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How Can We Identify Active, Former, and Potential Floodplains? Methods and Lessons Learned from the Danube River

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Abstract: Floodplains are a fundamental source of multiple functions and services. Despite their various benefits, a dramatic reduction in floodplain areas has occurred in most large river systems over the last few centuries, and is still ongoing. Human modifications (such as river regulation, dam construction, and land use changes) due to economic growth, increasing population size, etc., were and still are drivers of major floodplain losses. Therefore, studies offering solutions for floodplain preservation and restoration are of great importance for sustainable floodplain management. This paper presents methods to identify active, former, and potential floodplains, and their application to the Danube River. We used hydraulic data, historical sources, and recent geospatial data to delineate the three floodplain types. Fifty hydraulically active floodplains larger than 500 ha were identified. According to our results, the extent of Danube floodplains has been reduced by around 79%. With the support of different representatives from the Danube countries, we identified 24 potential floodplains. However, the share of active and potential floodplains in relation to former floodplains ranges between 5% and 49%, demonstrating the huge potential for additional restoration sites. This analysis contributes to an understanding of the current and the past floodplain situation, increases awareness of the dramatic floodplain loss along the Danube, and serves as a basis for future floodplain management.

Keywords: floodplain management; historical floodplains; preservation; restoration potential; flood risk management; hydrodynamic modeling

1. Introduction

1.1. Research Context

Floodplains are a fundamental source of multiple functions and services [1–4]. During overbank flooding, water is temporally stored in the floodplain, leading to the deceleration of the flood wave and reduction in the flood peak. Hence, floodplains contribute to mitigate flood risk in riparian areas [5–7], a characteristic that will be even more important in the future, as climate change is expected to increase flood and drought magnitude and frequency of occurrence. During droughts, floodplains slowly release stored water, reducing the impact of dry seasons [8]. Moreover, floodplains provide important ecological and recreational services [2]. They are very prolific habitats, even more than their neighboring river and uplands, due to their exchange with lateral and upstream sources (e.g., nutrient-rich sediments) [9]. This leads to high biodiversity (floodplains are the habitats of many Europewide endangered species), productivity (agriculture, fishery, pasture land), regulation processes (climate, nutrients, flood events), recreational and aesthetic values, and corresponding economic importance [2,9–13]. The sum of ecosystem service provisioning is greater in natural systems [1,14]. Therefore, scientists, governments, and the public are currently increasing their interest in floodplain habitats and their restoration [10]. This interest corresponds with the urgent need to maintain and restore floodplains and their vegetation, hydrologic dynamics, and sediment transport capabilities [9]. Human modifications of river morphologies, and our activities on floodplains, have led to a dramatic reduction in the extent of formerly flooded areas [9,15,16]. The reasons for this are manifold: floodplains are extremely attractive for agricultural cultivation and urban development due to their soil fertility, low topographic slope, and water availability [6]. The technical achievements of the industrial revolution allowed large-scale engineering work, such as river training and drainage systems, leading to an intensified usage of the flood-prone areas for agriculture and urban development [17]. In fact, Europe and North America have faced a loss of up to 90% of former floodplains [9,16]. Regarding the Danube area, previous studies report a loss of around 70% along the Danube River, and up to 80% in the Danube Catchment [18,19]. The Middle and Lower Danube sections have lost 75% and 72% of their morphological floodplains, respectively, excluding the Danube Delta [20].

Not only have floodplains been lost in the past, but their preservation is still threatened by various factors. Only very few large rivers are free-flowing [21]. Social changes (economic growth, increasing population, urbanization) connected to other anthropogenic drivers (climate change, land use changes, overharvesting, pollution) [9,22,23] are pressuring freshwater resources, and, in turn, are modifying the hydrological cycle, which is the most predominant factor affecting floodplains [9]. Lately, the presence of invasive species, the increased cultivation of crops for energy production, and the renovation of existing dikes, have also proven to be potential floodplain threats [24].

Floodplain preservation and restoration are key components in environmental and water policies in Europe [25–27], since a series of major floods revealed the vulnerability and limits of structural flood protection measures [7,28–30]. Floodplain restoration measures are considered a valid solution to reviving lost functions and services in terms of flood protection and ecology [11,14,31]. Accordingly, historic river courses and their floodplains should be taken into consideration for potential restoration. In the Danube River Basin, 520 km^2 of floodplain was partly or totally reconnected to the main channel between 2009 and 2015, followed by about 100 km^2 during 2015–2021. Until 2027, 234 km^2 of floodplain is planned to be partly or totally restored [32].

Despite these great achievements and ambitious plans, many obstacles still hinder floodplain restoration measures. On the floodplain, we find settlements, forestry, and/or agricultural land uses, and the river is used for navigation, hydropower, and/or as a drinking water supply [19]. For transboundary rivers such as the Danube, the diversified legal framework also plays an important role: small-scale, site-specific projects do exist, but restoration efforts should aim towards a larger scale [19,24].

1.2. Background

In general, floodplains are the areas alongside a river course that are flooded when the river discharge exceeds the capacity of the channel [33]. Riparian areas that are more or less regularly flooded under natural conditions (without any dikes or levees) are called morphological floodplains. If they are flooded at the time, they are called "recent floodplains" (or "current floodplains" or "levee foreshores"). The disconnected areas, which have been cut off from the river's flooding regime, are referred to as "old floodplains" ("historic floodplains", "levee backlands", or "former floodplains") [24].

According to Tockner and Stanford [9], a floodplain can be identified hydrologically as an area inundated by a 100-year return period, geomorphologically as an area covered by recent alluvial deposits, and ecologically as an area colonized by organisms adapted to flooding. Nanson and Croke [34] also observe, on one hand, an engineering interpretation of the term (called "hydraulic floodplain"), which focuses on the aspect of regular inundation, separate from the presence of alluvial sediment; on the other hand, "genetic floodplains" are referred to as "the largely horizontally-bedded alluvial landform adjacent to a channel, separated from the channel by banks, and built of sediment transported by the present flow-regime" [34]. Using the inundated areas of a 100-year return period to identify the "active" or "recent" floodplains is the most common approach in the literature. Several other studies [18,20,24] have used this approach. Our definitions of active, former, and potential floodplains are provided in Section 2.3, as the steps of the methodology are derived based on these definitions.

Several methods [18,20,35–37] can be found in the literature to identify former and morphological floodplains. Schwarz [18] delineated morphological floodplains along the Danube River using the most recent and accurate digital elevation model (DEM) at that time, focusing on the definition of postglacial terraces. This author also used high-resolution satellite data and physical riparian landscape features to define such terraces. They concluded that additional data sources will be available in the next few years that will help improve their raw delineation. In Germany, flood probability maps of less frequent (extreme) events were used together with digital terrain models to identify morphological floodplains [24]. Hauer et al. [35] used satellite data to delineate the morphological floodplain at the Vjosa River in Albania. Guerrero et al. [38] used a functional landscape approach to identify the spatial extent of potential locations for floodplain restoration. The study was applied along the Lahn River in Hesse, Germany, where hydrologic, topographic, and pedological information was combined to delineate potential restoration areas. This approach is useful for areas with limited data availability, but does not take the historical aspect of the floodplains into account. Moreover, the parameters used for the estimation are only valid for the study area, as shown by Perosa et al. [39].

On smaller scales, various methods have been used in the past few years to investigate former floodplains from disparate historical periods. Niller [40] explored the changes in the prehistoric riverine landscape close to Regensburg (Germany). By studying soils, indicators of the stability of a landscape, interrelationships can be found between anthropogenic influences on the landscape and soil type. Based on an analysis of colluvial deposits, flood loams, and soils, the author discovered anthropogenic interventions in the natural landscape in the prehistoric era. However, ultimately, only absolute dating makes it possible to establish reliable relationships for settlement archaeological features. To analyze the Danube River and its floodplains in Roman times, Arauner [41] used HQ_{1000} simulations, DTM, geological maps, archaeological reference points, historical maps, and groundwater simulations, and combined them with the performance data of reconstructed Roman military vessels with the conditions of an ancient river system, to obtain realistically quantifiable predictions for Roman inland navigation. This method is detailed, but its tradeoff is that it requires archaeological data, which are often not available in other river systems.

In the pursuit of understanding the status of landscapes in the past, Molnar et al. [42] and the Bavarian State Library [43] digitalized historical maps by Heinrich von Schmitt and Adrian von Riedl, respectively. However, the sole digitalization, i.e., georeferencing, of these maps is not sufficient for the delineation of former floodplains. Skublics et al. [44,45] created an historical DEM of a river section in Germany for a two-dimensional (2D) hydrodynamic model using the historical maps of Adrian von Riedl to determine the river course, and estimated the bed elevation from other historical sources (e.g., Kern [46]). With hydraulic modeling, they investigated the effect of river training on flood retention [44,45]. Schober et al. [47] calculated the impact of floodplain changes using the following Floodplain Evaluation Matrix (FEM) [5,48] parameters: flood peak reduction, flood wave translation, and water level change. They compared the current status with the historic status and found that the floodplain losses and consequent land use changes significantly modified flood characteristics and flow regimes over the last few decades, as also shown by Skublics and Rutschmann [36]. In addition to the hydrological and hydraulic effects, the loss of floodplains is also accompanied by ecological and socio-economic changes (e.g., valuable habitat losses, land use change, etc.). Therefore, the FEM is a method that uses hydraulic, hydrological, ecological, and socio-economic parameters to evaluate floodplains, and thus, should contribute to their preservation. To investigate floodplains with the FEM, clear start and end points of the floodplain need to be defined. It is possible to assess all three floodplain types with this method, and determine their value using the set of parameters. The active and potential floodplains identified in this paper were subsequently evaluated using the FEM; the results of this evaluation can be found in Eder et al. [49]. In this way, a basis for decision making is created, which could lead to the reconnection of identified potential floodplains, and support a fundamental principle of flood risk management, to providing more space for rivers [50,51]. Schwarz [18] and the DPRP [20] estimated potential restoration areas along the Danube River based on land use, hydromorphological properties (e.g., flooding dynamics), size, location, and the overlap with protected areas. Experience has demonstrated that political and socio-economic factors (such as property structure or the political agenda) are far more important than actual land use when it comes to the realization of restoration projects [20].

1.3. Research Questions

Since accurate global assessments of wetland extent are elusive due to the complexity and highly dynamic nature of wetlands themselves [9], focus should be on specific catchments, to reduce uncertainty. The goals of the current authors are to present methods used to identify active, former, and potential floodplains, and to compare the three floodplain types for the Danube River case study. Therefore, the following research questions apply to this work:

1. What are the most suitable methods for identifying active, former, and potential floodplains?
2. Where are the active, former, and potential floodplains along the Danube River, and what are their land uses?
3. What is the ratio between active, former, and potential floodplains along the Danube River?

Moreover, this work provides an upgrade on the inventory and status of the floodplains along the Danube River.

2. Material and Methods

2.1. Study Area—Danube River

The Danube River Basin covers more than 800,000 km^2, which accounts for 10% of continental Europe, and includes territories of 19 countries, with 80 million people living within its perimeter, making it the most international river basin in the world [52]. The basin is heterogeneous, as one third is mountainous and has a mean altitude of

450 m [53]. The Danube River flows from the Black Forest Mountains in Germany to the Black Sea in Romania; it is 2857 km long, and has a mean annual discharge at the mouth of 6486 m^3/s [54]. The Danube River connects 27 large, and over 300 smaller, tributaries [1].

The river is important for inland transportation, a use that is incompatible with the conservation or restoration of ecologically sensitive river stretches and floodplains [19]. About 39% (or 1111 river km) of the Danube River itself is impounded by 83 dams [52]. The river has been channelized, confined by levees, impounded, and polluted, and its floodplains have been converted into agricultural land, poplar plantations, and fisheries [54,55]. Nonetheless, the river has relatively unaltered hydrology, with frequent "flood" and "flow" pulses [9]. The riparian vegetation is adapted to the changes from dry to wet ecosystems [54], although invasive species can also be found [9]. Among the many Danube fauna species found on the IUCN Red List (https://www.iucnredlist.org/ accessed on 20 May 2022), the ship sturgeon, the Danube salmon, and the white-tailed eagle are the best known [19]. Simultaneously, invasive fauna species were found in the last Joint Danube Survey [19].

Regarding water quality, between the 1950s and the 1970s, urban and industrial pollution has been a relevant issue, although nowadays, the river exhibits relatively good water quality (classes II to II–III) [54].

Concerning future trends in terms of expected climatic changes, the Danube River Basin is going to be affected differently due to its huge area. In Northwest Europe, where part of the Upper Danube is located, increasing autumn and winter rainfalls are expected to enhance flood probability. In Southern and Eastern Europe, where the Middle and Lower Danube are located, decreasing precipitation (up to 20% in Central Europe, as high as 45% in Eastern Europe, as in Bulgaria, Hungary, Slovakia, and Romania) and increasing evaporation are expected to decrease flood probability in medium and large catchments [19,56]. The projected effects of climate change (low water during the growing season and higher water temperatures) are likely to negatively affect disconnected floodplains [9,19]. In terms of land use changes, population growth is expected to enhance demands for land for settlement, agriculture, and forestry, which in the past have already resulted in large-scale river regulation measures for flood protection, navigation, and hydropower. Due to these past changes, the Danube River and its tributaries have been progressively constrained for flood protection, navigation, and hydropower [53].

2.2. Data Sources

This paper builds on the EU-funded "Danube Floodplain (https://www.interreg-danube.eu/approved-projects/danube-floodplain#! accessed on 25 March 2022)" project that aimed at improving transnational water management and flood risk prevention, focusing on floodplain management. Different representative entities (national water agencies, universities, etc.) from the countries along the Danube River collaborated in this project. In Table 1, we list the data sources that we used to identify and analyze the active, former, and potential floodplains along the Danube River.

In terms of hydrological data, this study used the medium (HQ_{100}) and extreme (HQ_{1000}) flood event outlines from the "Danube FLOODRISK" project to identify active, former, and potential floodplains. In the scope of the "Danube FLOODRISK" project, hazard and risk maps were prepared for the entire Danube River in 2012. Three different flood scenarios (frequent event, HQ_{30}; medium event, HQ_{100}; extreme event, HQ_{1000}) were investigated using various hydrodynamic models (2D, quasi-2D, and 1D). In this study, for some countries (e.g., Germany, Hungary) we used more recent maps of inundated areas to use the most updated data set in terms of flood-prone areas. Table 2 provides an overview of the models that were used to calculate the inundation areas.

Table 1. Overview of all data sources used for identifying the active, former, and potential floodplains along the Danube River. *Country code:* DE = Germany, BW = Baden-Württemberg, BY-Bavaria, AT = Austria, SK = Slovakia, HU = Hungary, HR = Croatia, RS = Serbia, BG = Bulgaria, RO = Romania.

Data	Source Name	Description	Countries
Hydrological	HQ_{100} outlines	The project "Danube FLOODRISK [1]" and/or national flood hazard maps provided the inundation areas of a flood with a 100-year return period. The representatives from each country involved in the "Danube Floodplain" project decided which sources ("Danube FLOODRISK" or national flood hazard maps) were used for their country. In the end, the HQ_{100} outlines used are based on calibrated 1D, quasi-2D and 2D hydraulic models.	DE, AT, SK, HU, HR, RS, BG, RO, MD, UA
	HQ_{1000} outlines	The project "Danube FLOODRISK" provided the inundation areas of a flood with a 1000-year return period. As with the HQ_{100} outlines, the representatives from each country selected the source of the HQ_{1000} outlines in their country, leading to the use of results from calibrated 1D, quasi-2D and 2D hydraulic models.	AT, SK, HU, HR, RS, BG, RO, MD, UA
	$HQ_{extreme, BW}$ outlines	The Baden-Württemberg State Institute for Environmental Protection provided the inundation areas of an extreme flood. An extreme event is statistically less likely than once in 100 years.	DE (State: Baden-Württemberg, BW)
	$HQ_{extreme, BY}$ outlines	The Bavarian Environment Agency provided the inundation areas of an extreme flood. An extreme event is statistically less likely than once in 100 years.	DE (State: Bavaria BY)
Historical	Pasetti map	A cartographic inventory of the Danube River and its riparian areas at the onset of the river regulation in the second half of the 19th century (1857–1867).	AT, SK, HU, HR, RS
	Franziscean cadastre [2]	The "Franziscean cadastre" is an historical map created between 1817 and 1861 to calculate land taxes, showing land cover/uses of each plot for the Habsburg Monarchy.	AT, HU
	I. [3] and II. [4] Military Survey Maps	The military survey maps from 1763–1787 and 1806–1869 show landscape structures, such as watercourses, and terrain topography.	AT, SK, HU, HR, RS, BG, RO
	Schmitt'sche Map [5]	In 1797, Heinrich von Schmitt started drawing a military map on behalf of the German Emperor Franz II.	DE
	Historical flood events map	The Bavarian Environment Agency provided data on flood events that have been observed in the past. The areal expansion and the flood line (outer boundary of the flood), as well as historical water level marks, are recorded.	DE (State: Bavaria BY)
	Written historical sources	Local chronicles, newspapers, and books are used to verify the delineated former floodplains; e.g., Sartori [57,58], LfU [59], Peckarova and Miklanek [60], and Nagy [61]	DE, AT, HU, RS
Geospatial data	Digital Elevation Model	The EU Digital Elevation Model [6] is found in the Copernicus database, and is based on SRTM and ASTER GDEM data, providing information in 25 m resolution.	DE, AT, SK, HU, HR, RS, BG, RO
	Land cover data set	The CORINE land cover data set [7] from the Copernicus database summarizes land cover into five categories: "Artificial surfaces", "Agricultural areas", "Forest and semi-natural areas", "Wetlands", and "Water bodies".	DE, AT, SK, HU, HR, RS, BG, RO
	Satellite images	Different sources (Google Earth, OpenStreetMap, World Imagery) were used for high-resolution satellite images.	DE, AT, SK, HU, HR, RS, BG, RO, MD, UA
Previous projects	Floodplains	Previous delineated morphological floodplains from Schwarz [18], a WWF funded project in 2010, are used as a basic reference for identifying former floodplains in the present study.	DE, AT, SK, HU, HR, RS, BG, RO, MD, UA
	BfN morphological floodplains (Altauen)	The morphological floodplain map was delineated by the Federal Agency for Nature Conservation [10], following the methodology reported in Günther-Diringer et al. [62].	DE

Notes: [1] https://environmentalrisks.danube-region.eu/projects/danube-floodrisk/ accessed on 25 March 2022; [2] www.mapire.eu/en/map/cadastral/ accessed on 20 May 2022; [3] https://maps.arcanum.com/en/browse/country/firstsurvey/ accessed on 20 May 2022; [4] https://maps.arcanum.com/en/browse/country/secondsurvey/ accessed on 20 May 2022; [5] https://maps.arcanum.com/de/synchron/schmittschekarte/?layers=35&bbox=705838.5570651566%2C4890580.581526183%2C2244363.0623891843%2C7177576.467818657 accessed on 20 May 2022; [6] https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1; [7] https://land.copernicus.eu/paneuropean/corine-land-cover/clc2018 accessed on 20 May 2022.

Table 2. Overview of the hydraulic models that were used to calculate the inundation areas for HQ_{100} and HQ_{1000} in each country.

Country	Model Used for HQ_{100} Outlines	Model Used for HQ_{1000} Outlines
Germany	2D models used for latest national flood hazard maps	2D models used for latest national flood hazard maps
Austria	2D steady models used for latest national flood hazard maps	2D steady models used in the "Danube FLOODRISK" project
Slovakia	2D models used for latest national flood hazard maps	2D models used for latest national flood hazard maps
Hungary	2D models used for latest national flood hazard maps	2D models used for latest national flood hazard maps
Croatia	1D unsteady model used in the "Danube FLOODRISK" project	1D unsteady model used in the "Danube FLOODRISK" project
Serbia	1D unsteady model used in the "Danube FLOODRISK" project	1D unsteady model used in the "Danube FLOODRISK" project
Bulgaria	1D unsteady model used in the "Danube FLOODRISK" project	1D steady model used in the "Danube FLOODRISK" project
Romania	1D and quasi-2D unsteady models used in the "Danube FLOODRISK" project	1D and quasi-2D unsteady models used in the "Danube FLOODRISK" project

An example of historical data is the "Pasetti map", a cartographic inventory of the Danube River and its riparian areas, created between 1857 and 1867 at a scale of 1:28,800; based on the Franziscean land survey, this map represents the time before the river regulation (1830). The "Pasetti map" represents an area from the German–Austrian border to the Iron Gate, and provides information regarding the riverbanks, the hydraulic situation, and roads in the riparian areas, features that are not included in the I. and II. military survey maps. For example, the inundation areas of a large flood event in 1830 are shown on the "Pasetti map". More information about this map can be found in Zeilinger [63]. The "Franziscean cadastre" and the military survey maps (1763–1787; 1806–1869) are also historical maps, produced by the later "k.k. Militärgeographische Institut", and provide valuable information about formerly flooded areas. Additionally, the "Schmitt map" (in German "Schmitt'sche Karte"), another military map, was also available; this map covers the missing German part of the Danube River. We used written documents, such as the reports of Satori [57,58], about the 1830 flood event, and reports on the disastrous 1876 floods collected by Nagy [61] to verify the inundated areas of the "Pasetti map". In general, we searched for local chronicles, newspapers, and other written documents for additional information about historical flood events to improve the delineation of the former floodplains.

In terms of geospatial data, the EU-DEM, part of the Copernicus database, is a single consistent elevation data set for Europe. It is based on SRTM and ASTER GDEM data, and provides information at 25 m resolution. Different sources (Google Earth, OpenStreetMap, World Imagery) provided high-resolution satellite images.

The CORINE land cover data set from the Copernicus database was used to analyze the land use of each active floodplain. The data set summarizes the land cover at the first level into five categories: "Artificial surfaces", "Agricultural areas", "Forest and semi-natural areas", "Wetlands", and "Water bodies". Appendix A reports all the land use categories and subcategories of the CORINE land cover data set.

Schwarz [18] delineated active morphological floodplains, and proposed areas for restoration (potential floodplains). The delineation is mainly based on the most recent and accurate DEM at that time, and focuses on the definition of postglacial terraces. High-resolution satellite data and physical riparian landscape features were also used to define such terraces. In the project's report, Schwarz [18] stated that additional data sources were going to be available in the upcoming years, with potential for improvement of the raw delineation. In another recent work [23], German morphological floodplains were identified and interpreted as natural inundation areas of a river, which would be occupied by more or less regularly recurring floods under natural conditions (no flood protection measures, such as dikes). Separated areas that are no longer flooded are called "old floodplains". These include polders without ecological flooding. Therefore, the floodplain areas delineated in these previous projects were used as references for identifying former floodplains in the present study.

2.3. Identification of Active, Former, and Potential Floodplains

In the following three subsections, we describe the methods used to delineate active, former, and potential floodplains along the Danube River. These methods can be applied to any river if the necessary data sets are available.

2.3.1. Active Floodplains

We define active floodplains as inundated areas (hydraulically active) during a flood event with a return period of 100 years (HQ_{100}). Several other studies, e.g., [1–3], used the inundation areas of HQ_{100} for delineating recent/active floodplains. Moreover, this return period was chosen because the EU Floods Directive (2007/60/EC) requires the preparation of flood hazard and risk maps for flood events with low, medium, and high frequency, in which "medium" frequency corresponds to a 100-year return period. Hence, inundation areas for a 100-year return period are widespread and available in Europe.

For our study, the flood hazard and risk maps for three frequencies (high, HQ_{30}; medium, HQ_{100}; low, HQ_{1000}) from the "Danube FLOODRISK" project were available for most of the Danube River. If more recent national flood hazard and risk maps were provided from individual countries, we used these maps as a data source.

Our developed method differs from previous methods, e.g., [1–3], as we introduce two delineation criteria to identify the main active floodplains (with the highest retention effects): **(i) ratio of $\mathbf{width_{Floodplain}/width_{Channel}}$; (ii) minimum size.** In a further step [49], we applied the Floodplain Evaluation Matrix (FEM), which requires delineated floodplains with a defined start- and endpoint. The two delineation criteria can vary and be adapted depending on the research question and the characteristics of the investigated river (e.g., basin size, river type). Considering our research intent and the characteristics of the Danube River, we set the width ratio to 1:1, meaning that an active floodplain starts if the width of the floodplain (excluding the main channel) is at least as wide as the channel width. If the width of the flooded area was smaller, then the area was defined as a riparian zone. In general, the width of the main channel was used for the ratio factor. An exception was the Eastern Wallachian Danube with the three largest islands (Balta Ialomita, Big and Small Islands of Braila), where the width of the respective largest branch was used. This was conducted because of the special characteristics of this section, where the side channels were considered as part of the river for several kilometers. In Figure 1, the applied delineation criteria for the Danube River are summarized, and an example of locating the start- and endpoint of a floodplain is presented.

The second criterion is the minimum size, which we used to distinguish two groups of floodplains that fulfilled the chosen width ratio of $\mathbf{Width_{Floodplain}/Width_{Channel}}$. This differentiation was required, since we focused on floodplains with the largest retention effects in the second stage of our research [49]. We assigned all floodplains larger than 500 ha to the 1st group. We chose this size since all Danube River Basin Management Plans (DRBMPs) [32,52,64] concern floodplains of basin-wide importance (area > 500 ha). Nevertheless, we also delineated all floodplains smaller than 500 ha (2nd group), and all riparian areas (3rd group) that neither fulfill the width ratio nor the minimum size, since these areas may be relevant for ecological and/or socio-economic aspects (e.g., habitats, agriculture, leisure time). We used a Geographic Information System (GIS, such as ArcGIS) to delineate the active floodplains and to assign them to one of the three groups. The three groups of this study are therefore defined as follows:

- **1st group:** floodplains with delineated start- and endpoint and *larger* than the defined minimum size;
- **2nd group:** floodplains with delineated start- and endpoint but *smaller* than the minimum size;
- **3rd group:** riparian zones, where the two delineation criteria are not fulfilled.

Delineation criteria	
Width ratio ($width_{Floodplain}/width_{Channel}$)	> 1
Minimum size	500 ha

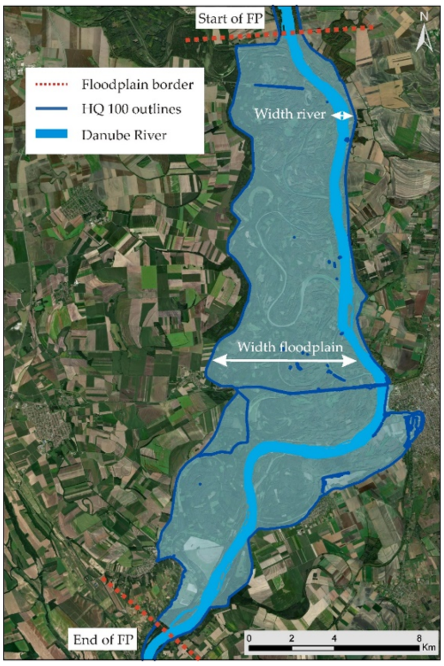


Figure 1. *Left*: Applied delineation criteria for identifying active floodplains along the Danube River. *Right*: Identified floodplain HU_DU_AFP07 (HU = Hungary, DU = Danube River, AFP = active floodplain) showing the concept of locating the start- and endpoint of a floodplain based on the width ratio ($width_{Floodplain}/width_{Channel}$).

2.3.2. Former Floodplains

We define former floodplains as areas that have been cut off from the river due to river training and regulation, but that would have potentially been flooded without these human interventions. As in earlier literature [18,24], we use the term morphological floodplain to describe the combination of active and former floodplains. Delineating former floodplains that were hydraulically active during an extreme flood event is challenging because hydraulic processes in the river and floodplains have changed significantly due to strong human intervention. Using different sources ranging from historical documents (e.g., reports, military survey maps) to current hazard maps (e.g., outlines of $HQ_{extreme}$) and DEM allows the estimation of the former hydraulically active floodplains. As an innovative part of this work, we developed a schematic approach to identify former floodplains along four consecutive steps (Figure 2). Each step includes mandatory tasks, and leads to potentially different data sources, as each river is described through different data sets. Therefore, the presented method is structured in a way that allows it to be applicable, even when certain data (e.g., $HQ_{extreme}$) are not available.

Step I: Estimation of former floodplains with current $HQ_{extreme}$ outlines

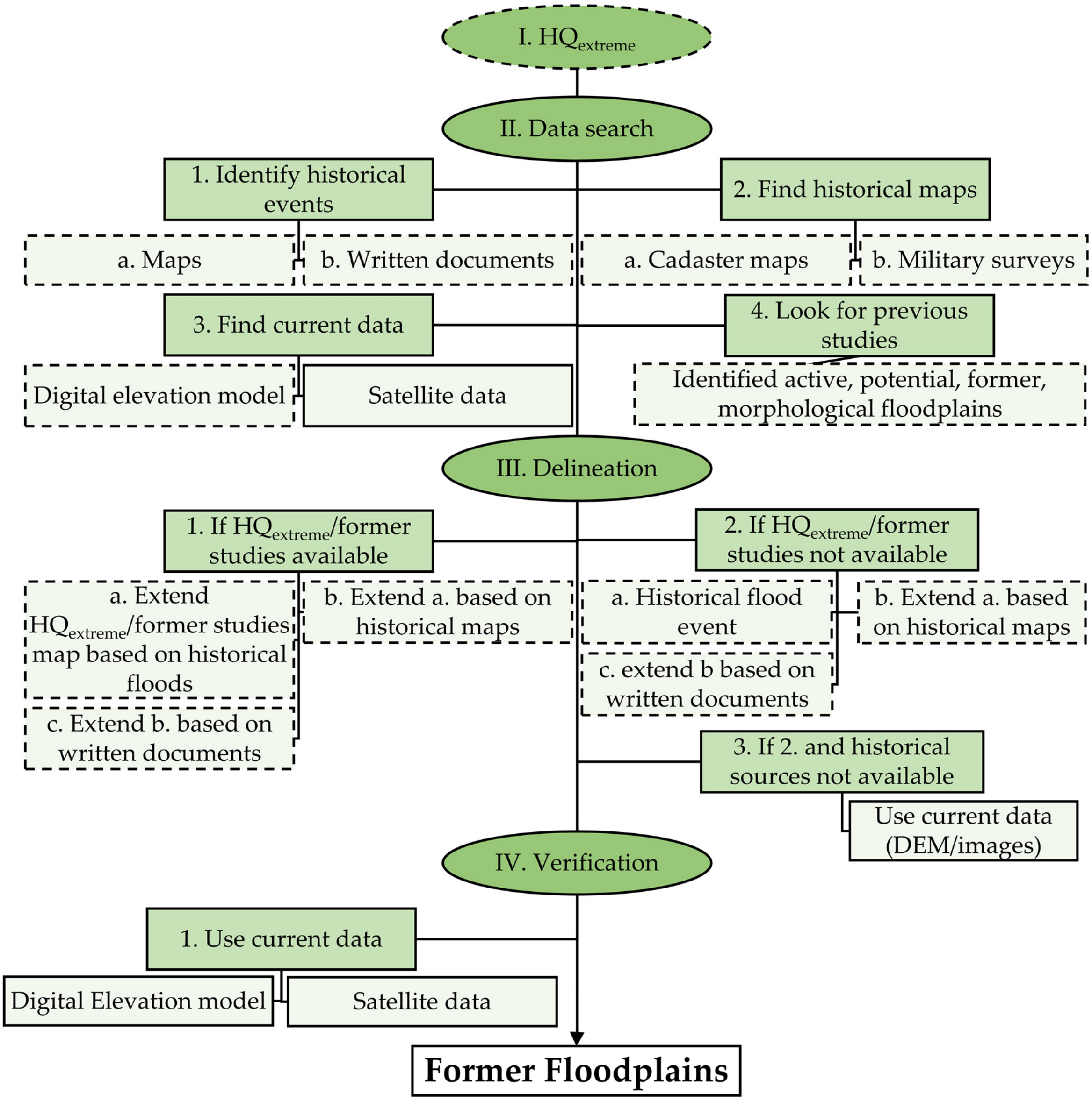


Figure 2. Schematic approach for the identification of former floodplains.

Very often, flood protection measures disconnect the former floodplains from the river system. In Europe, the design discharge of these measures mostly corresponds to a 100-year return period (medium frequency). Events with a low frequency (e.g., 1/1000 probability) are called "extreme" (which corresponds to the discharge $HQ_{extreme}$), and can lead to overflow or failure of the existing flood defenses. This results in flooding of the areas behind the protection facilities, thereby reactivating the former floodplains, or at least part of them. Hence, current $HQ_{extreme}$ outlines can serve as a starting point for the extent of former floodplains. This step depends on the data availability of the $HQ_{extreme}$ outlines, and is therefore optional. If the data set is available, the outlines are imported into a GIS. The extent of $HQ_{extreme}$ outlines is seen as an estimation of the former floodplains. Two methods exist to verify whether the $HQ_{extreme}$ inundation areas reliably represent the former floodplains: (i) using historical sources (e.g., documentations, maps) and (ii) cross-checking whether existing flood protection measures are overtopped or not. In fact, if the flood defenses protect the hinterland during an $HQ_{extreme}$ event, the formerly inundated areas identified with the $HQ_{extreme}$ outlines might yield an underestimation of the actual former floodplains. Additionally, historical sources can deliver further information about the hinterland, for example, the presence of flood-prone areas (see step III).

For the Danube River, we used the HQ_{1000} outlines from the "Danube FLOODRISK" project as a starting point for the extent of the formerly flooded areas. Except for Germany, the HQ_{1000} inundation areas were not available, so we used updated $HQ_{extreme}$ maps outlined by the environmental agencies of the Federal States of Baden-Württemberg [65] and Bavaria [66] in the German sections. In most cases, the current flood protection facilities are overtopped along the Danube during extreme events, indicating areas that were disconnected from the river by the flood defense.

In areas where measures were not overtopped, information from other sources is needed to understand whether the hinterland behind the defense measures can be classified as a former floodplain. In step II, sources of such information were collected. In step III, the collected data were used to check and extend the estimated former floodplains.

Step II + III: Search for data sources (historical, current) and delineation of former floodplains

For simplicity, we present steps II and III together in this subsection. Step II focuses on the data research. In step III, former floodplains are delineated based on the data acquired in step II.

The goal was to delineate the maximum extent of former floodplains, and historical sources (such as military survey or cadastre maps, local chronicles, newspapers, gauging data, etc.) can contain crucial information about formerly flooded areas. Hence, step II focuses on finding such sources.

First, historical flood events can be identified based on local chronicles, newspapers, historical–topographical descriptions, and gauging data [67]. A compilation of past flood events serves as a basis for an in-depth investigation of the extent such events, which could subsequently lead to the former floodplains. For the Danube case study, we used previous investigations [59,60,67] on historical floods along the Danube River to identify the major flood events from the past.

The next step was to search for maps showing the flooded areas of historical events. For the Danube River, we found the "Pasetti map", a cartographic inventory of the Danube River and its riparian areas at the onset of the river regulation in the second half of the 19th century, showing the inundation areas of an extreme flood event in 1830. For Bavaria, the Bavarian Environment Agency (LfU) provided an historical flood events map [68], which indicated the greatest extent of a flood observed in the past. The maps showed that the flood events exceeded, in some parts, the $HQ_{extreme}$ outlines identified in step I. In these sections, we extended the preliminary former floodplains according to the inundation areas from the "Pasetti map" and the LfU historical map.

On occasion, (military) cartographers mapped the flooded areas several years after the flood event in a simplified and partly flawed manner. Historical sources from authors more familiar with the local situation (e.g., flood damages, victims) can help to correct such errors [69]. Hence, the inundation outlines must be verified with written documents and geodata, such as digital elevation models, when used to delineate the former floodplains. Since the "Pasetti map" was created about 30 years after the 1830 flood, and before the 1876 floods, we verified the mapped inundation outlines with other historical sources (reports on flood events, local chronicles, newspapers, etc.). Some of these written documents [57,58,61] indicated villages that were affected by the flood of 1830, which were not shown in the map, or, in contrast, the map showed larger inundated areas than documented. In these cases, the inundation outlines were corrected according to the written sources. In the German section of the Danube, the extension of the $HQ_{extreme}$ outlines, the LfU historical maps, and the floodplains drawn from the "Schmitt map" (see next paragraph) were compared with the locations of the settlements, where floods took place according to literature [59,60]. The comparison was performed by georeferencing the settlements using GIS software (QGIS [70]), and none of the added points were located outside of the already identified areas.

However, most maps do not show any information about previous flood events. Instead, they show the typical coloring of wetlands, floodplain forests, moist pastures, and meadows, as well as landscape structures, such as watercourses, and terrain topography, which allow one to delineate former inundation areas.

Cadastral maps, which show the land use of each plot, and military maps, which focus on the geographical situation and landscape structures, complement each other, and can be used to identify formerly flooded areas. At the Danube River, the "Franziscean cadastre", the I. and II. military survey maps, and the "Schmitt map" were used in sections that were not covered by the "Pasetti map" or by the LfU map (e.g., for the German section in Baden-Württemberg). The maps were incorporated into QGIS using the Web Map Tile Service (WMTS) of the company Arcanum (https://www.arcanum.com/en/ accessed on 25 March 2022). Again, the starting point was the HQ_{1000} outline. If the cadastral map and/or the military survey maps indicated former floodplain areas that the HQ_{1000} did not cover, then the polygon was adapted and extended.

Searching for previous projects or studies on former floodplains is also part of step II. Keywords such as "morphological floodplains", "former floodplains", or "historical floodplains" may be used to find further studies on floodplain reconstruction. We used the previous studies of Schwarz [18] and Koenzen and Günther-Diringer [10], which we previously described in Section 2.2, as basic references, and compared their delineated floodplains to the newly identified former floodplains.

If none of the above data sets are available, recent DEMs and satellite images can be used to identify postglacial lower terraces and breakthrough valleys, which often represent the boundaries of the former floodplains. In theory, these data sets alone could be used to identify former floodplains. However, delineating formerly flooded areas without historical and hydraulic data is not recommended. If other data sets are available, DEMs and satellite images are used to verify the delineated former floodplains (see step IV).

Step IV: Verification of former floodplains with DEM and satellite images

The verification of former floodplains with a current DEM and high-resolution satellite images is very limited, since the terrain might have changed significantly. This step aims at discovering and correcting coarse errors in the historical maps. For example, according to the historical maps, the river's course runs over an older/higher river terrace, valley slope, or even a mountain. This apparent error can be easily detected with the DEM or satellite images. We used the EU-DEM and current satellite images (Google Earth, OpenStreetMap, World Imagery) to check the plausibility of the delineated former floodplains along the Danube River.

2.3.3. Potential Floodplains

We define potential floodplains as areas that are currently not inundated by an HQ_{100} event, but have the potential (from a hydraulic, ecological, and socio-economic perspective) to be reconnected to the river system, leading to inundation during flood events with a 100-year return period. A step-by-step approach based on hydraulic and historical data was developed to identify potential and "operational" potential floodplains. The method is organized along five consecutive steps (Figure 3), with the option to exclude the last step V, which leads to the "operational" potential floodplains that have already been discussed in detail (regarding technical, political, and economic feasibility) among stakeholders, decision makers, and experts. The first four steps are compulsory, and sufficient to identify potential floodplains of a river. Depending on the individual project or research question, it might be necessary to include and apply step V (Detailed Planning of Reconnection Measures with Stakeholders and Decision Makers). To meet our objectives and answer our research questions, it was sufficient to apply the first four steps of the method, which led to the potential floodplains.

Step I: Estimation of Former Floodplains

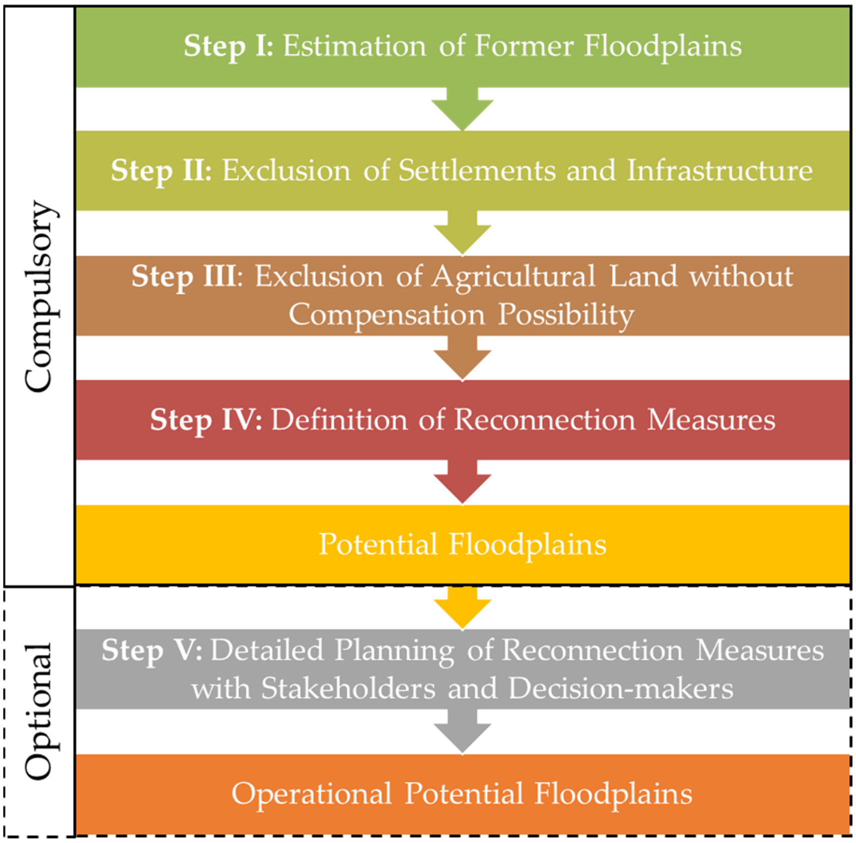


Figure 3. Sequence of the identification method for potential and "operational" potential floodplains.

A detailed delineation of former floodplains is challenging and time-consuming. In general, the method described in Section 2.3.2 or the application of hydraulic models is recommended. The latter is the most time-consuming and cost-intensive approach, especially if the former floodplains must be identified for an entire river. Hence, using the inundation areas of an $HQ_{extreme}$ event provides an opportunity to roughly estimate the extent of the former floodplains, especially if the focus of the investigation is on potential floodplains and not on formerly flooded areas. For the Danube River, we used the former floodplains identified via the method described in Section 2.3.2.

Step II: Exclusion of Settlements and Infrastructure

The estimated former floodplains are the basis for identifying potential floodplains. Nowadays, settlements, individual houses, and infrastructure are often located in formerly flooded areas. If this is the case, the operator of the method must decide if complementary local flood defense measures (e.g., dikes, protective walls, etc.) are feasible to protect the human-made structures. With additional flood protection measures, the settlements and infrastructure are excluded from the former floodplain.

Step III: Exclusion of Agricultural Land without Compensation Possibility

Many formerly flooded areas are used for agriculture due to their natural characteristics (low slope, soil fertility, water availability). In general, such areas are not considered "no go" areas for potential floodplains, but certain agricultural areas can be excluded from the potential floodplains, if land ownership or the legal framework do not allow compensation, or if the compensation is too expensive. To identify only realistic potential floodplains, the user can exclude some agricultural areas.

The potential floodplains presented in this study are one output of the EU project "Danube Floodplain", for which different representative entities (national water agencies, universities, etc.) from countries along the Danube River collaborated with each other and with external stakeholders in delineating potential floodplains. The entities identified the potential floodplains in their own country, and excluded some agricultural areas where they identified no realistic chance for restoration, i.e., due to political agenda, urban development, or land ownership.

After excluding selected agricultural land and settlements/infrastructure from the previous step, the former floodplains are reduced to the delineated potential floodplains.

Step IV: Definition of Restoration Measures

Restoration measures (e.g., relocation, slitting, or removal of dikes) must be defined to ensure that the identified potential floodplains are inundated, at least during an HQ_{100} flood, which corresponds in this study to a reconnection of the river system. Hydrodynamic models are used to verify whether the defined/potential restoration measures would lead to a reconnection of the delineated potential floodplain. If not, the potential measures must be adapted. If reconnection is not feasible, then the defined area should not be selected as a potential floodplain. We defined several restoration measures for the potential floodplains at the Danube River, ranging from dike relocation to deepening lateral branches/oxbows or removing bank stabilizations. The results of step IV can then be used as a discussion basis in step V.

Step V: Detailed Planning of Restoration Measures with Stakeholders and Decision Makers

The last step is optional, and gives, as a result, the "operational" potential floodplains, upon which stakeholders, decision makers, and experts can agree regarding technical, political, and economic feasibility. The potential floodplains and the defined restoration measures/ideas from step IV are the basis for discussion among the interested parties. The discussions should focus on the feasibility of reconnection of the identified areas from a technical, political, and economic perspective; for example, land availability and purchase, planning and implementation costs, future compensation in the case of flooding, maintenance and monitoring costs, or political willingness.

In the Danube River case study, this last step was excluded for time and funding reasons, since the first four steps were sufficient to achieve the "Danube Floodplain" project's goal of identifying potential floodplains along the Danube River.

2.3.4. Naming Convention

To assign each floodplain a unique, identifiable code, we developed a naming convention. The code consists of four different parts. The first part is the country code with two characters. The following country codes are used in this study: DE = Germany, AT = Austria, SK = Slovakia, HU = Hungary, HR = Croatia, RS = Serbia, BG = Bulgaria, RO = Romania, MD = Moldova, UA = Ukraine. The second part is the river code with two characters (e.g., DU = Danube River), the third part the floodplain type (AFP = active floodplain, FFP = former floodplain, PFP = potential floodplain), and the fourth is the consecutive number of the floodplain within the country in flow direction of the river. If a floodplain is transboundary, all countries are listed in the code, beginning with the upstream country, and the number starts at the first transboundary floodplain of these countries. Here are two examples:

- The 1st transboundary active floodplain at the Danube River between Austria and Slovakia, AT_SK_DU_AFP_01;
- The 4th potential floodplain at the Danube River in Germany, DE_DU_PFP_04.

3. Results

In this section, we present the results of applying the presented methods along the Danube River. The results build on the work of the "Danube Floodplain" project, where the spatial database "Danube Floodplain GIS (http://www.geo.u-szeged.hu/dfgis/ accessed on 20 May 2022)" was created to present the project's outputs and make them available to the public.

3.1. Active Floodplains along the Danube River

In total, 4711 km^2 (see Table 3) of hydraulically active floodplains were identified (incl. main river channel and excl. the Delta), with Romania having the largest share of 30% (around 1435 km^2). Hungary, Serbia, Germany, and Austria have a relatively large share between 11–15%, and 6 and 7% of the active floodplains are located in Croatia and Bulgaria, respectively. The share of Ukraine and Moldova is relatively low, especially since the Danube Delta is not considered in this estimation (due to its unique characteristics). However, with an area of 3394 km^2, the Danube Delta is the largest wetland along the Danube River, and its importance for ecology is immense.

Table 3. Comparison of the active floodplains of the Danube River (without the Delta) in the riparian states. In the 1st group, all active floodplains fulfill the two delineation criteria (ratio factor, minimum size); 2nd group, the minimum size is not fulfilled; 3rd group, neither the ratio factor nor the minimum size is fulfilled. *Country codes:* DE = Germany, AT = Austria, SK = Slovakia, HU = Hungary, HR = Croatia, RS = Serbia, BG = Bulgaria, RO = Romania, MD = Moldova, UA = Ukraine. The relative share in the last column presents the proportion of the total floodplain area in a country in relation to the total floodplain area along the Danube River.

Size of Active Floodplain Incl. Main Channel in km² without Delta					Rel. Share [%]
Country	**1st Group**	**2nd Group**	**3rd Group**	**Total**	
DE	492	101	13	**606**	13
AT	415	21	65	**500**	11
SK	89	0	78	**168**	4
HU	595	29	65	**688**	15
HR	294	0	13	**307**	6
RS	331	42	267	**640**	14
BG	82	37	232	**351**	7
RO	728	146	561	**1435**	30
MD	-	-	0.22	**0.22**	<1
UA	-	-	15	**15**	<1
Danube River without Delta	**3027**	**375**	**1309**	**4711**	**100**
[%]	**64**	**8**	**28**	**100**	

Fifty hydraulically active floodplains (without the Danube Delta) meet the two delineation criteria described in Section 2.3.1. We assigned these 50 floodplains to the 1st group of floodplains, which are evaluated in more detail in Eder et al. [49]. These 50 floodplains cover 3027 km^2, which is about 64% of the total area (4711 km^2) inundated during an HQ_{100} event. A total of 101 active floodplains are smaller than 500 ha, and were assigned to the 2nd group of floodplains. Most of them (58) are found in Baden-Württemberg, where the river width is relatively small, and therefore, the first criterion (ratio factor of $width_{Floodplain}/width_{Channel} > 1$) was easy to fulfil. With 375 km^2, the floodplains in the 2nd group account for only 8% of the total inundated area. The 3rd group includes the riparian zones, where the two delineation criteria (ratio factor, minimum size) are not fulfilled. The riparian zones cover 1309 km^2, which is about 28% of the total area inundated during an HQ_{100} event. Romania has the largest share of the 3rd group, with 43% (561 km^2).

In Figures 4 and 5, all active (red), potential (orange), and former (green) floodplains are presented for the three Danube sections (upper, middle, and lower).

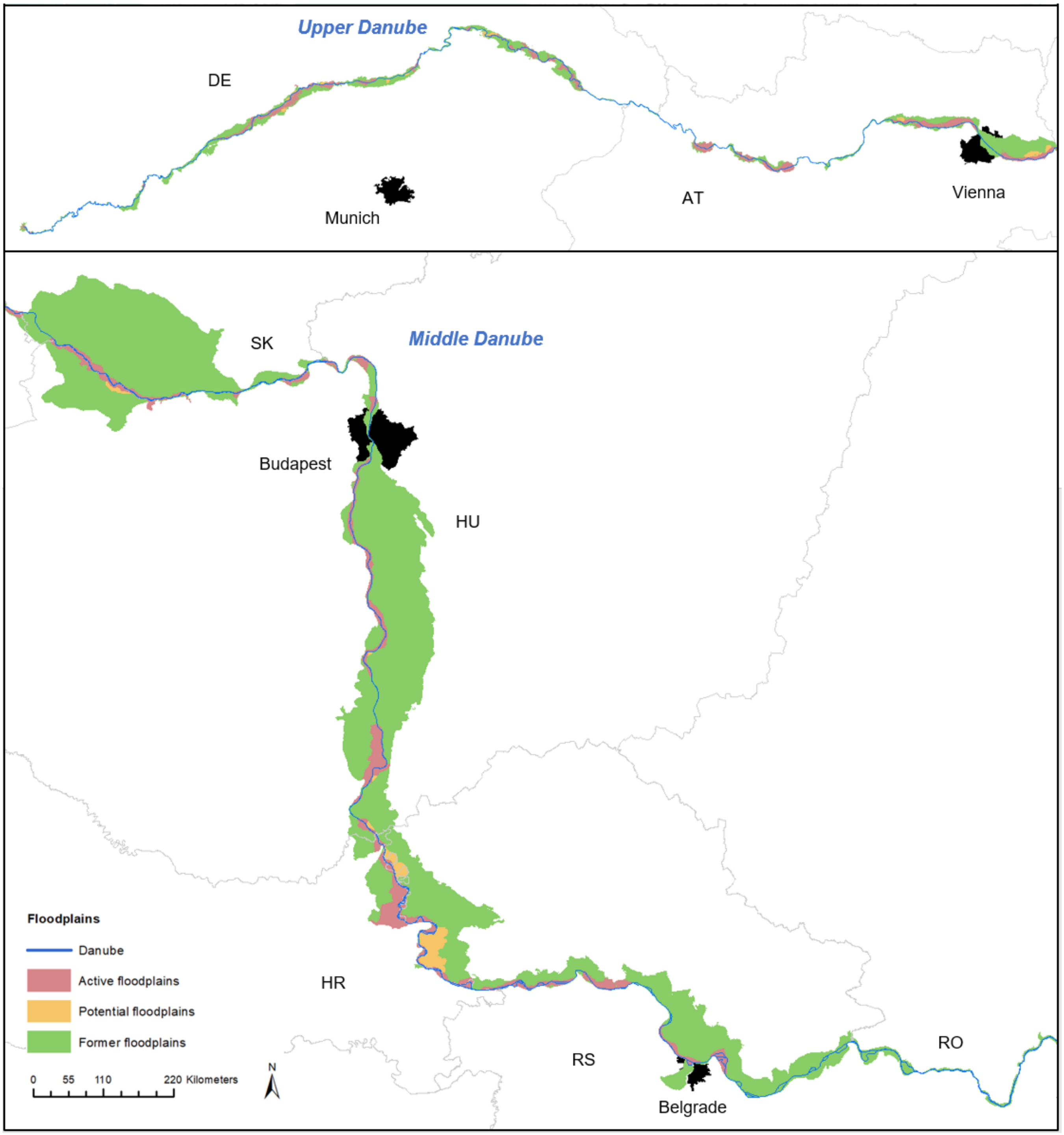


Figure 4. Overview of the active, former, and potential floodplains at the Upper and Middle Danube.

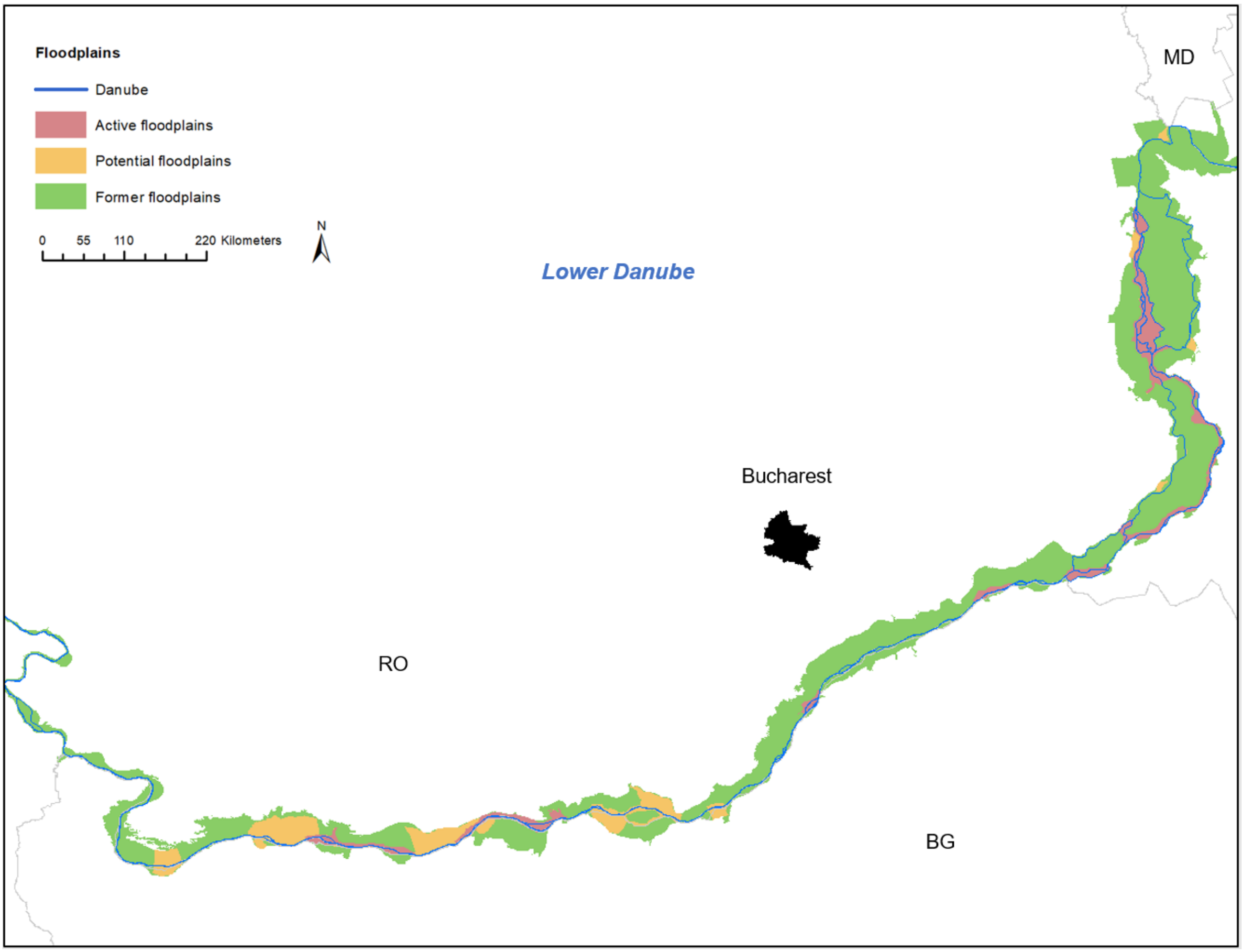


Figure 5. Overview of the active, former, and potential floodplains at the Lower Danube.

In Figure 6, all active floodplains larger than 500 ha (average value around 5800 ha) are sorted from up- to downstream, and the total area of each floodplain is presented. Each floodplain received a unique, identifiable code (see Section 2.3.4) that is plotted on the abscissa. Out of the 50 floodplains, only five have an area larger than 150 km^2: two of them are located in the upper (DE, AT), two in the middle (HU, HR-RS), and one in the lower (RO) Danube section. Thirty-two floodplains have an area below 50 km^2. Germany has ten hydraulically active floodplains larger than 500 ha, Austria five, and one is transboundary. Slovakia has only six transboundary floodplains. Hungary has the most floodplains, eight only in Hungary and ten transboundary. Croatia shares one floodplain with Hungary and five with Serbia. Serbia has ten floodplains (five transboundary and five in Serbia only). Bulgaria shares six with Romania. Romania also has four floodplains on its own territory.

Figure 7 illustrates the land uses for all active floodplains > 500 ha. The percentage of agricultural land varies from 0.4% to 96%, with a mean of 25%. In the upper and middle part of the Danube, the floodplains have, in general, a higher percentage of agricultural areas and a lower percentage of forest and semi-natural areas, especially in Germany and Austria. The share of the forest and semi-natural areas ranges from 0 to 95%, with a mean of 41%. At the end of the Middle Danube, and in the Lower Danube, forest and semi-natural areas are dominant. Wetland cover is only present at 20 out of 50 active floodplains, mainly located at the Lower Danube. The percentage of artificial surfaces is always under 7%.

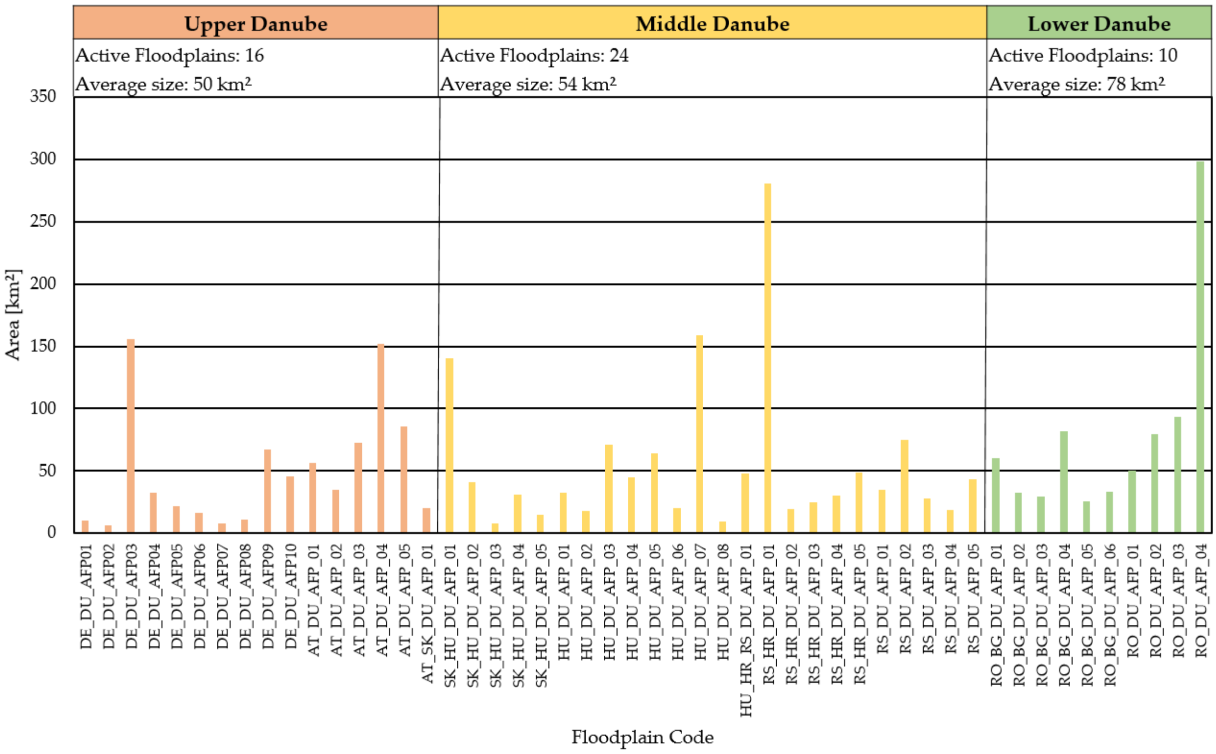


Figure 6. Area distribution of active Danube floodplains (>500 ha) from up- to downstream.

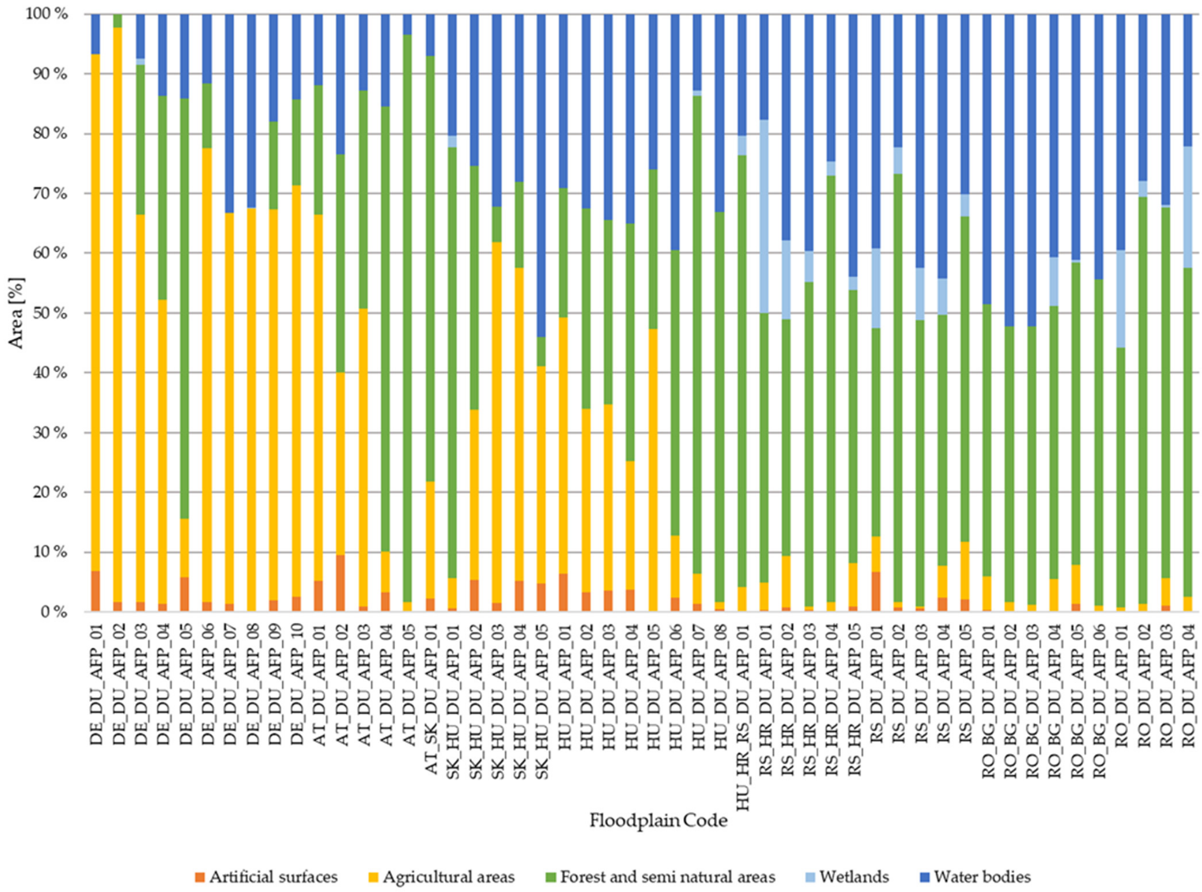


Figure 7. Distribution of land use classes, as percentages, for all active Danube floodplains from up- to downstream.

3.2. Former Floodplains along the Danube River

The identified former floodplains amount to 22,853 km^2 (incl. main river channel and excl. the Delta), with Romania having the largest share of around 6459 km^2 (28%), followed by Hungary with 5338 km^2 (23%), Serbia 3389 km^2 (15%), and Slovakia 3161 km^2 (14%). Around 6% are each located in Germany (1457 km^2), Austria (1251 km^2), and Bulgaria (1435 km^2). Croatia has the lowest share, with 645 km^2 (3%). Figures 4 and 5 show in green the delineated former floodplains. Table 4 compares the active with the former floodplain area and provides the percent loss of floodplain for each country. About 60% of the former floodplains were lost in Germany and Austria. With 95%, Slovakia shows the highest floodplain loss of all countries. In Hungary, the former floodplains have been reduced by 87%. Croatia shows the lowest reduction, with 52%. Serbia and Romania's current active floodplain areas are about 20% of the original area. Bulgaria shows a decrease of 70%. The total loss of former floodplains along the Danube River equals 79% without the Danube Delta.

Table 4. Comparison between active and former floodplain area for each country (incl. main river channel and excl. Delta).

Country	Active FP (km^2)	Former FP (km^2)	Floodplain Loss (%)
DE	606	1457	58%
AT	500	1251	60%
SK	168	3161	95%
HU	688	5338	87%
HR	307	645	52%
RS	640	3389	81%
BG	351	1152	70%
RO	1435	6459	78%
MD	0.2	-	
UA	15	-	
Danube without Delta	**4711**	**22,853**	**79%**

Figure 8 presents the current land uses of the delineated former floodplains in each country. The figure shows that the former floodplain areas are mostly used as agricultural areas. In Slovakia, 80% of the former floodplains are used for agricultural purposes. In Germany, Hungary, Serbia, and Romania, between 60–69% of the original area is cultivated. The share of the former floodplains used for farming in Austria and Bulgaria is 47% and 55%, respectively. The former floodplain areas in Croatia are the most natural, with 37% forest and semi-natural areas, 16% wetlands, and 11% water bodies. With 18%, the highest share of artificial surfaces is found in Austria, followed by Germany with 13%. In all other countries, the percentage of artificial surfaces is 10% or lower. Solely in Croatia, the combined share of forest and semi-natural land use, wetlands, and water bodies exceeds 50%. In all other countries, the share of these combined land uses averages only at 28%.

3.3. Potential Floodplains along the Danube River

In the scope of the "Danube Floodplain" project, representative entities from the countries Germany, Austria, Slovakia, Hungary, Croatia, Serbia, Bulgaria, and Romania applied the methodology presented in Section 2.3.3 to delineate potential floodplains in their countries. In total, 24 potential floodplains covering an area of 1090 km^2 were identified. In Figures 4 and 5, all potential floodplains along the Danube River are shown in yellow. Half of the delineated potential floodplains are extensions of active floodplains. Some of these extensions are relatively small and increase the flooded area only by 2–10% (median = 13%). Others double or quadruple the size of the active floodplains. The other half of the delineated potential floodplains are additional areas that could be flooded in the case of an HQ_{100} event after some restoration measures. The newly inundated areas range between 3 and 205 km^2. The analysis of the current land use on the potential floodplains shows that the share of agricultural areas ranges from 54% to 83% (Table 5). In the Upper Danube, this share is the highest. Hungary and Serbia have the largest share of forest and semi-natural areas (39% and 33%, respectively).

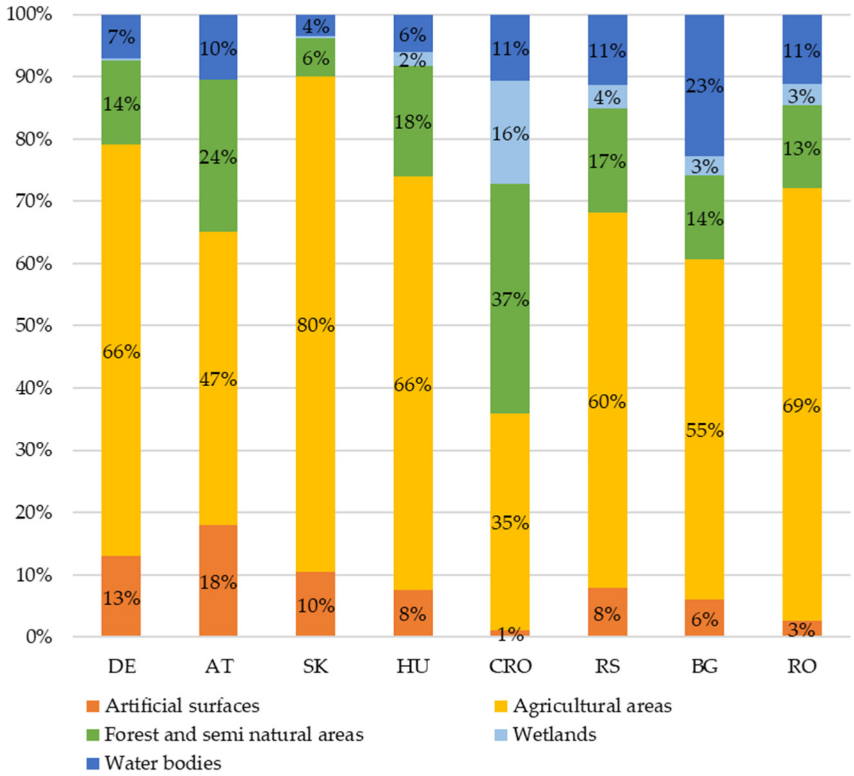
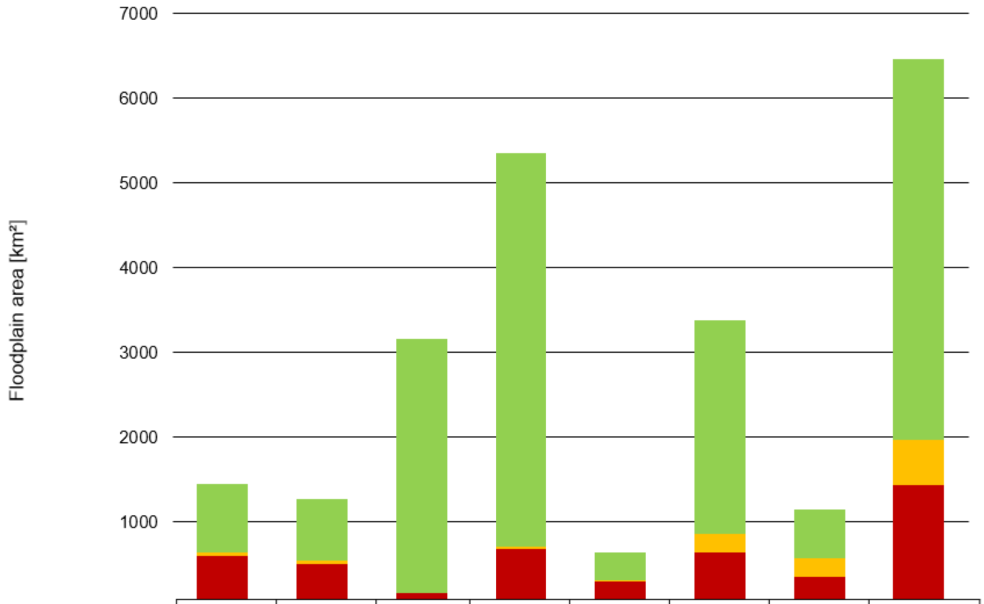


Figure 8. Current land uses in the former floodplains for each country.

Table 5. Current land use of the identified potential floodplains.

Country	Artificial Surfaces	Agricultural Areas	Forest and Semi Natural Areas	Wetlands	Water Bodies
DE	0%	79%	15%	0%	7%
AT	0%	83%	17%	0%	0%
HU	0%	57%	39%	4%	0%
RS	0%	65%	33%	0%	2%
BG	0%	54%	18%	1%	28%
RO	0%	67%	13%	7%	13%

In Figure 9, the active, former, and potential floodplains in each country are compared. To assess how much of the former floodplain is still a hydraulically active or a potential floodplain, the percentage of the former floodplain that is active or potential, and the sum of the two, is provided for each country. In Germany and Austria, the identified potential floodplain area is between 39 and 45 km^2, which would increase the active floodplain by around 3–4% of the former floodplains. Combined, the active and potential floodplains represent 45% (DE) and 44% (AT) of the former floodplains in these two countries. In the present study, no potential floodplains were identified in Slovakia and Croatia, although only 5% (168 km^2) of the former Slovakian floodplains are still active. Forty-eight percent of the former floodplains have been preserved in Croatia, but it must be considered that, at 645 km^2, the former Croatian floodplains are by far the smallest. Additional 28 km^2 (1% of the former floodplains) floodplain areas were delineated in Hungary. In total, active and potential Hungarian floodplains cover an area of 716 km^2, or 14% of the previously inundated areas. Serbia and Bulgaria could increase their active floodplains by about 221 km^2 (7% and 19% of the former floodplains) with the potential ones, resulting in a preservation of 861 km^2 (26%) and 573 km^2 (49%). The identified potential floodplains in Romania equal 8% (536 km^2) of the former floodplains. The sum of active and potential floodplains shows that, in Romania, 30% (1971 km^2 without Danube Delta) of the former floodplains could be preserved.



	DE	AT	SK	HU	HR	RS	BG	RO
former FP [km²]	1457	1251	3161	5338	645	3389	1152	6459
potential FP [km²]	39 (3%)	45 (4%)	0 (0%)	28 (1%)	0 (0%)	221 (7%)	222 (19%)	536 (8%)
active FP [km²]	606 (42%)	500 (40%)	168 (5%)	688 (13%)	307 (48%)	640 (19%)	351 (30%)	1435 (22%)
Sum AFP + PFP [km²]	**645 (45%)**	**545 (44%)**	**168 (5%)**	**716 (14%)**	**307 (48%)**	**861 (26%)**	**573 (49%)**	**1971 (30%)**

Figure 9. Area analysis of active, former, and potential floodplains along the Danube River. The percentages show how much of the former floodplains are still hydraulically active, or a potential floodplain, in each country.

4. Discussion

4.1. Methods for Identifying Active, Former, and Potential Floodplains

To identify the active floodplains, a hydraulic approach that uses the inundated areas of a 100-year return period was chosen, in alignment with previous literature [10,18,20,71]. One major advantage of this approach is that the HQ_{100} outlines are widespread and available for Europe. In contrast to previous studies [18,20], we classified the active floodplains into three groups, allowing a detailed analysis of the largest active floodplains along the Danube River. We focused on floodplains of basin-wide importance (area > 500 ha) since all DRBMPs [32,52,64] also deal with these floodplains. Other methods that use pedological and geological information [38] were not chosen due to the different availability and data quality in the Danube countries. Moreover, we considered the hydraulic approach more suitable, since, in a previous study, Eder et al. [49] used hydraulic models to calculate the retention capacity of each identified floodplain.

Identifying former floodplains is a major challenge, since human interferences have changed the river landscapes considerably, but as Hohensinner et al. [72] and Kiss et al. [73] showed, reconstruction of the historical characteristics and its surroundings prior to these interventions is possible. Various studies and methods [11,13–15,17,18] can be found in the literature that delineate former floodplains along different rivers and river sections. Some approaches use geospatial data (DEM, satellite imagery), hydraulic data (e.g., $HQ_{extreme}$ outlines), and/or historical sources, such as maps and local chronicles. Based on the concepts and techniques presented in previous studies, we developed a systematic method organized along four consecutive steps leading to the former floodplains along a river. The goal was to develop a replicable method that can be applied to other large rivers along their whole watercourse. Since the data basis for each river is individual, our method uses different data sources (geospatial, hydraulic data, and historical sources), and is structured such that it is also applicable if certain data (e.g., $HQ_{extreme}$) are unavailable. The application of the developed method shows that the different data sets complemented each other very well. Hauer et al. [35] showed that an approximate delineation of the former floodplains is possible only with a current DEM and satellite imagery. These data sets allow for identifying postglacial low terraces and breakthrough valleys. Delineation using only these data sets is not recommended, and should only be applied if no other data are available. Another method to delineate the former floodplains more accurately is to use 2D hydrodynamic models. To delineate the formerly flooded areas, the hydraulic modeler has to create an historical DEM that represents the historical characteristics of the river and its surrounding landscape before human interference. Skublics and Rutschmann [36] developed a 2D hydraulic model for a 270 km section along the German Danube, and simulated the inundation areas prior to the implementation of any human modifications. Since creating such a model requires a lot of time and resources for an entire river, we did not consider this option.

After delineating the former floodplains, potential floodplains should be identified to find possible restoration sites. Floodplains have a fundamental role in the river ecosystem, and provide numerous ecosystem services [1–3,74]. However, the reconnection of former floodplains is still a major challenge because different social needs (e.g., settlements, agriculture, hydropower, nature protection, etc.) and legal frameworks must be considered [75,76]. Our goal was to identify potential floodplains that have the potential to be reconnected in the future. Based on the former floodplains, areas for settlements and infrastructure, and certain agricultural areas (where land ownership or the legal framework does not allow compensation, or is too expensive) are excluded from the potential floodplains. Since decision makers and stakeholders play key roles in restoration projects [77–79], they should already be involved in the delineation process of the potential floodplains. In our case study (see Section 2.3.3—step III), some stakeholders excluded certain agricultural areas, where they considered restoration measures unfeasible. Hence, the potential floodplains delineated in this study represent only a small part of all potential restoration sites at the Danube River. Our aim was not to identify all potential restoration sites, but only the more realistic ones, where decision makers and stakeholders can see opportunity for future restoration projects.

All the applied methods and used data come with limitations and uncertainties, starting with the HQ_{100} outlines, which were calculated with a hydraulic model. Statistical inference plays a role here, since extreme values were extrapolated from historical data sets that are used in the model. Other uncertainties exist, for example, in the representation of the terrain and the roughness parameterization in the model. We used the results from calibrated and validated hydrodynamic models (used in the "Danube FLOODRISK" project and from national flood hazard and risk maps) to reduce uncertainty. We relied only on hydraulic data to define the active floodplains, since this approach has proven to be reliable in the past, and because we used $HQ_{extreme}$ outlines to delineate former floodplains. Thus, our approaches are based on comparable sets of data.

Moreover, we used historical data, which are also characterized by substantial uncertainties. For examples, different cartographers were involved in creating the historical maps used in our study, who certainly deployed different levels of accuracy in their work. As mentioned above, information from historical sources should be verified with current data sets or other historical sources: DEM or inundation areas based on hydraulic modeling can help conduct a plausibility check. Nevertheless, the delineated active, former, and potential floodplains and their absolute numbers presented here must be seen in light of inherent uncertainties. The mentioned sources of uncertainties may lead to incorrect results on a local scale, but the larger the study area, the better the accuracy, since they can level off. Combining and cross-checking different data sources (hydraulic data, historical sources, and current geospatial data) helps to minimize incorrect results and allows for the creation of a floodplain inventory that serves as a basis for future floodplain management.

4.2. Active, Former, and Potential Floodplains at the Danube River

The report by the DPRP [20] was the first evaluation of active, former, and potential floodplains along the Danube River. The study is mainly based on historical, topographical, and thematical maps and satellite images. Schwarz [18] updated the evaluation of the floodplains along the Danube River based on the most recent and accurate DEM at that time, and focused on the definition of postglacial terraces. As recommended by Schwarz [18] (the study by Hein et al. [19] is based on the results of his research), the present investigation completely revised and refined the delineation of active floodplains based on the results of hydraulic models, improving the delineation of earlier work. In total, we identified 347 km^2 fewer active floodplains than Schwarz [18]. Fifty hydraulically active floodplains larger than 500 ha were evaluated in a next step with the Floodplain Evaluation Matrix (FEM) [5,48] to assess the value of these areas for flood protection, ecology, and socio-economy [49].

The comparison with previously delineated former floodplains of Schwarz [18] showed that the delineation with the data at that time was matching in some parts. Still, in other areas, the new sources led to changes in the extent of the former floodplains. In total, we identified 2067 km^2, in addition to the formerly flooded areas from the previous study [18]. Especially at the Middle Danube, the former floodplains are around 2180 km^2 larger than in Schwarz [18]. In the upper and lower sections, the former floodplains are smaller by 97 km^2 and 16 km^2, respectively.

This paper builds on the outputs of the "Danube Floodplain" project, where representatives ranging from national water administrations and universities to NGOs collaborated to delineate the potential floodplains using the presented method. All the national partners identified the potential restoration sites in their countries of responsibility. The Danube River case study shows that, even though perhaps more realistic potential floodplains were identified, with 24 potential sites and a total area of 1090 km^2, the potential floodplains delineated in our work are much smaller than reported in an earlier assessment by the DPRP [20], which delineated ten areas for future restoration covering 2774 km^2. In Schwarz [18], 196 potential restoration sites with a total size of 8102 km^2 (1797 km^2 on active and 6305 km^2 on former floodplains) were reported. In both past studies, agricultural land uses were not excluded from the potential floodplains. In our investigation, the political and socio-economic conditions have led to large areas, such as Balta Ialomita, Big and Small Islands of Braila, which are former floodplains, not being identified as potential areas, although they are mainly used for agriculture. The reason for this is that the involved representatives of these countries did not see these areas as realistic restoration areas. The combined share of active and potential floodplains compared to the former floodplains ranges between 5% and 49% in the individual countries, with a median of 37%, showing that the potential in each country is still high. Hence, the potential floodplains delineated in this study represent only a small part of all potential restoration sites at the Danube River. One future goal should be to increase these percentages and identify even more potential floodplains.

The total loss of former floodplains along the Danube River equates to 79%, without the Danube Delta, which is comparable with other large rivers, such as the Rhine, with a loss of 84% [80], or the Lower Mississippi, with a reduction of about 90% [81]. The results of the ratio between active, potential, and former floodplains show that there are significant differences between the three Danube sections. In the upper section, the share of active floodplains on the former floodplains is about 41%, which is much higher compared to the 14% coverage of the formerly flooded areas in the Middle Danube. One reason for this is that the Upper Danube is an alpine river with many breakthrough valleys, where a large expansion of floodplains is not possible due to the limitation of the mountains, and thus only smaller areas could be disconnected there. In the Middle Danube, there is the Pannonian lowland, where the flat terrain enabled the inundation of an average 30–35 km wide area. These large floodplain areas offered the perfect place for agricultural activity, so they were disconnected by artificial levees. Moreover, the construction of flood protection dikes began earlier in the middle section [82], which might have contributed to the disconnection of larger areas from the former floodplains. After breaking through the Carpathian Mountains, the Danube River passes through the Wallachian lowlands in the lower part of the river, where the river had more space to expand than in the upper section. At the Lower Danube, 23% of the formerly flooded areas are still inundated during a 100-year return period. The current land use shows that most hydraulically preserved floodplains in the upper section have lost their natural properties. Especially in mountainous regions where space is limited, the valley bottom, where the rivers and their floodplains are located, is used for agriculture. At the Lower Danube, hardly any agricultural uses are found on the active floodplains. One reason for this might be that the flood characteristics in the upper and lower sections are quite different. At the Lower Danube, the floodplains can be inundated for several weeks during a flood event due to lower flood dynamics [83,84], which would also substantially reduce the period for agricultural use. However, on the former and potential floodplains, the land uses are more or less similar for all countries, since these areas are mainly used for agriculture, followed by forest and semi-natural areas. Fremling et al. [81] showed that most of the former floodplains along the Lower Mississippi are also used for agricultural purposes.

4.3. Floodplain Management

Floodplain ecosystems are among the most diverse and productive on the planet [85]. Despite their numerous benefits, up to 90% of former floodplains are lost or impaired by human activities in Europe and North America [9]. Economic growth, increasing population size, and ongoing urbanization threaten the remaining active floodplains. Creating an inventory of active, former, and potential floodplains along a river could support the preservation and restoration of floodplains since, in this way, the losses and potential restoration sites can be shown.

However, various stakeholders and decision makers have differing and sometimes conflicting priorities [19]. In fact, floodplain restoration implies tradeoffs among multiple aspects (ecology, ecosystem services, land uses, costs), thus, a compromise must be met among all interested groups [12], and requires solving multiple organizational issues (discussions with landowners, meeting deadlines, securing funding, supervising staff, and cooperating with politicians), as well as scientific work [86].

How can we encourage stakeholders to see floodplain restoration as a positive measure? It should be made clearer that the restoration of potential floodplains does not only indirectly benefit people by benefitting the environment, but also directly via better economic possibilities. For example, the restoration in Babina and Cernovca (RO) in the Danube Delta has brought back the traditional economic occupations of the local population —fishing, hunting, reed harvesting [87]. Therefore, funders and planners should ensure that the full range of values of restoration projects is assessed and measured to facilitate decision making [4]. Multiple methods exist for evaluating restoration measures of potential floodplains in all its facets, e.g., through ecosystem services assessments [88,89], multicriteria decision-making methods [90], or cost-benefit analyses [91,92]. Another way to facilitate floodplain restoration is to evaluate the identified potential floodplains with the Floodplain Evaluation Matrix (FEM), which could demonstrate the value of the additional areas for flood protection, ecology, and socio-economy, and also increase the willingness to reconnect the identified areas. Eder et al. [49] assessed the potential floodplains delineated in this study with the FEM.

A major class of stakeholders involved in the implementation of floodplain restoration projects are landowners, who, in some cases, do not agree with trading their land. If land acquisition is not possible, another solution would be to make a contract with private partners, i.e., a public–private partnership [86]. Payments for ecosystem services, i.e., payments to landowners or managers to provide or protect ecosystem services [88], can be effective elements with which landowners and farmers receive payments to manage their land properly and avoid public costs related to unsustainable land use (e.g., water contamination or soil degradation) [93], benefitting landowners as well as others [94]. This voluntary scheme could facilitate the adoption of environmentally sound land use practices, making economic factors include otherwise unvalued externalities in their floodplain management [95]. For this, it should be made clear in advance how the restoration measures might affect landowners, for example, it would be useful to estimate whether and by how much farmers might experience losses in terms of agricultural production.

Learning from previously implemented projects could also help get ideas on the next steps to follow after delineating active, former, and potential floodplains. For example, the "Room for the River" program (completed in 2018 in the Netherlands [96]), included over 30 projects along four major rivers, and was not only able to reduce the risk of flooding, but also to provide valuable habitats and offer high potential for tourism and recreation [93,97,98]. On the Danube, much work was already conducted by the Integrated Danube Programme (IDP), which was adopted for the Upper Danube (from the source rivers Brigach and Breg to the town of Ulm), and aimed to combine flood protection and ecological restoration of floodplains [12], floodplain restoration along the Danube between Neuburg and Ingolstadt, and along the Danube's Green Corridor [99].

Some results from the "Danube Floodplain" project and this study contribute to the latest version of the Danube River Basin [32] and Flood Risk Management Plan [32], giving some strategic guidance and a restoration roadmap. However, a concrete large- or basin-scale restoration program is still missing at the Danube level. This is due to the high international level of the catchment [19], which leads to inconsistencies in river management legislation, differences in socio-economic conditions, and high complexity and heterogeneity of the environmental problems. Moreover, data availability also plays a role [1].

Nevertheless, even on large rivers, restoration work can still be performed successfully [12]. To reach this goal, stakeholder involvement should be improved and long-term planning should be undertaken [86]. On one hand, we need to show all the benefits of restoration (flood risk, ecosystem improvement, etc.) to attract funding from different sources [100]. On the other hand, we should not take ecological improvement for granted, and standards for measuring the success of an ecological river restoration should be used [101]. Within the "Danube Floodplain" project, a catalogue of floodplain restoration measures (Deliverable 5.2.1 (https://www.interreg-danube.eu/approved-projects/danube-floodplain/outputs accessed on 20 May 2022)) was created to promote win–win measures for reaching multiple goals (e.g., flood risk reduction, ecological improvements, etc.). After restoration is implemented, monitoring the floodplain will be fundamental, to ensure that the system functions in a sustainable way or to understand whether additional measures are needed for the system to operate in a self-regulatory manner [12]. The results of monitoring should then be communicated to funders, stakeholders, restoration practitioners, scientists, and policy makers [101].

5. Conclusions

Methods used to identify active, former, and potential floodplains are presented and applied for the case study of the Danube River. For identifying active floodplains, a hydraulic approach based on the inundation areas of a 100-year return period was used, as this data set is widespread and available for many large rivers. Hydraulic data, historical sources, and current geospatial data were combined to delineate former floodplains. This approach enables a more accurate delineation of formerly flooded areas in comparison to using only one data set. The comparison with the active floodplains showed that 79% of the former floodplains along the Danube River were lost due to human pressures, such as land use change, river regulation, and dam construction. Based on the identified former floodplains, potential floodplains were delineated with the support of different representative institutions from the basin countries, ranging from national water agencies and universities to NGOs. Twenty-four potential floodplains covering 1090 km^2 were identified. However, the share of active and potential (arising from the former) floodplains ranges between 5% and 49%, indicating that further work could be undertaken to identify additional restoration sites. It was also shown that the involved institutions were acting conservatively when establishing restoration areas so that large-scale restoration sites were rarely delineated, although former floodplains are mainly used for cultivation purposes. Agricultural usage is also the predominant land use on the active floodplains at the Upper Danube. At the Lower Danube, the active floodplains have a more natural land use, where the forest and semi-natural class is dominant. Additionally, potential floodplains are mainly used for cultivation purposes, a factor that will have to be considered when actually implementing the restoration measures.

This work, along with others before, is a wake-up call regarding the dramatic floodplain loss that has taken place so far, and could still happen in the future. A comprehensive and systematic analysis of active, former, and potential floodplains along a river or in a catchment contributes to an understanding of the current, as well as the past, floodplain situation. Others can use this example as a basis for the analysis of floodplain loss and restoration potential, and for future-oriented floodplain management. An application at other large rivers (e.g., Nile, Mississippi) is desirable, and an inventory of active, former, and potential floodplains would help floodplain managers in the future (or preferably at present time) with the preservation and restoration of floodplains. Providing an online inventory, such as the "Danube Floodplain GIS (http://www.geo.u-szeged.hu/dfgis/ accessed on 20 May 2022)", which shows some of the results of this study, could raise awareness of the immense floodplain loss, allowing the public to actually visualize the former floodplains on a map and compare them with the identified active floodplains. Evaluating active and potential floodplains can deliver arguments for preserving and restoring these areas, and support more sustainable floodplain management.

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Appendix A

LEVEL 1	LEVEL 2	LEVEL 3
1. ARTIFICIAL SURFACES	1.1. Urban fabric	1.1.1. Continuous urban fabric 1.1.2. Discontinuous urban fabric
	1.2. Industrial, commercial and transport units	1.2.1. Industrial or commercial units 1.2.2. Road and rail networks and associated land 1.2.3. Port areas 1.2.4. Airports
	1.3. Mine, dump and construction sites	1.3.1. Mineral extraction sites 1.3.2. Dump sites 1.3.3. Construction sites
	1.4. Artificial, non-agricultural vegetated areas	1.4.1. Green urban areas 1.4.2. Sport and leisure facilities
2. AGRICULTURAL AREAS	2.1. Arable land	2.1.1. Non-irrigated arable land 2.1.2. Permanently irrigated land 2.1.3. Rice fields
	2.2. Permanent crops	2.2.1. Vineyards 2.2.2. Fruit trees and berry plantations 2.2.3. Olive groves
	2.3. Pastures	2.3.1. Pastures
	2.4. Heterogeneous agricultural areas	2.4.1. Annual crops associated with permanent crops 2.4.2. Complex cultivation patterns 2.4.3. Land principally occupied by agriculture, with significant areas of natural vegetation 2.4.4. Agro-forestry areas
3. FOREST AND SEMI-NATURAL AREAS	3.1. Forests	3.1.1. Broad-leaved forest 3.1.2. Coniferous forest 3.1.3. Mixed forest
	3.2. Scrub and/or herbaceous associations	3.2.1. Natural grassland 3.2.2. Moors and heathland 3.2.3. Sclerophyllous vegetation 3.2.4. Transitional woodland-scrub
	3 .3. Open spaces with little or no vegetation	3.3.1. Beaches, dunes, sands 3.3.2. Bare rocks 3.3.3. Sparsely vegetated areas 3.3.4. Burnt areas 3.3.5. Glaciers and perpetual snow
4. WETLANDS	4.1. Inland wetlands	4.1.1. Inland marshes 4.1.2. Peat bogs
	4.2. Marine wetlands	4.2.1. Salt marshes 4.2.2. Salines 4.2.3. Intertidal flats
5. WATER BODIES	5.1. Inland waters	5.1.1. Water courses 5.1.2. Water bodies
	5.2. Marine waters	5.2.1. Coastal lagoons 5.2.2. Estuaries 5.2.3. Sea and ocean

Figure A1. Overview of the three levels of land uses categories of the CORINE land cover data set.

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