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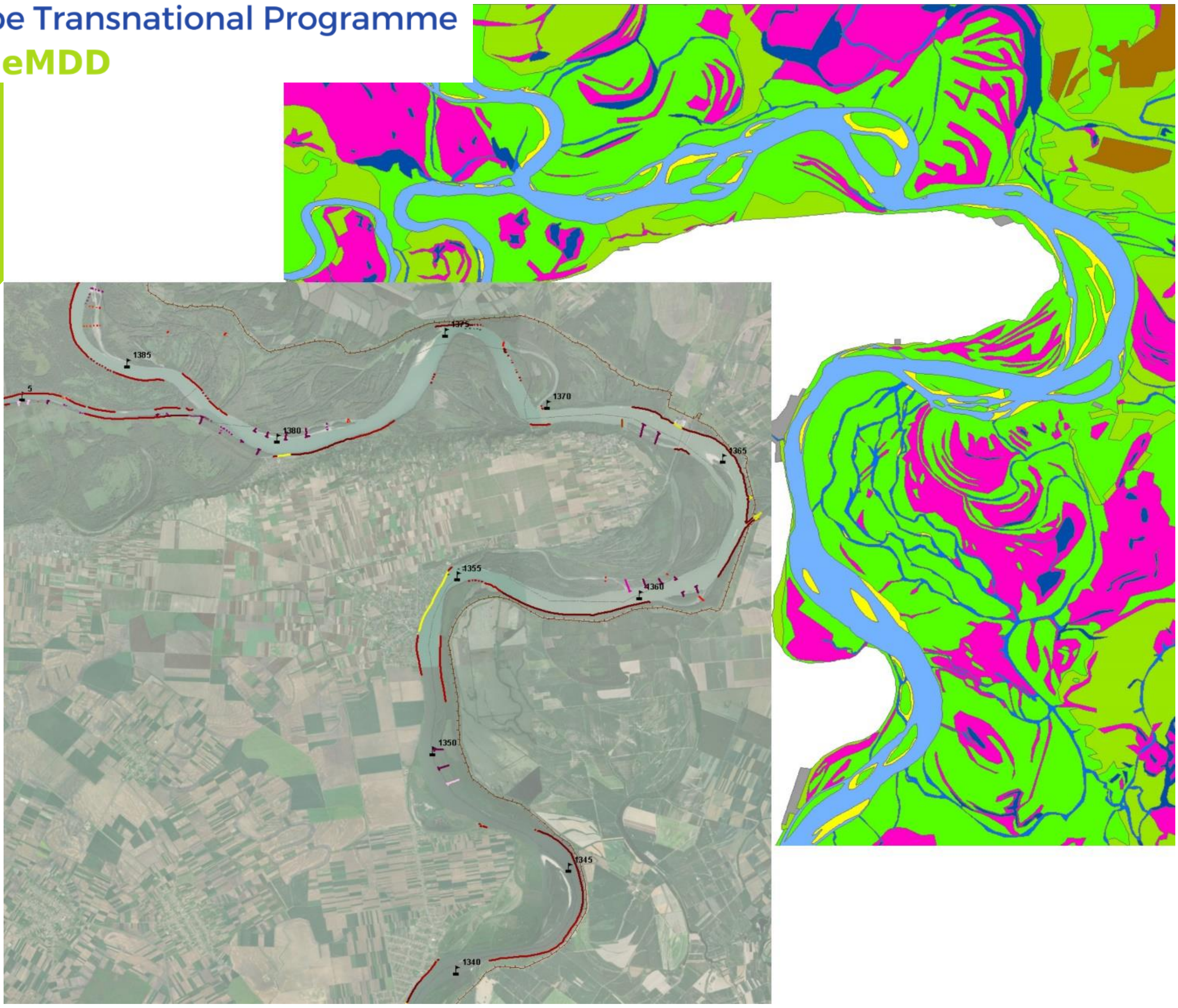


# *River Training Structures and Historical Mapping within the Mura-Drava-Danube TBR*

DTP3-308-2.3- lifelineMDD
D.T1.2.1 „River Training Structures“
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# IMPRESSUM

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# Executive Summary

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 MDD TBR the study provides two major data sets. First it provides an inventory of river training structures and secondly it shows first time the historical habitat distribution, which is of major importance regarding referencing and targeting river restoration activities.

## River training structures

The inventory of river training structures include all kind of groynes (namely "T"-groynes as intact, overgrown, disconnected, collapsed), training walls (only on Danube), transversal fills to cut off side-channels, all kind of rip-rap (intact, overgrown, collapsed), concrete walls (also for harbors, settlements), hydropower embankments, flood dykes but namely transversal structures as dams, ramps and ground sills. In total 2,300 structures with a length of 1,676 km can be find in the MDD TBR, only this figures indicate the tremendous importance for the understanding of channel morphology and deficits in hydromorphology, which is also strongly linked to sediment deficit and hydropower.

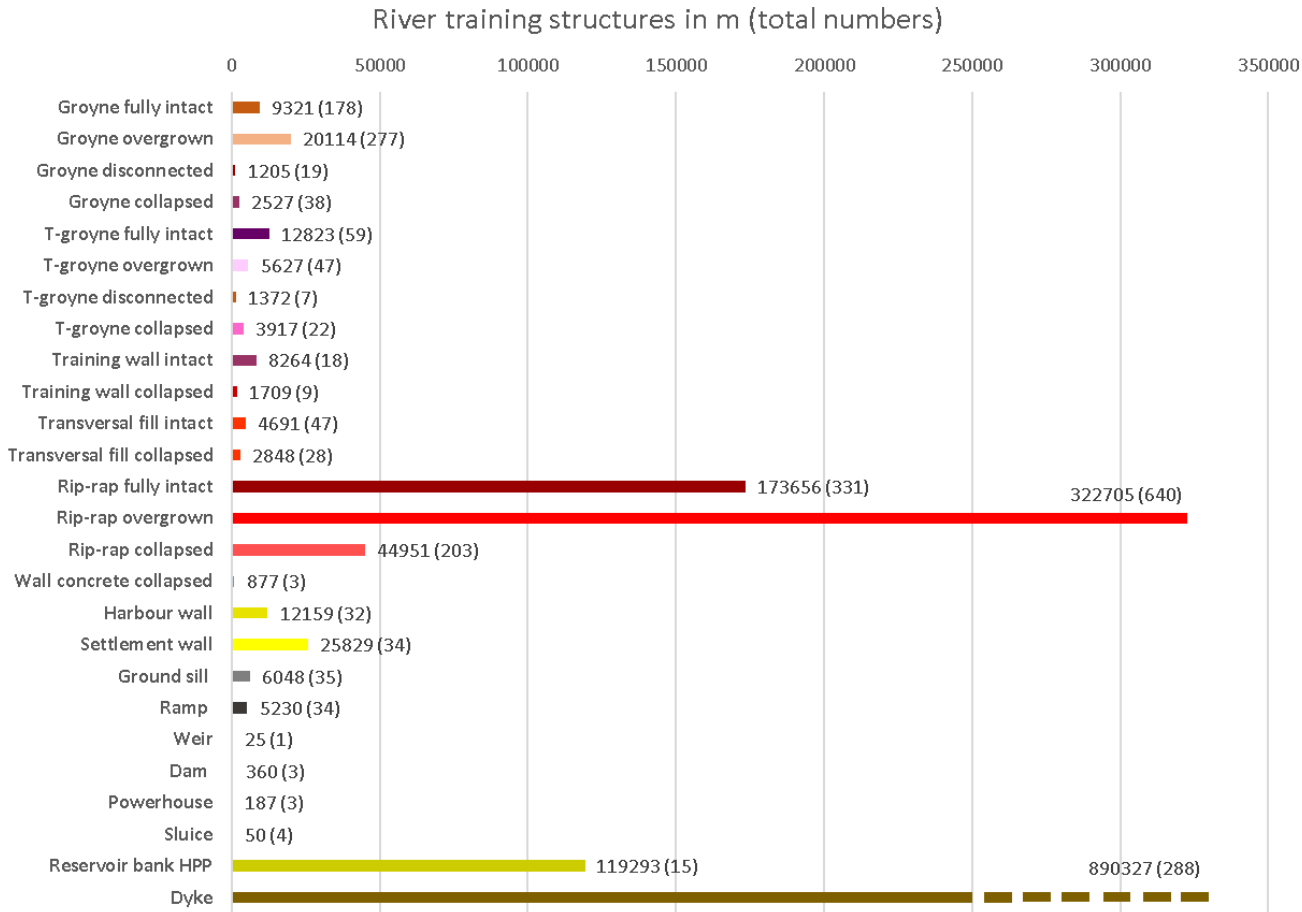


*Figure ES 1 (Executive Summary): Total distribution of river training structures in the entire MDD TBR.*

## Historical mapping

The historical mapping is mostly based on the second Austrian-Hungarian Military survey from about 1860 but combines the first survey from 1780 to reconstruct the position for the cut-off meanders for lower Drava and some meander cut-offs on Danube. Therefore, the historical mapping is not focusing on one particular year but tries to deliver the best possible option to provide a reference in particular for all kind of channels, bars, islands and riparian habitats.

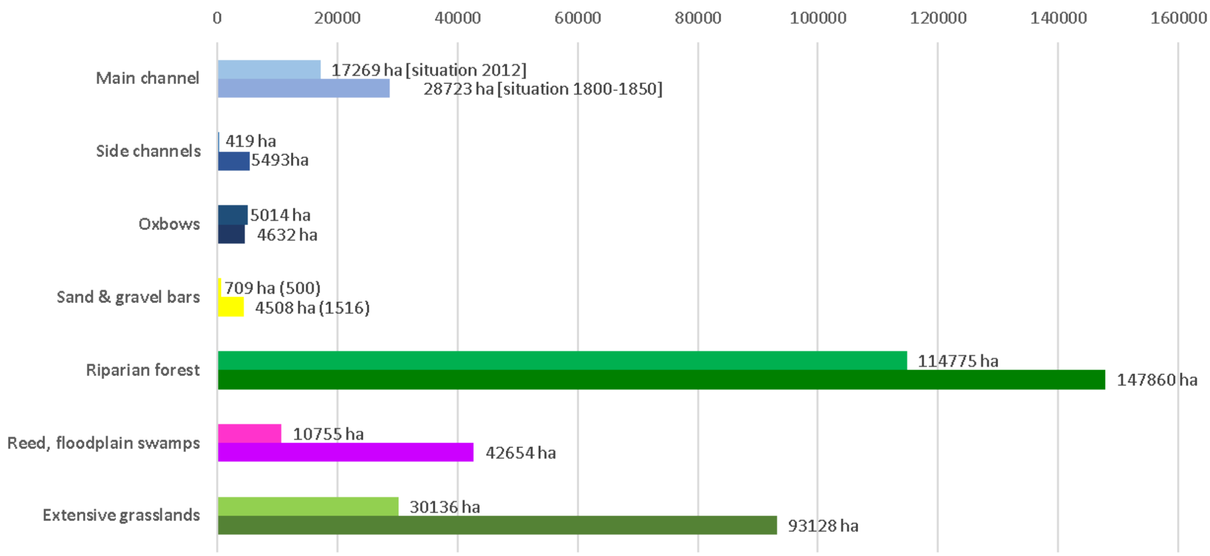


*Figure ES 2: Total distribution of core habitats in the historical state (1800-1850 and nowadays (2012).*

The losses of riparian habitats are tremendous and reach 60-90 percent for the most dynamic habitats like all kinds of channels, gravel and sand bars as well as river and floodplain islands (lateral connectivity).

## Conclusions and Outlook

Both tasks the inventory of river training structures as well as the historical mapping allow the first time to entirely quantify and link the historical status before major human interventions and the massive impact of river regulation in the past and today. Assessed for the main river section types it is possible to address the particular deficits and to provide the background for potential restoration measures and finally point out where regulation works could be removed.

# I. Introduction

The present report is the result of a study conducted within the DTP3-308-2.3 lifeline MDD, financed by the European Union´s Interreg Danube Transnational Programme. The area analyzed and targeted by the present study (hereinafter called "target area") comprises river sections in the 5-country Biosphere Reserve Mura-Drava-Danube (TBR MDD, Figure 1), shared between Austria, Slovenia, Hungary, Croatia and Serbia. Spanning Austria, Slovenia, Hungary, Croatia and Serbia, the lower courses of the Drava and Mura Rivers and related sections of the Danube are among Europe's most ecologically important riverine areas. The three rivers form a "green belt" 700 kilometres long, 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. Step by step the TBR MDD was realized: Hungary and Croatia (in 2012), Serbia (in 2017), Slovenia (in 2018) and Austria (2019) achieved UNESCO designation. The pentalateral designation was submitted in 2020 and designation finally achieved in September 2021.

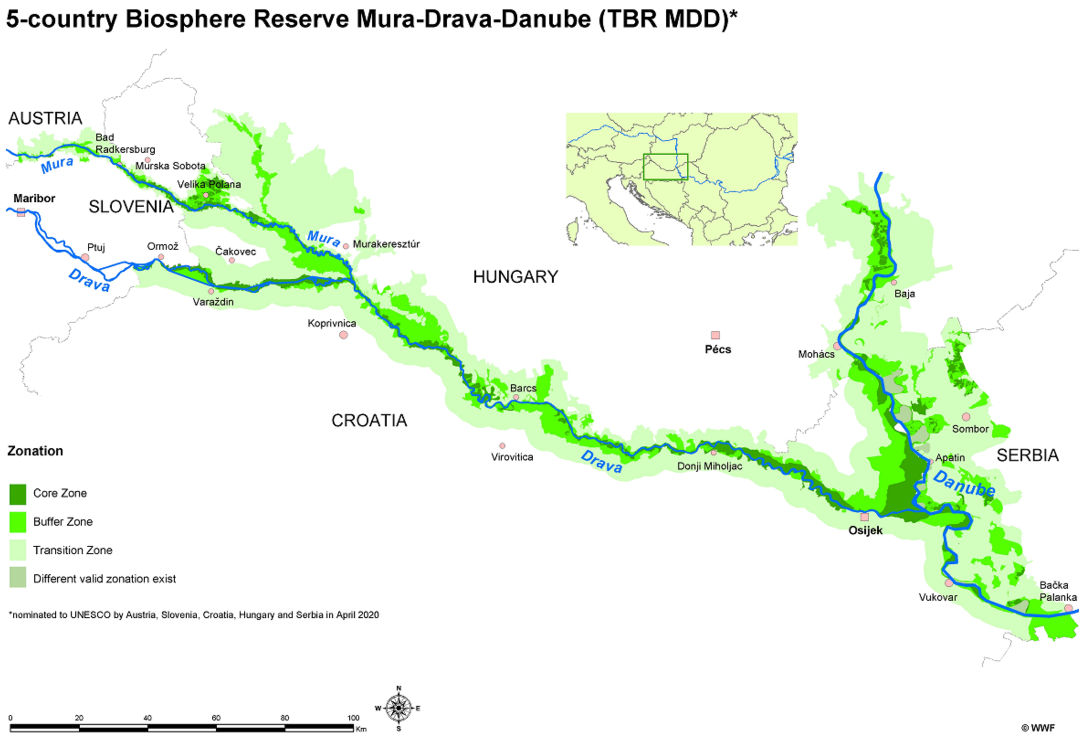


*Figure 1. Map of the 5-country Biosphere Reserve Mura-Drava-Danube according to UNESCO designation in September 2021 (WWF Austria)*

The project´s work package for Establishing the scientific knowledge base (Work Package T1) has proposed as its aim to establish, as a first, a scientific knowledge base regarding vertical, lateral and longitudinal connectivity within the Mura-Drava-Danube bio-corridor. All studies' results and the overlaid GIS data collected therefore build the basis for a synthesis report on biotic indicators and abiotic framework conditions. This builds the basis for long-term conservation and restoration goals within the 5-country Biosphere Reserve Mura-Drava-Danube (TBR MDD) as well as for formulation of a TBR MDD River Restoration Strategy, elaborated in the framework of the same project (Output OT2.4). The facts and results presented in this project therefore come from a first ever such scientific assessment, which was done between July 2020 and (Month) (year), harmonized on 5-country scale, setting the ground for future decision-making on 5-country level on river management and restoration. Whereas such activities and knowledge in each of the countries involved in the TBR MDD partly exist, this was the first time methods and area were harmonized for monitoring and studies of the biotic elements and the abiotic framework conditions for the Mura-Drava-Danube river corridor.

The inventory of river training structures for the Danube, Drava and Mura is of great importance for the understanding of the current and past development of the river channels but also the development of the entire riparian corridor (flood dykes). The investigations cover a wide range of data sets provided by countries, NGO's and individuals as well as previous hydromorphological mapping of the TBR MDD rivers.

The report assesses the current status of river training structures in terms of types of structures such as longitudinal reinforcements (bank rip-rap, flood dykes), groynes, and transversal structures such as dams, weirs, ramps and sills. Further, the structures are quantified allowing the determination of length/percentage of reinforced versus dynamic banks. It is possible to analyze the general development and to identify those reaches with much and less training structures and subsequently the demand for restoration proposals and options (which is covered in the Synthesis report on science-based needs for action (D.T1.3.1)).

Furthermore, the results of this study are embedded in the greater context of the originating project lifelineMDD and provided as input for the elaboration of a sediment balance and morphology study, as well as for two biotic studies regarding birds nesting and fish populations along the three rivers.

In addition to the overview, it was decided to map the historical situation, namely to support the evaluation regarding morphology and sediment balance (D.T1.2.3) (to calculate and compare total river length before regulation, to calculate and estimate channel width variability as well as bar and islands count and development). Finally, the historical mapping was expanded to the entire active main and side-channel river corridor and floodplain area to compare the riparian landscape in the past with those of today (based on the land structure/habitat mapping from 2012). This comparison in conjunction with the definition of River section types will help define targets for restoration projects.

# II. Methodology

The following chapter gives the introduction and describes the method to obtain and harmonize respective data for training structures and the historical mapping. The framework for both data products is a wide range of already existing data in combination with a systematic check with high-resolution satellite images.

## A. River section types

The definition of overall River section types (RST) for the three rivers is an important step to characterize the different river types and to assess all results accordingly throughout all work packages and in particular the scientific studies. The following eight River section types are defined for the three rivers and, based on EU REFORM project definitions (Gurnell et al. 2016) they characterize the rivers as described in table 1 and figure 2 below.

*Table 1: River section types (RST) for Mura, Drava and Danube.*

| River Section Type | Location and rkm | Short characteristic according to EU-Reform terminology |
|---|---|---|
| | | |
| MUR1 | Mura rkm 143 (Spielfeld/AT) – rkm 85 | Valley unconfined, multi-thread to transitional, anabranching |
| MUR2 | Mura rkm 85 (Mura near Ljutomer) – Rkm 45 (near Letenye) | Valley unconfined, transitional, wandering with anabranching reaches |
| MUR3 | Mura rkm 45 (near Letenye) – rkm 0 (Drava confluence, Örtilos) | Valley unconfined, single thread, meandering |
| DRA1 | Drava rkm 310 (Ormoz) – rkm 235 (Mura confluence, Örtilos/Legrad) | Valley unconfined, multi-thread, anabranching with short braided reaches |
| DRA2 | Drava rkm 235 (Mura confluence, Örtilos/Legrad) –rkm 185 (near Babocsa) | Valley unconfined, transitional, wandering with anabranching and meandering reaches |
| DRA3 | Drava rkm 185 (near Babocsa) – rkm 0 (Danube confluence, Aljmas) | Valley unconfined, single thread, meandering |
| DAN1 | Danube rkm 1,433- 1382 (upstream Drava confluence to Fajsz) | Valley unconfined, single thread, meandering (partly two main branches) |
| DAN2 | Danube rkm 1382-1,295 (downstream Drava confluence to Ilok) | Valley partly unconfined, single thread, meandering (along the less high terrace) |

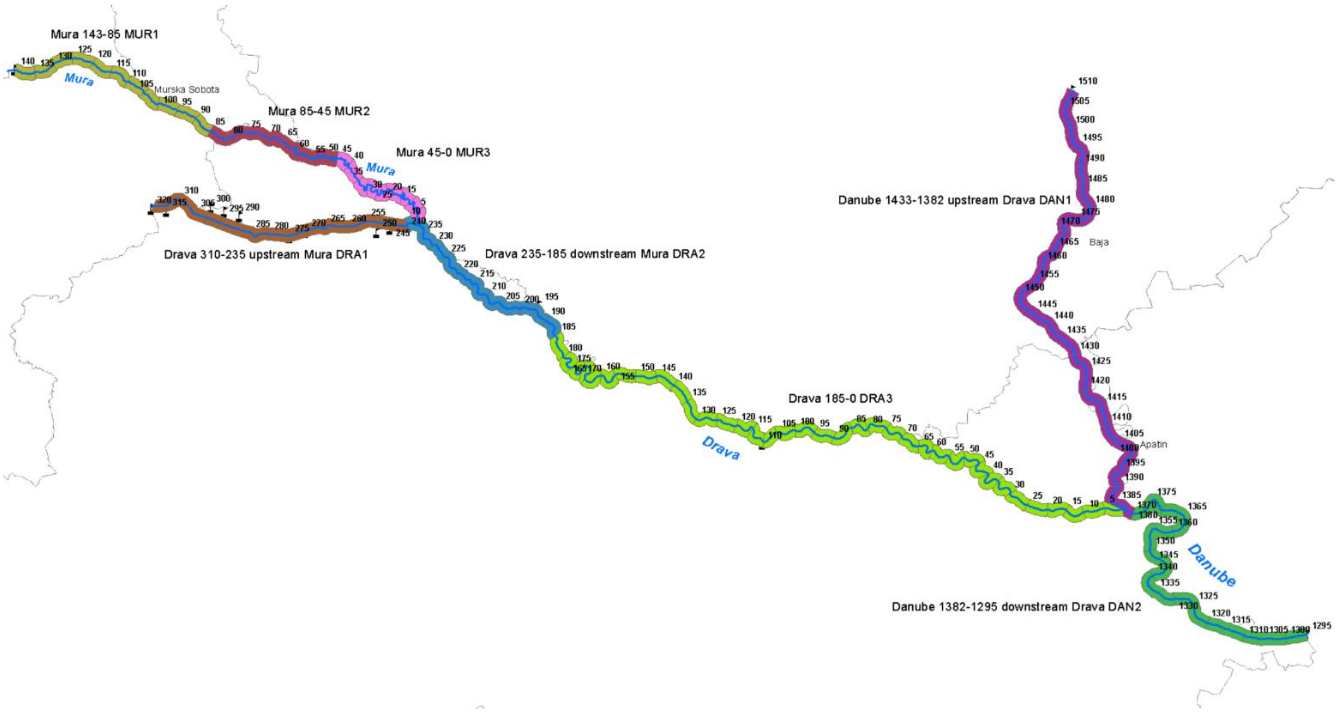


*Figure 2: Overview of the eight River section types (RST) and rkm together with the visualization and assessment segments of 10 km for Danube and 5 km for Mura and Drava.*

## B. Visualization and assessment segments

To allow a seamless visualization and assessment of river training structures, but also for the final synthesis (overlay) with the other scientific studies the introduction of assessment segments, with a standard size of 10 rkm for the Danube and 5 rkm for the Mura and the Drava provides and facilitates the overall understanding of pressures, status and restoration planning (more explanations are provided in the Synthesis report on science-based needs for action (D.T1.3.1)).

## C. River training structures

The mapping of the river training structures comprises all transversal and longitudinal structures including dams, weirs, sluices, ramps and sills as well as any kind of bank stabilization, namely rip-rap, concrete walls, groynes, training walls and cross-dykes (transversal fill) in side channels.

The following parameters are collected for the training structures:

- Position (as line GIS features; the mapping scale is at least 1: 10,000)
- Type and status (fully intact, overgrown, disconnected, collapsed)
- Height in relation to vegetation line (as far as visible)
- Inclination (in particular for groynes)

The mapping of training structures contributes to the sediment balance and transport study (D.T1.2.3), namely to an improved understanding of morphology and potential bank restoration in general. Furthermore, it should answer the following questions and tasks:

- Where can we find the most reinforced and regulated stretches and "cross-sectional bottlenecks" as by infrastructure and close flood dykes?
- General proposal for a (river section type-specific) restoration strategy
- Input for restoration potential analysis for River section types or individual stretches or even summary/characterization of stretches by density/type of structures.

Initially, it was planned to cover certain fieldwork and review of structures by the two ground teams investigating fish and river birds. But due to many constraints in the challenging pandemic period and staff and time shortcomings, the field checks have been omitted with the important exception of a detailed field survey on training structures for the "upper" Mura stretch in Slovenia between rkm and 50 to 143 serving also to calibrate the inventory for other river stretches.

**Data collection**

The data collection took several months and the following list gives only a brief overview of data sources:

- Official digital information, received for Croatia including the Drava Atlas[1].
- Official analogue (tabular) information e.g. for Hungary (by rkm).
- Former (1990ties) and current navigation maps for Danube (Danube Navigation Commission 1990-2022).
- Review of mapped structures before 2015 in previous projects and various field images collected from ca. 2005 onward.
- Online mapping and review based on high-resolution images (aside of Google Earth also official WMS ortho-images by HR/HU/SI/AT) including also multi-temporal checks of KML files with GE "history" files, showing images since about 2010 (in some cases back to 2002), including various images with altering shadows, even for some areas images from vegetation-free periods, enabling the free view on banks and structures.
- Check of hundreds of field survey images as based on the Exif picture coordinate data information (mostly based on bird surveys 2021).

[1] https://www.google.at/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwi02a65zq3xAhUMPOwKHWqEBsoQFnoECAsQAA&url=http%3A%2F%2Fwww.voda.hr%2Fsites%2Fdefault%2Ffiles%2Fpdf_clanka%2Fhv_81_2012_131-138_milas.pdf&usg=AOvVaw0mGR2tsfZZBI31Em1XNk92

The following river training structures are covered:

**Dams, ramps and sills:**

Major transversal barriers in river systems are dams, in the case of the TBR MDD these are the three hydropower dams in Croatia (Ormož, Varaždin and Donja Dubrava). Ramps are usually river regulation structures to stabilize channel incision (riverbed erosion) as a consequence of bank reinforcement and sediment deficit downstream of hydropower plants upstream. In the TBR MDD ramps can be found in the residual water "old" Drava stretches between the three hydropower plants ("Stara Drava") and one at the upper margin of Mura at rkm 142 (previously planned as hydropower plant, but never implemented). Finally, sills and ground sills should also stabilize the river bed. According to the current navigation map in the Danube some ground fill lines (parallel short lines not spreading over the entire river bottom) can be found in the sharp bends and pools at the 180-degree turn of Danube near Bogojevo -Erdut.

**Groynes:**

Groynes are constructed to keep and reflect the flow current in the middle of the channel and to protect banks from being eroded. Aside from large rivers in particular the low water correction of navigable rivers requires numerous groynes to maintain a rather stable and deep fairway. Therefore, the frequency of groynes increases from upstream to downstream and is highest, in case of the TBR MDD, in the Danube . Typically, we can find groynes and T-groynes connected to the banks.

**Training walls:**

To shrink and reduce the fairway width the construction of parallel training structures can be recorded only for Danube (and Drava mouth). Unfortunately, training walls can also obstruct former side-channel entries. In heavily modified rivers those structures are used to generate ship wave-free shallow water bodies.

**Bank reinforcements:**

The long-lasting and continuous bank reinforcement prevents any lateral shift and side erosion of river channels. While the Upper Mura in Austria and Slovenia is mostly regulated by bank reinforcements (rip-rap), the length and coverage of bank stabilization further downstream decreases and, in most cases, only steep banks and bends of meanders are fixed by rip-rap. "Rip-rap" was classified into "rip-rap" (fully intact, partially fresh rip-rap, properly visible in the aerial images), "rip-rap overgrown" (old but mostly functioning and stable bank reinforcement, vegetation indicates the age of structures but the invisibility makes it difficult to estimate the conditions, supplementing ground images support the assessment), and, finally, "rip-rap collapsed" (on locations where obviously the "protection line" of rip-rap is interrupted or where ground images indicate the partial erosion of banks behind a protection or destroyed or immersed stones).

**Flood defense dykes:**

In addition to training structures inside the channels and along the banks, flood defense dykes are the most important longitudinal regulation work. No specific parameters have been recorded, but flood protection is usually dimensioned for a 100 years flood.

**Covered parameters:**

**Length:** in m (T-groynes include groyne and parallel structure together)

**Inclination:** The degree of structures against the river axis in flow direction. Usually, groynes point into the middle of the channel (90°) or slightly declined (100-110°) or inclined (70-80°) while banks and parallel structures would have a 0° angle towards the channel axis. Regarding flood dykes the line segments are split if the dyke significantly divert (increase) from the basic inclination entry of 0-10°. The T-groyne inclination is handled the same as for basic groynes.

**Height of structure:** This is a very general estimation by vegetation line and available field images. While bank reinforcement (rip-rap) is basically constructed to cover the bank line at least at MW (mean water) many groynes or transversal fills inside channels are constructed as "low water correction" features (LW), however, as navigation is not from importance on Drava and Mura many groynes are constructed as reflectors and for bank protection and therefore those groynes are also on MW level. Channel incision can further cause the "raise" of structures and those groynes or transversal fills build originally on LW level become functioning structures on MW level as well. The same can be observed for overgrown structures, where tree growing increase the resistance and structure height. Most overgrown groynes are set to "MW" due to the hydraulic function of covering trees. As on Danube most of the recently constructed groynes tend to be on LW level (low water regulation purpose), many older groynes reach MW due to the slow but steady channel incidion over decades. For side channels, this implies further less free-flowing conditions and further deteriorations. Despite of detailed information the dyke protection levels were assumed for HW100 (most probably, locally, dykes must be reinforced or the freeboard should be increased). Nevertheless, the estimation serves only as a first assessment, based on the different water levels of provided satellite images (past 10 years) and field images, where available.

**Data geometry:**

The mapping scale for the entire project region is approximately 1:10,000. As almost all training structures have a linear character the preparation of separate point and polygon data layers was omitted. Even dams and ramps have a specific width of the regulated channel and the length is additional information. T-groynes are regularly two merged lines, one for the "groyne" and a second for the "T" parallel structure to the bank. Therefore, the length of T-groynes summing up the entire length of the structure obstructing and reflecting the local river current.

**General development and today's situation of structures**

Over the past decades and for the large rivers much longer, up to a century river training and stabilization measures took place and it is often possible to find overgrown structures only by old maps. No inventories exist and only by chance, e.g. during work in the forests or after floods those old structures appear again. Often parallel "protection lines" for banks could be found, an aspect which should be considered for restoration measures.

The mapped structures called "overgrown" are usually covered by dense vegetation and indicating a certain "age" of the structure (20-30 years), but it is not easy to determine the functionality of those structure. Other typical situations are "detached" groynes or erosion behind rip-rap after floods up to the disappearance and occurrence of deep pools. Sometimes structures prepared to work as groyne, rip-rap or training wall collapse over time but still hold some regulation function. Groynes can be combined with other transversal structures such as transversal fills also to regulate side-channels entries.

A special country survey during low water level of Mura in Slovenia was conducted by Monika Podgorelec from the Institute of the Republic of Slovenia for Nature Conservation contributing valuable field data for comparison (high consistency with the overall inventory) and calibration for the methodology and for other river reaches.

The following collection of images should give a general impression of river regulation:

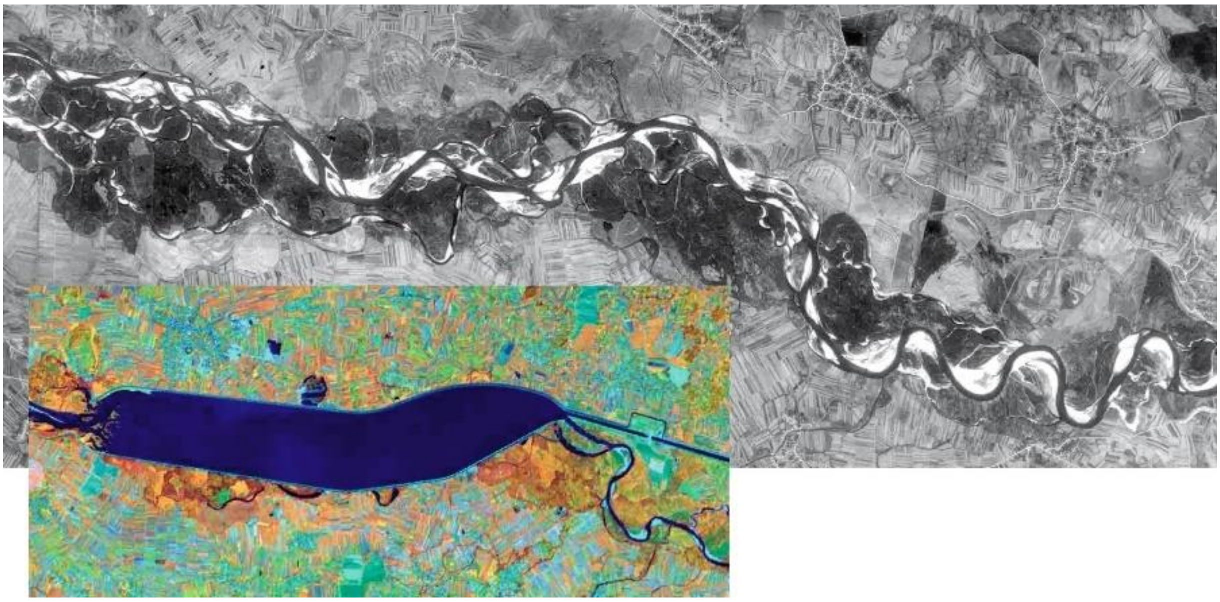

*Figure 3: Major changes along the "upper" Drava of the project area due to hydropower constructed between 1970-1990 (Schwarz 2013).*

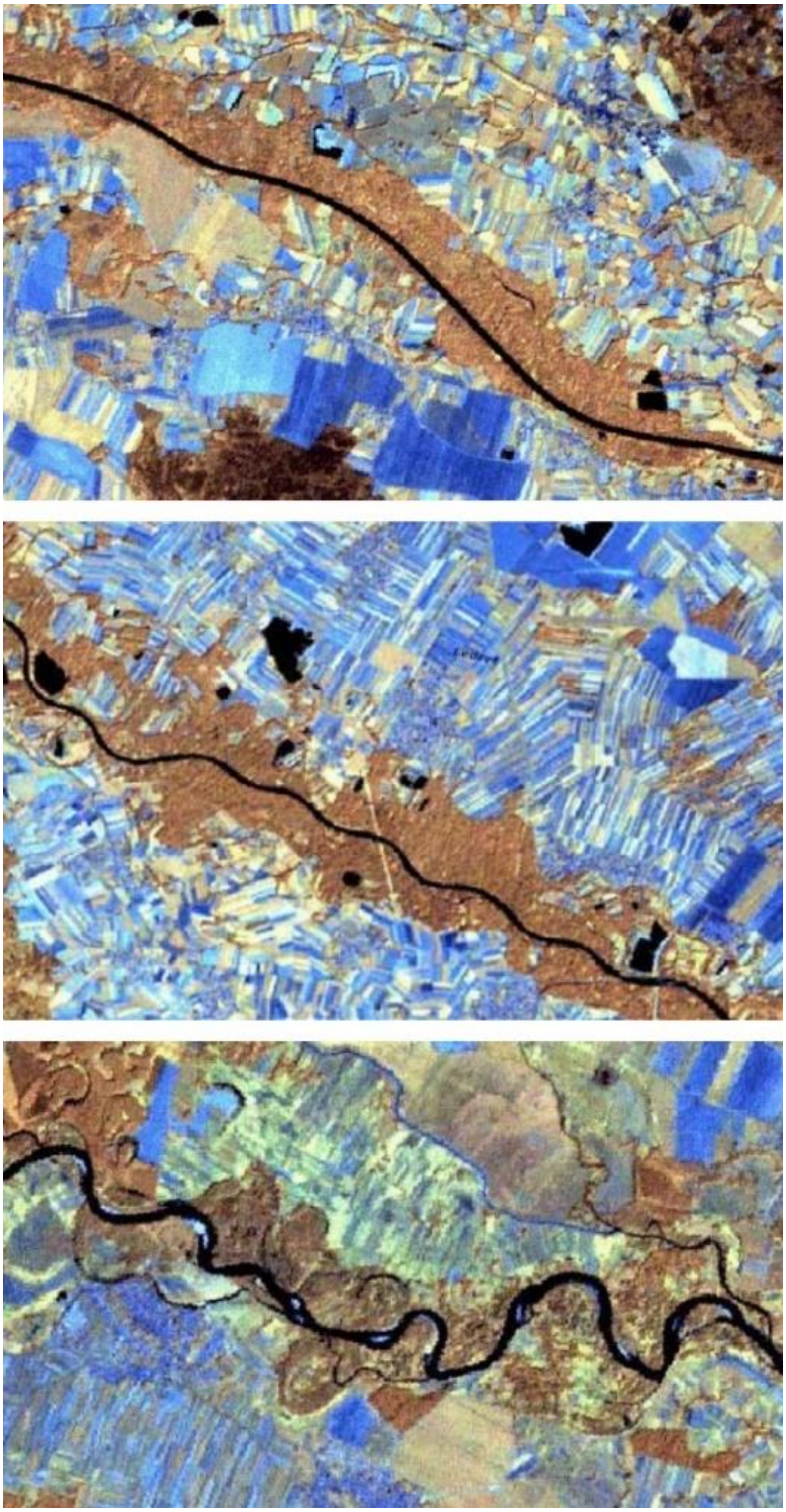

*Figure 4: Obvious degrees of river regulation for three subsequent Mura reaches (spatially rotated to get flow direction from northwest to southeast) starting with the totally regulated, straight AT-SI border Mura followed by SI Mura with the slightly pendulous main channel and the HR-HU Mura with partially near-natural river course and strong lateral shift (Schwarz 2007).*

*Figure 5&6: Bank reinforcement on the Danube near Vukovar, Images: WWF/Arno Mohl, Darko Grlica.*


*Figure 7: The typical repertoire of river regulation in the project area: Groyne construction in the foreground (2), bank protection on the right side (1), training wall on the left upper side (3) and cross dyke (transversal fill) closing the side channel in the upper central part (4). Finally, the flood dyke (5), immediately behind the softwood (invisible), complement the regulation works. © Credit: WWF/ A. Mohl.*

*Figure 8: On the Danube T-groynes (in this case disconnected from bank) can be find in larger numbers end size to stabilize the fairway. © Credit: Wolfgang Kraier.*

### Visualization and assessment of river segments

To summarize and assess/compare training structures for different river reaches, it is possible to quantify the structures within pre-defined "segments" of the same length (10 rkm segments for Danube and 5 rkm segments for Drava and Mura).

Analyzing the density of regulation works within the 10 rkm sections for Danube and 5 rkm sections for Drava and Mura in five classes allows a suggestive visualization of the degree of alteration. This excludes the flood dykes and focuses only on the river channels and banks, which may lead to less accurate results than an overall hydromorphological assessment including the floodplain, e.g. as completed for JDS/Danube (Schwarz & Hoebart 2021), but significantly supports and quantify the findings.

In this approach, we simply sum up the length of training structures (without flood dykes) per 5 and 10 rkm segments. Basically, for the 5 rkm segments, a five-class system with equal classes of 2 km sums for both banks together is applied, while for the Danube, i.e. 10 km segments, a 4 km sum for both banks would represent the situation. In case of numerous groynes in addition to extensive bank reinforcements, the total length of regulation works can even exceed the entire length of both banks per 5 or 10 rkm segment.

## D. Historical mapping

The historical mapping of river corridors is mainly based on the 2nd Austro-Hungarian Military survey (~1860), complemented by earlier spots of the 1st Austro-Hungarian Military survey for meander cut-offs (~1780) and comprises all waterbodies (main channel, side channels, oxbows), islands, bars and riparian forests within the active floodplain. For comparison with the status quo, the overall landscape mapping of 2012 (Schwarz 2013) is used.

Historical mapping together with the analysis of the current situation allows the systematic evaluation of width analysis of cross-sections, river centerline/axis, sinuosity, main riparian habitats and serves as a basis to define River section types and to propose type-specific restoration measures.

**Approach**

- Mapping of the core elements for the morphological assessment, namely the sinuosity and length of river axis, main channel with major side branches (following the delineation approach for comparison map, Schwarz 2013), permanent side-channels, sand and gravel bars and islands with riparian forest.
- Additionally mapping of major riparian and floodplain habitats, such as riparian forest (soft and hardwood), oxbows, reed and floodplain swamps as well as grasslands (mainly pastures).
- Mapping scale is roughly 1:20,000, which allows the extraction of all cartographical features.

Data collection (the years represent the survey time for the project area, usually the maps base on mapping campaigns over several years):

- the 1st Austro-Hungarian Military survey "Josephinian survey" from about 1780: used only as a reference and between rkm 80-120 to get the original picture on the early rectified lower meander reach of HU-HR border (Austrian State Archive (Österreichisches Staatsarchiv) (2021).
- 2nd Austro-Hungarian Military survey "Franzisceian survey" from about 1860: core mapping base (Austrian State Archive (Österreichisches Staatsarchiv) (2021).
- 3rd Austro-Hungarian Military survey "Franzisco-Josephinian survey" from about 1880: only as a reference to understand the major rectifications and reaction of the river system (Austrian State Archive (Österreichisches Staatsarchiv) (2021).

- For upper Mura (better spatial resolution): Small Mura River map (Kleine Murstromkarte) from 1809-1815 (County Archive Styria (Landesarchiv Steiermark) 2022).
- For Danube: Pasetti map from 1859-67 (Austrian State Archive (Österreichisches Staatsarchiv) (2021).
- Additional maps and b&w images from 1900-1990 to understand the long-term development.

Finally, the mapping intends to generate maps that show a state of the rivers with the least possible human alteration (1800-1850) but does not intend to map a specific historical state corresponding to a precise year as for many other historical evaluations (e.g. Schwarz 2009). Of course, the intercomparison of historical maps through the last three centuries would deliver much more additional information such as the development time frame of specific habitats (rejuvenation of habitats, habitat cycles, compare Hohensinner et al. 2011). Therefore, the current mapping should be understood as a starting point for further historic analysis of the riparian landscape.

As the initial evaluation step the historical mapping was exactly overlaid and statistically compared with the contemporary mapping (already existing, Schwarz 2013):

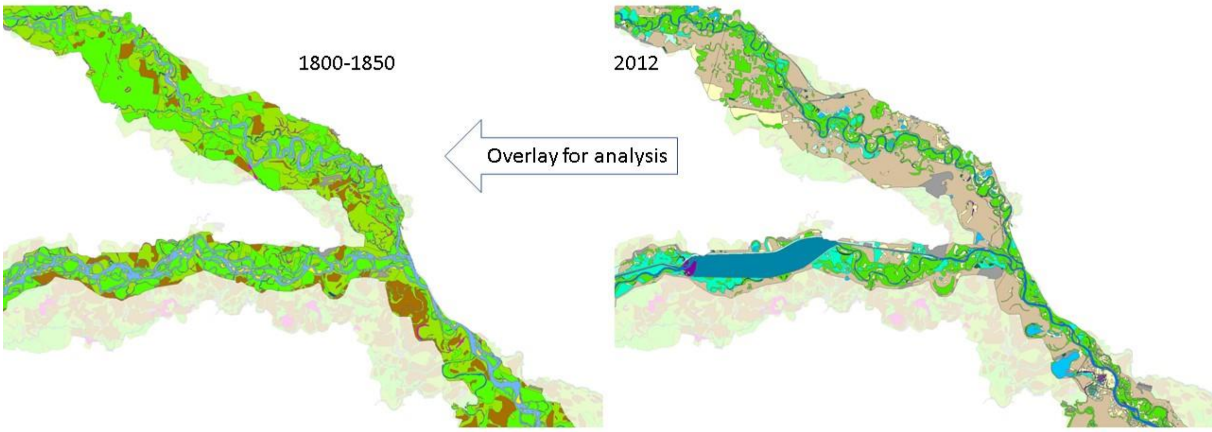


*Figure 9: For the overlay analysis the initially larger area mapped for the historical situation was cut out by the mapping from 2012 allowing the precise overlay analysis (the 2012 mapping is unchanged and therefore no particular boundary as such of the former floodplain was applied to both maps, but the coverage comprises most of the morphological floodplain area (for the historical situation even beyond), but in particular the relevant riparian habitats in the active river-floodplain corridors.*

# III. Results

The results are organized in several GIS data layers, as line elements for training structures and as polygon elements for the historical mapping as well as for River section types and the visualization/assessment segments. Basic quantitative result charts are included in this report, but the data is further investigated in the sediment balance and transport study (D.T1.2.3) and the synthesis report on science-based needs for action (D.T1.3.1). All detailed maps are included in the Map Annex at the end of this report.

## A. River training structures

In total 651 km of rivers are considered for the evaluation (370 km for Drava, 143 for Mura and 138 for Danube), therefore the total bank length including major side channels can be estimated at ca. 1,350 km. In total about 2,300 items (groynes, rip-rap bank sections, flood dykes sections) with a length of 1,676 km were recorded.

Before going into the in-depth view of the channel and bank regulation works it is interesting to take a look at the shrinkage of the floodplain: the total sum of the length of flood defense dykes is approximately 890 km. This is more than the entire length of the three rivers. In other words, flood dykes can be found at least on one bank at full length. Most of the dykes were constructed between 1950-1970, however close to major settlements dyke building started 100 years ago, while the youngest constructions, often close short gaps or enforce reaches close to settlements (e.g. on SI and HR Mura).

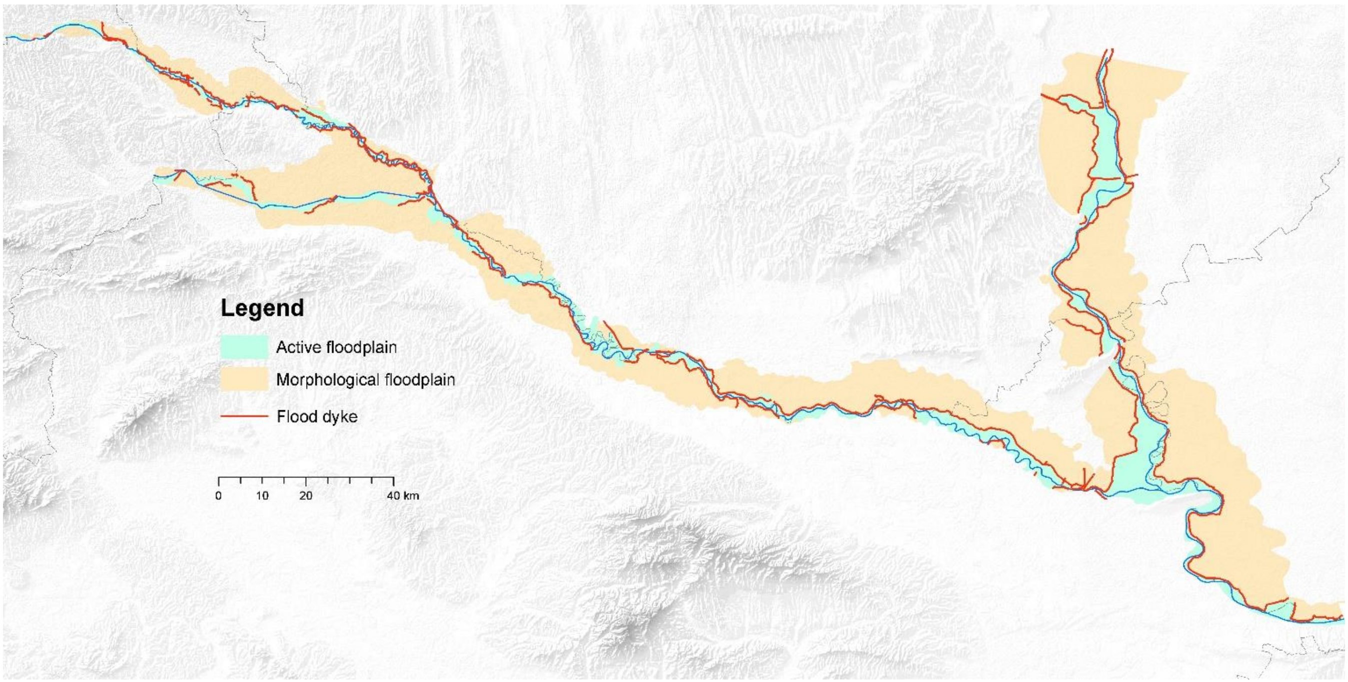


*Figure 10: The outline of flood defense (red lines) and the morphological (green) as well as active floodplain (yellow) indicating the considerable loss of floodable area as such but also the remaining spots.*

The focus of mapping the training structures was set on groynes and longitudinal bank reinforcements. In particular, groynes, T-groynes and rip-rap were collected in different categories (e.g. overgrown, collapsed, disconnected). Figure 11 shows the usual distribution of regulation works (in this example the combination of groynes and rip-rap to prevent the lateral shift of the main channel).

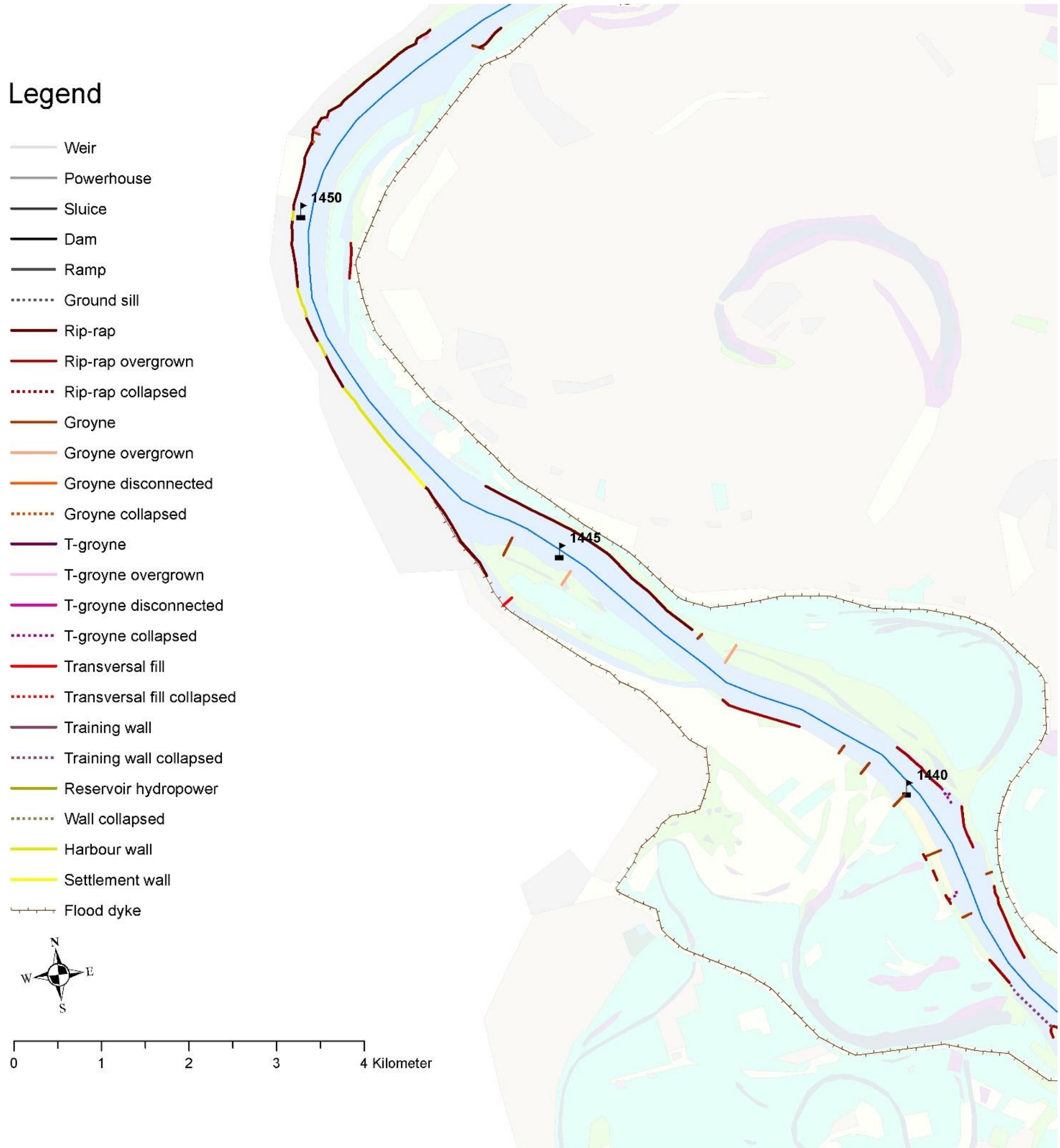


*Figure 11: Example map showing typical river training structures like groynes, bank reinforcements and flood dykes (all detailed maps can be found in the map annex).*

Figure 12 shows the total length of structures comprising all kinds of groynes, training walls, transversal fills, rip-rap, other bank walls, but also dams, ramps or sills as well as flood dykes and their total number for the entire project area.

The bank reinforcements (rip-rap) prevail with a total length of 538 km (ca. 40% of the entire bank length of main channel and side channels). In addition, 647 groynes regulate the river in stretches without continuous bank reinforcements. Considering that groynes have on average a regulatory influence on a length of 300 m, an additional 200 river km can be considered as regulated (this raises the previously mentioned share to 55% of all banks).

Considering the fact that lowland rivers don't need complete reinforcement of both banks, e.g. only protection of the steep banks in meander bends, more or less the entire river sections analyzed are under a regulated scheme. Channel incision caused by sediment deficit but also by the aforementioned regulation works and additionally 75 transversal fills (cutting of major side channels) makes the need for restoration obvious.

But there is hope: several important meander bends or short anabranching reaches still remain without regulation and can serve as reference sites for restoration activities. 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.

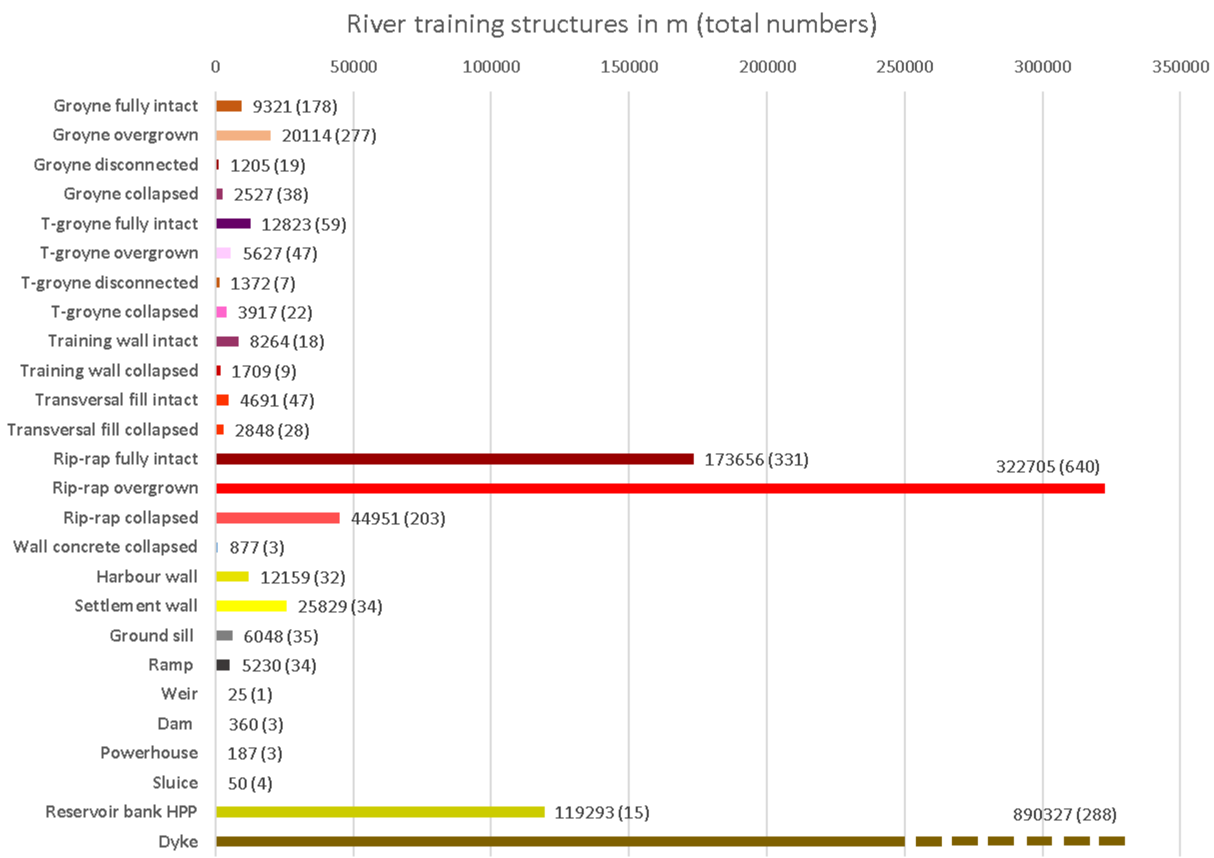


*Figure 12: Overall distribution of river training structures in total length and the total number for the entire TBR MDD.*

Based on the defined 8 River section types above (compare table 1 and figure 1), the following distribution of regulation works can be concluded:

### Danube 1433-1382 upstream Drava DAN1

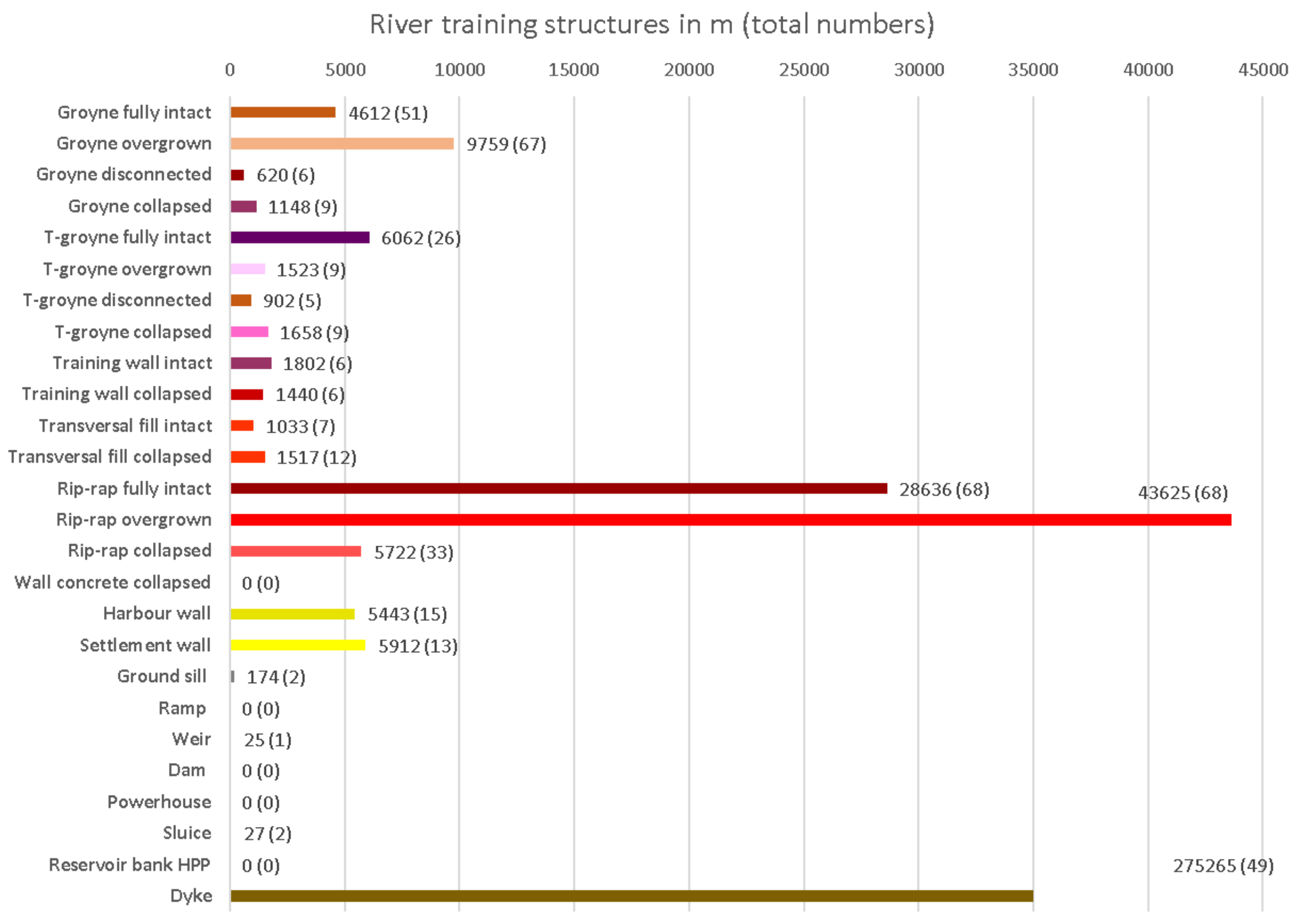


*Figure 13: River training structures in m (total numbers) in the upper Danube section in Hungary, upstream to the Drava confluence.*

The entire types of structures can be observed in the upper Danube section in Hungary. Upstream of the Drava confluence, numerous groynes can be found.

### Danube 1382-1295 downstream Drava DAN2

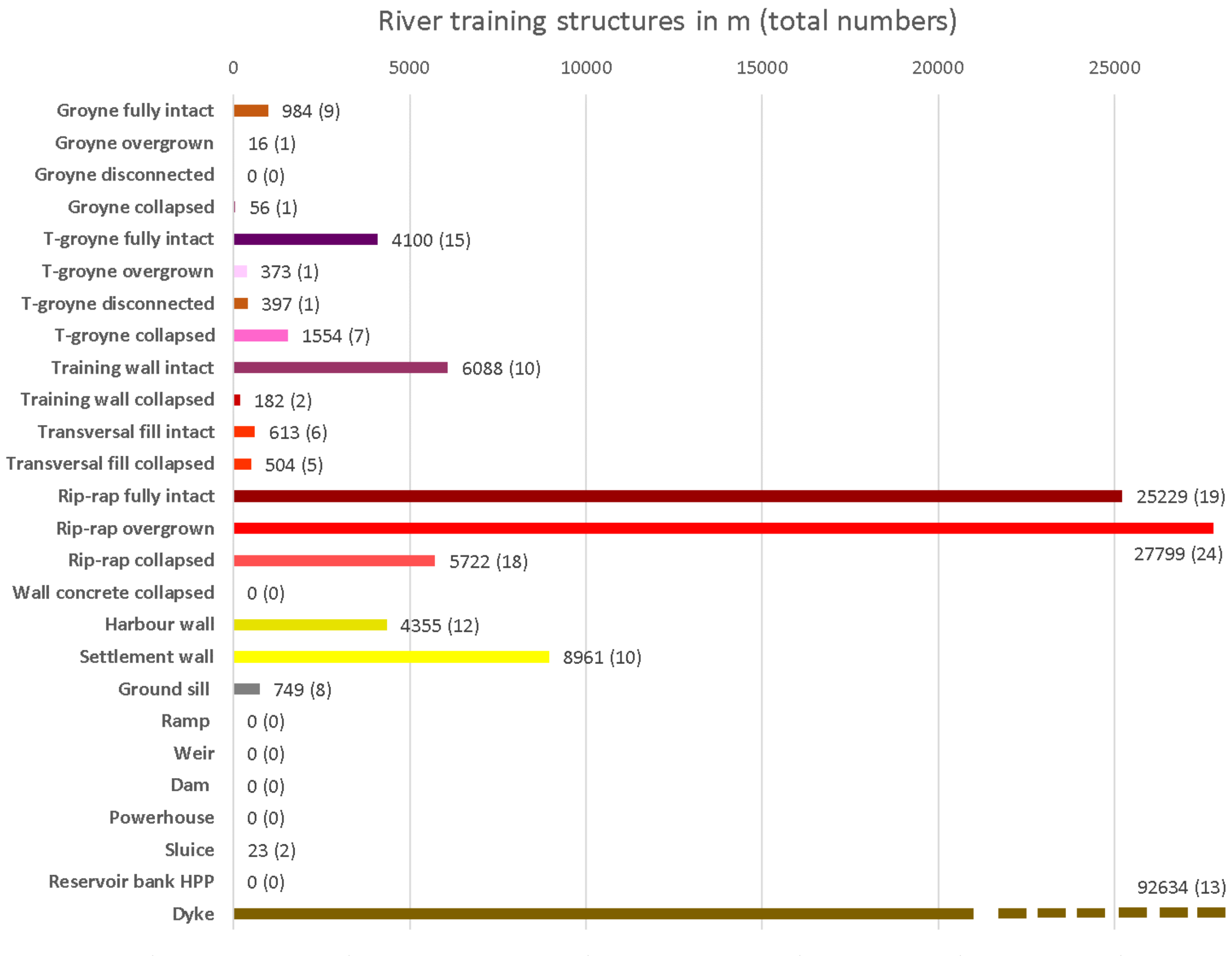


*Figure 14: The Danube stretch downstream of Drava confluence looks similar, but with much less groynes.*

Downstream of the Drava confluence T-groynes dominate the groyne type in general. Significant training walls can be find at the lower end of the reach (near Bačka Palanka). The Danube bank in Vukuvar is reinforced for several kilometers.

### Drava 310-235 upstream Mura DRA1

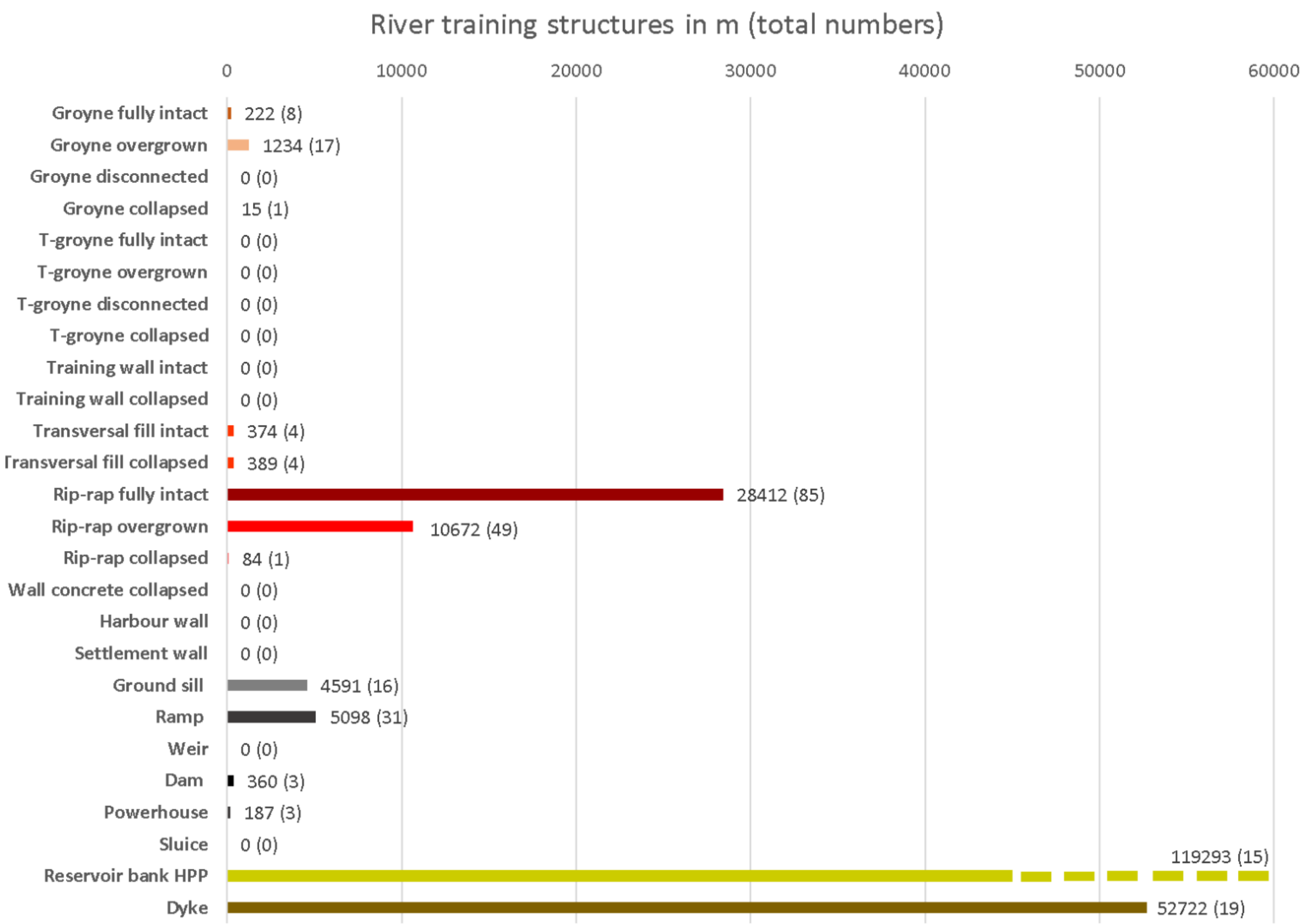


*Figure 15: Starting at the upper end of Drava in the project area the three hydropower plants strongly alter the river. Not all categories can be found but additionally as mentioned the concrete hydropower reservoir and tailrace canal banks comprise 120 km and within the residual "old Drava" reaches in between the hydropower plants all recorded 30 ramps can be found in this mostly altered section.*

Regarding the longitudinal barriers and regulation works three major hydropower dams with three powerhouses (turbines) can be found on HR Drava, among ramps and ground sills.

The length (width) of the 31 ramps sum up to 5,098 m, 16 ground sills to 4.591 m, the three hydropower dams (Ormoš, Varaždin and Donja Dubrava) and power houses to in total 547 m. Furthermore, the length of the three hydropower reservoirs and their tailrace canals with concrete banks amounts to 119.29 km.

## Drava 235-185 downstream Mura DRA2

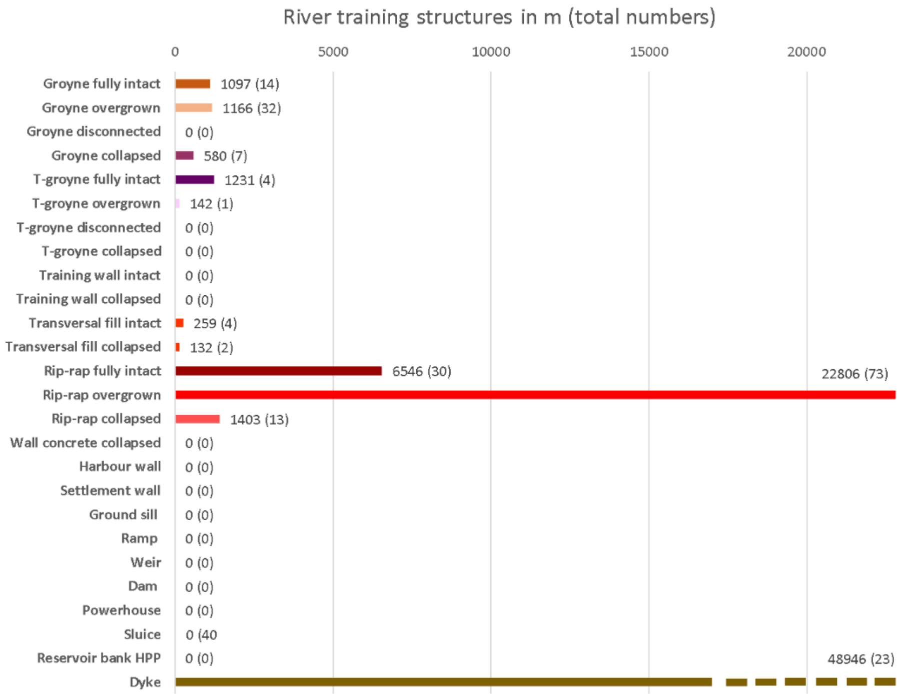


*Figure 16: In the free-flowing section downstream of the Mura confluence several small groynes can be recorded (many fall in the overgrown category or could be collapsed- visible only by fieldwork).*

## Drava 185-0 DRA3


*Figure 17: On the lower Drava all kinds of training structures are present. Again, the high number of old and small groynes is remarkable. Furthermore, the city of Osijek significantly expands the reinforced concrete Drava banks.*

## Mura 143-85 MUR1

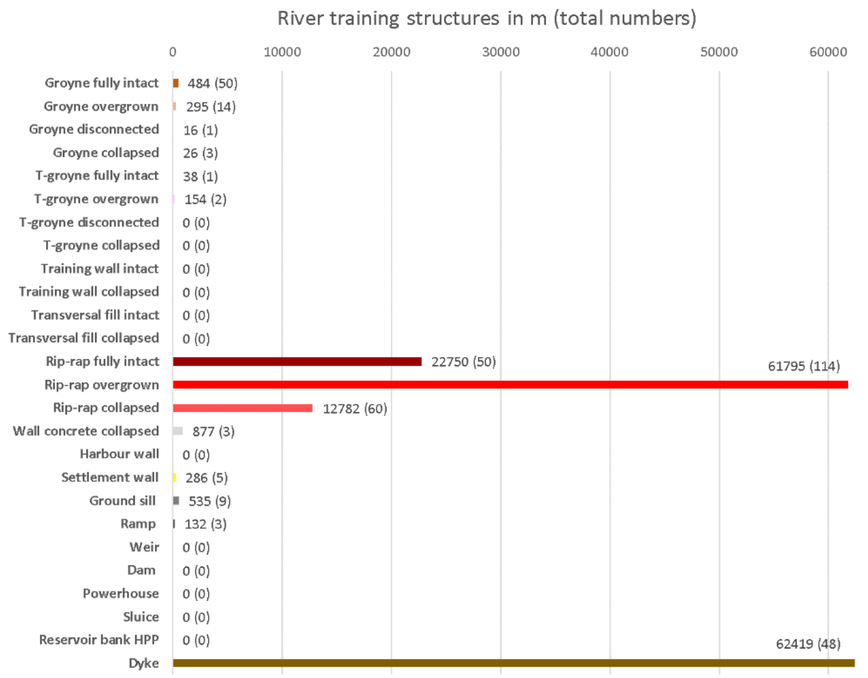


*Figure 18: The upper Mura in the project area is characterized by nearly continuous bank reinforcement (rip-rap), only very few and short (restoration) sites allow lateral erosion. Again, as for the Drava, many river training structure types are not present. As for Drava, the most upper reach of the Mura is also most impacted by river regulation.*

## Mura 85-45 MUR2

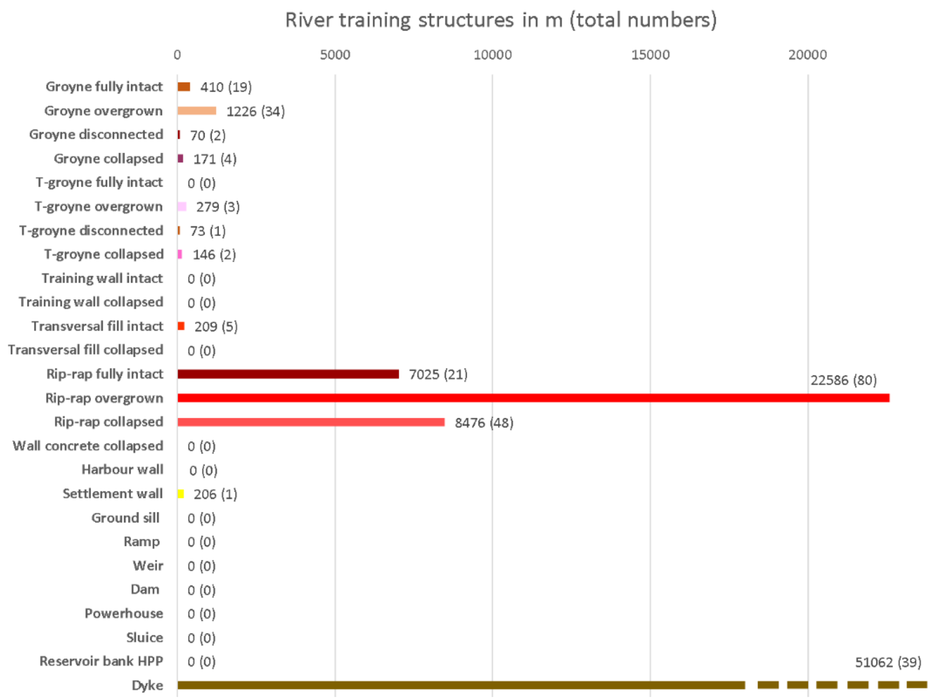


*Figure 19: This river section includes much less protected banks and in some reaches groynes take on the stabilization of banks in river bends.*

## Mura 45-0 MUR3

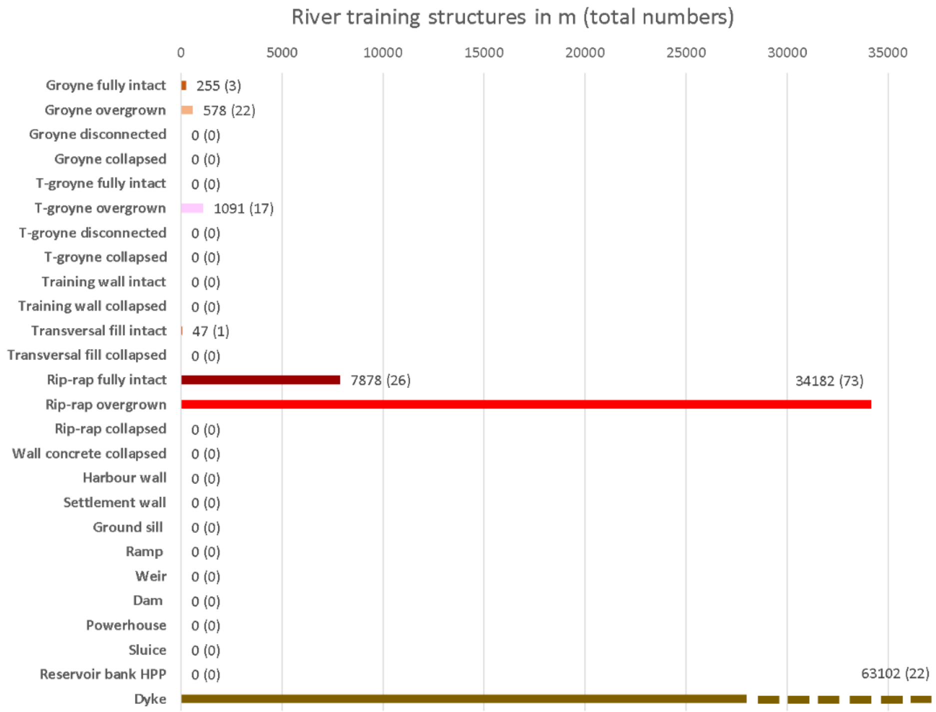


*Figure 20: The lower Mura is characterized by the systematic conservation of stable meanders by protecting the steep banks of the meander bends.*

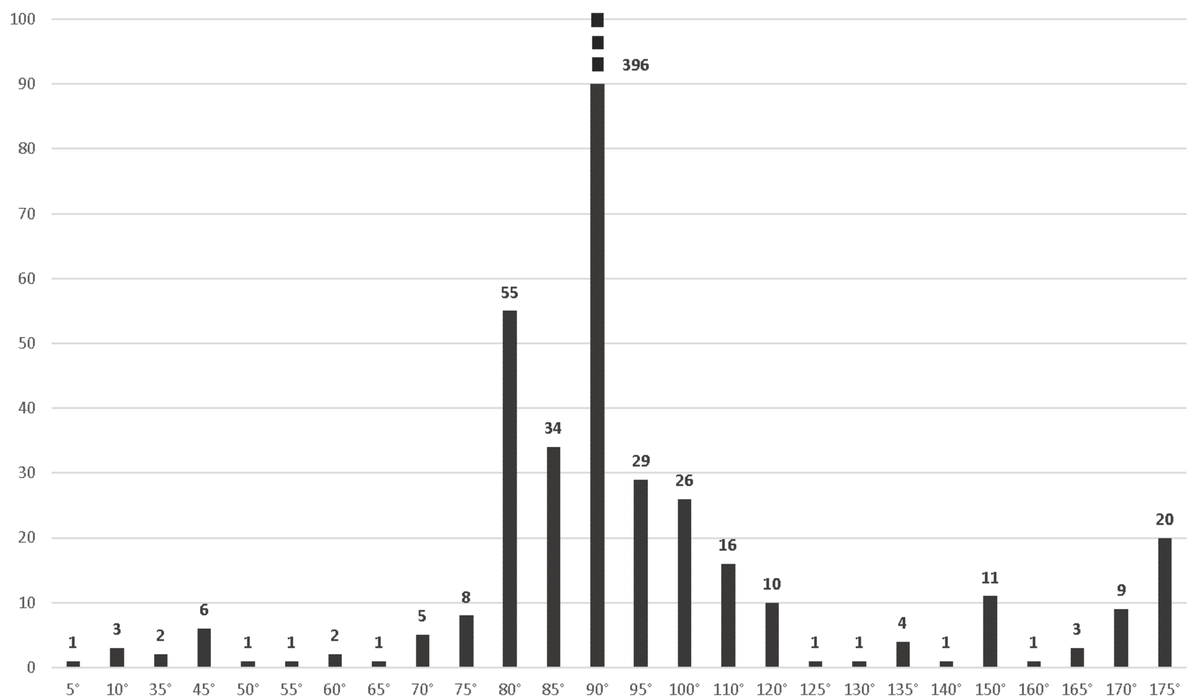


*Figure 21: Inclination for all 647 groynes and T-groynes: Obviousely 90° groynes prevail (396), while in total 132 are inclining in the flow direction (> 90°) and 119 against flow direction (< 90°). 175° and 5° respectively represent groynes which are close to parallel training works.*

The following figure 22 summarizes the density of training works within the 10 and 5 rkm segments respectively. It highlights those stretches with less structures in light and abundant structures in dark colors.

Only one single 5 rkm segment on 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 regulations works together, rip-rap, training walls and groynes, but not the flood dykes).

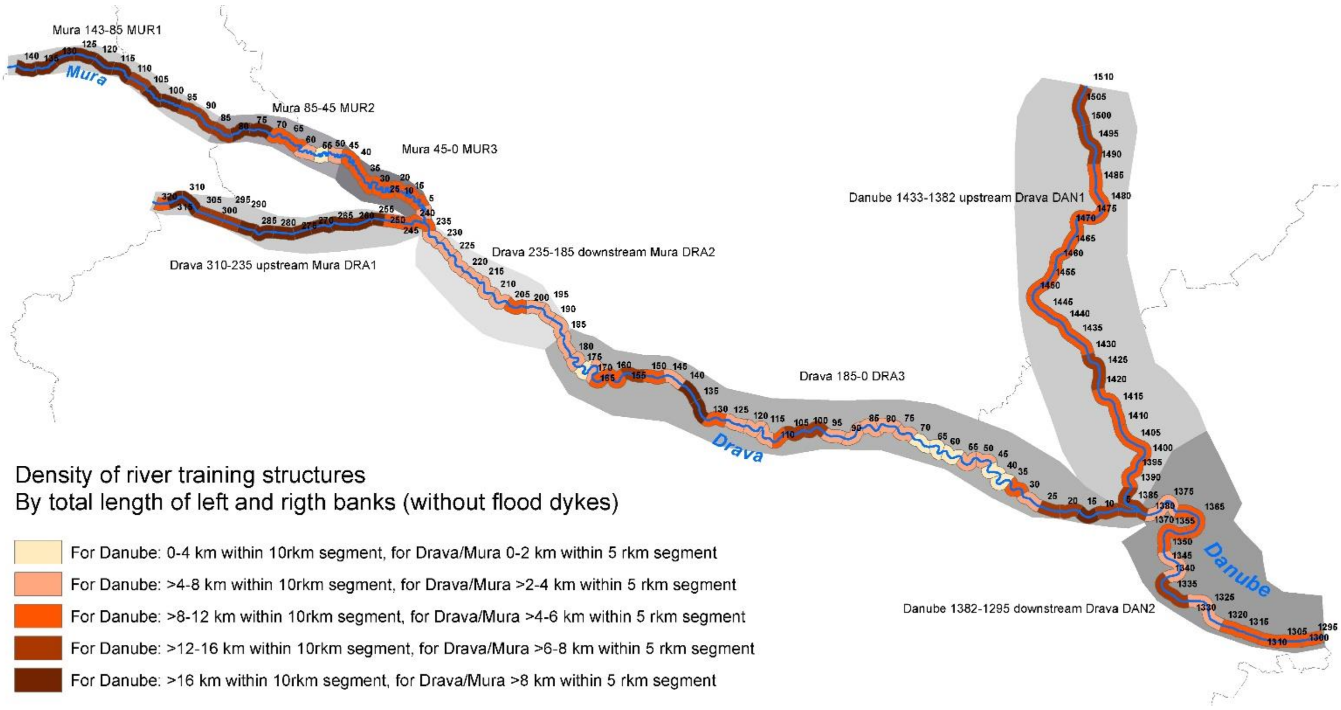


*Figure 22: As based on the density of recorded training structures it is possible to provide an initial "alteration" map reflecting the changes in the river changes and its banks.*

## B. Historical mapping

The historical mapping comprises a total area of some 6,055 $km^2$ (605,511ha with in total some 11,300 polygons) and allows for the first time to have a concise base for entire river corridors making comparisons with the current situation possible. In this report an analysis from 2012 (Schwarz 2013) is applied for this purpose. For the analysis only the overlap with the mapping of 2012 was considered to allow a prcise calculation of respective habitats. The additional mapped area for the historical situation includes additional lowland areas, as for tributaries, waste forests and pastures and serves only as basic background (compare the atlas maps in the annex showing the entirely mapped historical area).

The aim of the historical mapping is:

- to analysis the core riparian habitats and comparison/overlay with the map from 2012 (elaborated for the TBR restoration project, Schwarz 2013; the assessment of individual stretches is also possible),
- and to evaluate the river centerline development and to provide data for the sediment/morphology team (D.T1.2.3) to analyze cross-sections of the floodplain including width variability and sinuosity of channels.

General mapping base is the second Austrian-Hungarian Military survey however, for the upper Mura (At-SI to SI-HR reach) the "Kleine Murstromkarte" provides much better resolution. Further, as explained in the method chapter (including references), it was necessary to substitute stretches on lower Drava with the first Austrian-Hungarian Military survey to include all former meander bends. Finally, for the Danube the famous Pasetti navigation map was used to amend the second Austrian-Hungarian Military survey for the central river corridor. Therefore, the historical mapping doesn't show one particular year in the past but tries to visualize the situation before major meander cut-offs. Therefore the summarizing period was set to "1800-1850".

Before looking at the detailed area comparison of the historical state of 1800-1850 with the situation in 2012 (compare method chapter) figure 23 (next page) presents a mapping example and figure 24 provides the total figures for mapped riparian habitats before the comparison of the reduced area. Therefore this chart can be seen as the total backbone of the river corridors in some parts beyond the TBR boundaries but it includes more or less all typical riparian habitats (with exception of river valley related remote dunes and try habitats around Đurđevac, grasslands near Koprivnica and Molve as well as additional lowland forests in Podravina in HR).

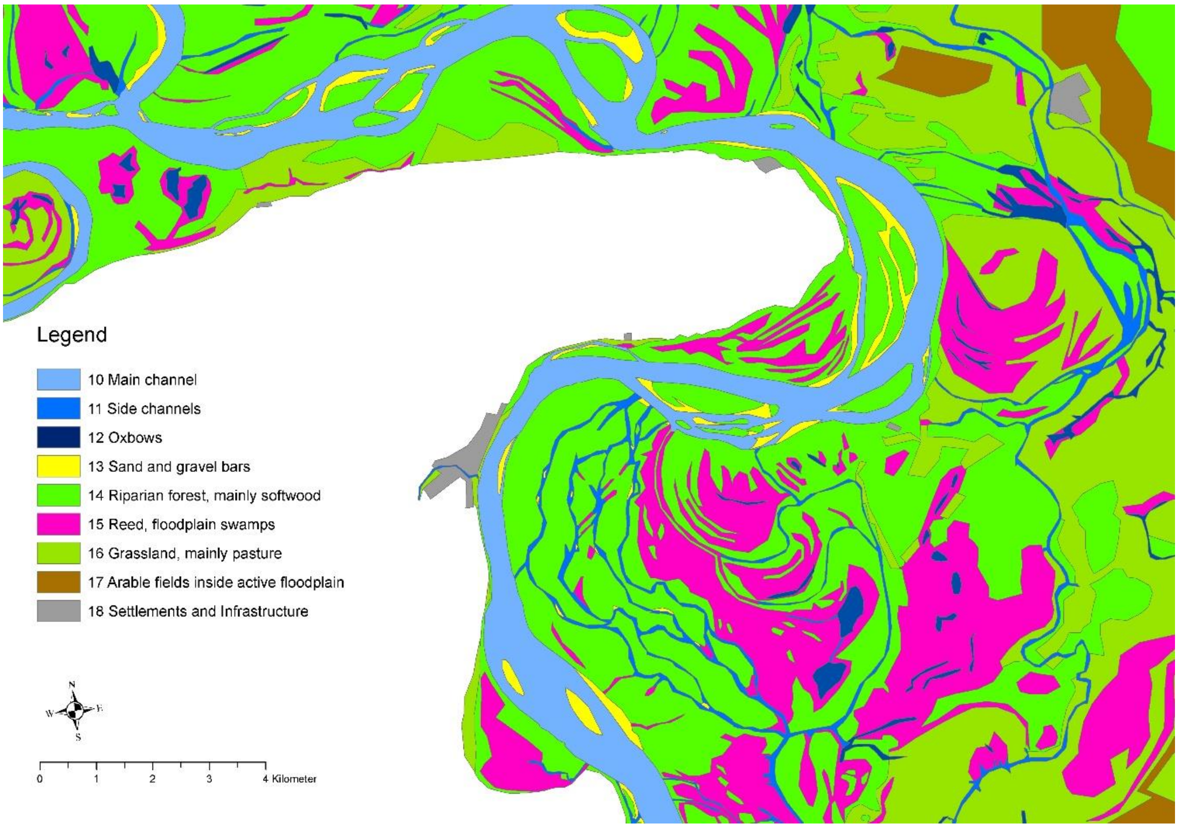


*Figure 23: Example for the historical mapping. One of the most dynamic and diverse areas on Danube can be found at and just downstream of the Drava confluence.*

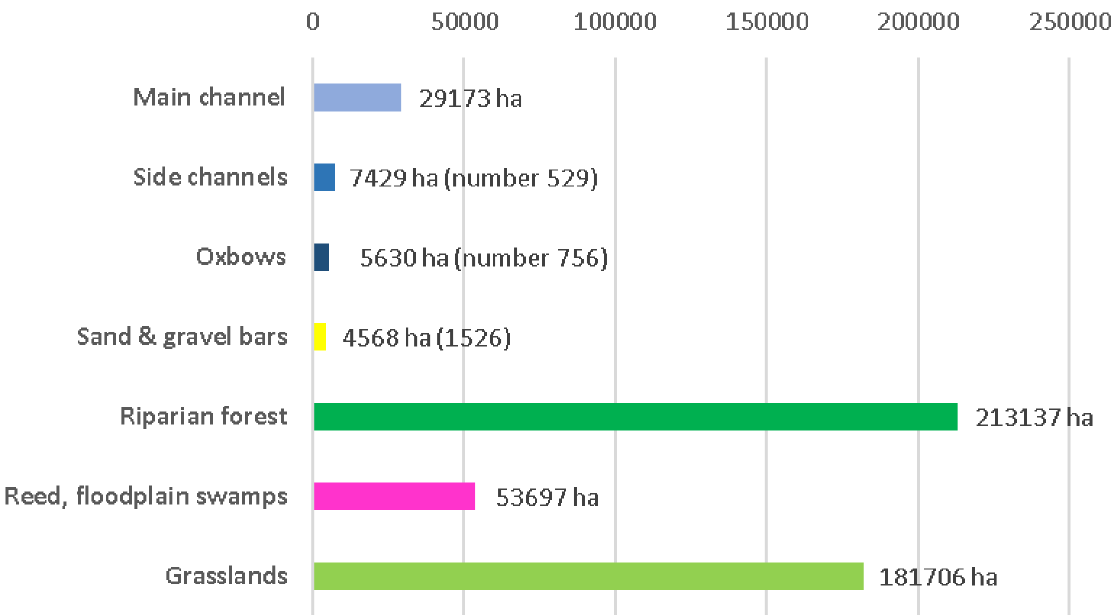


*Figure 24: Total mapped historical area without agriculture and settlements before cutting with the contemporary map overlay for precise comparison which reduces almost all values (even the main channel was mapped slightly beyond the TBR boundaries, side-channels include also lower courses of tributaries).*

From this point all analysis is using the spatially reduced historical data set to allow a direct comparison of the historical situation with today. The total area is shrunk significantly from 6,057 km² to 3,529 km² but still covering the core riverine habitats.

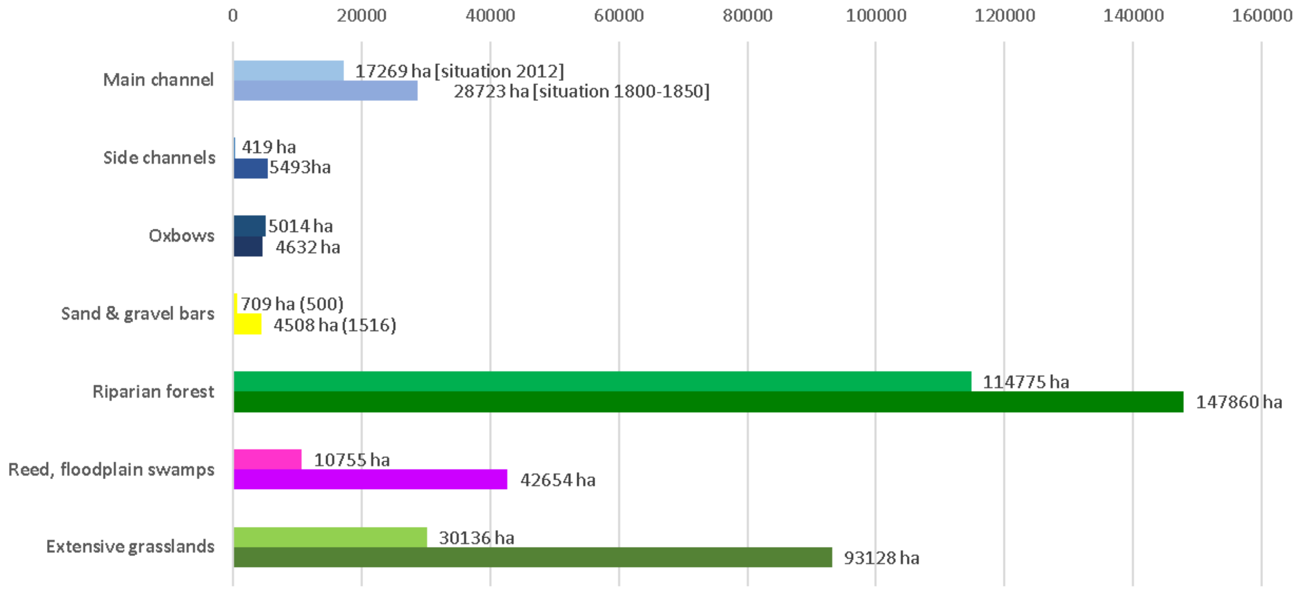


Figure 25: Total project area with river and floodplain habitats (for side channels, oxbows and bars also the number in brackets). The upper bar represents the situation in 2012, the lower bar the situation before major regulation (1800-1850).

While the loss of main channel surface, side channels, sand and gravel bars as well as wetlands is considerable, the surface of oxbows increases even slightly. However, the historical maps do not include many small water bodies e.g. in the Kopački Rit "swamps", which distorts the result slightly. However the trend is explainable as many former main channels and major branches were cut-off during the regulation starting latest with 1820-30 onwards and fall into oxbows and standing waters. Depending on morphology the natural "life expectation" for oxbows can be at least 250 years, as some are already included in the very first map from late 18th century. But it depends also strongly from usage and connectivity (fine sediment input during floods).

Comparing the covered area and the number of major riparian habitats (figure 26 on next page), the loss over time is obvious, but also the shift of habitats. While the total area of the main channel surface (including all main side branches) has been reduced from 29,723 to 17,269 ha (a loss of 42%) and 493 side channels with an area of 5,493 ha to 80 side channels with only 419 ha (a loss of 92%), the area and number of gravel and sand bars decrease for 84% and 67% respectively. Looking for the loss of islands including main channel river and floodplain islands on side channel systems (islands must include riparian forest, single gravel and sand bars doesn't count)" regarding the individual rivers (table 2 on next page), the upper courses of Mura and Drava (strongly anabranching system) are strongly affected.

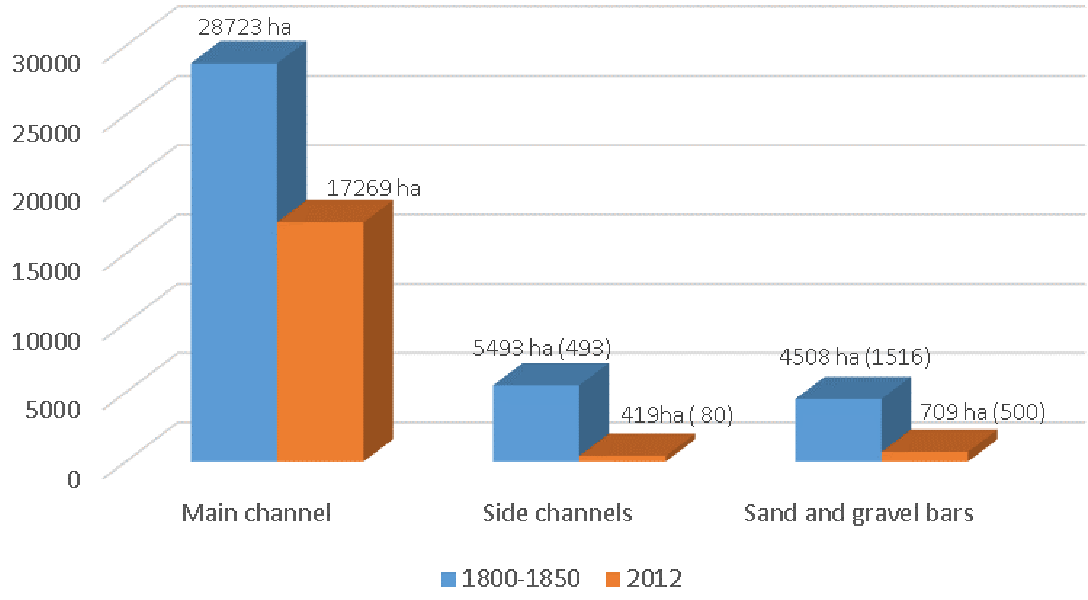


Figure 26: Comparison of “core” riparian habitats

*Table 2: Total number of islands including river islands in the main channel and branch system as well as floodplain islands surrounded by permanent side channels (for Danube islands compare Schwarz 2019).*

| River | 1800-1850 | 2012 | Loss |
|---|---|---|---|
| Mura | 363 | 16 | -96% |
| Drava | 391 | 84 | -79% |
| Danube | 162 | 59 | -64% |

The comparison of riparian forests including soft and hardwood forests is difficult as the current values include large parts outside the flood dyke. Furthermore, the separation of soft and hardwood as well as wood with pastures – pastures with wood or deforestation is not possible or different throughout the map series for the historical state. However, the comparison of any kind of riparian forests in the past and today at least allows the basic understanding and dramatic loss of regularly flooded and ecological intact riparian forests. Because riparian forests were converted into poplar plantations or become remnants outside of the active flood regime (flood dykes). Extracting and analysing poplar plantations outside of the flood dykes, the original riparian forests are double the contemporary riparian forests. Most of the hardwood forests can be found outside the flood dykes, and are connected only by strong groundwater dynamics (Slavonian oak forests in Podravina), but in difference to many other Western European countries, those hardwood forests still exist to a significant extent.

Aside from the comparison problem of the share of poplar plantations, which sums up to 50% of today’s riparian forests, the distribution or, prior to calculation, the better definition of “side channels” in both maps is also important to investigate.

Again, the 8 River section types have to be presented in detail:

### Danube 1433-1382 upstream Drava DAN1

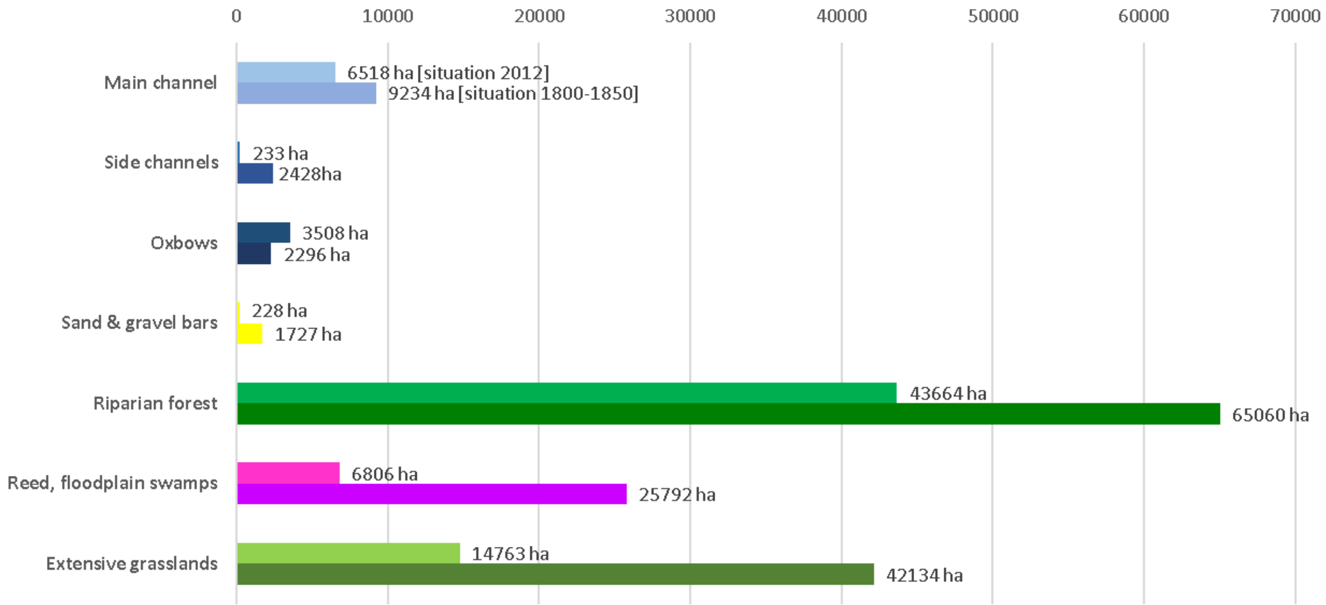


*Figure 26: Aside from the strong reduction of main channel surface, side channels and sand bars, it is interesting to see increasing numbers of oxbows. Even the ration is too much pronounced due to limited oxbow visualization in the historical map the general trend seems to be correct, parts of former channels turned into oxbows.*

### Danube 1382-1295 downstream Drava DAN2

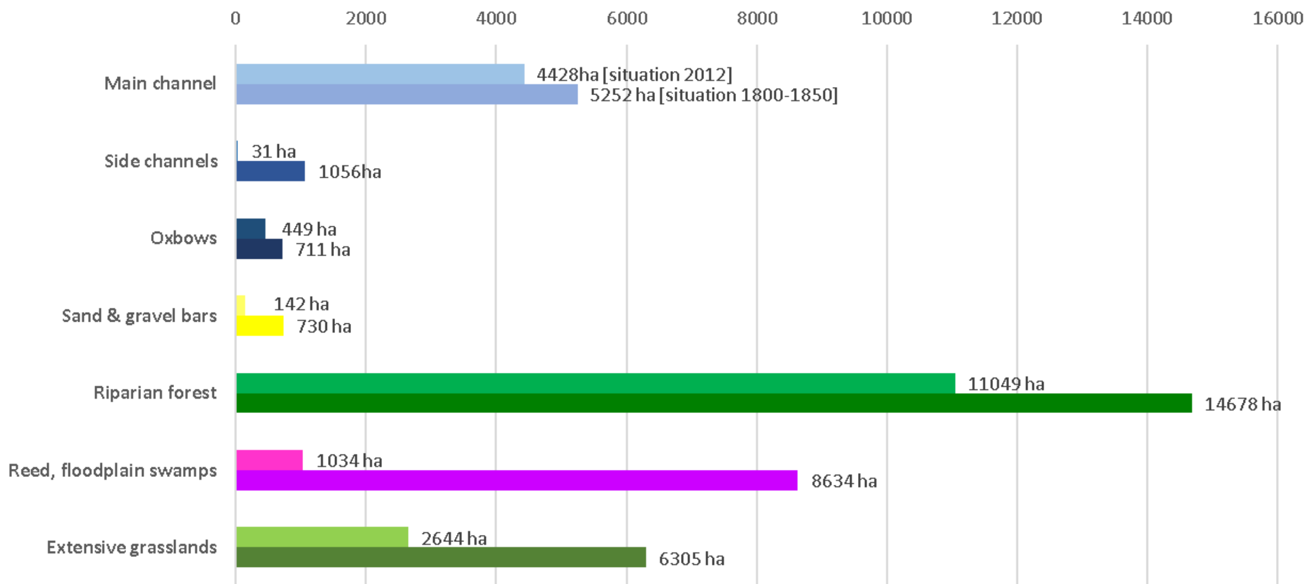


*Figure 27: Dramatic losses due to flood dyke construction close to the river can be assumed for side channels, oxbows and wetlands for this section.*

## Drava 310-235 upstream Mura DRA1

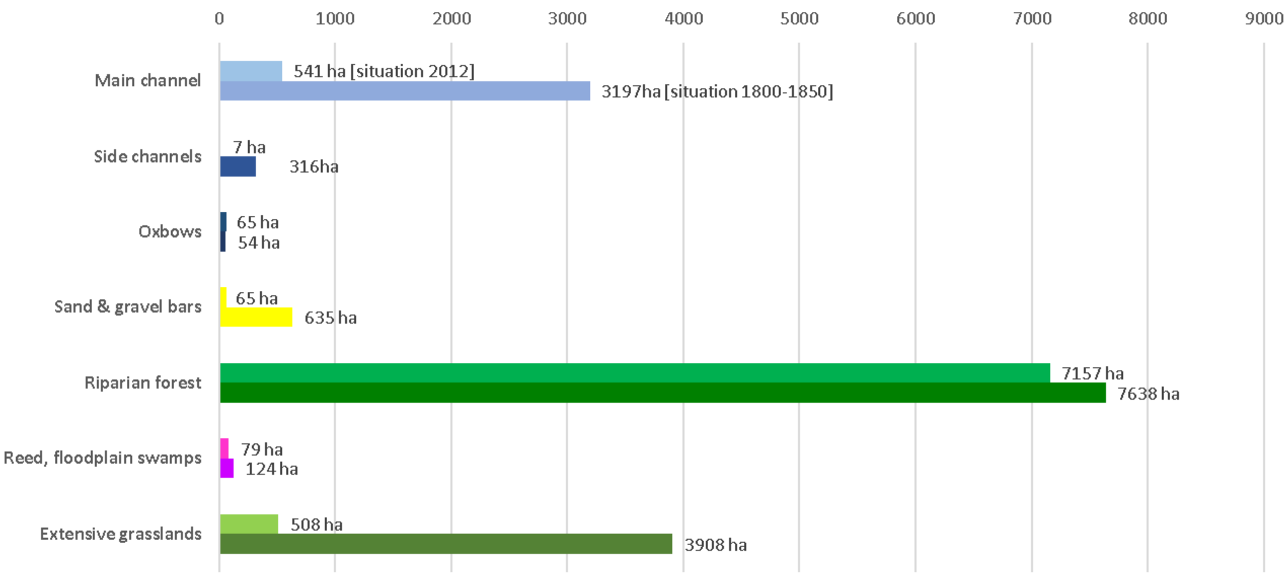


*Figure 28: In particular, the strong reduction of all kinds of river channels (the hydropower reservoirs and tailrace canals are excluded from the calculation) and of gravel bars in this mostly altered section can be recorded. Riparian grasslands, mostly pastures decreased also drastically.*

## Drava 235-185 downstream Mura DRA2

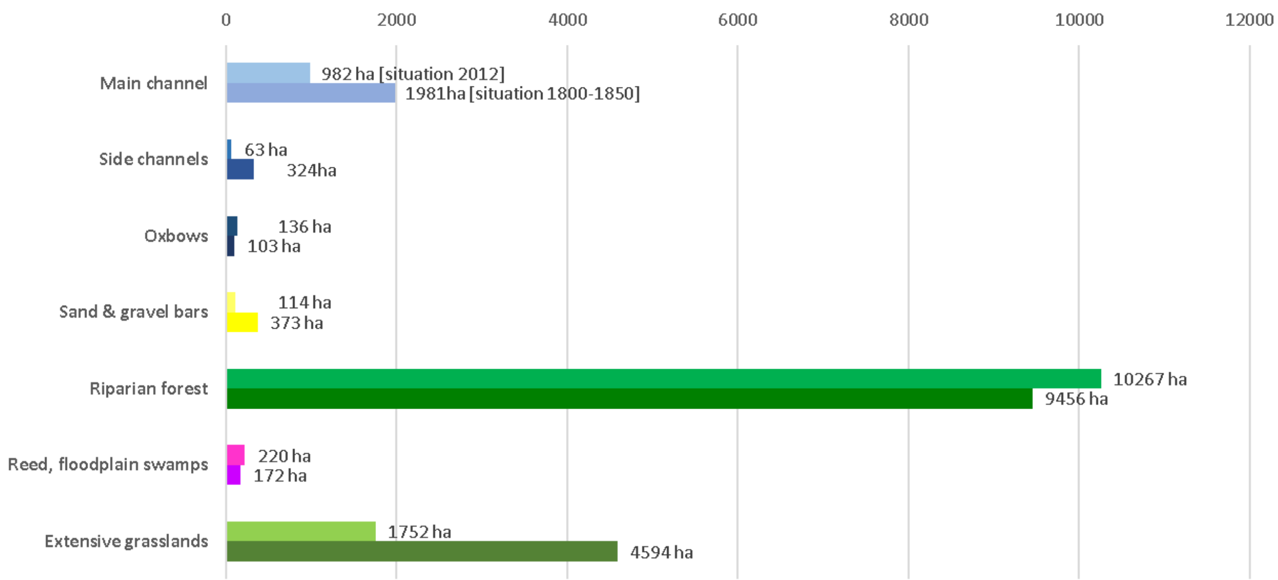


*Figure 29: The losses in the section are much less in comparison with Drava1 but still show the strong reduction of channel surface to the half and for bars even to a third. Fortunately, this reach includes still significant grassland areas, today mostly used as hay meadows. Riparian forests (always including also poplar stands) even increased (most probably former grasslands) and includes also large parts of the Slavonian oak forests.*

## Drava 185-0 DRA3

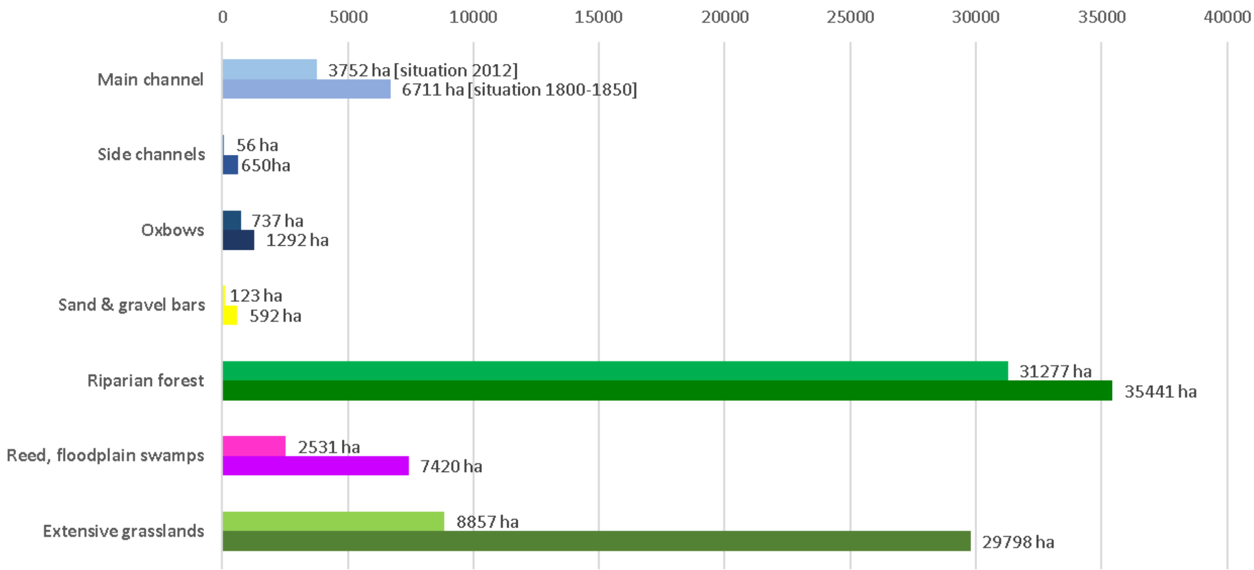


*Figure 30: Significant losses can be concluded for oxbow and wetland habitats within the formerly extremely dynamic and permanently shifting meander belt along lower Drava.*

## Mura 143-85 MUR1

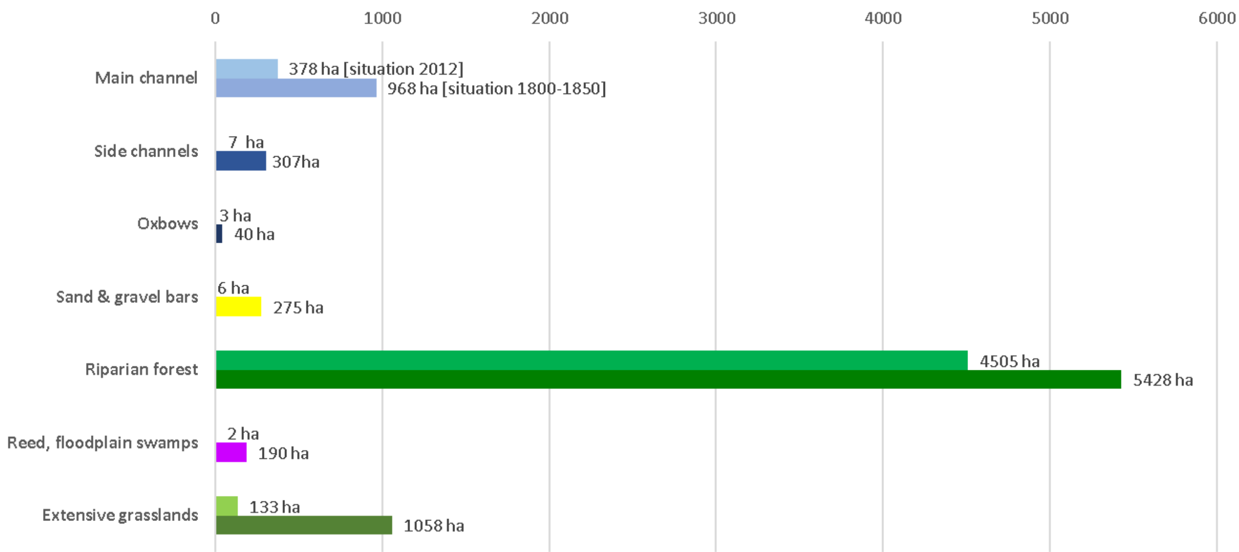


*Figure 31: As for the “upper“ Drava1 the upper Mura lost a lot of channel and pioneer habitats due to strong river regulation.*

### Mura 85-45 MUR2

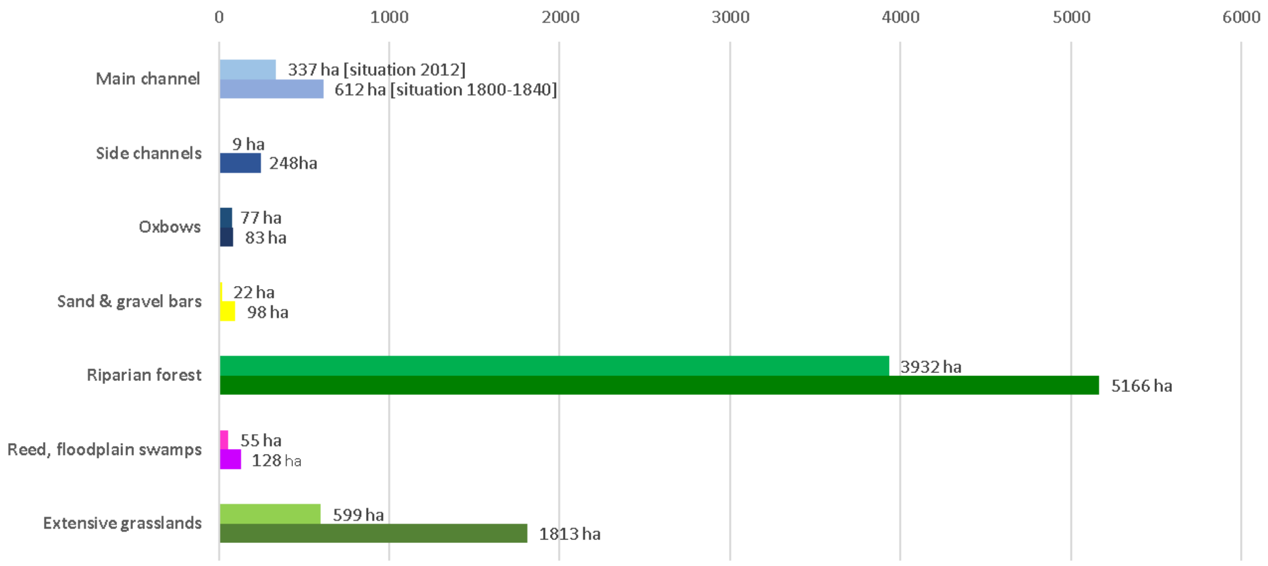


*Figure 32: The loss is much less in comparison with Mura1. The reduction of the riparian forest is located at the margins of the floodplain which is today arable land.*

### Mura 45-0 MUR3

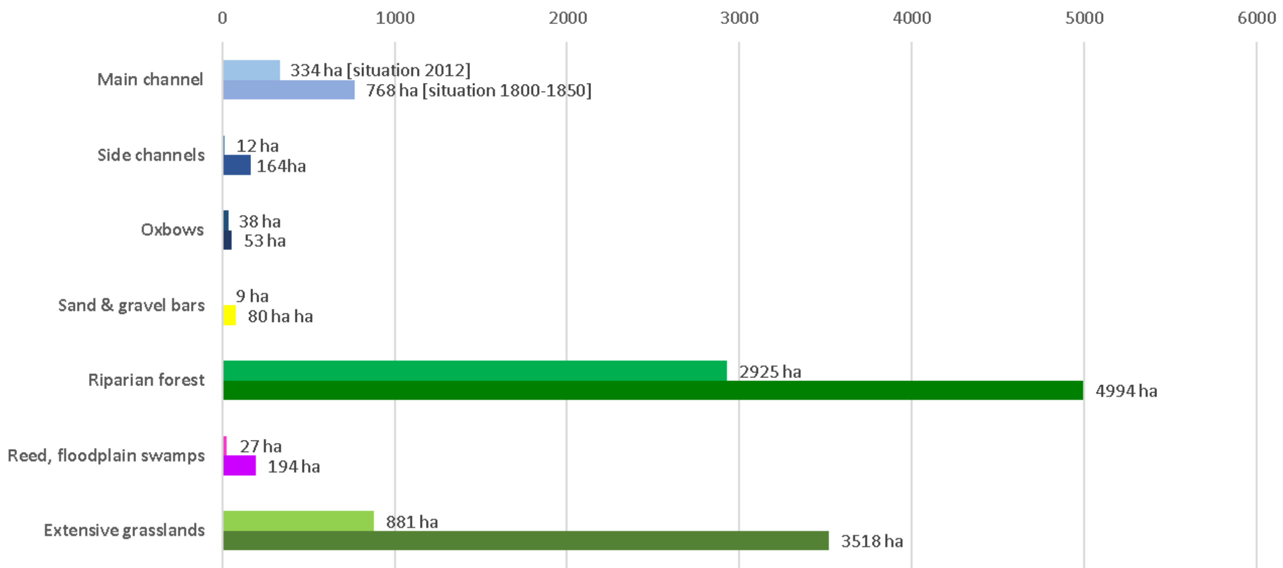


*Figure 33: While the lower Mura seems to be still a rather intact meandering lowland river today the fixation of meanders through river regulation led to a decrease of all habitats and the reduction of floodplain, the melioration/drainage of meadows and the increase of arable land is evident.*

# IV. Discussion

The mapping of the training structures strongly supports any hydromorphological assessment of the rivers in the MDD TBR, and the density and effectiveness maybe surprise comparing the remaining rather intact river reaches in the TBR with other Western European rivers.

The density of training structures directly reflects the morphological character and lateral shift of channels. The specific situation of the long iron curtain borderline (between FYROM and HU), the missing industrial spots along the rivers (absence of navigation) characterize the density and types of regulation works, although more or less the entire rivers are regulated on both banks, with a few exceptions of high steep banks or in the forests of lower Drava.

While the historical mapping delivered clear ratios of losses for the inner river corridor as recorded for many other European rivers the coverage of and distribution of forests and grasslands should be discussed more differentiated. The unique situation in lower Drava with the remaining economically important oak forests which are “plantations” but host important biodiversity and ecosystem services can be not compared. On many European rivers, those hardwood forests are completely disappeared, mainly used for intensive agricultural usage. In the historical situation, many wet grasslands (pastures) were frequent on upper softwood stands converted in many cases to poplar plantations. Therefore, the total coverage of forests drops not everywhere in the same size.

Finally, both inventories clearly indicate the losses of riparian habitats, underline the effectiveness of training structures, document the ongoing decreasing lateral connectivity (which have also other causes like sediment deficit), but will enable also management and restoration options.

# V. Conclusions & actions recommendations

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 endeavors in the river corridor.

**River training structures**

- Not surprisingly long reaches of the three rivers have been regulated with numerous bank protection measures (riprap and groynes).
- Several side channels have been cut off in the past through transversal fills or deflecting structures having a great potential for restoration.
- However, all rivers still preserve longer stretches with much fewer regulation structures, which can serve as a reference for restoration.
- The largest part of the river corridor is not interrupted by transversal structures; only the Drava upstream of the Mura confluence has been impacted by three hydropower plants with shallow reservoirs, tailrace canals, and partly unmodified, partly strongly regulated former river reaches additionally serving as flood conveyance channels.
- Current or most recent construction of regulation works serve the purpose of navigation improvement (Danube and lower Drava, just 80 km upstream of the confluence) and infrastructure protection (bridges, flood dykes).
- Some training structures can be address to drivers like the hydropower on upper Drava and navigation in Danube and lower Drava.

**Historical mapping**

- The historical mapping allows a unique analysis and comparison of the historical and current situation, in particular regarding river length, sinuosity, width variability and active floodplain extension/structure, and can serve as a reference for the general and type-specific restoration framework.
- The mapping clearly indicate the dramatic losses of dynamic riparian habitats such as all kind of channels, main branches and side channels, gravel and sand bars and finally river and floodplain islands.

The outcomes strongly underline the type-specific assessment and restoration potential for the River section types. The location of river regulation works where it is not absolutely necessary or already collapsed is a clear source for potential restoration activities.

# VI. References

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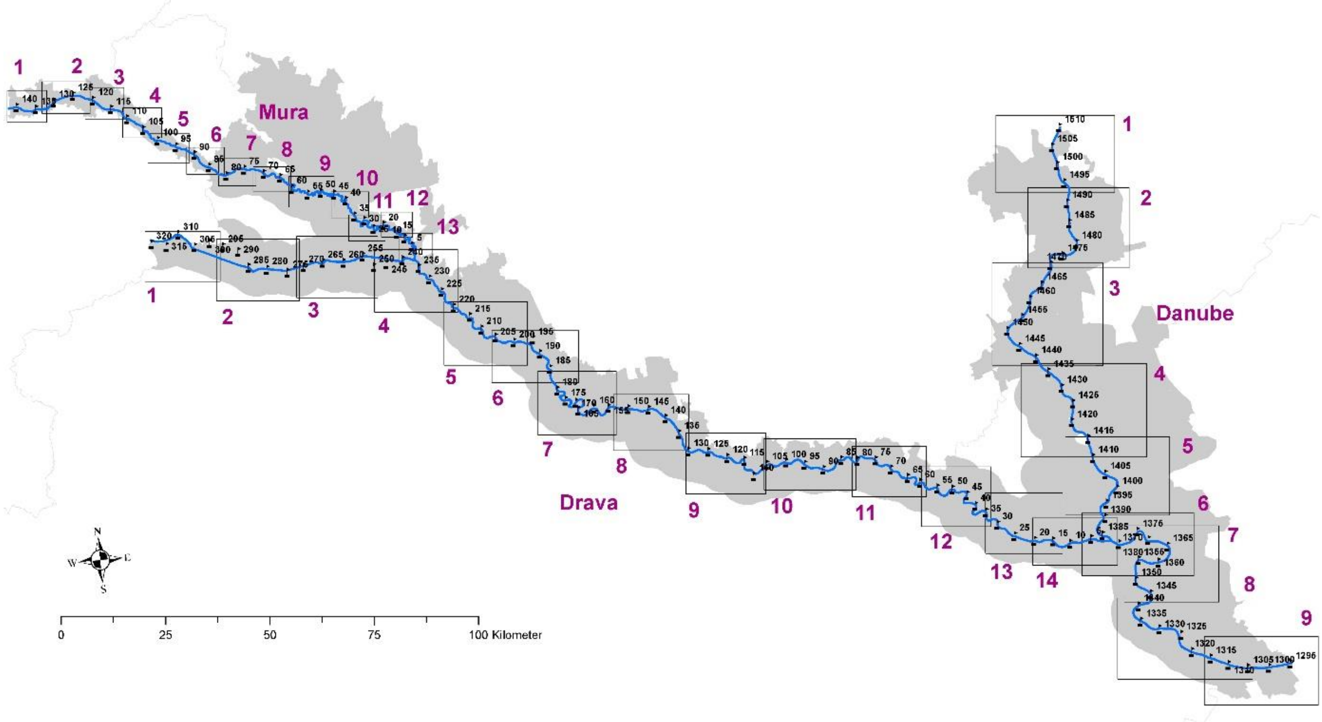
# VII. Map annex

Rivers are covered from upstream to downstream in the order Mura, Drava and finally Danube.

The scale of maps for Mura is 1:25:000, for Drava 1:50,000 and for Danube 1:75,000.

The maps include the contemporary rkm for orientation and are listed as Mura map 1-13, Drava map 1-14 and Danube map 1-9.

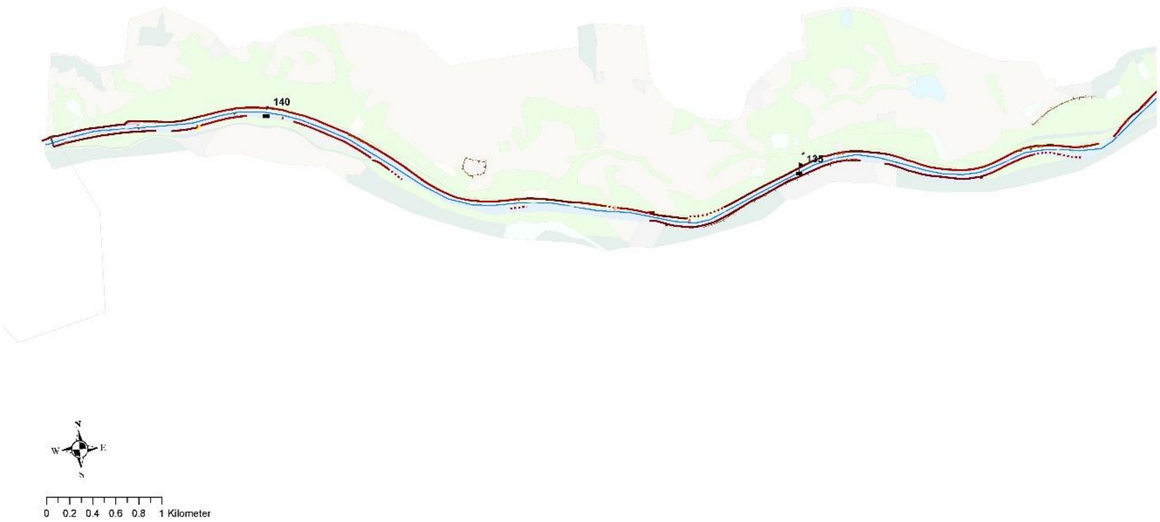
Sheet boxes for the map annex



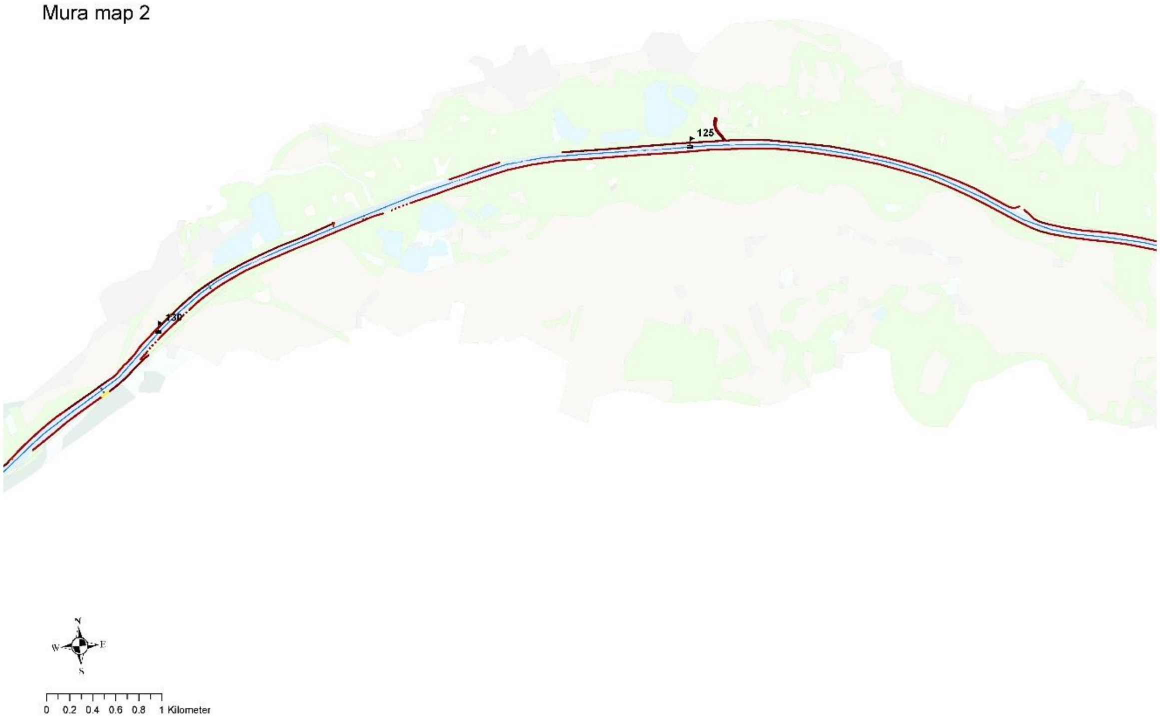
## A. River training structures

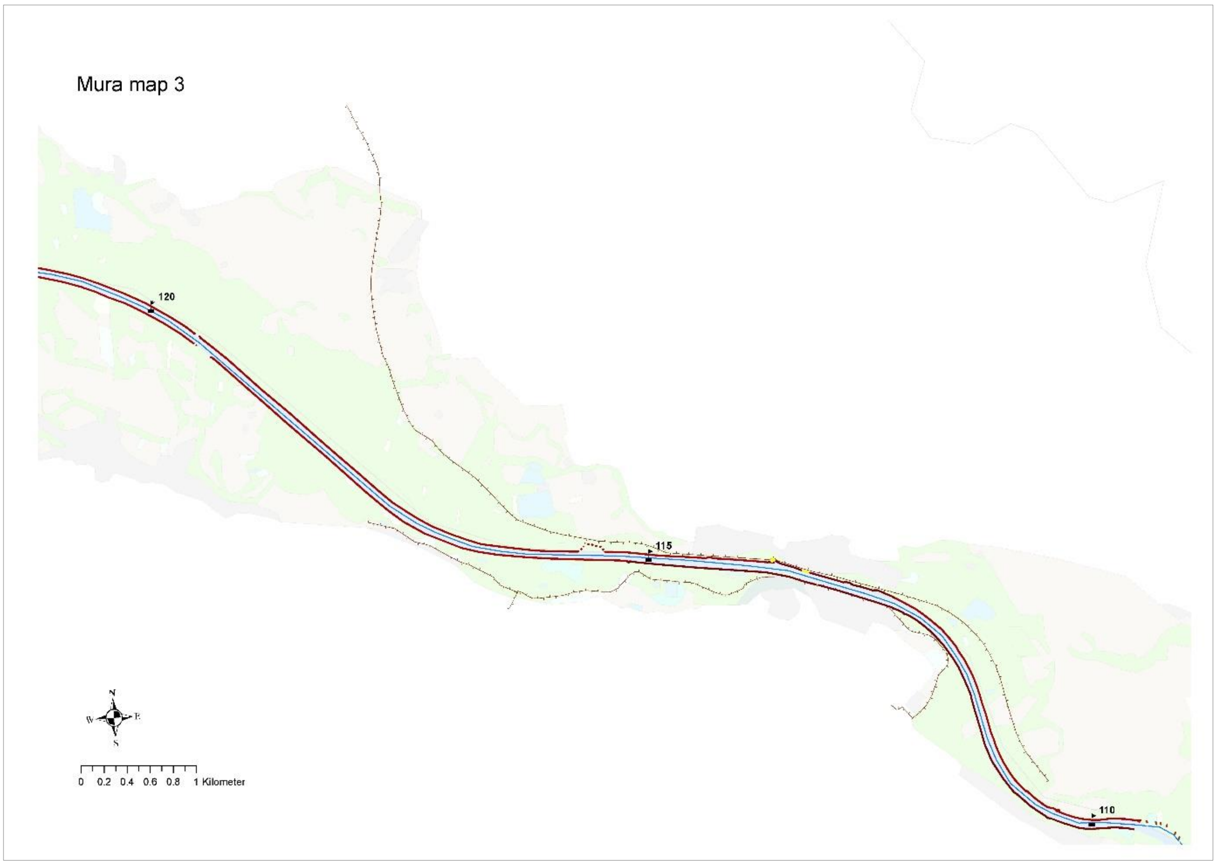
Map legend for the river training structures:

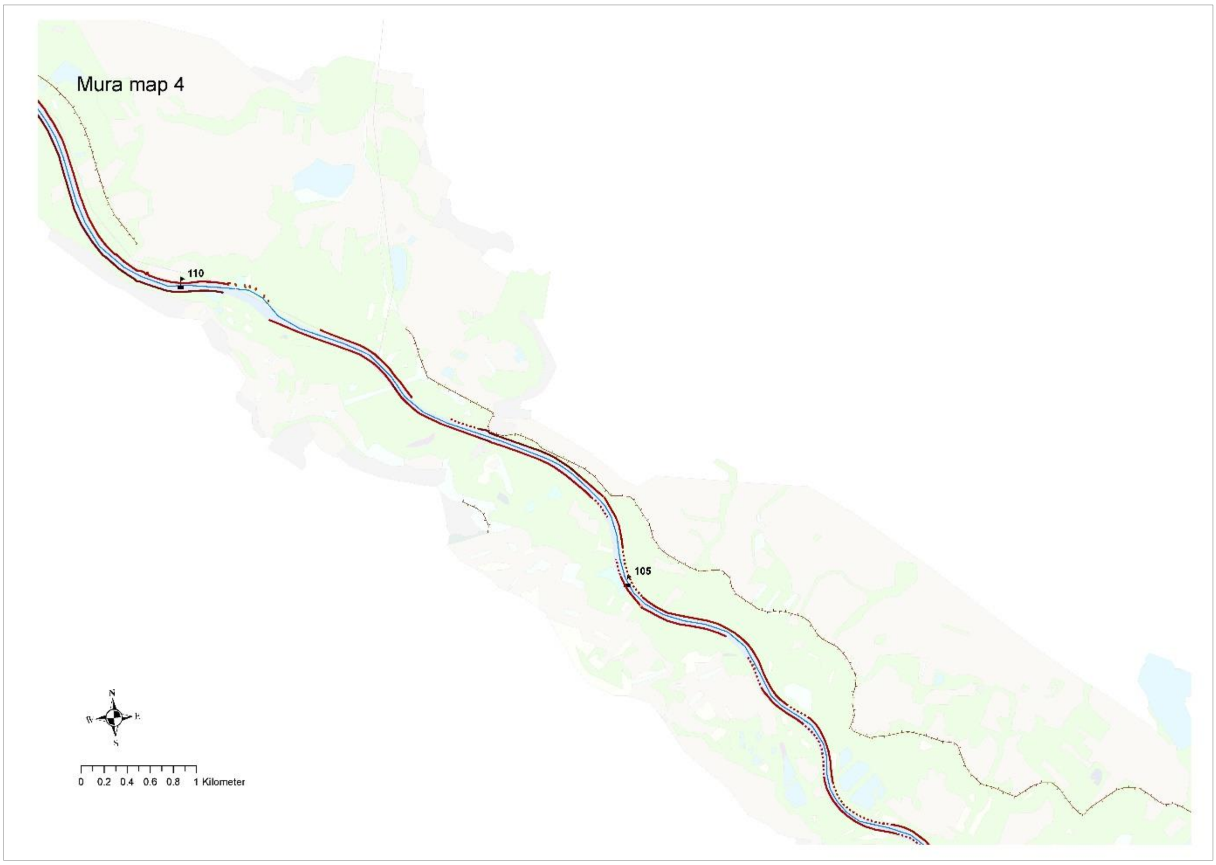
Mura map 1

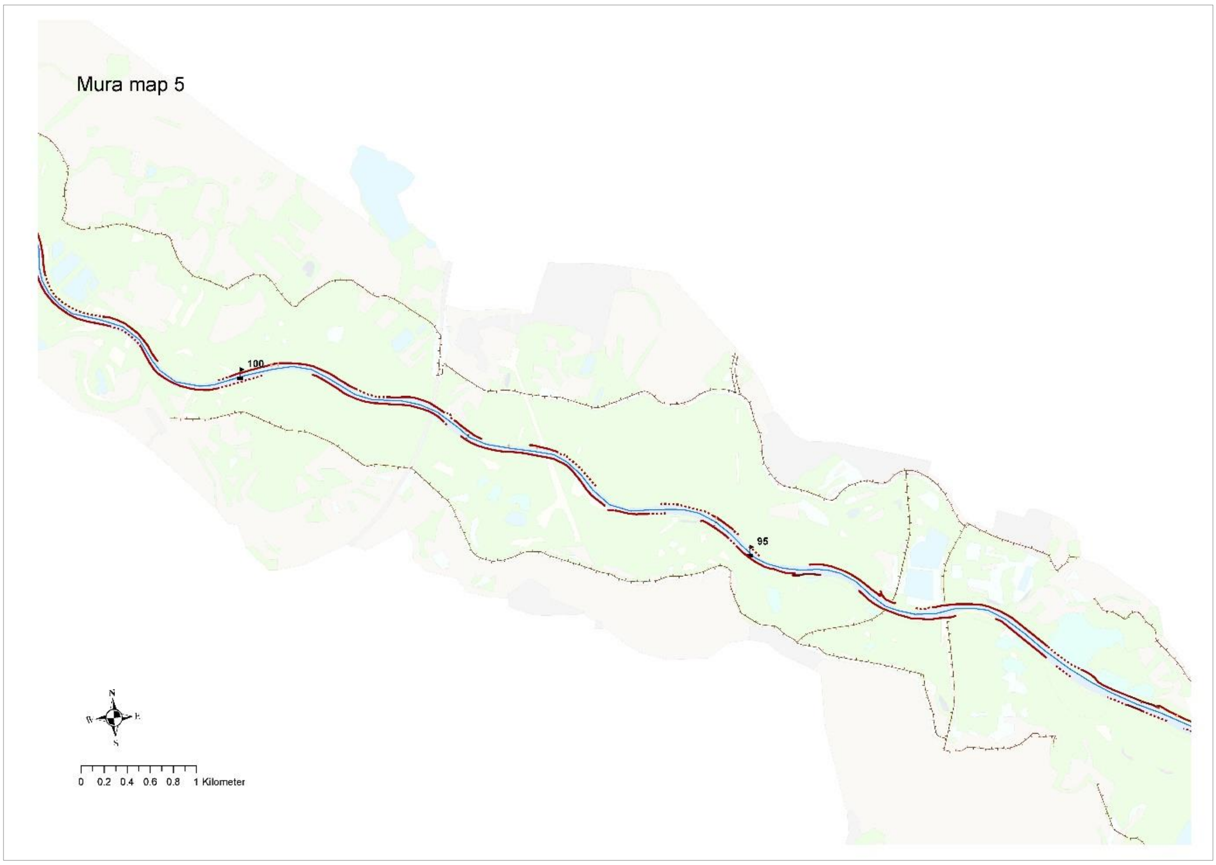



Mura map 2



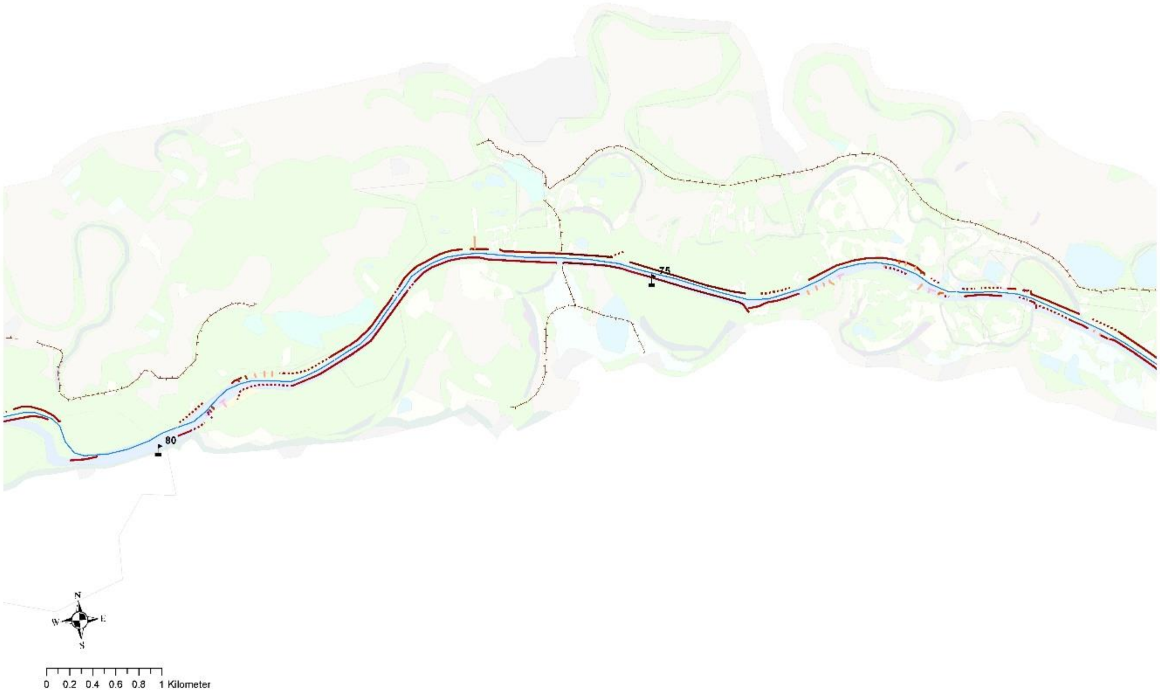

Mura map 3
120
115
110
0 0.2 0.4 0.6 0.8 1 Kilometer


Mura map 4
110
105
0 0.2 0.4 0.6 0.8 1 Kilometer


Mura map 5
100
95
N
W
E
S
0 0.2 0.4 0.6 0.8 1 Kilometer

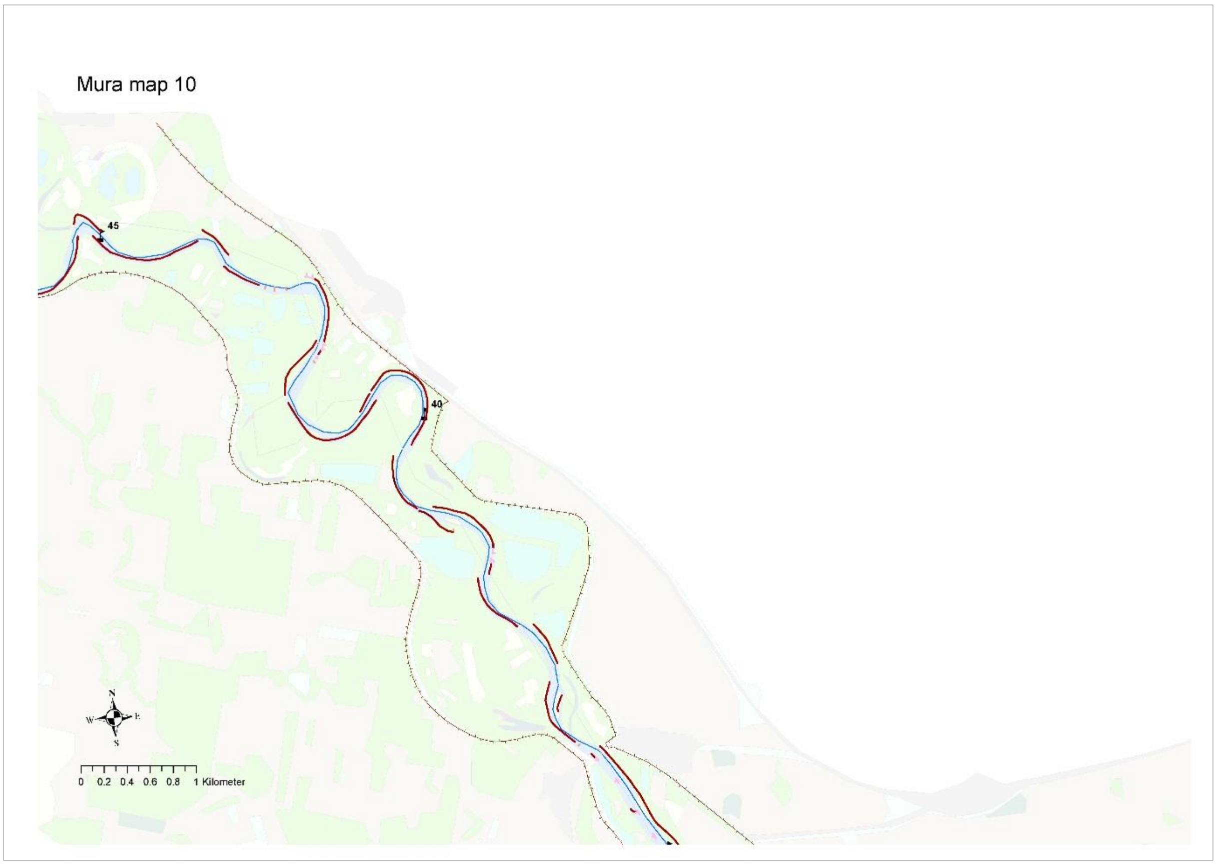

Mura map 6
90
85
80
N
W
E
S
0 0.2 0.4 0.6 0.8 1 Kilometer

Mura map 7

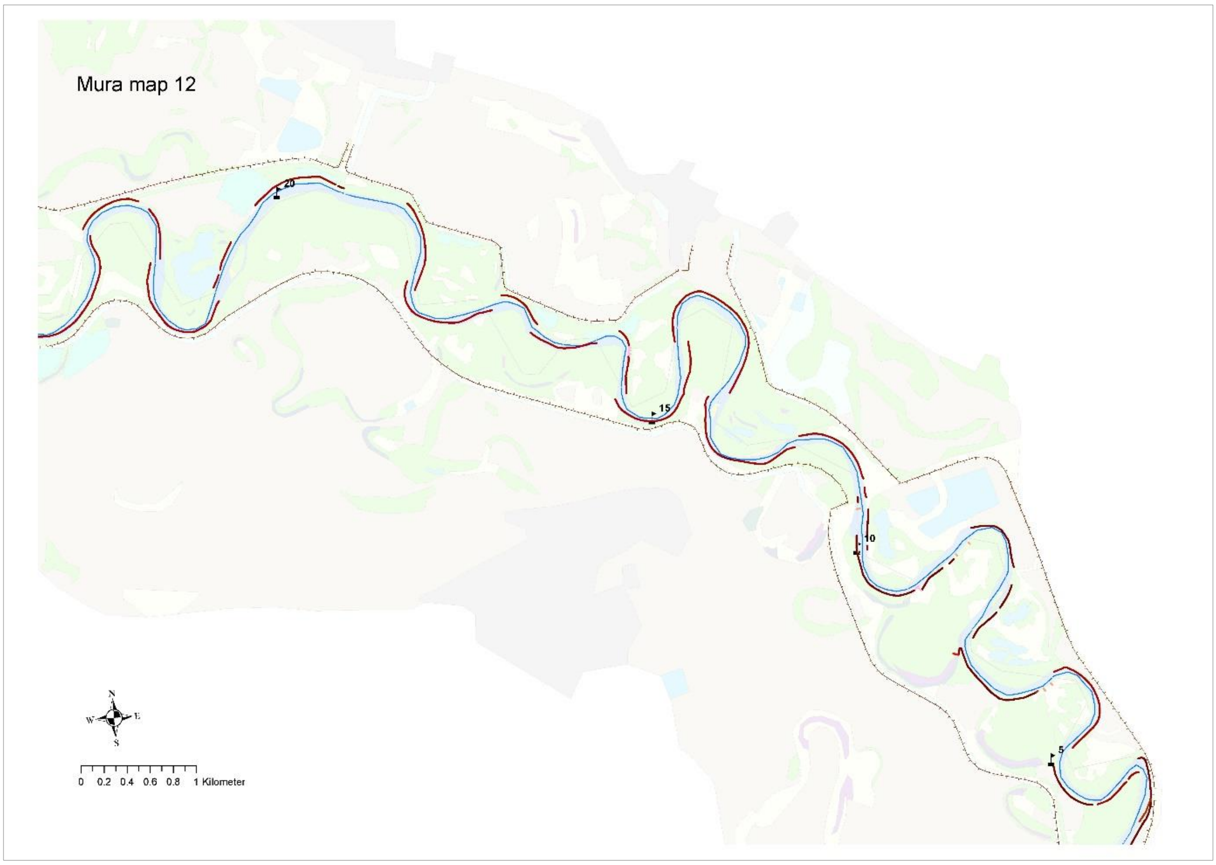


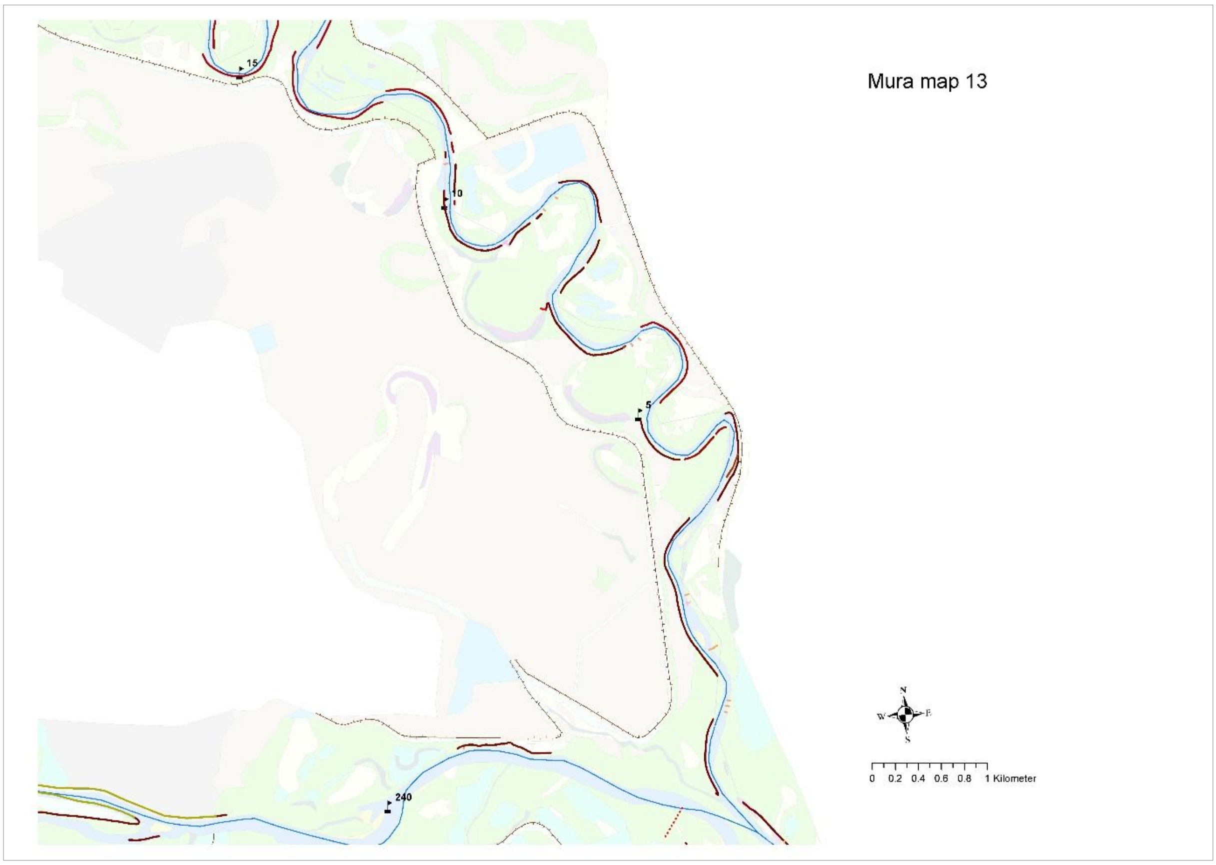

Mura map 8


Mura map 9
60
55
50
N
W
E
S
0 0.2 0.4 0.6 0.8 1 Kilometer

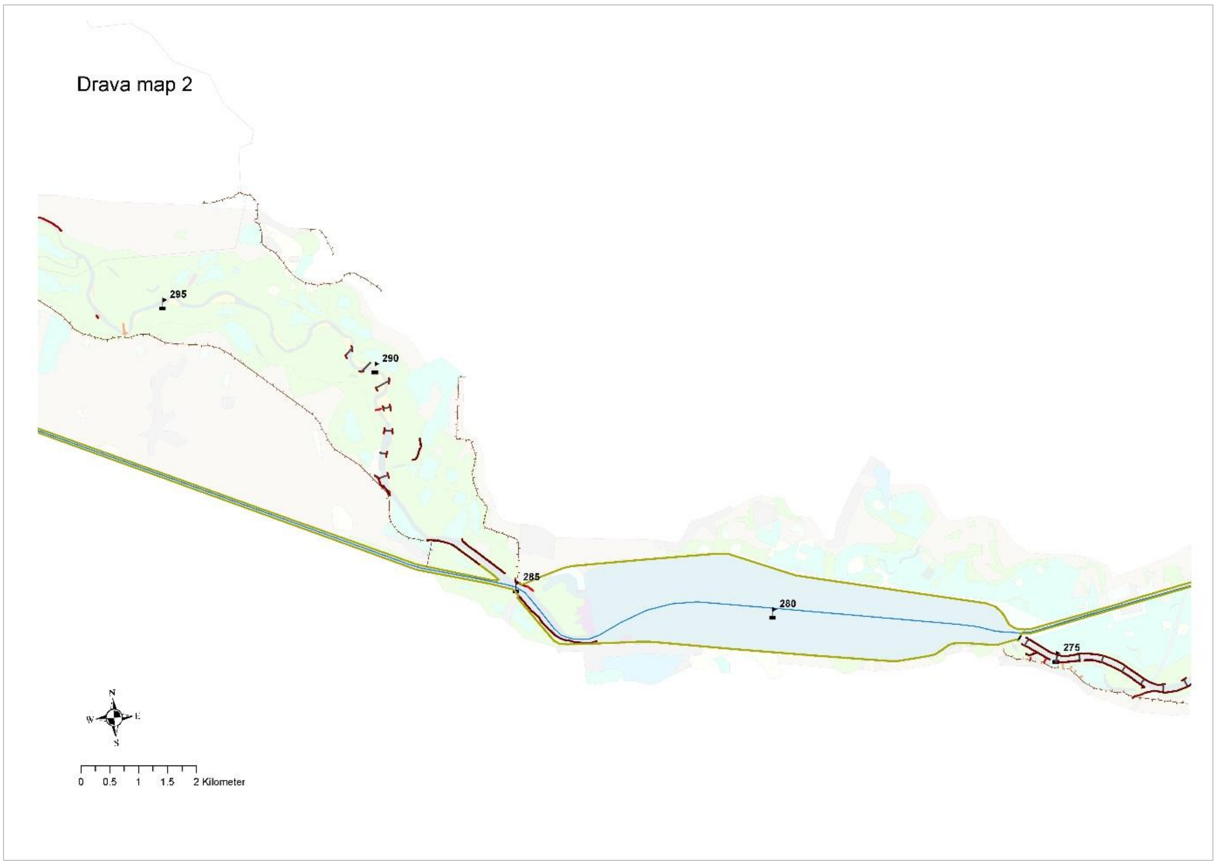

Mura map 10
45
40
N
W
E
S
0 0.2 0.4 0.6 0.8 1 Kilometer


Mura map 11
35
30
25
N
W
E
S
0 0.2 0.4 0.6 0.8 1 Kilometer

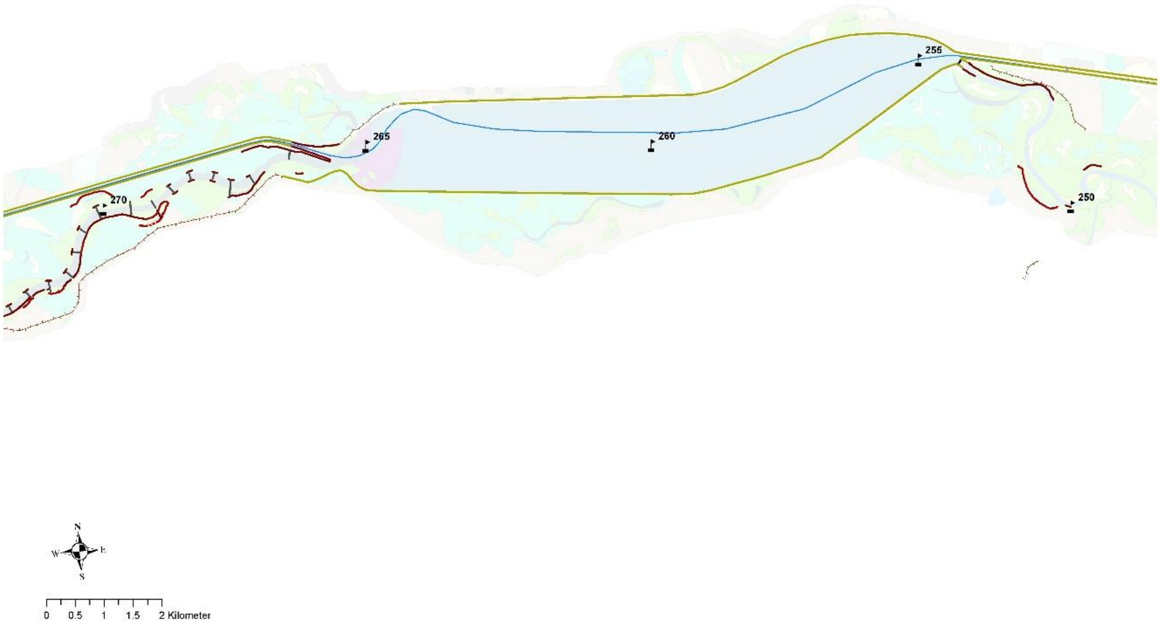

Mura map 12
20
15
10
5
N
W
E
S
0 0.2 0.4 0.6 0.8 1 Kilometer


Mura map 13
15
10
5
240
N
W
E
S
0 0.2 0.4 0.6 0.8 1 Kilometer

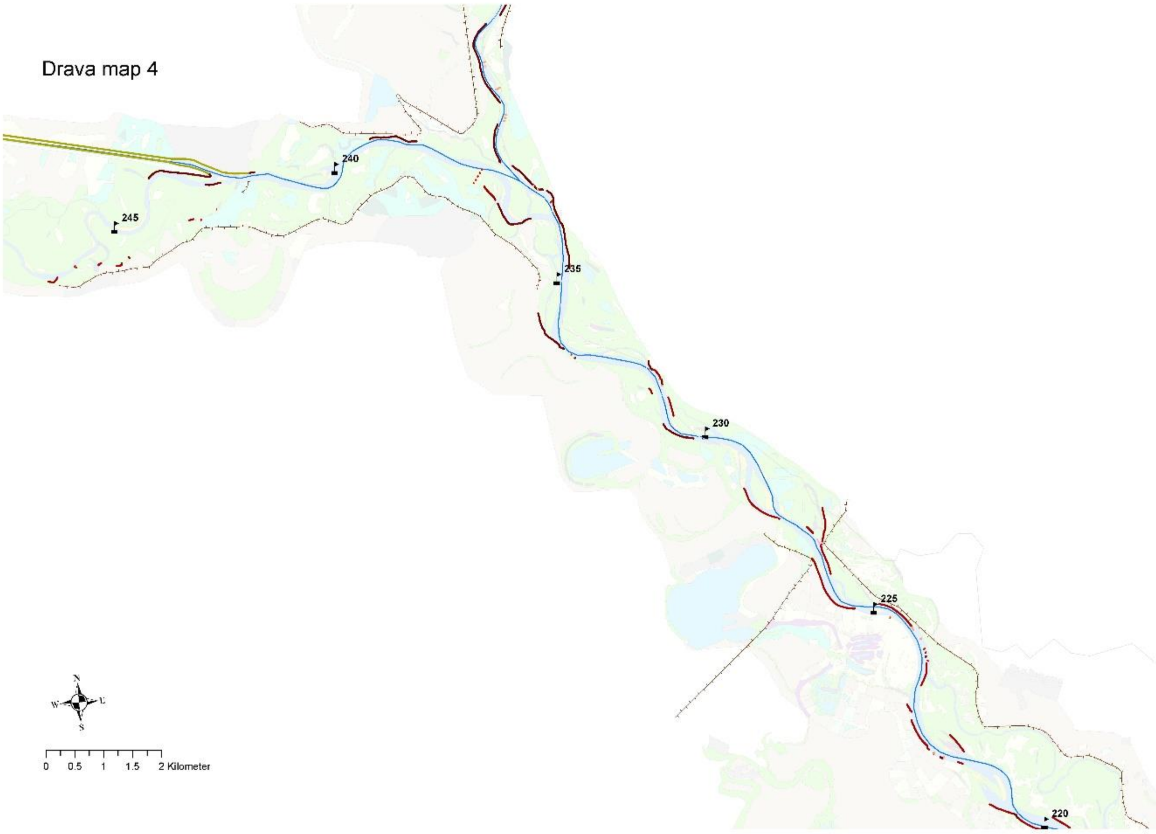

Drava map 1
310
300
320
315
305
N
W
E
S
0
0.5
1
1.5
2 Kilometer


Drava map 2
295
290
285
280
275
N
W
E
S
0
0.5
1
1.5
2 Kilometer

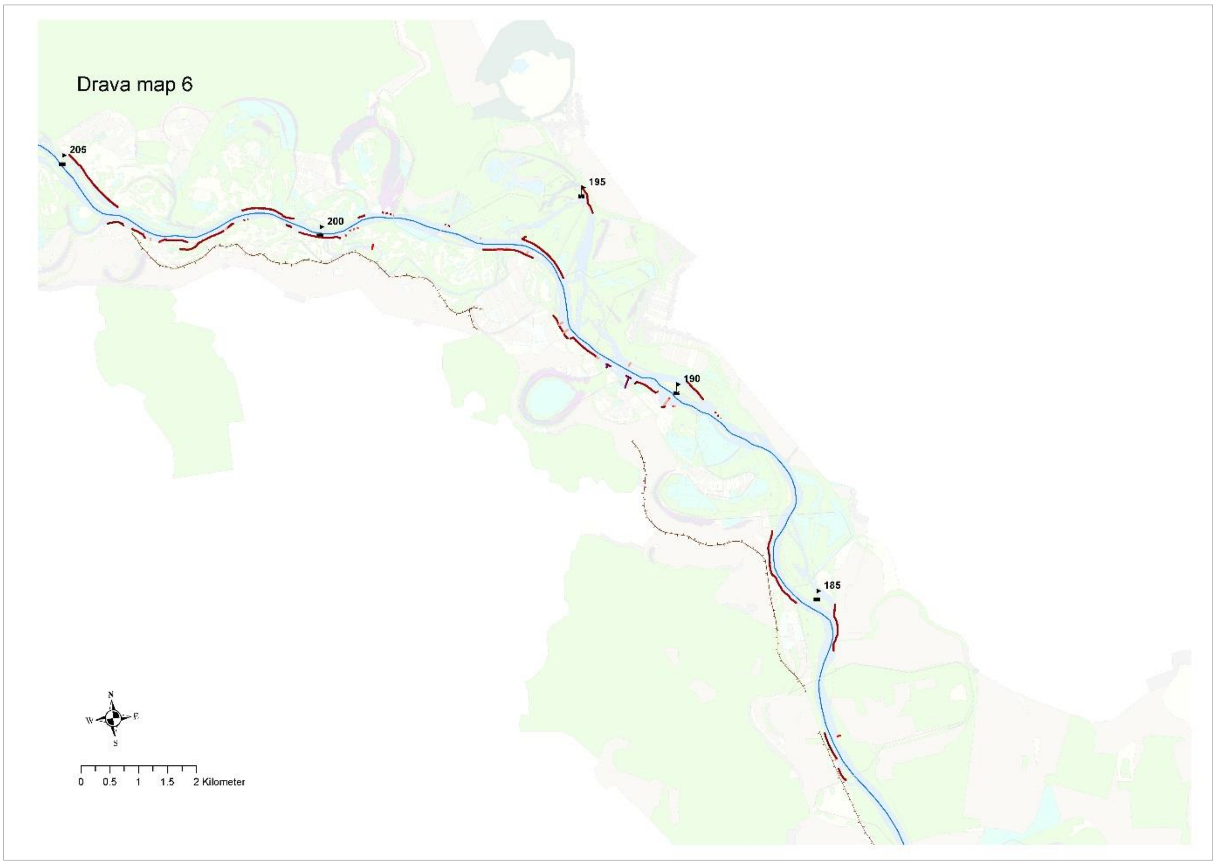
Drava map 3

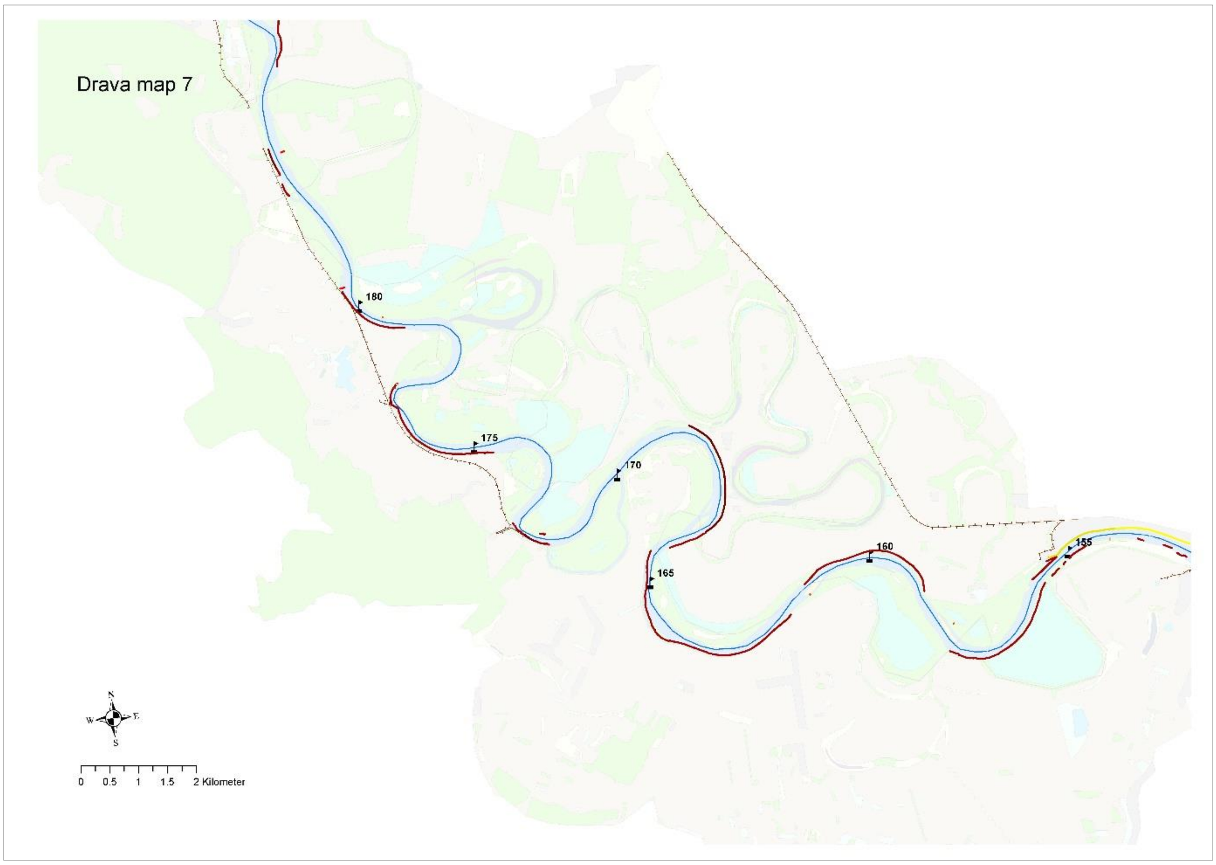



Drava map 4



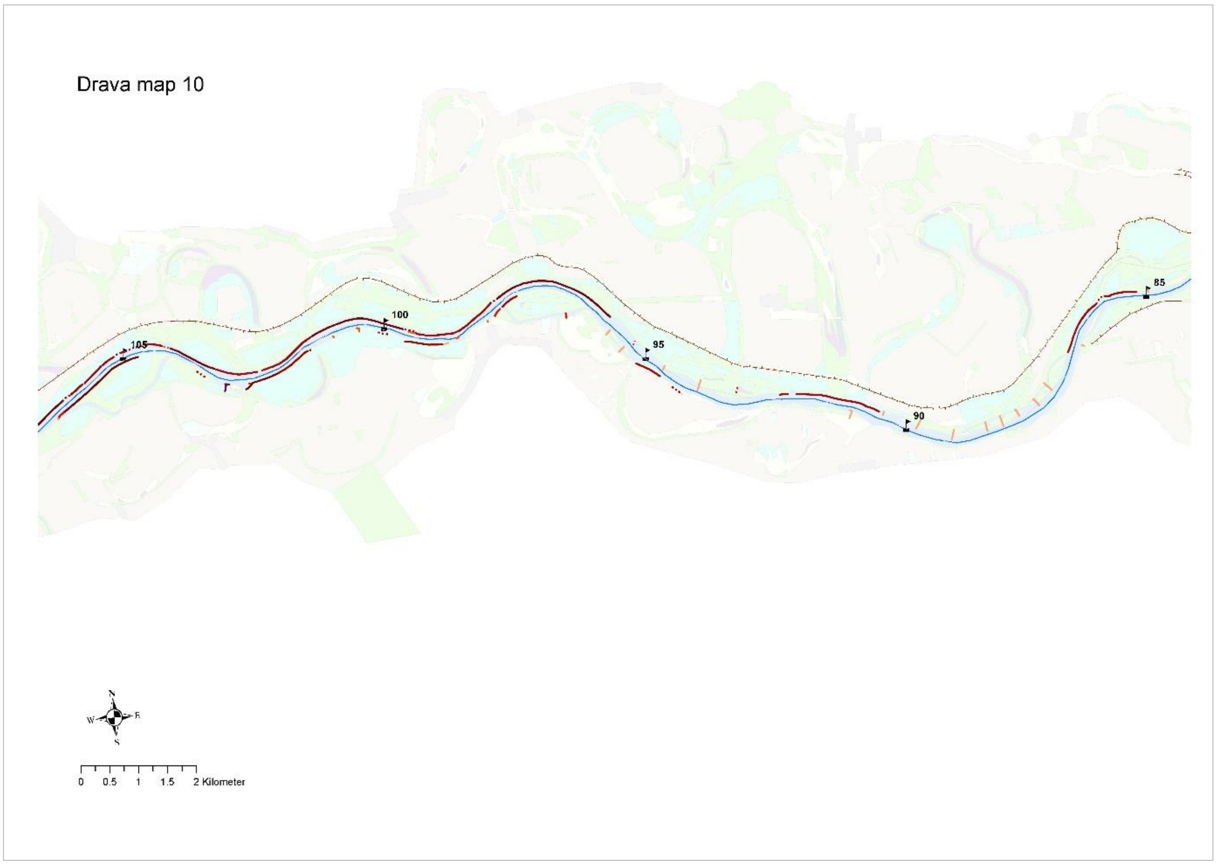

Drava map 5
220
215
210
205
200
N
W
E
S
0 0.5 1 1.5 2 Kilometer


Drava map 6
205
200
195
190
185
N
W
E
S
0 0.5 1 1.5 2 Kilometer

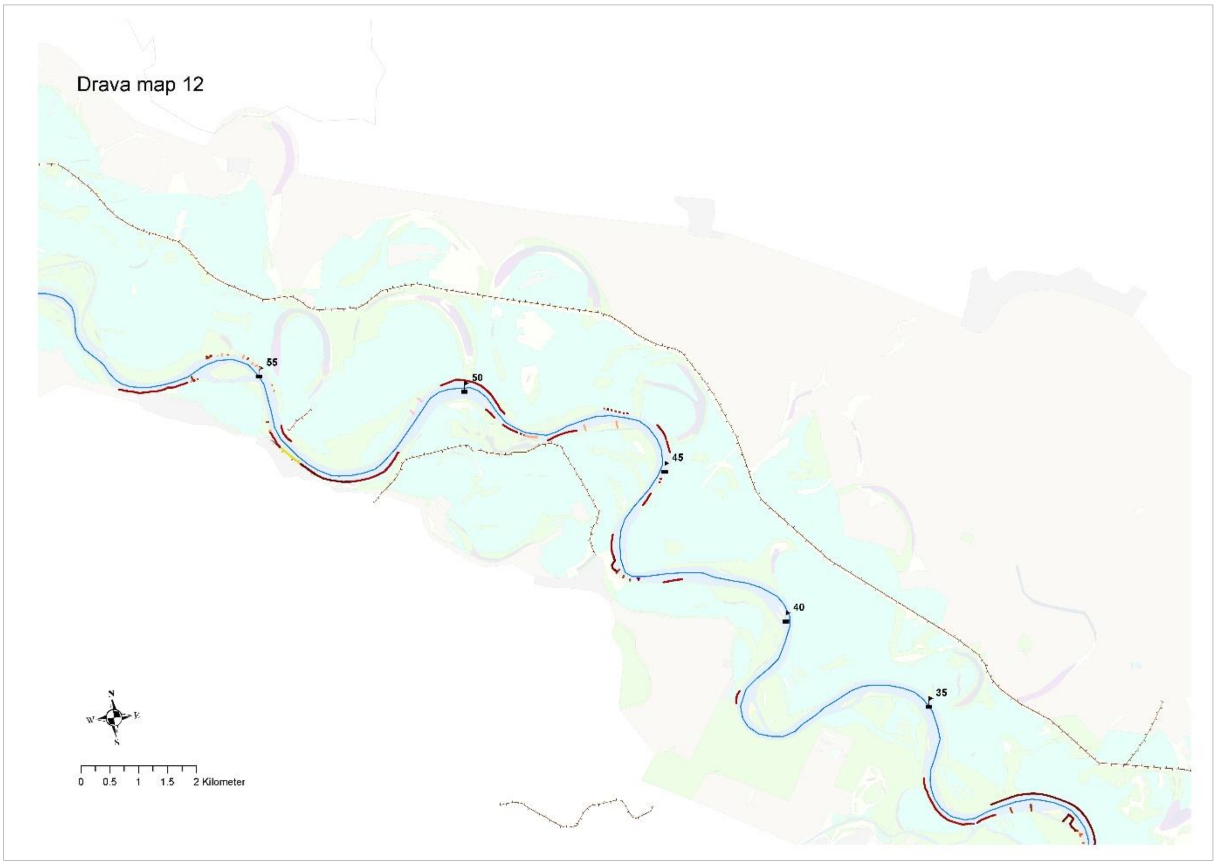

Drava map 7
180
175
170
165
160
155
0 0.5 1 1.5 2 Kilometer


Drava map 8
150
145
140
135
0 0.5 1 1.5 2 Kilometer

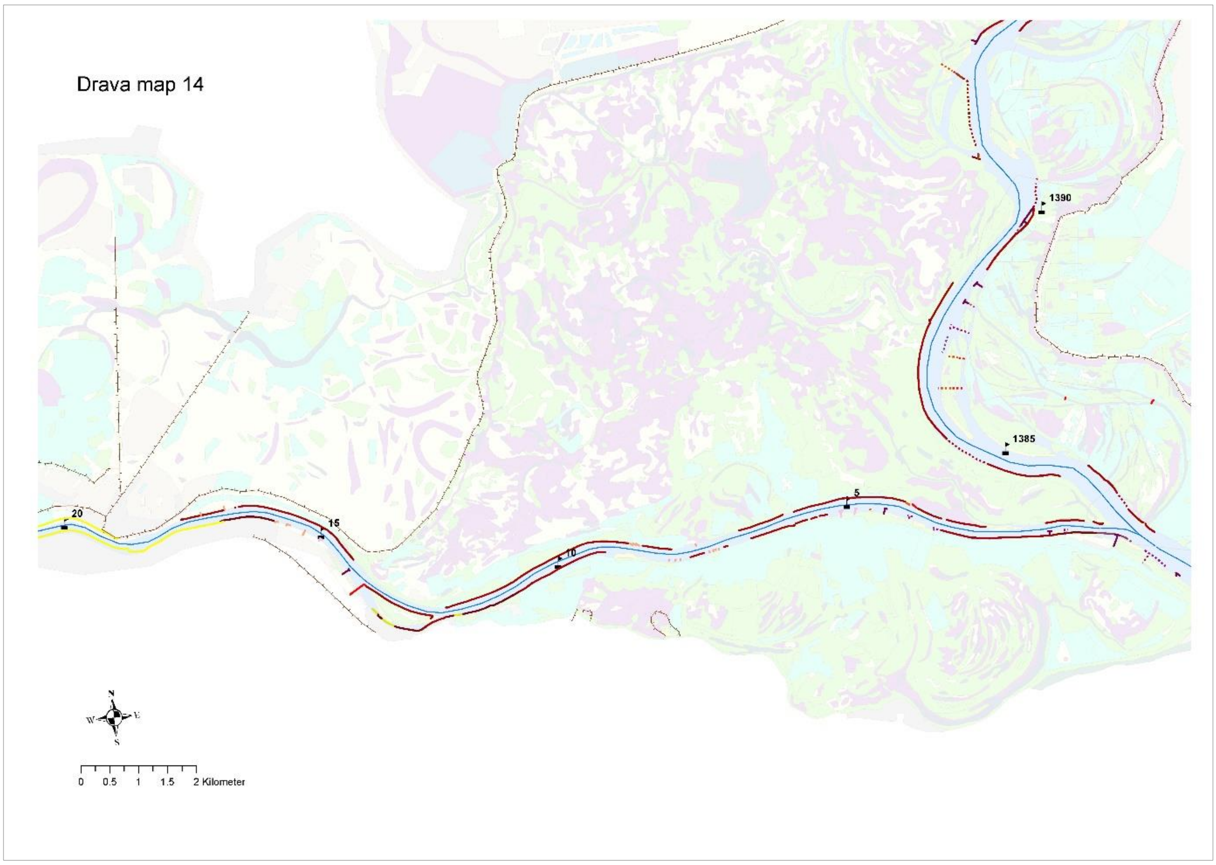

Drava map 9
130
125
120
115
110
0 0.5 1 1.5 2 Kilometer


Drava map 10
105
100
95
90
85
0 0.5 1 1.5 2 Kilometer

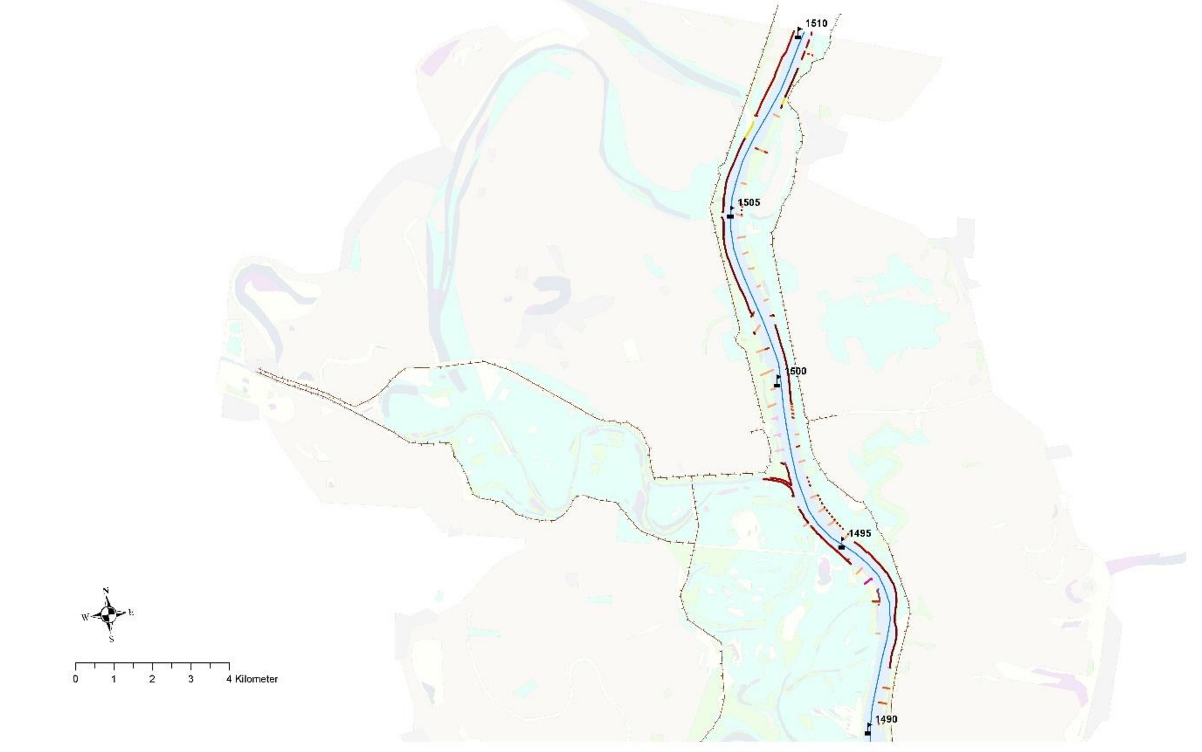

Drava map 11
85
80
75
70
65
60
0 0.5 1 1.5 2 Kilometer


Drava map 12
55
50
45
40
35
0 0.5 1 1.5 2 Kilometer

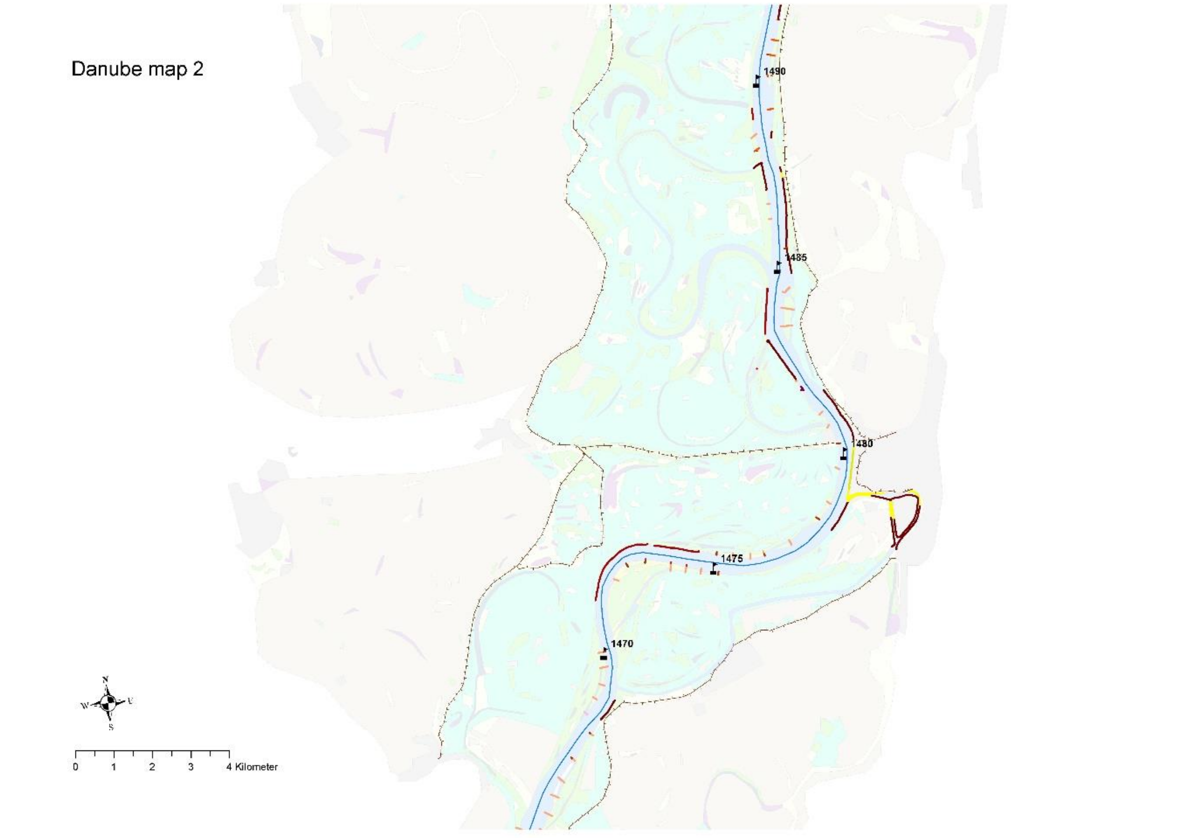

Drava map 13
35
30
25
20
15
0 0.5 1 1.5 2 Kilometer


Drava map 14
1390
1385
20
15
10
5
0 0.5 1 1.5 2 Kilometer

Danube map 1

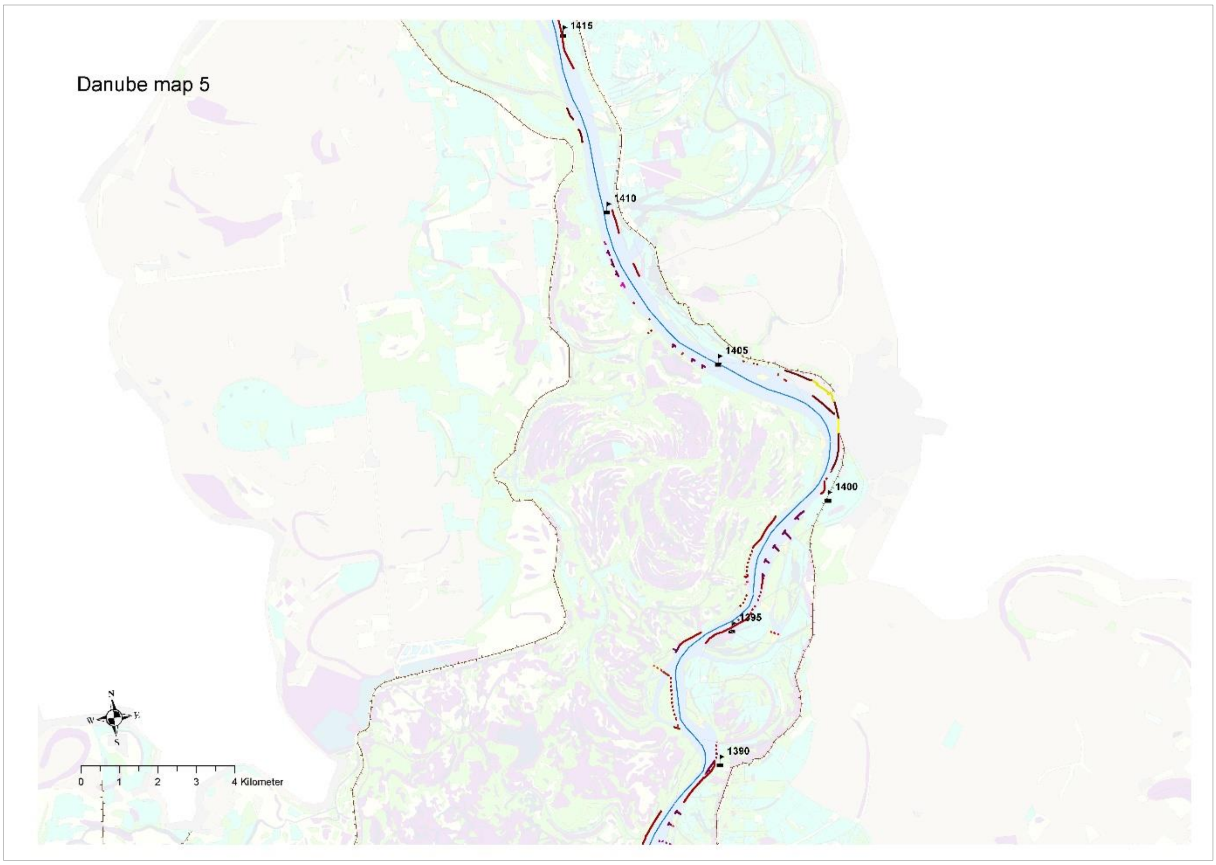


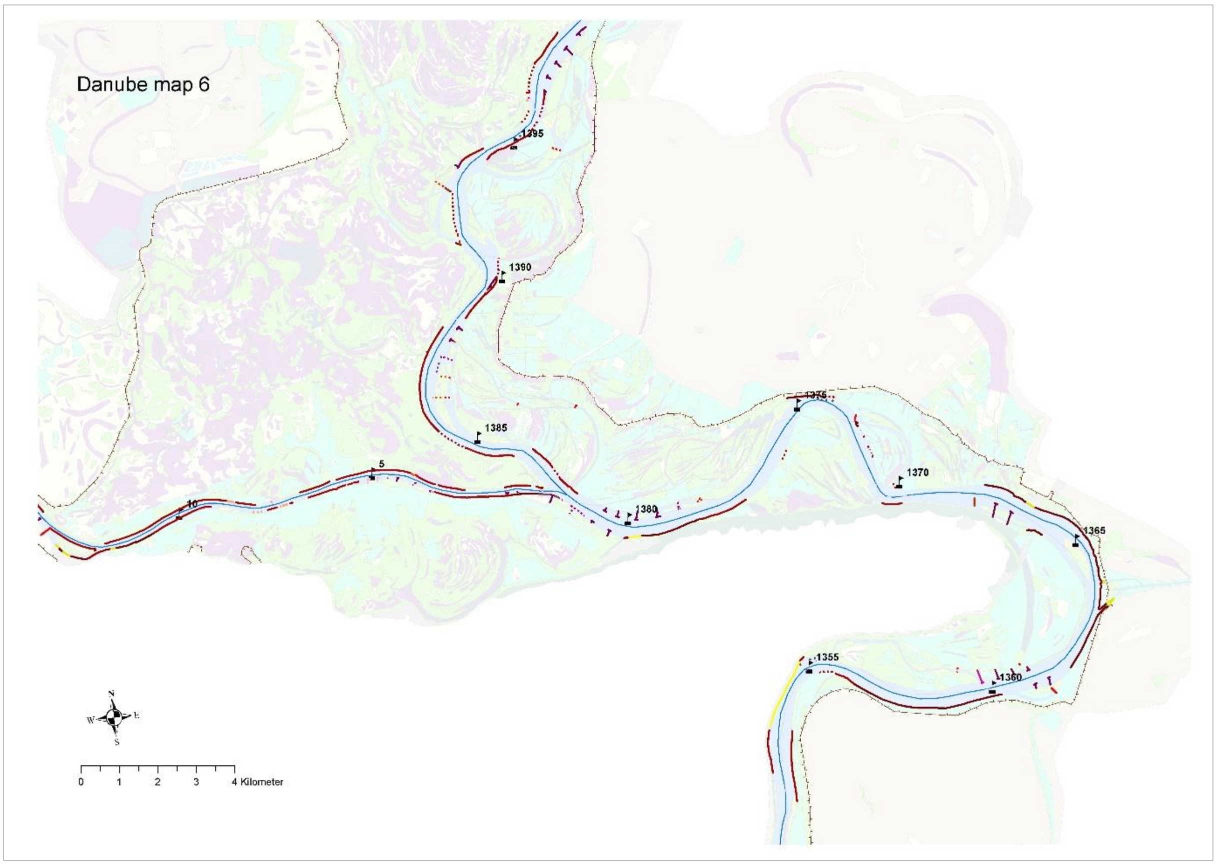

Danube map 2

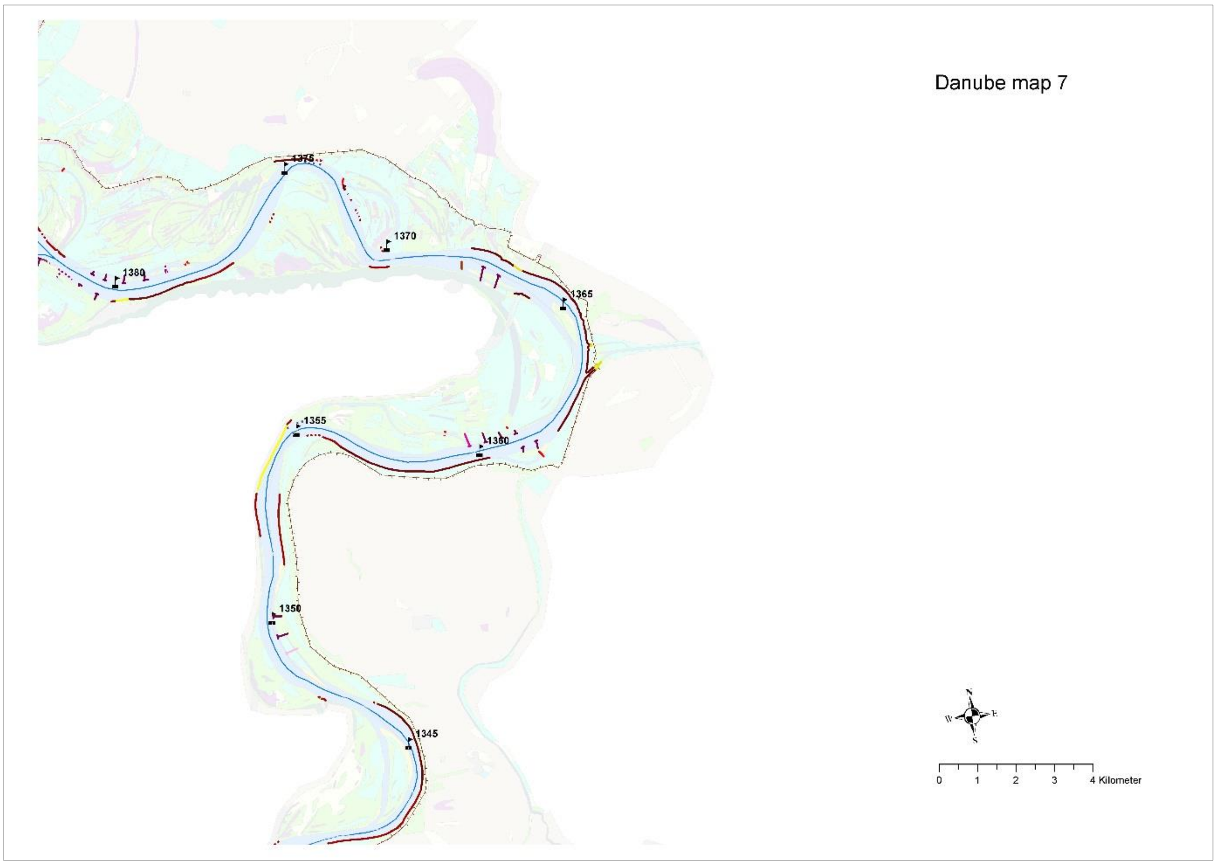


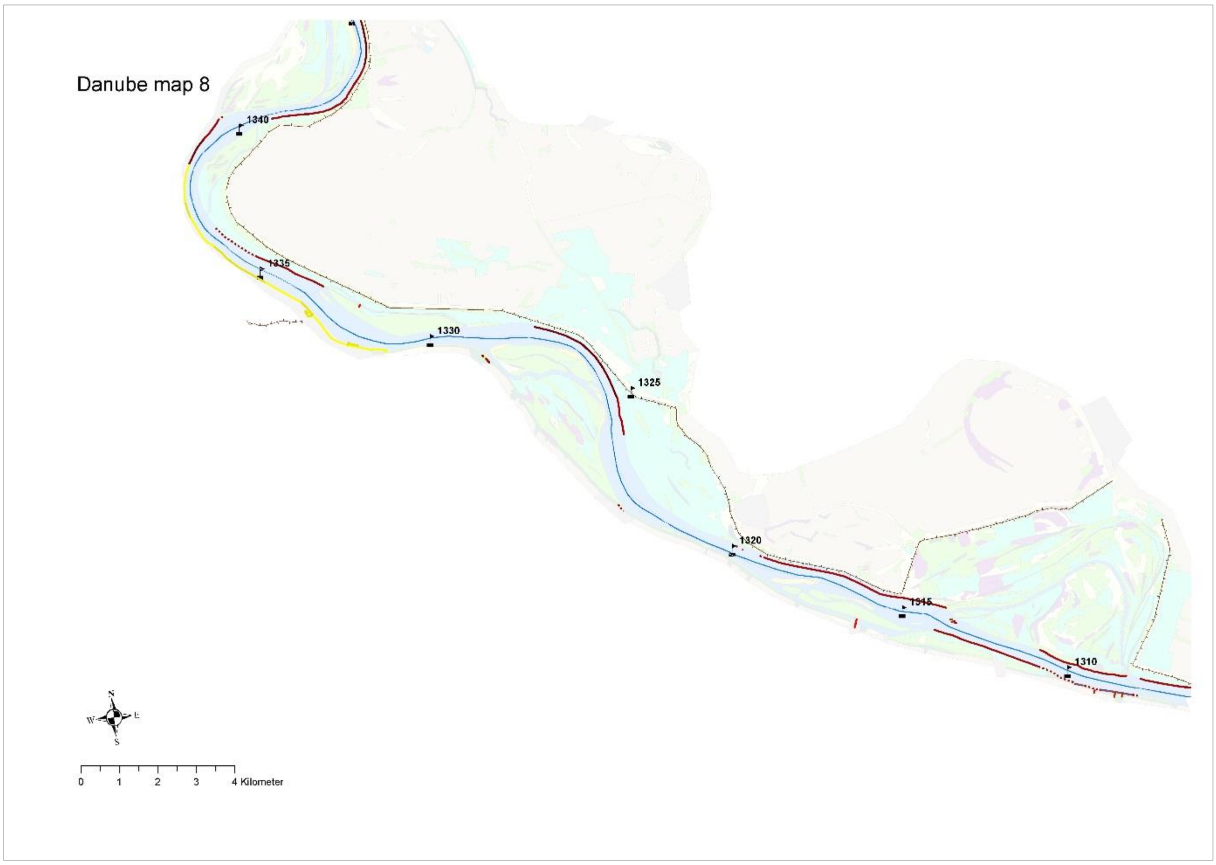

Danube map 3
1465
1460
1455
1450
1445
1440
0 1 2 3 4 Kilometer

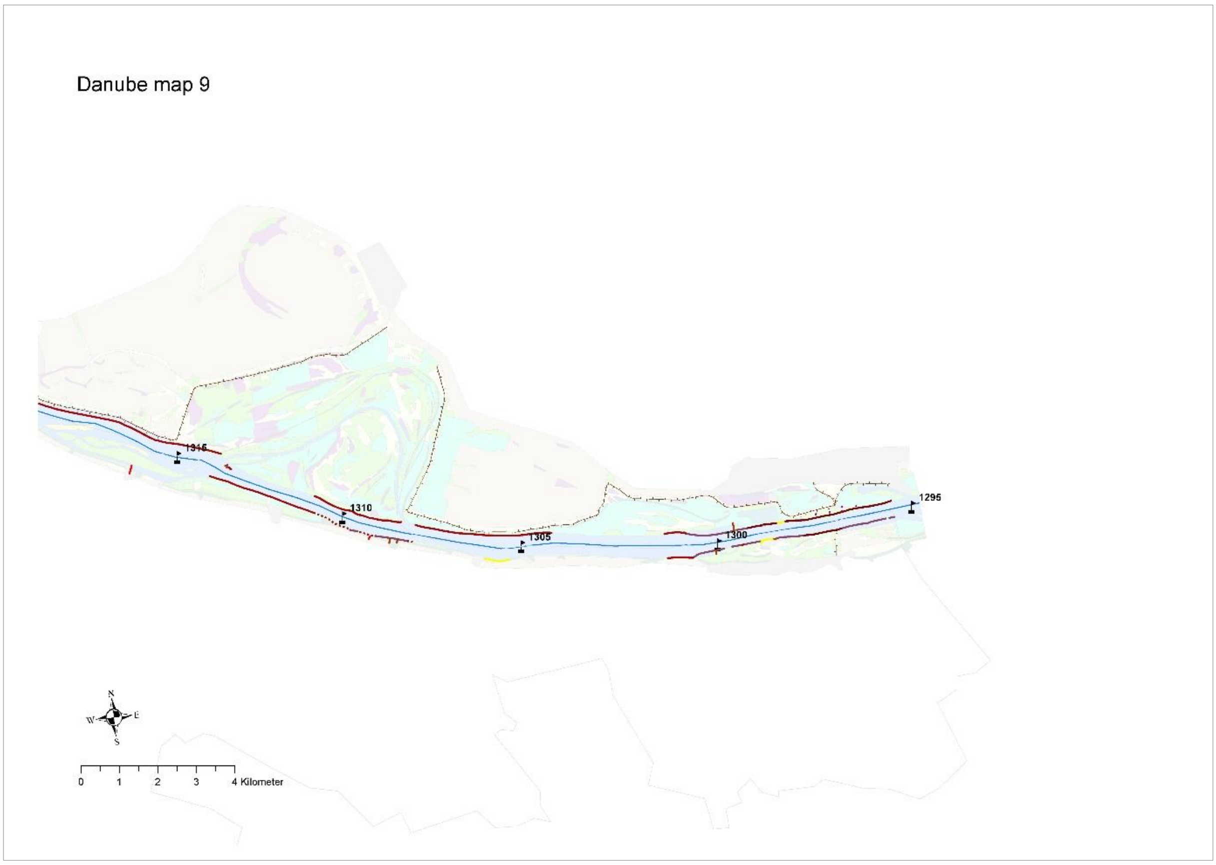

Danube map 4
1435
1430
1425
1420
1415
0 1 2 3 4 Kilometer


Danube map 5
1415
1410
1405
1400
1395
1390
0 1 2 3 4 Kilometer


Danube map 6
1395
1390
1385
1380
1375
1370
1365
1360
1355
5
10
0 1 2 3 4 Kilometer


Danube map 7
1375
1370
1380
1365
1355
1360
1350
1345
0 1 2 3 4 Kilometer

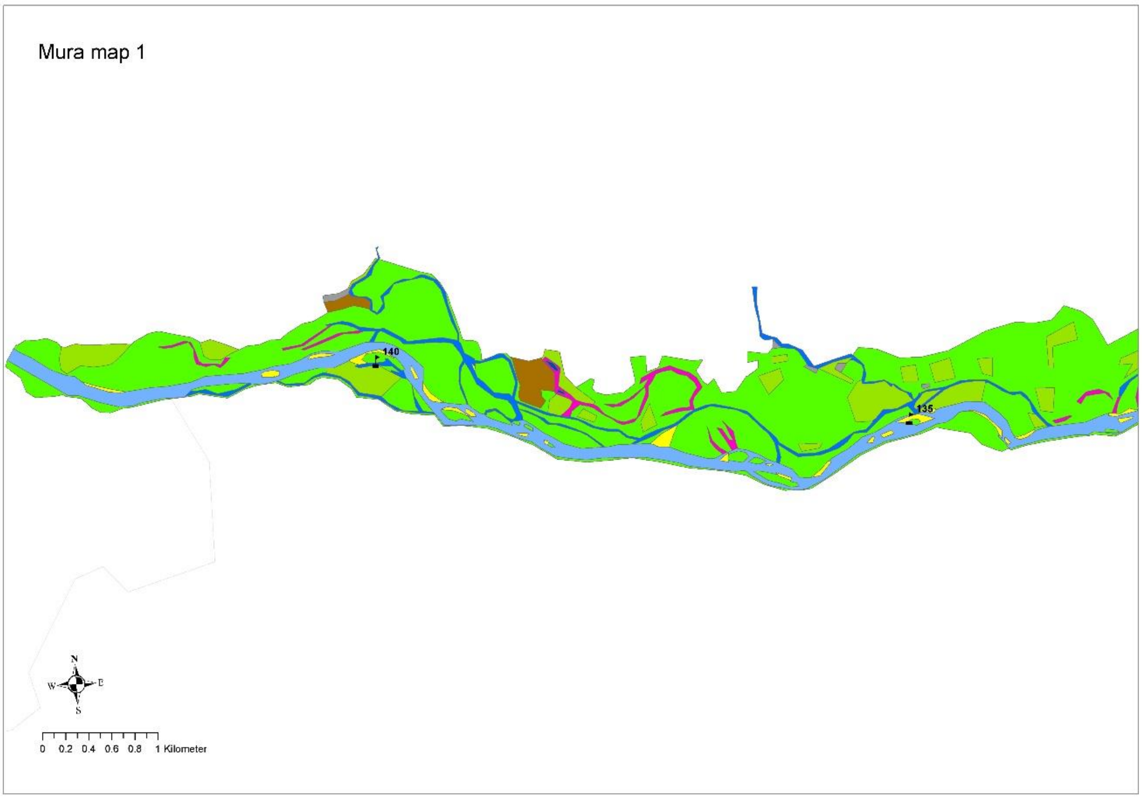

Danube map 8
1340
1335
1330
1325
1320
1315
1310
0 1 2 3 4 Kilometer

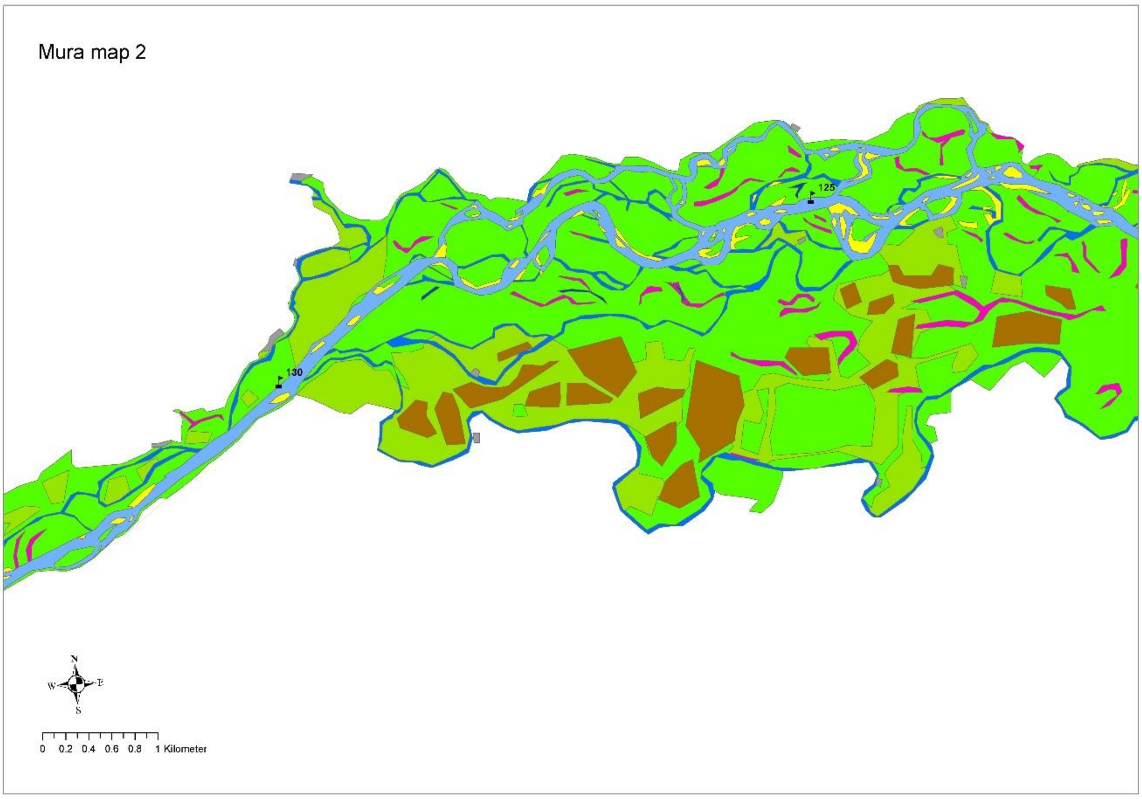

Danube map 9
1315
1310
1305
1300
1295
N
W
E
S
0
1
2
3
4 Kilometer

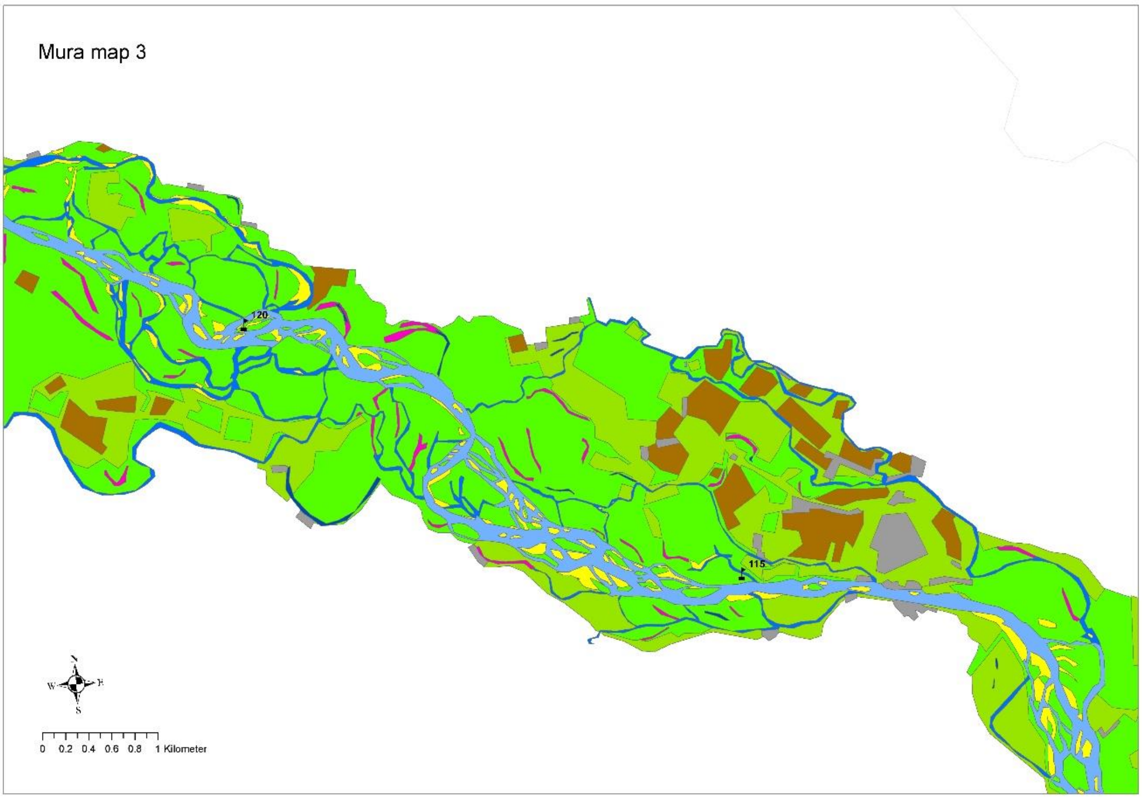
## B. Historical mapping

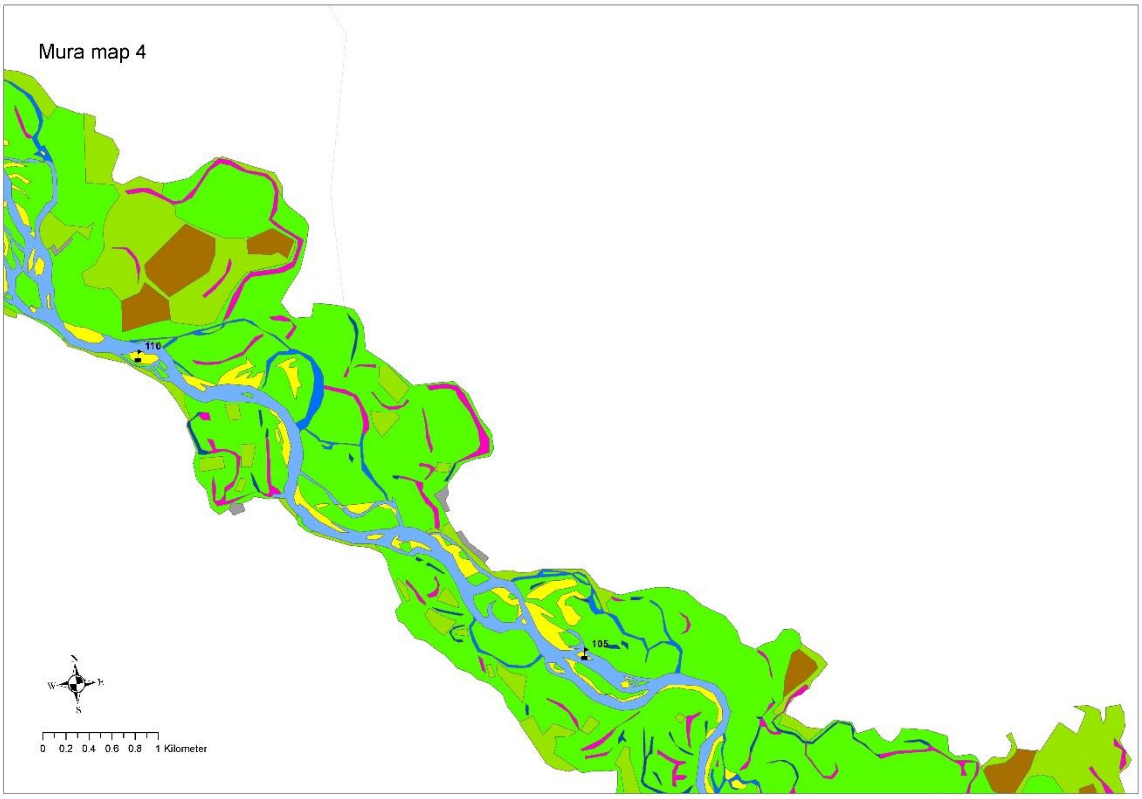
Map legend for the historical mapping:

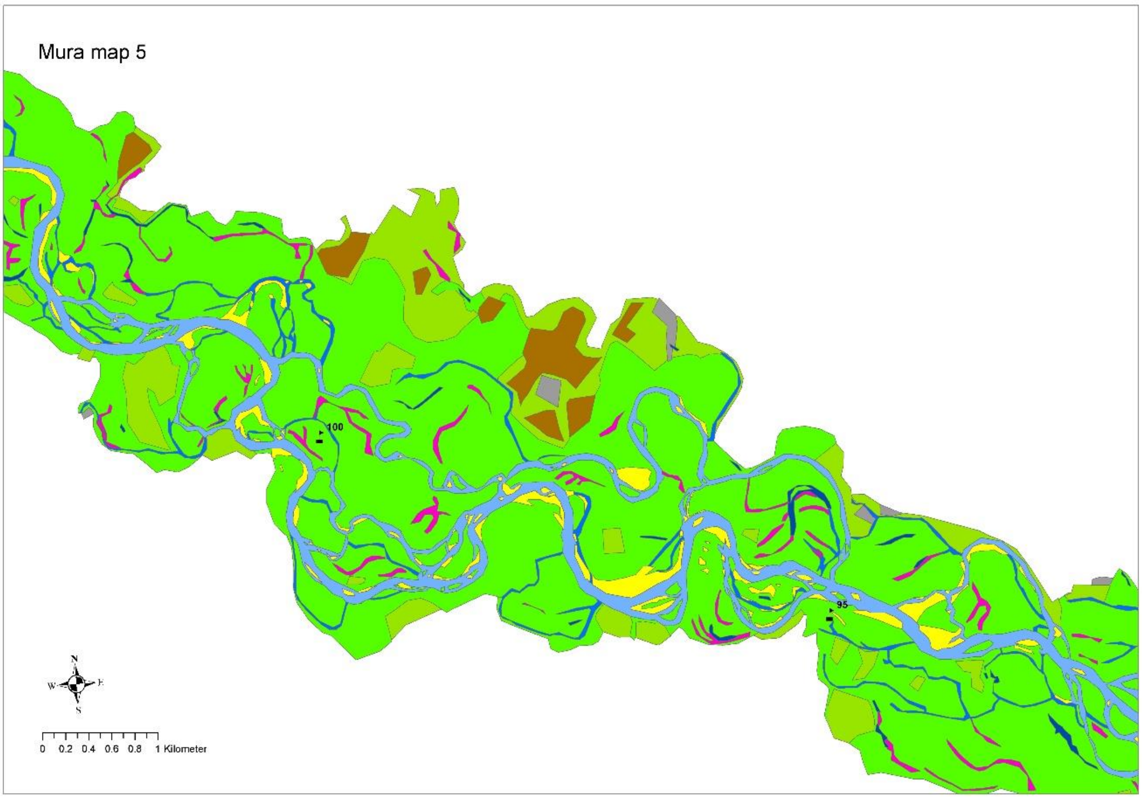
- 10 Main channel
- 11 Side channels
- 12 Oxbows
- 13 Sand and gravel bars
- 14 Riparian forest
- 15 Reed, floodplain swamps
- 16 Grassland, mainly pasture
- 17 Agriculture and arable land
- 18 Settlements

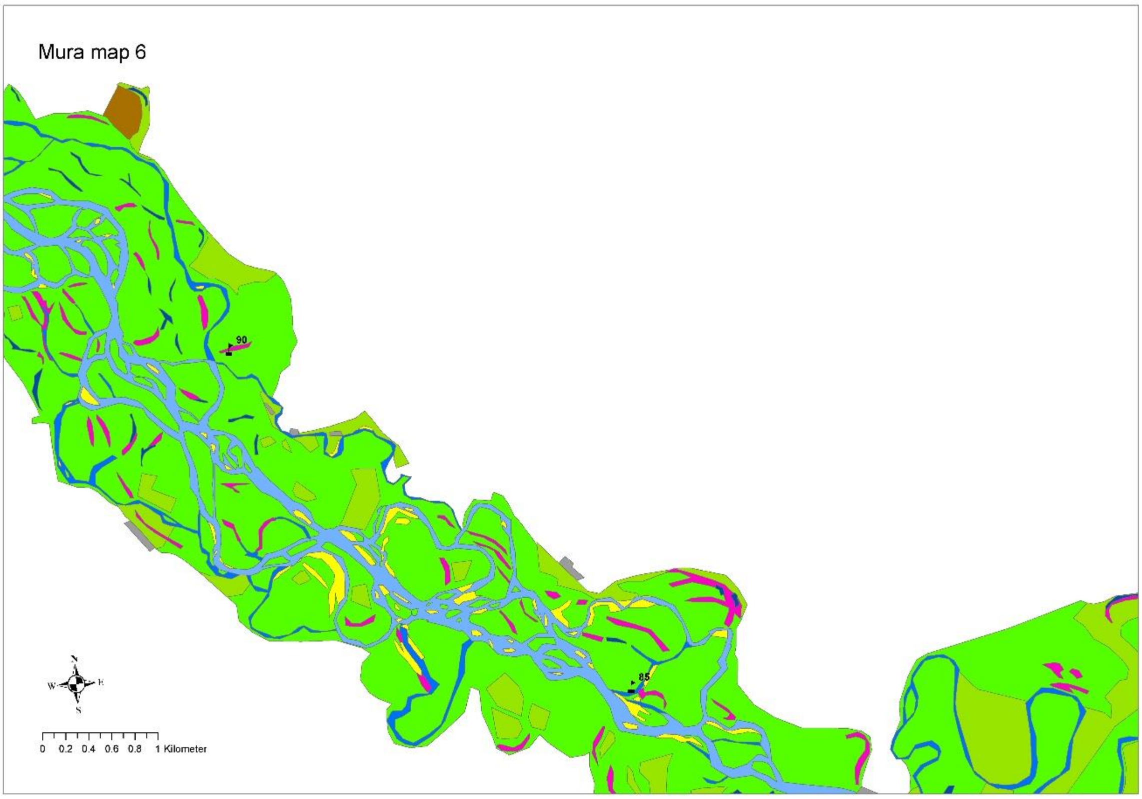

Mura map 1
140
135
N
W
E
S
0 0.2 0.4 0.6 0.8 1 Kilometer

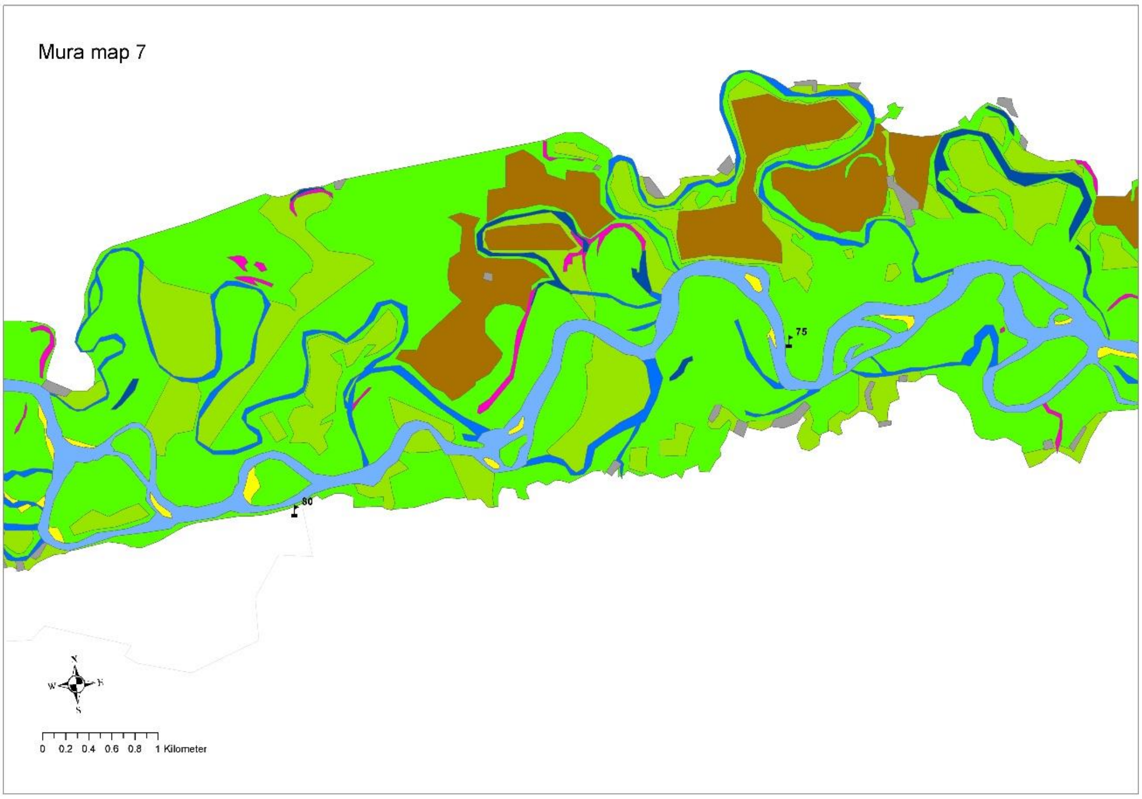

Mura map 2
130
125
N
W
E
S
0 0.2 0.4 0.6 0.8 1 Kilometer

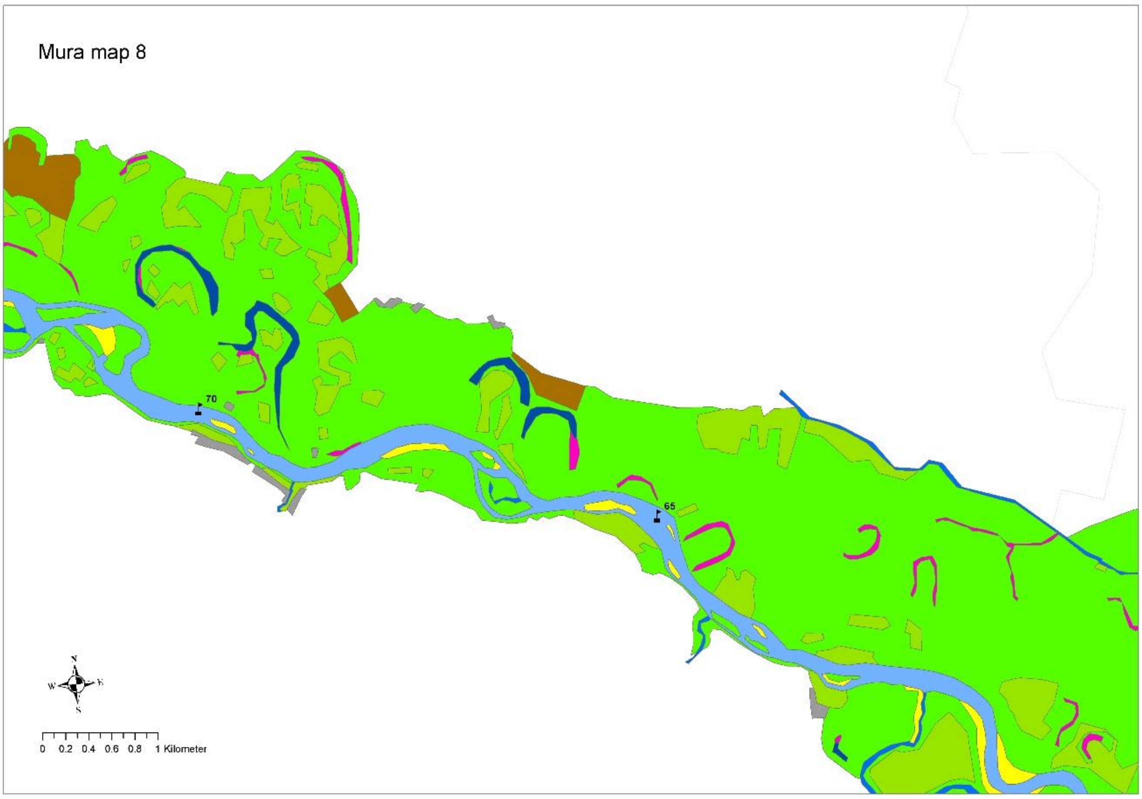

Mura map 3
120
115
N
W
E
S
0 0.2 0.4 0.6 0.8 1 Kilometer

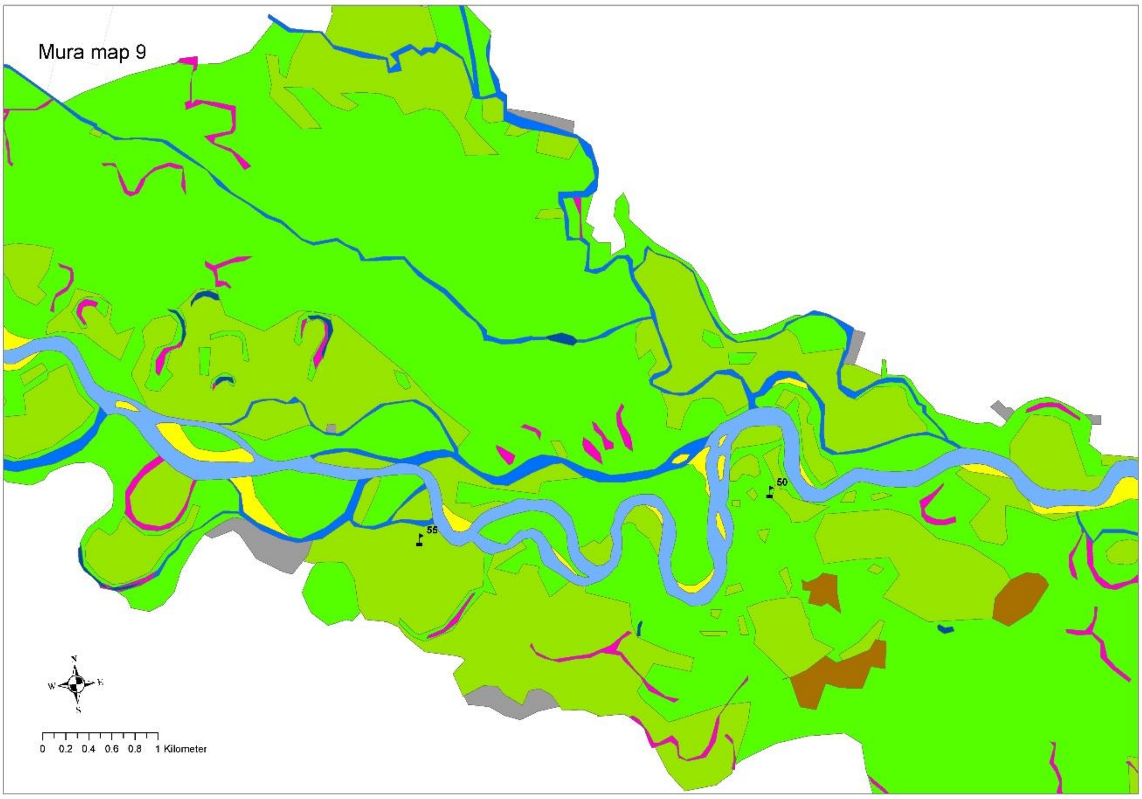

Mura map 4
110
105
N
W
E
S
0 0.2 0.4 0.6 0.8 1 Kilometer

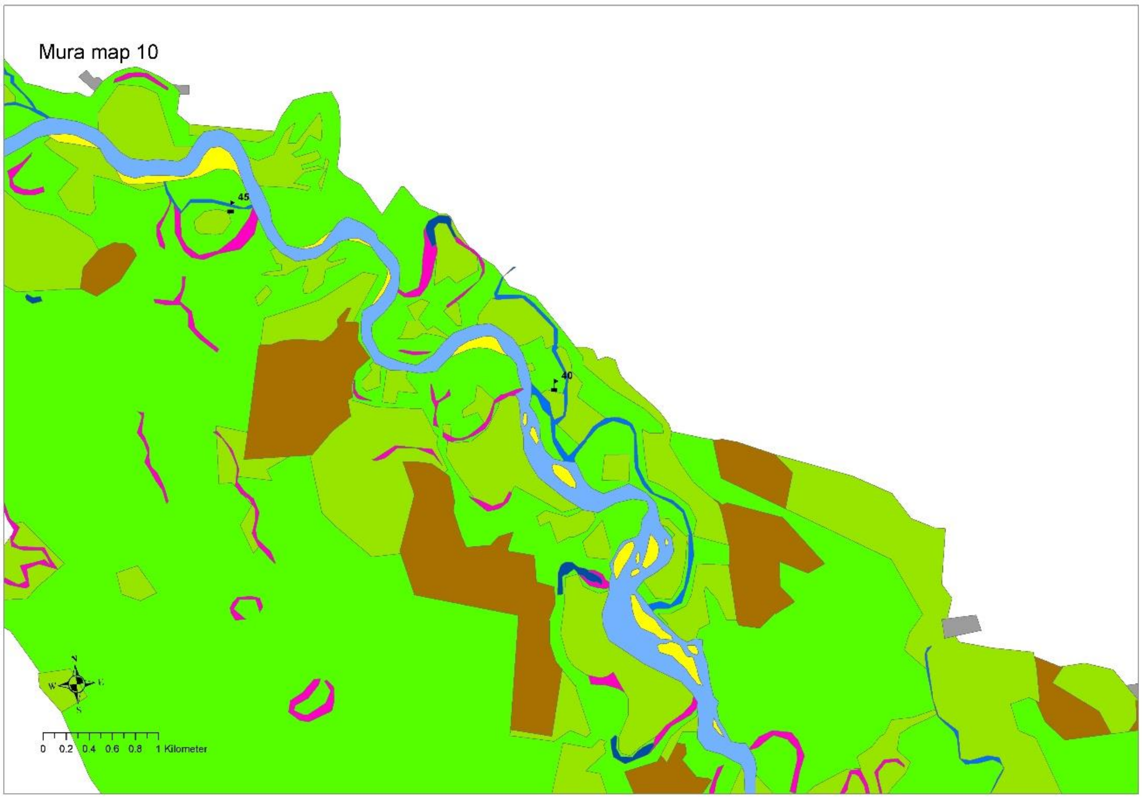

Mura map 5
100
95
N
W
E
S
0 0.2 0.4 0.6 0.8 1 Kilometer

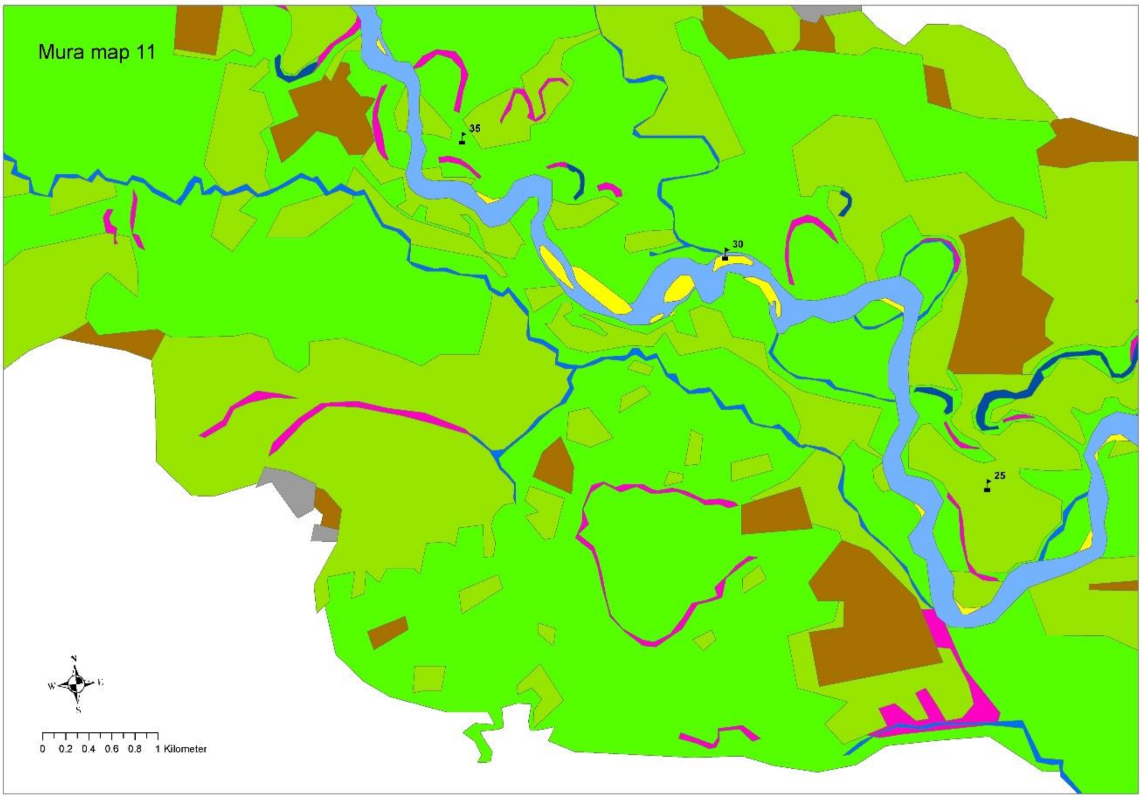

Mura map 6
90
85
N
W
E
S
0 0.2 0.4 0.6 0.8 1 Kilometer

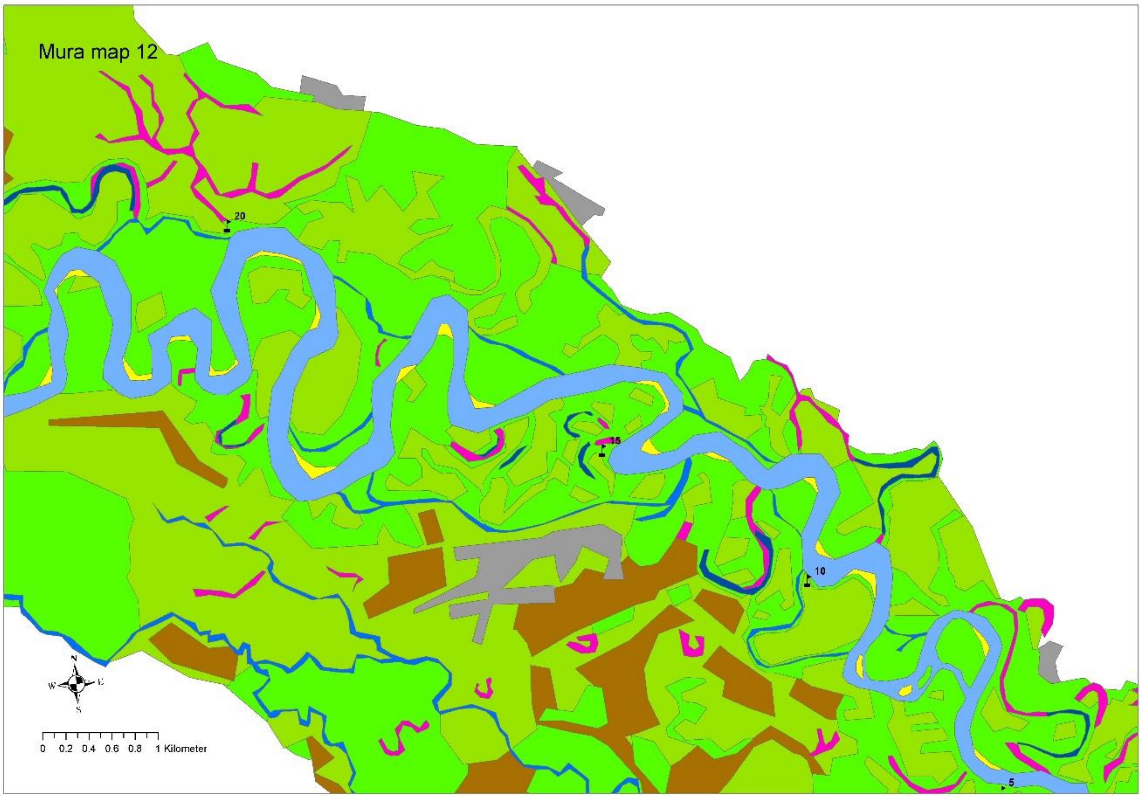

Mura map 7
80
75
0 0.2 0.4 0.6 0.8 1 Kilometer

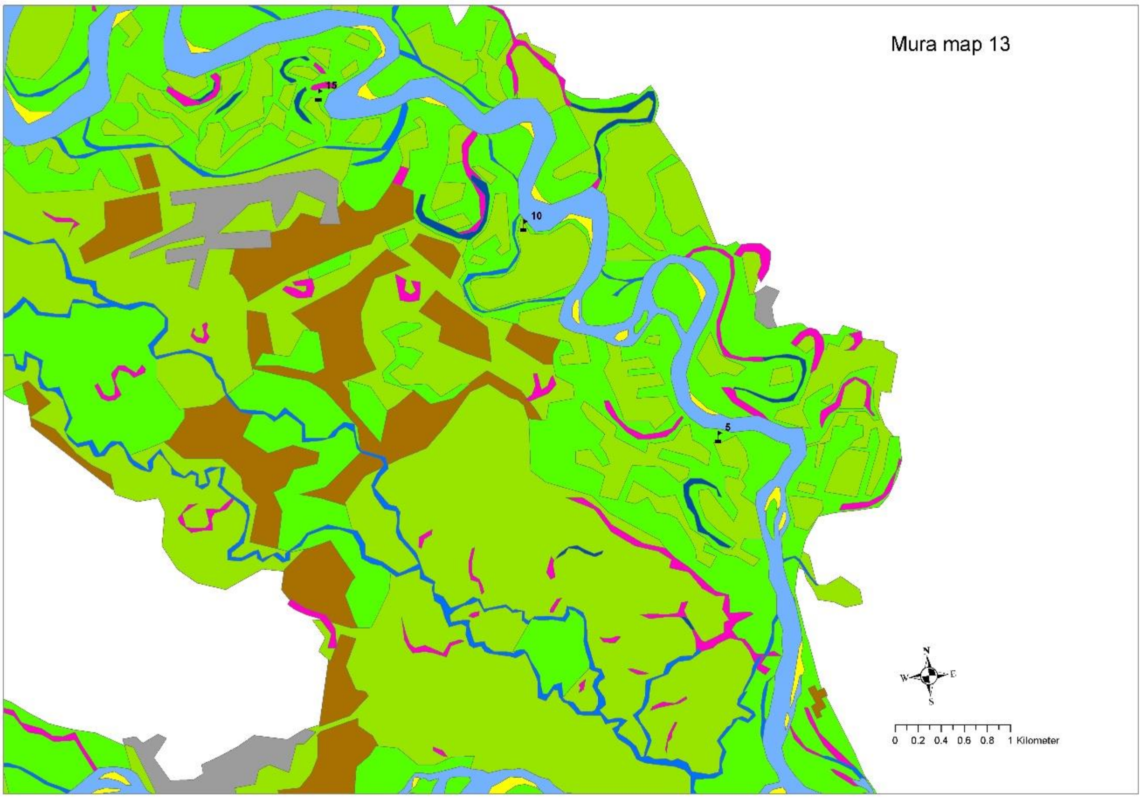

Mura map 8
70
65
0 0.2 0.4 0.6 0.8 1 Kilometer

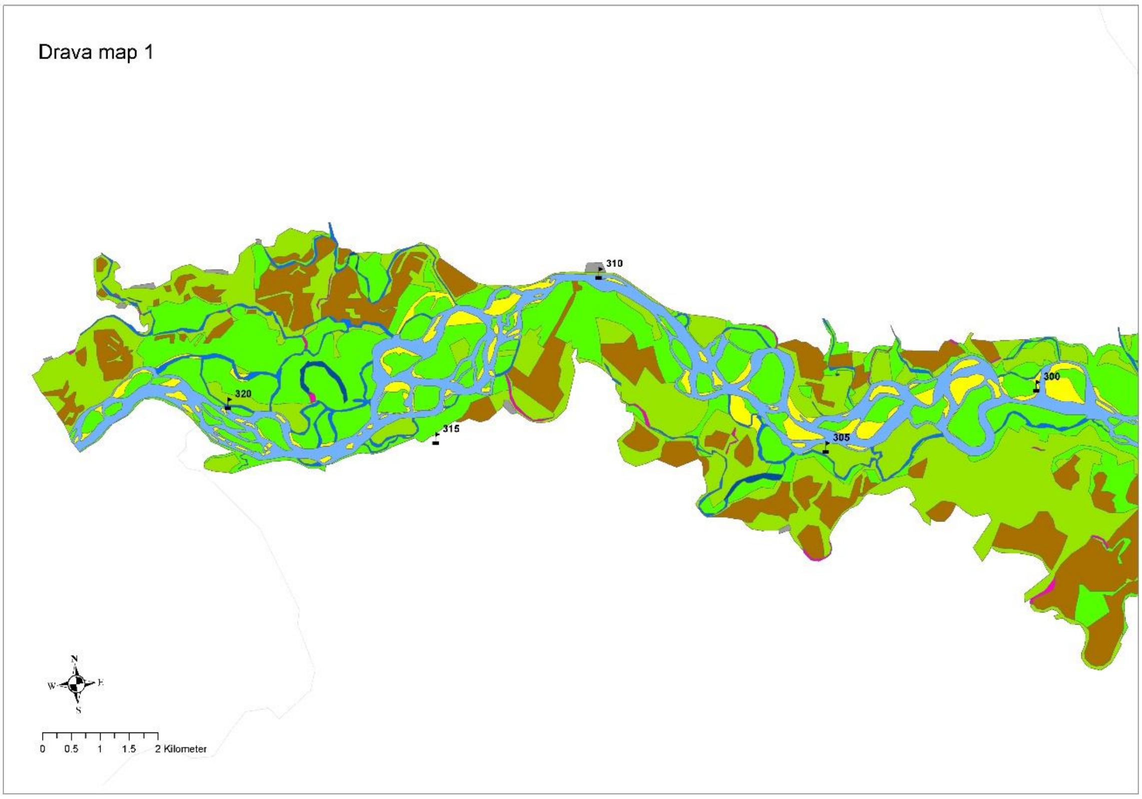

Mura map 9
55
50
0 0.2 0.4 0.6 0.8 1 Kilometer

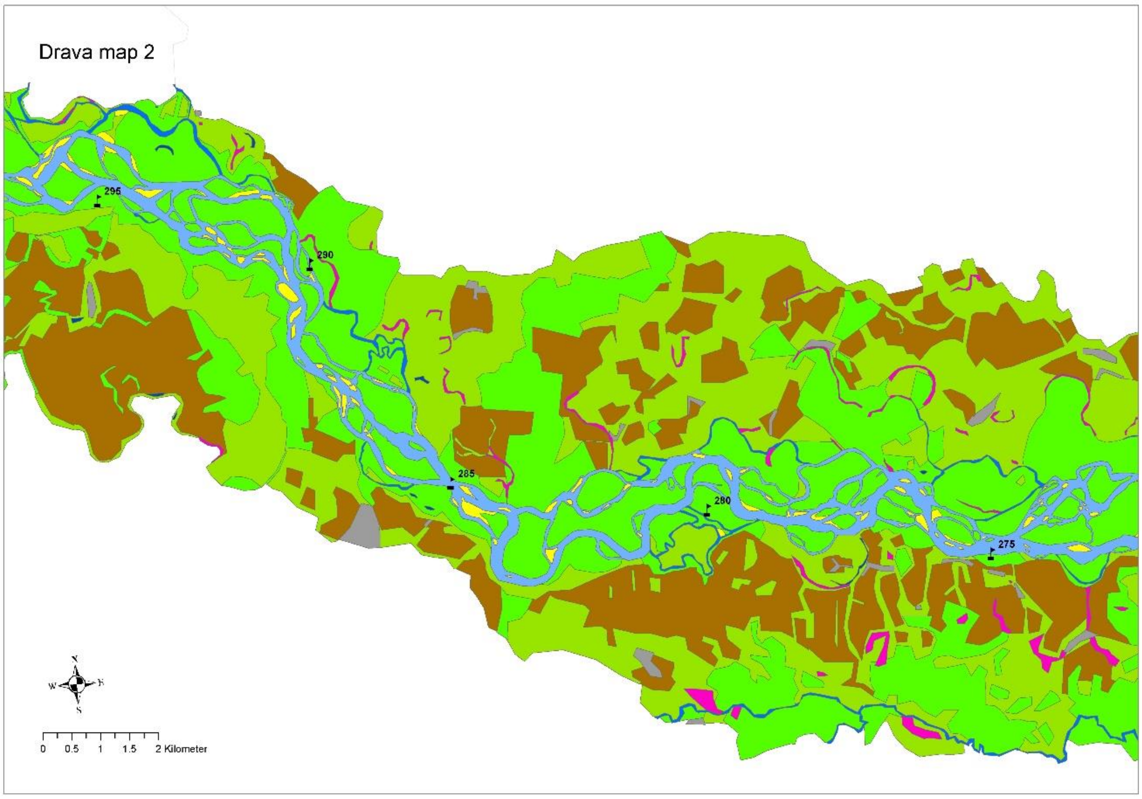

Mura map 10
45
40
0 0.2 0.4 0.6 0.8 1 Kilometer

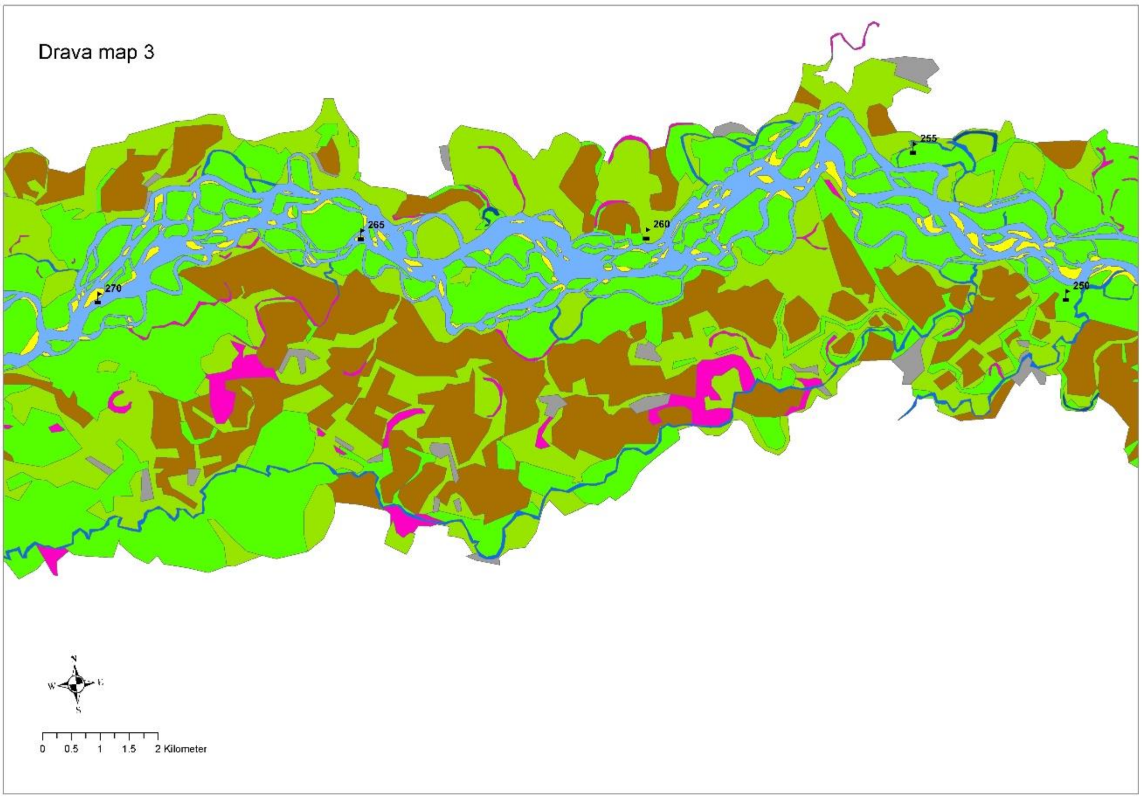

Mura map 11
35
30
25
0 0.2 0.4 0.6 0.8 1 Kilometer

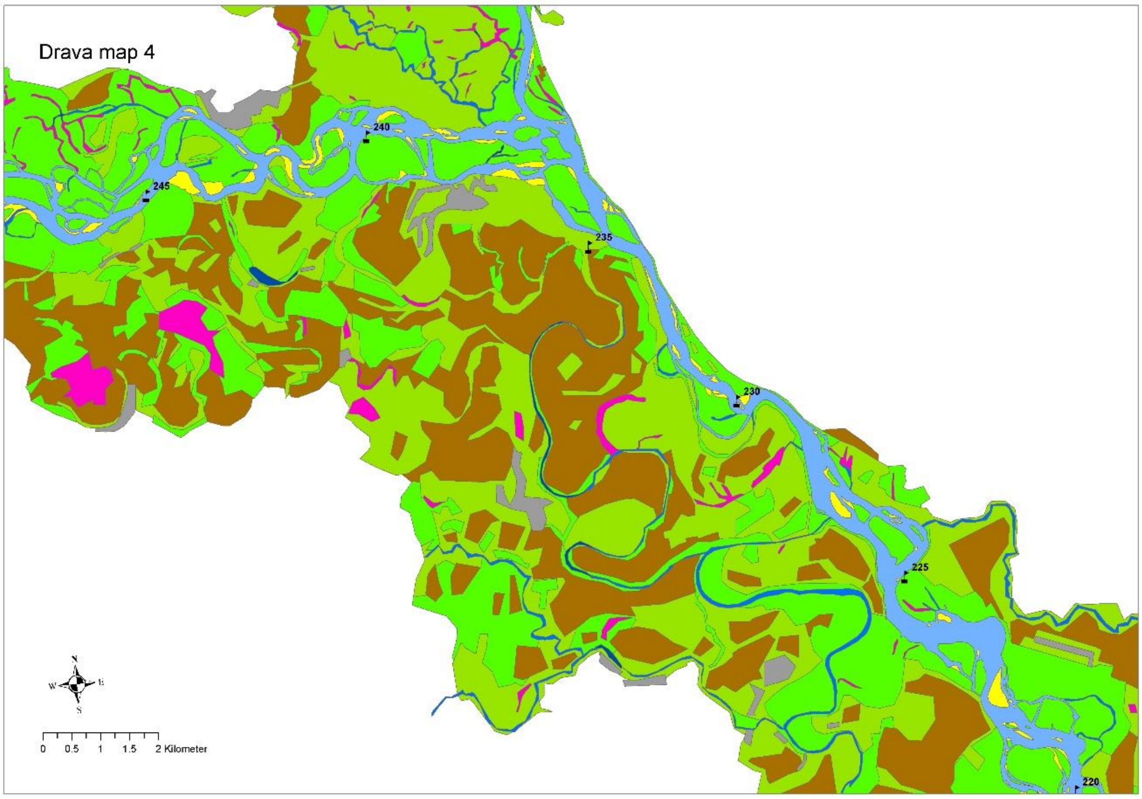

Mura map 12
20
15
10
5
0 0.2 0.4 0.6 0.8 1 Kilometer

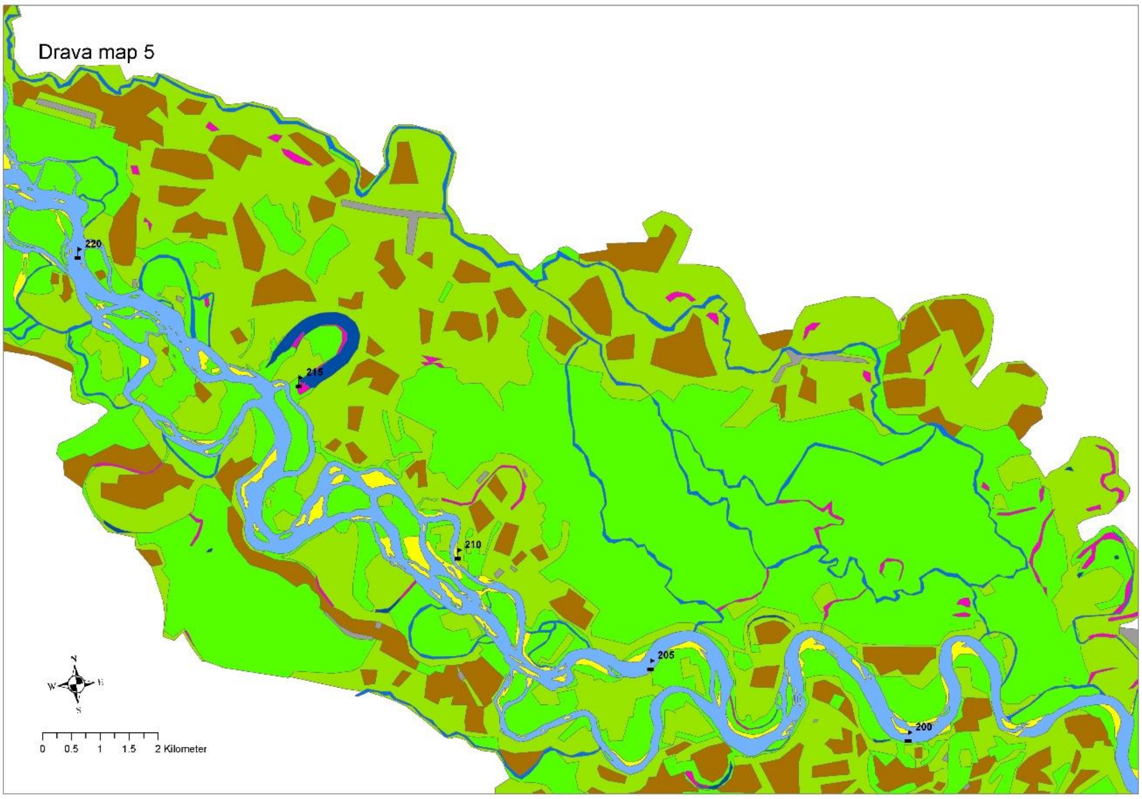

Mura map 13
15
10
5
N
W
E
S
0 0.2 0.4 0.6 0.8 1 Kilometer

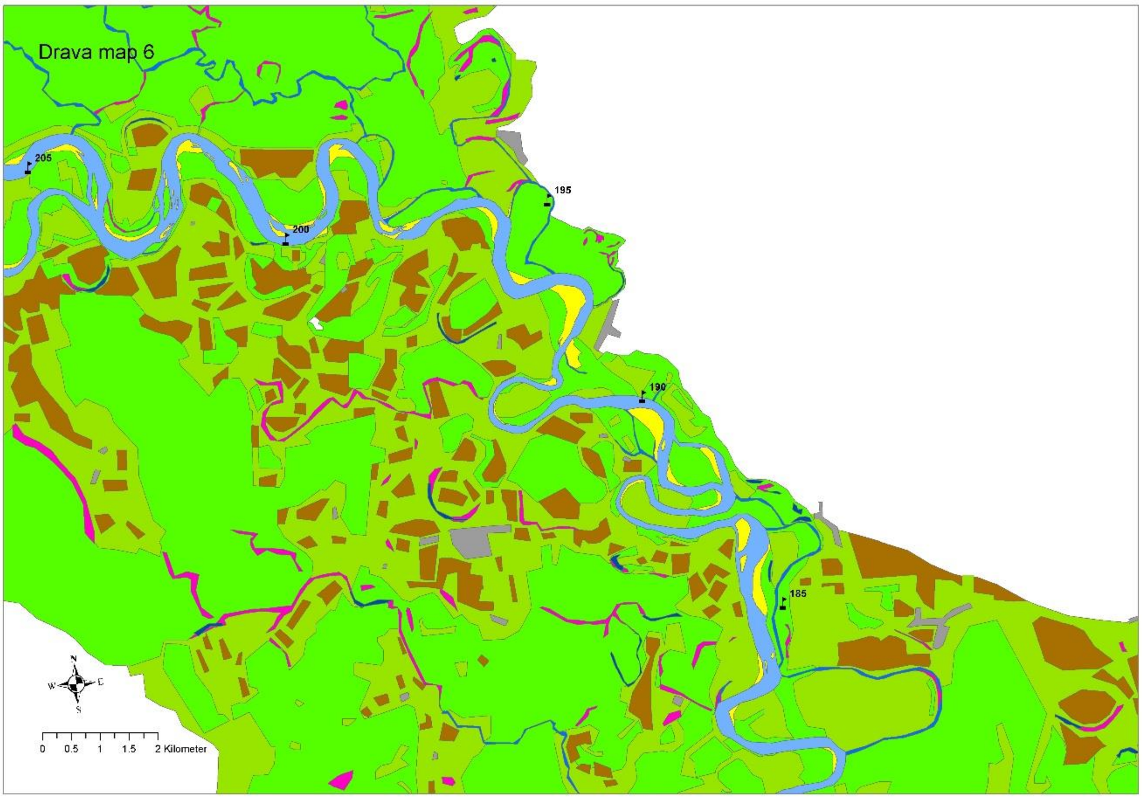

Drava map 1
310
320
315
300
305
0 0.5 1 1.5 2 Kilometer

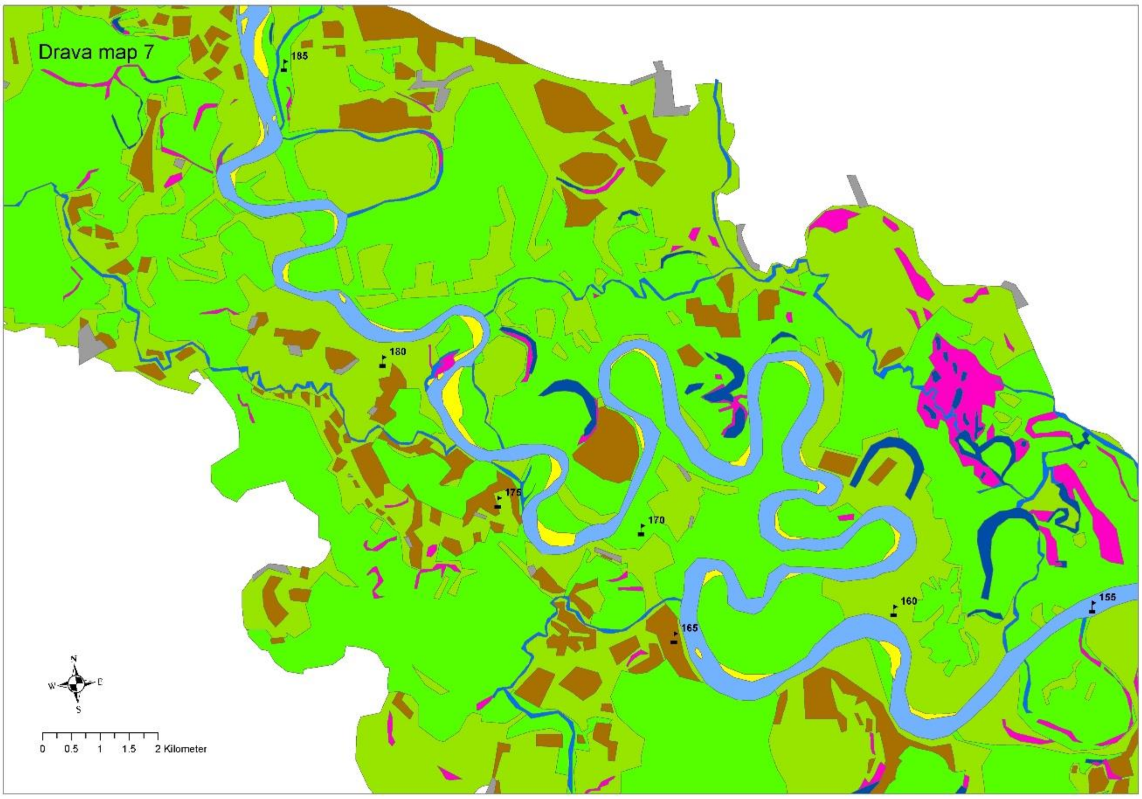

Drava map 2
295
290
285
280
275
0 0.5 1 1.5 2 Kilometer

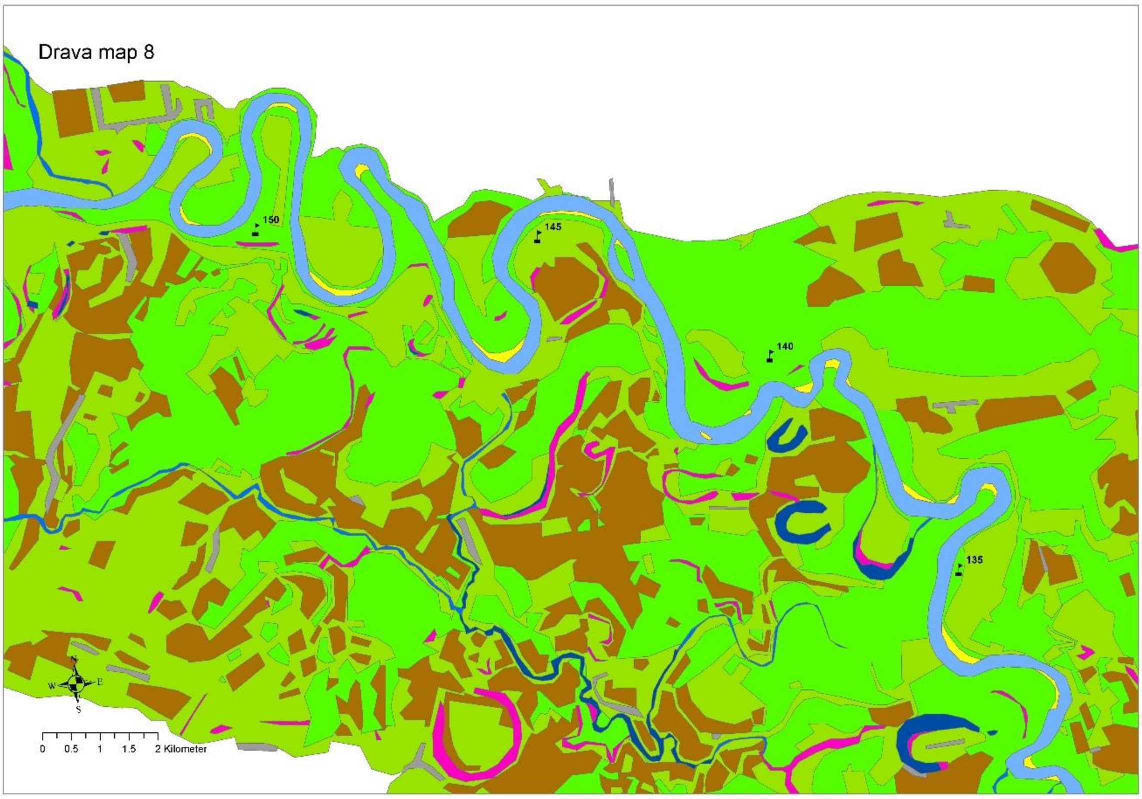

Drava map 3
270
265
260
255
250
0 0.5 1 1.5 2 Kilometer

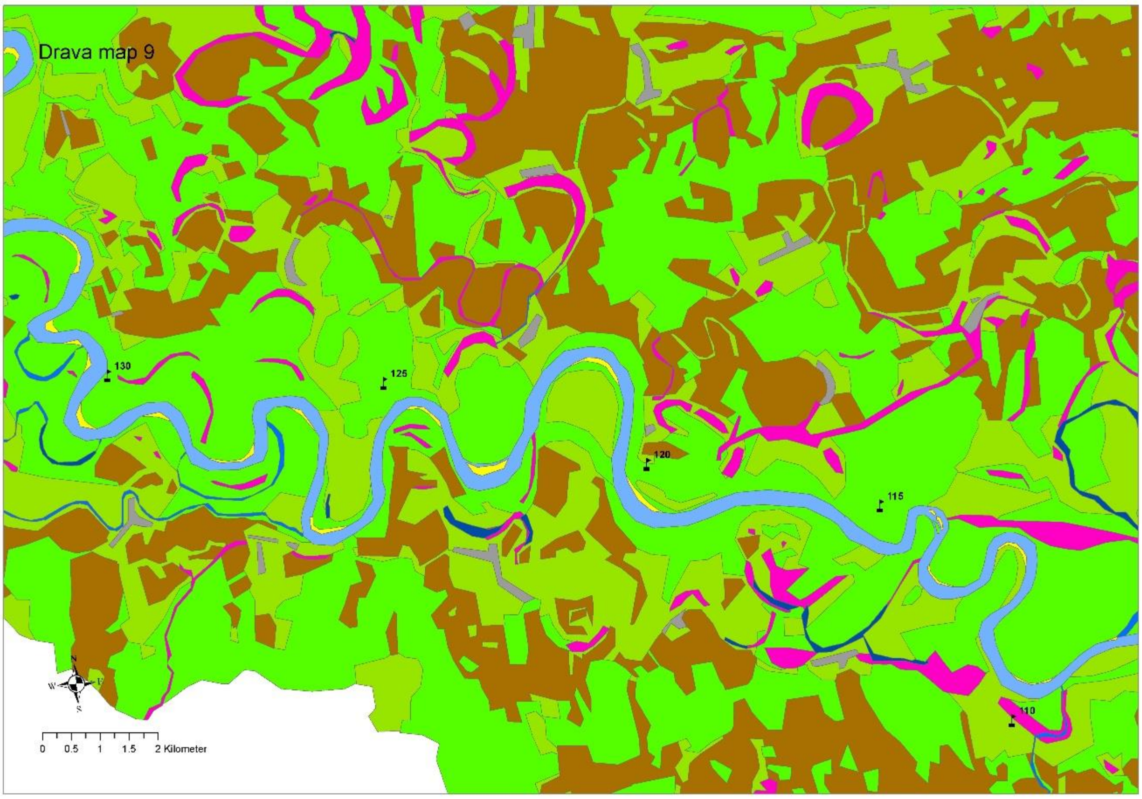

Drava map 4
245
240
235
230
225
220
0 0.5 1 1.5 2 Kilometer

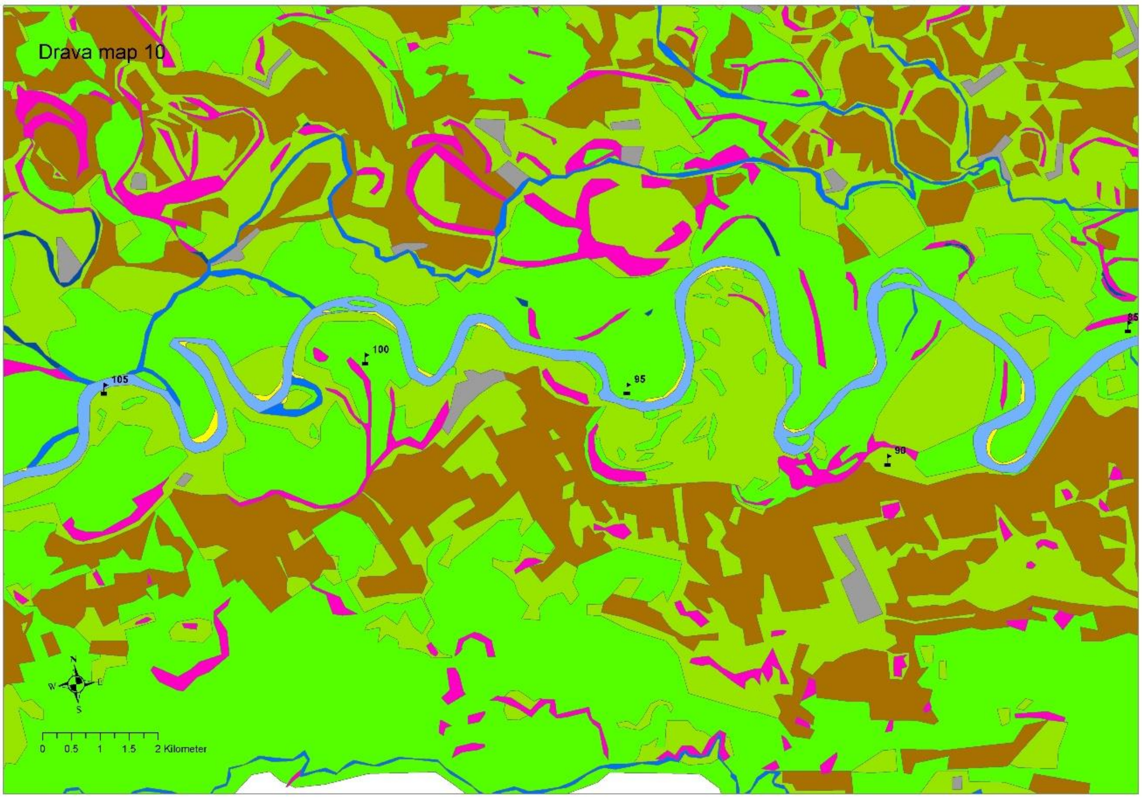

Drava map 5
220
215
210
205
200
0 0.5 1 1.5 2 Kilometer

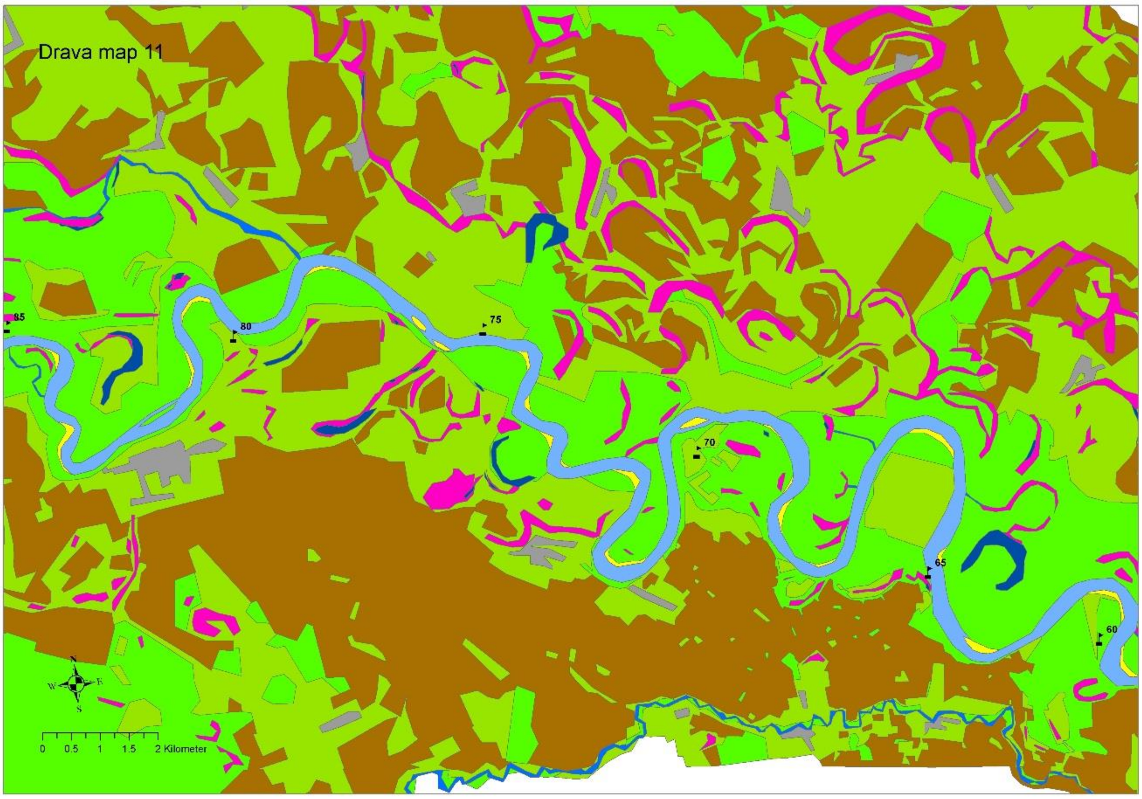

Drava map 6
205
200
195
190
185
0 0.5 1 1.5 2 Kilometer

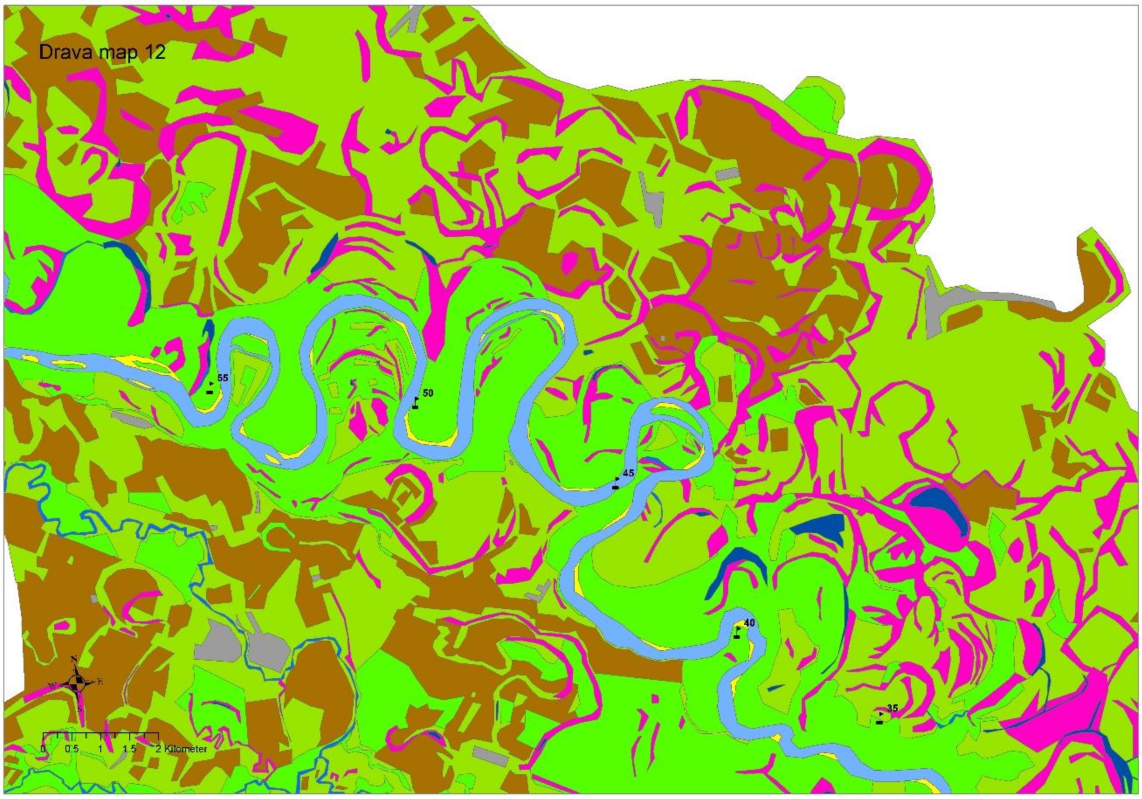

Drava map 7
185
180
175
170
165
160
155
N
W
E
S
0
0.5
1
1.5
2 Kilometer

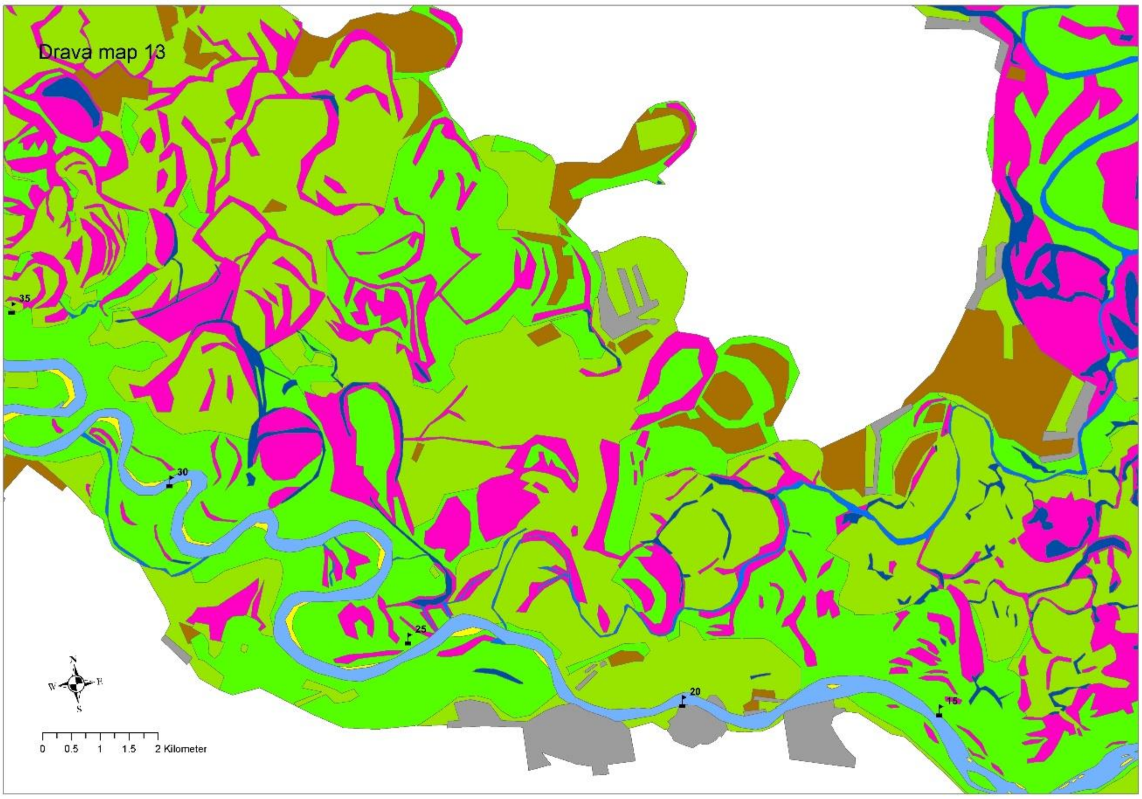

Drava map 8
150
145
140
135
N
W
E
S
0
0.5
1
1.5
2 Kilometer

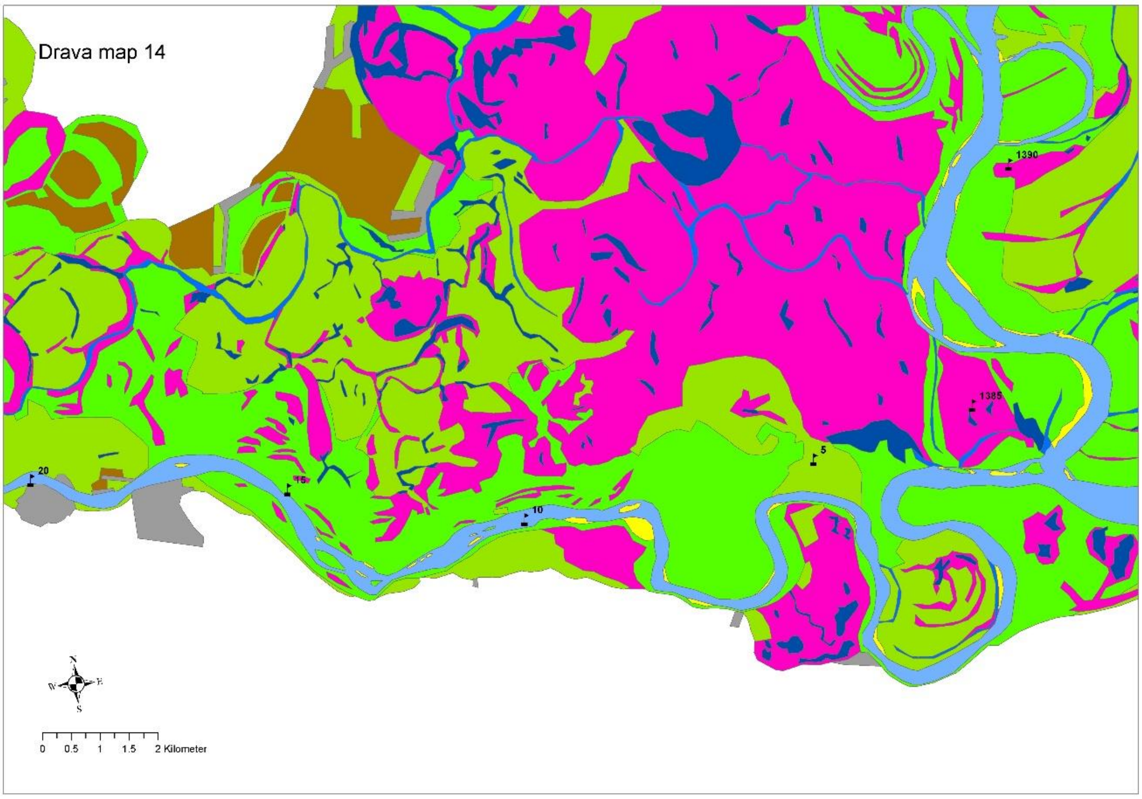

Drava map 9
130
125
120
115
110
0 0.5 1 1.5 2 Kilometer

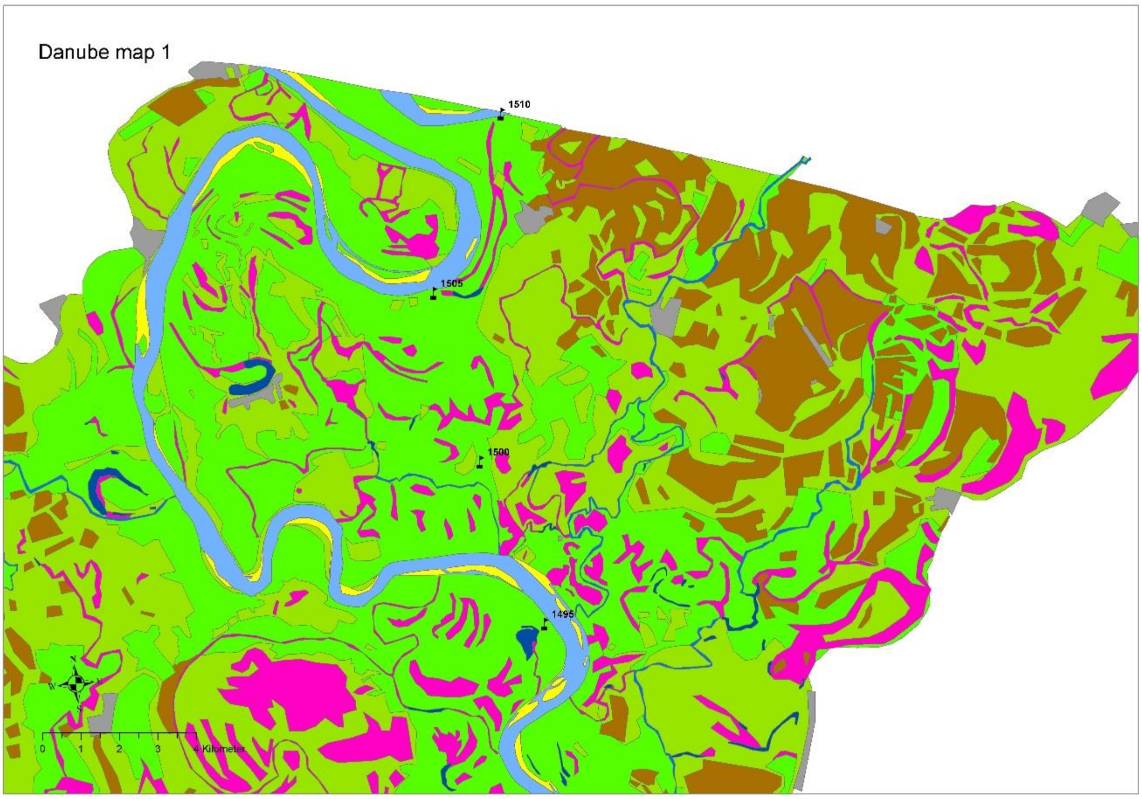

Drava map 10
105
100
95
90
0 0.5 1 1.5 2 Kilometer

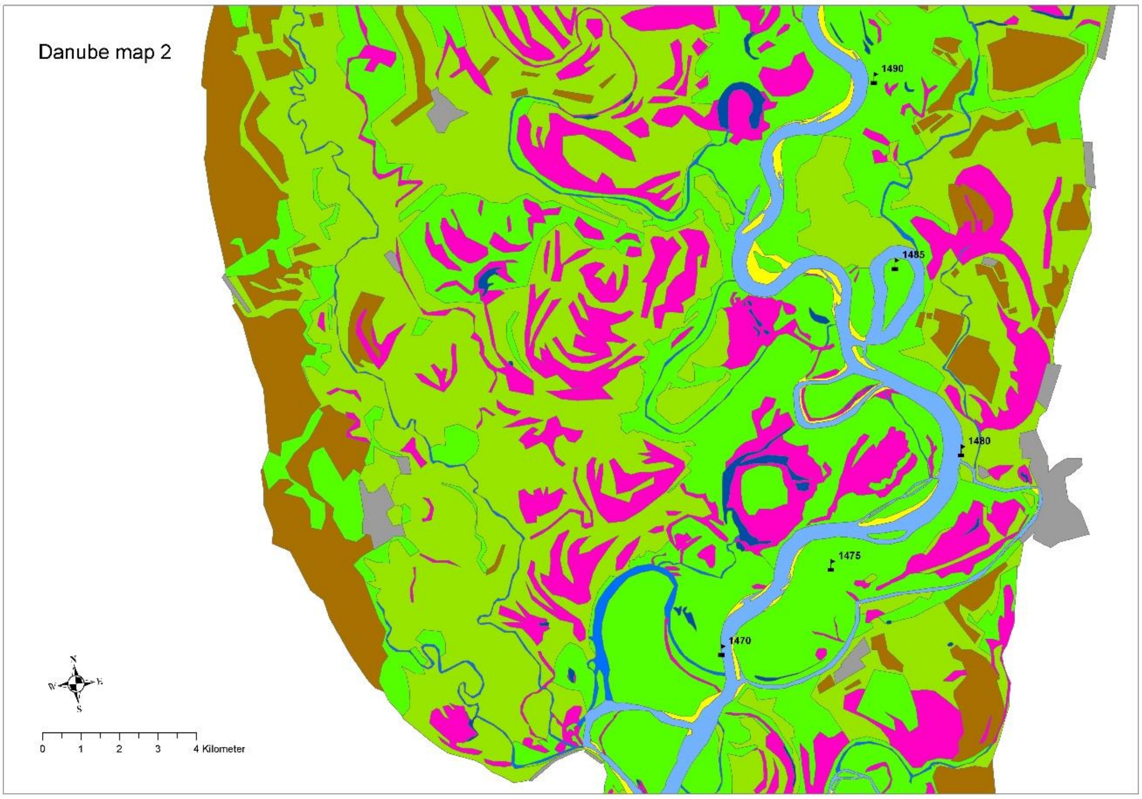

Drava map 11
85
80
75
70
65
60
0 0.5 1 1.5 2 Kilometer

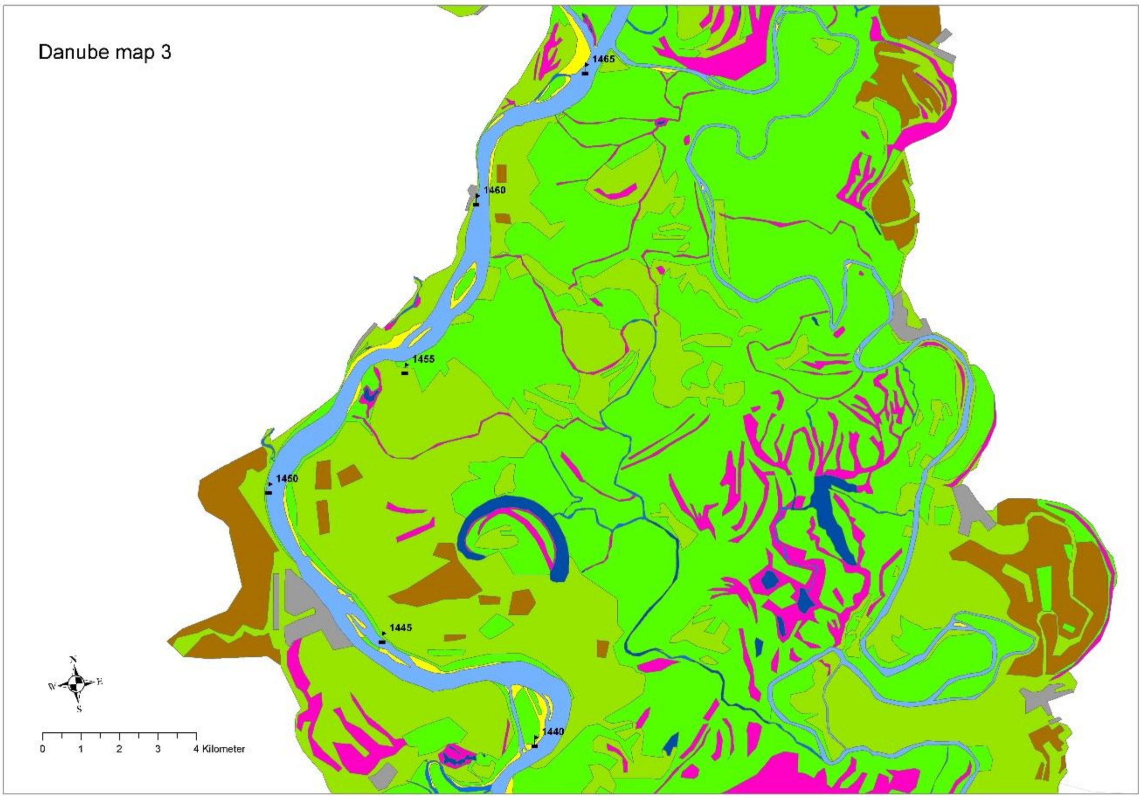

Drava map 12
55
50
45
40
35
0 0.5 1 1.5 2 Kilometer

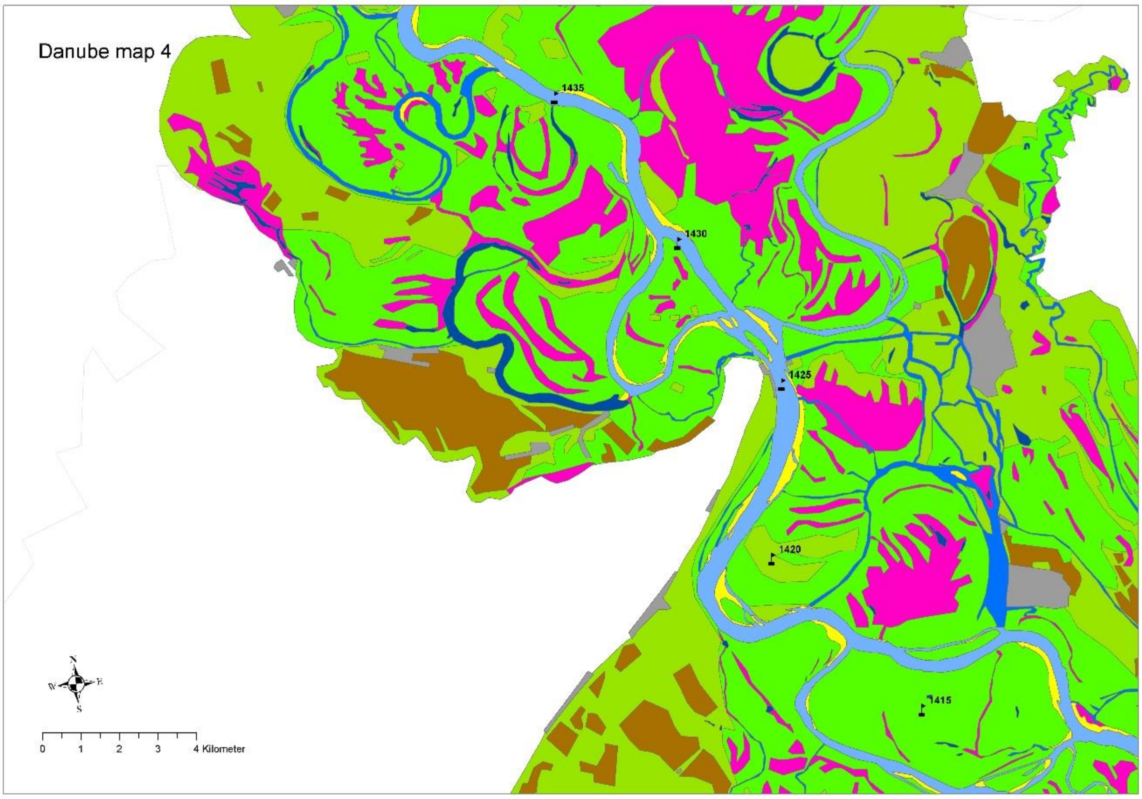

Drava map 13
35
30
25
20
15
0 0.5 1 1.5 2 Kilometer

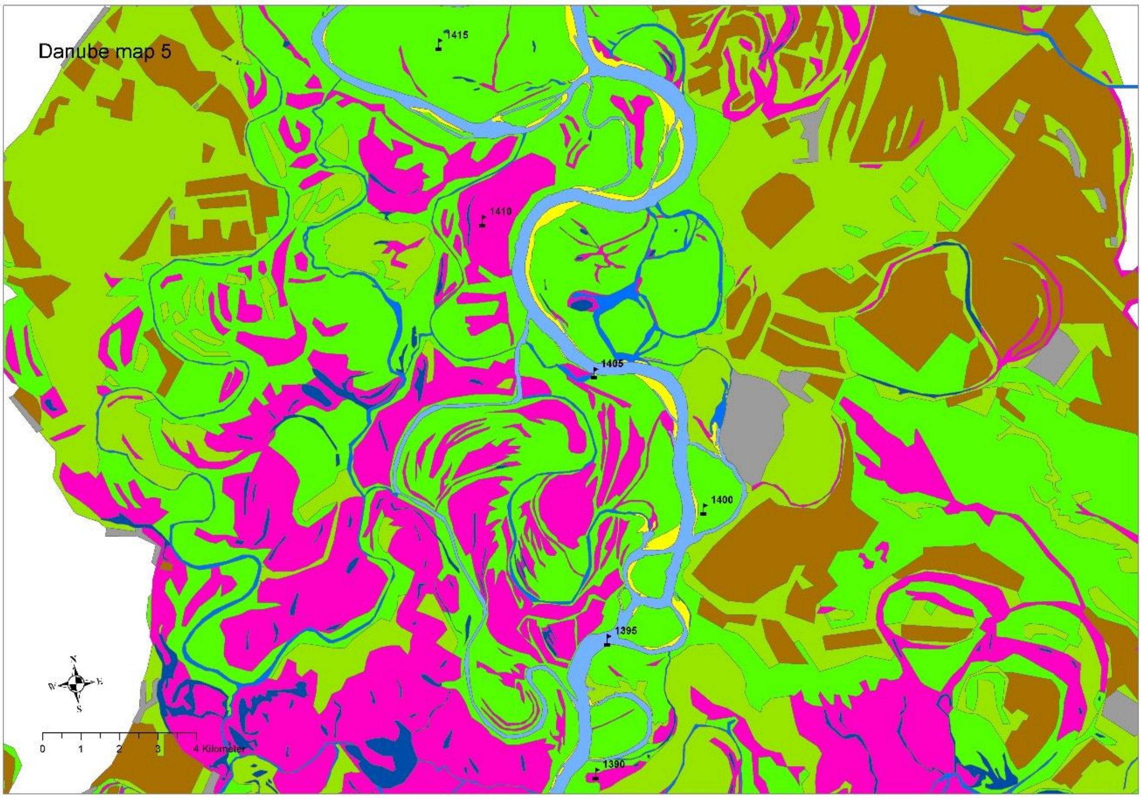

Drava map 14
1390
1385
20
15
10
5
0 0.5 1 1.5 2 Kilometer

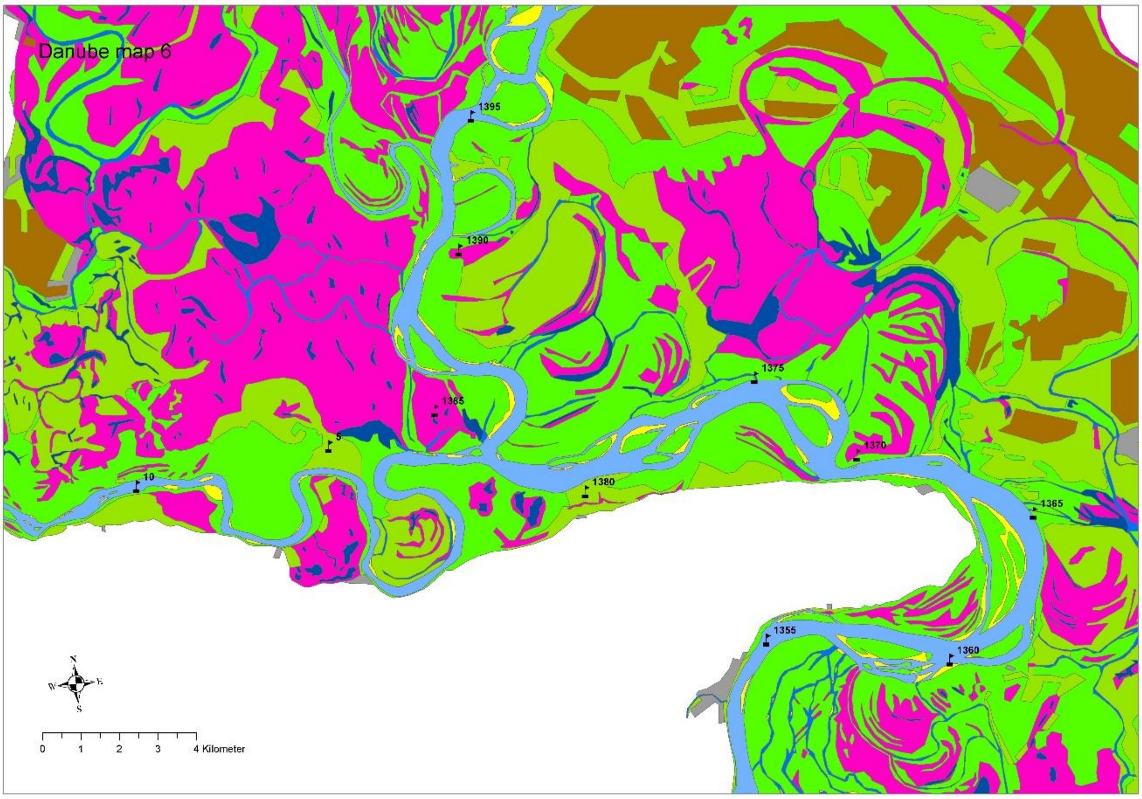

Danube map 1
1510
1505
1500
1495
0 1 2 3 4 Kilometer

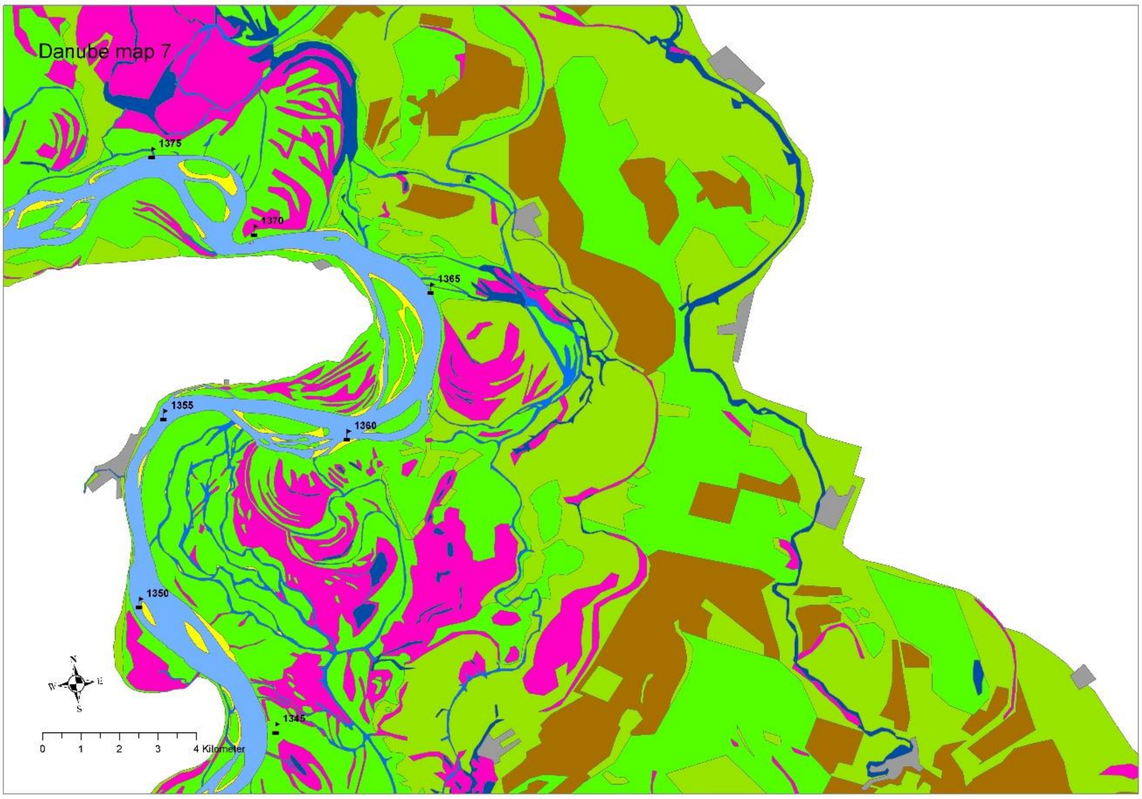

Danube map 2
1490
1485
1480
1475
1470
0 1 2 3 4 Kilometer

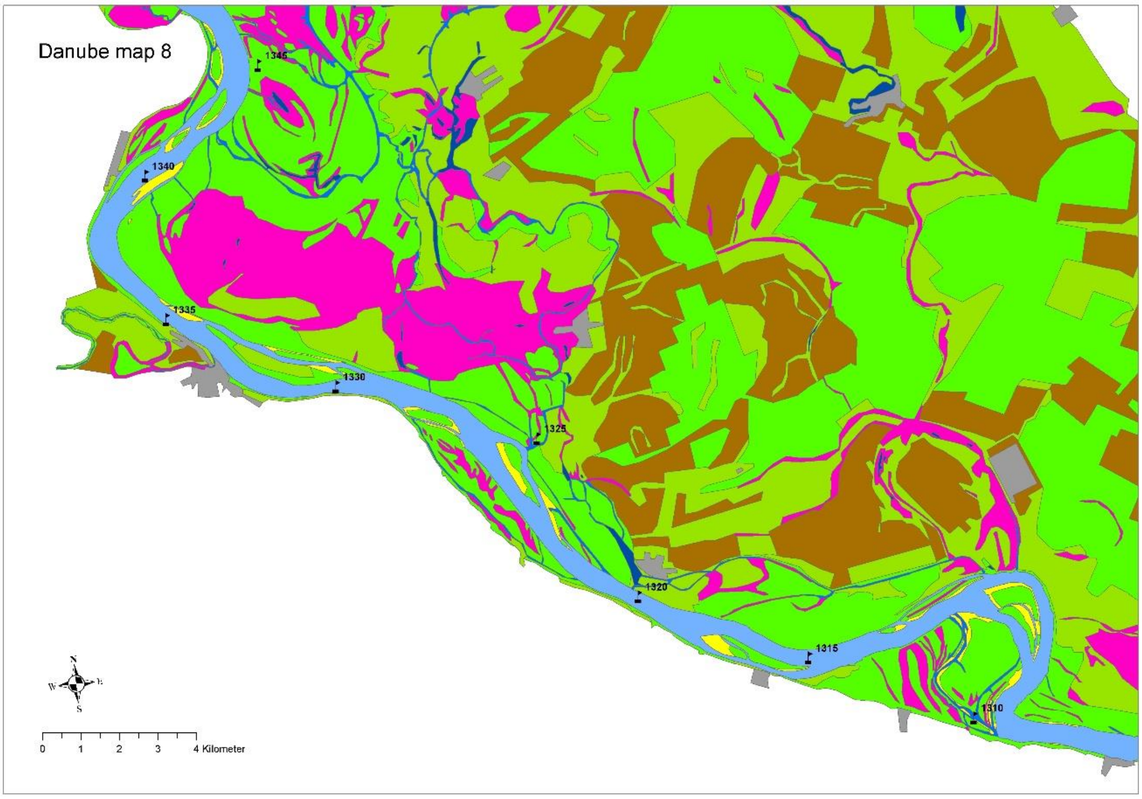

Danube map 3
1465
1460
1455
1450
1445
1440
0 1 2 3 4 Kilometer

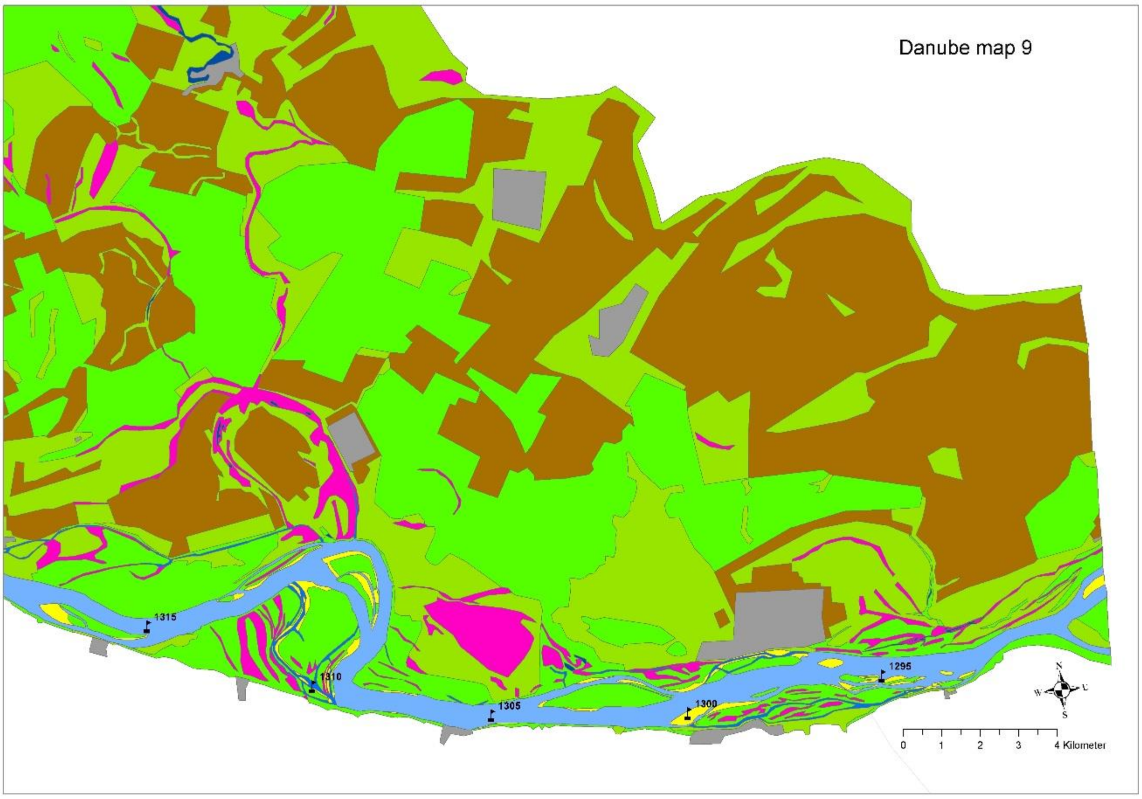

Danube map 4
1435
1430
1425
1420
1415
0 1 2 3 4 Kilometer


Danube map 5
1415
1410
1405
1400
1395
1390
0 1 2 3 4 Kilometer


Danube map 6
1395
1390
1385
1380
1375
1370
1365
1360
1355
5
10
0 1 2 3 4 Kilometer


Danube map 7
1375
1370
1365
1355
1360
1350
1345
N
W
E
S
0
1
2
3
4 Kilometer


Danube map 8
1345
1340
1335
1330
1325
1320
1315
1310
N
W
E
S
0
1
2
3
4 Kilometer


Danube map 9
1315
1310
1305
1300
1295
0
1
2
3
4 Kilometer