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STATISTICAL CALCULATIONS OF THE TISZA RIVER CHANNEL CHANGES ALONG VEZSENY AND MARTFŰ (HUNGARY) FROM 1873-2010

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Abstract: The study presents the channel changes along a 17km length of a Tisza River bend by Martfű. Along the study we were trying to answer the question - what kind of deformations were caused by anthropogenic regulations (such as bank revetments) along the examined river channel in horizontal and vertical aspects in the post-engineering times. Furthermore, the objective was to determine in detail how the river channel regulation works influenced the channel parameters like reach length (L_R), Chord length (H), Width (W) and the profile of cross sections. Different aspects of the analyzed river bend were identified. The results show that, the regulation works influenced the geomorphology of the channel, e.g. decrease in average width of the channel, the level of low water levels decreased in the period of 1911-1920 and in 1921-1930 no negative values were recorded after the regulation of the riffle. The cross section areas by the revetments decreased more intensively than the non-stabilized cross section areas. After the stabilization works - by the 1st, 4th, and 6th sections -, the midstream has been growing by the 2nd and 3rd sections between 312-310 km-s. As a result of increased erosion a cutbank has been developing between 311-310 km-s.

Key words: channel incision, bank revetments, channel regulation, channel narrowing, cross sections, channel planform

1. INTRODUCTION

Rivers play a key role in water management or agriculture. Because of infrastructure development, floodplains, river sections or entire rivers have been affected by intensive human activity. Floodplain swamps have been drained, ancient floodplains have become agricultural areas and different regulation works have changed channel courses.

Natural rivers and forms adjacent to the river channel are always in change (Rhoads et al 2008). Human activity affects the channel morphology and fluvial processes in various ways (Newson et al., 1997, Knighton 1998). Indirect influences, including land-use and management (Marchetti 2002), changes to the catchment, urbanization and land drainage (Stover & Montgomery 2001, Liébault & Piégay 2001, Wellmeyera et al., 2005) alter the river run-off and sediment yield (Frings et al., 2009, Hoffmann et al., 2010). A wide range of direct impacts influence the channel itself, e.g. dam construction (Surian 1999, Grams & Schmidt 2002, Draut et al., 2011), reservoirs and grade-control structures, channelization (Simon & Rinaldi 2006), artificial cut-offs and rectification (Biedenharn et al., 2000, Cserkész-Nagy et al., 2010, Słowik 2011), instream mining (White et al., 2010), installation of groynes, artificial bank stabilization (Wallick et al., 2006, Kiss et al., 2008, Cserkész-Nagy et al., 2010, Ollero 2010, Zawiejska & Wyżga 2010, Michalková 2011), channel horizontal changes (Antonelli et al., 2004) etc. Active meandering rivers are one of the most dynamic and sensitive elements of the landscape (Hooke 2007). Anthropological impacts are changing the flow characteristics, bed-sediment characteristics of lowland rivers as well as affecting channel stability, flood risk and biodiversity (Frings et al., 2009). The channel incision is part of anthropological impacts (and of course channel incision can be natural process by strong vegetation cover), which often leads to further network development where the channel migrates into previously non-incised surfaces. Incised channels are particularly dynamic and can cause larger peak flows (Simon & Rinaldi 2006). Bank revetments provide local protection of the river bank in highly erodible areas, primarily the cutbanks of meanders (Smith & Winkley 1996). The results of Arnaud-Fassetta (2003) showed that the degradation of the channel bed was increased by bank heights along the Rhone River and in its delta immediately after the artificial channel narrowing, which caused bank response to the channel incision.

Smith & Winkley (1996) showed that the engineering activities have been altering the channel. As a result, the overall gradient and the top-bank width increased. In some sections the gradient increased as an effect of the construction of artificial cut-offs. Channel width is an important feature of river morphology that can adjust to changes in the flow regime relatively quickly (Surian 1999). The effects of wing-dams were analysed by Pinter & Heine (2005) on the Lower Missouri River, where their measurements including cross-sectional area, flow velocity, and channel width have been collected for the last 70 years. Their results showed that the changes in channel geometry and flow dynamics occurred at the same time as dam constructions, the impact of which revealed itself in the reduction of cross-sectional area.

Winterbottom (2000) showed that on the Tay and Tummel Rivers in Scotland the channel size reduction between 1747 and 1899 was caused by embankment constructions along the rivers. The dam construction and flow regulation did not occur until the 1950s. Therefore, the embankments caused the channel incision. The studied section of Dráva River by Kiss et al., (2011) showed that the reservoir construction and local cut-off and groyne works on river channel influenced the hydro-morphology of the river. As result of dam constructions the water stages dropped, lower stages became more frequent and floods almost disappeared. The drop in water-level can be explained by water storage of the reservoirs, and also by degradation of the channel bed below the dams. As a result of bank protection works on the Piave River (Italy) the river can still move laterally, although the available width for planform shifting is narrower than its natural braid belt (Surian 1999).

The aim of this research was to quantify the river bed changes and to connect them to human impacts (revetments, channel regulations) or natural processes along the biggest bend of the Tisza River. These human impacts are not exactly known in this bend, furthermore the analysed bend have huge impacts on the flooding processes because there are three sections where the channel was narrowed than other parts of the bend which decreasing the flood conductivity of the channel.

2. STUDY AREA

The study area was chosen in the Middle Tisza River section, with 20 km-s far from Szolnok (Fig. 1) to the south. The studied river section is between 318-301 river km-s counted from the downstream river outlet. The average high level of floodplain areas and fluvial loess covered flood fringes are between 80-100 m a.s.l. The average relative relief is about 1-2 m/km^2. The thickness of Pannon Quaternary sediments by Martfű is about 100 meters and consists in mostly sandy and clayey sediments. The study area is located on the north part of the South-Tisza subsiding. The research area is surrounded with flood fringes from north, from east and from south-east where the average height is about 87-98.5 m a.s.l. This is the largest river bend along the Tisza River which was not cut off. On the area the first embankments were finished by 1853-1866. Later – from 1876 to 1945 – these embankments were altered to achieve its final stage (Balogh et al., 2005).

The regulation of the riffle between 314-311 km-s (Fig. 2) along Ciprus-Island (Fig. 2) - was finished by 1911 and the island is nowadays part of the floodplain (Balogh et al., 2005). The reason for the formation of this island was the resistant channel material along Vezseny, thus major depths were not formed there, but the channel became wider along the mentioned island, which was in favor of riffle (Iványi 1913). Between the 311-300 km-s the channel is mostly consist of easily erodible older sandy sediments. Under Martfű the channel is still deepening and became narrower (Nagy et al., 2005).

The Tisza catchment area amounts to 157135 km^2, of which 110463 km^2 is outside the Hungarian border. Before the river regulation the total length of the Tisza was 1419 km, which decreased to 966 km after regulation. Nowadays the total length of the river is 964 km. 102 of the river bends were cut-off by artificially (Stelczer 1976, Balogh et al., 2005). The Tisza River catchment area is asymmetrical, so the left side tributaries influence flood stages, which means that the local precipitation in these catchments controls the whole Tisza system (Andó & Vágás 1972). The floodplain area of the river between the embankments is 1050 km^2 but the original flood is 16500 km^2 (Szlávik 2000). Along the river there is a 1440-km flood protection embankment system (Balogh et al., 2005). The present zero level of the river was fixed in 1842, which was the recorded lowest water level at that time. In 1890-1892 the Water Institute measured the high points and the cross sections all along the river (978 pieces) (Botár & Károlyi 1971).

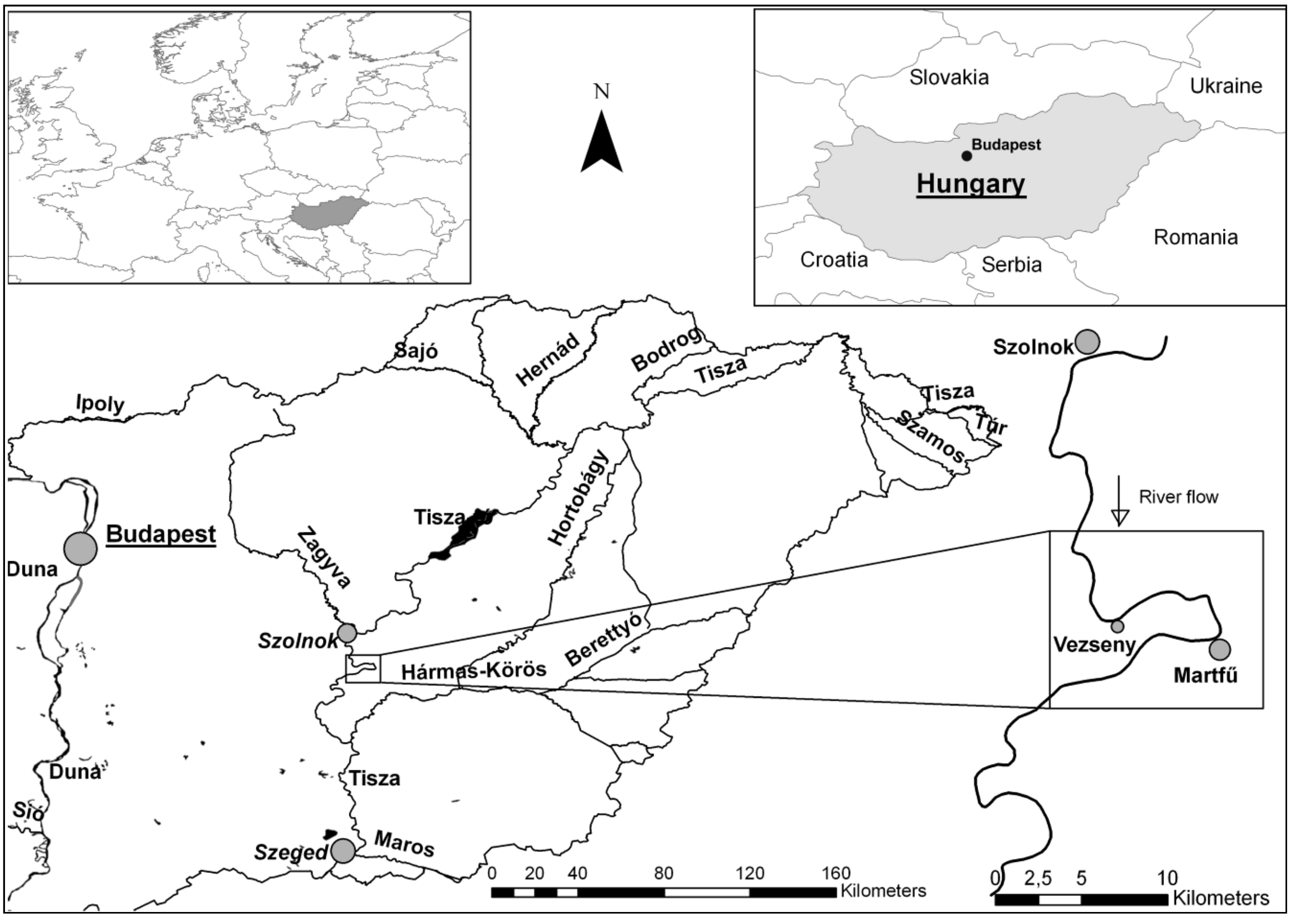

Figure 1. Catchment basin of the Tisza River in Hungary with the study area.

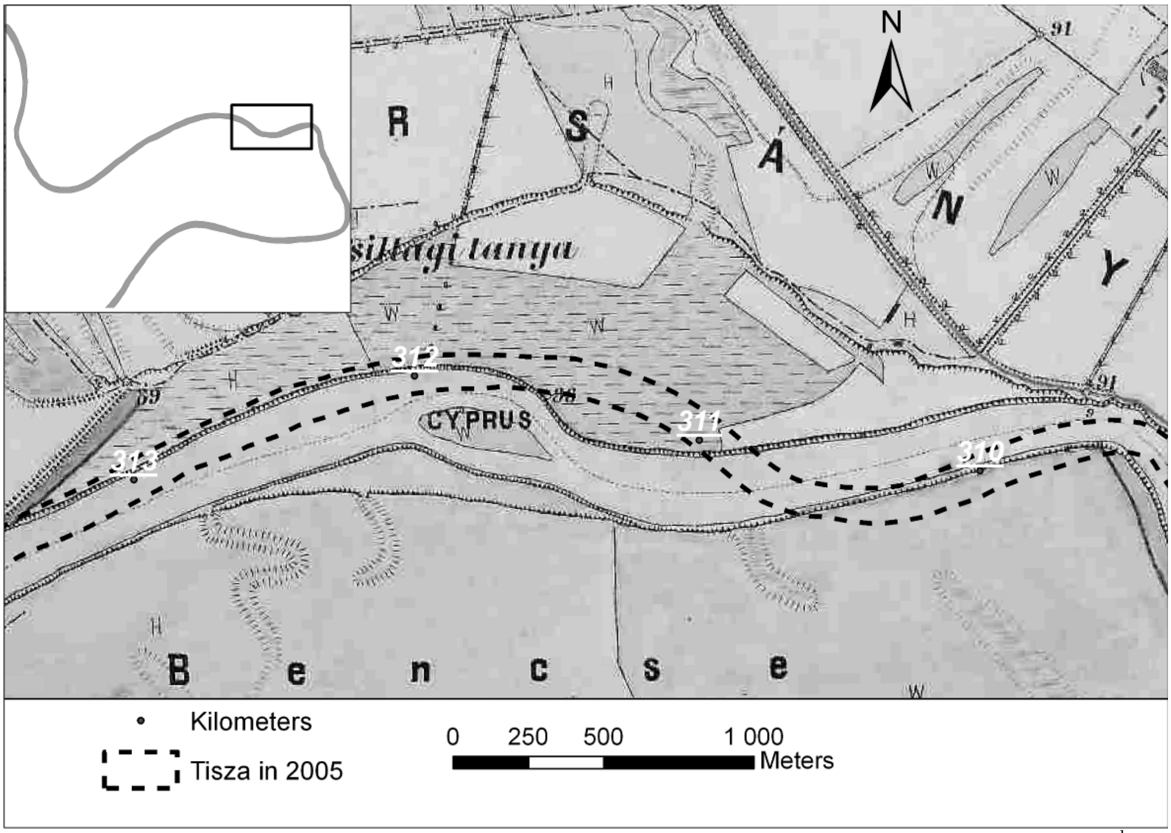

Figure 2. The Tisza River in (1869-1873) by the regulated riffle with the Ciprus-Island. (Background map: 3rd Military Mapping Survey of Austria-Hungary, source: KÖTIVIZIG)

3. METHODS

3.1. Measurement of the channel parameters

The following materials were used for calculating the river channel vertical changes: 3rd Military Mapping Survey of Austria-Hungary (1869-1873), an aerial photo (2005), an ortophoto (2001), a series of hydrological survey maps (1929-1932, 1967, 1977) and the Tisza regulation map (1982), the Tisza River historic and contemporary maps (1830-1890). The cross sections were surveyed by the following years 1929, 1957, 1976 and 2000 and they were used to compare the horizontal and vertical changes of the river channel. These data sources (maps, aerial photos, cross sections) were provided by KÖTIVIZIG (Middle-Tisza Region Environment and Water Management Directorate). The maps were georeferenced in the Unified Hungarian Projection System (EOV). Arcgis version 10 and Quantum GIS Copiapó 1.6 programs were used for the calculations of channel parameters (Fig. 3).

A detailed isoline map was used for the digital terrain model. The channel depth points were measured twice: in July and September 2011. The depths were recalculated into m a.s.l. The equipment used for the measurement was Garmin Fishfinder 80 and the depth points were recorded with Garmin Geko 201 GPS, where the coordinates were calculated into EOV (Unified Hungarian Projection System).

3.2. Measurements of hydrological parameters

Water stage data from Martfű gauging station (Fig. 4) were used for hydrological analysis which was downloaded from *www.vizadat.hu*. The station was set up in 1901 and the water stage has been measured continuously but unfortunately discharge data are not available. The water level duration plot was used to compare vertical channel changes of the channel. The water level duration diagram was calculated from a daily water stage from 1901 to 2010. The water stages were ordered in every 10 years- from the highest to the lowest - without paying attention to when it was recorded within the given 10 years. Then the water stages were categorized in every 10 cm (like 870-860, 859-850 cm) and the frequency in each 10 years was checked. That number which shows how many data are in each of the classed group is called the class frequency index. The water stage duration is calculated by ordering of frequency indexes from the highest to the lowest water stages. It shows how often in the analysed period water levels reached or exceeded the lowest level in a particular category (Németh 1959).

4. RESULTS

4.1. Lateral channel changes

The whole bend was divided into 7 sectors, four of which are freely developing: 2nd, 3rd, 5th and 7th, while the others are stabilised: 1st, 4th, and 6th (Fig. 4).

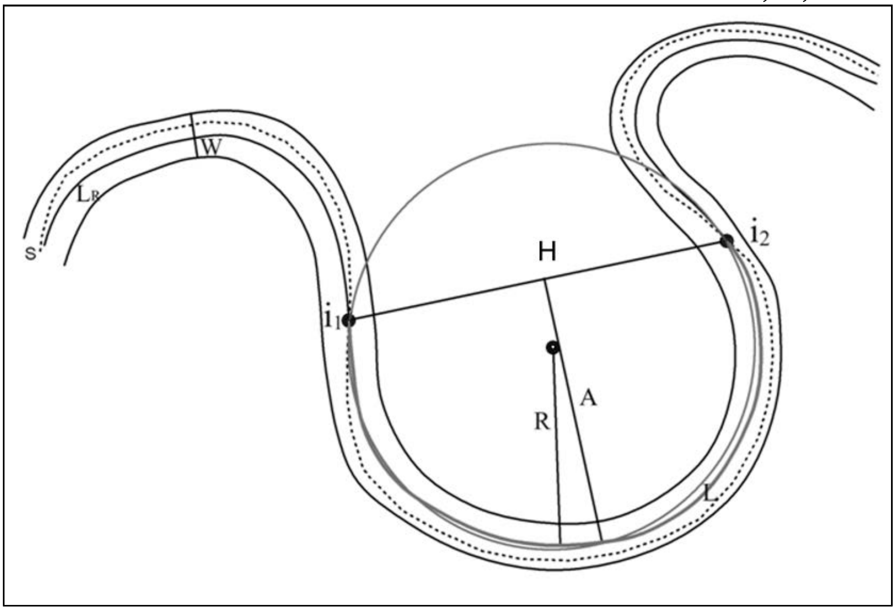

Figure 3. Calculated parameters: Reach length (L_R) - Maximal lengths of midstream, Bend length (L) - thalweg length between two inflexion points, Chord length (H) - The length of the distance between two neighboring inflexion points, Width (W) The distance between bank lines at right angles to the midstream, measurements were made in every 400 meters, Amplitude (A) - The longest perpendicular distance between chord and midstream, Radius of curvature (R) - The largest circle, which can be fitted into the bend which is perpendicular to the midstream, Development index (meandering index) (M_i) The ratio of amplitude and the length of chord. It's growing with the development of the bend, S – stream centre-line.

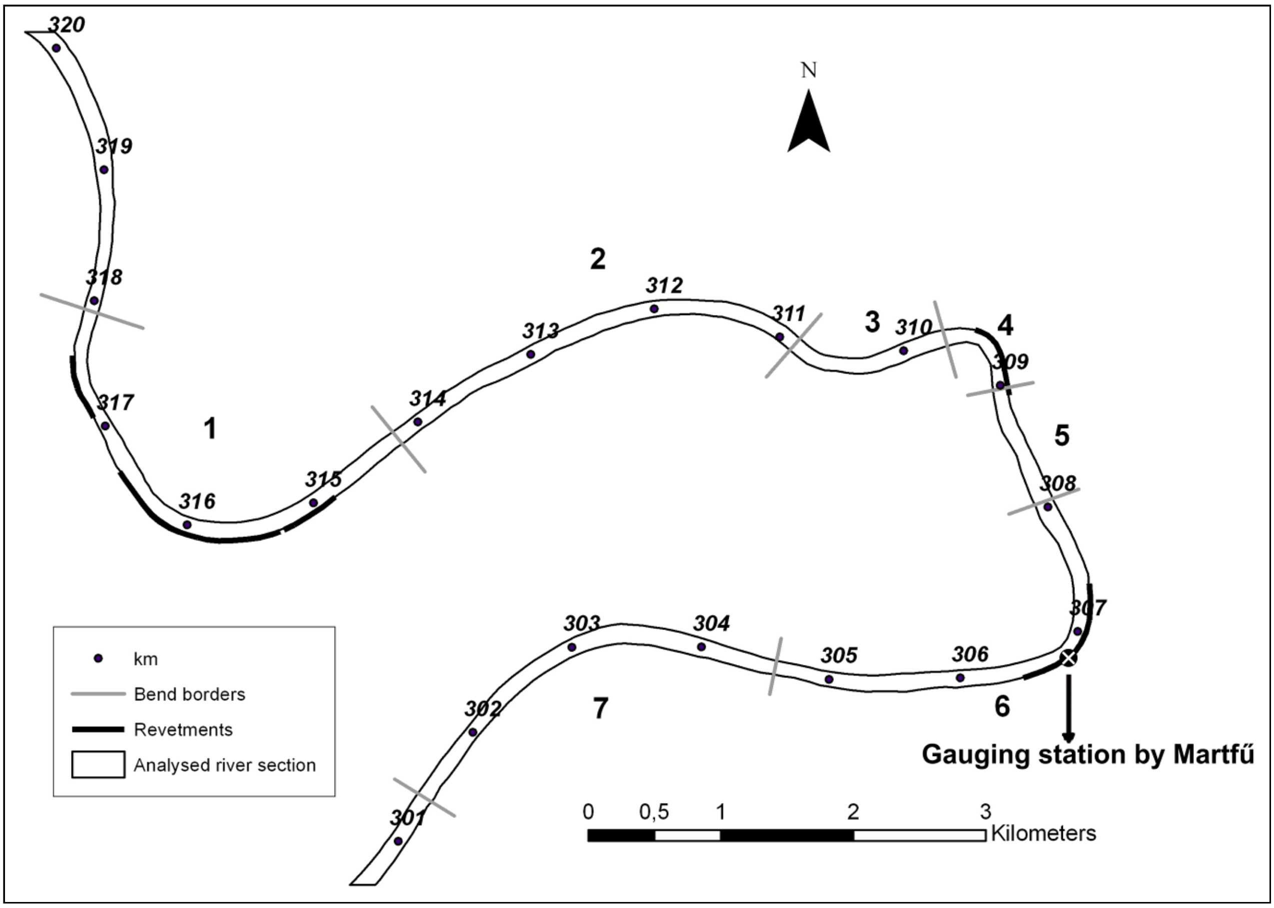

Figure 4. The location of the numbered river sections together with revetments.

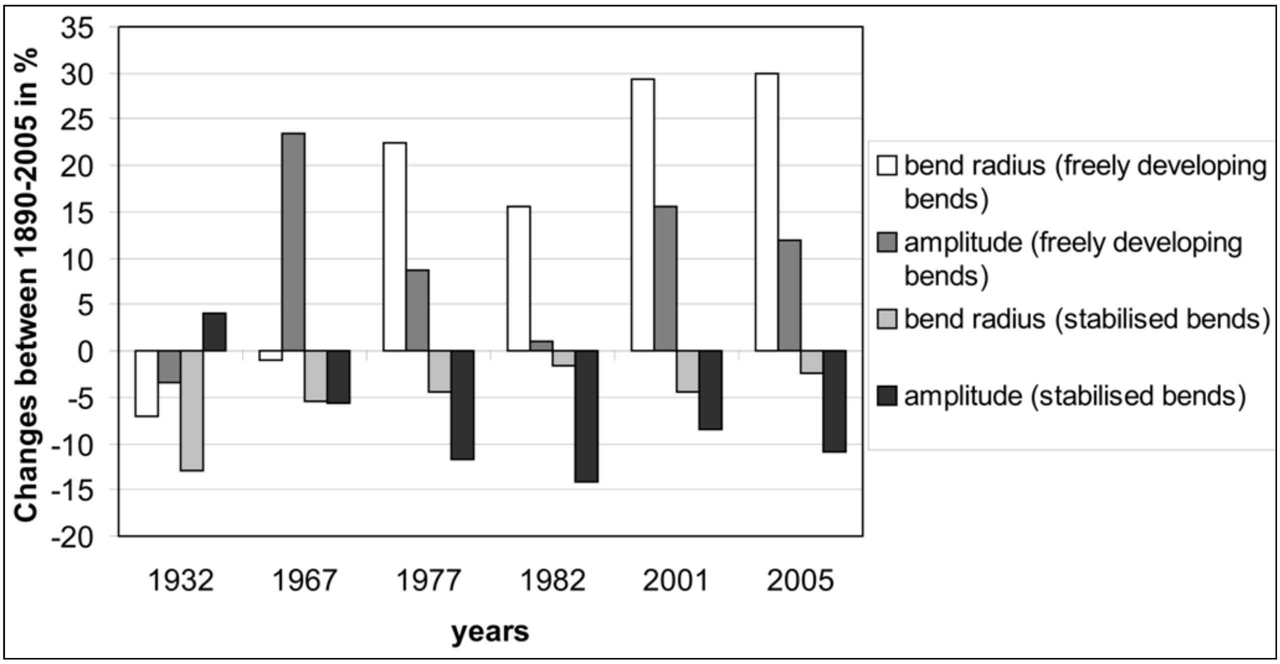

Figure 5. Bend radius and amplitude parameter changes in percentage comparing to 1890.

The channel stabilization was required in bend (1) to avoid the erosion in the settlement adjacent to the river (Vezseny), whereas in the bends (4) and (6) the channel had to be strengthened because of a highway construction. The horizontal moving of the channel was compared to the position of the river in 1890 to identify changes in the channel geometry (this year is before the regulation works).

Figure 5 and figure 6 show on diagram the changes of stabilised (1st, 4th, and 6th) and freely developing (2nd, 3rd, 5th and 7th) bends. For the stabilised bends, amplitude, arched lengths and chord lengths have been decreasing steadily. The increasing of bend radius (by 10 %) in case of stabilised sections shows that the development of the stabilised concave bank has stopped but the convex bank has been developing. The shape of bends is continually becoming sharper. As the figure 5 shows the bend lengths and chord lengths increased by 18% (0.5%/year) in the freely developing bends in the years 1932-1967, but in the following years this process decreased by 3%, as possible impact of stabilised sections.

Figure 7 compares changes in the analysed channel width. The impact of revetments is clearly visible along the 315-313 km, 310-309 km and mainly in 307 km, because of a stronger narrowing than in other sections. The average width of the channel in the analysed river section decreased between 1890 and 2005 by ~50 meters.

The midstream became longer more than 100 meters as comparing to 1890, which was mostly caused by intensive concave erosion between the 312-310 km of the river reach. The summarized bend radius was growing as results of above mentioned process by the revetments and as results of development of freely developing sections (Table 1).

The largest channel narrowing occurred (Fig. 8) by the stabilised sections: 1st (with 49 meters), 4th (with 44 meters) and 6th (with 31 meters). A significant bend shifting appeared between 312-311 km, where the channel was regulated. The shifting of this section was by 170 meters north-east as compared to 1932 (No. 2nd part of Fig. 8).

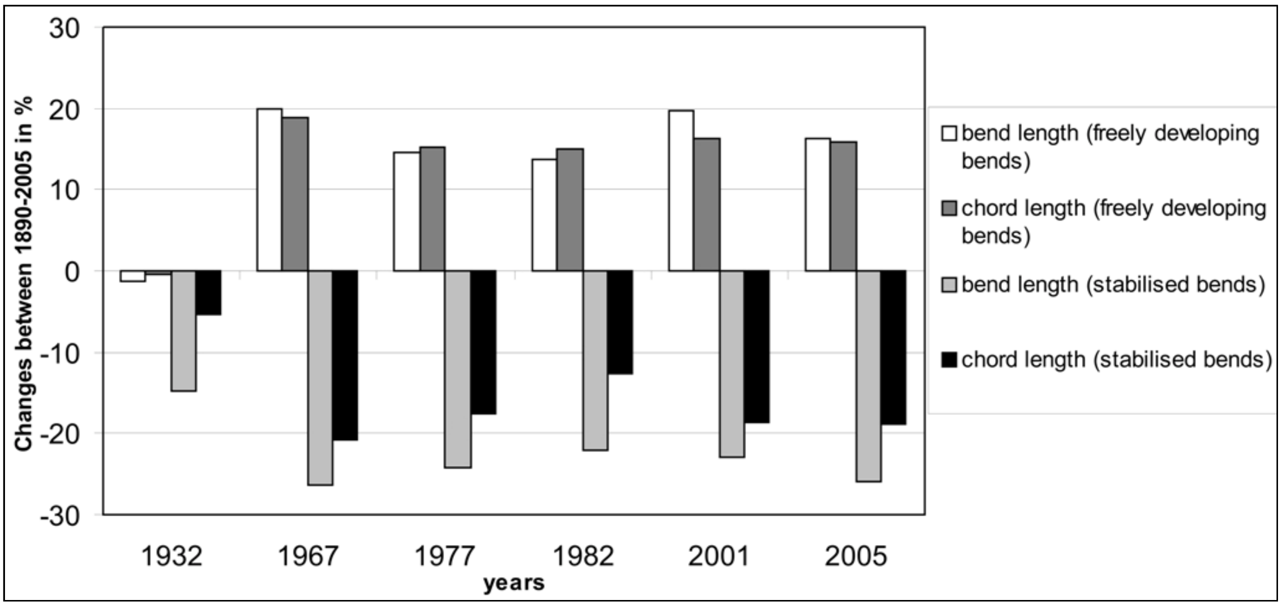

Figure 6. Arched length and chord length parameter changes in percentage comparing to 1890.

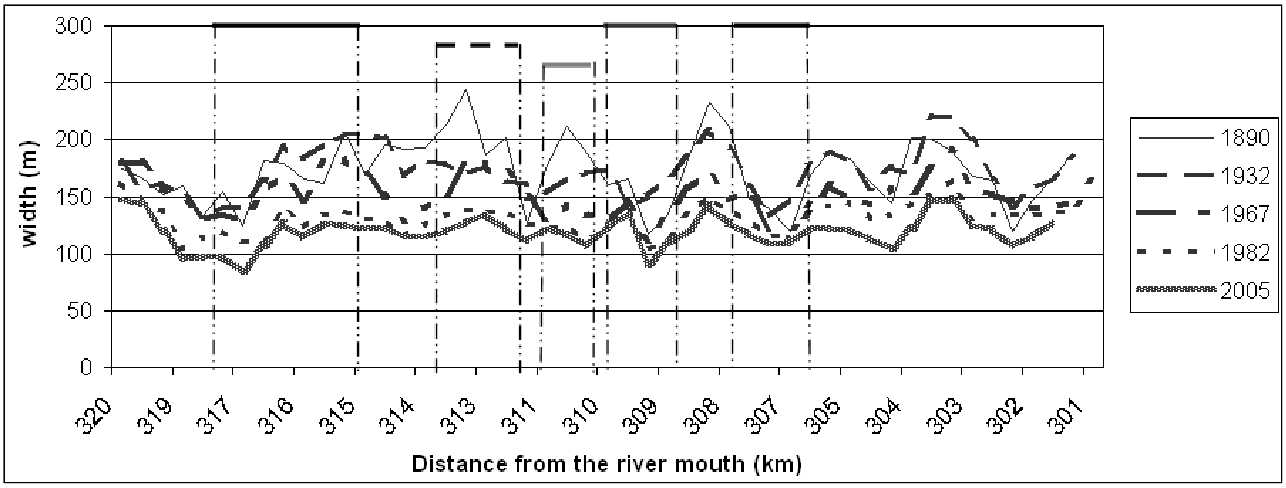

Figure 7. The width changes of the analysed river section. (Black line revetments, pecked line regulated channel, grey line cutbank)

Table 1. Summarized bend parameters from 1873 to 2005

Analysed parameters in years	*1873*	*1890*	*1932*	*1967*	*1977*	*1982*	*2001*	*2005*
Averaged width (m)	180	172	172	151	133	132	129	119
Midstream (m)	19401	19327	19486	19582	19576	19564	19590	19574
Bend length (m)	16994	16669	16442	16764	16437	16636	17052	16508
Chord length (m)	13675	13587	13197	13479	13449	13770	13544	13410
amplitude (m)	4527	4407	4474	4592	4196	4009	4394	4267
Development index	4.39	3.6	3.93	4.59	4.76	5.09	4.12	4.68
Bend radius (m)	4552	4654	4233	4540	5276	5108	5491	5537

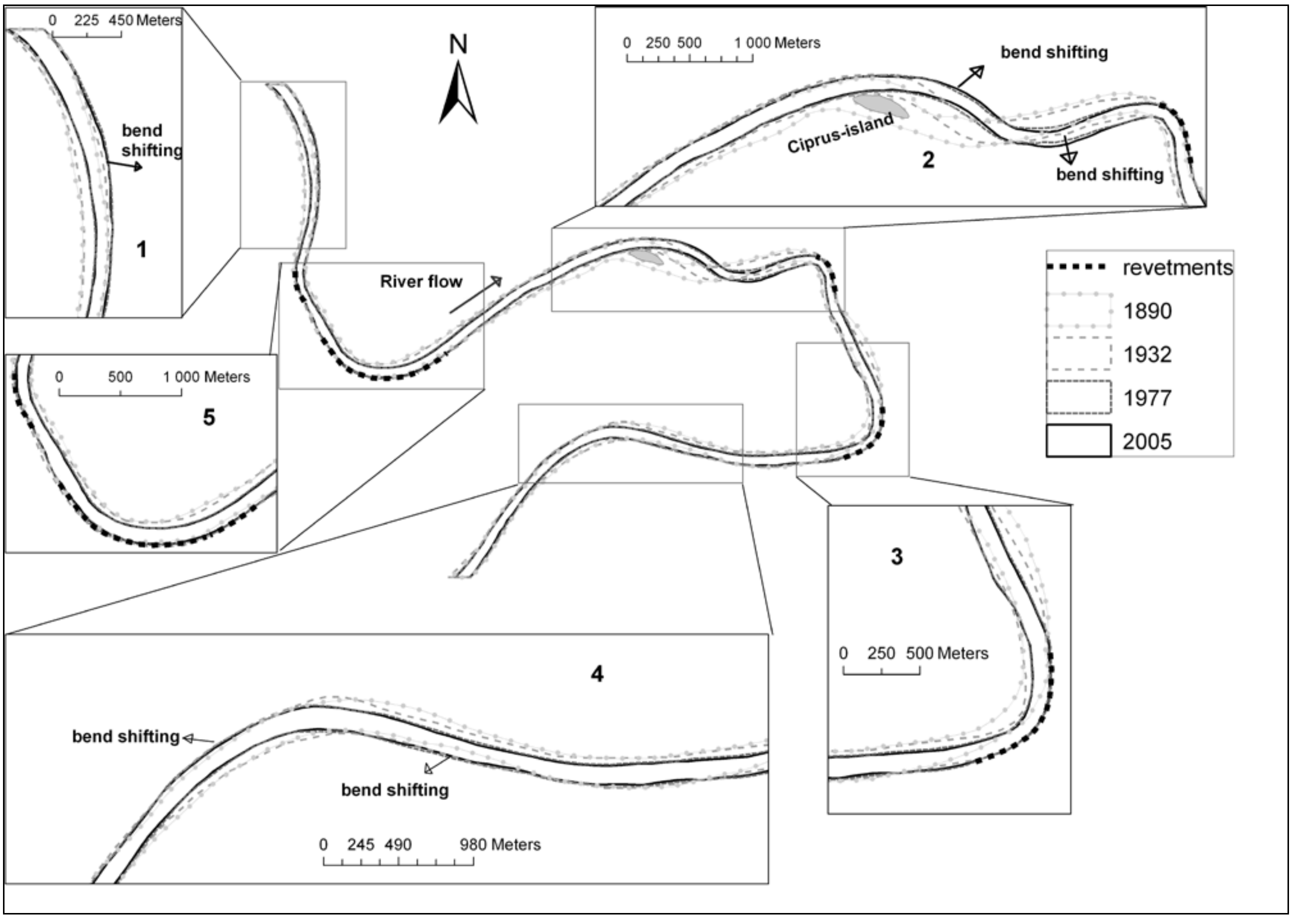

Figure 8. The horizontal developing of the analysed river sections from 1890 to 2005 together with the revetments.

The cutbank - between 311-310 km - was shifting by 185 meters from 1890 to 2005 to southward as result of the regulated and not stabilised river section. The midstream became 250 meters longer from 1890 to 2005 for the entire studied section.

4.2. Vertical channel changes

Table 2 shows the results of the analysed cross sections. The cross sections analysis shows that the narrowing process for the freely developing river channel was more intense than in the channel with revetments. The narrowing process - which reached 23-76 meters - was more intensive in the freely developing channel from 1929 to 2000 and the possible reason is the influence of the regulated sections. On the other hand, the cross sectional area did not change so considerably for the cross profile No. 175, where it grew by 6% and in No. 181, where it decreased by 11%. The cross section No. 177 reveals the most visible impacts of revetment for the non-stabilised channel because it is the closest to the revetment sector among all of them. Here the area of cross section decreased most intensively by 43 % from 1929 to 2000. For cross sections with revetments the most intensive changes were observed by No. 176. For the cross profile No. 180 the revetment had existed long before 1929. It shows little changes of the shape index and a decrease of width by 8 meters. Here the revetment had to be constructed because of the proximity of a highway. The revetment of cross-section no. 182 had to be constructed because of a car-ferry crossing. As it is visible in the data there was not a large impact on the cross section. The shape index changed by one meter from 1929 to 1957 and then remained on the same level, while the width and the area of cross section behaved in a similar way.

Table 2. Parameters of the analysed cross sections (compare Fig. 8).

		Freely developing cross sections			**Cross sections with revetments**		
	Years	**175**	**177**	**181**	**176**	**180**	**182**
	1929	14	11.6	13.2	12.7	15.8	14.3
	1957	15	12.4	14.5	12.9	16.5	14.2
	1976	17	12	15.5	13.4	16.2	15.1
Deepest points (m)	*2000*	14.9	12.7	16.2	13.7	15.2	14
	1929	12.3	19.6	15.3	17.1	9.6	11.4
	1957	9.8	13.9	10	10.8	10.4	9.9
	1976	8.3	11.9	9.8	11.3	9.3	9
Shape index (W/h)	*2000*	10	12	8.9	11	9.5	9.6
	1929	172	228	201	217	152	162
	1957	146	172	145	140	172	141
	1976	141	143	152	151	151	136
Width (m)	*2000*	149	152	144	150	144	134
	1929	1211.5	1865	1493.7	1518.7	1544.8	1543.4
	1957	1197.7	1266.7	1244.4	1262.7	1667.5	1059.8
	1976	1370.6	1028.3	1427.9	1218.5	1589.1	1218.9
Area of cross section (m^2)	*2000*	1291.1	1062.7	1344.2	1126.8	1292.4	1048.8

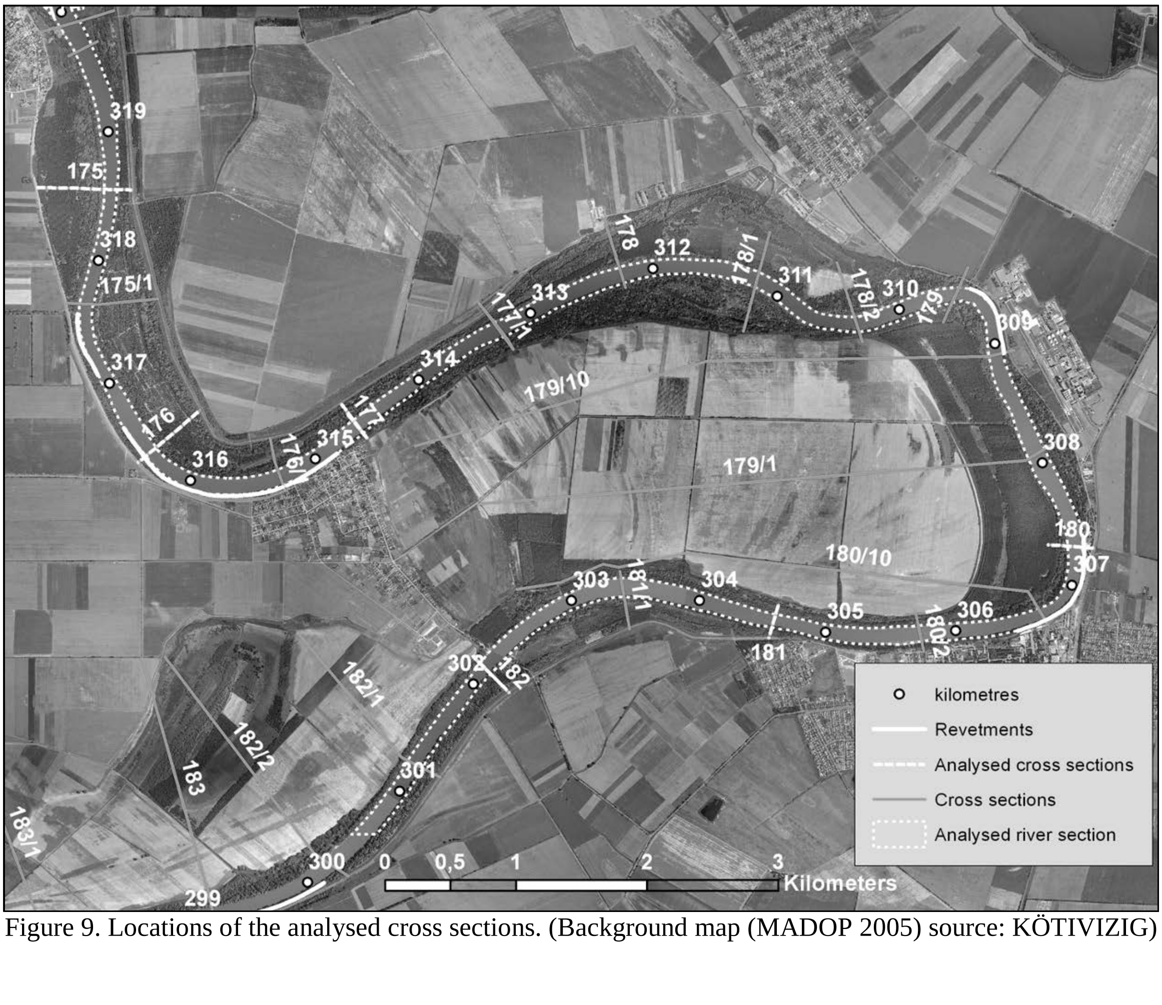

Figure 9. Locations of the analysed cross sections. (Background map (MADOP 2005) source: KÖTIVIZIG)

The measured cross sections are indicated in (Fig. 9). Section No. 176 and No. 177 have been chosen for a long-term analysis and to demonstrate and compare human impact on the channel development. One type is located in the freely developing channel sector and the other in the stabilised sector. For the purpose of calculating, the hydraulic radius the depths were counted from 85 m a.s.l. which was the average height of the bank sides and it was needed to fix a height point to correlate.

The chosen cross section (nr. 177) (Fig. 10) is located between 314 and 315 km, where the bend was not stabilised. For that reason in the years 1929 to 2000 the channel shifted 21 meters westward without any shape deformation. Shape index is a ratio between a maximum width and depth. If the ratio is increasing over time, the cross section tends towards a trapezoidal or U-shape, whilst if it is decreasing a V-shape develops (Kiss et al., 2008). Changes in the geomorphologic activity of the river are strongly related to changes of the width-depth ratio of the main channel (Schoor et al., 1999). The cross section w/h ratio was 19.6 in 1929, which later decreased to 12 in 2005. Moreover, the channel is V-shaped, which is probably caused by the bend stabilization upstream of the measured cross section. No channel incision was noticed in the years 1957-2000. The cross sectional area was reduced by 800 m^2, which is 47% comparing to the year 1929. The east side bank of the river is continuously shifting westward and the west side is keeping up with this process.

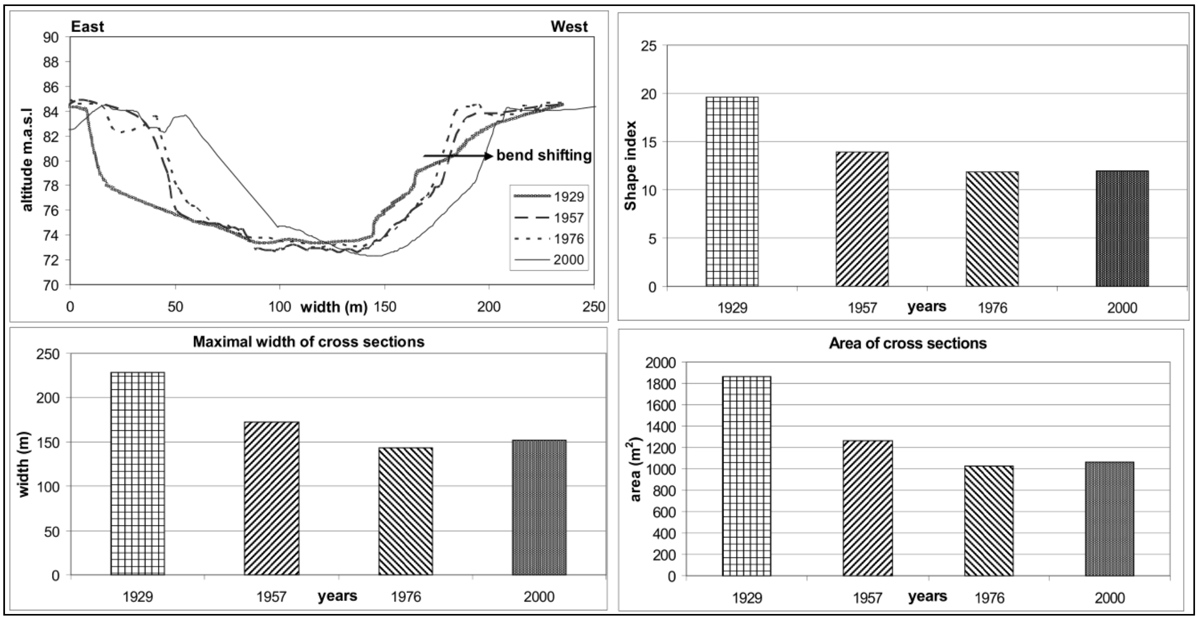

Figure. 10 Freely developing river channel with lateral shifting (cross section nr. 177).

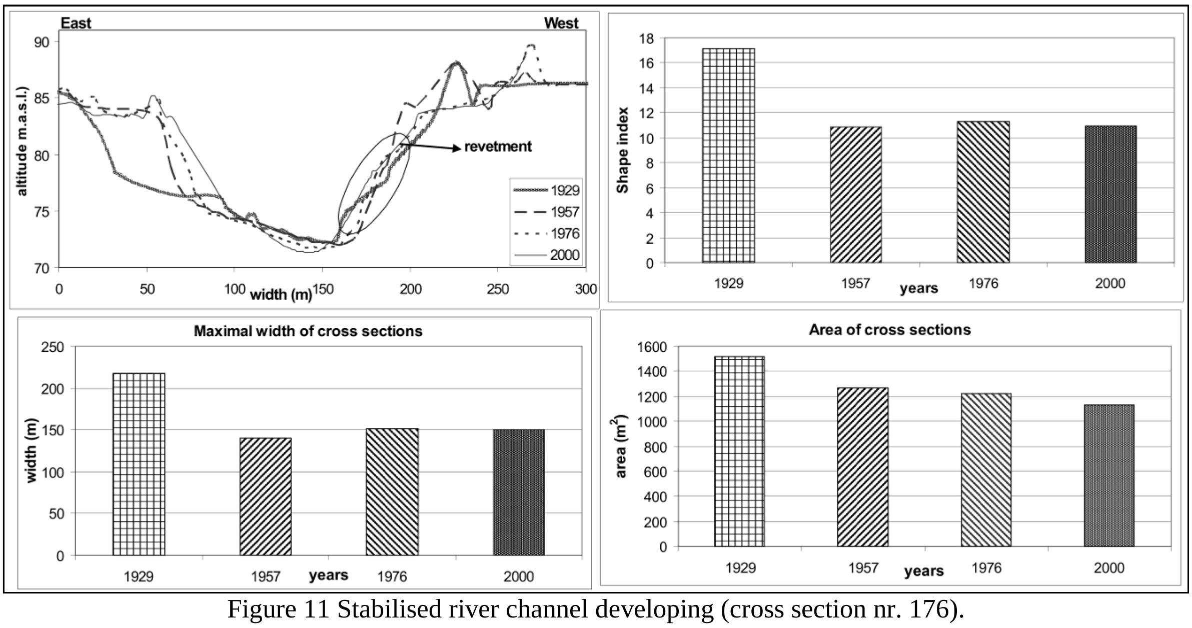

Figure 11 Stabilised river channel developing (cross section nr. 176).

The Tisza channel was stabilised in Vezseny (cross section number 176) because of the settlement located on the concave river bank. On figure 10 the revetment existing in 1929 is indicated. Due to this bank protection the river channel was getting narrow comparing to 1929. The river bed incised one meter and from 1929 to 2000 the width decreased by 70 meters and the cross section area fell by 400 $m^{2,}$ which means a decrease of 36 %. The w/h ratio decreased from 17.1 to 11, which means the cross section U shape changed into V one due to the effect of regulation works.

A digital terrain model was created basing on a topo map and the channel depth measurements. The 3rd, 4th and 6th bends are the deepest parts of the studied Tisza channel. At the regulated sand bar (2nd bend) the water level is 3-4 meters deep in the stream centre-line but in the 3rd bend, where the most intensive erosion occurs, the depth reaches 9-10 meters. The deepest channel sections are located near the bank revetments. Here the average depths reach 11-14 meters. The shortest bend radius is accompanied by the deepest channel section found within the studied area (Fig. 12).

4.3. Changes in hydrology

Changes of a rivers water duration curves can driven from historic records of water level changes (Schoor et al., 1999). On figure 13) the period of 1901-1910 negative values (black line) of the water level were recorded at the gauging station of Martfű. The lowest recorded stage was -228 cm below the zero level in 1904. By the middle of 1910 – 1920 when the regulation of the sand bar by Vezseny had been finished the lowest recorded water level in the period of 1911-1920 was -199 (in 1912) (grey line). Moreover, in 1921-1930 no negative values were recorded except one: -181 cm in 1930. In the period of 1931-1940 the river achieved a new equilibrium of lateral movement. Later an incision process occurred. Because of the river channel regulation the inchannel alluvia deposited in the neighborhood of the gauging station were washed away and consequently, the river bed got deeper (period of 1941-1960). The channel incision is clearly visible from the low water duration like period of 1941-1960, 1961-1980 and 1981-2010. On the other hand, the occurrence of high water levels were increasing (Fig. 12) and exceeded 800 cm, which is the highest amount on the flood prevention scale and means that water spills over into the embankment zone. In the period of 1961-1980 the duration was 4% and in 1981-2010 this value reached 11%. The newest flood records appeared after 2000.

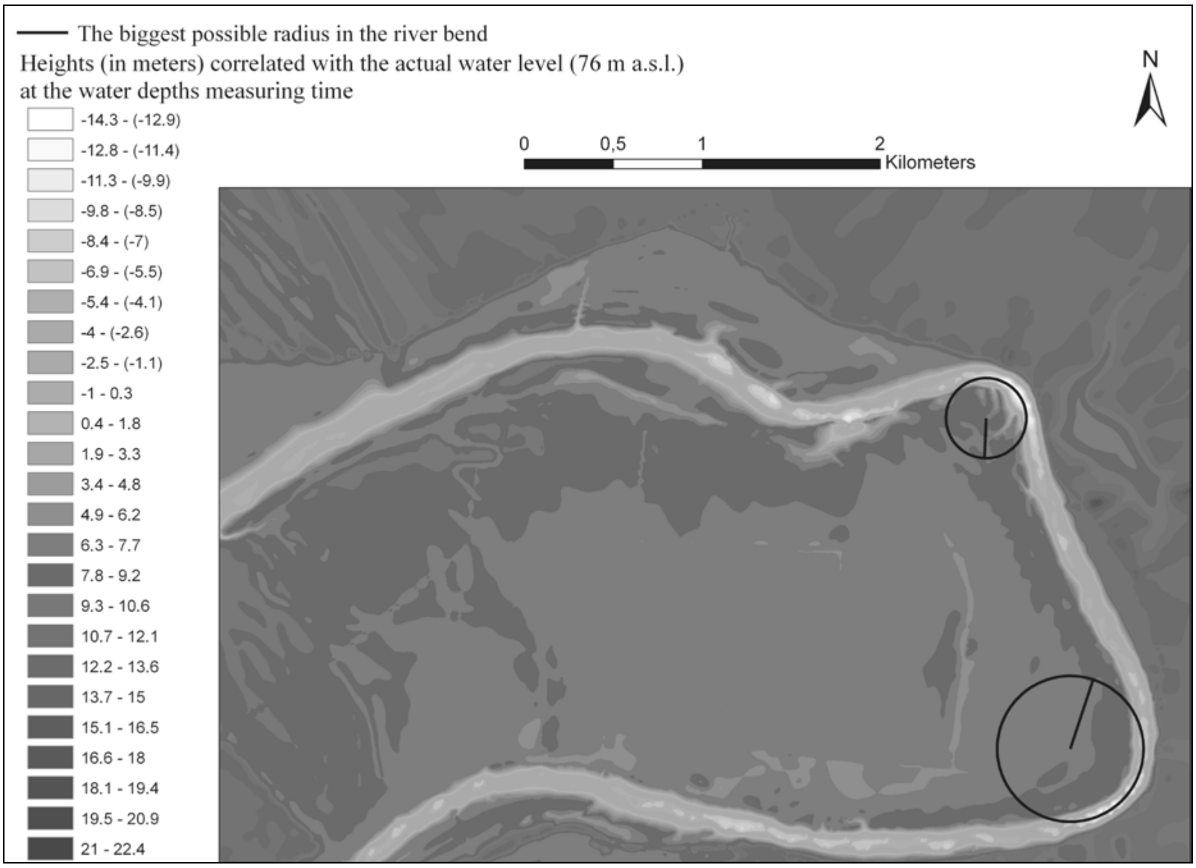

Figure 12. Channel morphology of the analysed river section

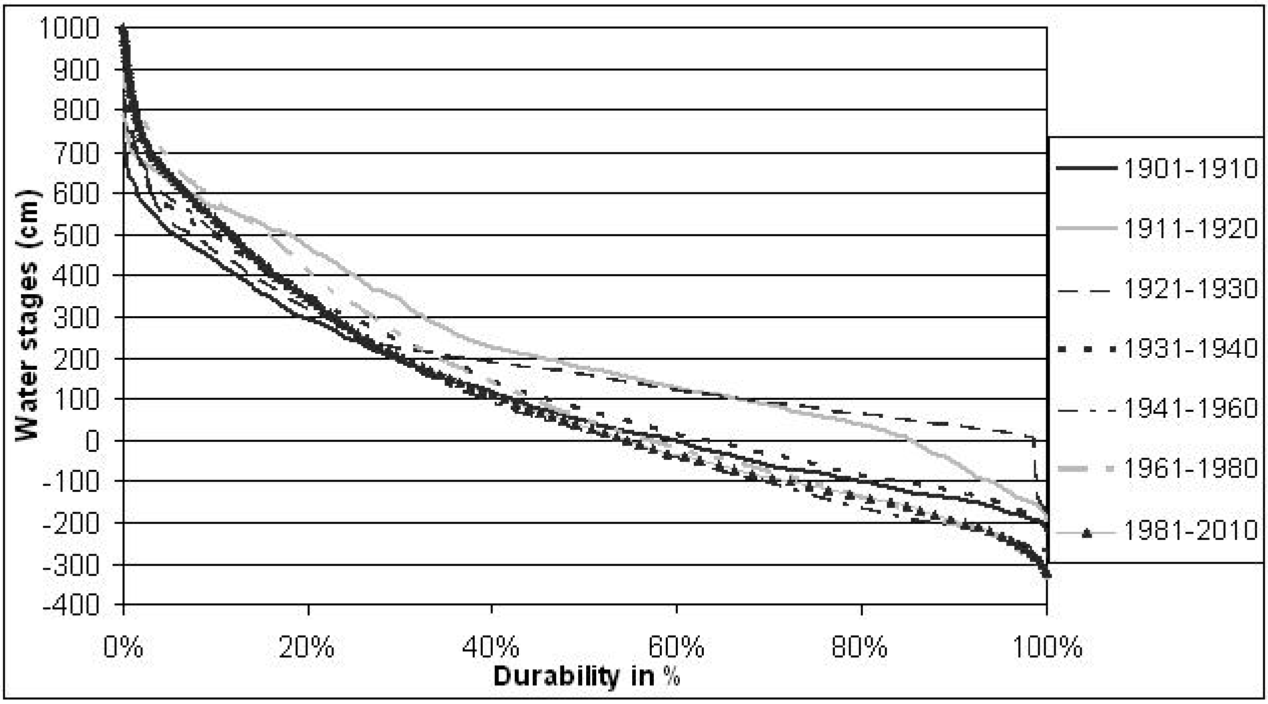

Figure 13. Changes in durability (%) of water stages as the result of channel regulation works.

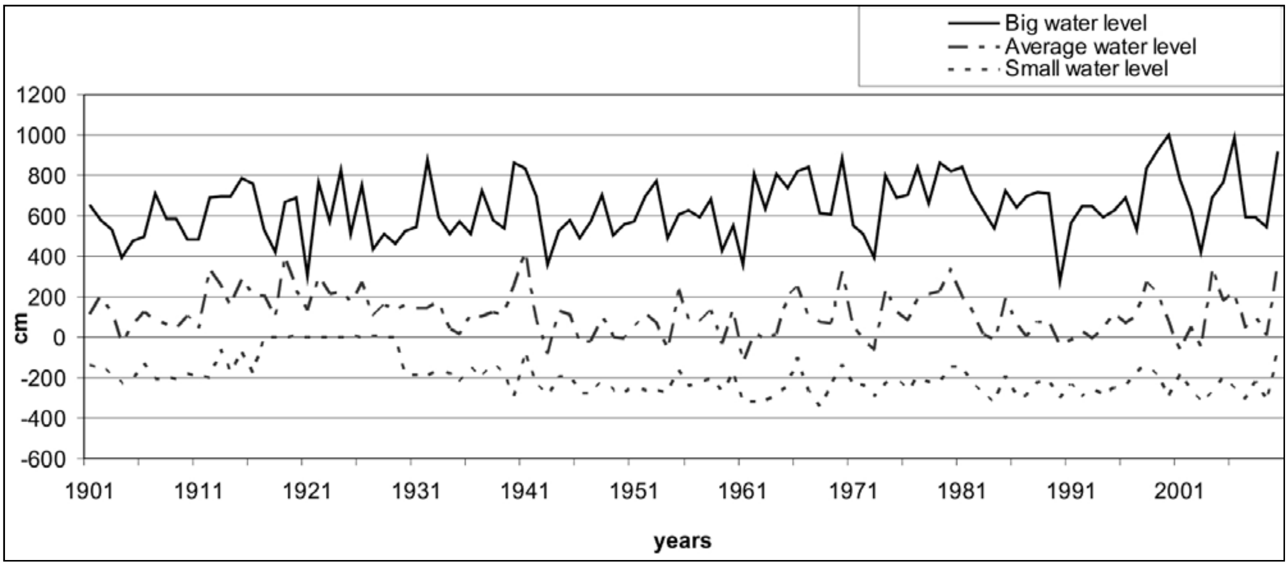

Figure 14. Each year's highest, smallest and average water level changes from 1901 to 2010 years at the gauging station of Martfű.

The causes of these record floods are complex, including both natural and human induced factors (Kiss et al., 2008) like temporal and spatial changes in the amount of precipitation, landuse changes in the catchment, the influence of tributaries and the Danube, floodplain narrowing caused by the embankments, low water slope and irregular floodplain width and elevation and overhighed summer dykes (Sándor & Kiss 2006). Figure 14 shows the highest, lowest and the average water level each year. No negative values for the lowest water levels were recorded from 1917 to 1929 which term was after the channel regulation works. The lowest water level was recorded in 1968. The lowest stage reached at that time amounted to -345cm. In the last ten years the low water stage (below -300 cm) was reached three times, which is in contrast with the appearance of the highest flood levels. An extreme situation was noticed in the year 2000 when the highest water level was recorded. After the flood the water level dropped dramatically to -295 cm.

5. DISCUSSIONS

Similar results were reported e.g. by Surian & Rinaldi (2003) in Italian rivers. The effects of human disturbance in form of bank protection structures were analysed by the authors. Their results show that the incision and/or narrowing are more intensive immediately after the disturbance and then calm down and become asymptotic. Several human interventions (dams, gravel and sand mining, channelization, land-use changes) were indicated as the causes of those changes in river morphology since they alter flow regime, channel boundary characteristics and especially sediment supply.

The results of the project for the lateral migration of the Tisza River show that the natural channel development reduced as an effect of human impact. The average channel widths decreased in the analysed channel reach by about 50 meters from 1890 to 2005. For the non-stabilised river bends the chord and bend length, bend radius and amplitude seemed to increase. In the stabilised bends these parameters decreased. Similar conclusions were drawn by Michalková et al., (2011) along the Sacramento River, where the Shasta Dam affected the channel geometry along the entire 140 km reach, reducing the active channel width.

The analysis of Ollero (2010) of the Ebro River showed that the revetment works stabilised the channel; the fluvial dynamics of the free meandering Ebro in Aragón were considerably reduced and almost eliminated, while the width decreased significantly. The study of Kiss et al., (2008) on the Lower Tisza from 1840-2001 analysed the effect of the river regulation works and focused on the planimetric and cross-sectional parameter changes. The average width of the channel decreased by 17–45%, which was accompanied by the decrease in the mean and maximum depth by 5–48%. The area of cross-sections which were influenced by revetments decreased by 6–19%, which resulted in a 6–15% decline in flood conductivity. The non - stabilised sections were influenced by upstream revetments. Therefore, their parameters show similar changes, but with a smaller rate. Zawiejska & Wyżga (2010) investigated the lower river course of the Dunajec River. Channelization works at the end of 19th century and the beginning of the 20th century were the principal cause of the channel incision where the river was effectively narrowed, straightened and confined to bank-protection structures. They compared gauge cross-sections from the years 1913–1998 and the results showed erosion of channel and lowering of water stages at the gauging station. It indicates the role of the river narrowing from the early 20th century in inducing significant channel incision. As a result of both processes, the width/depth ratio of the Dunajec channel at Żabno decreased substantially from 31 in 1913 to 14.3 in 1998. Although the river type which the authors (Zawiejska & Wyżga 2010) analysed was different, the rules of physical behavior do not vary when we compare the results.

6. CONCLUSIONS

In the presented research managed to summaries the anthropogenic impacts and natural processes on the analyzed river bend. Even though of revetments by the 1st, 4th, and 6th sections, the midstream is still growing by the 2nd and 3rd sections. The bend radius by the revetments was decreased comparing to 1890, but after 1932 started increasing as result of developing of convex bank. By these sections was the highest narrowing. Managed to show the influence of channel regulation works on hydrology from the water stages and water durability diagram where the low water levels decreased in the period of 1911-1920 and in 1921-1930 no negative values were recorded. This unusual behave of water stages started after regulation works. After 1931-1940 to nowadays the channel incised which is represent the lower water levels. The analysis of cross sections by the non-stabilized bends show that they deformed a slightly and their widths decreased, which was caused by the stabilized sections. The geometry of the stabilized channel sections changed. The shape of the bends with revetments was deformed, the concave bank erosion stopped, the maximal channel width and its cross-profile area decreased. In the stabilized bends the deepest parts of the channel were found. In this case there is a relation between the smallest bend radius and the deepest section.

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