Historical analysis of habitat turnover and age distributions as a reference for restoration of Austrian Danube floodplains

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Abstract

Today, natural reference sections are not available for most rivers in the Western world and, consequently, restoration projects increasingly rely on historical references. The 350-km-long Austrian Danube river section has also been changed dramatically by channelisation and hydropower plant construction. Currently, a research project is attempting to reconstruct the former habitat turnover of the alluvial Danube landscape in the Machland (Upper/Lower Austria) based on the analyses of historical sources between 1715 and 1991. The results of this study point to a dynamic equilibrium of both morphological habitat succession and permanent habitat regeneration related to intensive fluvial disturbances. This equilibrium can be referred to as a "shifting habitat mosaic". Natural fluvial dynamics not only altered habitat area shares, but also resulted in high habitat age diversities. The reconstructed age distributions point to very short life spans of certain habitat types. Over the long term, the varying intensity of disturbances presumably yielded a range of spatio-temporal patterns of habitat compositions and age distributions typical for the Danube river ecosystem. This balance between destruction, formation and developmental processes contributed to the meta-stability of the overall river-floodplain system and thus represents a primary factor in the ecological integrity of river landscapes.

Keywords: Danube River, floodplain, habitat dynamics, turnover, succession, regeneration, age distribution, historical change, channelisation.

1 Introduction

River landscapes are understood as complex, multi-dimensional ecosystems that are basically determined by the interrelationship between spatial patterns and ecological processes operating on a variety of spatial and temporal scales (Levin and Paine [1], van der Nat *et al.* [2], Tockner *et al.* [3]). In particular, the relationships between fluvial disturbances, ecosystem patch structures and biodiversity have been recognized as fundamental principles in running water ecology (Huston [4, 5], Hughes [6], Townsend *et al.* [7], Ward *et al.* [8]). While specific investigations have been conducted on the habitat dynamics of current rivers (e.g. Kollmann *et al.* [9], Gurnell *et al.* [10], Arscott *et al.* [11]), only few detailed data are available regarding the large alluvial rivers in the Western world prior to channelisation (e.g. Decamps *et al.* [12], Roux *et al.* [13], Hohensinner *et al.* [14, 15]).

This study was designed to improve our basic knowledge of such natural habitat dynamics, with a focus on the Danube river landscape in the Austrian Machland between 1715 and 1821. The central questions are (1) whether certain habitat types naturally experienced a significant trajectory towards higher successional stages rather than a limited development due to strong fluvial dynamics (habitat regeneration) and (2) whether – over the long term – a natural habitat composition typical for the Danube River can be identified (Amoros *et al.* [16, 17], Bravard *et al.* [18], Bormann and Likens [19]). Based on the available historical data, the discussion of former habitat conditions focuses on the spatial and temporal analyses of habitat turnover and age distributions.

This case study demonstrates that historical habitat analyses are qualified to provide essential reference data for the development of river-type specific restoration concepts according to the specifications of the EU Water Framework Directive (EU [20], Jungwirth *et al.* [21], Hohensinner *et al.* [22]).

2 Study site

The studied Danube river section (river-km 2094 - 2084) is located in the eastern Machland region along the border of Upper and Lower Austria (fig. 1). It is strongly influenced by three large alpine tributaries (Inn, Traun and Enns), which before power plant construction were all rich in bedload (HZB [23], UNESCO [24]). Danube discharge is mainly influenced by alpine flow conditions; it peaks in spring/summer due to the snowmelt in the Alps (low flow = 860 $m^3 s^{-1}$, mean flow = 1800 $m^3 s^{-1}$, mean annual flood = ca. 5800 $m^3 s^{-1}$; WSD [25], unpublished data of WSD, Mader *et al.* [26]). The 33.8 km^2 study site coincides with the present 10-year flood area, which is delimited to the north by the terrace of the Würm glaciation and to the south by the Tertiary hill country. Prior to channelisation, 22.2 km^2 (66 %) of the study site belonged to the active zone (AZ, fig. 2). The AZ includes the active channel system (water bodies and unvegetated gravel/sand areas), vegetated islands and young floodplain sections that were presumably formed during Modern times, i.e. since about 1500 A.D (Kohl [27, 28]). Originally, the AZ was totally inundated every 3-5 years.

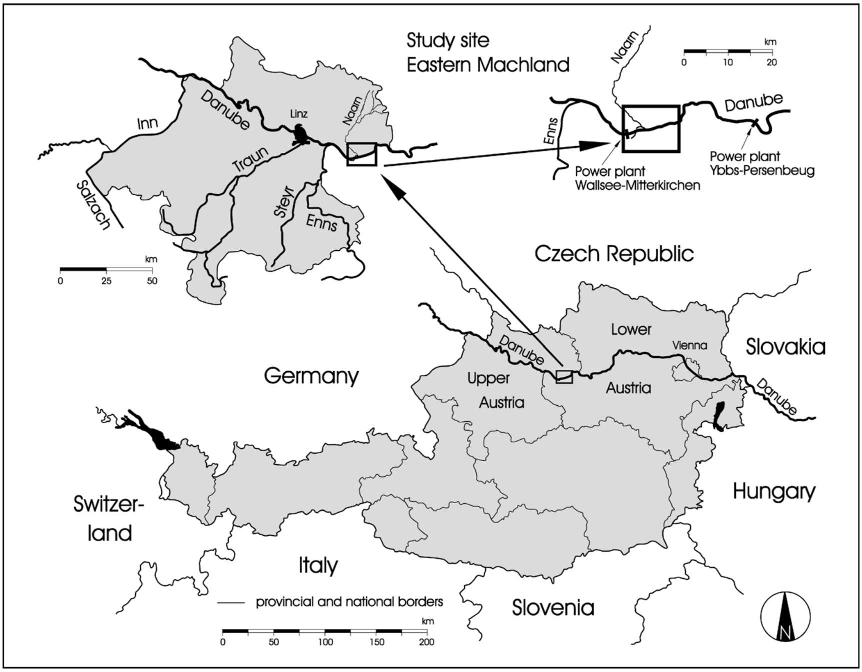

Figure 1: Location of the study site in the eastern Machland, Upper/Lower Austria (river-km 2094 - 2084).

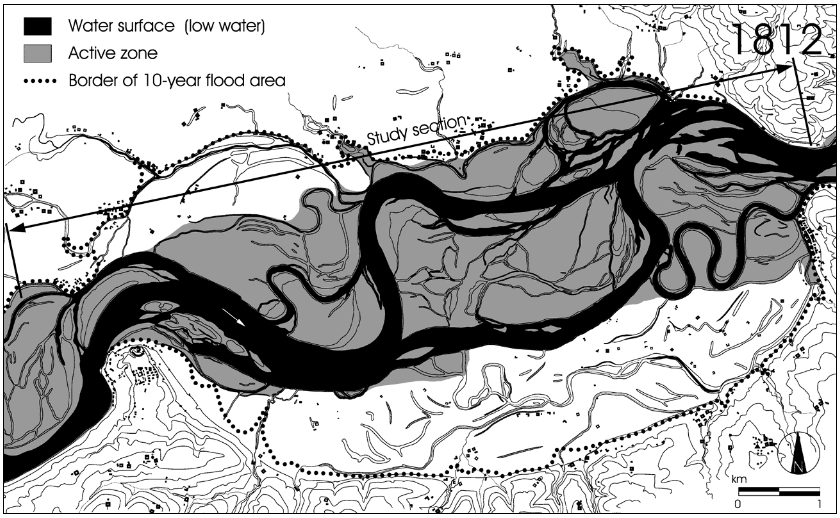

Figure 2: Study site overview prior to channelisation in 1812. Dotted line: border of study site, grey area: active zone including water bodies (black).

The remainder of the study site is formed by the "lower postglacial valley floor" that aggraded during Roman times or in the Early/High Middle Ages (Kohl [29]). On average, the width of the whole study area is 3200 m, that of the AZ 2100 m. According to the river/floodplain classification schemes of Nanson and Knighton [30] and Nanson and Croke [31], the study section naturally corresponds to a *gravel-dominated, laterally active anabranching river* with a *medium-energy non-cohesive floodplain*, i.e. *wandering gravel-bed river floodplain*.

The first river engineering measures along this Danube reach were initiated around 1826 and the major channelisation phase was already completed in 1859. In the 20th century, two hydropower plants – Ybbs-Persenbeug (1957, 23 km downstream) and Wallsee-Mitterkirchen (1968, at the upstream border of the study area) – were constructed (fig. 3). Today, the investigated Danube section is the head of the reservoir of the hydropower plant Ybbs-Persenbeug, and most floodplain waters are separated from the main channel by artificial levees.

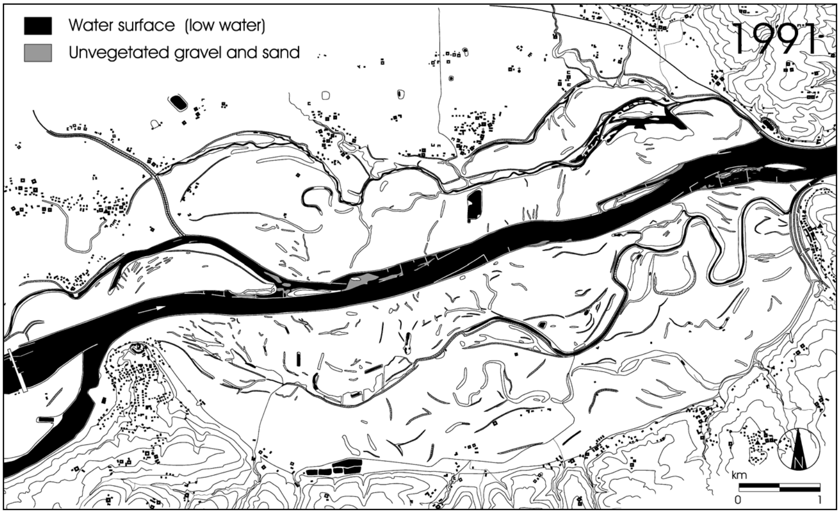

Figure 3: Danube river landscape after channelisation and hydropower plant construction in 1991.

3 Data sources and methodology

120 historical maps of the study site that comprise information on terrain topography, river morphology and land use were collected in various Austrian archives. Of these, 45 selected maps were superimposed over current detailed topographical surveys using AutoCAD Overlay. Planform accuracy was checked by means of 20 - 30 mapped landmarks (churches, streets, terrain structures, ...) that have remained unchanged till today. The 12 most accurately surveyed maps were scanned, geometrically corrected using the landmarks, vectorised and

finally rasterised. This work was performed step by step, beginning with the most precise surveys from 1991 in chronological order backwards to 1715. The result was a standardised series of 12 maps comprising the pre-channelisation period (1715, 1775, 1812, 1817, 1821), the initial channelisation phase (1829, 1832, 1835, 1838), the end of channelisation (1859), and the situations after channelisation (1925) and after hydropower plant constructions (1991, fig. 3).

In this study, the definitions of the different types of habitats are based on the functional classification scheme of river/floodplain biotopes introduced by Amoros *et al.* [16, 17] (see table 1). The areal extents of the various types of aquatic habitats were determined based on the vegetation limits that correspond to the boundaries of the active channels (water bodies + gravel/sand bars = approx. water covered area at summer mean water; Church [32]).

Table 1: Definitions of the analysed aquatic and terrestrial types of habitats.

Habitat type	Abbr.	Definition
Eupotamon A	Eu A	main channel arms (lotic)
Eupotamon B	Eu B	side arms (lotic): at low flow connected to the main channel at both ends
Parapotamon A	Para A	highly dynamic backwaters (semi-lotic): abandoned braided channels/backwaters blocked upstream by bare gravel/sand deposits, with intact downstream connections
Parapotamon B	Para B	less dynamic backwaters (semi-lotic): abandoned braided channels/backwaters blocked upstream by vegetated deposits, with intact downstream connections
Plesiopotamon/ Palaeopotamon	Plesio	isolated water bodies (lentic): permanent or temporary standing water ecosystems
Tributaries	Trib	sub-catchment channels (lotic)
Vegetated areas below bankfull	VABB	vegetated areas between the gravel/sand zone and elevated floodplain areas, low-lying shore zones and islands, vegetated abandoned channels
Elevated floodplain areas	EFA	higher floodplain terrain: vegetated areas at approx. bankfull level and above, mostly older terrain

The analysis of habitat succession is based on the degree of hydrological surface connectivity and refers to a continuum of morphological/ecological succession stages (supposed succession trajectory: Eu A develops to Eu B – Para A – Para B – Plesio – VABB – EFA). Habitat regeneration occurs if habitat areas develop back to an earlier successional stage, e.g. when a main channel arm migrates, thereby eroding floodplain terrain (EFA develops to Eu A). The habitat turnover and age analyses were accomplished by raster GIS methods (one raster pixel in the maps corresponding to a 10 x 10 m cell in nature). Beginning with the situation in 1715, each of the cells was tracked through the time situations till 1991, whereby the changes of habitat type were recorded. As a result, for each of the tracked time segments the percentage of the habitat area shares exhibiting succession, constancy or regeneration can be calculated and charted for any type of habitat. The general turnover trends are reflected by Spearman's rank correlation coefficients r_s and 2-tailed p-values (t-approximation, 5% significance level).

For the calculation of habitat age distributions, the raster GIS analysis was supported by numerous geological studies, pedological investigations and surveys (e.g. Kohl [27, 28, 29], Makovec [33]). Here, a two-step query was conducted to calculate the habitat age for each pixel/cell: (1) a comparison to determine whether the type of habitat in the cells remained unchanged. If so, the meanwhile elapsed time period was added to the former cell age. (2) if the type of habitat had changed, the former cell value/habitat type was discarded and the new one adopted, thereby assuming the maximum possible age of the new habitat structure. According to this method, the resulting habitat ages represent maximum values calculated based on the maximum possible cell ages.

4 Results

The analysis of relative turnover rates shows that the individual types of habitats were differently affected by the natural fluvial dynamics (fig. 4).

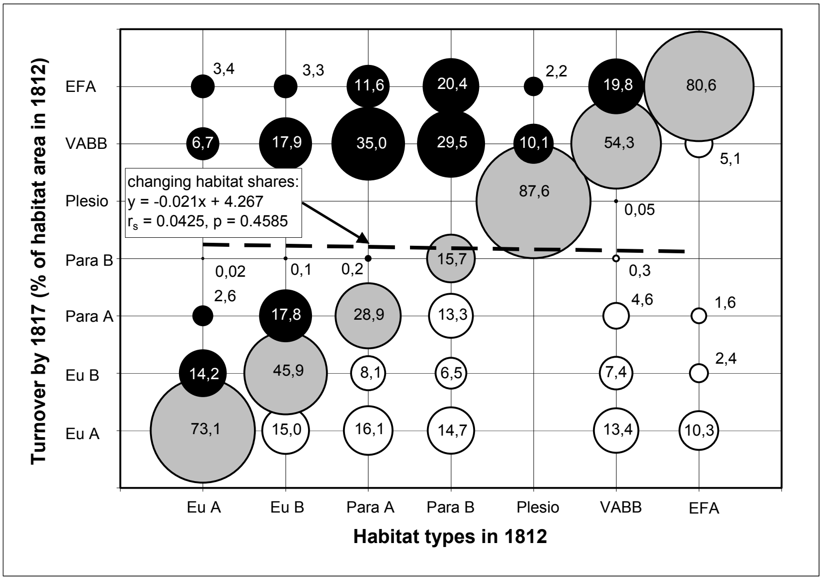

Figure 4: Relative habitat turnover rates under natural conditions 1812 - 1817 within the active zone (%). The habitat types are arrayed along a gradient of hydrological connectivity referring to increasing levels of morphological succession. X-axis: habitat types in 1812, y-axis: habitat development between 1812 and 1817 measured in percent of the original habitat area in 1812; grey spheres: habitat shares remaining stable, black: succession, white: regeneration.

For example, prior to channelisation from 1812 to 1817, parapotamal habitats (Para A and B) that are typical for the alluvial Danube sections not only experienced the highest succession rates (in total 47% and 50%, respectively) but also showed the highest rates of regeneration (24% and 34.5%; fig. 4). Eupotamon A, referring to the initial stage of habitat succession, and elevated floodplain areas (EFA), referring to the terminal stage, were characterised by the lowest relative turnover rates (27% and 19%, respectively).

The Spearman`s rank correlation coefficient r_s (shown by the best fit line in fig. 4) represents the general trends of natural habitat turnover. Regarding the period 1812 - 1817, r_s is close to zero ($p > 0.05$). The non-existent correlation points to a balanced habitat development encompassing both successional and regenerating forces, which are almost equally operant within the riverine ecosystem. In fact, r_s shows that no specific trend of spatial habitat turnover (regeneration or succession) can be identified. Similar results are also derived for the subsequent pre-channelisation time segment 1817 - 1821 ($r_s = 0.0368$, $p = 0.6756$), while the time segment 1821 - 1829, when the first major river engineering measure was carried out, already shows a slightly varying general trend of spatial habitat turnover ($r_s = 0.1130$, $p = 0.0468$).

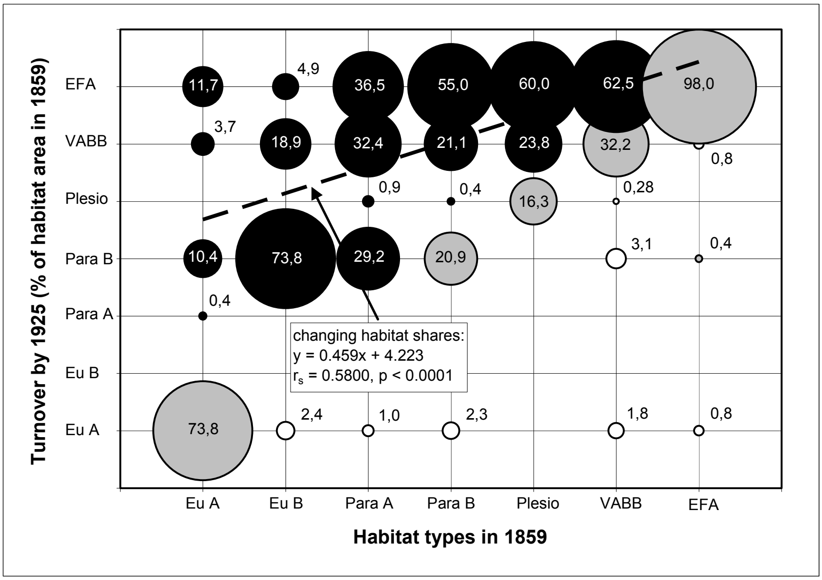

Figure 5: Relative habitat turnover rates after channelisation 1859 - 1925 within the active zone (%) (For explanation see figure 4).

After the termination of the major channelisation measures in 1859, up to 1925, habitat regeneration dropped substantially (fig. 5). In contrast, the relative shares of habitats that experienced morphological succession increased considerably; this was mainly attributed to the large areas of the former active channel system that had become isolated from the main channel and exhibited strong terrestrialisation. For this time segment, the general trend of habitat turnover expressed by Spearman's r_s strongly illustrates the highly significant human-induced alterations of the riverine ecosystem ($r_s = 0.5800$, $p < 0.0001$). The further development of the river landscape from 1925 up to 1991 was characterised by ongoing terrestrialisation processes ($r_s = 0.5580$, $p < 0.0001$).

The presented patterns of spatial habitat turnover prior to and after channelisation are also reflected by the calculated habitat age distributions. The age distributions allow the typical life spans of certain habitat types to be estimated. Naturally, the Danube-typical aquatic habitats of Parapotamon B not only showed high spatial turnover rates but also featured very short life spans. Thus, 90 % of its area showed values of maximally 20 years (see arrows in fig. 6). The intense channelisation measures up to 1859 created large, very young artificial backwaters (Para B), which is also shown by the specific age distribution (90 % younger than 4 years in 1859). After channelisation, habitat aging proceeded to analogous maximum ages of 68 years in 1925 and 107 years in 1991. The floodplain habitats belonging to the low-lying vegetated areas (VABB) were also characterised by a very "young" age structure: 50% of this type of terrestrial habitat were naturally younger than 5 years. Together with the progression of terrestrialisation after channelisation, these habitats gradually diminished or grew older. In 1925, 50% of this habitat type already attained up to 60 - 65 years and even 125 years in 1991.

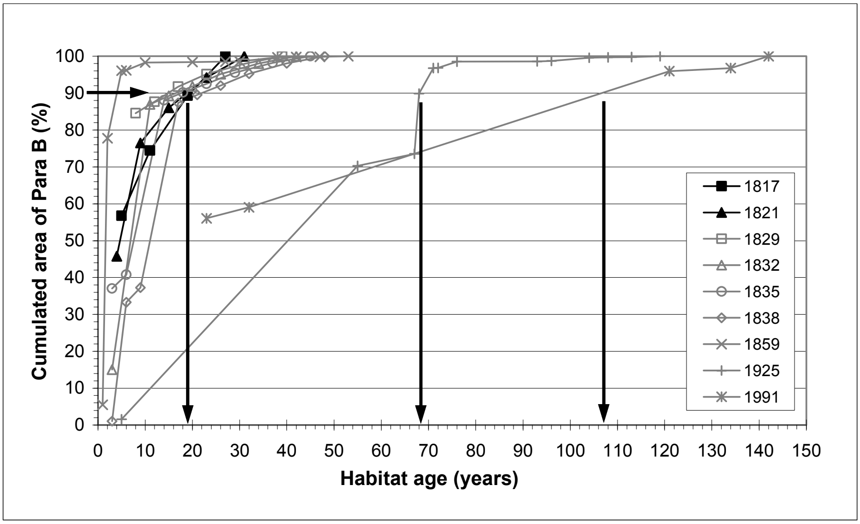

Figure 6: Habitat age distributions of Parapotamon B expressed as cumulative area shares (%) in relation to the habitat age (years). black graphs: age distributions prior to channelisation; arrows indicate the maximum ages corresponding to 90 % of the habitat area (see text).

5 Discussion

Natural riverine ecosystems and their constituting habitats undergo a successional sequence towards a specific terminal stage conditional on the given abiotic and biotic determining factors (e.g. altitude, climate, soil conditions, hydrological regime, etc.) that constrain their individual development (Bravard *et al.* [18], Amoros and Roux [34], Schnitzler [35, 36]). This general trajectory of succession is counteracted by fluvial disturbances, leading to a dynamic balance of differently morphologically and ecologically developed habitats that basically governs the competitive interactions between species and communities (Huston [4, 5], Hughes [6]). Bormann and Likens [19, 37] proposed the "shifting-mosaic steady-state model" to explain the patchy mosaic structure of temperate forests. This model is also suggested to explain the complex nature of river-floodplain ecosystems (Arscott *et al.* [11], Ward *et al.* [8], van der Nat *et al.* [2]). Accordingly, small parts of an ecosystem may fluctuate widely with time due to disturbances, but on a broader spatial scale the proportions of different patch types of an ecosystem will remain constant (Pickett and White [38], Baker [39]). Applying this model to the Danube River ecosystem prior to channelisation implies that some habitats must have developed towards higher successional stages while others showed regeneration due to the strong hydromorphological dynamics.

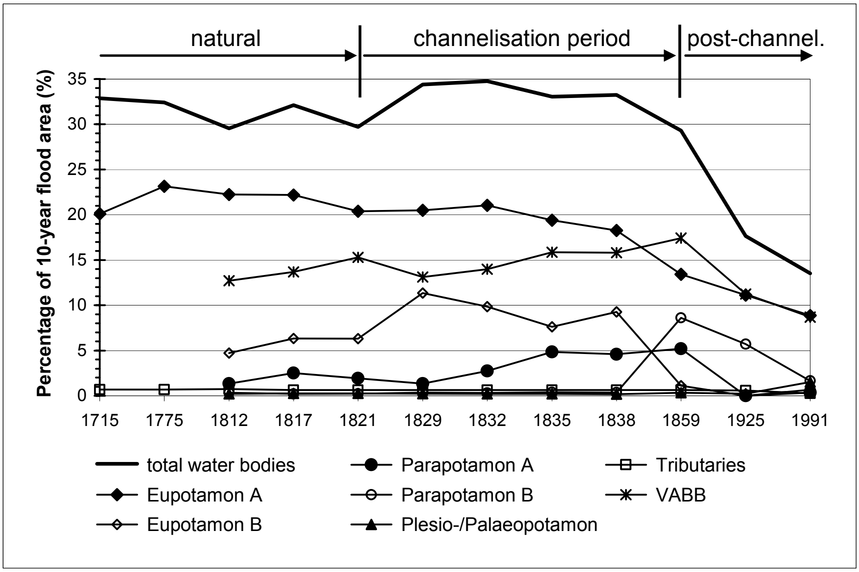

Figure 7: Habitat composition: spatial development of different habitat types related to the 10-year flood area 1715 to 1991 (%). Area shares of aquatic habitats refer to the active channel area.

The spatial habitat turnover rates calculated for the pre-channelisation time segments support the hypothesis of a “shifting habitat mosaic” that – over the long term – results in a habitat composition typical for the alluvial sections of the Austrian Danube River. This is also supported by the areal extents of the individual habitat types at different time situations (fig. 7). The data point to a comparably constant habitat composition under natural conditions (1715 - 1821). Channelisation substantially changed this typical habitat composition (1829 - 1991).

The natural balance of morphological habitat succession and regeneration also implies largely stable habitat age distributions, i.e. the balance of habitat aging and rejuvenation. If the hypothesis of a “shifting-mosaic steady-state” applies to the alluvial Danube ecosystem, then the overall mean age of the river landscape would not change substantially over the long term. In order to verify this assumption, the individual habitat age distributions are combined and the mean weighted age of the total active zone is calculated for each time situation beginning with 1817 (fig. 8).

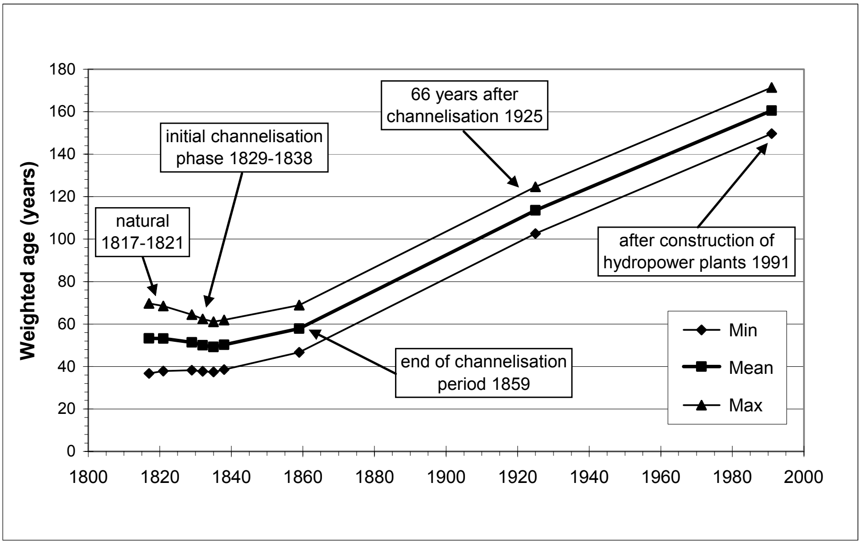

Figure 8: Age development of the total active zone from 1817 to 1991 based on weighted average ages of the different habitat types. Depending on the age modelling method, the age values generally represent maximum values calculated based on the maximum possible cell ages (compare chapter 3). Minimum and maximum graphs refer to the range of the potential start age of raster cells that are older than 1715 A. D. in the habitat age model.

For both totally human-unaffected situations 1817 and 1821, the mean weighted age is 53 years. This dropped slightly during channelisation due to the increased morphological dynamics caused by the river engineering measures.

After channelisation, the weighted age of the river landscape increased significantly up to 161 years in 1991.

6 Conclusion

The results of this study support the applicability of the "shifting-mosaic steady-state model" to human-unimpaired, anabranched large river systems such as the Austrian Danube river section. The detailed analysis of habitat turnover indicates that some habitats followed trajectories towards higher successional stages while other elements of the river landscape were structurally regenerated by the intensive fluvial dynamics of the Danube River. This balance between destruction, formation and developmental processes contributed to the meta-stability of the overall river-floodplain system and thus represents a primary factor in the ecological integrity of riverine landscapes. Human interferences clearly and significantly altered the naturally characteristic habitat patterns, as expressed in substantially altered habitat compositions, habitat turnover and age distributions.

The presented data point to a natural range of typical habitat patterns and habitat dynamics that were characteristic for the original Danube River landscape under the given hydrological conditions. This provides a solid basis for (1) the description of natural reference conditions for future restoration programs in comparable Danube river sections, (2) a profound assessment of human-induced impacts on the river ecosystem and (3) the definition of *high ecological status* and *maximum ecological potential* according to the EU Water Framework Directive (EU [20], Jungwirth *et al.* [40, 41, 21]).

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