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Change of regulating ecosystem services in the Danube floodplain over the past 150 years induced by land use change and human infrastructure

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Abstract

Ecosystem services in floodplains are manifold. The regulating services regarding hydrological issues (e.g. flood protection, water purification) are of particular importance along rivers, and depend strongly on size and land use of the floodplain. In this paper, we transfer the commonly known land use changes in floodplains over the last 150 years into significant changes of the amount of different regulating ecosystem services. We investigated a floodplain stretch of 17 km along the Danube in Germany (approx. 90 km^2). Thus, we mapped the spatial expansion of the active floodplain and the land use distribution for three different times: the earliest (not the pristine) state of 1869 on the basis of a historical map, 1963 after river regulation and 2013 as navigation channel with a hydropower dam on the basis of aerial photographs. The land use types woodland, grassland, arable land, settlements, and water bodies were distinguished. On the basis of land use as a proxy, we calculated the potential of four ecosystem services (flood retention, nitrogen and phosphorous retention, habitat provision) according to the method of Scholz et al. (2012a). The spatial extension of the active floodplain was continuously reduced from 56 km^2 (1869) to 18 km^2 (1963) to 11 km^2 (2013). The amount of grassland and arable land was reduced significantly in the active floodplain, whereas woodland increased. This entails a decrease of flood retention (-80%), and nutrient retention (nitrogen: -60%, phosphor: -76%). Likewise, habitat provision was significantly reduced. In total, the potential benefits for humans have been negatively affected over the time by land use change and, above all, by the construction of embankments. Therefore, ecosystem services should be regarded by future floodplain management.

Zusammenfassung

Ökosystemleistungen in Auen sind vielfältig. Insbesondere die regulierenden Leistungen, die eng mit der Fluss-Hydrologie verknüpft sind (z. B. Hochwasserschutz, Wasserreinigung), sind stark von der Auengröße und der dortigen Landnutzung abhängig. Wir übertragen in diesem Beitrag die allgemein bekannten Landnutzungsänderungen in Auen innerhalb der vergangenen 150 Jahre in signifikante Änderungen verschiedener regulierender Ökosystemleistungen. In einem Auenabschnitt von 17 km Länge entlang der Donau in Deutschland (ca. 90 km^2) wurde die Ausdehnung der rezenten Aue und die Landnutzung in drei verschiedenen Zeitschnitten erfasst: der erste Zeitschnitt 1869 (nicht der ursprüngliche Zustand) auf der Grundlage einer historischen Karte, der zweite nach der Flussregulierung (1963) und der dritte nach der Errichtung eines Wasserkraftwerks (2013)

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auf der Grundlage von Luftbildern. Wald, Grünland, Acker, Siedlungen und Wasserflächen konnten unterschieden werden. Mit den Landnutzungstypen als Proxy wurde das Potenzial von vier Ökosystemleistungen (Hochwasserschutz, Stickstoff- und Phosphor-Retention, Habitatbereitstellung) nach der Methode von *Scholz* et al. (2012a) berechnet. Die Fläche der rezenten Aue wurde kontinuierlich von 56 km^2 (1869) auf 18 km^2 (1963) und auf 11 km^2 (2013) reduziert. Der Anteil an Grünland und Acker in der rezenten Aue wurde deutlich verringert, während sich die Waldflächen vergrößerten. Daraus folgt eine Verringerung des Hochwasserschutzes (-80%) und der Nährstoff-Retention (Stickstoff: -60%, Phosphor: -76%). Auch die Habitatbereitstellung wurde deutlich reduziert. Insgesamt wurden die potenziellen Ökosystemleistungen durch die Änderung der Landnutzung und vor allem durch die Ausdeichung der Aue über 150 Jahre negativ beeinträchtigt. Aus diesem Grund sollten Ökosystemleistungen bei zukünftigen Planungen in der Aue berücksichtigt werden.

Keywords flood regulation, nutrient retention, habitat provision, historical maps, active and former floodplain

1. Introduction

It is widely acknowledged that our human existence depends on the functioning of healthy ecosystems (*MA* 2005). Especially floodplain ecosystems offer many benefits to human society, which cannot be achieved by other ecosystems (*Maltby* et al. 2009; *Turner* et al. 2008) and cannot be supplemented by technical solutions. The concept of ecosystem services (ES) was developed to highlight the importance of biodiversity and to systematically monitor these services. By implementing the concept, for example, the effects of land use change on biodiversity and on ES can be interpreted as advantages and disadvantages for human well-being (*TEEB* 2010). The term ecosystem service includes the human beneficiary, but the demands of society and therefore the used ecosystem services change between regions (*Brouwer* et al. 2016; *Nedkov* and *Burkhard* 2012) and especially over time (*Bürgi* et al. 2015; *von Haaren* et al. 2014). For a comparison of the historical development without knowledge of the historical demands, it is more appropriate to calculate ecosystem service potentials as capacity of an ecosystem to provide goods and services. The potential of ES is not dependent on human demands, but can be calculated as distinct entities (*Burkhard* et al. 2014; *von Haaren* et al. 2014). Mapping and assessing of ecosystem services is applied by a variety of methods and approaches (*Maes* et al. 2012). Proxy-based methods, e.g. based on land cover or land use, are appropriate to estimate large-scale trends of ES in floodplains spatially (*Clerici* et al. 2014; *Stürck* et al. 2014) or temporally (*Lautenbach* et al. 2011), also when no other data is feasible. Simplified land use data can be distinguished from historical maps and from aerial photographs. In latest research papers not only land use was compared (*Xu* et al. 2017; *Früh-Müller* et al. 2015) but also ES over several decades (*Tomscha* and *Gergel 2016*; *Zhang* et al. 2016; *Bürgi* et al. 2015; *Lautenbach* et al. 2011).

Along the Danube in Germany, as in other Central European regions, the very early settlements occurred in or near floodplains due to water availability, high plant productivity on fertile soils and easier transport routes, demonstrating the overwhelming role of ES in floodplains already millennia ago (*ABSP* 2007). Some regulating ES occur exclusively in floodplains or wetlands as they depend on the hydrological situation of flooding or oscillating water levels, e.g. flood protection, nutrient retention, clearing drinking water. The same applies to biodiversity: Several typical habitats and species exist only or mainly in floodplains. On the other hand, the naturally very dynamic floodplains were massively impacted by humans to control this dynamic and to increase the ability to use these landscapes more intensively (*Hohensinner* et al. 2014; *Diaz-Redondo* et al. 2017). Due to human infrastructures and hence land use changes, the potential of floodplains to provide ES like ‘flood retention’ has tremendously decreased since the 19th century (*Früh-Müller* et al. 2015) and the typical floodplain habitats have been highly threatened since then (*Ellwanger* et al. 2012). The use of floodplains in the beginning was followed by regulation of the river for shipping, land reclamation or power production and led to a reduction in size of the active floodplains in Germany, on average of two-thirds, sometimes up to 90% of its former extent (*Brunotte* et al. 2009). Especially the regulating ES strongly depend on the hydrological connectivity of river and floodplain (*Scholz* et al. 2012a). No detailed measures, but a simplified method is required to calculate the potential of ES to demonstrate the effects of the changed hydrological connectivity. The changed flood retention potential, for instance, was calculated for the Danube by a sophisticated two-dimensional hydrodynamic modelling (*Skublics* et al. 2016), but can also be estimated by more simplified methods (*Mehl* et al. 2012). For the nutrient retention rough estimation values on the basis of land use and soil types (*Gäth* et al. 1997; *Schulz-Zunkel* et al. 2012) and for habitat provision, a method to estimate the ecological potential on the basis of land use data (*Günther-Diringer* et al. 1999) exists.

To our knowledge, no studies have yet investigated and compared different ES on declining areas such as the reduced floodplain areas over time. Hence, the comparison of ES both over time for the total floodplain and relatively for a spatial entity in the floodplain depending on the changed land use will provide new insights. These estimates can be compared with the development of arable fields as a proxy for provisioning ES in the active as well as in the former floodplain. A more detailed estimation of the provisioning services was rejected as the provisioning services in floodplains are strongly dependent on additional inputs (*Burkhard* et al. 2014), which are difficult to calculate, as for instance arable fields have to be cleared, prepared and protected against summer floods. Further, the set of provisioning services and also their value have changed over time (e.g. fish production in the Danube was economically important in earlier days, but it is no longer today). *Scholz* et al. (2012a) developed a method to assess the regulating ecosystem functions (i.e. potential of ES) in floodplains in Germany. Due to the nationwide approach and the lack of detailed data for the whole country, simplified land use data were used as proxies. We wanted to test this approach on a floodplain stretch along the Upper Danube in Germany, so we asked the following questions:

- Can land use change and reduction in size of active floodplains be identified and quantified over almost 150 years within the morphological Danube floodplain by interpreting historical maps and aerial photographs?
- Are there structural differences in the land use composition between active and former floodplain and between the different periods?
- How did the potential of regulating ES change over time calculated by a proxy-based estimation on that land use?

2. Methods

2.1 Study site

The study site is located in the floodplain along the Upper Danube River in Southern Germany (see small map in *Fig. 1* in Section 3.1) between the river kilometres 2.344 and 2.311 at an altitude of 314 to 330 meters above sea level. Here, the meandering Danube has a mean discharge of ca. 450 m^3/s and a water level amplitude of several meters within a year due to a pluvial-nival flow regime with both winter and summer floods (*LfU* 2017a; *Skublics* et al. 2016). The surrounding landscape unit called “Dungau” is a cultural landscape with highly fertile and intensively cultivated loess plains (*LfU* 2011).

The potential natural vegetation is an alluvial hardwood forest, accomplished with aquatic vegetation, reed and alluvial softwoods. The assumed pristine vegetation type distribution in the floodplain is 69% woodland, 3% reed, 14% open soils and 14% water bodies (*Mehl* et al. 2012). The region was already cultivated 7000 years ago due to the fertile soils and the richness of fishes (*ABSP* 2007). There was no settlement within the floodplain until the Middle Ages, but on the terraces close by. In the 14th century, first regulation and straightening measures were implemented to protect settlements and arable fields. From 1837 to 1883, the meandering Danube in Germany was regulated (short cuts, constant width of 130-140 m) to improve shipping. Moreover, levees were constructed to protect the arable lands against summer floods, whereas the winter floods should bring fertile sediments to the fields (*ABSP* 2007). Hence, in the early 20th century further regulation measures (e.g. low water regulation) took place, the river bed deepened up to 2-3 cm per year. Since the 1970s, as a technical solution against river bed deepening, hydropower dams have been built in the river. The barrage Straubing (2.324 km) with a height of 7 m (44 MW capacity), completed in 1995, is located in the study area. Since 1992, the Danube has been connected with the river Rhine via the Rhine-Main-Danube-Canal, enabling shipping from the Black Sea to the North Sea. Despite all these severe impacts, the Danube and its floodplain are still an essential biological corridor in Europe and a hotspot of natural habitats (*Weiger* and *Margraf* 2003).

We investigated the floodplain at a stretch of 17 km upstream and downstream of the hydropower dam

Straubing. It has a size of more than 9,000 ha using the borders defined by *Brunotte* et al. (2009) on the basis of Holocene sediments and a digital elevation model in the scale 1:100,000. The entire floodplain (further called morphological floodplain) is divided into the active floodplain (periodically inundated by the lateral overflow of the riverbanks) and the former floodplain (actual river dynamics inhibited by human infrastructure like dams or levees). The expansion of the active floodplain has changed over time. For 2013, the actual border of the active floodplain is according to *Brunotte* et al. (2009). For the historical time cuts 1963 and 1869, the active floodplain was defined referring to the experience of the water management authority on the basis of the maps, the domination of the arable fields and the dimension of different flood events.

2.2 Digital map sources

We analysed historical maps and aerial photographs of 1869, 1963 and 2013. The oldest geometrically usable maps available for the whole study area date from 1869. Those topographic maps ("Positionsblätter") do not represent the pristine situation but rather the situation after first, slight regulations in the 19th century. Eight georeferenced coloured maps deriving from calculated triangulation in the scale of 1:25,000 were provided by *LVA* (2017). As a next time cut, the situation after the low water regulation and damming was investigated using the first completely available aerial photographs (1:24,000) of July 1963. The original photos were scanned, rectified and geocoded. As the last time cut, actual digital true colour orthophotos of June/July 2013 (ground solution 0,4 m) were used. For the distribution of soil types, the digital soil map of Bavaria (scale 1:25,000) (*LfU* 2017b) was used for all time cuts.

2.3 GIS and statistical analysis

Digitalisation of the land use types and data analysis was conducted using ArcGIS 10.4 (2016). Five categories of land use were distinguished: grassland, woodland, arable land, settlements and water (separated into Danube and other water bodies). They could clearly be differentiated visually on the aerial photographs by colour and texture, except for the photographs of 1963 with a lower resolution. For the historical maps, the types could be differentiated by the colours given in the map legend, but no automated distinguishing could be transformed (cf. *Früh-Müller* et al. 2015). When the interpretation was not clear, the more intensive land use type (e.g. arable land instead of grassland) was chosen in order to not over-estimate the calculation of the proxy-based ecosystem services. The area size of the single land use types was calculated for each floodplain segment of 1 km differentiated into active and former floodplain according to *Brunotte* et al. (2009).

We used a non-parametric multivariate analysis of variance (Kruskal-Wallis test) to test the differences between time cuts in general and a U-test as post hoc test for differences between single time cuts with IBM SPSS Statistics, Version 24 (2016). A Spearman rank correlation was calculated between different ES values and floodplain size. To obtain the main differences in the land use composition of the single floodplain segments between the different time cuts and the active and former floodplain, a principal component analysis (PCA) with log(x+1) transformed land use data was calculated by using the programme PC-ORD 6.08 (2011). In the PCA, the first two principal components determine a coordinate system where the segments with a similar land use composition were plotted close to each other and segments with different land use composition show a bigger distance. Additionally, a PCA was conducted solely for the land use data of the active floodplain with the ES values as a second matrix, so significantly correlating ES could be identified.

2.4 Calculation of ecosystem services

The method of *Scholz* et al. (2012a) to calculate regulating ES potentials in floodplains was implemented or slightly adapted. Flood retention (cf. *Mehl* et al. 2012) was calculated as loss of retention volume. The retention volume of the active floodplain was calculated by using different roughness values k_{st} for the different land use types (grassland, settlement: 20; woodland: 7; arable land: 15; water: 40) and was compared to the retention volume in the morphological floodplain with the pristine vegetation (k_{st} 11). Nutrient retention (cf. *Schulz-Zunkel* et al. 2012) was calculated for nitrogen and phosphorous. For nitrogen retention, arable land and settlements were not regarded at all, water bodies were rated with the highest denitrification rates (300 kg/ha/a); for woodland and grassland different soil types led to different denitrification

(5-250 kg/ha/a) according to *Gäth* et al. (1997). For phosphorous retention, in watered areas a typical value of 3 kg/ha/a was assumed, whereas on terrestrial land the retention mainly depends on the different roughness value of the land use types. As a rule of thumb, 1 kg/ha/a was stated as the mean value and in total five degrees from 0.5 to 5 kg/ha/a were defined. The identified land use types were regarded as follows: settlements 0,75 kg/ha/a, arable land 1 kg/ha/a, grassland 2,5 kg/ha/a, woodland 5 kg/ha/a. For habitat provision for floodplain typical biodiversity, the method of *Scholz* et al. (2012b) could not be implemented, as neither wetlands nor protected areas could be differentiated on historical maps or aerial photographs. We simply rated the entire area of the land use types woodland, water and grassland in the actual floodplain as potential ES habitat provision. Especially in the earlier time cuts, it can be assumed that all these land use types provide habitats. For 2013, the area which was covered with these land use types in the active floodplain was completely protected by Natura 2000 showing the good estimation for habitat provision. As a rough proxy for the service food provision, the area used as arable land was regarded, only to compare it with the regulating services and to detect trade-offs between them.

3. Results

3.1 Land use changes

Land use distribution has changed significantly over time (*Fig. 1*; *Table 1*). In 1869, grassland and arable land were almost equally represented in the morphological floodplain with slightly more grassland (42% and 43%), whereas woodland covered only 5%. Settlements were detected on 186 ha and water on 94 ha. In 1963, in contrast, arable land was the dominating land use with 64% (increase of 52%), leading to a decline of grassland and woodland. Areas with settlements, in contrast, doubled and the watered areas slightly decreased, but the mean results for the floodplain segments were not significant for both between 1869 and 1963. By 2013, the arable land had again slightly declined, but still covered 55%, whereas grassland had further declined and then covered only 37% of the former grassland in 1869. Woodland, on the other hand, increased from 394 ha in 1869 to 484 ha in 2013. The strongest increase can be described for the settlements and the watered areas, which in 2013 had both reached the fourfold cover of 1869.

The shape of the river Danube in the investigation area was changed, one meander was cut off and the river-line was harmonised with a uniform width in 1963. Consequently, the expanse of the Danube was reduced by 24%. Due to the construction of the hydropower dams, the water level raised upstream of the dam, the river expanded and few backwaters filled up. The expanse of the river had again increased by 2013 but, in comparison to 1869, still a loss of 11% can be observed.

There are spatial differences in the changes regarding the active and the former floodplain (*Fig. 1; Table 1*). From 1869 to 1963, the size of the active floodplain was reduced by 66% from 5043 ha to 1736 ha. Until 2013, the straightening for navigation purposes and the construction of a hydropower dam had led to a further decline to 1011 ha, which in total is a reduction of 80% compared to 1869. Already in 1869, the active floodplain only covered 65% of the morphological floodplain, but in 2013 only 13% of the morphological floodplain was still active floodplain.

The PCA of the single floodplain segments, differentiated by active and former floodplain (*Fig. 2A*), showed a clear separation for these two groups, but also for the different time cuts. The land use composition of the former and the active floodplain can be separated by the second axis, mainly due to the higher occurrence of arable land and settlements. Especially for the two time cuts 2013 and 1963, no overlap of segments of the former and the active floodplain could be detected indicating the completely different land use composition of these groups. In 1869, the separation was not so distinct, neither between the former and active floodplain nor to the other time cuts. Especially the active floodplain of 1869 cannot be separated from all other groups, documenting a similarity of land use distribution to both active and former floodplain in the latter time cuts.

In the active floodplain (*Table 1*; *Fig. 3*), the dominating land use is grassland (1869: 60%; 1963 and 2013: 49%), but in 1869 and 1963 it was followed by arable land (32% resp. 42%). In 2013, arable fields only covered 17%, whereas the percentage of woodland had significantly increased (18%). Notably, no woodland from 1869 had remained on the same site until 2013. Settlements in the active floodplain decreased in absolute numbers from 74 ha in 1869 to 34 ha in 2013, but not significantly regarding the mean of the single segments, whereas the watered areas increased significantly and doubled their size from 76 ha in 1869 via 20 ha in 1963 to 124 ha in 2013.

Change of regulating ecosystem services in the Danube floodplain over the past 150 years induced by land use change and human infrastructure

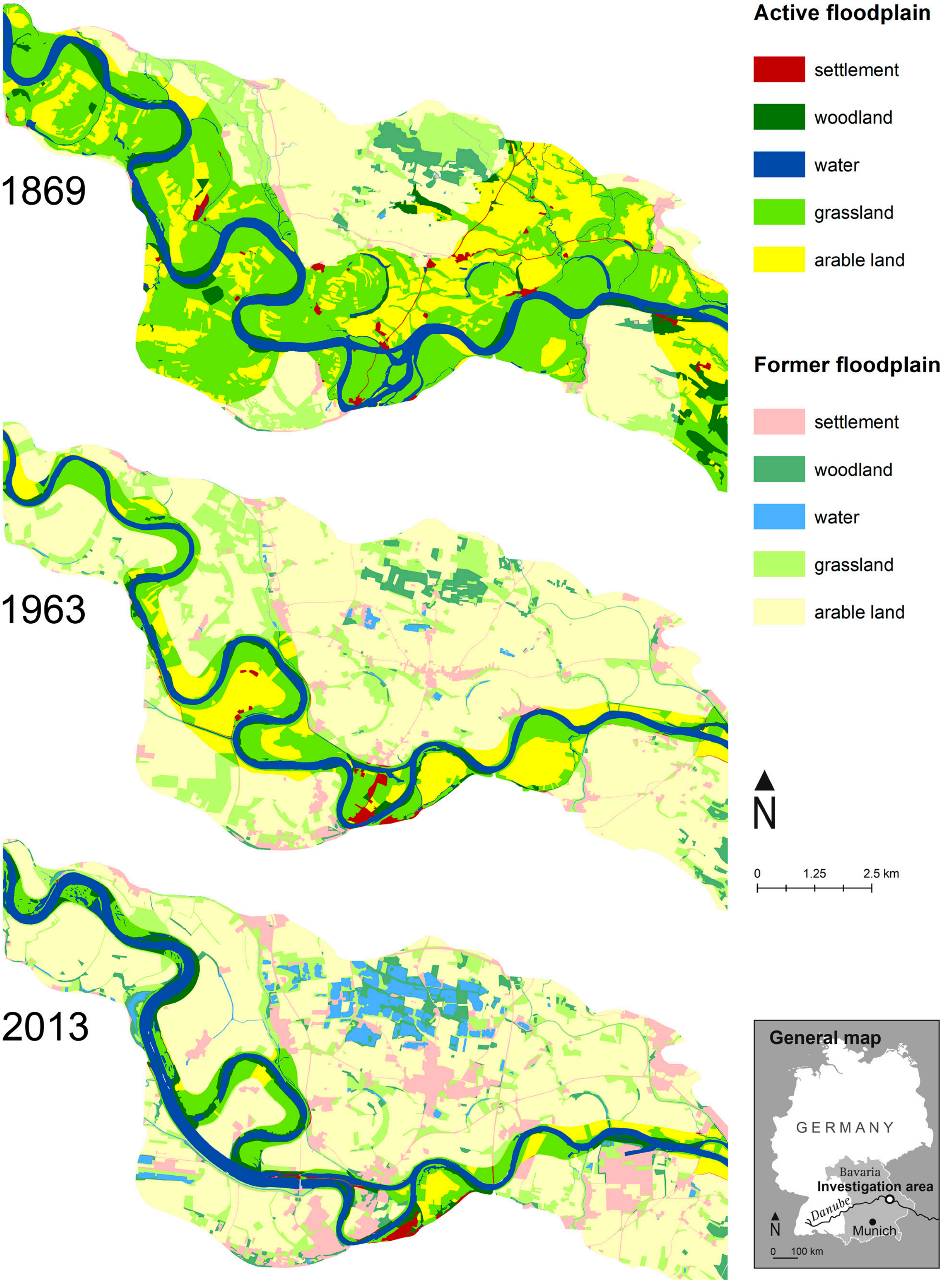

Fig. 1 *Land use in the morphological floodplain of the study site along the Danube River (see small map) for the three time cuts 1869, 1963 and 2013, derived from historical maps (1869) and aerial photographs (1963, 2013). The more transparent colours symbolise the land use in the former floodplain. Source: Own elaboration*

Table 1 Distribution of land use types in ha and % of land use change for the different time cuts in the study site along the Danube River in Germany. Source: Own elaboration

Land use	Area [ha]			Area [%]			Change [%] between		
	1869	1963	2013	1869	1963	2013	1869-1963	1963-2013	1869-2013
Morphological floodplain									
Arable land	3511	5326	4583	42	64	55	52	-14	31
Grassland	3593	1868	1341	43	22	16	-48	-28	-63
Woodland	394	275	484	4.7	3.3	5.8	-30	76	23
Settlements	186	378	935	2.2	4.5	11	103	147	402
Water bodies	94	72	499	1.1	0.9	6.0	-23	589	430
Danube	584	442	517	7.0	5.3	6.2	-24	17	-11
Active floodplain									
Total area	**5043**	**1736**	**1011**				**-66**	**-42**	**-80**
Arable land	1630	729	169	32	42	17	-55	-77	-90
Grassland	3042	858	498	60	49	49	-72	-42	-84
Woodland	221	82	186	4.4	4.7	18	-63	126	-16
Settlements	74	47	34	1.5	2.7	3.4	-37	-27	-54
Water bodies	77	21	124	1.5	1.2	12	-73	496	61
Former floodplain									
Total area	**2733**	**6184**	**6832**				**126**	**10**	**150**
Arable land	1881	4597	4414	69	74	65	144	-4	153
Grassland	551	1011	843	20	16	12	83	-17	53
Woodland	173	193	298	6.3	3.1	4.4	12	54	72
Settlements	112	332	901	4.1	5.4	13	196	172	706
Water bodies	16	52	376	0.6	0.8	5.5	223	627	2246

The dominating land use in the former floodplain (*Table 1*; *Fig. 3*) in all time cuts was arable land, the percentage changed from 69% in 1869 to 74% in 1963 to 65% in 2013. In 2013, in the increased former floodplain even the spatial extension of arable land was smaller than in 1963. Overall, the percentage of the different land use types did not significantly differ between 1869 and 1963, but for settlements (13%) and water (6%) a significant increase between 1963 and 2013 could be observed. Woodland did not significantly differ at all with a low percentage of 5%.

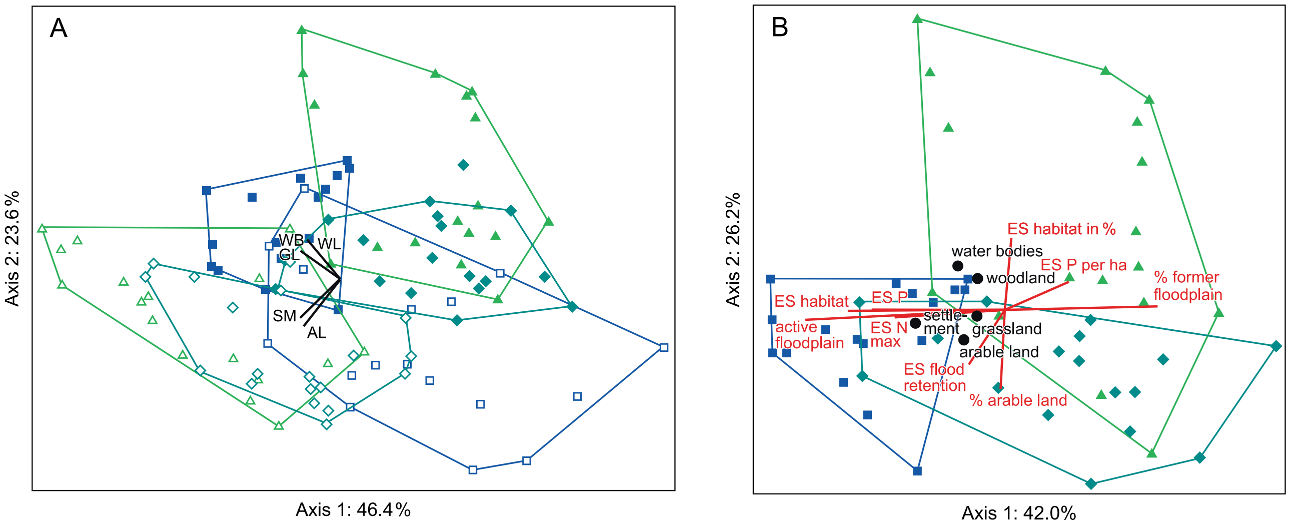

Fig. 2 Principal component analysis (PCA) of the single floodplain segments. A: differentiated in former and active floodplain. B: only active floodplain segments correlated with the significant ES-values in red. Blue squares: 1869; petrol rhombs: 1963; green triangles: 2013. Filled symbols: active floodplain; hollow symbols: former floodplain; black lines: biplot of land use types; WL: woodland, WB: water bodies; GL: grassland; SM: settlements; AL: arable land. Source: Own elaboration

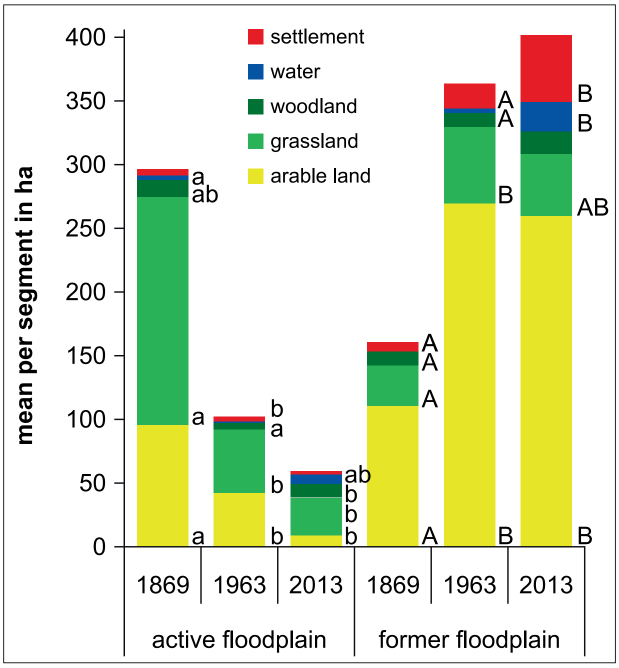

Fig. 3 *Mean land use distribution of the single segments of the active and the former floodplain for 1869, 1963 and 2013 in ha. Significant differences between the time cuts for each land use type were indicated by different letters for the active floodplain in lower case (a, b), for the former floodplain in upper case (A, B). AB or ab means no differences either to a or to b. For the active floodplain, there was no significant difference for the settlements; for the former floodplain there was no difference for woodland. Source: Own elaboration*

3.2 Effects on the ecosystem service potential

Apart from the nitrogen retention value per area, all other ES potentials showed significant differences in the Kruskal-Wallis test regarding the time cuts (*Table 2*). Implementing the post hoc test, many values differ significantly between all years (nitrogen and phosphorous retention per year, flood retention, habitat provision as area and as percentage of the morphological floodplain). Phosphorous retention per area, habitat provision as percentage of the active floodplain and arable land as percentage of the active floodplain only differ between 2013 and the two other time cuts, not between 1869 and 1963. The area of arable land in the morphological floodplain, as a proxy for food provision, is only significant between 1869 and the two other time cuts, but not between 1963 and 2013.

For the total stretch of 17 km, the flood retention was reduced significantly over the time from 60% of the pristine floodplain to 32% (34 billion m^3 to 7 billion m^3). The nitrogen retention was drastically reduced from a maximum of 754 t/a in 1869 to 226 t/a in 1963 and 124 t/a in 2013, whereas the retention per ha remained more or less stable with a mean of 95 kg/ha/a. For phosphorus retention, the values declined from 9.9 t/a in 1869 to 2.2 t/a in 1963, but increased in 2013 to 3.6 t/a due to a highly increased rate per area (3.9 kg/ha/a in 2013). The areas of habitat provision do not differ strongly between 1963 (56 ha) and 2013 (46 ha), but in 1869 more than the threefold amount of 190 ha could be observed. The percentage of habitats in the active floodplain, in contrast, had its maximum in 2013 (79%) and significantly lower amounts in 1963 (58%) and 1869 (65%).

Table 2 *Mean of ES values of the floodplain segments for the different time cuts and the assumed pristine situation. Significant differences between the time cuts were indicated by different letters (a, b, c) for each column. Where no letters are given, the Kruskal-Wallis-test was not significant. Min: minimum; Max: maximum; mo: morphological; flp: floodplain; act: active. Source: Own elaboration*

	Retention of nitrogen			**Retention of phosphorous**		**Flood retention**	**Habitat provision**			**Arable land**	
	Min [kg/a]	Max [kg/a]	Mean [kg/ha/a]	[kg/a]	[kg/ha/a]	[% of mo.flp]	[ha]	[% of act.flp]	[% of mo.flp]	[% of act.flp]	[ha in mo.flp]
Pristine	46262	63914	120	1966	4.30	1.00	492	1.00	1.00	0.00	0
1869	27378^{a}	44351^{a}	88	580^{a}	1.99^{a}	0.63^{a}	190^{a}	0.65^{a}	0.39^{a}	0.31^{a}	207^{a}
1963	10115^{b}	13320^{b}	102	133^{b}	1.82^{a}	0.40^{b}	56^{b}	0.58^{a}	0.12^{b}	0.40^{a}	313^{b}
2013	5653^{c}	7294^{c}	96	211^{c}	3.89^{b}	0.32^{c}	46^{c}	0.79^{b}	0.00^{c}	0.16^{b}	270^{b}

The PCA (*Fig. 2B*) shows a strong correlation for almost all ES and for the size of the active floodplain with the first axis, which separates the land use distribution of 1869 from the newer ones. The size of the active floodplain is significantly positively correlated with all ES (flood retention: 0.9; nitrogen retention: 0.8; phosphorous retention: 0.6; habitat provision: 0.9). The second axis, in contrast, separates the segments of 2013 from the other ones due to the higher amounts of woodland and water bodies. This axis is positively correlated with a high percentage of areas for habitat provision and negatively correlated with the percentage of arable land in the active floodplain. The size of arable land in the morphological floodplain, on the other hand, did not show any correlations in the PCA and only weak negative correlations with nitrogen retention (-0.37**) and flood retention (-0.38**).

4. Discussion

The aim of this study was to evaluate the change of the regulating ES over time in a certain stretch of the Danube floodplain on the basis of different land use types. We could clearly distinguish five land use categories on the given data bases and could demonstrate large differences in the three time cuts covering almost 150 years, which correspond to the industrial revolution of European societies with a large increase in human population and in settlements (*Früh-Müller* et al. 2015). On a more precise database, land use could be differentiated in detail (*Xu* et al. 2017; *Lautenbach* et al. 2011; *Vermaat* et al. 2016) and thus the ability to provide certain ES would vary immensely. Therefore, one has to be aware that the given values are just an orientation guide and a qualitative comparison of the ES. For the ES flood retention, for which we used a simplified Strickler value according to *Mehl* et al. (2012), huge differences are obvious: Corn fields just before their harvest can reach a Strickler value of 1 (*Hartlieb* 2005), whereas we applied a value of 15. Also, the nutrient retention value is an estimated value, as the potentially flooded areas and not the real flooding events were used for calculation, but the conservative estimation reduces over-estimation. Especially for the estimation of the habitat provision, no qualitative indicators could be regarded due to the existing database. For instance, the strong negative effect of the hydropower dam (constant water level) on biodiversity could not be additionally valued for 2013 as recommended by *Scholz* et al. (2012b) due to the method, which only regards the size but not the quality of the areas. Nonetheless, the presented calculation is a valid guideline, which brought interesting results.

The investigated area is a highly productive landscape with a comparably high percentage of arable land today (*Brunotte* et al. 2009; *Xu* et al. 2017), which was more or less the same 150 years ago. Already in 1869, the amount of woodland was almost negligible, demonstrating both the importance of the landscape for food provisioning and the demands of the people in this time. Only the amount of grassland was reduced significantly over time until 2013, whereas water bodies as a product of gravel mining and especially settlements in the former floodplain have increased by a factor of four in the last 150 years. A development over time can be demonstrated to a more distinguished functional separation of active and former floodplain. In contrast to the earlier time cuts, agriculture and settlements, which have both a high vulnerability against flooding, were strongly reduced in the active floodplain in 2013, whereas grassland, woodland and water bodies had increased confirming the results of *Xu* et al. (2017) for the same river. In contrast, in the times around 1869, probably frequent damages occurred to the large amount of arable land and settlements in the active floodplain and, therefore, the active floodplain was reduced tremendously in size over the time.

This loss of active floodplain was the overwhelming parameter for the change in the potential of regulating ES, regardless of the determined land use types. The differences in the ES per land use types are not so huge that the loss of 66% or 88% of active floodplain since 1869 can be compensated. Only for the loss between 1963 and 2013, which is still 42%, the phosphorous retention or the percentage of habitat provision can be increased by a more adapted land use in 2013, but not nitrogen retention or flood retention. For the provisioning ES, which is simply expressed by the area of arable fields, the total amount increased from 1869 to 1963, but decreased again until 2013. Comparing it with the regulating ES, both decreased during this period and no trade-offs, which were often documented (e.g. *Haines-Young* et al. 2012; *Tomscha* and *Gergel* 2016), could be found for the Danube floodplain. This might be due to increased pressure on arable land by settlements and gravel pits (resulting in water bodies) in this area during this time span. In contrast, for 1869, a trade-off between regulating services and agricultural use can be assumed in years with summer flooding events for the same site in the active floodplain. At that time, the fertility of the arable land in the active floodplain depended on the winter floods, whereas famines could occur when summer floods destroyed the harvest.

5. Conclusions

In the investigated Danube floodplain area, the land use change and the decline of the regulating ES can clearly be correlated to a functional separation of active and former floodplain and most of all to the reduction of the active floodplain. Already in 1869, the active floodplain had been reduced by a third compared to the pristine floodplain, which further increased up to an almost 90% reduction by 2013. The demands of the historical societies on regulating ES could hardly be estimated, but it would be necessary to calculate their needs and, hence, the lack of ES for the different time cuts (*Nedkov* and *Burkhard* 2012). Due to the increased settlements, the demands for flood protection (cf. *Früh-Müller* et al. 2016 on the river Main; *Nedkov* and *Burkhard* 2012; *De Roo* et al. 2003) and also for pure drinking water or food provision have increased in the region over time. For future planning, the calculation of the most important ES, which can solely be delivered in active floodplains, might be helpful (*Pusch* 2016) to distinguish the appropriate dimension and the land use of the active floodplain (*Schindler* et al. 2016).

Therefore, two options should be discussed. First, does the need exist to enlarge the active floodplain, surely taking the safety of settlements into account, and to change the land use to a more natural land use in the enlargement offering many ES? For example, not only the flood retention was enhanced by levee relocations along the river Elbe, but also all regarded regulating ES and habitat provision (cf. *Scholz* et al. 2012c). Or, second, is it sufficient to enhance the ES by solely adapting the land use on the remaining floodplain? For instance, to reduce the risk of flooding for settlements along the Danube, clearing stripes in flooded woodlands were efficient (*Haimerl* and *Ebner* 2006). Increasing the connectivity and the flooding frequency of water bodies could enhance nutrient retention (*Natho* et al. 2013), but also the ecological integrity of the floodplain (*Pander* et al. 2015). Technical solutions could also compensate the lost services (flood protection by levees, drinking water treatment, fertilizing the arable land). Even for the negative ecological effects on the ecosystem, like missing flooding or oscillating water level, technical solutions could be implemented like ecological flooding or low water management (*Stammel* et al. 2012). But one has to be aware that technical solutions might break down in extreme situations, e.g. breakdown of technical infrastructure against flooding like in 2013 (*Blöschl* et al. 2013), whereas many services would be provided for free by an intact and larger active floodplain ecosystem. The investigation of the historical development can help to find the critical size of a floodplain, when the positive effects of higher agricultural gains will be counterbalanced by the negative effects due to the loss of regulating ES in an active floodplain.

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