Received: 10 November 2020 | Revised: 14 June 2021 | Accepted: 15 June 2021

DOI: 10.1002/wat2.1545

FOCUS ARTICLE

WIREs WATER WILEY

Managing floodplains using nature-based solutions to support multiple ecosystem functions and services

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Funding information
European Cooperation in Science and Technology, Grant/Award Number: CA16209; Javna Agencija za Raziskovalno Dejavnost RS, Grant/Award Number: P2-0180; Ministerstvo Školství, Mládeže a Tělovýchovy, Grant/Award Number: LTC18025

Edited by: Stuart N. Lane, Editor-in-Chief

Abstract

Floodplains include unique environments shaped over a long time horizon along rivers and smaller streams and formed by alluvial sediments. As floodplains are flat, often with highly fertile and well-accessible land, they have become the intrinsic focus of human society—while providing a variety of goods and ecosystem services. Intensive land use of floodplains is degrading their natural values and significantly reducing their ecosystem functions and services. A significant part of these key services is related with the ability of floodplains to retain water and nutrients, which can be understood as a flood control and a water-retention function. Although these ecosystems serve a number of other basic functions, the importance of floodplains as a place for water retention during extreme discharges caused by intense rainfall or snowmelt and the supply of water in times of drought are essential under conditions of global change. In order to increase the ability of floodplains to perform these functions, it is increasingly required to preserve the connectivity of rivers with surrounding floodplains and adapt human activities to maintain and restore river ecosystems. This article reviews the recent understanding of floodplain delineation, the most common causes of disturbance, the ecosystem functions being performed, discussing in turn the measures being considered to mitigate the frequency and magnitude of hydrologic extremes resulting from ongoing environmental changes.

This article is categorized under:

Water and Life > Conservation, Management, and Awareness
Engineering Water > Planning Water

1 | INTRODUCTION

Floodplains are specific parts of the natural landscape, whose formation and existence are due to their association with a watercourse, allowing the exchange of flow, sediment, nutrients, and organisms (Amoros and Bornette, 2002; Benjankar, Egger, Jorde, Goodwin, & Glenn, 2011). Mostly defined as an area along the watercourse, floodplains are usually formed by alluvial sediments deposited during floods of varying magnitude and associated geomorphological processes (e.g., Lewin, 1978; Nardi, Vivoni, & Grimaldi, 2006). Flooding, with a wide variety of discharge magnitudes and events ranging from extreme low flow events to infrequent high flow events (Poff et al., 1997; Whiting, 2002), underpin floodplain ecosystem dynamics and influences a variety of biophysical and territorial features (e.g., fluvial landforms, soil hydrology, or vegetation patterns), being a crucial process for ecosystem functioning. The timing, duration, and magnitude of floods influence the structure of riparian communities (Auble & Scott, 1998; Scott, Shafroth, Auble, & Eggleston, 1997), as well as ecosystem functions and services. At the same time, flooding can be a dangerous phenomenon when floodplains are intensively developed (de Martino, de Paola, Fontana, Marini, & Ranucci, 2012). The strength of connectivity between a river and the surrounding terrestrial environment (i.e., the floodplain) varies depending on the hydrogeomorphic control of the downstream flux of water and materials—both dissolved and particulate matter (Stanford, Lorang, & Hauer, 2005). A river should retain a flow regime with sufficient variability to encompass the flow levels and events that support important floodplain processes (Opperman et al., 2010). Lateral exchange between river channels and their floodplains, known as hydrologic connectivity, has been identified as a key variable in biodiversity and composition of aquatic (e.g., Desjonquères, Rybak, Castella, Llusia, & Sueur, 2018; Leigh & Sheldon, 2009; Paillex, Dolédec, Castella, Mérigoux, & Aldridge, 2013) and terrestrial (e.g., Casco, Neiff, & de Neiff, 2010; Souter, Wallace, Walter, & Watts, 2014) biological communities. Hydrological connectivity also represents a key feature supporting ecosystem processes such as nutrient turnover and geomorphic change (Hein, Baranyi, Reckendorfer, & Schiemer, 2004; Schönbrunner, Preiner, & Hein, 2012; Welti, Bondar-Kunze, Tritthart, Pinay, & Hein, 2012 or Park, 2020).

Floodplain ecosystems are unique in terms of their constantly recurring hydrological dynamics (Funk et al., 2019; Schindler et al., 2014; 2016), which result from the interaction of geomorphic, hydrological, and biological processes (Tomscha et al., 2017). Together with the outstanding ability of floodplains to retain water (Getirana et al., 2017), such intrinsic dynamics modify morphology and water conditions and ensure the high diversity of natural conditions, as well as their temporal variability (Tockner et al., 2000), maintaining a highly diversified mosaic of habitats, from open soils to deciduous forests (Fischer et al., 2019), with a marked variability of aquatic, semi-aquatic and terrestrial habitats (Hughes et al., 2005). Worldwide, with some of the most distinctive examples found in Europe, floodplains are threatened by the loss of floodplain and riparian habitats, as well as by pollution and alteration of hydromorphological conditions (Funk et al., 2020; Habersack et al., 2016; Vörösmarty et al., 2010). The most obvious effect of human activities is urbanization, which increases the proportion of impermeable surfaces in floodplains, degrades landform diversity, and affect sediment balance by altering runoff regimes (Chin, 2006; Booth and Bledsoe, 2009; Raška et al., 2019). Additionally, levee construction along rivers often exacerbates the downcutting of riparian forests or plant communities and increases in bank height, reflecting the urgent need for channel stabilization measures following changes in flow or sediment regimes (Zachary et al., 2003). Higgisson et al. (2020) considers water resource development to be one of the main causes of floodplain degradation, which has led to a decline in floodplain ecological condition.The embankment and isolation of rivers from their floodplains, which allows their intensive use for agriculture, settlements or traffic routes, are among the most common interventions in Central and Southern European floodplains (Hein, Schwarz, et al., 2016). The floodplain that remains active are altered due to these changes and habitat regeneration is hindered (Díaz-Redondo et al., 2017). Where floodplain forests remain, they are mostly converted from naturally regenerating stands to stands managed for forestry. The extensive hardwood forests of Central European floodplains are of particular economic importance (Klimo and Hager, 2008). Wetlands are being replaced by plant communities adapted to the water regime of reservoir shorelines (Keddy, 2010), or even with forestry systems using non-native tree species (Hughes et al., 2012). Recreation in floodplains is increasing in many parts of Europe, being a threat to conservation goals as well as a chance for a better public appreciation of the value of floodplains and rivers (Hughes et al., 2012). Channel stabilization and peak flow reduction in turn, disconnect a river channel from a floodplain, reducing both the channel migration rates and the channel avulsion (rapid channel shift during floods; Shields Jr et al., 2000, Zachary et al., 2003). Approximately 70–90% of Europe's current floodplain area is estimated to be ecologically degraded due to human activities over the centuries, especially since the early 1950s (EEA, 2018), thus we can summarize that Europe is the continent most affected by disconnection of floodplains from rivers (Nilsson et al. 2005; Schindler et al. 2016). Tockner and

Stanford (2002) suggested that approximately 46% of floodplains in North America (excluding northern Canada and Alaska) were intensively cultivated, and 11% of floodplains across Africa were farmed at the beginning of the 21st century. According to Erwin (2009), 90% of floodplains in North America are described as "cultivated" and non-functional. Furthermore, climate projections in many parts of Europe, as well as other regions of the world, indicate an increasing occurence of intense rainfall and prolonged droughts, which would affect the condition of floodplains (e.g. Moradkhani et al., 2010; Schneider et al., 2011; Politti et al., 2014 or O'Briain, 2019). This article brings an overview of ecosystem functions and services provided by floodplains and focuses on (a) operational frameworks for defining floodplains, (b) major causes of their disturbance, and (c) more general approaches for protecting and restoring these ecosystems. The issue of floodplain protection is outlined in this study with examples of the current situation in several Central and Southern European countries.

2 | FLOODPLAIN DEFINITION

2.1 | Floodplain as a soil phenomenon

Different approaches have been adopted over the time to distinguish the floodplains from other landscape types. Derived from the definition of a floodplain as an area along a watercourse formed by alluvial sediments deposited during floods, gathering information on the soil properties or spatial extent of the inundation area is the most relevant approach. A necessary prerequisite for this approach is data available at a relatively detailed scale (spatial resolution) and comparable across larger territorial units or countries (Jakubínský et al., 2020). Using soil data, a floodplain is usually defined based on the spatial distribution of hydromorphic soils, characterized by the temporary or permanent wetting of soil pores. Fluvisol is the most widespread floodplain soil type, formed by erosion of sediments in the upland zone and deposited in lowland sites with flat valley bottoms in the transfer (piedmont) zone (WRB, 2015). Another soil type that commonly found within a floodplain is Gleysol (WRB, 2015), the formation of which is influenced by periodic recurring or persistent excess moisture in the near-surface soil layers. In addition, a much less widespread soil type within a floodplain is Phaeozems (Fluvic Phaeozems according to WRB [2015]), in the form of deep semi-hydromorphic soils. The spatial extent of certain soil types represents a stable component of the landscape. In fact, even after a possible loss of floodplain connectivity with the watercourse due to anthropogenic interventions, the soil types remain for a long period of time, although the floodplain itself loses its natural functions.

2.2 | Hydrologically conceived floodplain

Hydrological and hydraulic data, mostly the results of modeling based on digital elevation models (DEMs), are often used to define floodplains, in particular using the extent of inundated areas of 100-year flood (e.g., Omer et al., 2003 or EEA, 2018). However, other values have been frequently used. For instance, Witner (1966) proposed an area of alluvial soils corresponding to 50-year floods. Within this hydrological approach, the identification of floodplains relied upon the creation of flood hazard maps, produced through detailed hydraulic modeling techniques (Grimaldi et al., 2013; Noman et al., 2001). Existing methods for delineating inundated areas using hydraulic simulations were reviewed by Noman et al. (2001) and Horritt and Bates (2002). Although these techniques and models can result in highly accurate delineation of a floodplain, they can be computationally expensive and time-consuming to run, requiring the calibration of a large number of variables and model parameters (e.g., Horritt and Bates, 2002; Liu and Gupta, 2007). Additionally, adequate input data (e.g., river cross-section or floodplain LiDAR data) are needed to obtain reliable results. The significant refinement and facilitation of modeling is currently related to the availability of very accurate elevation data provided by remote sensing technologies such as LiDAR (Light Detection and Ranging) methods in a number of affluent countries (e.g. Bezak et al., 2018; Rak et al., 2018; Ureta et al., 2020). In contrast to soil data, operational definitions by flooded area are highly dependent on valley floor terrain characteristics and any anthropogenic intervention can directly affect the extent of inundated areas and, thus, floodplains defined in this manner.

Since hydrologically and hydraulically defined floodplains depend on terrain characteristics, this delineation approach is also understood as a "hydrogeomorphic method" (Nardi et al., 2006). This method uses GIS technologies and hydrologic modeling techniques (e.g., HEC-RAS software; Ackerman et al., 2009; Patel et al., 2016) to delineate floodplains as buffers at a specified distance from the watercourse (Entwistle et al., 2019), depending on the elevation of the terrain above the river water level. Floodplain delineation approaches (based on hydrologic–hydraulic and soils data) often achieve very similar results in terms of the spatial extent of the defined floodplains in non-urban areas, as evidenced in Figure 1. In urban areas, on the other hand, both approaches can be very different in terms of the location of the borderline between the floodplain and the surrounding landscape, due to anthropogenic influences (e.g., the presence of levees, flood protection walls and road or railway embankments).

In the Figure 2a, a broad active floodplain, which is limited by the slope edge adjacent to the valley floor, is depicted. In contrast, Figure 2b shows the influence of anthropogenic landforms (presence of levees) affecting the extent of the active floodplain, which is inundated during regular flood events. Behind the levee, the pedologically defined floodplain (also referred to as the "geologic floodplain" according to Fuller [2018]), i.e., alluvial soil types formed in the past, actually shows intermittent connectivity with the riverbed in the presence.

2.3 | Floodplain according to specific vegetation

As floodplains represent a specific environment formed by a long-term connectivity with a watercourse, in the case of less-significant anthropogenic interventions and a minor modification of the natural environment, they can also be defined on the basis of specific vegetation cover. These are almost always communities of azonal vegetation that do not

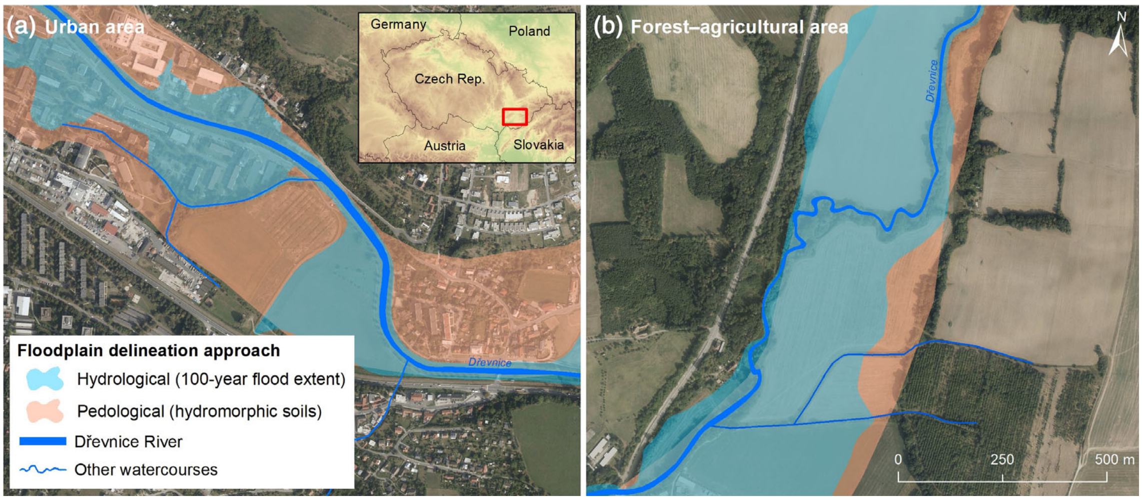

FIGURE 1 Comparison of floodplain areas defined on the basis of hydrological and pedological data along the Dřevnice River in the Czech Republic, in urban (a) and forest-agricultural (b) landscape.
Source: authors, based on data provided by T. G. Masaryk Water Research Institute and Research Institute for Soil and Water Conservation

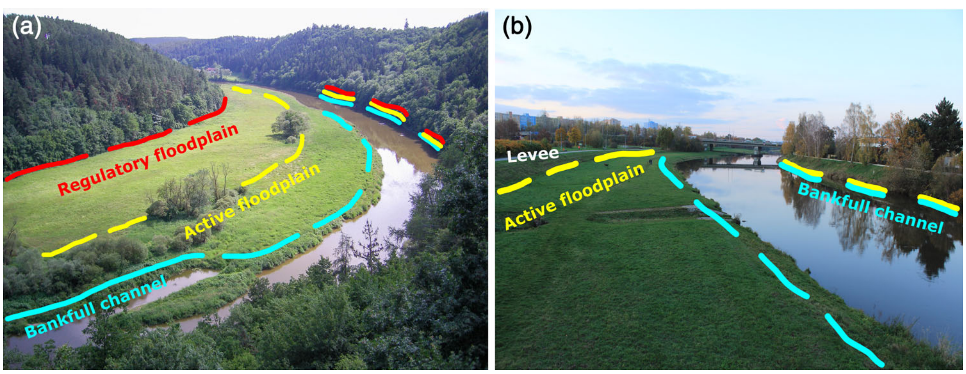

FIGURE 2 (a) Floodplain area covering the entire valley floor in the case of a near-natural landscape (the Berounka River floodplain, Czech Republic); (b) urban floodplain limited by the presence of levees (the Vltava River floodplain in České Budějovice, Czech Republic).
Source: authors

occur in any other landscape type than in floodplains, depending on the specific location relative to the channel axis (Tockner and Stanford, 2002). Spatiotemporal variability in surface and groundwater hydrology, microclimate, geomorphology, and soils, combined with inter- and intraspecific competition, results in distinctive floodplain biodiversity (Hughes et al., 2005; Meli et al., 2014; Robinson et al., 2002; Salo et al., 1986) that is most evident along aquatic–terrestrial boundaries (Bunn and Arthington, 2002). Dynamic fluvial processes cause habitat rejuvenation and succession (Hohensinner and Drescher, 2008), resulting in habitat heterogeneity (Opperman et al., 2010), which supports a floodplain with a shifting mosaic of habitat patches in terms of species, age classes, and physical structure (Ward et al., 2002). Many authors (e.g., Evette et al., 2014; Sponseller et al., 2013; Corenblit et al., 2014 or McShane et al., 2015) identify hydro-climatic constraints such as climate, soil moisture availability and fluvial disturbance as a major factor influencing vegetation near watercourses. Gurnell et al. (2016) propose the conceptual model of vegetation—hydrogeomorphology interactions using so-called dynamic zones within river corridors where different hydrogeomorphological processes dominate so that plants and hydrogeomorphological processes interact in different ways.

3 | THE ECOSYSTEM FUNCTIONS AND SERVICES OF A FLOODPLAIN

Floodplains represent one of the most productive ecosystems on Earth (Opperman et al., , 2010b). The high degree of biodiversity and level of primary productivity of floodplains exceed the production of either purely terrestrial or aquatic ecosystems (Tockner and Stanford, 2002). The dynamics and naturally high biodiversity of floodplains are responsible for their high multifunctionality (Meli et al., 2014; Funk et al., 2020). Focusing on the value of global ecosystem services, Costanza et al. (1997) found that floodplains are the second best ranked ecosystem type, behind estuaries, in terms of their per hectare value to society. Despite representing <2% of the Earth's terrestrial land surface area, floodplains provide approximately 25% of all "terrestrial" (i.e., non-marine) ecosystem service benefits, with the regulation of disturbance (i.e., attenuation of flood flows) providing the greatest value (Akanbi et al., 1999). Floodplains contribute to a wide range of ecosystem functions by controlling the regional hydrologic cycle and the retention and transformation of nutrients in river systems (Sanon et al., 2012; Schindler et al., 2014; Weigelhofer and Hein 2015). Their connectivity patterns are also crucial for the provisioning of ecosystem services, including floodwater retention (e.g., Clilverd et al., 2016; Habersack et al., 2015; Schober et al., 2015), nutrient retention (e.g., Hein et al., 2004; Natho et al., 2013; Newcomer Johnson et al., 2016), or greenhouse gas emission retention (e.g., Audet et al., 2013; Funk et al., 2020). Other ecosystem services provided by floodplains include surface water filtration (Mitsch et al., 2001; Noe and Hupp, 2005), groundwater recharge (Hein et al., 2004; Jolly, 1996), water purification (Hein, van Koppen, et al., 2016), and provision of food and fiber (e.g., fish, timber, and other plant resources; Welcomme, 1979). Fisheries supported by floodplain productivity provide one of the most tangible examples of an economically and socially valuable ecosystem service (Opperman et al., 2010). Furthermore, recent efforts to quantify the cultural ecosystem services provided by floodplains and river ecosystems point to a range of non-material benefits (Funk et al., 2020; Hale et al., 2019). Traditionally, floodplains provide various water-related recreational opportunities, including swimming, boating, angling, and ice skating (Funk et al., 2020). River landscapes may also be valued for their aesthetic quality and cultural or heritage significance (Ghermandi et al., 2020; Thiele et al., 2020; Tieskens et al., 2018). A list of the key ecosystem functions and services provided by floodplains can be found in Table 1.

Floodplain ecosystem services are inextricably linked to hydrology (Morris et al., 2009); the hydrologic regime of a floodplain determines what will grow there and how it can be used (Posthumus et al., 2010). Forest ecosystems in particular depend on natural hydrological and biological diversity (Turner et al., 2016), which are very important for the delivery of regulation, provisioning, and cultural services (Mamat et al., 2018; Xu et al., 2017). Our understanding of ecosystem services can benefit greatly from drawing on classic river–floodplain principles that recognize both longitudinal and lateral connectivity (Tomscha et al., 2017).

Floodplains host a unique suite of habitats, and their composition and condition can serve as indicators of the ecosystem services they are able to provide (Burkhard et al., 2012; Podschun et al., 2018). Riparian systems (vegetation in close proximity to the watercourse) are those of a highest importance; due to their spatial location and connectivity with stream channels, they are inundated periodically and play an important role in water infiltration and aquifer recharge (Gonzalez del Tanago et al., 2011), as well as flood attenuation and hydrological risk reduction (Horn and Richards, 2006). Anderson et al. (2006) reported that these are especially smaller floods (with an average recurrence interval of 2 or 5 years) that are more sensitive to the riparian vegetation conditions, and in these cases riparian

TABLE 1 The frequently cited ecosystem functions and services of floodplains and their measured parameters/indicators (a nonexhaustive list)

Category of service (CICES section)	Ecosystem function	Class of ecosystem service (CICES v5)	Parameter/indicator
Provisioning	Production (biomass)	Fibers and other materials from cultivated (and wild) plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials); Animals reared for nutritional purposes	Gross output[1]; Annual biomass increase[2]; Nutritive productivity[2]
	Water-retention and evapotranspiration	Surface water used as a material (non-drinking purposes); Ground and subsurface water for drinking	Difference between water rainfall and evapotranspiration[3,4,5]; Potential for water provision[6]
Regulation and Maintenance	Water-retention	Hydrological cycle and water flow regulation (Including flood control, and coastal protection)	Time to fill water capacity; Curve number (CN) [7]; Quality of land cover, slope, soil permeability and flow length[8]; Floodplain water storage volume[9,10]; Effective retention volume[11,12]; Net supply of water remaining after evapotranspiration losses[4]; Water holding capacity[13]; Retaining coefficients for forest management [5]
	Self-cleaning processes of water	Mediation by other chemical or physical means (e.g. via Filtration, sequestration, storage or accumulation)	Nutrient leaching [1]; Nitrogen leaching from floodplain area [4]; Total nitrogen and total phosphorus removed from water[3]; Phosphorus load in the river modeled by InVEST[15]; Water quality index [6]; Diversity of the instream macroinvertebrates[16]
	Evapotranspiration and Condensation	Regulation of chemical composition of atmosphere and ocean (e.g., greenhouse gases concentration, isotopic variance in atmospheric moisture); Carbon sequestration by terrestrial ecosystems	Inverse values of daily temperatures range for land use types [2]; Evapotranspiration[17,18,19]; Albedo of land use types[17]; Extent of vegetation cover[14]; Evapotranspiration and heat exchange based on functional plant traits [20]; Land surface temperature[21]
	Carbon capture	Carbon sequestration by terrestrial ecosystems	Carbon sequestration by plants[2]; Above ground carbon storage [22]; Global warming potential[1]; Carbon stock [6]; Fluxes of greenhouse gases for land use types[10,4]
	Mineralization and accumulation of organic matter, storage and recycling of nutrients	Decomposition and fixing processes and their effect on soil quality	Soil carbon stock [1]; Organic matter layer and total nitrogen in top soil[2]; Floodplain connectivity[14]
	Functions of species composition and diversity	Maintaining nursery populations and habitats (Including gene pool protection)	A species value indicator[1]; Habitat-conservation value[1]; Riparian quality index[2,23]; Habitat provision index[24]; Fish capacity index [22]; Diversity of the instream macroinvertebrates [16]; Proportion of natural land cover weighted by a condition index[4]; Presence of threatened species[14]; Habitat value according to Habitat Valuation Method[25]

TABLE 1 (Continued)

Category of service (CICES section)	Ecosystem function	Class of ecosystem service (CICES v5)	Parameter/indicator
Cultural	Recreation	Characteristics of living systems that enable activities promoting health and wellbeing, recuperation or enjoyment through active or immersive interactions; Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions	Possibility to experience the terrain, Presence of protected areas, Water surface area, Presence of sandbanks and meanders, Visibility depth, Minimum width for (non-) motorized boating[26]; Frequency of tourists per year[27]; Content of geotagged photographs uploaded to social media sites[28,31,32]; Diversity of potential for nature experiences[29]; Recreation potential, Recreation opportunity spectrum[30]
	Heritage	Characteristics of living systems that are resonant in terms of culture or heritage	Density of monuments and cultural-historical facilities, Density of archeological and natural monuments[26]; Content of geotagged photographs uploaded to social media sites[28,32]
	Aesthetic values	Characteristics of living systems that enable aesthetic experiences	Landscape diversity, naturalness and uniqueness[26,33]; Level of aesthetic value[27]; Content of geotagged photographs uploaded to social media sites[28,32]

Note: Source: authors. [1]Posthumus et al. (2010); [2]Felipe-Lucia et al. (2014); [3]Boithias et al. (2016); [4]Ausseil et al. (2013); [5]Morri et al. (2014) [6]Larsen et al. (2012); [7]Fu et al. (2013); [8]Nin et al. (2016); [9]Grygoruk et al. 2013; [10]Peh et al. (2014); [11]Pithart et al. (2010); [4]Ausseil et al. (2013); [12]Karpack et al. (2020); [13]Ghaley et al. (2014); [14]Peters (2016); [15]Johnson et al. (2012); [16]Ncube et al. (2018); [17]West et al. (2011), [18]Smith et al. (2013); [19]Serna-Chavez et al. (2017); [20]de Bello et al. (2010); [21]Alkama and Cescatti (2016); [22]Tomscha et al. 2017; [23]Gonzalez del Tanago et al. 2011; [24]Fischer et al. 2019; [25]Seják et al. (2010); [26]Thiele et al. 2020; [27]Ajwang' Ondiek et al. 2016; [28]Ghermandi et al. 2020; [29]Funk et al. (2020); [30]Grizzetti et al. (2019); [31]Tieskens et al. (2018); [32]Hale et al. (2019); [25]Thiele et al. (2020); [33]Thiele et al. (2019). CICES stands for the Common International Classification of Ecosystem Services developed by the European Environment Agency (EEA).

vegetation affects the magnitude of a flood event and the resulting damage. As an important landform agent and flow resistance factor, riparian vegetation is responsible for the majority of energy losses in fluvial systems by controlling sediment erosion, transport, and deposition in both the channel and floodplain (Corenblit et al., 2008; Gonzalez del Tanago et al., 2011). The most important ecological functions of the riparian zone include providing a habitat and refuge for aquatic and terrestrial species, facilitating biological connections across the landscape, maintaining plant diversity, providing organic material to aquatic food chains, and controlling stream water temperature (Forman, 1999; Gonzalez del Tanago and Garcia de Jalon, 2011). These functions are all related to the dimensions, longitudinal continuity and vegetation structure of riparian corridors (Gurnell et al., 2016), becoming particularly important in regions with a Mediterranean-climate (Stella et al., 2013). In addition, riparian vegetation provides many other aesthetic and economic benefits, including food resources (Pusey and Arthington, 2003).

4 | DISTURBANCE, PROTECTION, AND RESTORATION OF FLOODPLAINS IN CENTRAL AND SOUTHERN EUROPE

Almost all large rivers in Central and Southern Europe are affected by dikes and other flood-protection measures, in major catchments, such as the Rhine, Elbe, Danube and Oder, only 10–20% of the former floodplains are left as inundation areas (Brunotte et al., 2009). Only 10% of the original extent of European floodplain forests has been preserved, most of which are located in Eastern Europe (Hughes et al., 2012). Areas with the best-preserved floodplain forests remained in Croatia along the Danube and Sava Rivers (Anić, 2008). Many floodplain areas were drained in the past in order to intensify agricultural use, for example in Slovakia (Holubová et al., 2003), in the Czech Republic (Brázdil et al., 2011) or in Hungary in large parts of the Tisza lowland basin (Szmańda et al., 2008). Recently, urbanization and the development of new transport routes along river valleys with associated channelization works are another threat to floodplains, particularly in some Mediterranean countries and in the more recent accession countries of Central Europe (Hughes et al., 2012). The construction of dams also has a significant impact on floodplains, not only affecting the area inundated by the construction of a waterworks, but the sediment starvation downstream of dams has perhaps the greatest potential to impact on floodplain development. According to Marren et al. (2014), we can identify several ways in which floodplains could potentially be affected by dams, with varying degrees of confidence, including a distinction between passive impacts (floodplain disconnection) and active impacts (changes in geomorphological processes and functions). According to EEA (2018), 15% of the European population lives in floodplains, rising to 25% in Austria, Slovakia and Slovenia. In Southern Europe, problems with water supply to agriculture have led to an intensive river regulation strategy, including the construction of reservoirs in upland valleys (Hughes et al., 2012). Many lowland rivers have been realigned to maximize agricultural production. These rivers are among the most regulated in the world (Magdaleno and Fernández, 2011), which is reflected in the poor ecological condition of their floodplains. The conclusion of the study by Kuiper et al. (2014), based on a meta-analysis of the scientific literature, was that altering of a natural flow regime reduces mean species abundance (MSA) of floodplains by more than 50% on average, and species richness by more than 25%. The effects on species richness and abundance tend to be related to the degree of hydrologic alteration. A list of the most common causes of floodplain ecosystem degradation and corresponding mitigation measures, usually taken in Central and Southern Europe can be found in Table 2.

As floodplains are valuable ecosystems that provide a range of ecosystem functions and services, it is necessary to address their protection and implement selected measures to ensure that their environmental values are maintained or restored (Hughes et al., 2008). According to EEA (2018), the protection and restoration of European floodplains is promoted within environmental policy, but only indirectly required—i.e., by the Water Framework Directive—WFD (2000/60/EC), the Floods Directive (2007/60/EC), the Habitat (1992/43/EEC) and Birds—HBD (1979/409/EEC) Directives, the EU 2020 Biodiversity Strategy, the Green Infrastructure initiative, the EU Climate Change Adaptation Strategy, and the Ramsar Convention. As the protection of such human altered floodplains along large European rivers is one of the objectives of the WFD and HBD (Funk et al., 2019), achieving these objectives require detailed planning of various compromise solutions that are ecologically, commercially, and socially acceptable (Rouquette et al., 2011). In addition to European legislation, the floodplains or at least some of the ecosystems found in Europe (e.g., floodplain forests or wetlands) are subject to legal protection at the level of individual countries. To illustrate the different approaches to floodplain management, here we outline the current situation in several Central and Southern European countries. In the Czech Republic floodplains are protected by law; according to Act No. 114/1992 Coll., a floodplain area is considered a "significant landscape element." From a practical point of view, this form of floodplain protection is not completely effective, as it is not clear how to approach the protection of already partially degraded floodplains. The

TABLE 2 The most common causes of floodplain degradation in central and southern Europe and appropriate measures to mitigate the effects of degradation (Source: authors)

Cause of floodplain degradation	Mitigation measure(s)
Drainage and riverbed reinforcement due to agricultural activities	River restoration (reestablish morphological river type and lateral connectivity), set initial measures for type-specific self-development of the river/the floodplain system, detention ponds construction, adopt ad hoc crop rotations and agricultural practices (tillage systems, soil cover management, etc.), check and rebuild old drainage systems.
Urbanization and transport infrastructure development	Develop urban green infrastructure and stormwater drainage management.
Technical/structural flood protection measures limiting lateral floodplain connectivity (embankment)	Creation of room for river (polders and areas suitable for periodic flooding) to alleviate floods where possible.
Dam construction and construction of torrent controls	Mitigate hydropeaking, implement fish bypasses and modify migration barriers in order to reestablish longitudinal continuum; remove or reconstruct torrent controls in headwater areas.
Land-use/land cover changes	Floodplain habitat restoration, modify land-use (afforestation of unused land a pastures).

same law provides for better protection of floodplains only if they are located in core zones of large-scale protected areas or in small-scale protected areas. In addition, floodplain protection is hampered by the absence of datasets that capture the precise spatial extent of floodplain ecosystems. Although floodplains in the Czech Republic represent a significant part of the landscape, covering approximately 10% of the total area of the country (Štěrba, 2008), ineffective legal protection has led to extensive degradation in the past and it is currently difficult to implement large-scale restorations that would improve the ecological condition of floodplains. Instead of complex restoration of floodplain ecosystems, these areas are more often subjected to construction of various flood protection measures, aimed at protecting residential and industrial infrastructure located directly in flooded areas (Loučková, 2014). Whether it is a structural measure located in the urban area of a floodplain (e.g., artificial levee or solid concrete wall) or outside urban areas (e.g., polder), all these measures affect biodiversity and the quality of ecosystem functions and services provided. While flood control measures implemented outside urban areas usually have a positive effect on several different ecosystem functions, on the contrary, measures implemented in built-up areas usually degrade many ecosystem functions. The poor condition of riparian habitats in the Czech Republic is also related to the practical maintenance of the River Basin Management Authorities based on the "Water Act" (No. 254/2001 Coll.), which aims to ensure sufficient space for the water flowing in the riverbed by cutting down forests on the riverbanks.

More often than entire floodplain areas, their individual parts (specific ecosystems or habitats) are protected by law; for example, in Slovakia, where wetlands, bogs or peat bogs, wet meadows, natural flowing waters and natural standing (lentic) waters are protected under Act No. 543/2002. There are no specific maps of floodplain areas in Slovakia; however, background materials are available that can be considered as proxy data of floodplain distribution—e.g., maps of Quaternary deposits (Maglay et al., 2009), soil maps (Hraško et al., 1993), or potential primary vegetation (Michalko et al., 1986). One of the most important localities where the protection of natural values of the floodplain is addressed in Slovakia is the great floodplain of the Danube River. An example of suitable measures to increase the environmental values of the floodplains is the LIFE project "Conservation and Management of Danube Floodplain Forests", which focuses on the conservation of the last remaining natural floodplain forests in the Slovak part of the Danube floodplain and the introduction of sustainable forest management in this area (BROZ, 2003). Restoration measures such as reconnection of meanders with the river system, increase of flow dynamics, excavation of sediment deposits from the meanders, and a special mowing scheme have been proposed and partially implemented to conserve the natural values and the derived human benefits (Holubová et al., 2003). Restoration of the Danube floodplain in Slovakia is perceived as an important factor in improving environmental values, as it is a highly anthropogenically modified area. Major interventions in this area include, for example, the construction of the Gabčíkovo waterworks, leading to a slow degradation of rare and endangered habitats of softwood floodplain forests in the Danube inland delta—see Figure 3 (Petrášová-Šibíková et al., 2017).

In Slovenia, conditions and limitations related to construction and activities in floodplain areas are defined by the "Decree on conditions and limitations for constructions and activities on flood risk areas" (PISRS, 2020). This regulation mentions the flooding and erosion processes of surface water and sea. The methodology that should be used to define endangered floodplain is determined by the "Rules on methodology to define flood risk areas and erosion areas connected to floods and classification of plots into risk classes." These rules use the concept of 10-year, 100-year, and 500-year return periods. Moreover, in relation to flood risk, the "Water Act" should also be mentioned. As a result of this legislation, flood hazard maps for various parts of the country have been prepared. However, since the adoption of this law about 10 years ago, a lot of construction has already taken place in floodplains, especially near the larger cities such as Ljubljana and Celje (e.g., Glavan et al., 2020). The floodplain area, defined based on the extent of flooding during the 100-year return period, where much of the urban development of the city of Ljubljana in Slovenia is located, is shown in Figure 4. The strong dependence of the floodplain extent on the terrain characteristics is a major drawback of this hydrological (hydraulic) approach, since in the case of urban areas or localities with traffic embankments, the course of the floodplain borderlines is intensively modified.

River lateral connectivity with floodplains is essential to create and maintain habitats for animals and plants, ensure ecosystem services and integrity, enhance carbon sequestration and storage (Wohl et al., 2017). A case study of the Orco River (North-Western Italy) is used to demonstrate how maintaining an adequate width of the river corridor and sustaining lateral river migration can be used as an effective solution to (a) mitigate flood risk, (b) minimize damage to transport infrastructure, (c) support the objectives of the EU Water Framework, Floods and Habitat Directives. The Orco river basin has a total area of about 910 km^2, of which 78% is located in the Alpine mountain range and 22% in the Po Valley plain. The Orco River flows on the southern slope of the Gran Paradiso massif, where an area of 11 km^2 is currently occupied by glaciers. In the Po Valley plain (between the municipality of Cuorgnè and the confluence with

FIGURE 3 Danube floodplain forest near the Gabčíkovo waterworks, Slovakia
(Source: Jaroslav Jankovič)

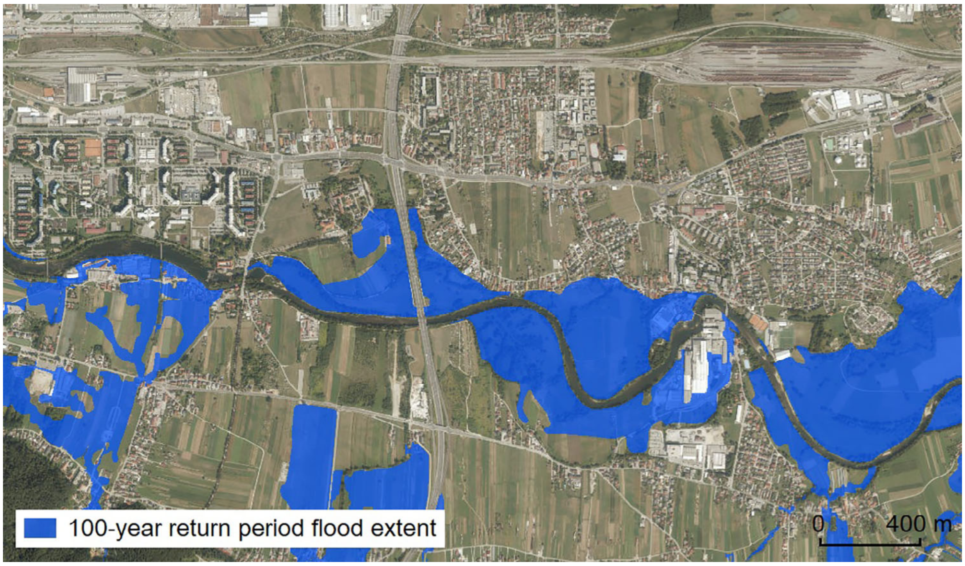

FIGURE 4 Significantly urbanized floodplain area (defined as the extent of flooding of the 100-year return period) of Ljubljanica River and its tributaries in the eastern part of Ljubljana, Slovenia
(Source: Geoportal ARSO, 2020)

the Po River near Chivasso municipality), the river is characterized by a wandering morphology with a significant lateral migration of bends, due to the intense sediment transport during the autumn and spring floods. Thanks to moderate anthropogenic pressures, the Orco River corridor still preserves a riparian forest in the floodplain, located between the river banks and the terraces. In late October 2019, a significant meander chute-cut occurred near San Benigno Canavese village (Figure 5), with a consecutive evolution of the chute channel in 2020. The chute channel has been formed in the floodplain peninsula enclosed by the meander loop, resulting in gradual closure of the abandoned channel. The chute channel is currently continuing to incise and widen into the floodplain. This process naturally preempted and avoided the realization of a river engineering measure envisioned by the authorities to reduce lateral bank migration towards the highway. The formation of this new channel did indeed reduce flood risk across the right river bank, minimizing possible damages to the highway and to the San Benigno Canavese village (Figure 5). The river bank protection by riprap at the outer bend of the meander is also currently not necessary because, after 16 months, the chute channel is acting as the main channel, conveying the discharge during the majority of time. The shortening of the river

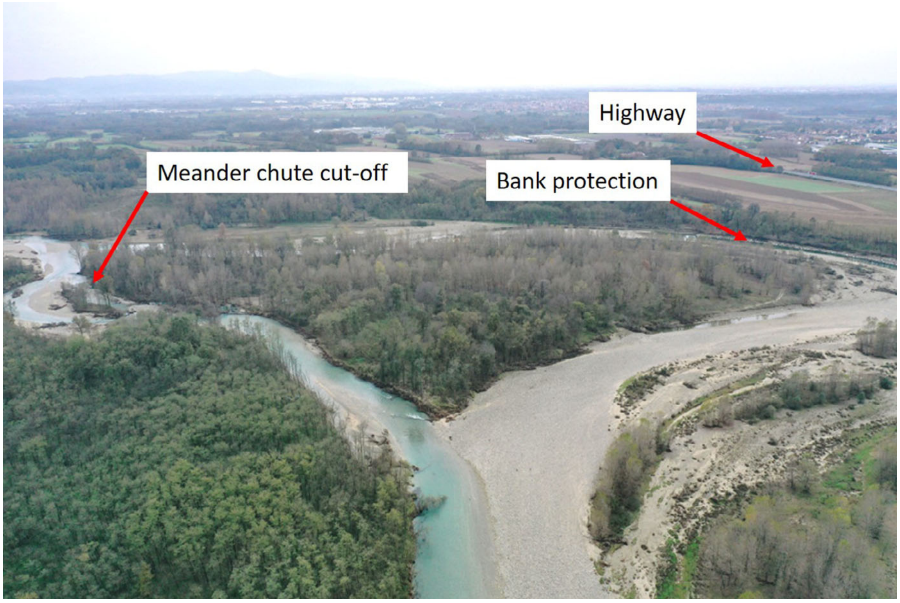

FIGURE 5 A meander chute cut-off on the Orco River near San Benigno Canavese village, Italy (Source: Paolo Maschio, Politecnico di Torino)

centerline has also resulted in increase in water gradient, with the consequent generation of erosion waves slowly migrating upstream, which will likely affect the hydraulic geometry upstream of the chute.

Water regulation in Italy provides for a very extensive stratification of planning competence, involving the national level, the regional administrative level and intermediary authorities whose sphere of influence extends beyond traditional administrative boundaries, such as the basin authorities (Salvati et al., 2012). This complex management framework often collides with the urgency of controlling, managing and regulating water flows in a very complex socio-economic context, such as in Italy and, more generally, Mediterranean Europe (e.g. Chelleri et al., 2015). Informal settlements spreading in the floodplain areas without considering sufficient buffer zones have sometimes led to severe conditions not only for ecosystems, but also for human health and life (Chelli et al., 2016; Ciommi et al., 2017; Gigliarano and Chelli, 2016). These situations are exacerbated by erosive processes due to land use changes, fires, landslides and abandonment of marginal lands (Salvati and Zitti, 2009; Salvati et al., 2011). Regional planning has mainly acted through integrated tools, which involved regional landscape plans, provincial coordination plans, river basin plans and planning at a more detailed scale of intervention, allowing both water regulation in contexts of particularly intense meteoric inflows, and emergency water management under drought conditions to be organized fairly effectively (e.g. Bajocco et al., 2012). Environmental policies at national and regional level have privileged the protection of relict floodplains in northern Italy, especially in flat areas, allowing the creation of habitats with high biodiversity, representing the natural extension of rivers with an alpine water regime (Smiraglia et al., 2016).

5 | DISCUSSION AND CONCLUSIONS

This article provided comparative insight into different approaches to floodplain delineation and outlined a conceptual nexus between floodplains and ecosystem functions, both illustrated with case studies. It is worth reiterating that direct human intervention (e.g., Entwistle et al., 2019; Lewin, 2013; Westra and de Wulf, 2006) can be seen as a major cause of floodplain ecosystem degradation, most evident in the urban landscape. There, the floodplain area is built-up and natural ecosystem functions are reduced due to loss of connectivity with the watercourse caused by river bank fortification and construction of levees along the river (e.g. Hein, van Koppen, et al., 2016 or Amoateng et al., 2018). In the agricultural landscape, the quality of ecosystem functions performed by the floodplain area is negatively affected by significant human-induced channel incision and narrowing, resulting in a lowering of the water table. As cropland is the most prevalent land-use category in floodplains in the Central and Southern European countries (cropland occupies between 40% and 60% of floodplain area according to EEA, 2018), the above anthropogenic interventions are the most common cause of reduced ability of floodplains to perform ecosystem functions. Drainage and replacement of floodplain forests by agriculture, primarily fields and meadows, is most common (Klimo et al. 2008), resulting in loss of inundation areas and increasing sediment and nutrient delivery to the river (van Andel and Aronson 2012).

Based on the above examples, it can be concluded that floodplain protection is at a different stage of development in each country and has different preferences. Since all floodplains in Central and Southern Europe are very intensively anthropogenically used and no change can be expected, multifunctional floodplain management can be seen as a solution to ensure the sustainable use of these areas. Multifunctional floodplain management can be defined as a management approach that aims at a balanced provision of multiple ecosystem services that serve the needs of local residents. Existing trade-offs imply the need of provisioning services reduction to decrease their dominance (Schindler et al., 2014). Landscapes can be enhanced by adding (or maintaining) semi-natural landscape features designed to provide multiple ecosystem services (Lovell and Johnston, 2009). The importance of investing in natural ecosystems, in particular urban green spaces, floodplains and areas for recreation, is recognized as a source of economic development in EU regional and cohesion policies (COM, 2011). In Germany, for example multifunctionality is to some extent included in legal regulations – the Federal Water Resources Act requires water managers to preserve, protect and even enhance natural habitats in order to manage water resources sustainably (Schindler et al., 2016).The solution to these ecologically unsatisfactory conditions, coupled with increased flood risk, is possible through the restoration of a watercourse or an entire floodplain (Keesstra et al., 2018). In order to find the optimal combination of spatially distinct large-scale and small-scale measures to increase habitat availability for all relevant species, detailed spatial planning is an important component of floodplain restoration (Remm et al., 2019). Weigelhofer et al. (2020) consider a combination of multiple-species (aiming at restoring natural hydrological dynamics) and single-species approaches (focusing on the conservation status of individual species) as a sound basis for decision-making processes in floodplain restoration in accordance with the EU Water Framework Directive and the Birds and Habitat Directives, as well as local legislation.

To ensure both ecologically and socially viable restoration efforts, future research should explore the following uncertainties and trade-offs. First, a proper delineation of current floodplains should take into account the legacy of Late Holocene climatic oscillations that influence the magnitude of sediment fluxes in floodplains (Stacke et al., 2014), as well as the legacy of past human activities (Swinnen et al., 2020, 2020). Decoupling the cause–effect feedback between these processes is difficult (Hoffman and Rohde, 2011), but crucial for establishing historical baselines of floodplain restoration to improve ecosystem functions. Second, given the uncertainties associated with ongoing climate change and its spatio-temporally varying impacts, floodplain management must consider the different scales at which socio-ecological systems are transformed (Liu et al., 2007), including (a) variations in floodplain adjustment processes (Chin, 2006), (b) the existing mismatches between the scales of ecohydrological processes and those of planning and policy interventions (Raška et al., 2019), and (c) complicated and dynamic property rights and tenure systems (Hartmann, 2009) and the social importance of floodplains (Richards et al., 2017). These issues point out the necessity to balance ecosystem functions with the livelihood benefits of direct floodplain use (Juarez Lucas and Kibler, 2016). Awareness of the social significance of floodplain ecosystems is likely to be a key element in improving the overall ecological conditions of floodplains and ensuring their sustainability, as only an awareness of this fact can lead to restoration efforts being supported by floodplain landowners.

ACKNOWLEDGMENTS

The authors would like to thank Paolo Maschio and Jaroslav Jankovič for providing a photo of the Orco River meander in Italy and the Danube floodplain forest in Slovakia. We are also grateful to the anonymous reviewers for their valuable comments and feedback, which helped to improve the quality of the article. This article contributes to the EU COST Action network "LAND4FLOOD: Natural Flood Retention on Private Land" (CA16209, http://www.land4flood.eu) and the complementary national Inter-COST Project (MŠMT LTC18025). N. Bezak work was partially supported by the Slovene Research Agency (ARRS) through grant P2-0180.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

Jiří Jakubínský: Conceptualization; funding acquisition; methodology; supervision; visualization; writing-original draft; writing-review & editing. **Marcela Prokopová:** Data curation; resources; writing-original draft; writing-review & editing. **Pavel Raska:** Conceptualization; methodology; writing-original draft; writing-review & editing. **Luca Salvati:**

Methodology; resources; supervision; writing-original draft; writing-review & editing. **Nejc Bezak:** Data curation; methodology; visualization; writing-original draft; writing-review & editing. **Ondřej Cudlín:** Data curation; methodology; resources; writing-original draft; writing-review & editing. **Pavel Cudlín:** Conceptualization; methodology; resources; supervision; writing-original draft; writing-review & editing. **Jan Purkyt:** Data curation; resources; visualization. **Paolo Vezza:** Data curation; writing-original draft. **Carlo Camporeale:** Data curation; writing-original draft. **Jan Daněk:** Data curation; writing-original draft; writing-review & editing. **Michal Pástor:** Data curation; resources; writing-original draft; writing-review & editing. **Tomáš Lepeška:** Data curation; resources; writing-original draft; writing-review & editing.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Jakubínský, J., Prokopová, M., Raška, P., Salvati, L., Bezak, N., Cudlín, O., Cudlín, P., Purkyt, J., Vezza, P., Camporeale, C., Daněk, J., Pástor, M., & Lepeška, T. (2021). Managing floodplains using nature-based solutions to support multiple ecosystem functions and services. *Wiley Interdisciplinary Reviews: Water*, e1545. https://doi.org/10.1002/wat2.1545