water

MDPI

Article

How Flood Hazard Maps Improve the Understanding of Ecologically Active Floodplains

Stephanie Natho

Institute of Environmental Science and Geography, University of Potsdam, Karl-Liebknecht-Straße 24-25, 14476 Potsdam-Golm, Germany; natho@uni-potsdam.de

Abstract: Floodplains are threatened ecosystems and are not only ecologically meaningful but also important for humans by creating multiple benefits. Many underlying functions, like nutrient retention, carbon sequestration or water regulation, strongly depend on regular inundation. So far, these are approached on the basis of what are called 'active floodplains'. Active floodplains, defined as statistically inundated once every 100 years, represent less than 10% of a floodplain's original size. Still, should this remaining area be considered as one homogenous surface in terms of floodplain function, or are there any alternative approaches to quantify ecologically active floodplains? With the European Flood Hazard Maps, the extent of not only medium floods (T-medium) but also frequent floods (T-frequent) needs to be modelled by all member states of the European Union. For large German rivers, both scenarios were compared to quantify the extent, as well as selected indicators for naturalness derived from inundation. It is assumed that the more naturalness there is, the more inundation and the better the functioning. Real inundation was quantified using measured discharges from relevant gauges over the past 20 years. As a result, land uses indicating strong human impacts changed significantly from T-frequent to T-medium floodplains. Furthermore, the extent, water depth and water volume stored in the T-frequent and T-medium floodplains is significantly different. Even T-frequent floodplains experienced inundation for only half of the considered gauges during the past 20 years. This study gives evidence for considering regulation functions on the basis of ecologically active floodplains, meaning in floodplains with more frequent inundation that T-medium floodplains delineate.

Keywords: active floodplain; frequent flood; flood hazard map; inundation; land use

check for updates

Citation: Natho, S. How Flood Hazard Maps Improve the Understanding of Ecologically Active Floodplains. *Water* **2021**, *13*, 937. https://doi.org/10.3390/w13070937

Academic Editor: Athanasios Loukas

Received: 25 January 2021
Accepted: 25 March 2021
Published: 30 March 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Floodplains are transition zones between terrestrial and aquatic ecosystems and, as such, one of the ecosystems providing the most ecosystem services on earth [1]. From the ecological point of view, floodplains are "areas that are periodically inundated by lateral overflow of rivers or lakes" [2] (p. 112). This description underlines that floodplains do not comprise the permanent lotic system of a river, as they would from a hydrological point of view that defines riparian zones as areas of the stream channel "between the low and high water marks and that portion of the terrestrial landscape from the high water mark toward the uplands where vegetation may be influenced by elevated water tables or flooding and by the ability of the soils to hold water" [3] (p. 623). Thus, floodplains are understood as areas adjacent to riverbeds structured by natural disturbances (floods) [4], such that zonation is known to represent successional stages [5] because vegetation communities are controlled by environmental gradients [4,6] like inundation (frequency, duration, depth and timing) [7] and are adapted to it [8]. But, floodplain width is temporally and spatially complex to determine and different approaches have been developed [9,10], mainly based on defining an active floodplain as a 100-year return period flood zone. However, the degree of connectivity between rivers and floodplains is determined by flow, and thus by times of inundation when both systems share water, nutrients, organisms and sediment budgets, as long as there is hydraulic connectivity and both natural flow dynamics and disturbances occur [4,11]. Likewise, it is questionable whether floodplains inundated statistically once every 100 years (for English [12] and German abbreviations of flooding frequencies, see Table 1, henceforth, the term 'T-year' will be used), represent active functioning floodplains well. From an ecological point of view, this T-100 floodplain is of rather limited ecological significance [2] for representing a functional floodplain. In contrast, the recurrence interval of 4.6 to 22 years is described to sustain riparian plant communities [13]. The recurrence interval of 10 to 20 years is described by [14] to be responsible for floodplain forest regeneration. Thus, there is an urgent need to delineate a functional floodplain to evaluate the conditions for sustaining floodplain habitats and their various functions.

Table 1. German and English abbreviations of calculated recurrence intervals for selected floods. The English abbreviations were obtained from [12]. The terminology applied in this study and its connection to flood hazard maps (FHM) and recurrence intervals is shown.

Applied Nomenclature in This Study		German	English	
Inundation Frequency According to FHM	**T-Year Recurrence Interval**	**Statistic Main Values as HQT**	**T-Year Recurrence Interval**	**Annual Exceedance Probability**
		HQ1	1	1
		HQ2	2	0.5
T-frequent	T-5	HQ5	5	0.2
	T-10	HQ10	10	0.1
	T-20	HQ20	20	0.05
	T-25	HQ25	25	0.04
	T-50	HQ50	50	0.02
T-medium	T-100	HQ100	100	0.001

For Germany, not only was a floodplain delineation based on a T-100 floodplain definition carried out, but the condition of this T-100 floodplain was also evaluated by the Federal Agency for Nature Conservation (BfN) together with the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) [10,15]—in total, only 1% of German floodplains are in a good state, equaling a near natural condition for which multifunctionality of floodplain ecosystems is expected, allowing all services to be provided [16]. In the following, 'functional floodplains' is used analogously to 'functional wetlands,' introduced by Entwistle, Hertiage [17] to describe the habitat in a floodplain fulfilling floodplain-specific functions and underlying regular inundation processes, similar to the term 'multifunctionality of ecosystems' used by Erős and Bányai [16], for example, for retaining water and nutrients, connecting habitats and enhancing water levels through the year. Then, regulating ecosystem services are expected to correlate almost linearly and positively with the ecological status of aquatic ecosystems [18].

So far, no research has been carried out to investigate spatial differences in the delineation of floodplains based on different inundation frequencies. Neither has the effect of different frequent inundation levels on the ecology of floodplains been analyzed on the landscape scale, covering rivers as a whole. One reason for this is that modelling the inundation of floodplains on this scale is time-consuming and expensive, and not carried out for ecological reasons only. Another reason is the difficulty of defining ecological indicators for ecosystem functioning documented by available and homogenous data on the landscape scale. Proxies to describe floodplain habitat quality were developed by Scholz, Mehl [19] for rivers in Germany and Erős and Bányai [16] applied a naturalness index to compare differing natural habitats in a case study along the Danube River. However, the Directive on the Assessment and Management of Floods (2007/60/EC, EC [20]) requests that flood hazard maps (FHM) be created for all river reaches with a significant flood risk in Europe.

These FHM represent so-called T-frequent, T-medium and extreme floods. In Germany, T-medium floods are defined as ≥T100 floods and are catastrophic [21] for humans and nature, as happened in 2013 with substantial direct and indirect monetary losses [22]. In contrast, T-frequent floods are defined by each federal state differently, with recurrence intervals from every 5 to 25 years corresponding to T5 to T25 (Table 1). Though having less impact on humans and the economy, these floods are disturbances necessary for floodplain ecosystems to sustain and regenerate riparian plant communities [13,14].

However, although FHM were not produced for ecological analysis, they provide an opportunity to compare the differences that these T-frequent and T-medium floods create in terms of flood extent, water depth and static stored water volume of T-frequent and T-medium floodplains (Figure 1). The comparison of hydraulically defined borders with ecology is approached by comparing the naturalness of land cover, habitats and vegetation cover. Are T-frequent floodplains more natural than T-medium floodplains, and consequently can T-frequent floodplains delineate the floodplains that are more relevant for floodplain functioning? The second analysis deals with the current inundation situation of T-frequent floodplains to approach how often the hydraulically delineated floodplains have been inundated in reality to fulfill floodplain-typical functions. Daily discharges are compared with the statistical discharge thresholds, leading to inundation of the T-frequent floodplains.

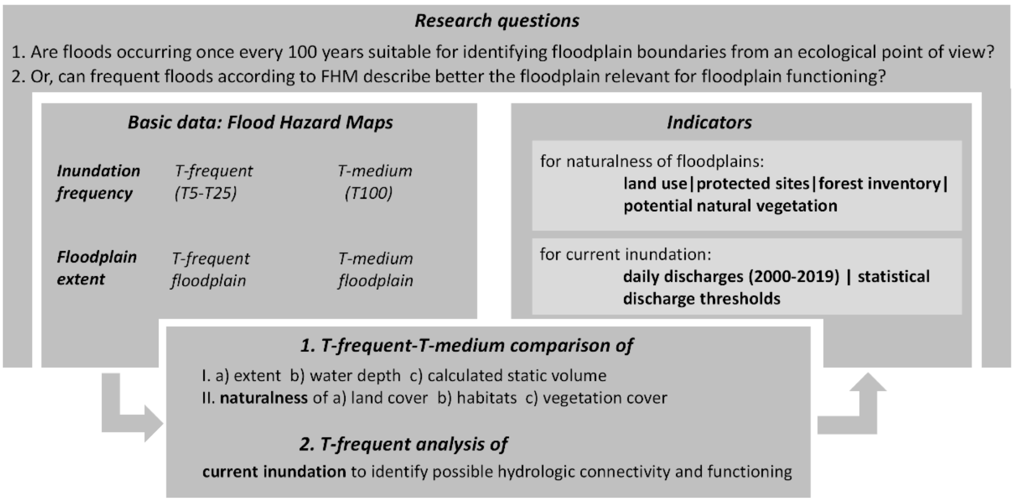

Figure 1. Operationalization of data used, developed indicators and research questions of this study.

2. Materials and Methods

2.1. Setting

Floodplains with flood hazard maps (T-frequent and T-medium floodplains) were considered along 79 rivers in Germany (Figure 2). These rivers were selected by BMU and BfN [15] to evaluate the floodplain status for German rivers.

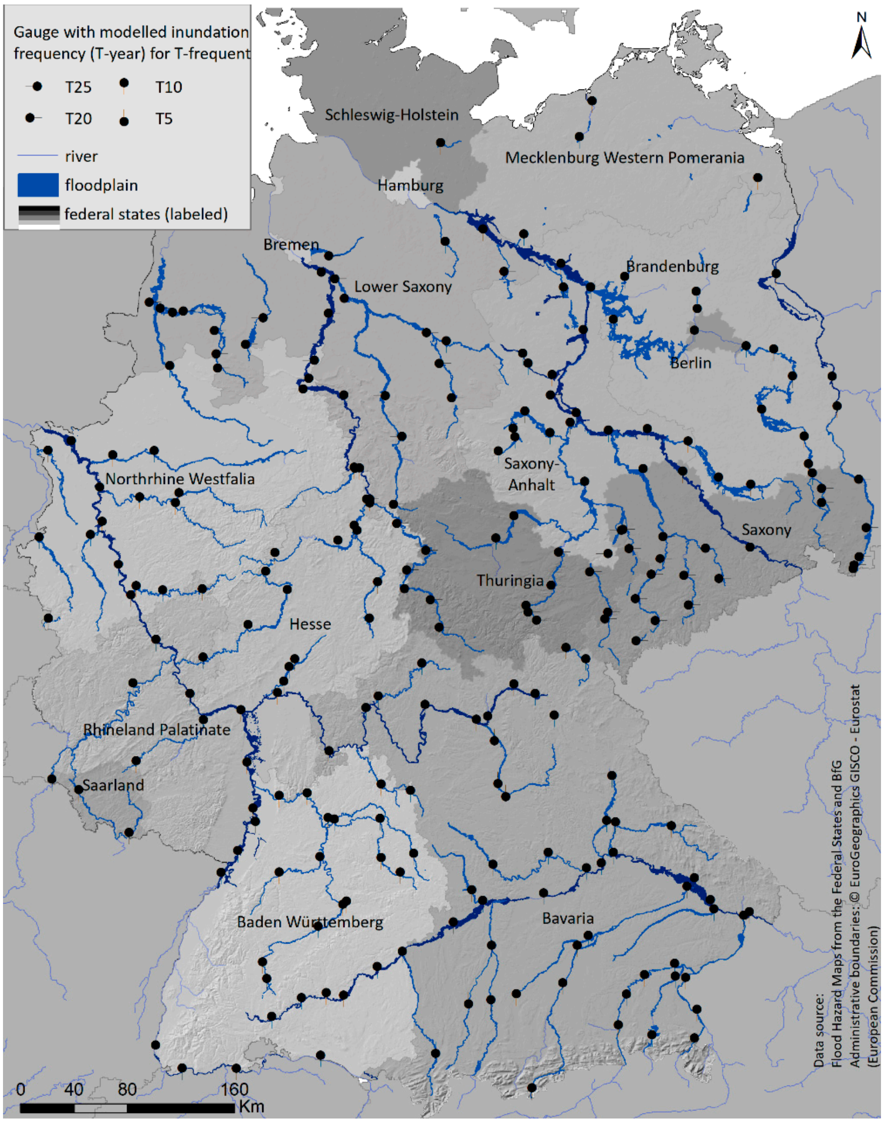

Figure 2. Overview of analyzed rivers and their floodplains in Germany. Federal states are displayed in different colors. Floodplains of the main rivers Rhine, Danube, Weser, Elbe, Ems and Oder are colored darker than the other rivers.

2.2. Data and Data Processing

First, FHM covering floodplains of each federal state were unified into a German dataset on T-frequent and T-medium floodplains for selected rivers (Figure 3). Then, various publicly available data covering the whole of Germany as well as discharge date were processed.

As each federal state is responsible for mapping flood hazards, FHM of high and medium flooding frequency (T-frequent and T-medium floods, respectively) were requested by the federal states relevant for the study, or where unavailable were obtained from the German Federal Institute of Hydrology (BfG, Table 2). Classified water depths obtained from the federal states or BfG were used to calculate proxies for static water volumes in the floodplain and river. Statistics were carried out with SPSS 27 to test the size of areas and the water depth between T-frequent and T-medium floodplains. To allow for a more detailed comparison between T-frequent and T-medium floodplains, hydrological boundaries on the scale of hydrological units [23] as a reference level were intersected with the floodplain data. This smallest catchment unit as a reference level then allows a further aggregation of catchments belonging to one gauge that were found in several but not all catchment areas

(Figure 4, for details, see Supplement). This 'gauge unit' also forms the basis for the last step of connecting T-frequent floodplains with discharges of the respective gauge.

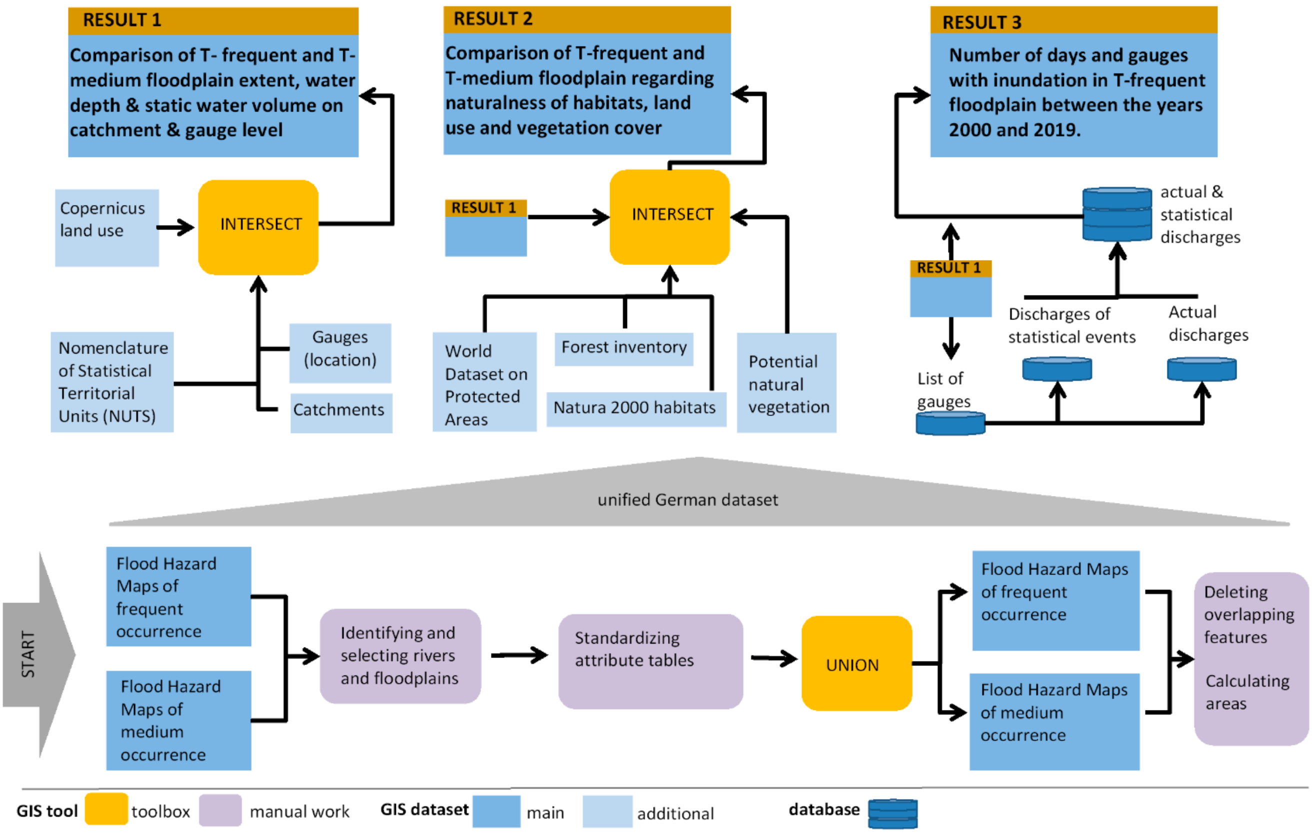

Figure 3. Schematic data processing of flood hazard maps for T-frequent (T5–T25) and T-medium (T100) floods.

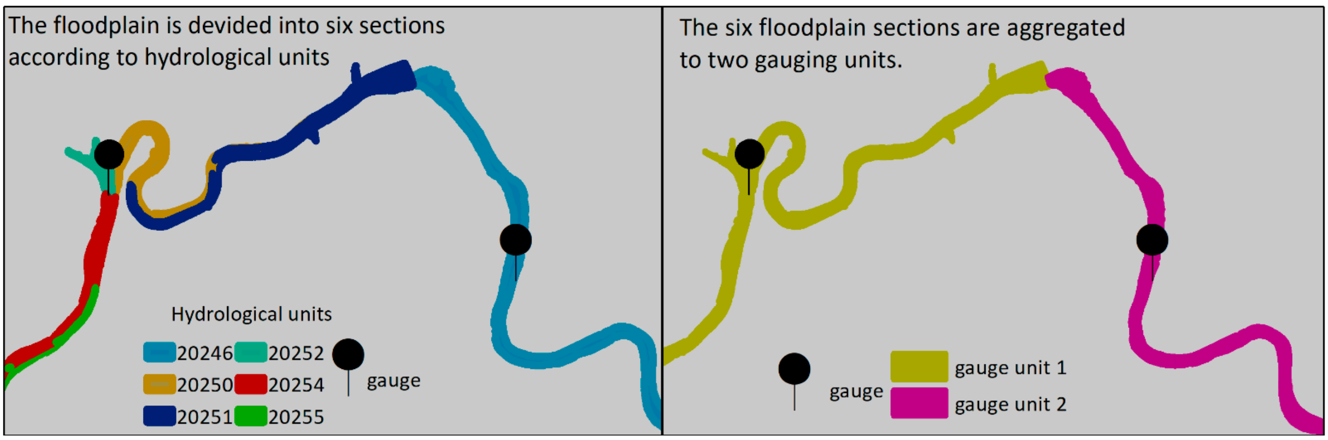

Figure 4. Scheme of applied small hydrological units (**left**) that can be aggregated belonging to one gauge, expressed as gauge unit, (**right**).

Table 2. Characteristics of flood hazard maps (FHM) applied in this study, collected from federal states (FS) or BfG (available under https://geoportal.bafg.de/download/opendata/ueberflutungstiefen/servicefeed.xml). The number of rivers investigated in T-frequent or T-medium floodplains is the same for most FS, except for * when the area is below 5 ha and in Saxony-Anhalt with information on one more river for T-medium floodplains.

FS	Recurrence Interval of T-Frequent and T-Medium Floods	Data Source	Area along Selected Rivers (1000 ha)	Number of Rivers
		FHM		
Brandenburg	T10/T20	FS	62.7/5	8
	T100	FS	129.6	8
Baden Württemberg	T10	FS	27.2	9
	T100	FS	36.7	9
Bavaria	T5/T10/T20	FS	3.2/55.3	21 *
	T100	FS	146.5	23
Bremen	T20/T25	FS	0	2
	T100	BfG	0.6	2
Hesse	T10/T20/T25	FS	25.3/0.8/0.9	10
	T100	BfG	40.2	10
Mecklenburg Western Pomerania	T10/T20	FS	2.8	5
	T100	FS	5.4	5
Lower Saxony	T10/T20/T25	FS	50.3/45	14
	T100	FS	126.7	14
North Rhine Westphalia	T10/T20/T25	FS	37.6/13.8/8.3	14
	T100	FS	72.9	15
Rhineland Palatinate	T10	FS	23.9	6
	T100	FS	30.1	6
Saarland	T100	FS	4.5	4
Saxony	T10/T20/T25	FS	19.3/8.2	10
	T100	FS	46.5	10
Saxony Anhalt	T10/T20/T25	FS	28.9/42.3	11
	T100	FS	94.3	12
Schleswig-Holstein	T10/T20	FS	0	2 *
	T100	FS	0.9	3
Thuringia	T10/T20	FS	14.5	6
	T100	FS	21.5	6

The land use naturalness index [16] evaluates land use classes according to the probability of hosting most natural floodplain habitats. In floodplains, the most important drivers are the intensity of human activities and the influence of inundation, which can be concluded to be lowest where land use intensity is highest. Following the naturalness index, wetlands, water, grasslands and forests are assumed to represent natural habitats more important for sustainable floodplain functioning than agriculture or urban land use. Land use in T-frequent and T-medium floodplains was compared by applying the Copernicus Land Use Dataset [24] for Riparian Zones [9,25] (Table 3) in differently detailed land use levels, namely level 1 (10 land use categories) and level 4 (109 land use categories; for details, see Supplementary Material and Table S1). Land use water representing the river itself or other water bodies was distinguished by level 4 values between 9000 and 9113 (river and interconnected river courses, differently classified in the basins) and average water depths $\geq$1.5 m obtained from classified FHM water depths (Table S2). Statistics were carried out to test the extent of different land uses between T-frequent and T-medium floodplains.

Table 3. Data sources of applied GIS datasets and database for evaluating the naturalness of floodplains.

Dataset	URL
Copernicus Land Use Dataset for Riparian Zones	http://land.copernicus.eu/local/riparian-zones/land-cover-land-use-lclu-image/view
GIS World Dataset of Protected Areas (WDPA)	https://www.protectedplanet.net/country/DE
Natura 2000 database and GIS data (Prod-ID: DAT-68-en)	https://www.eea.europa.eu/data-and-maps/data/natura-11

A further indicator for naturalness was calculated by comparing the distribution of protected sites as well as protected habitats in T-frequent and T-medium floodplains. Therefore, Nature Reserves (lowest degree of human activity allowed, NR), National Parks (NP), sites protected by the Ramsar Convention on Wetlands of International Importance (RAM), Sites of Community Importance according to the European Program Natura 2000 (SCI), Special Protected Areas according to the Birds Directive (SPA) and Landscape Protection Areas (highest degree of human activity allowed—LPA) were extracted from the Geoinformation System (GIS) World Dataset of Protected Areas (WDPA) [26,27]. National agencies input their high-resolution data into the WDPA (World Database on Protected Areas) open-access database, updated on a monthly basis. Statistics were carried out to test the areas of protection sites between T-frequent and T-medium floodplains. There are 20 protected habitats found in German floodplains [28]. Information on these protected habitats was obtained from the Natura 2000 database and GIS data (Table 3) after having combined the gauge units with the Natura 2000 sites and their habitats. Statistics were carried out to test the number of habitats between T-frequent and T-medium floodplains.

The potential natural vegetation (PNV) presents the natural land cover without human alteration and was requested from BfN [29]. After intersection with FHM, the current land cover was contrasted with the PNV. To evaluate the forest quality of riparian forests, various parameters from the Forest Inventory [30] were analyzed for the plots within the boundaries of FHM (for details, see Table S3) to estimate the naturalness of the remaining riparian forests.

In the third step, the present hydrological conditions were analyzed. From the first result (Figure 3), the list of gauges was obtained for which discharge data were requested by several authorities. A database was created containing information on daily discharges between 2000 and 2019, as well as the FHM relevant statistical events and their respective discharges from relevant gauges (Figure 3) to quantify the number of days at each gauge, with discharges leading to inundation of the floodplains according to T-frequent floods. T-frequent floods are defined differently by each federal state as T5, T10, T20 or T25 (Table 2), but the applied discharges are not available in the FHM dataset. The statistical gauge data were used as a proxy for frequencies considered in the FHM. Although the FHM were not necessarily modelled with the gauge data obtained from the authorities, these statistical values suggest a nationwide approach to determining how often T-frequent floodplains were inundated in the last 20 years and whether discharges leading to inundation occur in wet years as well as dry years. Therefore, dry years are defined as years in which the average discharge lies below 50% of long-term average discharge (MQ), whereas wet years are defined as years in which the average discharge is above 150% of long-term average discharge.

3. Results

3.1. Comparison of Extent, Water Depth and Static Water Volume between T-Frequent and T-Medium Floodplains

In total, for the selected rivers, 476,000 ha of T-frequent floodplains and 758,000 ha of T-medium floodplains are modelled for FHM along 12,509 river km. There is a significant difference between the extent of T-frequent and T-medium floodplains (Mann-Whitney U test, $p < 0.01$, N = 456) on the basis of the reference level of gauge units. A detailed comparison on the basis of 240 gauge units is presented in Figure 5. Of those, 228 gauge units are covered by both datasets. For these 228 gauge units, the share of T-frequent floodplains in relation to T-medium floodplains is calculated also according to the length of rivers (Figure 5a). In 30 gauging units (or along 940 river km) (Figure 5a), T-frequent floodplains cover more than 90% of T-medium floodplains. Along more than 6000 river km, only 75% or less of the T-medium floodplain is already inundated during T-frequent floods. Average river water depths increase from 3.2 m to 3.4 m, and in the floodplain from 1.2 m to 1.5 m for T-frequent floods and T-medium floods, respectively, being significantly different in terms of median and distribution (river water depth; N = 450: Mann-Whitney U test, $p < 0.05$ Kolmogorov Smirnov independent samples test, $p < 0.05$; for floodplain water depth; N = 456: Mann-Whitney U test, $p < 0.01$ Kolmogorov Smirnov independent samples test, $p < 0.01$). The water volume stored (in total 8.2 Mio m^3 and 14.5 Mio m^3, respectively) in the floodplain is twice as high as in the river in T-frequent floodplains, whereas it is three times higher than the river volume in T-medium floodplains.

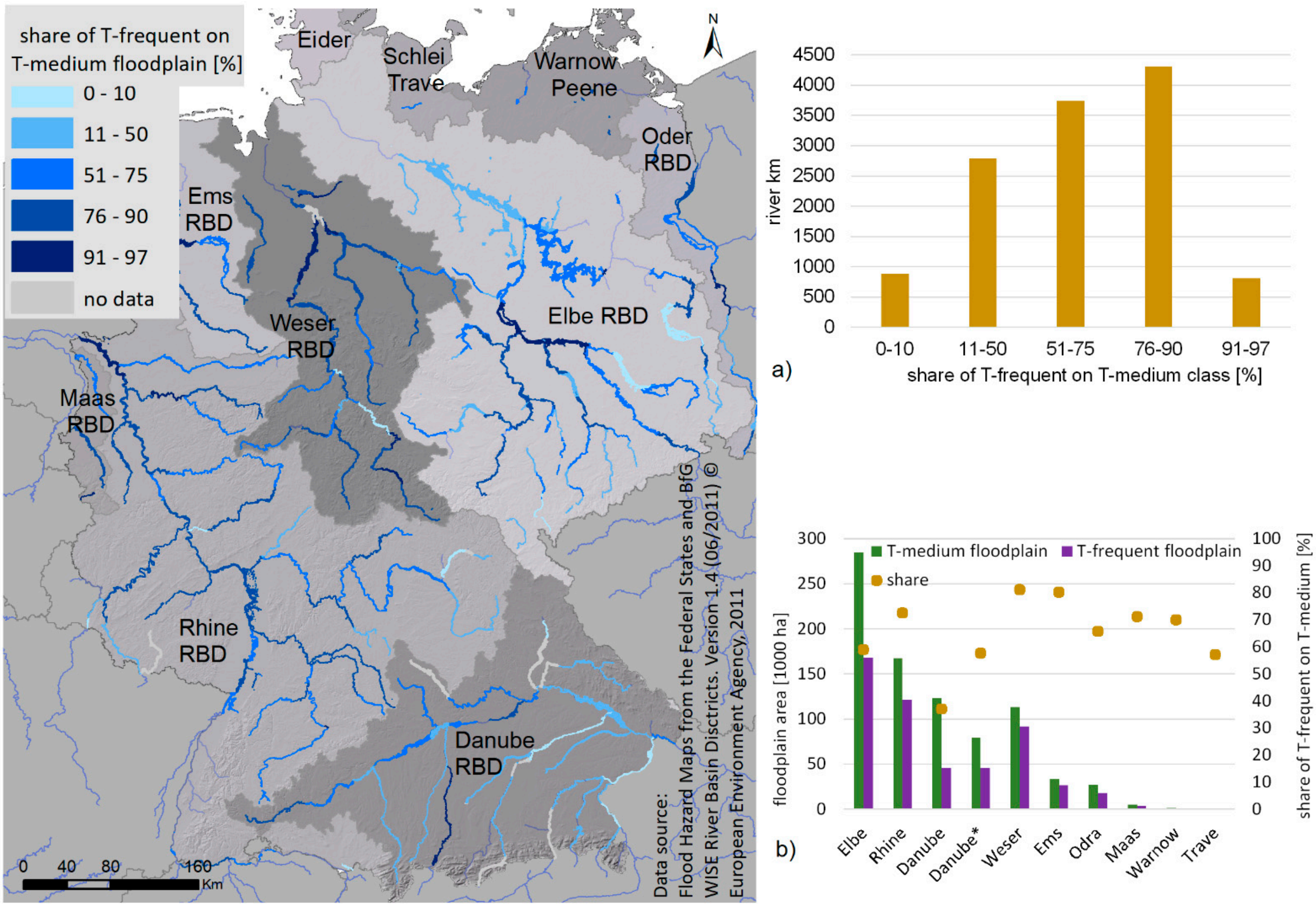

Figure 5. Comparison of T–medium and T-frequent areas, T–frequent area as % of T–medium. (**a**) Comparison on the basis of river basin districts. Danube * is an adapted calculation for the T-medium due to missing T–frequent results for 700 km of selected rivers in Bavaria. (**b**) Comparison with river length based on the hydrological units.

Aggregating gauge units into river basins, the largest T-medium floodplains belong to the Elbe and Rhine (Figure 5b). T-frequent floodplains are much smaller for the Danube, because for some rivers a T-frequent modelling has not yet been carried out. Therefore, Danube* considers the floodplains for which both scenarios exist in the Danube river basin. Here, T-frequent covers almost 60% of T-medium similar to Trave and Elbe. This is still lower than for most of the other river basins and means that only 60% of T-medium floodplains are inundated during T-frequent floods. The highest accordance is found for the floodplains of the rivers Weser and Ems (80%), meaning that 80% of T-medium floodplains are already inundated in T-frequent floods.

3.2. *Indicating Naturalness: Land Use, Protected Habitats and Vegetation Cover*

Differences in the naturalness between T-frequent and T-medium floodplains are best seen by non-natural land use, arable land and urban area, indicating little inundation and strong human impacts on the basis of gauge units (Mann-Whitney U test, $p < 0.01$, N = 467). Arable land more than doubles and urban area increases more than 60% (Figure 6a). The more natural land uses, grassland and forest, almost double, whereas the most natural land uses, wetland as well as water and others, increase less than one-third. Only the increase of water is statistically significant (Mann-Whitney U test, $p < 0.01$, N = 467).

T-frequent is modelled with different inundation frequencies by each federal state. Whereas most federal states use T10 or T20 floods, along some rivers T5 or T25 floods are also modelled. Looking into more detail in these T-frequent floodplains, the arable land in these inundated areas shows a strong increase from T5 to T25, and riparian forests and grassland show a strong decrease (Figure 6b). To summarize, not only between T-frequent floodplains and T-medium floodplains, but already in T-frequent floodplains with decreasing inundation frequency, the more natural land uses decrease whereas land uses with more human impact increase.

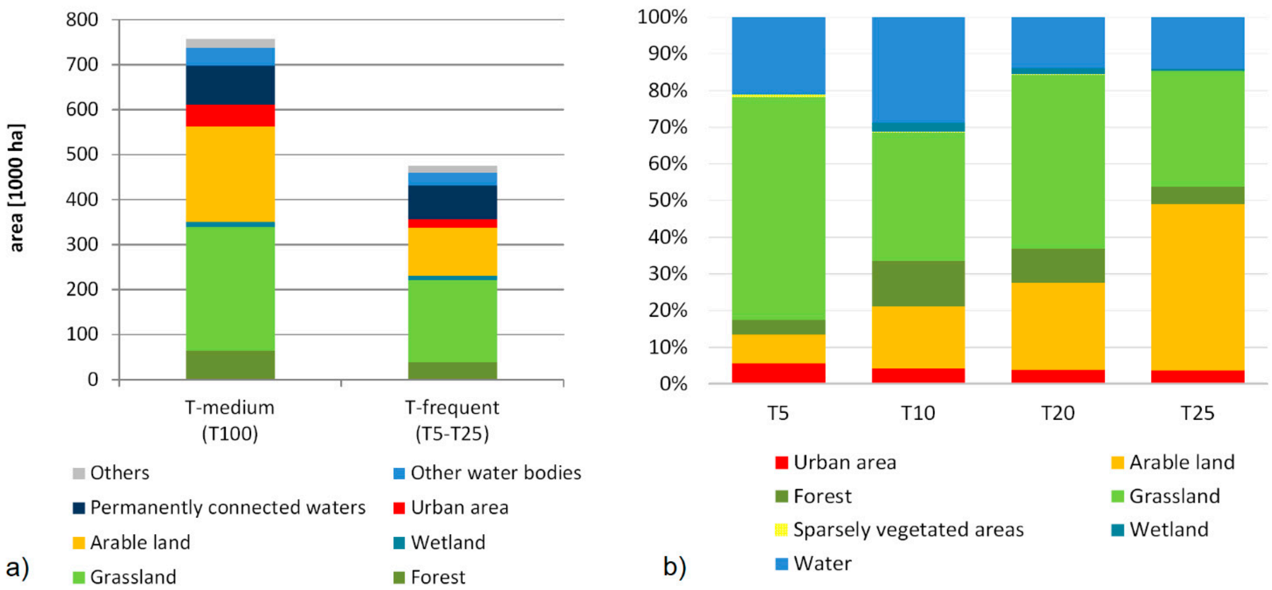

Figure 6. (**a**) Land use in frequent and medium FHM (T-frequent and T-medium). (**b**) Land use in T-frequent differentiated according to the flooding frequencies modelled at different sites.

The naturalness of T-frequent and T-medium floodplains is compared in terms of protected habitats, the general protection status and the occurrence of protected and floodplain typical habitats, and (where available) the quality of protected habitats is considered. Looking at protection status in general, 80% of T-frequent floodplains and 72% of T-medium floodplains are protected, most of them by multiple categories on the regional, national and international levels (Table 4). The difference on the level of gauge units is not statistically significant (Mann-Whitney U test, p = 0.136, N = 4394), meaning that the decrease of inundation does not statistically affect the distribution of protection site areas. Altogether, there are 2405 (in T-frequent floodplains) and 2925 (in T-medium floodplains) protection sites with the highest numbers of LPA (highest degree of human activity allowed) and NR (lowest degree of human activity allowed). NR are smaller than other protected sites and represent 21% of T-frequent floodplains and 17% of T-medium floodplains. The difference between the protection categories in T-frequent and T-medium floodplains is not statistically significant but visible when comparing the dominant land use types of non-natural arable lands and more natural grasslands within these protection categories: arable land increases from T-frequent floodplains to T-medium floodplains by 77% in LPA, but only by 33% in NR. For grassland, the increase is less than 50% for LPA, and 25% for NR.

Table 4. Extent and number of protection sites for T-frequent and T-medium.

	Protection Sites in T-Frequent			**Protection Sites in T-Medium**		
	Area [ha]	**%**	**Number**	**Area [ha]**	**%**	**Number**
Landscape Protection Area (LPA)	266,272.5	55.9	896	389,903.9	51.5	1113
National Park (NP)	5618.2	1.2	2	6055.5	0.8	2
Nature Reserve (NR)	101,227.7	21.2	755	126,557.6	16.7	900
Ramsar Site	19,267.2	4.0	11	25,050.2	3.3	11
Site of Community Importance (SCI)	215,918.5	45.3	572	283,845.7	28.5	692
Special Protection Area (SPA)	188,576.5	39.6	169	279,247.6	36.9	207

The comparison of current vegetation cover and potential natural vegetation [29] in floodplains confirms the low degree of naturalness of both T-frequent and T-medium floodplains—forests would be the potential natural vegetation of more than 85% of both T-frequent and T-medium floodplains. Today, approx. 8% of T-frequent and T-medium floodplains are covered by forests, meaning that there is a significant amount of riparian forest outside of T-frequent floodplains. The floodplain-typical broadleaved forest covers more than 80% of forested sites according to Copernicus data (Table 5) in both T-frequent and T-medium floodplains, and the share of coniferous forest is increasing from T-frequent to T-medium floodplains. Knowing that floodplain forests would be the PNV, the quality of remaining floodplain forests (Natura 2000 habitats 91E0 and 91F0) were analyzed by the Natura 2000 dataset on protected habitats as well as by the forest inventory. At least 85% of both habitats according to the global assessment are in a good or better state. But, only very few forest stands investigated by the forest inventory intersecting the FHM scenery of T-frequent and T-medium floods account for these habitats: 2.6% in T-medium floodplains and 3.5% in T-frequent floodplains. Therefore, forest quality of other forest habitats is approached by the parameters 'restrictions', 'harvest limitations' and 'stocking'. Restrictions (being too wet for forestry) and reductions in harvest are not found to any significant extent (<5%), whereas restrictions from protection are found for 15% of the sites. The forest inventory only gives limited insight into the status of floodplain forests, and the small number of plots within floodplain borders is very likely to be less conclusive than expected.

From the Natura 2000 datasets, the extent of floodplain forests is more conclusive than the data from the federal inventory. In the T-frequent floodplain, there are 25,000 ha (T-medium floodplain 27,000 ha) of 91E0 and in the T-frequent floodplain 13,950 ha (T-medium floodplain 14,088 ha) of 91F0. But, the Natura 2000 datasets contain unexpected limits because the exact location of these habitats in SCI sites is not given. However, the small additional contribution of T-medium areas to Natura 2000 riparian forest habitats (approx. 2000 ha) is clearly visible and in contrast to the other floodplain forests that are also found outside T-frequent floodplains. The extent of forests provided by Natura 2000 agrees very well with the 38,000 ha of riparian forests monitored in Copernicus land use data. Today, most forest sites are replaced by grasslands (T-frequent floodplains) and grasslands and arable land (T-medium floodplains). In grasslands, floodplain-obligate habitats are different types of meadows (Natura 2000 habitats 6410, 6430, 6440 and 6510). The quality of grassland habitats is good or better for at least 70% according to the general assessment of Natura 2000 sites. There was no statistically significant difference between the number of the 20 Natura 2000 habitats found in the T-frequent and T-medium floodplains (Mann-Whitney U test, $p = 0.512$, N = 40).

Table 5. Comparison of different forest nomenclature of the Copernicus land use riparian zones dataset applied in different river basins and their respective area calculated for T-frequent and T-medium floodplains. Aggregation was carried out mainly in the category of tree canopy density (TCD). Areas of identified riparian floodplains are in bold.

2018 Level 4 Code	Old Level 4 Description	Applied Level 4 Code	Applied Level 4 Description	Area [ha] T-Frequent		Area [ha] T-Medium	
3.0.0.0	**UA Forest**	3.0.0.0	UA Forest	5974		6941	
3.1.1.0	Natural & Semi-Natural Broadleaved Forest	3.1.1.0	**Natural & Semi-Natural Broadleaved Forest**	**7325**	**30,474**	**14,051**	**43,123**
3.1.1.1	**Riparian & Fluvial Broadleaved Forest (T.C.D. > 80%)**			**23,150**		**29,072**	
3.1.2.0	Highly Artificial Broadleaved Plantations	3.1.2.0	Highly Artificial Broadleaved Plantations	2		3	
3.1.2.1	**Riparian & Fluvial Broadleaved Forest (T.C.D. > 50–80%)**	3.1.1.0	**Natural & Semi-Natural Broadleaved Forest**	**10**	**6200**	**92**	**8585**
3.1.3.1	**Riparian & Fluvial Broadleaved Forest (T.C.D. > 30–50%)**			**6190**		**8492**	
3.2.1.0	Natural & Semi-Natural Coniferous Forest	3.2.1.0	Natural & Semi-Natural Coniferous Forest	82	2501	298	5839
3.2.1.1	Riparian & Fluvial Coniferous Forest (T.C.D. > 80%)			1381		3381	
3.2.2.1	Riparian & Fluvial Coniferous Forest (T.C.D. > 50–80%)			0		6	
3.2.3.1	Riparian & Fluvial Coniferous Forest (T.C.D. > 30–50%)			1037		2154	
3.3.1.0	Natural & Semi-Natural Mixed Forest	3.3.1.0	Natural & Semi-Natural Mixed Forest	411	3553	682	6621
3.3.1.1	Riparian & Fluvial Mixed Forest (T.C.D. > 80%)			1971		4337	
3.3.2.1	Riparian & Fluvial Mixed Forest (T.C.D. > 50–80%)			0		1	
3.3.3.1	Riparian & Fluvial Mixed Forest (T.C.D. > 30–50%)			1171		1601	
3.4.1.0	Transitional Woodland & Scrub	3.4.1.0	Transitional Woodland & Scrub	943	4106	1733	6068
3.4.1.1	Transitional Woodland & Scrub			3163		4335	
3.4.1.2	Lines of Trees & Scrub	3.4.2.0	Lines of Trees & Scrub	486	650	735	987
3.4.2.0	Lines of Trees & Scrub			164		252	

3.3. Actual and Statistical Inundation in T-Frequent Floodplains

T-frequent floodplains were attributed to 1418 hydrological units (T-medium floodplains to 1535 hydrological units). Then, the floodplains belonging to the hydrological unit were aggregated to 240 gauge units (such as seen in Figure 4), and thus 240 gauges are considered in this study. MQ was available for 230 gauges, a long-term time series of discharges (2000–2019) for 240 gauges, discharges in the range of T-frequent for 205 gauges, and statistical discharges of T100 for 200 gauges. 121 gauges in the East, Southeast and middle of Germany have experienced one or more floods in the range of T-frequent floods in the past 20 years (Figure 7). For 84 gauges, no discharges exceeding T-frequent floods were recorded. The years 2002, 2010 and 2013 were identified as wet years, with 133, 51 and 48 gauges having average yearly discharge exceeding long-term MQ by a factor of 1.5. The years 2000, 2018 and 2019 were identified as dry years, with 11, 11 and 14 gauges, respectively, having half an average yearly discharge of long-term MQ (Figure 7a,b). In these dry years, discharges >T10 floods have not occurred, and it is not known from FHM modelling how much of the T-frequent floodplain is inundated in these more frequent floods. It is also not known how much of the T-medium floodplain is inundated at discharges exceeding T-frequent floods. But, from the discharge data of the past twenty years, inundation of T-medium floodplains occurred for the Elbe and Danube, with severe damages from 100 year floods in 2002 and 2013 [31]. However, focusing on the discharges and floodplains relevant for more regular inundation and functioning of floodplains, it is also relevant how long the floods lasted (Figure 7b). The long-term average is exceeded for up to 220 days in wet years, whereas the duration of very frequent floods (T1/T2) is less than 20 days.

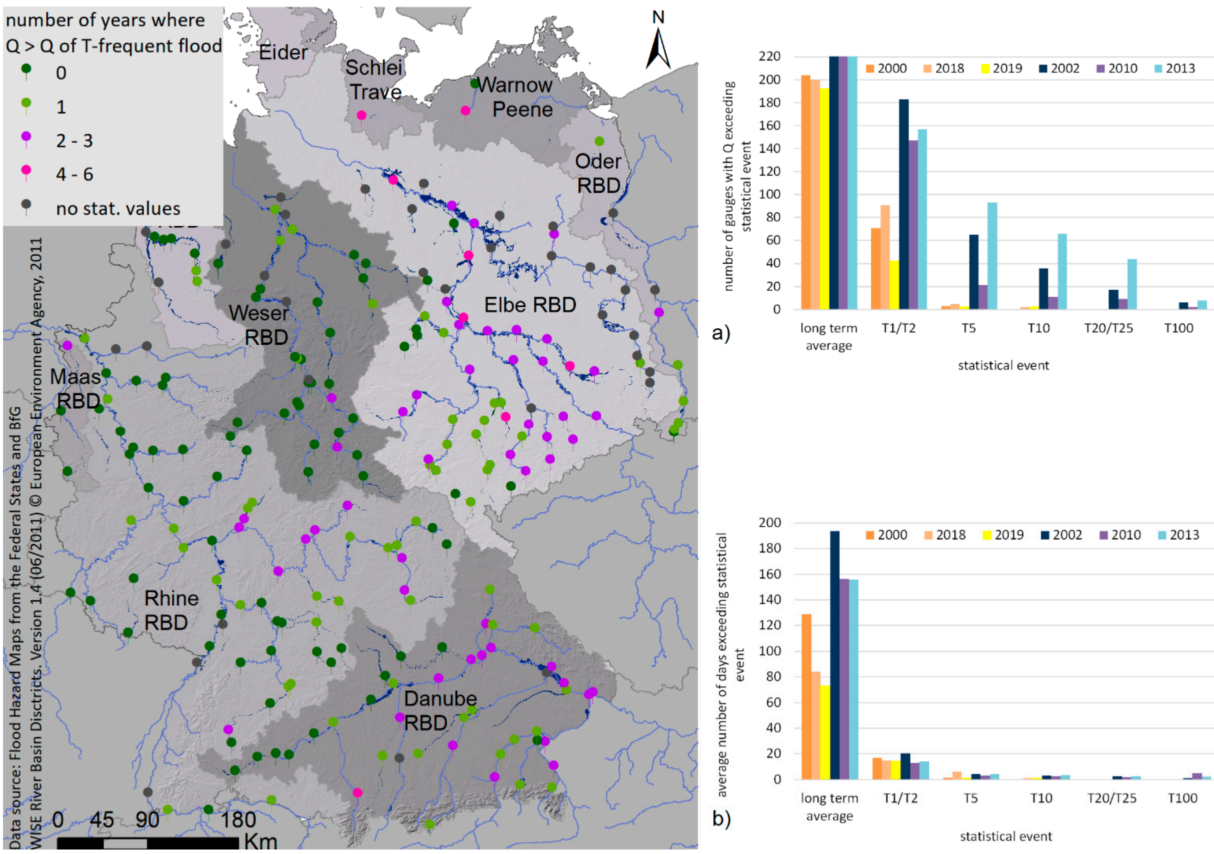

Figure 7. Gauges showing the numbers of years with discharges (Q) exceeding the statistical events of Q of T–frequent floods. (**a**) Comparison of discharges exceeding selected thresholds including long–term average (average) at gauges all over Germany in dry (orange to yellow) and wet years (blue and purple) between 2000 and 2019. (**b**) Average number of days with discharges exceeding selected thresholds for all gauges with exceedance.

Combining the knowledge of differences in the floodplain extent of T-frequent and T-medium floods for many rivers and current gauging data, this indicates that in current times T-frequent floodplains represent a better-connected floodplain than a T-medium floodplain but still with inundation for only part of the floodplains.

4. Discussion

4.1. Delineating Floodplain Borders Considering Their Importance for Regulation Functions

Many approaches consider the active floodplain defined by T-medium borders as the decisive area for calculating ecosystem services in floodplains [19,32–34]. Floodplains belong to the ecosystems with the highest number of functions and services they deliver [1]. However, borders of 100-year floods do not describe functioning floodplains for all functions. This is because strongly flood-dependent regulation functions [35] like nutrient retention [36], water regulation in the definition of [35] and carbon sequestration not only in plants but especially in soils after sedimentation [37] need natural disturbance regimes that connect the river and floodplain to exchange matter and energy [4] on a regular basis and not once every 100 years. This study shows that taking the T-medium floodplain extent equaling a 100-year flood extent as the basis for calculating nutrient retention, carbon sequestration or water regulation on a yearly basis strongly overestimates the function for many German rivers because the extent of T-medium floodplains differs from T-frequent floodplains and they are not connected to the exchange of nutrient, water and carbon fluxes by inundation of river water. Elbe, Trave and Danube river basins have the highest discrepancies between T-frequent and T-medium, because their T-medium floodplain is still comparatively large and in a better state than other German river basins [10]. It does make more sense to delineate T-frequent floodplains for most of the 79 rivers considered in this study. A further aspect considering more frequent floods as floodplain borders for regulation functions is that larger floods like T-medium have a very different effect on the system than frequent floods. Large-magnitude peak flows are disastrous and lead to processes like floodplain resetting [38]; and there is a higher risk for contamination of floodplains through damaged critical infrastructure like waste water treatment plant overflow [39], creating some disadvantages of floodplains strongly modified by large flood inundation. However, pollution from the outwash of polluted water bodies and soils (e.g., heavy metals) can already occur during floods with recurrence intervals of 3–4 years [40] or with changing flooding frequencies and is strongly related to the sediment transport of each river and its physical-chemical conditions [11,41]. On the other hand, frequent floods ($\geq$T10) are responsible for floodplain maintenance, for example, preservation of the morphology [42,43], or habitat maintenance sustaining physical habitat and completing lifecycles [44] with less impact on human infrastructure and resulting contamination. Smaller floods serve effectively as channel maintenance due to their higher recurrence intervals [21] and may already be important for sediment transport before bankfull discharges occur [44]. At least for 157, 119 and 68 gauges, T5, T10 or even T20 and thus inundation of some floodplains have occurred at least once between 2000 and 2019. With this short time series it is not the aim of this study to conclude whether the frequency of floods has increased or decreased. However, counting floods in the 240 gauges supports the very diverse picture of discharge trends [45,46] or the non-coherence of high flood years in Germany [47]. But, anthropogenic river flow regulation in general [4] and the consequential riverbed incision [45] decrease hydrological connectivity of floodplains and the necessary frequent inundation or disturbance regime. Frequent floodplain inundation is crucial for functioning floodplain ecosystems, and restoration can only be successful if hydrological connectivity is given not only by morphological structures but also by natural flood regimes and frequent disturbances.

4.2. Indicator for Naturalness of Floodplains and Ecosystem Functioning

Finding indicators for the naturalness of floodplains resulting in sustainable floodplain ecosystem functioning [16] is the aim of this study. The new aspect is that floodplain delineations of T-frequent and T-medium floodplains are considered.

Land use is known to be a good indicator for ecosystem health [48] and naturalness [16]. However, for natural land uses, habitats or protection sites there was no significant change between T-frequent and T-medium floodplains. This is because wetlands as most natural land use [16] cover less than 2% of T-medium and T-frequent floodplains. Although this is more than is reported by Entwistle, Heritage [17] for floodplains in England, it is still far from a natural condition in both floodplain scenarios. Similar is the coverage of riparian floodplains with 8% and no statistical difference between T-frequent and T-medium floodplains. The low coverage of wetlands, forests and waters is similar for T-medium floodplains in Europe [17,34]. However, all are very important for different aspects of biodiversity [4] and as connecting elements. Since 1992, several of their habitats are considered as habitats of community importance, with residual alluvial forests even being listed as priority habitats in Annex I of EC [49]. Grassland, with mostly managed grasslands, is the dominant land use in the cultural landscapes of the floodplains, in both T-frequent and T-medium floodplains. So-called wet meadows result from past extensive agricultural practices. Since intensification has been carried out, losses of these species-rich sites are reported for Germany [50]. Although the land use classification scheme does not allow a specific targeting of species-rich meadows, the land use class of mesic grassland with tree cover < or >30%, as well as the consideration of Natura 2000 grassland habitats including these species-rich meadows, reveals the importance of T-frequent floodplains, because this is where 86% of this land cover is located. However, mesic grasslands only cover less than 1% of T-frequent and T-medium floodplains.

In contrast to the natural land uses, the highest statistical difference was found for arable land, indicating high land use intensity and human impact [16], as well as reduced inundation. With an average of 28% in T-medium floodplains and 22% in T-frequent floodplains, this is lower than a share of >40% arable land in T-medium floodplains in various European countries [34]. Nevertheless, shares of >40% of arable land also occur in T-medium floodplains in 28 gauge units and in T-frequent floodplains in 20 gauge units.

All forest areas found in Copernicus land use are protected, with hardwood forest representing former inundation conditions due to its possible age [51]. Open areas promoted by large floods are important for softwood forests to rejuvenate [51] and for other plants to colonize new sites [52], but fixed shorelines along German rivers still prevail.

4.3. Reliability of Results: Limits of FHM Data

FHM are created to express the inundation of geographical areas associated with different flood scenarios [20]. These FHM are not created for all rivers, because there are simply too many river kilometers. Therefore, the federal states have chosen different approaches to reduce the river lengths to be considered, for example, to only rivers with catchments >10 km^2, rivers where floods are known to show adverse consequences, or those with known high potential losses from expert knowledge or comprehensive cadastres. As a result, the length of the rivers considered varies tremendously due to the different population and settlement densities in the floodplains. In Baden Württemberg, 14,050 km are considered for evaluation; FHM were created for 11,000 km, although only 4980 km are considered risk-rivers (Risikogewässer) [53]. In contrast, Mecklenburg Western Pomerania (MWP) only considers 43 km of rivers to be relevant for FHM [54] because of low population densities and mainly grassland in riverine areas. The respective FHM area is much lower than the active floodplain evaluated by [10]. Only in the Saarland were FHM of frequent floods not modelled at all. As a result, for most federal states the coverage of main rivers is very thorough and the FHM of the river km considered by [15] are very similar. As stated above, the difference in MWP is so great that the FHM (frequent and medium) cannot be used to estimate the inundation extent of the main rivers there, although for Saarland statements are only possible for medium floods. In summary, it was not the intention behind the FHM but they serve as a good representative of floodplain areas at frequent and medium inundation for most federal states, allowing a German-wide analysis.

Comparing the extent of inundated areas provided by FHM and the land use within borders of the Copernicus approach [9,25], a very good coverage was observed. Differences occurred in a few catchments like the Hase and Ems in Lower Saxony and MWP, where lowland rivers have wider floodplains.

5. Conclusions

Defining a floodplain and estimating its functions and ecosystem services based on a 100-year flood extent (T-medium) leads to an overestimation and considers large parts of floodplains that are not hydrologically connected and thus not functional on a yearly basis. The difference in inundation extent is clearly shown in this study and should be considered for future assessments of ecosystem services in floodplains. This is particularly relevant for regulation services, which directly depend on current inundation conditions. For provisional, supporting and cultural services, consideration of the entire active floodplain is important because the whole floodplain contributes to ecosystem functioning, such as serving as a refuge area when the floodplain fills with water. It is still challenging to quantify the quality of inundated floodplains. Land use as an initial rough proxy cannot lead to an extensive answer but serves as a starting point. In this study, especially land use representing non-natural conditions, urban areas and arable land showed significant differences between T-frequent and T-medium floodplains. Floodplain-obligate habitats were investigated but the location of spatial data was not detailed enough for conclusive analysis. However, further coherent ecological data are needed to quantify how hydrologically defined borders correspond to ecological patterns.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/w13070937/s1. Specification of methodology including Table S1 (applied legend for Copernicus land use within floodplains), Table S2 (Transformation of water depth classes and applied average water depth), Table S3 (Parameters from the forest inventory database).

Author Contributions: Conceptualization, S.N.; methodology, S.N.; formal analysis, S.N.; investigation, S.N.; writing—original draft preparation, S.N.; writing—review and editing, S.N.; visualization, S.N.; funding acquisition, S.N. The author has read and agreed to the published version of the manuscript.

Funding: This research was funded by Deutsche Forschungsgemeinschaft, project number 390612937.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to ongoing research but will be available upon request after 2022.

Acknowledgments: I thank the Deutsche Forschungsgemeinschaft for funding this study (project number 390612937), research assistant A.C. Kra for her help in preprocessing parts of the flood hazard maps, research assistant N. Voss for her help in conducting parts of the literature research and A. Popiel for proofreading the manuscript. I acknowledge the support of the Deutsche Forschungsgemeinschaft and Open Access Publishing Fund of University of Potsdam.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Costanza, R.; D'Arge, R.; de Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O'Neill, R.; Paruelo, J.; et al. The value of the world's ecosystem services and natural capital. *Nature* **1997**, *387*, 253–260. [CrossRef]
2. Junk, W.; Bayley, P.B.; Sparks, R.E. The flood pulse concept in river-floodplain systems. *Can. Spec. Publ. Fish. Aquat. Sci.* **1989**, *106*, 110–127.
3. Naiman, R.J.; Décamps, H. The ecology of interfaces: Riparian zones. *Annu. Rev. Ecol. Syst.* **1997**, *28*, 621–658. [CrossRef]

4. Ward, J.V. Riverine landscapes: Biodiversity patterns, disturbance regimes, and aquatic conservation. *Biol. Conserv.* **1998**, *83*, 269–278. [CrossRef]
5. Poff, N.L.; Allan, J.D.; Bain, M.B.; Karr, J.R. The natural flow regime: A new paradigm for riverine conservation and restoration. *BioScience* **1997**, *47*. [CrossRef]
6. Fernandes, M.R.; Aguiar, F.C.; Ferreira, M.T. Assessing riparian vegetation structure and the influence of land use using landscape metrics and geostatistical tools. *Landsc. Urban Plan.* **2011**, *99*, 166–177. [CrossRef]
7. Leyer, I. Effects of dykes on plant species composition in a large lowland river floodplain. *River Res. Appl.* **2004**, *20*, 813–827. [CrossRef]
8. Jackson, M.B.; Colmer, T.D. Response and adaptation by plants to flooding stress. *Ann. Bot.* **2005**, *96*, 501–505. [CrossRef]
9. Weissteiner, C.J.; Ickerott, M.; Ott, H.; Probeck, M.; Ramminger, G.; Clerici, N.; Dufourmont, H.; De Sousa, A.M.R. Europe's green arteries—A continental dataset of riparian zones. *Remote Sens.* **2016**, *8*, 925. [CrossRef]
10. Brunotte, E.; Dister, E.; Gunther-Diringer, D.; Koenzen, U.; Mehl, D. Flussauen in Deutschland–Erfassung und Bewertung des Auenzustandes. In *Naturschutz und Biologische*; Bad Godesberg: Bonn, Germany, 2009.
11. Schulz-Zunkel, C.; Krueger, F. Trace metal dynamics in floodplain soils of the river elbe: A review. *J. Environ. Qual.* **2009**, *38*, 1349–1362. [CrossRef]
12. Weaver, J.C.; Feaster, T.D.; Gotvald, A.J. *Magnitude and Frequency of Rural Floods in the Southeastern United States, through 2006—Volume 2, North Carolina. 2009, U.S. Geological Survey Scientific Investigations Report 2009–5158*; BiBlioGov: Reston, VA, USA, 2011; p. 111.
13. Chapin, D.M.; Beschta, R.L.; Shen, H.W. Relationships between flood frequencies and riparian plant communities in the Upper Klamath Basin, Oregon. *J. Am. Water Resour. Assoc.* **2002**, *38*, 603–617. [CrossRef]
14. Hughes, F.M.R.; Rood, S.B. Allocation of river flows for restoration of floodplain forest ecosystems: A review of approaches and their applicability in Europe. *Environ. Manag.* **2003**, *32*, 12–33. [CrossRef] [PubMed]
15. BMU; BfN. *Auenzustandsbericht. Flussauen in Deutschland*; Bundesamt fur Naturschutz: Bonn, Germany, 2009.
16. Erős, T.; Bányai, Z. Sparing and sharing land for maintaining the multifunctionality of large floodplain rivers. *Sci. Total Environ.* **2020**, *728*, 138441. [CrossRef] [PubMed]
17. Entwistle, N.S.; Heritage, G.L.; Schofield, L.A.; Williamson, R.J. Recent changes to floodplain character and functionality in England. *CATENA* **2019**, *174*, 490–498. [CrossRef]
18. Grizzetti, B.; Liquete, C.; Pistocchi, A.; Vigiak, O.; Zulian, G.; Bouraoui, F.; De Roo, A.; Cardoso, A.C. Relationship between ecological condition and ecosystem services in European rivers, lakes and coastal waters. *Sci. Total Environ.* **2019**, *671*, 452–465. [CrossRef]
19. Scholz, M.; Mehl, D.; Steinhauser, A.; Kasperidus, H.D. Ökosystemfunktionen von Flussauen–Analyse und Bewertung von Hochwasserretention, Nährstoffrückhalt, Kohlenstoff, Treibhausgasemissionen und Habitatfunktion. In *Naturschutz und Biologische*; Bad Godesberg: Bonn, Germany, 2012.
20. EC. Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks. *Off. J. Eur. Union* **2007**, *288*, 1–8.
21. Wolman, G.M.; Miller, J.P. Magnitude and frequency of forces in geomorphic processes. *J. Geol.* **1960**, *68*, 54–74. [CrossRef]
22. Schulte in den Bäumen, H.; Többen, J.; Lenzen, M. Labour forced impacts and production losses due to the 2013 flood in Germany. *J. Hydrol.* **2015**, *527*, 142–150. [CrossRef]
23. Venohr, M.; Hirt, U.; Hofmann, J.; Opitz, D.; Gericke, A.; Wetzig, A.; Natho, S.; Neumann, F.; Hurdler, J.; Matranga, M.; et al. Modelling of nutrient emissions in river systems–Moneris–Methods and background. *Int. Rev. Hydrobiol.* **2011**, *96*, 435–483. [CrossRef]
24. Clerici, N.; Paracchini, M.L.; Maes, J. Land-cover change dynamics and insights into ecosystem services in European stream riparian zones. *Ecohydrol. Hydrobiol.* **2014**, *14*, 107–120. [CrossRef]
25. Clerici, N.; Weissteiner, C.J.; Paacchini, M.L.; Boschetti, L.; Baraldi, A.; Strobl, P. Pan-European distribution modelling of stream riparian zones based on multi-source Earth Observation data. *Ecol. Indic.* **2013**, *24*, 211–223. [CrossRef]
26. UNEP-WCMC; IUCN. Protected Planet: [The World Database on Protected Areas (WDPA)]. Available online: www.protectedplanet.net (accessed on 17 December 2019).
27. UNEP-WCMC. World Database on Protected Areas User Manual 1.5. *UNEP-WCMC.* 2017. Available online: http://wcmc.io/WDPA_Manual (accessed on 17 December 2019).
28. Schindler, S.; O'Neill, F.H.; Biro, M.; Damm, C.; Gasso, V.; Kanka, R.; van der Sluis, T.; Krug, A.; Lauwaars, S.G.; Sebesvari, Z.; et al. Multifunctional floodplain management and biodiversity effects: A knowledge synthesis for six European countries. *Biodivers. Conserv.* **2016**, *25*, 1349–1382. [CrossRef]
29. BfN. *Potential Natural Vegetation of Germany*; Bundesamt fur Naturschutz: Bonn, Germany, 2011.
30. Polley, H.; Heinrich, J. *Aufnahmeanweisung für die dritte Bundeswaldinventur (BWI) (2011–2012)*, 2nd ed.; Johann Heinrich von Thünen Institute: Braunschweig, Germany, 2011.
31. Natho, S.; Thieken, A.H. Implementation and adaptation of a macro-scale method to assess and monitor direct economic losses caused by natural hazards. *Int. J. Disaster Risk Reduct.* **2018**, *28*, 191–205. [CrossRef]
32. Stammel, B.; Amtmann, M.; Gelhaus, M.; Cyffka, B. Change of regulating ecosystem services in the Danube floodplain over the past 150 years induced by land use change and human infrastructure. *Erde* **2018**, *149*, 145–156. [CrossRef]

33. Natho, S.; Venohr, M.; Henle, K.; Schulz-Zunkel, C. Modelling nitrogen retention in floodplains with different degrees of degradation for three large rivers in Germany. *J. Environ. Manag.* **2013**, *122*, 47–55. [CrossRef]
34. EEA. *Flood Risks and Environmental Vulnerability: Exploring the Synergies Between Floodplain Restoration, Water Policies and Thematic Policies*; European Environmental Agency: Copenhagen, Denmark, 2016.
35. Kienast, F.; Bolliger, J.; POtschin, M.; de Groot, R.S.; Verburg, P.H.; Heller, I.; Wascher, D.; Haines-Young, R. Assessing Landscape Functions with Broad-Scale Environmental Data: Insights Gained from a Prototype Development for Europe. *Environ. Manag.* **2009**, *44*, 1099–1120. [CrossRef]
36. Gordon, B.A.; Dorothy, O.; Lenhart, C.F. Nutrient retention in ecologically functional floodplains: A review. *Water* **2020**, *12*, 2762. [CrossRef]
37. Hupp, C.R.; Kroes, D.E.; Noe, G.B.; Schenk, E.R.; Day, R.H. Sediment trapping and carbon sequestration in floodplains of the lower Atchafalaya Basin, LA: Allochthonous versus autochthonous carbon sources. *J. Geophys. Res. Bio-Geosci.* **2019**, *124*, 663–677. [CrossRef]
38. Yarnell, S.M.; Petts, G.E.; Schmidt, J.C.; Whipple, A.A.; Beller, E.E.; Dahm, C.N.; Goodwin, P.; Viers, J.H. Functional flows in modified riverscapes: Hydrographs, habitats and opportunities. *BioScience* **2015**, *65*, 963–972. [CrossRef]
39. Arrighi, C.; Masi, M.; Iannelli, R. Flood risk assessment of environmental pollution hotspots. *Environ. Model. Softw.* **2018**, *100*, 1–10. [CrossRef]
40. Lyubimova, T.; Lepikhin, A.; Parshakova, Y.; Tiunov, A. The risk of river pollution due to washout from contaminated floodplain water bodies during periods of high magnitude floods. *J. Hydrol.* **2016**, *534*, 579–589. [CrossRef]
41. Ponting, J.; Kelly, T.J.; Verhoef, A.; Watts, M.J.; Sizmur, T. The impact of increased flooding occurrence on the mobility of potentially toxic elements in floodplain soil—A review. *Sci. Total Environ.* **2021**, *754*, 142040. [CrossRef]
42. Opperman, J.J.; Luster, R.A.; McKenney, B.; Roberts, M. Ecologically functional floodplains: Connectivity, flow regime, and scale. *JAWRA J. of the Am. Water Resour. Assoc.* **2010**, *46*, 211–226. [CrossRef]
43. Trush, W.J.; McBain, S.M.; Leopold, L.B. Attributes of an alluvial river and their relation to water policy and management. *Proc. Natl. Acad. Sci. USA* **2000**, *97*, 11858–11863. [CrossRef] [PubMed]
44. Hayes, D.S.; Brandle, J.M.; Seliger, C.; Zeiringer, B.; Ferreira, T.; Schmutz, S. Advancing towards functional environmental flows for temperate floodplain rivers. *Sci. Total Environ.* **2018**, *633*, 1089–1104. [CrossRef]
45. Bormann, H.; Pinter, N.; Elfert, S. Hydrological signatures of flood trends on German rivers: Flood frequencies, flood heights and specific stages. *J. Hydrol.* **2011**, *404*, 50–66. [CrossRef]
46. Hall, J.; Arheimer, B.; Borga, M.; Bradzil, R.; Claps, P.; Kiss, A.; Kjeldsen, T.R.; Kriaciuniene, J.; Kundzewicz, Z.W.; Lang, M.; et al. Understanding flood regime changes in Europe: A state-of-the-art assessment. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 2735–2772. [CrossRef]
47. Merz, B.; Dung, N.V.; Apel, H.; Gerlitz, L.; Schroter, K.; Steirou, E.; Vorogushyn, S. Spatial coherence of flood-rich and flood-poor periods across Germany. *J. Hydrol.* **2018**, *559*, 813–826. [CrossRef]
48. Allan, J.D. Landscapes and riverscapes: The influence of land use on stream ecosystems. *Annu. Rev. Ecol. Evol. Syst.* **2004**, *35*, 257–284. [CrossRef]
49. EC. Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. *Off. J. Eur. Union* **1992**, *206*, 7–50.
50. Krause, B.; Culmsee, H.; Wesche, K.; Bermeier, E.; Leuschner, C. Habitat loss of floodplain meadows in north Germany since the 1950s. *Biodivers. Conserv.* **2011**, *20*, 18. [CrossRef]
51. Dister, E. Geobotanische Untersuchungen in der hessischen Rheinaue als Grundlage für die Naturschutzarbeit. Ph.D. Thesis, Georg-August-Universität Göttingen, Göttingen, Germany, 1980.
52. Burkart, M. River corridor plants (Stromtalpflanzen) in Central European lowland: A review of a poorly understood plant distribution pattern. *Glob. Ecol. Biogeogr.* **2001**, *10*, 449–468. [CrossRef]
53. Reich, J.; Moser, M.; Dapp, K.; Heiland, P. *Hochwasserrisikomanagement-Planung in Baden-Württemberg*; Infrastruktur & Umwelt: Darmstadt, Germany, 2016.
54. Hoffmann, T.G.; Kreßner, L. *Ergänzung des Berichtes zur Vorläufigen Bewertung des Hochwasserrisikos der Binnengewässer nach EU-HWRM-RL in Mecklenburg-Vorpommern*; biota Institut für Ökologische: Bützow, Germany, 2013.