (Austria, Slovenia and Croatia), the Lower Drava River basin is one of the most intensively hydroelectrically exploited basins in the world (Zakwan *et al.* 2021). The problems are not only technical, but also economic, social and political. There is a need to develop an understanding and willingness of operators to agree on operation and cooperation for mutual benefit. River management and contingency plans are particularly important in the TBR MDD to minimise flood hazards caused by dams and protect and strengthen the structure of native fish communities and other water-bound organisms in the TBR MDD. Such rivers need more management interventions with free-flowing rivers (Palmer et. al. 2008).

22. Enhancement of riparian vegetation as a buffer to land used for agriculture or artificially kept free of vegetation.

Riparian vegetation has several important functions related to aquatic habitats, including filtering runoff from agricultural land, moderating water and ambient temperatures through evapotranspiration and reducing solar energy input through shading. Therefore, riparian vegetation has potential to mitigate the warming effects of climate change (Bond *et al.*, 2015). In considering beneficial effects of riparian vegetation, it remains important to plan restoration of such vegetation considering nature protection goals, i.e. focusing on locally typical and autochthonous species.

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ANNEX

Annex A.1. Sections of the Mura, Drava and Danube as proposed by Schwarz et al. (2022).

River	Section		Rkm from	Rkm to
Mura	M1	Spielfeld – Croatian border	143	85
	M2	Croatian border – Hungarian border	85	45
	M3	Hungarian border - Drava confluence	45	0
Drava	Dr1	Ormož – Mura confluence	310	235
	Dr2	Mura confluence – Heresznye	235	185
	Dr3	Heresznye – Danube confluence	185	0
Danube	D1	Sio confluence – Drava confluence	1510	1382
	D2	Drava confluence – Backa Palanka	1382	1295

Table A1: Sections of the Mura, Drava and Danube as proposed by Schwarz et al. (2022).

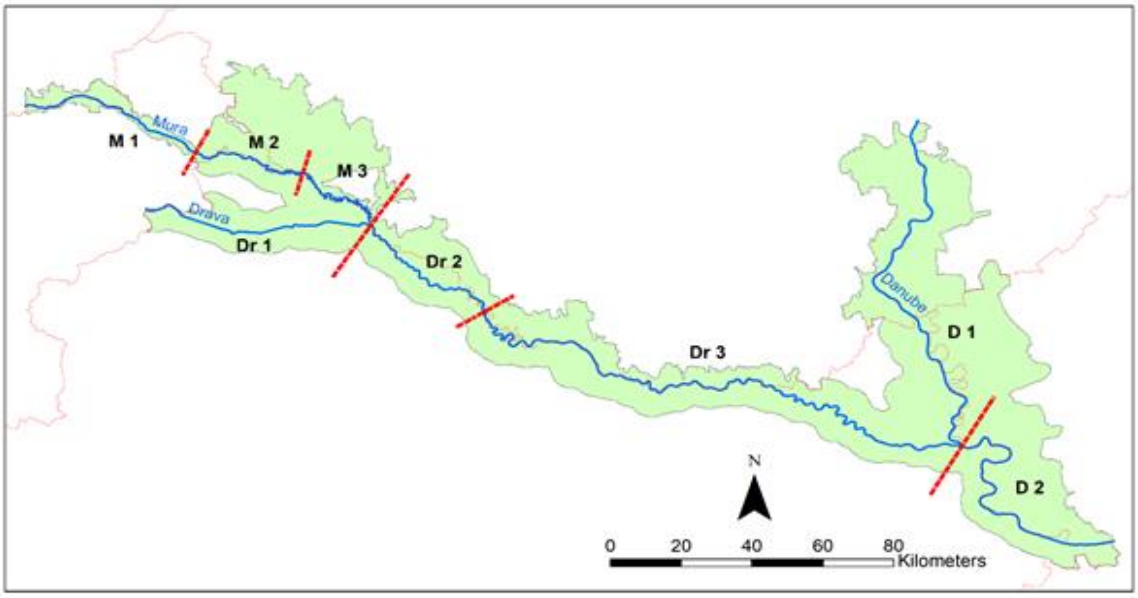


Figure A1. Division of the Mura, Drava and Danube into sections as proposed by Schwarz (2022).

Annex A.2. Data from studies and methodology.

Study	Data / Input provided for Synthesis	Method used for collection of data / elaboration of result
Fish Community Characterization of the Mura-Drava-Danube Region	• Fish community structure based on electrofishing: standardization based on the fished area **(1) Quantitative data collection:** density per hectare (Individuals/ha) and biomass per hectare (kg/ha) **(2) semi-quantitative data collection (3) qualitative data collection** (relative fish frequencies, length frequency, number of species, age structures, differences in community structure, ecological and reproductive guilds etc.) • Hydrological situation between 2010 and 2020, as well as 2021 • Composition of the fish community based on eDNA: standardization based on quantity of positive PCR-replicates out of 12 replicates conducted as well as the total number of DNA sequences	• Electrofishing in July 2021 in nine sections (S1 – S7, SR, SD) of Mura and Drava: strip fishing method with electrofishing boats applying a stratified-random-sampling approach as described by Schmutz et al. (2001), strips: each existing habitat type within the defined section were sampled at least three times, ranging from 50 – 300 m, which usually took between 2 and 10 minutes. The relative amount of caught to uncaught fish (catch estimate, expressed as percentage for each individual) was used in further calculations. • eDNA additionally to the electrofishing as described in Taberlet et al. (2012), where 20 – 42 litres of water were filtered, duration of filtering was 18 – 45 minutes, in the sections (S1 – S7 and SD, whereby sections S1 and S5 were sampled at both up- and downstream section ends).
Fish Study Serbia	• Fish community structure: as above • water level analysis of stations Bezdan, Bogojevo and Backa Palanka between 2016 and 2020 • physical and chemical parameters (conductivity, temperature, dissolved Oxygen and saturation, pH, transparency, depth)	• Two electrofishing sampling rounds at two different Danube discharge-levels from July to September 2021 in two Danube backwater-systems (Gornje Podunavlje and Bukinski rit), sampling transects from five defined mesohabitats at three sites were selected in each pilot area with different connectivity/distance to the Danube main channel: CPUE (Catch Per Unit Effort) optimally at 20 m per individual habitat.
Bird Study	• Distribution maps for seven target species (number of individuals and breeding pairs per species with GPS coordinates, number of breeding sites and breeding status of recorded individuals)Linear	• First-ever joint 5-country field river breeding bird census (mapping) for the transboundary river corridor MDD implemented in 2021 and 2022. Due to 550 km long stretch for river birds mapping on Mura, Drava and Danube rivers, three groups of bird experts from Slovenia (DOPPS Birdlife

	density of breeding sites/breeding pairs for each target species per 5 km (Mura, Drava) and 10 km (Danube) segments • Linear density of breeding sites for bank breeders and for bar breeders per 5 km (Mura, Drava) and 10 km (Danube) segments • Estimation of breeding population size for selected target species in season 2021 & 2022 per river • Trends for selected target species for Mura, Drava and Danube (left/Serbian bank not included due to insufficient data)	Slovenia), Croatia (Natural History Society Drava) and Serbia (University of Novi Sad) were involved. • Methodology used was standardized as much as possible (defined ToR for the TBR MDD: 1-2 round per year, by boat, end April-Mid July, the number of birds and breeding pairs (bp) assessed according to breeding code of EBCC breeding atlas code (Keller et al. 2020, Slovenian version according to Mihelič et al. 2019) • Points in the digital layer have a standardised attribute table, that include fields in this order: English species name; Latin name of species; No.(of birds individual or pair); Unit; Breeding code* (after EBCC; probability of nesting); Country (AU-SLO, SLO, HR…); River; River KM; maybe Location-the nearest settlement; x/y coordinates in WGS84; Date; Legit & det. Note) • Linear density of breeding pairs for each target species calculated as total number of species breeding pairs in one segment divided by segment lenght (assessment segments (5 rkm for Mura, Drava, 10 rkm for Danube) as defined by Schwarz (2022) • Linear density of breeding sites for bank breeder (bar breeders) is a total number of breeding sites of bank breeders (bar breeders) per 5 km (Mura, Drava) and 10 km (Danube) segments, as defined by Schwarz (2022) • Trends for target bird species in "Slovenian" stretch of Mura after Božič (2022) were calculated using rtrim-package (Bogaart et al. 2018), which is a specially developed program for analysing ecological data with missing values, specifically time-series of counts using Poisson regression (Pannekoek & van Strien 2005). Rtrim-package was used in R (R Core Team 2013).
River training structures and historical mapping within the Mura-Drava-Danube TBR	GIS data layers: training structures, historical mapping, river section types, extent of human impact on morphology **(1) Total length of river banks impacted by training structures** (dams, ramps, sills, groynes, training walls, bank reinforcements, flood defence dykes) and the number of structures	• 4-step method: (1) definition of 8 river section types based on the EU REFORM project definitions; (2) definition of assessment segments (5 rkm for Mura, Drava, 10 rkm for Danube); (3) digital mapping of river training structures. Collection of position, type and status, height in relation to vegetation line and inclination or river training structures (all transversal and longitudinal structures incl. dams, ramps and sills, or bank stabilisation like rip-rap, concrete walls, and transversal fills in side-

	(2) Historical mapping of river corridor's morphology and habitat types **(3) Quantitative analysis of changes** (mainly losses) of river habitats in the corridor	channels; (4) Historical mapping of the river corridor's morphology based on the 2nd Austrian Military Field Survey (~1860) complemented by the 1st Austrian military field survey (~1780) and other historical detail maps; comparison against the present time landscape mapping (2012). Mapping of main and side channels, oxbows, islands, bars and riparian forests within the active floodplain. • Digital data collection from available digital databases • Online mapping and review based on high-resolution images • Field survey for upper Mura stretch in Slovenia between rkm and 50 to 143 serving also to calibrate the inventory for other river stretches.
Sediment Mobilization Study	• **Hydrological data** is summarized after the Hydrological Study of the Mura River (FGG, January 2012), the considered area was examined for the flow scenarios Q5, Q2 and mQs. • **Geodetic basis:** ○ bathymetry and topography data of inundations from several data sources, a riverbed survey was performed and the banks and inundation were recorded. ○ data from past projects and analyses were used for riverbed in the wider processing area. • **Suspended load data** according to the study "Transport of sediments on the Mura" performed using laser diffraction directly upstream of the Petanjci gauging station; ○ **Bed load sediment** sampling in the area of theconsidered riverbed widening and a sample in the downstream section was performed.	• **Bathimetric survey** of the existing state and the state after construction was done using drone, sonar, boat and motor. (1) Contours that were created were imported to a 3D Survey programme (3D model of the Mura riverbed of the project for HPP Hrastje-Mota was applied): GPS data and DEM of state before the works were combined. DEM of state after the works was also provided and compared to the state before. (2) **Inundation area**: The National Classified Point Cloud (LIDAR) was used to create the digital elevation model (DEM). (3) **For the planned measures**, the geometry of the riverbed for revitalization scenarios was modified in the Autodesk Civil 3D software environment or ArcGIS 3. • Project documentation of the widening with relocating the riparian protection, 3 semi-circular shaped areas excavation and a rock structure is made. • 3 samples of sediment were taken in the pilot area for the sowing curves and information on the amount and composition of the excavated sediment introduced into the riverbed was provided.
Sediment Study	• **Planform change** • **Historical maps** as basis of analyses from the Second Military Survey of the Austrian Empire	• **Planform change:** For analyses of planform change present and historic planform properties needed to be projected onto a common line. For this

(started in 1815) partly complemented with sections from the Josephinian Land Survey (conducted from 1763 to 1787).

- The analyses of the **present condition** of river training is based on a mapping conducted by Schwarz (2013).

- **Bed level change:** Long-term analysis using gauging stations within the TBR MDD existing since the 20th century.
- **River stage data** was used to assess the annual values for the maximum, minimum and mean discharge.
- **River stage data in combination with discharge data**, the average annual mean flow of a given period was calculated (periods: 1993-2019 and 2010-2019).
- **Cross-sectional channel evolution**: Along the Drava river, in the most upstream section Dr1, repeated cross-sectional surveys of the residual flow stretches at the hydropower plants Varaždin, Čakovec and Dubrava were provided for this study. Repeated cross section surveys from the Mura section were available along the border between Austria and Slovenia for more than the last 40 years.

Sediment transport:

- (1) Recordings of **suspended sediment transport** were provided for 12 locations at varying periods of time. (2) Data on **bedload transport data** was available at Letenye (Mura) Botovo, Bélavár, Barcs and Drávaszabolcs (Drava) between 1986 and 2003.

purpose, Schwarz (2022) used elevation maps to establish valley axes of the three TBR rivers.

- Width analysis: Perpendicular cross sections were placed along the valley axes at 500 m intervals, which were used to examine the widths of discharging channels. The **total discharging width** in one section was then given by the sum of the widths. The **discharging width** (total width between the left water's edge of the most left-discharging channel and the right water's edge of the most right-discharging channel) was determined as a measure of the overall width of the river morphology.
- The **sinuosity** of the TBR rivers was assessed by the quotient of the length of river centreline and the length of the respective valley axis.
- For analyses of **river bend radii**, polylines were analysed.
- **Sediment budgets** were derived via analysing cross-sectional changes and by calculating sediment yields from recorded bedload and suspended sediment data.
- The tool CHEVO (Klösch et al., 2019a) was used to assess **morphological changes** in terms of riverbed incision/aggradation, migration of the channel and widening/narrowing. Next to cross section geometries from repeated surveys, the required input is the channel forming discharge, the manning value and the slope.
- **Implications of morphodynamics**: By using the tool HyMoLink (Klösch et al., 2019b) repeated cross section surveys were used to evaluate the relevance of occurring morphodynamics for habitats (especially on habitats for rejuvenation).

Climate Change Study	• Data of regional climate simulations carried out in WCRP European Coordinated Regional Downscaling Experiment (EURO-CORDEX) provided by Earth System Grid Federation (ESGF) were retrieved and analysed. • Analysis is done on monthly, seasonal, and annual basis, and also for four time periods namely 1976-2005 (reference period), 2021-2050 (near future), 2036-2065 (mid-century) and 2071-2100 (end-century).	Climate change assessment was carried out based on a multi-model ensemble of bias-corrected regional climate scenarios, a given parameter or climate indicator is calculated for each individual model before taking the ensemble mean: • the historical and future temperature and precipitation for TBR MDD were analyzed to select most suitable five regional climate models (RCMs) for each scenario (RCP4.5 & RCP8.5) • the daily data of selected RCMs were downscaled and bias-corrected against the gridded observation E-OBS data from European Climate Assessment & Dataset (ECA&D) • the bias-corrected data were validated and the climate change signals for temperature and precipitation in future periods were calculated • climate extreme indices from bias-corrected data were calculated and the changes in extreme events in future periods under different scenarios were quantified
Climate Change and Hydrology Study	• Data of regional climate simulations carried out in WCRP European Coordinated Regional Downscaling Experiment (EURO-CORDEX) provided by Earth System Grid Federation (ESGF) were retrieved and analysed. • Analysis is done on monthly, seasonal, and annual basis, and also for four time periods namely 1976-2005 (reference period), 2021-2050 (near future), 2036-2065 (mid-century) and 2071-2100 (end-century).	In this study, hydrological modelling of climate change impacts on runoff in the Drava River basin has been performed. The scope of work included the following tasks: 1.1 collect and analyse data needed for the model (meteorological, hydrological, digital terrain model, land use, soil maps, etc) 2.1 perform an analysis and make the selection of the meteorological and hydrological stations from which the data will be collected and used for the modelling; 3.1 set up the model, including calibration to observed data; 4.1 using the observed and modelled hydrologic and meteorological data, create simulation forecasts for future scenarios.

Study on Hydropeaking Effects	• Data collected from hydropower plant operators and hydrographic services • Max. resolution available: 60 minutes (SI, HR); 10 minutes (AT)	The study applies both main approaches used in hydrology for describing hydropeaking waves: the Eulerian approach and Lagrangian approach. A. Eulerian view. In this study, all sub-daily flow fluctuations whose maximum flow rate exceeds 10% of the estimated intensity of natural flow fluctuations related to mean flow conditions ($GW_{10,}$ i.e., 10% of GW_{100}) are analyzed. All available time series are evaluated, the annual frequencies of the documented flow fluctuations are presented and exemplified using the year 2019 (available for all hydrographs except Donji Miholjac. The intensity of the flow fluctuations is presented referring to the data basis of 60 and 15. For the Donja Dubrava hydrograph, the frequency and intensity of the sub-daily fluctuations are presented additionally on a monthly data basis, since this river section is analyzed in more detail. B. Lagrangian view. The empirical hydrological method PeakTrace, (R-package HydroRoute) was applied to enable the routing of hydropeaking waves in order to assess the changes in unsteady flows along the Drava River downstream of Donja Dubrava. The goal was to link PeakTrace results (hydrological scenarios) to ecological responses, e.g., by incorporating critical thresholds of specific river organisms and life stages. Such thresholds usually refer to stage measurements (e.g., cm/min or cm/h) and not to flow-related metrics (e.g., $(m^3/s)/min$). The flow-related PeakTrace results had to be transformed into stage-related metrics, which was done by regression models.

Annex A.3. Sampling sites for underlying studies

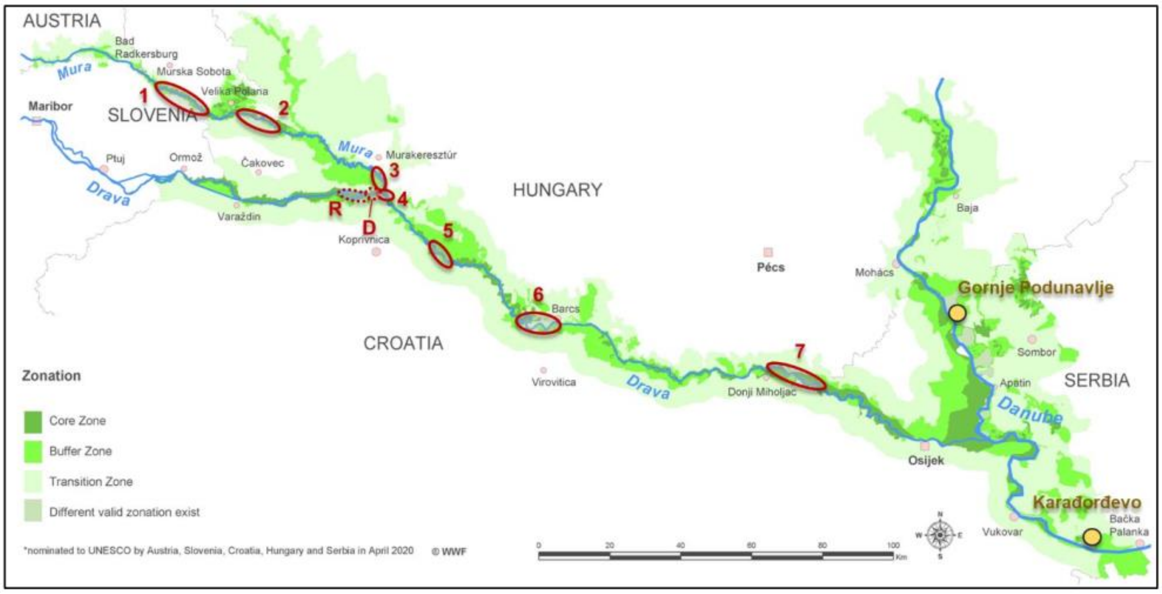


Figure A2: Fish Study: Distribution of sampled sections in Mura and Drava (red, samples conducted by BOKU) and yellow (sampling in Serbian Danube backwaters, conducted by INCVP). Sections 1 to 7 describe the longitudinal gradient in the Mura and Drava rivers. Sections "R" (residual flow stretch of HPP Donja Dubrava) and "D" (section below the HPP) were sampled additionally to gain insights in potential effects of hydropower operation.

Figure A3: The Mura, Drava and Danube riverbed between Ceršak (SLO) and Bačka Palanka (RS), where the census of selected breeding bird species was conducted in the 2021and 2022 seasons. Different colours represent the sections, where different bird experts conducted the field bird census. Light green line – Božič 2022, blue line – Grlica 2022, dark green line – Radišić 2022, grey line – no bird census.

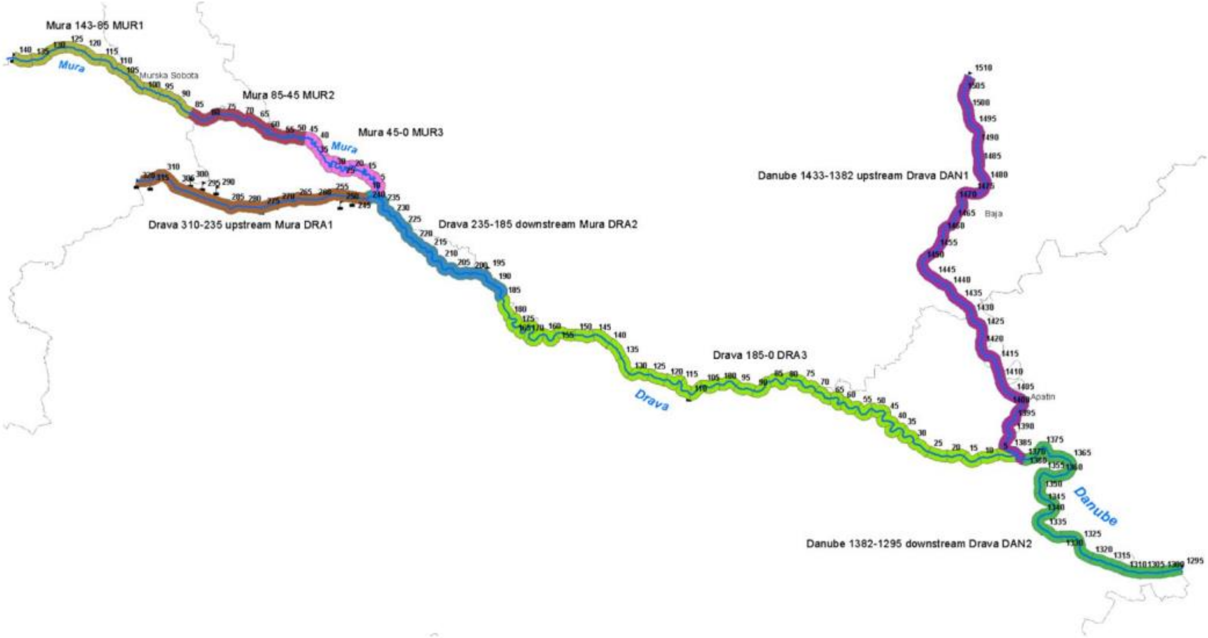


Figure A4: River training structures: Overview of the eight River section types (RST) and rkm together with the visualization and assessment segments of 10 km for Danube and 5 km for Mura and Drava.

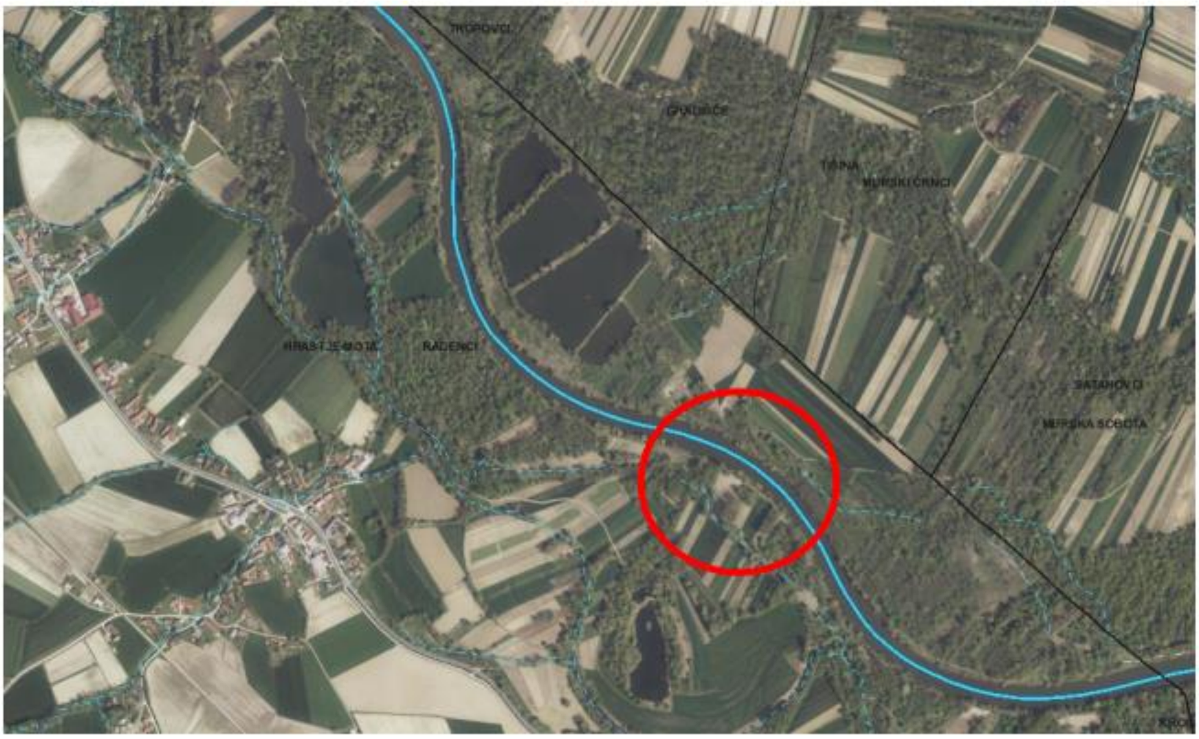


Figure A5: Sediment Mobilisation Study: Map of the study area and the location of the pilot area in WPT2.

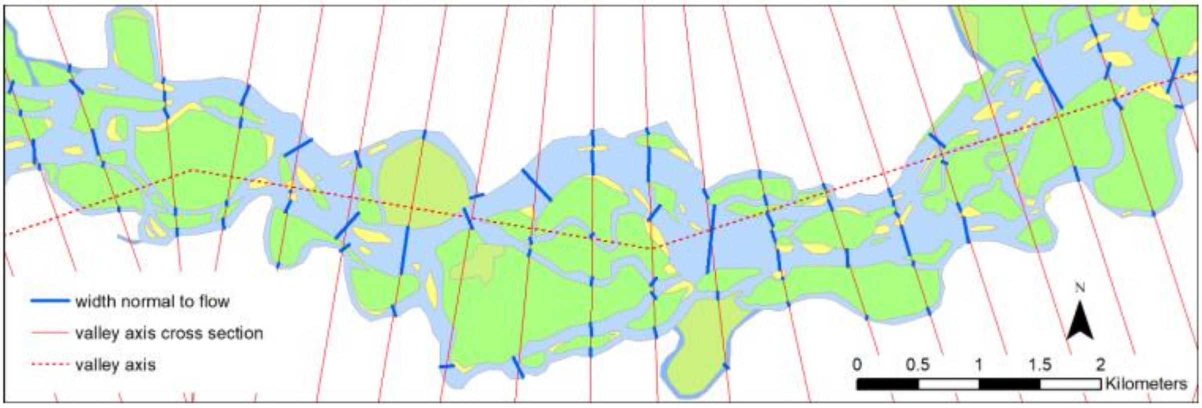


Figure A6: Sediment Study: Methodology of the width analysis: Along the valley axis (red, dotted), perpendicular cross sections (red) were placed at a distance of 500 m. Along these valley cross sections, again cross sections (blue) were placed at each intersection of the valley cross section with the centre lines of the individual channels. The sum of the individual blue cross sections along a valley cross section results in the discharged width of the respective valley cross section.

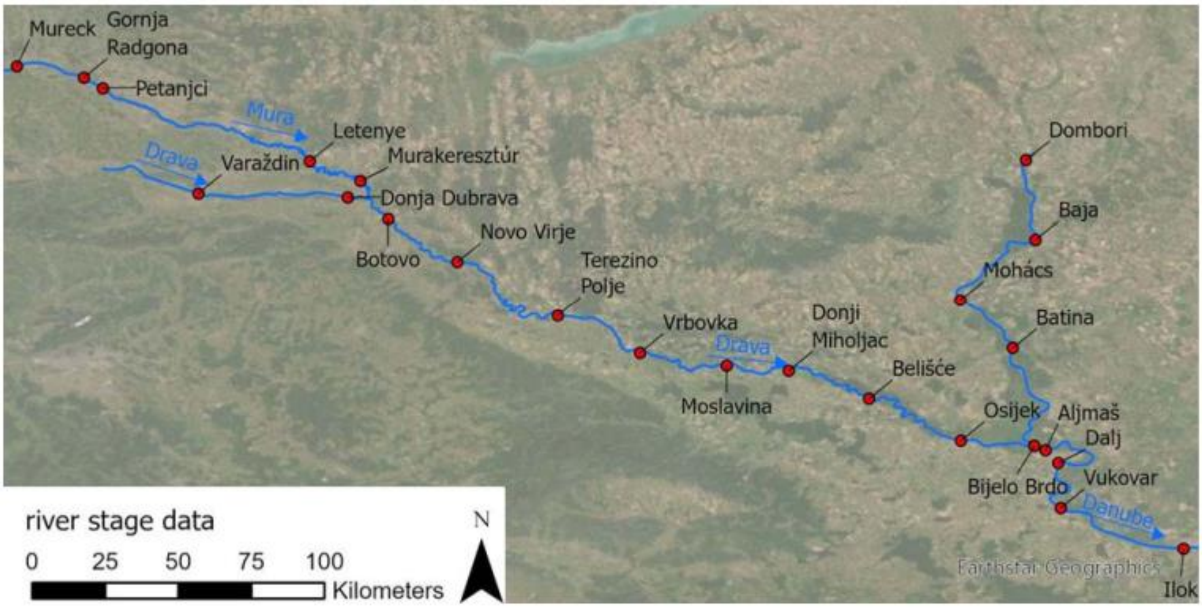


Figure A7: Sediment Study: Considered gauging stations.

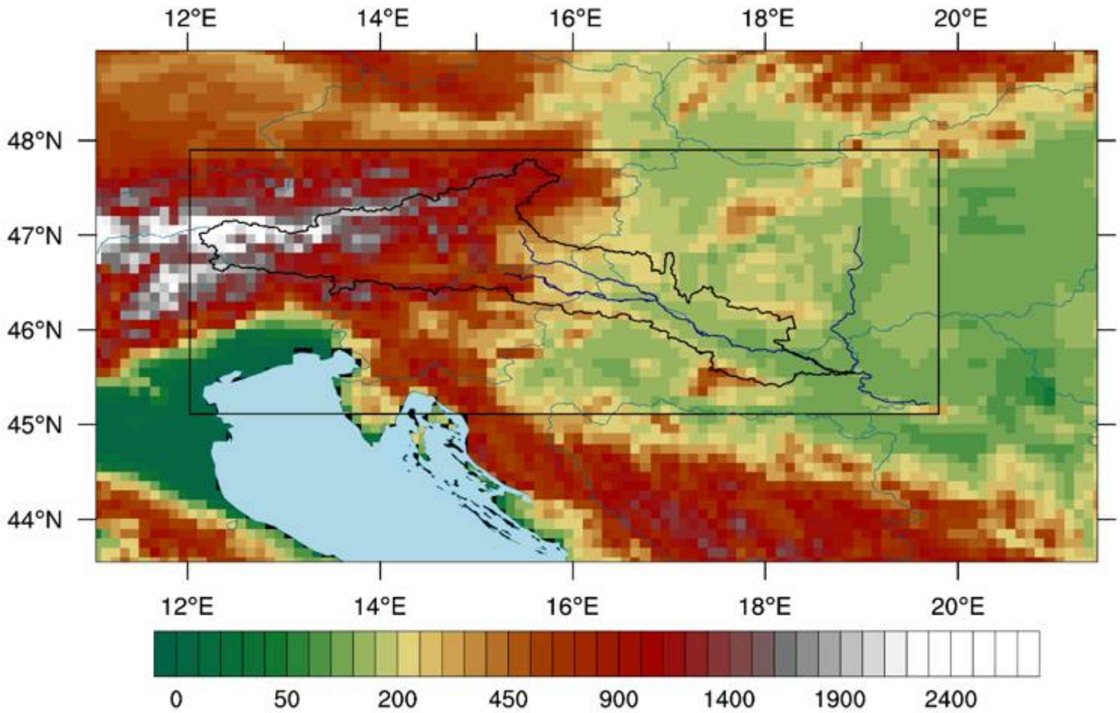


Figure A8: Climate Change and Hydrology Study: Geographical domain showing topographic elevation of E-OBS gridded dataset. The climate data is downscaled to this domain; however, the analysis is done for the area highlighted with a rectangular box. (Drava River basin is also outlined).

Table 1A: Hydrographs used for Eulerian analysis

Hydrograph ID	River	Name	Catchment (km^2)	MQ (m^3/s)	Time series
212043	Isel	Hinterbichl	107	5	1976 - 2021
212183	Isel	Waier	285	11	1976 - 2021
212092	Isel	Brühl	518	21	1976 - 2021
212167	Isel	Lienz	1.199	40	1976 - 2021
212316	Drau	Lienz-Peggetz	1.876	56	1977 - 2021
212324	Drau	Oberdrauburg-OWF	2.112	61	1977 - 2020
213660	Drau	Dellach-OWF	2.199	67	2013 - 2021
212357	Drau	Sachsenburg (Brücke)	2.561	69	1976 - 2020
213199	Drau	Drauhofen	3.674	109	1976 - 2021
213215	Drau	Amlach	4.790	131	1976 - 2020
213173	Drau	Lavamünd Ort	11.052	255	2005 - 2019
213595	Drau	Lavamünd Grenze	12.007	258	2011 - 2019
600420	Drau	Dravograd (Q-KW)	12.609	280	2010 - 2021
600421	Drau	Maribor - Otok (Q-KW)	13.417	297	2010 - 2021
600422	Drau	Ptuj	13.575	325	2019 - 2021
600423	Drau	Borl	14.624	53	2010 - 2021
600412	Drau	Donja Dubrava	16.682	317	2003 - 2019
600413	Drau	Botovo	31.038	475	2001 - 2019
600414	Drau	Novo Virje Skela	31.803	484	2001 - 2019

Hydrograph ID	River	Name	Catchment (km²)	MQ (m³/s)	Time series
600415	Drau	Terezino Polje	33.916	492	2001 - 2019
600416	Drau	Donji Miholjac	37.142	509	2001 - 2016
600417	Drau	Belisce	38.500	524	2003 - 2019

(Hydrograph ID – internal database ID, MQ – mean flow, Catchment size calculated by GIS analysis)

Table 1B: Hydrographs used for Lagrangian analysis

Hydrograph ID	River	Name	Catchment (km²)	MQ (m³/s)	Time series	Station	Distance to HPP (rkm)	LAG (h)
600412	Drava	Donja Dubrava	16.682	317	2003 - 2019	S1	5,4	0
600413	Drava	Botovo	31.091	475	2001 - 2019	S2	20,4	03:00
600414	Drava	Novo Virje Skela	31.852	484	2001 - 2019	S3	47,1	08:00
600415	Drava	Terezino Polje	34.209	492	2001 - 2019	S4	94,3	18:00
600416	Drava	Donji Miholjac	38.031	509	2001 - 2016	S5	165,3	36:00
600417	Drava	Belisce	38.445	524	2003 - 2019	S6	192,8	43:00

(Hydrograph ID – internal database ID, MQ – mean flow, Station – hydrograph number downstream of the hydropower plant Donja Dubrava, HPP – hydropower plant, rkm – river kilometer, LAG – flow time between S1 and S_x,)

Annex A.4. Synthesis Overlay analysis in percentages

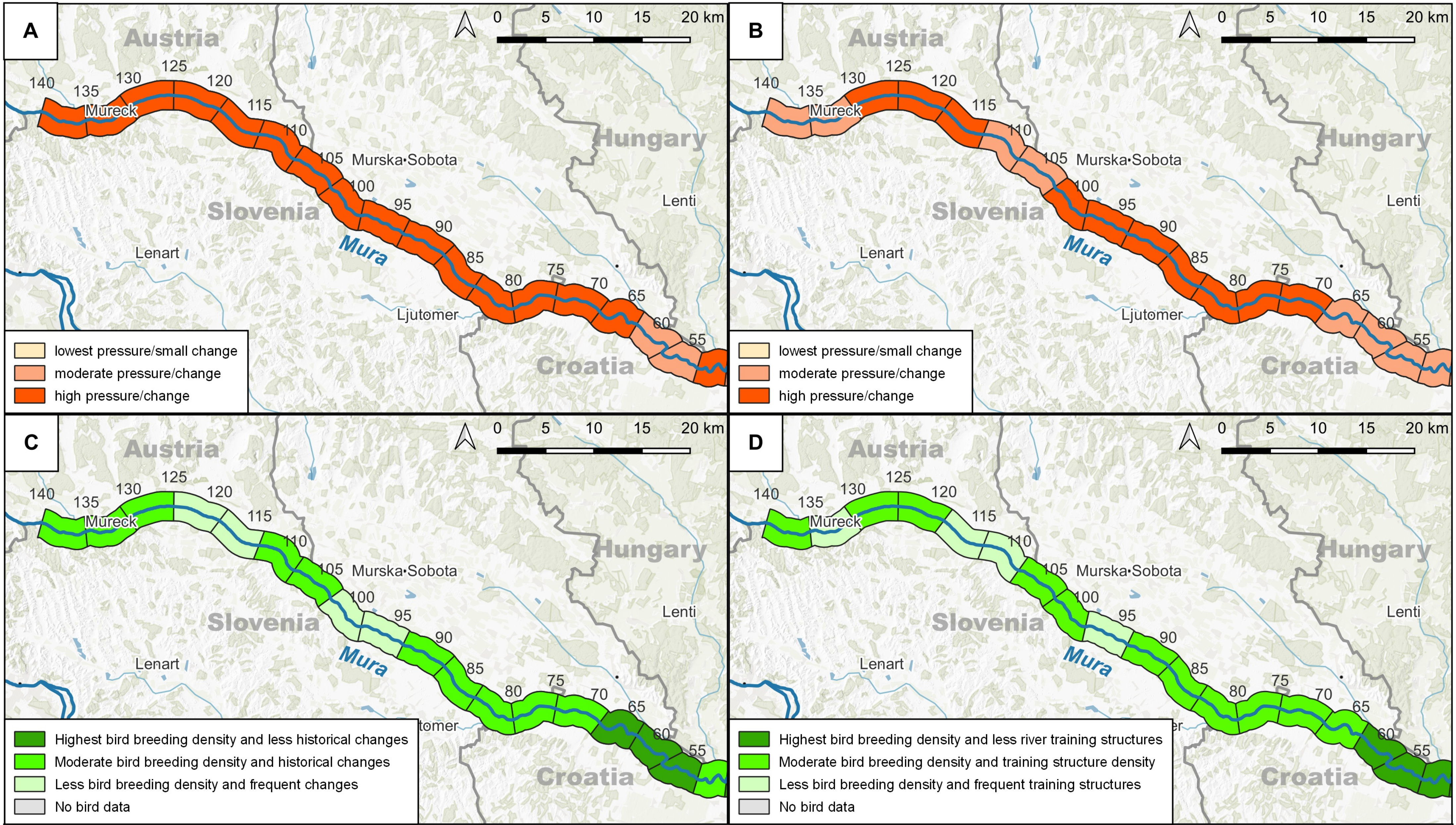
A.4.1. Linkage of the historical mapping of river morphology and river training structures: percentage split of analysed sections per class

Class	Worst value	Mean value
Lowest pressure/small change	1,47 %	7,35 %
Moderate pressure/change	26,47 %	68,38 %
High pressure/change	72,06 %	24,26 %

A.4.2. Linkage between morphology (historical changes/ present river training structures) and bird breeding site density: percentage split of analysed sections per class

Class	Historical changes	River Training structures
Highest bird breeding density and less historical changes/ river training structures	16,18 %	11,76 %
Moderate bird breeding density and historical changes/ training structure density	59,56 %	56,62 %
Less bird breeding density and frequent changes/ training structures	7,35 %	14,71 %
No bird data	16,91 %	16,91 %

Annex A.5. Synthesis Overlay maps in detail



Section 1: Mura from Mureck (AT) to Muraszemenye (HU)
A: Linkage of the historical mapping of river morphology and river training structures (worst value)
B: Linkage of the historical mapping of river morphology and river training structures (mean value)
C: Linkage between historical changes and the current bird breeding site density
D: Linkage between the current river training structures and bird breeding site density

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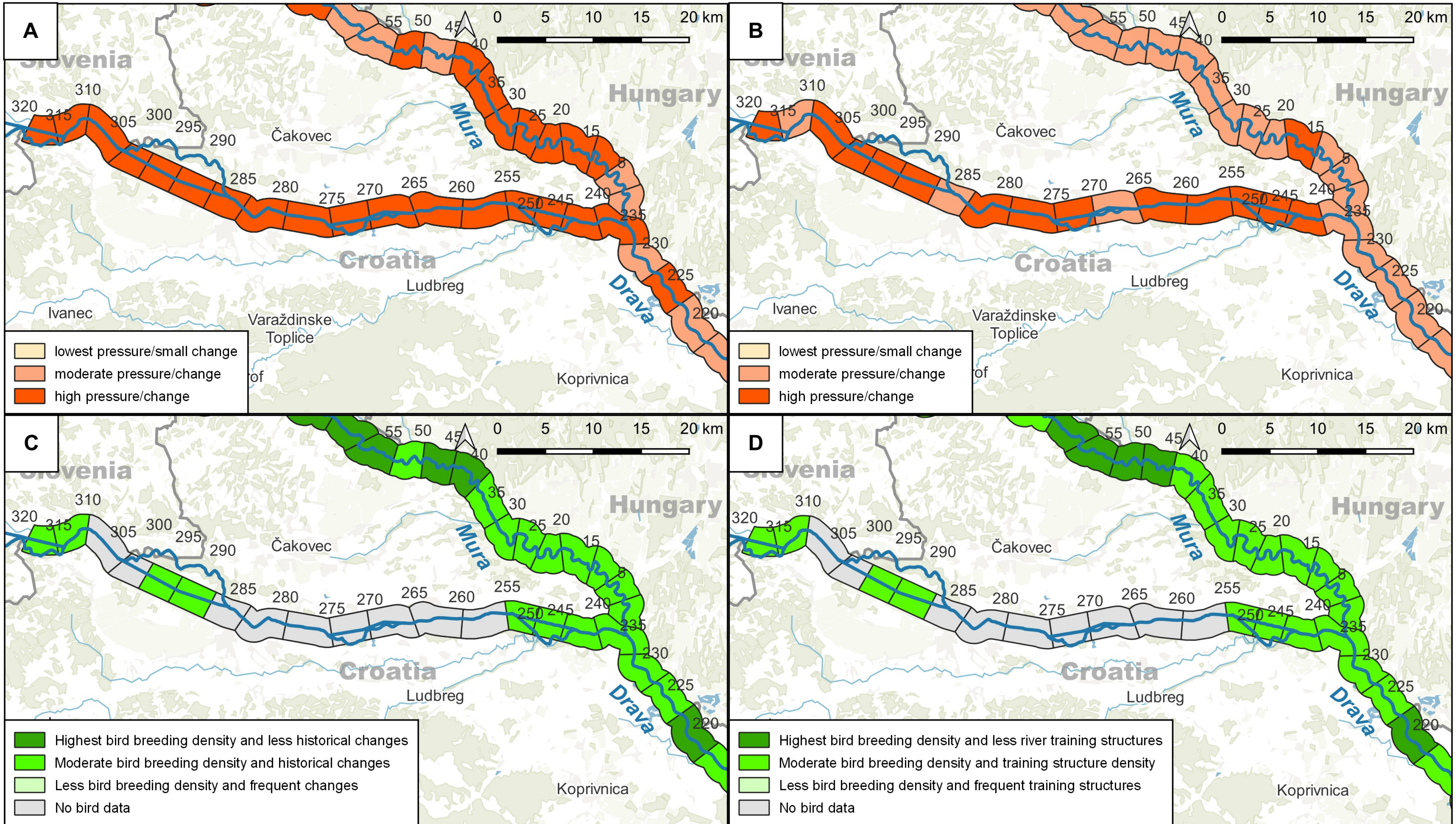

Section 2: Mura from Muraszemenye (HU) to Legrad (HR), Drava from Dubrava Križovljanska to Botovo (HR)
A: Linkage of the historical mapping of river morphology and river training structures (worst value)
B: Linkage of the historical mapping of river morphology and river training structures (mean value)
C: Linkage between historical changes and the current bird breeding site density
D: Linkage between the current river training structures and bird breeding site density

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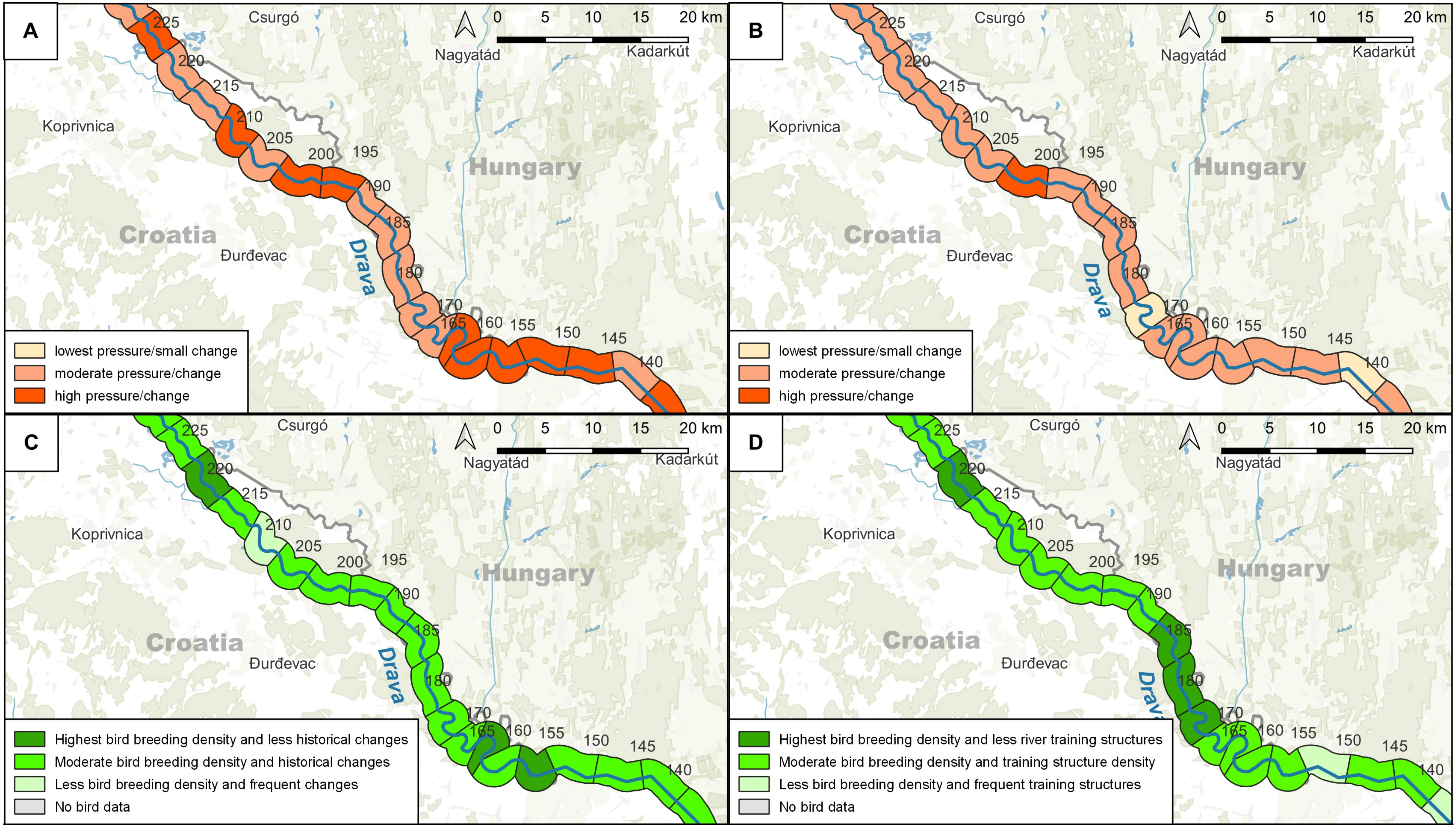

Section 3: Drava from Botovo (HR) to Felsőszentmárton (HU)
A: Linkage of the historical mapping of river morphology and river training structures (worst value)
B: Linkage of the historical mapping of river morphology and river training structures (mean value)
C: Linkage between historical changes and the current bird breeding site density
D: Linkage between the current river training structures and bird breeding site density

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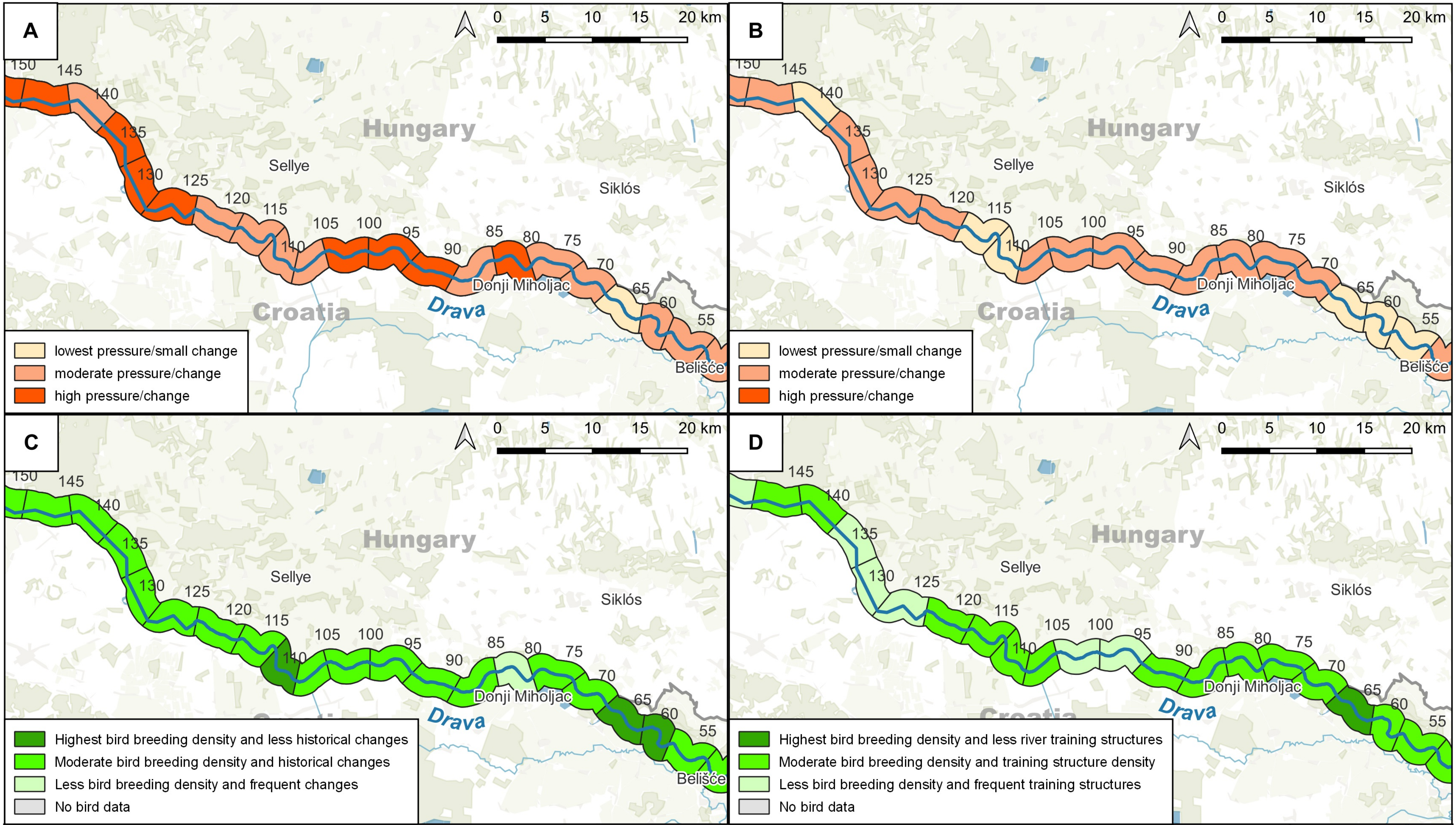

Section 4: Drava from Felsőszentmárton (HU) to Belišće (HR)
A: Linkage of the historical mapping of river morphology and river training structures (worst value)
B: Linkage of the historical mapping of river morphology and river training structures (mean value)
C: Linkage between historical changes and the current bird breeding site density
D: Linkage between the current river training structures and bird breeding site density

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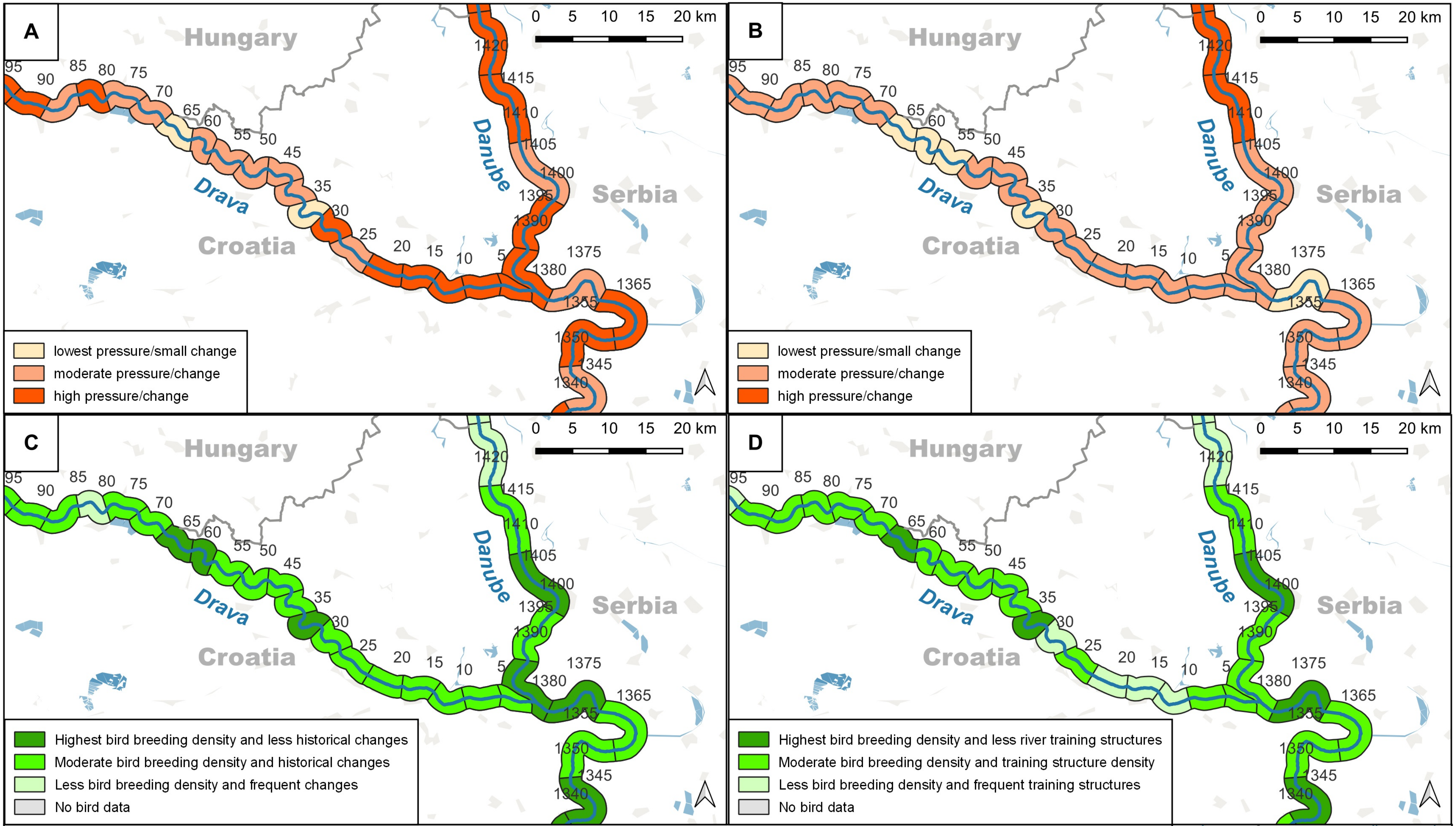

Section 5: Drava from Donji Miholjac (HR) to confluence, Danube from Batina to Borovo (HR)
A: Linkage of the historical mapping of river morphology and river training structures (worst value)
B: Linkage of the historical mapping of river morphology and river training structures (mean value)
C: Linkage between historical changes and the current bird breeding site density
D: Linkage between the current river training structures and bird breeding site density

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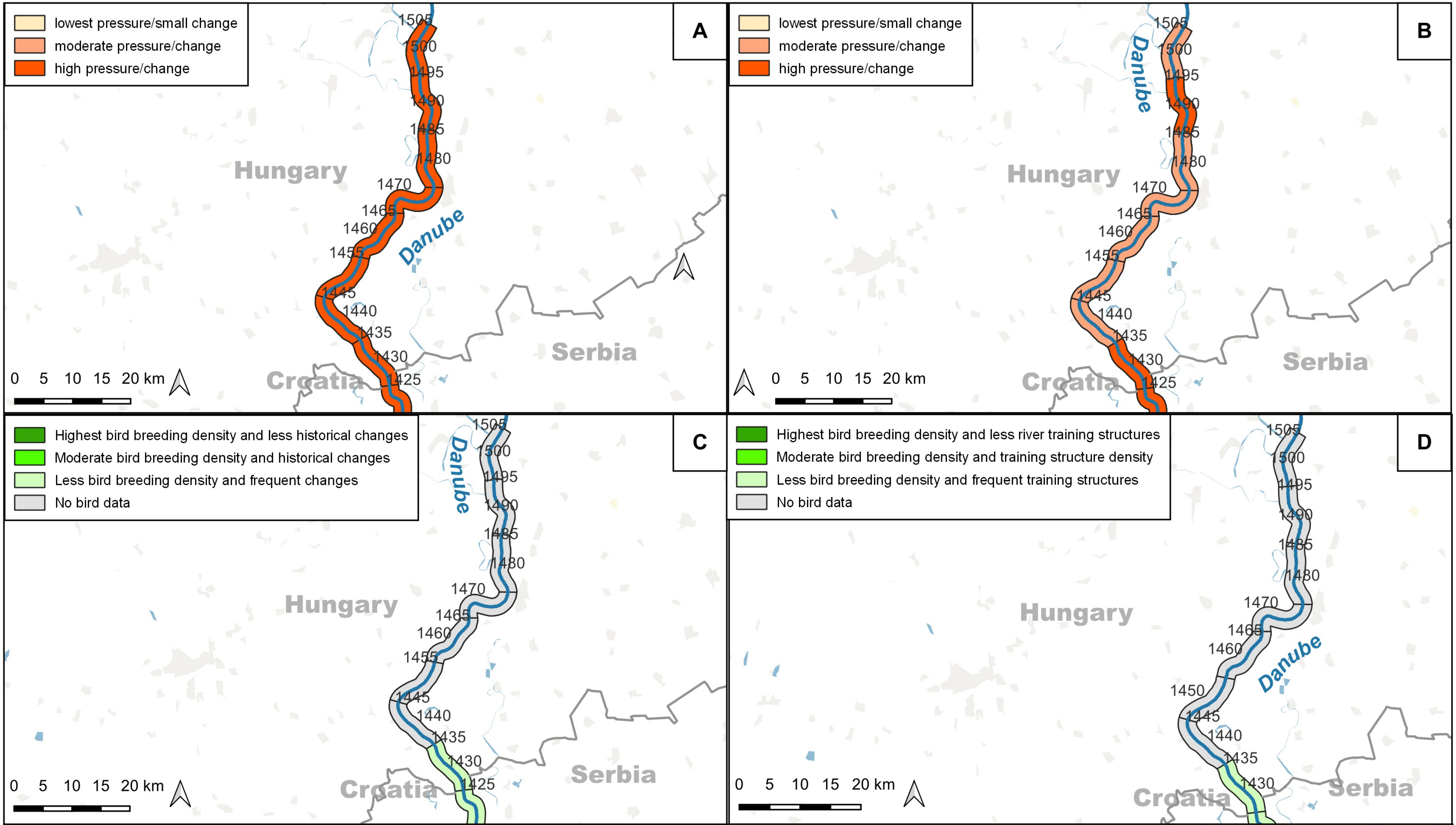

Section 6: Danube from Kalocsa (HU) to Mohács (HU)
A: Linkage of the historical mapping of river morphology and river training structures (worst value)
B: Linkage of the historical mapping of river morphology and river training structures (mean value)
C: Linkage between historical changes and the current bird breeding site density
D: Linkage between the current river training structures and bird breeding site density

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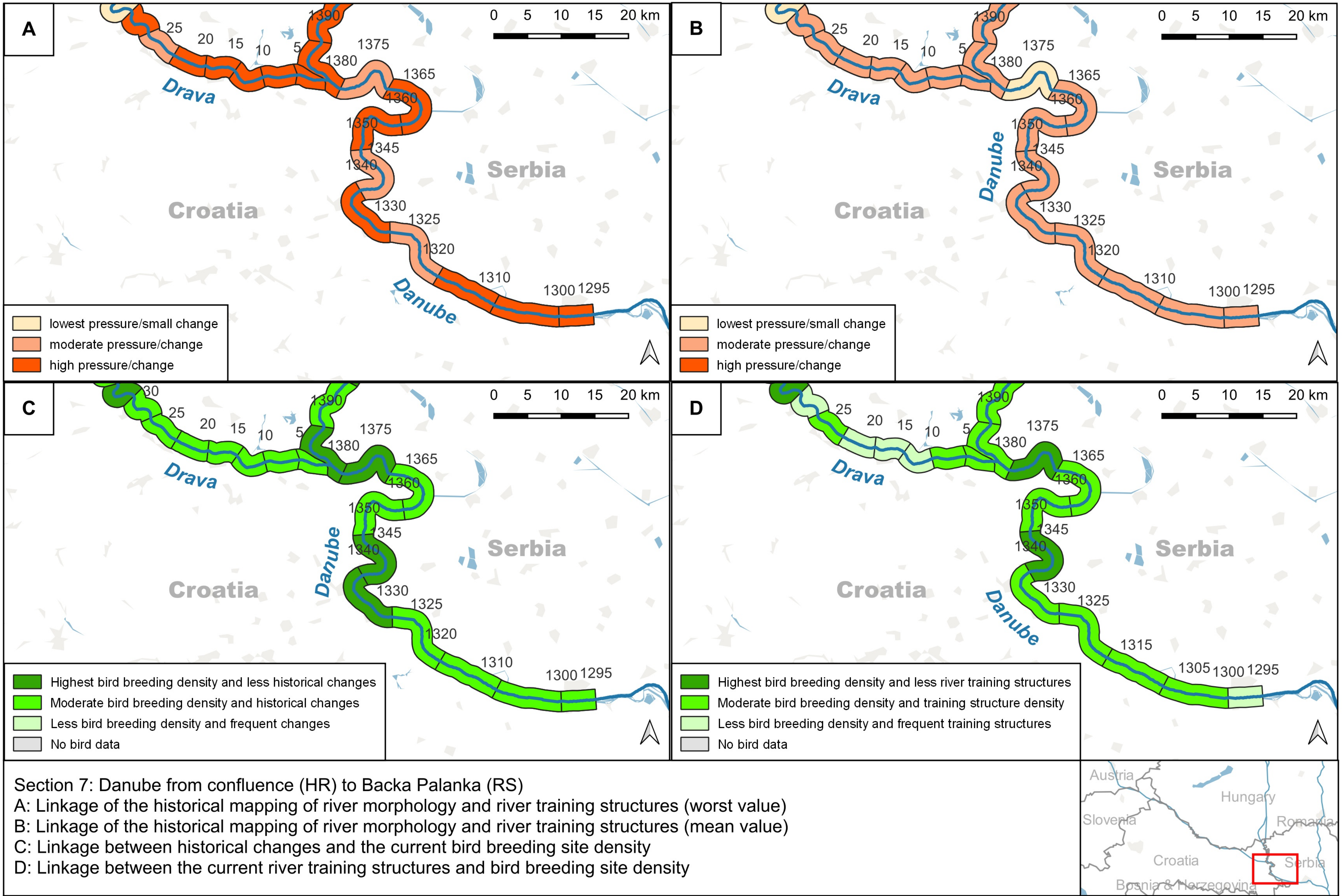

Section 7: Danube from confluence (HR) to Backa Palanka (RS)
A: Linkage of the historical mapping of river morphology and river training structures (worst value)
B: Linkage of the historical mapping of river morphology and river training structures (mean value)
C: Linkage between historical changes and the current bird breeding site density
D: Linkage between the current river training structures and bird breeding site density

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