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THE INFLUENCE OF THE RIVER REGULATIONS ON THE AQUATIC HABITATS IN RIVER DANUBE, AT THE BODAK BRANCH-SYSTEM, HUNGARY AND SLOVAKIA

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Abstract: Human influences increasingly modify the fluvial dynamics while the value of the clear drinking water worldwide increases. Water demand escalates as the population grows and as the engineering technology evolves. However the near-river inhabitants perceives the less sustainable water management concepts, from extreme floods through decrease of river recreation sites and termination of oxbow-lakes, the near-natural dynamics of the river has been forgotten. The aim of our study was to explore the near-natural river dynamics comparing with the current conditions and to examine its sustainability. The river landscape system in near-natural circumstances was highly related to the predictable fluvial disturbances, which sustained both the lateral and the vertical connectivity of the river branch system. During floods the main channel was able to refresh the habitats of the side-arms and the backwaters. The ebb and flow of the river was unhindered through channels, which were established to lead away the floods rolling back the level of it, and to collect the residual waters of the ebb. River regulation of the late 19th century and the construction of the Slovakian hydropower dam system in the late 20th century extremely changed the physical framework conditions of the upper part of the Danube in Hungary. The study analyses the effect of human impacts on the aquatic habitats, through the spatio-temporal changes of the aquatic habitats. It was hypothesized, that based on historical maps we can make difference between the natural and human induced river dynamics patterns which can help to project the potential effects of the river renaturalization and the construction of water reservoirs on aquatic habitats.

Keywords: landscape evolution, river regulation, river dynamics, succession, connectivity

1. INTRODUCTION

1.1 Study area

Szigetköz and Csallóköz are both part of the Little Danube Plain in North-Western Hungary and South–Western Slovakia forming an inland delta-like river system around the national borderline between Slovakia and Hungary (Fig. 1, Fig. 2.).

The ancient Danube started to develop in the Upper Miocene Epoch, when the Lake Pannon disappeared from the region between 9-9.5 million years ago. At this time the coarsest sediments (boulders, cobbles) has been deposited in the Little Plain (Stelczer, 1971). The flood basin region is one of the deepest subbasins of the Little Plain (Mattick et al., 1996). Thickness of Quaternary sediments in the area of Szigetköz region is about 200-400 m, the thickness of the Pannonian sediments are about 3000-3500 m. The mean fall of the riverbed is about 28 cm/km between Rajka and Szap, 13 cm/km between Szap and Csallóközaranyos (Somogyi, 1983). The study area is situated at the meeting point of these two different river run-off conditions.

The historical habitat analysis of the present study focused on the Bodak branch-system (rkm 1832-1827) in the upper part of the anabranching section alongside of the borderline between Hungary and Slovakia, investigating both the left and the right side of the alluvial cone (Fig. 2.). The studied area was about 45 km^2 (Fig. 2.).

Connectivity, habitat heterogeneity and a moderate scale of floods are key factors controlled by the dynamics of fluvial processes, which conducts to high biodiversity of riverine ecosystems (Ward et al., 1999) creating the mosaics of the habitats and preventing the final succession.

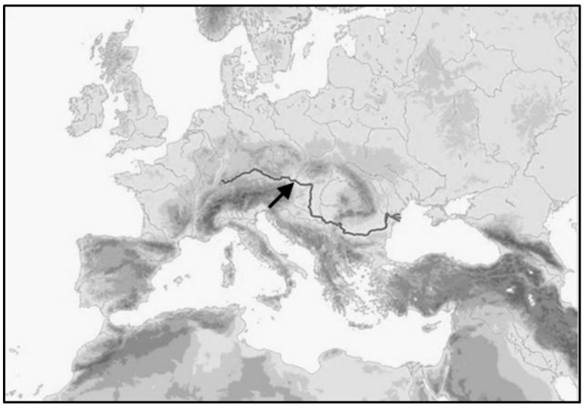

Figure 1. The geographical position of the studied area at the Danube, in Europe (Source: euratlas.net)

The disequilibrium in fluvial processes disadvantageously modifies lateral and vertical river connectivity, whereas dams and weirs disrupt or reduce the longitudinal flow (Rinaldi et al., 2013). Although the absolute magnitudes of floods are determined by hydrological conditions, the disturbances they cause in the floodplain ecosystem depend also on the vertical tendency of the river channel (Dofour & Piégay, 2008). In aggrading river systems the intensity of flood scouring and deposition prevents recovery of plant communities before the next disturbance, whereas in incising river system the terrestrialization of aquatic water bodies within the floodplain and the maturation of plant communities occur with less frequency of floods, reduced scouring and more deposition in the floodplain surface (Rinaldi et al., 2013).

However nowadays, the regulated rivers show one-way development processes – succession – this situation can change in the near future due to the consequences of the anthropogenic climate change. Scientific evidences show an increase in mean- and extreme precipitation events, which implies that extremely high flood events might become more frequent (Christensen & Christensen, 2003), what may increase in flood damage (Bryndal, 2014) caused by flash floods.

The Szigetköz and Csallóköz section of the Danube is one of the most affected floodplains by human-modifications in Central Europe (Fig. 1, Fig. 2.); the main arm and the side arms are also defined as strongly regulated stretches (ICPDR, 2009). Its semi-natural geomorphologic processes and landscape dynamics have been altered until the end of the 18th century and were highly modified by the operation of the Gabčikovo hydropower dam since the end of the 20th century (Hohensinner et al., 2014).

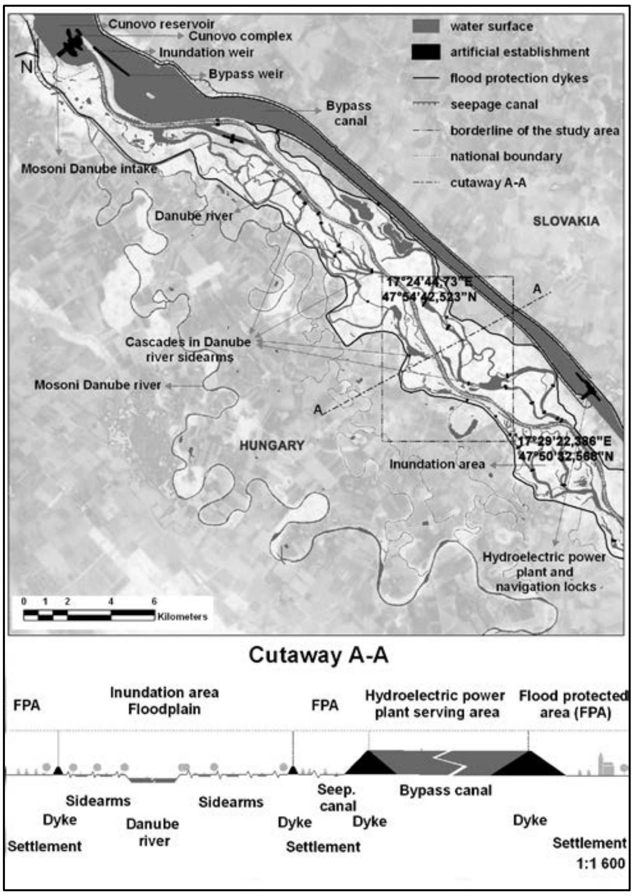

Figure 2. The hydrotechnical construction of the Szigetköz, Csallóköz nowadays and the situation of the study area.

1.2. Functional changes of the river

At the semi-natural phase of the rivers there was no need for defend against floods. One of the best examples to prove this statement is a special form of water management. It was typical along the Danube and it had a great influence on the evolution of settlement structures (Andrásfalvy, 2007). The fund of this water management form was a specific establishment, called “fok”, which led the water from the main channel to the pits, oxbows meadows, generating favorable conditions for fish reproduction. The conscious divert of water diminished the devastating effects of the superior floods and led the water back on the same way to the main stream (Andrásfalvy, 1973). In the end of the 18th century in the upper-part of the Danube at Vienna, in Austria intensive river-engineering works were performed from 1775 to 1849 (Hohensinner et al., 2013).

The mean river regulation of the Szigetköz was held from 1886 to 1896 (Ihrig, 1973) with the aim of ensuring the shipping claims and to assure rapid ice and sediment run-off at mean water level, with riverbed dredging and dikes.

In the late twentieth century a hydropower plant was put into operation in Slovakia, a few kilometers to the North from the Old-Danube channel. The river Danube was diverted into a 29 km long bypass canal and only 20% of its discharge has remained in the former riverbed (Iványi et al., 2012) (Fig. 2.). However a water supply system is in operation between Hungary and Slovakia from 1997, the incidence of the temporal flushing of the branches has diminished and consequently the gradual sedimentation process began with the lack of regular floods which maintained the gravel substrate (Farkas-I. & Guti, 2014) (Fig. 2.). The growing fine sediment layers along the shorelines provided good substrate for aquatic and semi-aquatic macrophytes and thereafter for spontaneous forestration (Farkas-I. & Guti, 2014).

2. METHODS

2.1. The used historical maps and the geography referencing methods

According to hydro-ecological studies the river ecological dynamics have to be investigated by four different dimensions; by the lateral, the longitudinal and the vertical connectivity of the floodplain with the main channel and by temporal dimension of the river (Amoros et al., 1987; Ward et al., 2001; Hohensinner et al., 2011). River regulation had high influence on the channel morphology. However the main aim of the river regulation is to reach the optimal balance system of the river floods. Extreme flood events were observed in the Szigetköz part of the Danube in 1809, 1838, 1845, 1850, 1862, 1883, 1954, 1965, 1991, 1997, 2002, 2006, 2013 (Tőry, 1952). The water level records were overthrown in 1838, 1954, 1991, 2002 and 2013. However there were no extreme high floods after the river regulation works of the upper Danubian part of Hungary for more than fifty years, from 1954 the water level records were overthrown relatively frequently, which means that the water-balance system has tilted may caused unexpected changes in the ecological system of the water-related species.

From 1800 onwards, plans to improve navigation gave rise to a series accurately surveyed river maps (Hohensinner et al., 2011). From the 1800's the water transport navigation required the accurate mapping of the riverbed (Hohensinner et al., 2011). Nowadays the paleopotamon habitats are cannot be found at the investigated areas. Beside that a new aquatic habitat element showed up, the bypass-canal with 14%, which is a total artificial system, and cannot be well fitted for the categories of the functional sets concept.

Repeated updates make it possible to reconstruct the short-term and long term changes in river morphology. For this purpose 28 historical maps were studied. The nine most accurately surveyed maps were georeferenced in ArcGIS 10.0. Mainly the floodplain was assayed, not the entire flood basin.

Long time period changes were analyzed between 1790-1820, 1830-1870, 1870-1946, 1955-1986 and 1986-2004. Short time periods were analyzed between 1820-1830, 1946-1955 and 2004-2013. Three time phases were sorted out in order to perceive the impact of human influence on habitat changes and the reaction of them. The semi-natural phase (maps of 1790, 1820, 1830 and 1870), the post channelization phase (maps 1946, 1955 and 1986) and finally the post hydropower dam state (2004, 2013).

Georeferencing was performed in case of the maps of the 20th century. Since the georeferencing of the military surveys were performed yet, in general the maps of the 19th century do not require any specific process except the map of 1830. In our study we used four, already georeferenced maps; the first military survey of the Habsburg Empire (Tímár et al., 2007), the second military survey of the Habsburg Empire (Tímár et al., 2007), the third military survey of the Austrian-Hungarian Monarchy (Biszak et al., 2007) and the topographic maps of Hungary in the period of World War II. (Tímár et al., 2008). The further non-georeferenced maps of 1830, 1955, 1986, 2004 and 2013 were corrected before applying them into ArcGIS. The non-georeferenced maps were built up from separated map sheets. Section mismatch errors were corrected in Adobe Photoshop program, using the 'Transform', Scale, Rotate, Skew tools. 'Flatten images' were gained from the superposed layers of the matched map sheets to decrease the file size. After we received a '.Tiff' file the next step was the adding of the raster layer to the 'ArcMap'. In the 'ArcCatalog' we modified the property of the '.Tiff' file, with the importation of the spatial reference of the already georeferenced maps in WGS84, UTM_33N coordinate system. After this procedure the 'ArcMap' was able to execute the georeferencing process of the not-yet georeferenced raster layers. Georeferencing was always disposed for the maps of the adjacent terms.

The fit of the maps and aerial photographs from different ages were performed by the selection and fitting of clearly defined landmarks as churches, castells, chapels, stone crosses and streets which still exist today and existed in the time of the preparation of the historical maps.

The "Georeferencing" tool of the ArcMap 10.0 showed the number of the residuals between the source raster data and the map data. We aimed to keep the residual values of the coordinates of the sources and the maps between 0 and 10. After the success of the 'Rectify' command of the raster data we started the digitalization of the maps which made it possible to get the spatial data of the fluvial habitat types.

2.2. The aquatic habitat characterization

Basically the evolution of islands is related to the co-evolution of aquatic habitats. The dynamism of the islands is determined by the spatial relationship to the thalweg, which determines the energy conditions of the river and the erosion-accumulation processes of the islands (Kiss & Andrási, 2014) and the aquatic habitats also.

The typology of the habitat analyses was based on the functional classification of Amoros et al., (1987), which depends on the flow velocity of the branches and on the intensity of lateral connectivity between the main channel, the side arms and the backwaters (Table 1). In order to minimize the subjectivity of the classification, we separated the habitats by the legend of maps, which had information about the flow velocity and field surveys. In the semi –natural phase the Bodak-branch was an anabranching channel – based on the historical maps, which were made before river regulation – and the borderline between the eupotamon-A and eupotamon-B type was not obvious at first glance. The difference between the two types showed by fluvial geomorphological features of the islands. We distinguished two types of the islands: 1) regular islands, where the longest diameter is parallel with the thalweg line which is the typical island formation in the area of the eupotamon-A habitat type, 2) irregular islands, where the longest diameter is perpendicular to the thalweg line and the enclosing stream is meandering. The irregular island formation is typical in the area of the eupotamon-B habitat type. The identification of the parapotamon, plesiopotamon and paleopotamon habitat types were based on the definitions of the 'functional sets' concept completed with the representation of riverine landscape diversity researches like Ward et al., (2001). The soil and the vegetation features of the deposits were red in the maps and it resulted separation of the parapotamon-A and parapotamon-B habitat types.

The river-regulation works, especially the cross-weirs led to uncertain changes in the aquatic habitat system of the floodplain, but a clear differentiation could have been used for segregate the eupotamon and parapotamon types, analyzing the run-off condition signs of the maps. Low flows with 0,8 m s^{-1} velocity were characteristic for eupotamon-B types, and abandoned channels were blocked by deposits in the upstream connection, with less than 0,8 m s^{-1} velocity, were part of the parapotamon-A and parapotamon-B types.

Table 1. Definitions of the fluvial origin habitat types

Habitat type	Definition
Eupotamon-A	Main stream
Eupotamon-B	Always connected side channels, with permanent flow
Parapotamon-A	Highly dynamic side arms, intact downstream connection, blocked upstream by bare gravel/sand deposits
Parapotamon-B	Less dynamic side arms, intact downstream connections, blocked upstream by vegetated deposits
Plesiopotamon	Isolated water bodies, close to the main channel, often connected
Paleopotamon	Isolated water bodies (oxbows in the meandering sector), seldom connected
Nul-potamon	Dry land in a holm, which has a potential to transform to aquatic habitat as rejuvenation and transform back to dry land, from an aquatic habitat formation as succession
Bypass-channel	Artificially created water body; part of the hydropower dam system

In the post hydropower dam state the formerly eupotamon-A habitat became less dominant than the artificial channel of the Gabčikovo according to areal sense. The flow conditions and the water supply decreased by 20%, the eupotamon-B habitat type became a cascade-like system as a result of the artificial water replenishment system. The connection between the main arm and the backwaters are sustained by floodgates, which are regularly open from time to time.

2.3. River bank characterization

According to the fluvial geomorphology characteristics before 1820 the river section was typically a braided channel system with longitudinal and transverse bars and eroding banks (Fig. 3). The composition of the broad valley was made of colluvial and alluvial fans (Rosgen, 1994). It had lateral adjustment, with abundance of sediment supply (Rosgen, 1994). By the time of 1830 the river section transformed to an anastomosed channel with well-vegetated floodplain and associated wetlands. The anastomosed channel has very gentle relief with highly variable sinuosities and generally stable streambanks (Rosgen, 1994).

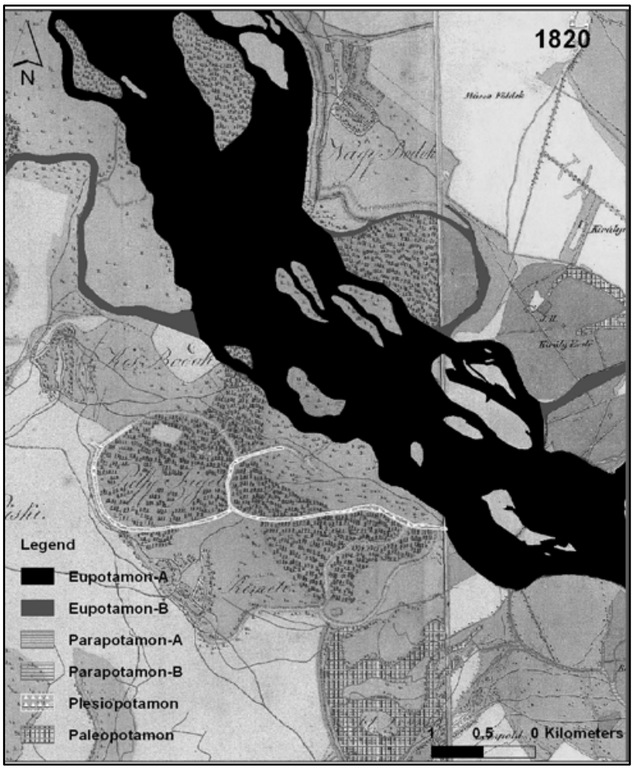

Figure 3. Spatial division in 1820. (Source: Second military survey; Tímár, 2007.)

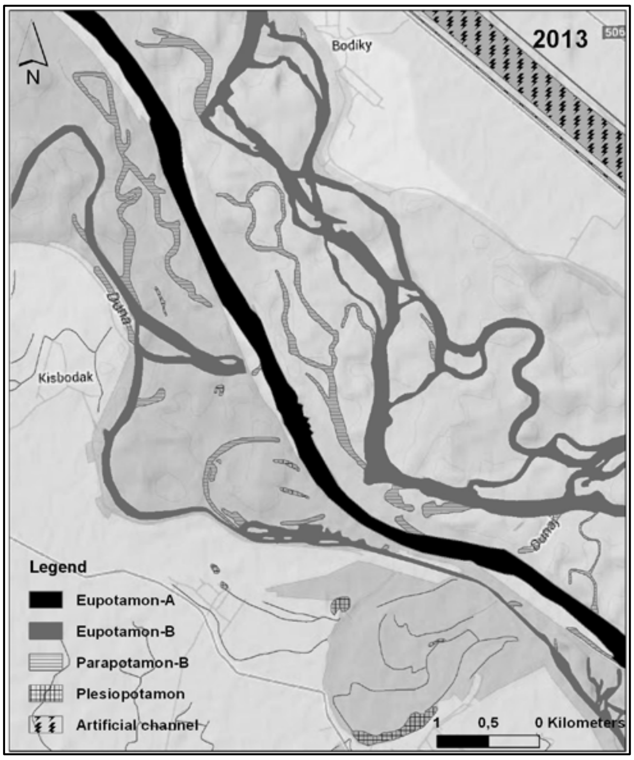

Figure 4. Spatial division in 2013. (Source: Google Earth)

The mean river regulation resulted a narrowed inundated area and straightened main-channel, with half separated side arms from the main-channel.

When the construction of the Cunovo Barrage and the Gabčikovo Hydropower Plant were putting into operation, respectively altered water flows and bed load transport of the river dramatically. After the diversion until the summer of 1993, most of the side-arms in the active floodplain were completely dried up (Ijjas et al., 2010). Nowadays (Fig. 4) the channel works with artificial water supply system. The present river dynamics are totally different than it used to be, before Gabčikovo. The side-arms are sustained by lenghty cascade-like system. At the cascades the runoff conditions are extremely high and the high velocity of the water don’t hold for long, but for 50 meters, and after that the branch get it’s usual run-off properties. It was the only solution to sustain some lateral connection between the vertically higher located side arms and the lower located main arm (the paradox situation is the result of river regulation and Gabčikovo Hydropower Plant).

2.4. Graph analysis

A graph-based representation of the stream network can happen in many ways (Erős et al., 2011). Our graph analysis was based on the comparison of the maps in a successive time order.

The total process was performed also in a successive time order; however the direction of the analysis between the adjacent aged maps is irrelevant to the associative operation.

1 $(a:b):c=a:(b:c)$

The time pair maps were overlapped to identify the identical aquatic habitats. We analyzed the change or the equality of the preceding and subsequent stage of the individual waters. Nodules represent the water types, which were existed in the relation to the studied time pairs. It means that we do not necessarily represent any possible aquatic types in the graph pictures.

Our graph-like visualisation of the river bank changes were displayed by La Text program. The transition numbers appear in the depicted graphs as the value and the thickness of the edges. The verticles were weighted according to the values of the connections. The ordered pairs were formed by the neighbouring stages in time of the individual potamons. Using the overlaying maps of the consecutive time periods we interconnected the neighbouring ecotype stages of the potamons individually. These confluencing ecotype stages were handled as oriented, unidirected graphs. The orientation of the direction represented the time vector, thereby we could analyze the backward and forward transformations of the potamons. If a single potamon fragmented into smaller units, the number of the transformations were counted in each cases. We also counted the cases when the individual potamon remained in the same ecotype. To handle the situations if a potamon discontinued or a new appeared we introduced the concept of the ’nul-potamon’ type.

3. RESULTS

3.1. Results of spatial analysis

In the semi-natural era the rejuvenation and succession of the aquatic habitats were both typical in the area. Some of the plesiopotamon waters became parapotamon-B type, which shows the capability of rejuvenation. Successive processes were also observable in the semi-natural era, when for example the eupotamon-B type aquatic habitats became parapotamon-A types. In this period of time the total areas of aquatic habitats changed between 7.27 km^2 to 11.2 km^2, which is about one quarter of the total investigated area (45 km^2). The terrestrial processes reduced the quantity of the aquatic habitats by more than 20% by the year of 1830. In the 1870’s the balance seemed to be restored with the total 11,19 km^2 of the aquatic habitats (Fig. 5.).

Eupotamon-A was the most characteristic element of the river. From the pristine condition of 1790 through 1820, 1830 and 1870 it was able to double its presence (1790: 3.77 km^2; 1820: 9.11 km^2), and loose from its proportion also (1820: 9.11 km^2; 1830: 5.2 km^2). The eupotamon-B habitat usually represented the 20% of the waters with its 1.5-2 km^2 average area. For 1820 this value decreased to 0.5 km^2, but this water type was able to increase its presence again in 1830 and 1870 also. Parapotamon habitats have a relatively low area over the entire period. Parapotamon-A formed less then 10% and 13% of the total area in 1830 and 1870, while parapotamon-B appeared only in 1820 with a negligible area and in 1830 formed only the 10% of the total area of the aquatic habitats. The proportion of the plesiopotamon habitats changed between 1-2%. The area of the paleopotamon habitat reached the 20% in 1790, but after then it showed a decreasing trend.

The river engineering works had a strong and decisive influence on the composition of the aquatic habitat system. In the period of 1870 and 1946 the total area of the water decreased by more than 20% and the area of eupotamon-A habitats decreased drastically, by 37%. The area of the eupotamon-B increased paralelly with the same ratio what was deprived from the eupotamon-A habitats. The area of the successed aquatic habitats – plesiopotamon, paleopotamon – showed a sharp and great increase reaching the 22% value.

In the period of 1986 to 2004 the area of parapotamon-B emerged by 8% and in 2013 this habitat enwrapped the 18% of the total area of the waters. Nowadays the area of the eupotamon-A type stagnates on circa 1.5 km^2, while the by-pass channel system enwrapped the 17% of the aquatic habitats, with its 1 km^2 at the investigated area. The eupotamon-B habitat type overlays the 40% of the aquatic habitats (2004: 2.23 km^2; 2013: 3.1 km^2) and the parapotamon-B habitats form the 10% of the waters (2013:1.2 km^2).

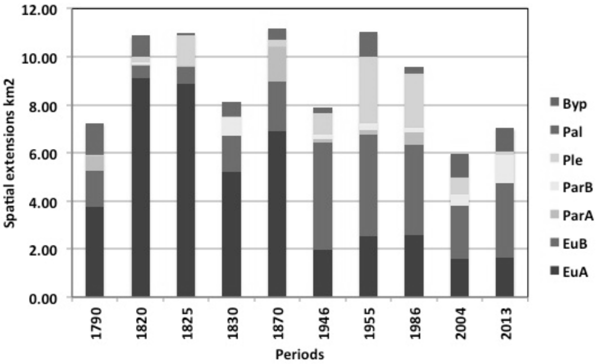

Figure 5. Spatial extension of the aquatic habitats from 1790-2013.

The eupotamon-B system was transformed into a highly arteficial cascade-like system. In 2013, after the replenishment intervention the parapotamon-B habitats represented the 17% of the total aquatic habitats. The eupotamon-A and eupotamon-B habitats kept the level of their real ratio, however the percentage area of the plesiopotamon habitats decreased to 11% for the year 2004 and formed only the 2% of the total water body in 2013. At the cascades the flow rate conditions are extremely high, but for 50 meters the branches have usual run-off properties.

We found significant decreasing trend in case of the areas of eupotamon-A ($p = 0.0085$, $R^2 = 0.59$) and eupotamon-B ($p = 0.011$, $R^2 = 0.57$) in the period of 1790 to 2013. The mean of the potamon area was 8.99 km^2 (SD=.1.97). Eupotamon-A had the greatest mean area with 4.41 km^2, eupotamon-B was the second largest potamon with 2.41 km^2 and the mean area of the other potamon types were less than 1 km^2 (Fig. 5).

3.2. Results of graph-analysis

We found significant decreasing trend ($p=0.0117$, $R^2=0.56$) in the standard deviation of the proportions compare the years of the semi-natural phase against the human influenced periods (Fig. 6).

Figure 6. Standard deviation of the proportion.

The standard deviation of the proportion of the transition numbers was higher above the average from 1820 to 1870. From 1790 to 1820 an intensive rise observed and the high value mainly remained until the 1830's, when the river engineering works started in the upper section of the Danube in Austria.

In the period of 1790-1820, the transitions (Fig. 7) show mostly remaining aquatic habitats, however nul-potamons transformed into parapotamon-B (n=3) representing some rejuvenating capability. Parapotamon-A transformed to plesiopotamon (n=2), while eupotamon-B and plesiopotamon transformed to nul-potamon (n=1:1), showing the succesive elements of the aquatic habitats.

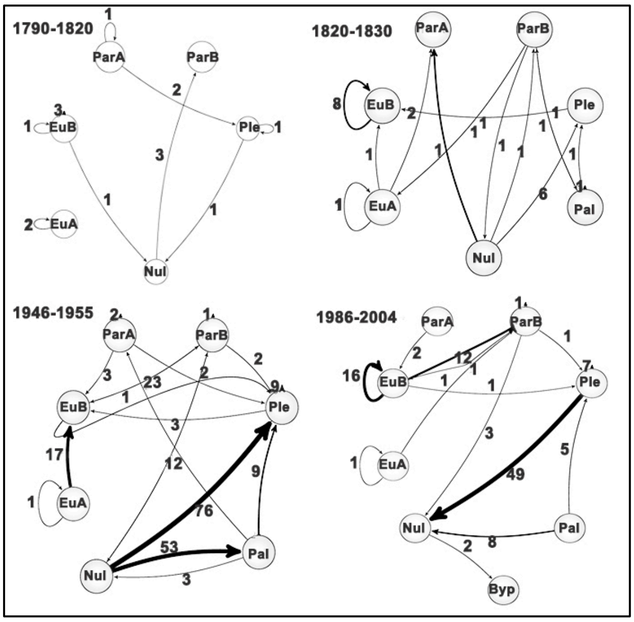

Figure 7. Graph analysis of different time periods; The circles with the abbreviations of the aquatic habitats mean the vertices, the lines with arrows mark the edges of the graphs and the numbers on the lines show the number of the related transitions of a given potamon type. EuA – eupotamon-A, EuB – eupotamon-B, ParA – parapotamon-A, ParB – parapotamon-B, Ple – plesiopotamon, Pal – paleopotamon, Nul – nul-potamon, Byp – bypass-channel.

In the period of 1820-1830 the direction of the transitions (Fig. 7) show two-way alterations. In this period of time the rejuvenation and the succession of the river was balanced by the dynamic equilibrium of the formation of dry areas (Nul potamon) and water bodies; parapotamon-A (n=1), parapotamon-B (n=1) and plesiopotamon (n=6) habitats. The paleopotamon habitats were able to transform into each other (n=1), in the direction of rejuvenation and succesion also, as the plesiopotamon and eupotamon-B habitats (n=2) also.

In the period of 1946-1955 (Fig. 7) the most determining component of the alterations could be the high flood of the year 1954. The islands and the floodplain area become divided by plesiopotamon type of marshes. On the water-protected area, paleopotamon habitats appeared on the former nul potamon fields. Beside that 17 separated eupotamon-B habitat types appeared on the site of the former eupotamon-A habitats. The bursting of the eupotamonA in 1946 led to great flood inundation in order to get back aquatic habitats for the river.

Between 1986 and 2004 (Fig. 7) the eupotamon-A habitat is totally separated from the other aquatic habitats. The succession of the area can be clearly determined. Some eupotamon-B habitats became parapotamon-B habitats (n=7), the paleopotamons are almost vanished from the area, because they transferred to nul potamon types (n=46) and a significant part of the plesiopotamon habitats became nul potamon types also. Beside that some rejuvenation can be seen, when nul potamon habitats became to be eupotamon-B (n=2) parapotamon-B (n=3). The transition between paleopotamon and plesiopotamon is in balance (n=6). The number of the plesiopotamon-related transitions was the most numerous (n=438) during the studied period (Fig. 8). The number of the plesiopotamon-related transitions showed the maximum (n=199) in 1955-1986 and the minimum (n=4) in 1790-1820.

The number of the eupotamon-B-related transitions was the third frequent with 244 cases. The number of the eupotamon-B-related transitions showed the maximum (n=52) in 1955-1986 and the minimum (n=9) in 1870-1946. The number of the transitions of eupotamon-A (n=50, maximum: 21 in 1870-1946; minimum (2,2) in 1946-1955 and 1955-1986), and parapotamon-A were the least frequent (n=49, maximum (11) in 1830-1870, minimum (3,3,) in 1820-1830 and 1986-2004 and the number of the artificial bypass channel (n=6). The total number of the transitions between the aquatic habitats were 56 in 1820-1830, 388 in 1946-1955, 502 in 1955-1986, 230 in 1986-2004 and 136 in the period of 2004-2013. Between 1820 and 2013 the total number of the eupotamon-B transitions showed significant increasing trend (p= 0.0235).

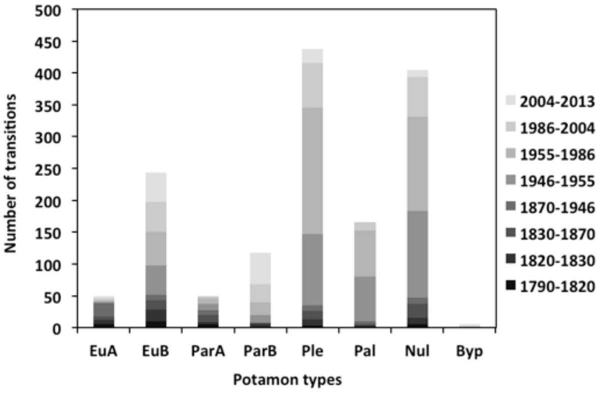

Figure 8. Number of transitions by potamon types.

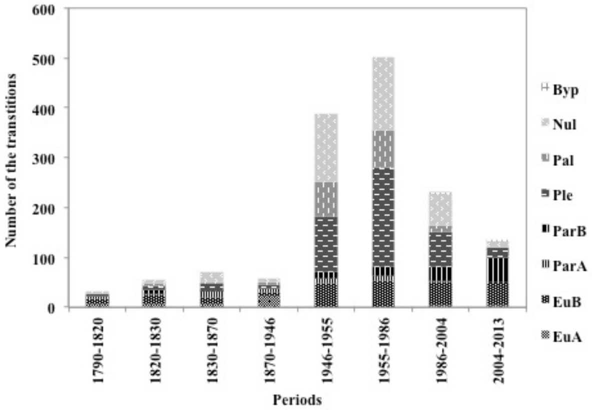

Figure 9. The number of transitions by potamon types in different time periods.

The same time-standardized approach showed that the frequence of the plesiopotamon-related transitions and the frequance of terminations and formations (Nul) were nearly equal (f_{Ple}= 83.39 and f_{Nul}=82.50), while the number of the frequence of the eupotamon-B-related transitions was 53.96 per year and in case of paleopotamon was 35.49. Eupotamon-A and parapotamon-A showed the least frequances within the natural potamons (f_{EuA}=6.63, f_{ParA}=7.55). Before 1946-1955 the average summarized number of the transitions was 54.75 (SD= 16.68), after this period the average summarized number of the transitions was 314 (SD= 162.85) (Fig. 9). Between 1820 and 2013 the percentage number of the parapotamon-A transitions showed significant decreasing trend (p= 0.0123).

Before 1946-1955 the average summarized frequence of the transitions was 2.31 per year (SD=2.23), after this period the average summarized frequence of the transitions was 21.79 per year (SD=14.28), while the period of 1946-1955 showed a peak with a frequence of 15.11 per year.

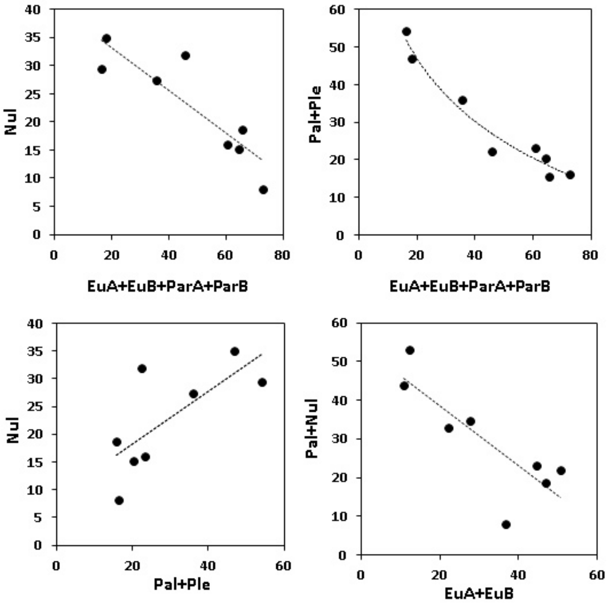

Figure 10. Upper left picture: the number of the transmissions between nulpotamon and eupotamon-A plus eupotamon-B, parapotamon-A, parapotamon-B gropups. Lower left picture: The number of the transmissions between paleopotamon plus plesiopotamon and nulpotamon. Upper rigth picture: the number of the transmissions between paleopotamon plus plesiopotamon and eupotamon-A plus eupotamon-B, parapotamon-A, parapotamon-B. Lower right picture: the number of the transmissions between nulpotamon and paleopotamon plus plesiopotamon, paleopotamon plus nulpotamon and eupotamon-A plus eupotamon-B groups.

Significant negative correlations were found between the transition numbers of the summarized number of the eupotamon-A plus eupotamon-B, parapotamon-A, parapotamon-B and nulpotamon p= 0.0035, R^2= 0.78 and between the transition numbers of eupotamon-A plus eupotamon-B, parapotamon-A, parapotamon-B and paleopotamon plus plesiopotamon (p= 0.0001, R^2=0.92) (Fig. 6). Also significant positive correlations were found between the transition numbers of the summarized number of the paleopotamon plus plesiopotamon, and nulpotamon p= 0.0429, R^2= 0.52 and a significant negative correlation the between the transition numbers of eupotamon-A plus eupotamon-B and paleopotamon plus nulpotamon (p= 0.0116, R^2=0.68) (Fig. 10).

4. DISCUSSION

It is known that the disturbed hydrosystems of regulated rivers show the phases of the ecological successions (Amoros et al., 1987). We found that the intensive river channelization resulted the human-induced succession of the fluvial ecosystem which progression was disturbed and restarted due to the built of the hydroelectric power plant. One of the main, drastic consequences of river regulation was the formation of one, simple main channel of the Danube and an incising sidearm system (Rinaldi et al., 2013) from the natural anabranching fluvial system.River regulation reduced the extension of the eupotamon-A aquatic habitats and cut off the lateral connection between the main stream and the branches which previously was occurred due to the 'fok' system (Andrásfalvy, 2007).

The temporal dimension shows the correlation between the cause and the effects of river regulation works. The graph analysis is suitable to characterize the spatio-temporal dynamics of the river system –the rejuvenation and succession of the water bodies – by using the chategories of the functional sets concept of Amoros, which defines the evolutionary series of the succession of the aquatic habitats. The study indicates that there is an exchanging relationship between the less successive and the advanced successive aquatic habitats.

In the pre-channelization era the channel was not stabilized, the channel gradient and the sediment caliber was higher than today, consequently there were no unnecessarily remaining stagnant water. The advanced river engineering of Austria, Vienna had significant effect on Szigetköz and Csallóköz. In the period of 1790 to 1820 an intensive rise observed in the spatial extension of the aquatic habitats. In the 1830's the process reversed and a slow decrease was observable (Fig. 5). The deposition process amplified because the run off conditions became higher in the upper section of the Danube at Vienna, and stayed the same at the Szigetkoz section of the Danube, while it had a sudden slow-down effect on the run-off condition of the river-channel. The terrestrial processes reduced the quantity of the aquatic habitats by more than 20% by the year of 1830. Reaching the year of 1870 the balance seem to be restored with the total 11,19 km^2 of the aquatic habitats (Fig. 5).

The embankment system prevented the further regeneration of the backwaters, causing stagnation in the withdrawing waters and the succession of the biotopes. The connection between the different aquatic habitat types has still subsisted slightly, because the blocking of the run-off conditions between the eupotamon-A and eupotamon-B types couldn't be implemented completely (Tőry, 1952). The eupotamon habitats were able to sustain the connection between the parapotamon and the plesiopotamon habitats. However connectivity was critical for the long-term persistence of biodiversity and consider relationships (Erős et al., 2011) among potamon types, it was not secured for the paleopotamon habitats, which added to the flood protected area. On the maps of comprehensive channelization it can be well traceable, that the flood protection dykes divided the floodplain into an inundated area. The eupotamon-A type which was typically well represented at the area in the pristine states became less significant (Fig. 5, Fig. 8, Fig. 9).

In the semi-natural phase (1790-1870) the fluctuation of the aquatic-habitat's area can be clearly seen (Fig. 5). The cause and effect can be found upper in the river system. Athough the Danube was always influenced by human modifications, it had less effect on the landscape before the industrial resolution. In the 17th and 18th centuries, the most simple bank protection measure was the placement of rows of wooden piles along the shore (Hohensinner et al., 2013).

In the early 19th century the improved transport facilities allowed wood to replaced with rock materials (Hohensinner et al., 2013). The advanced river engineering of Austria, and especially Vienna had significant effect on Szigetköz and Csallóköz. The deposition process amplified because the run off conditions became higher in the upper section of the Danube at Vienna, and stayed the same at the Szigetkoz section of the Danube, while it had a sudden slow-down effect on the run-off condition of the river-channel.

Despite the fact, that there were no extreme high floods after the river regulation works of the upper Danubian part of Hungary for more than fifty years, from 1954 the water level records were overthrown relatively frequently, which means that the water-balance system has tilted. This phenomenon can cause unexpected changes in the ecological system of the water-related species.

After hydropower plant operation the hydro-morphological dynamics became less intensive. The results of our dynamics approach is in accordance with the findings of Krno et al., (1999) since the river regulation works and pollution of the Danube in the past affected the benthos fauna negatively.

Recently there are no significant paleopotamon habitats in the studied area, because the artificial water supply system sustains lateral connection with the habitat types, which are at the other side of the dykes. That is the reason why the maps show a few plesiopotamon types rather than paleopotamon habitats.

The disconnection of the side-arm from the main stream caused the transition of parapotamon side arms into plesiopotamon type with the development of macrophytes and eutrophication. In paralell, the eupotamon-B stresm altered to parapotamon-B type, which is the manifestation of the intensive succession in the area.

The succession process of the aquatic habitats in the terrestrial point of view means, that the number of partially amalgamated islands and completely amalgamated islands increased after antropogen effects. A Hungarian research for an another river, called Hernád has already evinced this hydromorphological process (Kiss & Andrási, 2014). The intensivity of osculating of the islands depends on the extent of the impact of human intervention.

Although the terrestrialization process of the side-arm system is generally recognized, the human-induced transformation of the system shows a surprising rapidity. The geomorhological evolution of the Szentendrei island of the Danube provides an excellent example for a similar, but much slower process of island fusion and the reaching its recent contiguous formation. This island also evolved from several smaller islands in more than fifteen thousand years (Mari, 2002). The time of transformation from the anabranching system to a contigous formation took more than five thousand years (Mari, 2002). As we presented, the transformation of the Szigetköz section from the anabranching river system to the contiguous formation took only four hundred years, which is less than the tenth of the natural transformation time which was found in case of the Szentendrei island.

The historical analysis of the habitat turnover of the Austrian part of the floodplains of Danube River revealed the dynamic equilibrium of both morphological habitat succession and the permanent habitat regeneration which intensively related to the fluvial disturbances (Hohensinner et al., 2011 and 2005) and it was real also for the Szigetköz and Csallóköz floodplain (Guti et al., 2010). In the other hand it is plausible that river regulations on the Austrian part of the Danube from 1775 also had a great effect on the Hungarian part of the river, preventing the factual start of the river regulations from 1820-1830.

The change of the vegetation cover also could play an important role in the forming of the alluvial river ecosystem (Ward & Stanford, 1995) and since locally and in medium scale the sudden channel changes extensively altered the habitat conditions causing the ecological succession of the riparian vegetation on the banks of the different alluvial banks of the Danube (Hohensinner et al., 2014). Our findings showed that the graph-analysis of the change of the fluvial system can provide a more information-rich, dynamics-based approximation than the simple, area-based studies showing the statistics of individual dynamics of the different ecotypes.

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