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BENCHMARKING FLUVIAL DYNAMICS FOR PROCESS-BASED RIVER RESTORATION: THE UPPER RHINE RIVER (1816-2014)

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ABSTRACT

Multi-temporal analysis of river-floodplain processes is a key tool for the identification of reference conditions or benchmarks, and for the evaluation of deviations or deficits as a basis for process-based river restoration in large modified rivers. This study developed a methodology for benchmarking fluvial processes at river segment level, focusing on those interrelations between morphodynamics (aggradation, erosion, channel shift) and vegetation succession (initial, colonization, transition) that condition habitat structure. Habitat maps of the free-flowing Upper Rhine River downstream from Iffezheim dam (France-Germany border) were intersected with a GIS-based approach. Patches showing trajectories of anthropization, changeless, progression and regression allowed for the identification of natural and human-induced processes over almost 200 years. Before channelization, the riverine system was characterized by a shifting habitat mosaic with natural heterogeneity, high degree of surface water connectivity and equilibrium between progression and regression processes. On the other hand, the following 175 years of human interventions led to severe biogeomorphologic deficits evidenced by loss of natural processes and habitat heterogeneity, hydrological disconnection between the river and its floodplain, and imbalance of progression versus regression dynamics. The main driving forces of change are found in hydromorphological impacts (channelization, regulation and hydropower plant construction). Regression processes are now almost absent and have to be the objective of process-based river restoration measures for the studied river-floodplain system. A sustainable view on water management and river restoration should aim at a more resilient riverine system by balancing the recovery of natural processes with societal needs.

KEY WORDS: process-based river restoration; Upper Rhine River; habitat structure; fluvial processes; biogeomorphology; reference conditions; deficits

INTRODUCTION

Rivers and their peripheral floodplains are integrated components of a single dynamic system (Tockner *et al.*, 2010). Their ecological richness and high productivity relies on a particular arrangement of aquatic and terrestrial habitat patches, in turn determined by a set of hydrological, geomorphological and biological interactions (Petts, 1989).

In natural river-floodplain ecosystems, provided that there is no significant change in climatic and hydro-sedimentary conditions over time (Hohensinner *et al.*, 2014), an equilibrium between progression (habitat development towards forests) and regression (re-setting of floodplain habitats) processes leads to a continuous spatial re-organization of habitats among several developmental stages, which can be referred as ‘shifting habitat mosaic’ (Stanford *et al.*, 2005). Furthermore, surface water connectivity allows for the interchange of water, sediments and biota between the river and its floodplain (Tockner *et al.*, 2010); and erosion/sedimentation processes create aquatic/terrestrial interfaces that favour biological diversity (Van Der Nat *et al.*, 2003).

Despite the distinctive individuality of the world’s major rivers, these potentially ecologically rich systems have undergone similar degradation trajectories, confined to single channels, with disconnected floodplains and low levels of habitat diversity (Petts, 1989; Buijse *et al.*, 2002; Surian and Rinaldi, 2003). Accordingly, the natural interactive processes that should structure the riverine landscape are greatly endangered (Tockner *et al.* 2010; Tockner and Stanford 2002; Hohensinner *et al.*, 2004, 2014), and few reaches of large rivers remain unaltered to investigate their dynamics over different time scales (Whited *et al.*, 2007).

Nevertheless, understanding the relationships between the effects of pressures over fluvial processes and the consequent habitat configuration across different spatial and temporal scales constitutes a major challenge not only for the study of large river's ecology in particular, but for river conservation and restoration in general (Ward and Stanford, 1995; Vaughan *et al.*, 2009; Magdaleno *et al.*, 2012; Gumiero *et al.*, 2013). Recent research has centred on interactions between hydromorphological processes and vegetation and their relevance to river management and restoration (Vaughan *et al.*, 2009; Gurnell *et al.* 2016).

In this line of investigation, this work adopted a biogeomorphologic perspective on fluvial dynamics as changes in space and time of riverine landforms and associated plant communities (Corenblit *et al.*, 2011). Therefore, we focused on geomorphological and vegetation dynamics occurring at the segment level, such as channel shift, aggradation, bank erosion, and riparian vegetation succession (after Frissell *et al.*, 1986 revised by González del Tánago and García de Jalón, 2006). We developed a methodology for the identification of trajectories of habitat change as indicators of geomorphological and vegetation dynamics, and applied this methodology to the evolution of a heavily modified segment of the Upper Rhine River along the last two centuries. As an integral component of the European cultural and natural heritage, the Rhine River is one of the best documented examples of historical evolution (Dister, 1986; Dister *et al.*, 1990; Frings *et al.*, 2014; Arnaud *et al.*, 2015), and offers a great opportunity to analyse the effects of anthropogenic impacts in natural processes.

The main aim of the research was to assess habitat structure and river-floodplain processes along history establishing benchmarks to better guide process-based river restoration measures. We associated reference conditions or benchmarks to very low human pressure, not necessary 'pristine' states (EC, 2003), and deficits to deviations from those benchmarks (based on Muhar *et al.*, 2007). We used parameters of spatial heterogeneity, surface water connectivity and balance of habitats and processes to analyse the selected benchmark and quantify biogeomorphologic deficits. We also determined if deficits were cumulative in time and if changes in water levels induced by hydromorphological impacts correlated with the expansion and contraction of habitats. Finally, we highlighted possible implications for water management and river restoration.

METHODS

Study area and historical background

From the Alps to the North Sea, the Rhine River has a length of 1,320 km and it drains an area of approximately 185,000 km² within nine different countries; the Upper Rhine River discussed in this paper is the river section between Basel (Switzerland) and Bingen (Germany) (Arnaud *et al.*, 2015).

This study was conducted on a 10 km length segment of the free-flowing Upper Rhine River downstream from Iffezheim dam to the confluence of the river Murg (Rhine-km 335-345, 114-110 m.a.s.l.), on the border between Germany and France (Figure 1). This segment is representative of the Upper Rhine River for having undergone the main historical hydromorphological impacts in the river (i.e. channelization and regulation) and for being situated in the transition area between the morphological braided zone (Basel-Rastatt) and the meandering zone (Rastatt-Mainz), with natural aquatic habitats and artificial gravel pits that are distinctive of both zones (Dister *et al.* 1990).

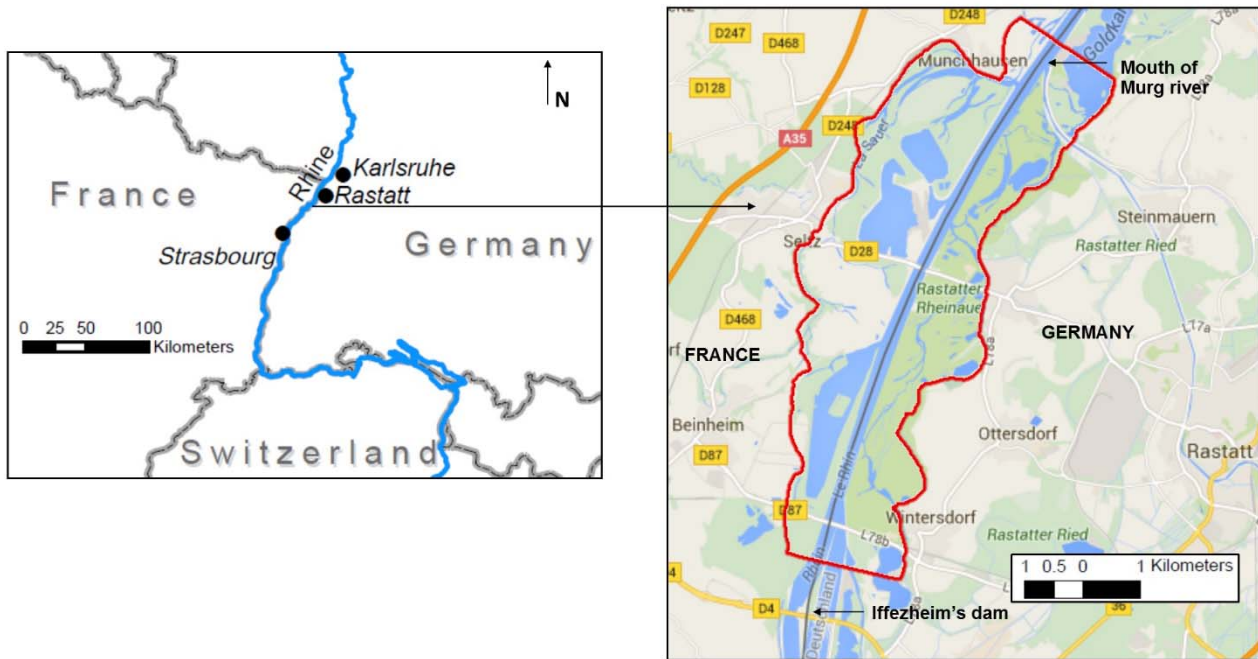


Figure 1. Location of the study area or active zone (red line on the right). Sources: OpenStreetMap and Google Maps.

Under potentially natural conditions, this segment can be classified as gravel-dominated, laterally active anabranching (Nanson and Knighton, 1996) and it is located on a medium-energy non-cohesive, wandering gravel-bed floodplain (Nanson and Croke, 1992). The flow regime is typically alpine with minimum discharges in winter and maximum discharges in spring/summer, as a result of precipitation and snowmelt in the Alps (Dister *et al.*, 1990).

The study area (2,572 ha) represents the river morphologically active zone prior to channelization (before 1840), and corresponds to the ‘genetic floodplain formed or reformed by contemporary processes’ (Nanson and Croke, 1992). The term “active zone” (AZ) was more closely defined by Hohensinner *et al.* (2004, 2014) as the area comprising water bodies, gravel/sand bars, islands and the adjacent floodplain formed by fluvial dynamics under hydroclimatic conditions during Modern times (since approximately 1500 A.D.). In our study site, the AZ width varies from 1.6 km to 3.4 km.

In the last 200 years, four periods can be identified by their association with the main hydromorphological impacts in the Upper Rhine River:

- Pre-channelization or benchmark (before 1840): similar to other large Alpine rivers (Danube, Rhône), the situation at the beginning of the 19th century was that of an almost unimpaired and highly dynamic fluvial ecosystem (Gallusser and Schenker, 1992).
- Correction and regulation (1840-1930): along the 19th century and beginning of the 20th century, the Upper Rhine River was converted into a single thread channel by cutting off meander bends and by building groins and bank revetments (Frings *et al.*, 2014).
- Extension (1930-1977): after the treaty of Versailles (1919), the Grand Canal d’Alsace (Basel-Breisach) was built along the left margin of the river, and ten hydropower plants from Kembs to Iffezheim were placed in the main channel or in side-channels (Dister *et al.*, 1990).
- Current situation (1977-present): after the construction of the Iffezheim dam (1977), the study area has progressively incorporated industry and settlements, with a special relevance of intensive gravel mining (Habersack and Piégay, 2007).

Materials and data

For centuries, the Upper Rhine's thalweg (line following the deepest riverbed points) has served as a border between France and Germany; thus, the riverine landscape has been the focus of several historical drawings and maps. Detailed maps were produced at the beginning of the 19th for planning river straightening and, up to the second half of the 20th century, they indicated the river bottom along the thalweg, the situation of water bodies, islands and gravel/sand bars within the aquatic area, as well as land uses in the floodplain (grasslands, forests, croplands and settlements).

Historical maps are not accurately dated, but as their purpose was defining international borders and cadastre, mapped wetted channel is assumed to represent mean water levels, as it is usual in cartography. Aerial photographs were selected from 1961 (30 June) and 1986 (27 July), ensuring at least one image every 30 years; dates of aerial images were checked against historical hydrological data to be representative of annual mean water level (Table I), for the extension of water bodies, islands and gravel/sand bars is particularly sensitive to water fluctuations (Arnaud *et al.*, 2015).

Because discharge data were not recorded until the 20th century, we selected registers of stage heights (annual low, mean and high water levels relative to the zero point of gauge) from the beginning of the 19th century onwards. Missing data in the study area (Seltz and Plittersdorf gauging stations) were estimated by computing the rating curve of the complete series (1815-2014) of the next downstream gauging station (Maxau).

Table I. Maps, aerial photographs and hydrological data used in the present study

Period and years	Maps and aerial photographs			Water levels		
	Author/ Source	Type	Scale or resolution	LW (cm)	MW (cm)	HW (cm)
Pre-channelization (before 1840)						
1816	BGB	M/BW	1:14,400	420	627	997
1828	BGB	M/BW	1:20,000	377	466	597
1838	BGB	M/C	1:20,000	346	458	590
Correction & Regulation (1840-1930)						
1852	BGB	M/C	1:20,000	230	374	681
1872	BGB	M/C	1:20,000	195	367	710
1893	RL	M/C	1:100,000	248	332	456
Extension (1930-1977)						
1937	RL	M/C	1:25,000	324	444	587
1961	GEO	A/BW	1:26,463	265	404	539
Current situation (1977-2014)						
1986	GEO	A/C	1:17,408	248	413	694
2014	LUBW	O/C	1m resolution	316	417	685

M: map; A: aerial photograph; O: orthoimage; BW: black and white; C: coloured

BGB: Bureau der Grossh, Badisch Oberdirection des Wasser und Strassen-Baues, Karlsruhe; RL: Reichsamt für Landesaufnahme; GEO: Géoportail (France); LUBW: Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg.

LW: Annual low water level; MW: Annual mean water level; HW: Annual high water level. *Source:* Bundesanstalt für Gewässerkunde

Diachronic analysis of habitat structure

For the ten selected time steps, habitat patches were digitized with ArcGIS software 10.2 (ESRI, Redlands, California, USA) and classified within natural (natural water body, gravel/sand bar, grassland and forest) or anthropic (regulated water body, artificial water body, cropland, settlement, industry and gravel pit) habitat categories. This habitat classification (Ward *et al.*, 2002) was limited by the information included in historical maps; in images, digitalization was carried out by visual interpretation, through differences in polygon texture, colour, density and size of vegetation. A subclassification of water bodies was established according to their gradient of connectivity with the main channel (Ward and Stanford, 1995): eupotamon (the main river and its side channels), parapotamon (river arms with a connection to the active channel at their downstream end) and plesiopotamon (disconnected river segments). Finally, islands were identified and subclassified (based on Belletti *et al.*, 2013) into young (predominantly gravel/sand bars), colonized (predominantly grasslands) and mature islands (predominantly forests or croplands).

The assessment of spatial structure was undertaken through different parameters. First, proportions of aquatic versus terrestrial habitats were calculated so as to establish the degree of terrestrialization. As some authors state (Ward *et al.*, 2002; Belletti *et al.*, 2013), island parameters are good indicators of habitat heterogeneity; therefore, we selected the evolution of island areas, although this indicator should be taken with caution due to its sensitiveness to flow level and to the accuracy of historical maps (Belletti *et al.*, 2013; Arnaud *et al.*, 2015). Surface water connectivity was evaluated in terms of area covered by the different types of water bodies (eupotamon, parapotamon and plesiopotamon), expressed as a percentage of the AZ (Ward and Stanford, 1995; Hohensinner *et al.*, 2004). Finally, correlations between water levels and habitat areas were calculated in order to test if the evolution of habitat structure is associated with water level fluctuations.

Multi-temporal analysis of river-floodplain processes

Each of the ten habitat maps was intersected with the subsequent one (ArcGIS 10.2), so that nine intersection maps were obtained. Trajectories of habitat change were identified as the intersection of habitat areas between two time steps (based on Whited *et al.*, 2007, with modifications by the authors). A first classification of four main trajectory categories (changeless, progression, regression and anthropization), was followed by a subclassification of thirteen subcategories according to geomorphological and vegetation processes (Table II). Next, the assessment of temporal dynamics was undertaken through the analysis of the balance of regression versus progression processes along the four periods considered. Both this balance of processes and that between aquatic and terrestrial habitats were considered with the aim of detecting the existence of a ‘shifting habitat mosaic’ (Stanford *et al.*, 2005).

Table II. Classification of trajectories of change and associated processes

Main trajectory	Geomorphological and vegetation process	Type	Description
Changeless (areas that show no change)			
Progression (involve growth towards the development of floodplain forests):			
	Initial-aggradation (Prog.)	Nat.	Areas that progress from water bodies to gravel/sand bars
	Colonization-natural	Nat.	Areas that progress from water bodies or gravel/sand bars to grasslands
	Colonization-land aband.	H.I.	Change from croplands or settlements to grasslands
	Transition-natural	Nat.	Change from water bodies, gravel/sand bars or grasslands to forests
	Transition-land aband.	H.I.	Change from croplands or settlements to forests
Regression (involve re-setting of the floodplain habitats):			
	Channel shift-erosion	Nat.	New areas of water bodies previously occupied by other habitats
	Initial-aggradation (Reg.)	Nat.	Creation of gravel/sand bars from any other habitat category
	Colonization-clearance	H.I.	Change from forests to grasslands
Anthropization (exclusively human-induced changes):			
	Cultivation	H.I.	Any habitat area converted to croplands
	Urbanization	H.I.	Any habitat area converted to settlements
	Industrialization	H.I.	Any habitat area converted to industry or to gravel pits
	Regulation	H.I.	Any habitat area converted to regulated water bodies
	Artificialization	H.I.	Any habitat area converted to artificial water bodies

Prog.: progression; Reg.: regression; aband.: abandonment

Nat.: natural; H.I.: human-induced

RESULTS

Diachronic analysis of habitat structure

In the Pre-channelization period (before 1840), natural areas occupied more than 95% of the TA, while anthropic elements (croplands) held an average 3% of the AZ area (Figure 2a). The channelization of the Rhine in the Correction and Regulation period (1840-1930) led to a considerable reduction of natural water bodies and to an increase in gravel/sand bars, forests and cropland areas (Figure 2b). Natural water bodies continued decreasing both during the Extension period (1930-1977) (Figure 2d), and in the Current situation period (1977-2014). During this last period, industry appeared within the AZ, artificial water bodies increased considerably and gravel/sand bars virtually disappeared (Figure 2d).

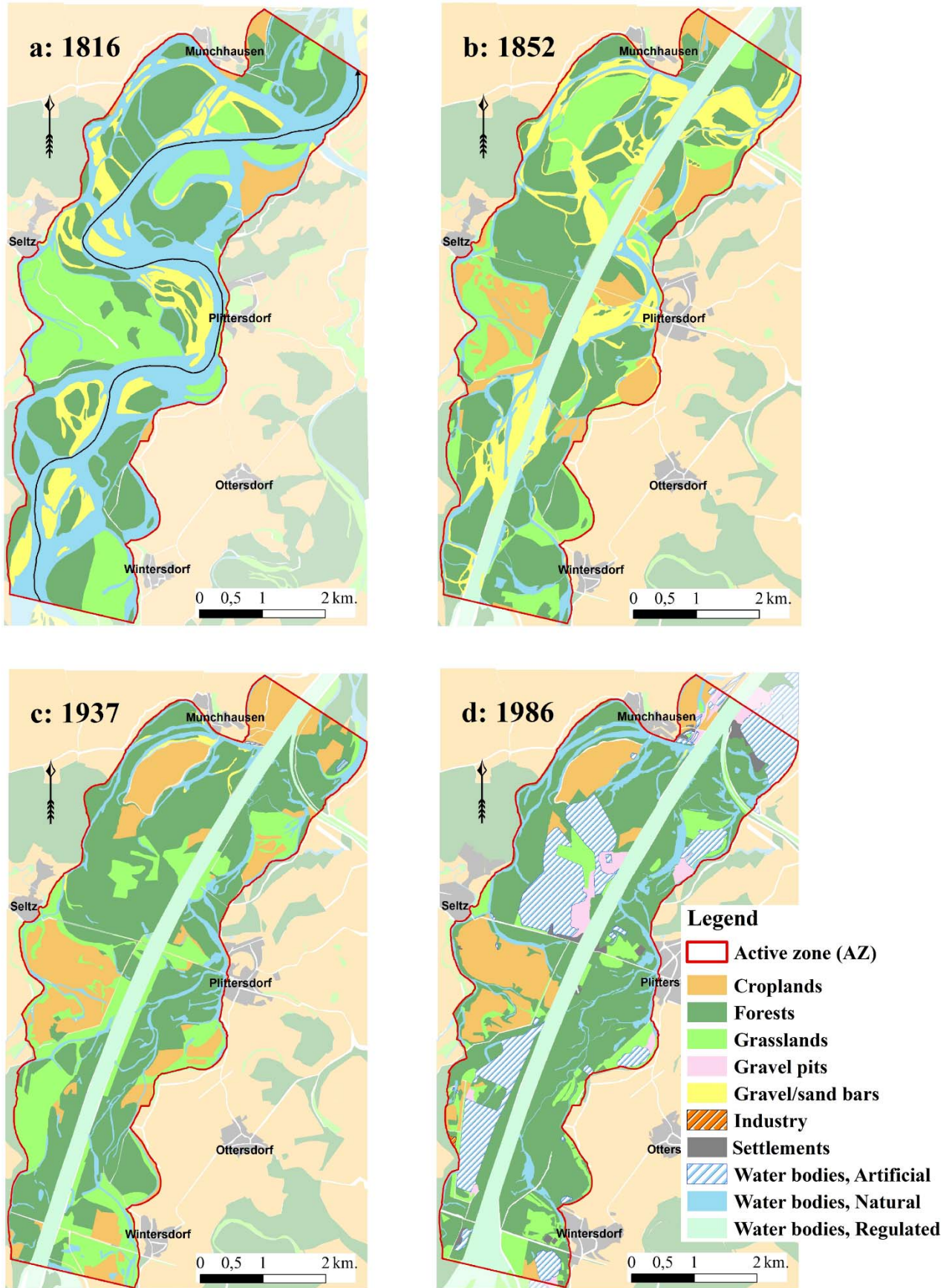


Figure 2. (a–d) Representative habitat maps for Pre-channelization (a), Correction and Regulation (b), Extension (c) and Current situation (d) periods. The black line in panel a indicates the position of the thalweg, as specified in historical maps.

Total river-floodplain habitat composition, in terms of aquatic and terrestrial habitat proportions, generally reacts very sensitively to channelization and damming with a tendency towards terrestrialization (Tockner and Stanford, 2002; Hohensinner *et al.*, 2004, 2014; Reckendorfer *et al.*, 2005). In the Pre-channelization period there was nearly a balance between aquatic and terrestrial habitats proportions; however, the percentage of terrestrial versus aquatic habitats was three times higher in the Correction and Regulation period, and even four times higher in the Extension period (Figure 3a).

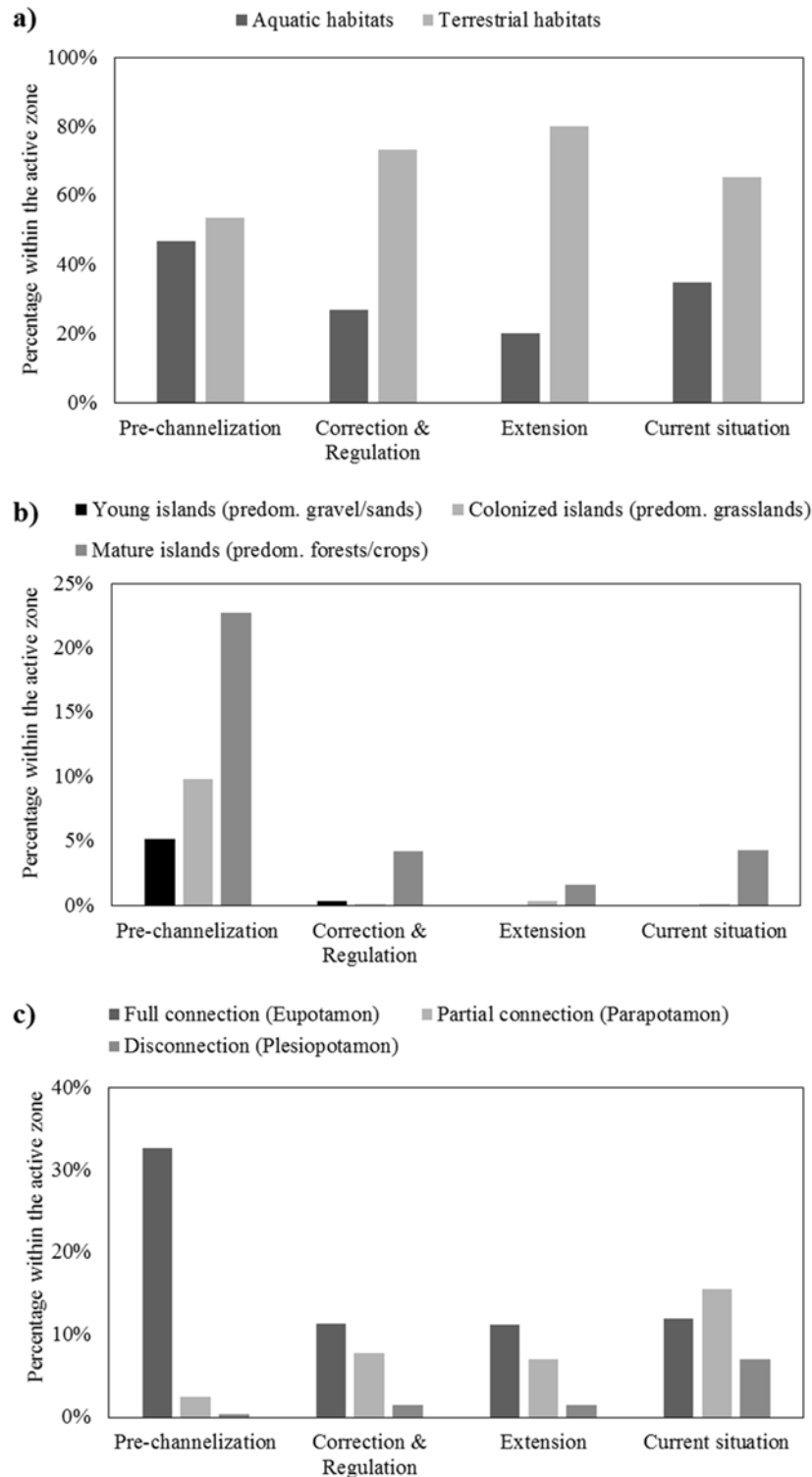


Figure 3. (a–c) Percentages of aquatic versus terrestrial habitats (a). Percentages of island types (b). Percentages of eupotamon, parapotamon and plesiopotamon (c)

Similarly, a high proportion of the AZ was occupied by islands in the Pre-channelization period (38% AZ); later, the proportion reduced considerably, especially in the Extension period (2% AZ), and young and colonized islands disappeared in the Current situation period (Figure 3b). Moreover, after the Pre-channelization period eupotamon decreased and parapotamon and plesiopotamon increased (Figure 3c). It has to be noted that the eupotamon area after straightening belongs to the channelized Rhine and that, although in the Current situation the aquatic component appears to grow, parapotamon and plesiopotamon areas correspond to artificial water bodies created from gravel mining.

Additionally, linear correlations were found between annual low and mean water levels (Table I) and some habitat categories: positive correlations with grasslands and natural water bodies, and negative correlations with forests and regulated water bodies (Table III). So for example, increases in annual low and mean water levels can be associated to increases in the extent of natural water bodies and, on the other hand, to decreases in forests and regulated water bodies areas.

Table III. Pearson correlation coefficients for a pairwise comparison between annual water levels and habitat areas (grey background and bold, $p < 0.05$)

Water levels	Natural habitats				Anthropic habitats					
	Forests	Grasslands	G./s. bars	Nat. w. b.	Reg. w. b.	Art. w. b.	Crop-lands	Settlements	Industry	Gravel pits
LW	-0.76	0.72	0.36	0.77	-0.79	-0.11	-0.61	-0.06	0.08	-0.22
MW	-0.72	0.54	0.39	0.70	-0.72	-0.11	-0.61	-0.11	-0.06	-0.14
HW	-0.33	0.02	0.34	0.34	-0.34	0.11	-0.45	0.10	0.08	0.03

LW: Annual low water level; MW: Annual mean water level; HW: Annual high water level

G./s.: Gravel/sand; Nat. w.b.: Natural water bodies; Reg. w.b.: Regulated water bodies; Art. w.b.: Artificial water bodies

Multi-temporal analysis of river-floodplain processes

The results of habitat change trajectories point to a significant decline in regression processes since the Pre-channelization period (Figure 4a). Although the changeless area is very high within the AZ along all four periods, the greatest average change occurs in the Correction and Regulation period, with high values of progression and anthropization average areas.

In the Pre-channelization period (before 1840), we can find a near balance between progression and regression areas, with a slight dominance of progression (Figure 4a). In fact, the first map on change trajectories (Figure 5a) shows more regression, whereas the second map (Figure 5b) presents more progression. This balance of processes along with the balance in aquatic and terrestrial habitats support the existence in this period of a 'shifting habitat mosaic' (Stanford *et al.*, 2005).

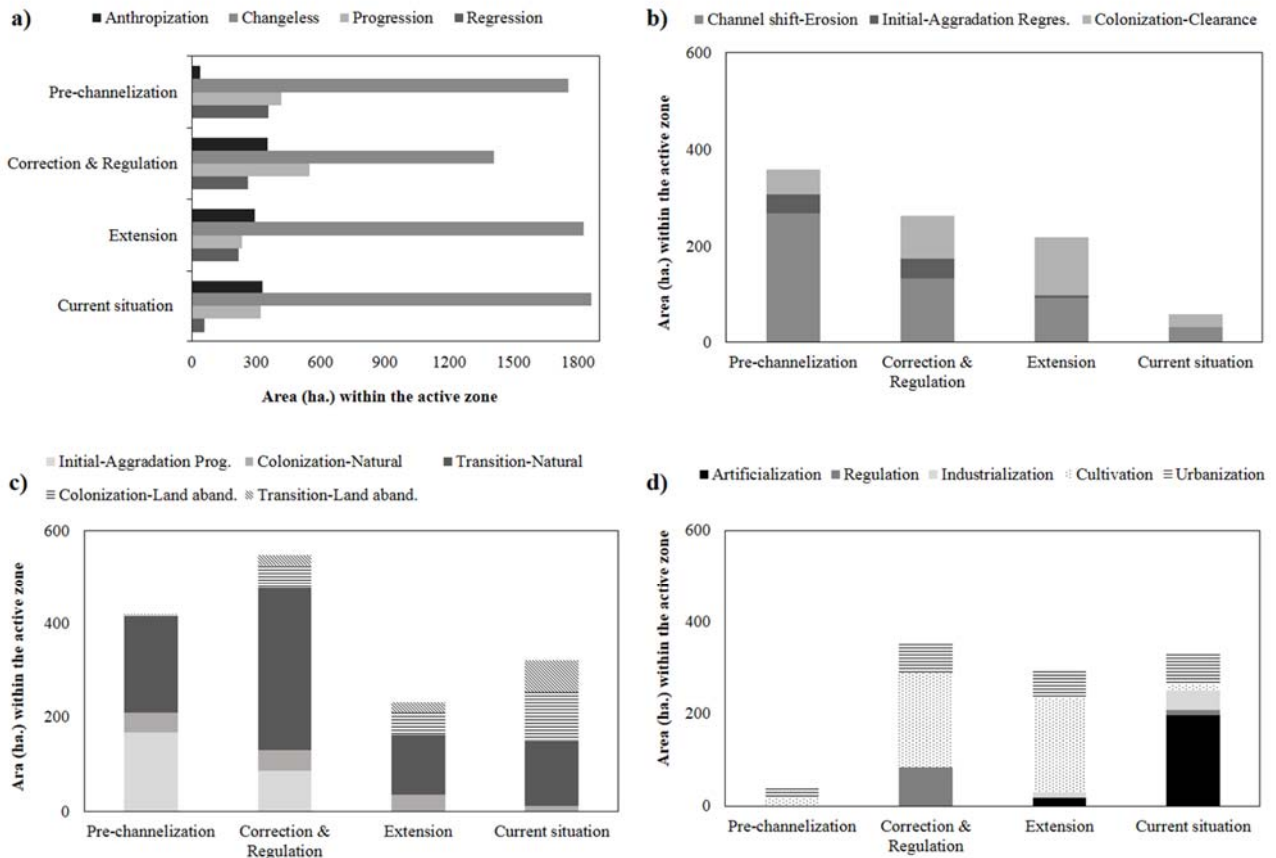


Figure 4. (a–d) Mean area (ha) within the AZ associated with main trajectories of habitat change (a) and with geomorphological and vegetation processes for Regression (b), Progression (c) and Anthropization (d) in the four time periods.

In general, the Correction and Regulation period (1840-1930) was characterized by a general imbalance between progression and regression processes (Figure 4a). This period begins with big changes in the time step 1838-1852 (Figure 5c): the drastic disconnection of former arms from the main river channel gave way to floodplain dewatering with an increase in progression processes, both aggradation (gravel/sand bars raised) and transition (the access to former inaccessible areas lead to more cultivation and to the clearance of former forests). Additionally, average data for this period show channel shift-erosion decreases and transition-natural increases (Figure 4b-c).

In the Extension period (1930-1977) there was an overall balance between progression and regression processes and the changeless area increased considerably (Figure 4a). More in detail, channel shift-erosion processes continued decreasing and initial-aggradation dynamics disappeared (Figure 4b-c).

The Current situation period (1977-2014) is the one with the greatest imbalance in progression and regression processes (Figure 4a), the latter being almost absent. After the construction of the Iffezheim dam, the period begun with a high percentage of changes (Figure 5h), but the last interval is characterized by an outstanding stability (Figure 5i). Extensive artificialization is also present and the large colonization and transition average areas are the result of land abandonment and natural succession processes (Figure 4c-d).

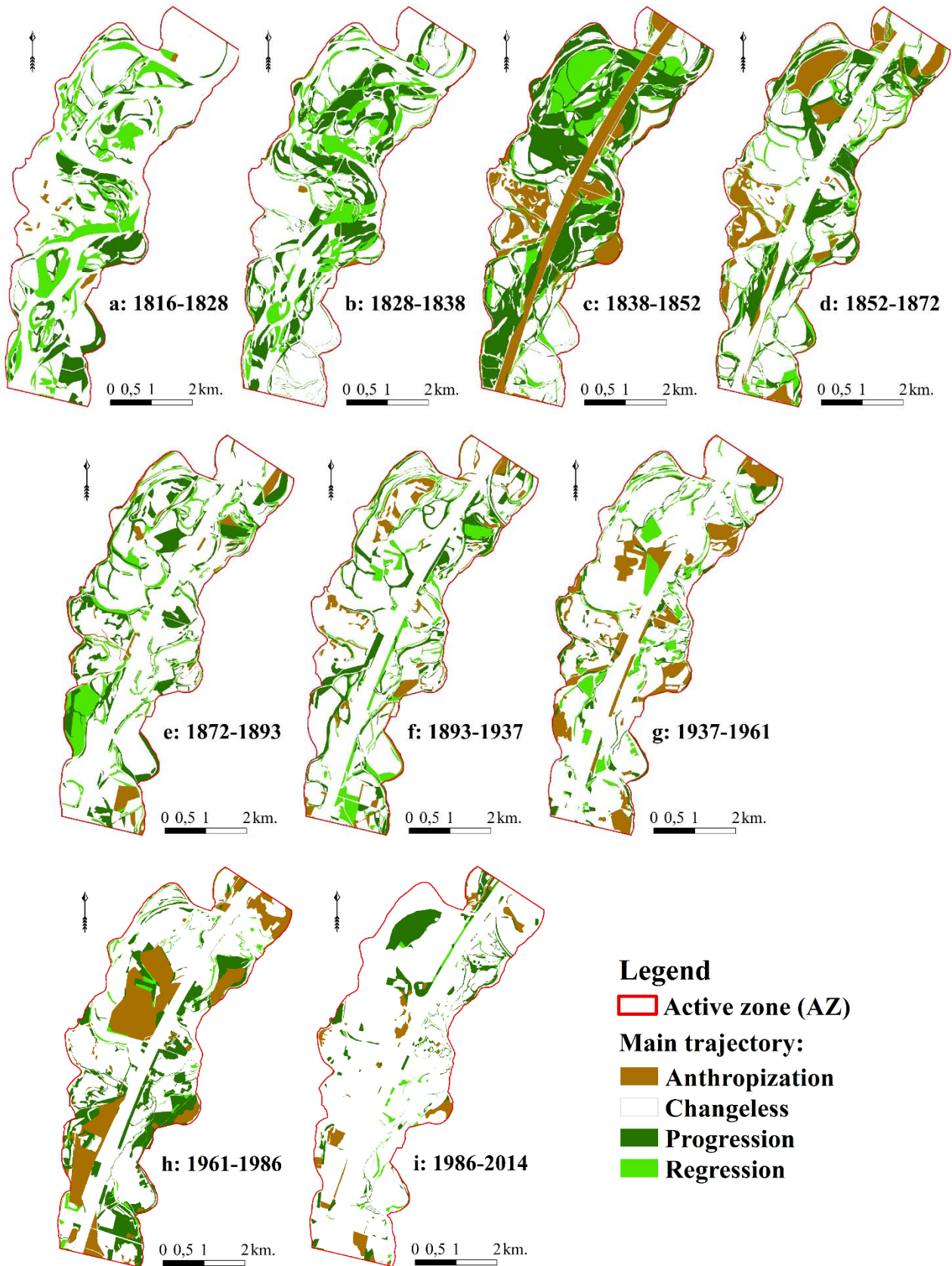


Figure 5. (a–i) Main trajectories of habitat change in each period: Pre-channelization (a, b), Correction and Regulation (c, d, e), Extension (f, g) and Current situation (h, i).

Finally, when evaluating processes evolution, results show both a decrease of regression processes and the corresponding biogeomorphologic deficit linked with a clear imbalance between progression and regression processes (Table IV).

Table IV. Percentages of regression and progression processes within the AZ and deviations from benchmark (biogeomorphologic deficit)

Period	Regression	Progression	Deviation Regression	Deviation Progression
Pre-channelization	13.9%	16.2%	---	---
Correction & Regulation	10.3%	21.3%	-3.6%	5.1%
Extension	8.5%	9.0%	-5.4%	-7.2%
Current situation	2.2%	12.5%	-11.7%	-3.7%

DISCUSSION AND CONCLUSIONS

Analysis of benchmarks and biogeomorphologic deficits

In view of the fact that the identification of reference conditions based on natural processes is lacking for large rivers, the present study identifies benchmarks for a heavily modified segment of the Upper Rhine River and calculates deviations on the coupling of geomorphology and vegetation, or biogeomorphologic deficits. The developed methodology has enabled us to establish trajectories of habitat change between 1816 and 2014, relate them to natural and anthropic processes behind, and recognise human modifications as main driving forces of habitat change and changes in water levels.

For the selected benchmark, the Pre-channelization period, our results reveal a continuous spatial reconfiguration while maintaining a similar habitat composition or ‘shifting habitat mosaic’ (Stanford *et al.*, 2005). Previous studies in the Tagliamento River (Tockner *et al.*, 2003; Van Der Nat *et al.*, 2003), in the Nyack River (USA) (Whited *et al.*, 2007), and in the Allier River (Geerling *et al.*, 2006; Metz, 2015) contributed to prove that this shifting habitat mosaic is a fundamental feature of natural river ecosystems, as long as the basic framework conditions (climate, hydrology, sediments, etc.) do not change (Stanford *et al.*, 2005).

In the past, islands were a common feature of European large river floodplains that influenced geomorphic processes (Van der Nat *et al.*, 2003; Magdaleno *et al.*, 2012); hence we have found that the AZ in our benchmark contained a 40% of island area, according to the analysed maps. Today few rivers maintain a high proportion of island area (Gurnell and Petts, 2002), but still some reaches of the Tagliamento River can present even more than 50% of island area (Tockner *et al.*, 2003).

The pre-channelized Upper Rhine also presented a natural high surface water connectivity (natural water bodies area amounted 36% of the AZ, of which 92% was eupotamon area), allowing for a dynamic exchange of water, sediments and nutrients between the river and the floodplain (Tockner *et al.*, 2010). Preceding research by Hohensinner *et al.* (2004) highlighted analogous high surface water connectivity (33% of the AZ was water-covered) in a similar riverine system, the Danube river in the Austrian Machland region prior to channelization (before 1826).

The balance between progression and regression processes in the Pre-channelization period has also been observed in the Danube River (Austria) before its straightening (Hohensinner *et al.*, 2014), and in current near-natural systems, such as the Tagliamento River (Van Der Nat *et al.*, 2003), and the Allier River, where Metz (2015) applied an adapted methodology to that presented in this study.

Coherently, all these results prove that a dynamic equilibrium of processes is also an intrinsic attribute of natural riverine systems, when framework hydroclimatic conditions are maintained.

After the Pre-channelization period, this Upper Rhine River segment has been degraded by channelization, regulation and gravel mining, in much the same way as other large rivers (Bravard *et al.*, 1986 in the Rhône River; Surian and Rinaldi, 2003 in large Italian rivers and Hohensinner *et al.*, 2004, 2014 in the Danube River). As a consequence of fragmentation and decoupling, eupotamon area has decreased from 33% to 12% within the AZ, and parapotamon is now basically represented by artificial water bodies, big lagoons from gravel mining activities. These large artificial backwater systems, despite their upstream connection, constitute stagnant water bodies that have replaced the lotic ones (Buijse *et al.*, 2002).

The loss of heterogeneity in the studied river section is evidenced by the virtual disappearance of gravel/sand bars and islands (respectively, from 12% and 40% in the benchmark, to 0.3% and 4% in the current situation). From findings in another section of the Upper Rhine River by Arnaud *et al.* (2015) and in the Ebro River (Spain) by Magdaleno *et al.*, 2012, we can confirm that gravel/sand bars and islands are extremely sensitive to hydromorphological impacts and their disappearance can be attributed to river bed degradation after channelization and regulation but, especially, to sediment trap as a consequence of damming. As previously mentioned, and stated by other authors (Magdaleno *et al.*, 2012), this indicator must be managed very carefully for it is influenced by water levels during the capture of the aerial photograph and by the accuracy of historical maps.

Correlations of annual low and mean water levels with some natural habitat areas (Table III) indicate that water level variations condition habitat expansion and contraction. Moreover, since the clear driving forces of change are associated with hydromorphological impacts (channelization and regulation), we also detected that the riverine system responded to the intensity and proximity of these impacts. Channelization works and the construction of the Iffezheim dam produced major changes at the beginning of second and fourth periods (Figure 5a-i), mainly progression and imbalance between progression and regression.

Furthermore, the effects of river training and damming are also identifiable in water levels evolution (Fig. 6). At first, water levels dropped considerably (in particular between 1840 and 1858) due to the channelization of the studied segment and to headwater erosion from downstream channelized sections. Bed degradation due to river correction and regulation is well documented in the Upper Rhine (Frings *et al.*, 2014; Arnaud *et al.*, 2015), as well as the consequent disconnection of the river from its floodplain with changes in both riparian vegetation and fauna (Dister *et al.*, 1990; Dister, 1999). From 1950's onwards, damming has contributed to the reduction of flood retention areas in the Upper Rhine in 130 km², causing among other factors an increase of rapid on-set floods, i.e. high flood events are more frequent but last for a shorter time (Dister, 1986). At present, the homogenization of annual mean and low water levels, along with the long-term legacies of embankments, have led to the disappearance of natural morphodynamics (i.e. reduction of channel shifts and aggradation dynamics).

In this regard, we can highlight that the clearest indicator of cumulative biogeomorphologic deficit is the gradual decrease on regression processes; for example, at present the combination of both channel shift/erosion and aggradation processes take place in no more than 0.3% of the AZ. Other studies in large rivers, such as Bravard *et al.* (1986) in the Rhône River, Gautier *et al.*, 2000 in the Loire River, and Surian and Rinaldi (2003) in Italian rivers, have revealed that they are affected by a restriction of a lack of channel mobility and lateral erosion that prevents the creation of colonization areas and leads to aged simplified communities.

These results can help understand the current situation of most heavily modified large rivers, where regeneration processes have almost disappeared. Therefore, both diversity associated with new geomorphic features and habitat heterogeneity linked to the existence of aquatic/terrestrial interfaces are highly impaired. Within the study site, the Rastatter Rheinaue protected area can be outlined as a

clear example of this condition as it still presents a high proportion of natural habitats but, as Dister *et al.* (1990) highlights, these are vestiges of former dynamic times for it is succession that mostly dominates. While the whole area is flooded on a regular basis (the 2-year flood), mainly because the Iffezheim dam does not retain a huge volume of water, the ecological deficit is associated with the fact that natural morphodynamics is now largely absent. Hence, this protected zone constitutes an appropriate target area for the application of process-based river restoration measures.

Implications for water management and river restoration

According to the WFD, maximum ecological potential for heavily modified rivers can solely underpin on what is feasible from a practical and financial perspective (Jungwirth *et al.*, 2005). The returning to a pre-disturbance state appears unrealistic and boundary conditions (i.e. limitations to the application of possible mitigation actions) have to be analysed before any action could be suggested (Buijse *et al.*, 2002). Particularly for this segment, the Rhine river basin management plan establishes that mitigation measures have to be compatible with water uses; consequently, in order to maintain flood protection and navigation, measures such as removing dikes, barrages and sluices cannot be implemented in the main channel (EC, 2003). However, other process-based river restoration measures, including lateral widenings and fixation openings, can help meeting the objectives of the management plan while taking into account the existing boundary conditions. Basically, given the existing circumstances, the main goals would revolve around re-establishing surface water connectivity as well as fluvial dynamics (Jungwirth *et al.*, 2005).

Previous experiences on river rehabilitation with a view on the recovery of processes give way to optimism. In the Danube National Park downstream Vienna, measures include reconnecting abandoned arms and small-scale lateral widenings, which naturally induce the creation of gravel bars and islands (Reckendorfer *et al.*, 2005). Similarly, the breaching of the embankments in the Rhône Brégnier-Cordon sector demonstrated that fluvial dynamics and vegetation regeneration can be reactivated (Bravard *et al.*, 1986). A recent experience in the Ebro River has showed that embankments removal has reactivated natural flood dynamics and has improved habitat diversity (Gumiero *et al.*, 2013). The management strategy behind aims at directing restoration efforts towards the minimization of expensive interventionism, maintenance needs and project costs, along with the promotion of the natural capacity for geomorphological renewal (Habersack and Piégay, 2007; Gumiero *et al.*, 2013).

In the frame of sustainability, provided that any such restoration work is also compatible population concerns, it may contribute to the partial or total restoration of ecological functions and services as well as biodiversity (Bravard *et al.*, 1986). Nevertheless, it is still necessary to monitor parameters on biogeomorphologic dynamics in order to gain scientific insight into the system adjustment and the real success of process-based restoration measures. The results will contribute to redefining water management and river restoration practice.

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