Available online at www.sciencedirect.com
ScienceDirect
Geomorphology 98 (2008) 96–110
GEOMORPHOLOGY
www.elsevier.com/locate/geomorph

Alterations of channel parameters in response to river regulation works since 1840 on the Lower Tisza River (Hungary)

Tímea Kiss [a], Károly Fiala [b,*], György Sipos [a]

[a] Department of Physical Geography and Geoinformatics, University of Szeged, Szeged, 6722, Egyetem u. 2-6, Hungary
[b] Directorate for Environmental Protection and Water Management of Lower Tisza District, Szeged,6722, Stefánia 4, Hungary

Received 17 January 2006; received in revised form 26 June 2006; accepted 21 February 2007
Available online 13 May 2007

Abstract

In the last few years an increase in the frequency and magnitude of floods was detected on the Tisza River, endangering large areas of Hungary. The causes of these record floods were complex, including both natural and human induced factors. This paper focuses on river management works and their effect on planimetric and cross-sectional parameters, with special attention to the flood conductivity changes to the river channel. During 19th century river regulation works, half of the total length of the Tisza River was altered by cut-offs, while in the 20th century mostly revetments and groynes were constructed. Subsequently, horizontal and vertical channel parameters have changed considerably due to semi-natural bed processes. In order to reveal changes, hydrological map series (1842, 1890, 1929, 1957, 1976 and 1999) and cross-sectional surveys from the same dates were analysed. Prior to the intensive human interventions (before 1890s) the river's course was highly sinuous with some very sharp bends. Due to cut-offs both the length and sinuosity of the Tisza River decreased by 35%, while the lengths of straight sections and the river's slope doubled. As a consequence the river incised by up to 3.8 m until the 1929 survey, resulting better flood conductivity, which improved flood safety. In the 1920s river management favoured bank stabilisation in order to stop the lateral migration of the channel. Despite these measures, meander development has continued, however, in a distorted manner. This is reflected by the opposing processes of lengthening centre-line on the one hand and gradually decreasing radius of curvature on the other. These processes can be explained by the continuous development of natural point-bars on the convex bank, and the lack of lateral retreat on the concave stabilised bank. The width of the river decreased by 17–45%, while its mean and maximum depth increased by 5–48%. The area of cross-sections influenced by revetments decreased by 6–19%, resulting 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. At present, the flood conductivity of the channel is worse than it was in its natural state. In all, it was found that the ongoing process of cross-sectional distortion is a significant factor in increasing flood stage and hazard, and high floods can be expected more frequently in the future partly due to this factor.
© 2007 Elsevier B.V. All rights reserved.

Keywords: Channel planform; Cross-section; Cut-off; Revetment; Flood hazard

1. Introduction

The horizontal and vertical parameters of channels are affected by several factors, which is broadly discussed in different geomorphological and hydrological studies (Schumm, 1977; Knighton, 1998; Bridge, 2003; Richard

* Corresponding author. Tel.: +36 62 544 545; fax: +36 62 544 158.
E-mail addresses: kisstimi@earth.geo.u-szeged.hu (T. Kiss), karolyfiala@freemail.hu (K. Fiala), gyuri@earth.geo.u-szeged.hu (G. Sipos).

0169-555X/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2007.02.027

et al., 2005). The effects of different anthropogenic activities on channel morphology are less widely investigated. However, the results of these studies must be incorporated into the process of river management, as is emphasized by several authors (Newson, 1997; Hey, 1997; Gilvear, 1999; Downs and Gregory, 2004; Chin and Gregory, 2005). Furthermore, some researchers have drawn attention to the fact that engineering works designed to stabilise the channel and to control floods often increase flood hazard (Tiegs and Pohl, 2005; Pinter and Heine, 2005). Even a slight change in valley cross-sectional area can increase flood hazard on a centennial timescale (Brooks, 2003). Other unfavourable processes might be initiated as well, for example destabilisation of infrastructure due to incision, lowering of the water table and soil salinisation (Arnaud-Fassetta, 2003).

Human activity affecting channel morphology and fluvial processes can be quite varied. Indirect influences, including land-use and management, changes to the catchment, urbanisation and land drainage, alter run-off and sediment yield. A wide range of direct impacts influence the channel itself, e.g. dam construction, reservoirs and grade-control structures, channelisation, artificial cut-offs and rectification, instream mining, installation of groynes, artificial bank stabilisation, etc. (Newson et al., 1997; Knighton, 1998; Uribelarrea et al., 2003; Antonelli et al., 2004). In response, several parameters of the channel might change. The most widely reported results are incision, narrowing and channel pattern change (see the review in Surian and Rinaldi, 2003).

Land management and urbanisation usually change basin hydrology, thus these can substantially alter flood frequency and lead to increased flood hazard (Stover and Montgomery, 2001; Kondolf et al., 2002). Nevertheless, indirect human impacts are very often combined with local channel transformations, as in the case of Italian and Alpine rivers, where catchment scale and local impacts were superimposed and led to incision. The first phase of incision (at the end of the 19th c.) was derived from land-use and land-management changes, while the second phase (1945–1960) was the result of instream gravel mining and construction of upstream dams (Rinaldi and Simon, 1998). The same phases were described by Antonelli et al. (2004) on the Rhone River, though they considered the second half of the 20th century as a relaxation period after human and climate induced channel adjustments. By contrast, sedimentation of the river-bed during the last 20 years has been reported on the Yellow River after a significant run-off decrease from the catchment due to climate change and varying human activities (Xu, 2002).

Direct anthropogenic interventions in lowland alluvial rivers include dredging and flood control works. These may lead to long profile degradation, channel narrowing (Liébault and Piégay, 2001), or incision (Rinaldi and Simon, 1998; Arnaud-Fassetta, 2003; Surian and Rinaldi, 2003). In smaller rivers channelisation is the typical means of river training, while in larger ones engineering projects mostly apply cut-offs. The effects of channelisation were studied e.g. by Brookes (1985) and Yates et al. (2003). They found that channelisation resulted in an increase in slope and a decrease in roughness. The channel became deeper and wider, which led to an increased bankfull velocity, thus finally bankfull discharge capacity became higher too. Investigations on the impact of artificial cut-offs reflect that increased slope leads to increased stream power (Laczay, 1977) and bed-load transport (Biedenharn et al., 2000), which can change channel geometry and water surface profiles (Smith and Winkley, 1996). Processes are very similar to those acting in the case of a natural cut-off (rapid widening, accelerated bank erosion, formation of bars and riffles, etc.), and in most cases, following rapid changes in the first 2–3 years, the channel needs a few additional years to relax and to become stable (Hooke, 1995).

Revetments and groynes are broadly used to prevent and stop bank retreat and to increase velocity by decreasing the width of the river. The function, structure, design criteria and materials of these installations are well described (Bridge, 2003; Brookes, 1997; Newson et al., 1997; Downs and Gregory, 2004); however, few measurements have been made on their impact on channel development and flood hazard. The effects of bank protection structures were analysed by Surian (1999) and Rinaldi (2003) on Italian rivers, which adjusted themselves to the new hydrological conditions by narrowing and creating a less wandering pattern. The effects of groynes (wing-dams) were studied by Pinter and Heine (2005) on the Lower Missouri River. They found that changes in channel geometry and flow dynamics clearly coincided with the time of groyne construction and other engineering activities. Furthermore, the reduction of cross-sectional area was also measured.

The aim of the present study is to investigate the consequences of the 19th and 20th century river management works on the channel of the Lower Tisza River, paying special attention to the local, bank stabilisation works of the 20th century. To reveal how the interventions have altered the channel, planform and cross-sectional measurements were made and analysed. In addition, the relation of channel-parameter changes to flood hazard was also evaluated, especially due to the increased flood water levels.

2. Study area

The Tisza River is the second largest meandering river in Hungary, draining the water of the eastern part (157,200 km^2) of the Carpathian Basin. Its total length is 962 km, of which a 596 km long section is in Hungary (Lászlóffy, 1982). A 25 km long reach was chosen as a study area on the Lower Tisza River (Fig. 1), north of the town of Szeged (200–225 dfd km: distance from the downstream river outlet).

2.1. River regulations

River regulation works along the Tisza River can be divided into two periods. Extensive works of uniform plans and design started in the late 19th century (Ihrig, 1973), and aimed at the protection of land from inundations, and the decrease of the duration of floods. The original 27,000 km^2 large floodplain (which occupied almost a third of the territory of Hungary) was reduced by the building of a 2940 km long levee system (Szlávik, 2000). Simultaneously, 102 cut-offs were made, which shortened the river by 38%. As the result of length reduction the slope was almost doubled at some sections (Dunka et al., 1996). During the 20th century, especially between 1930 and 1960 river management was mostly confined to the construction of revetments and groynes. The aims of these works were (1) to stop the lateral erosion at bends which migrated too close to levees and villages; (2) to facilitate shipping by tightening wide reaches; and (3) to train sharp bends in order to improve the flood conductivity of the channel. The installation of revetments and groynes was the most intensive in the 1930s (Fig. 2), and as a result 44% of the bank of the Tisza River was stabilised. These works were planned for the maintenance of sections measuring several kilometres (approximately the length of a meander), and their effects on the system as a whole have never been studied in detail.

On the Lower Tisza 7 cut-offs were made between 1855 and 1864, reducing the length of the 105 km long section by 19 km. From among these, three are located on the studied reach (Fig. 3). The levee system reduced the 6–8 km wide natural floodplain to approximately 1 km. However, as the levees are not parallel, at some places the width of the artificial floodplain is only 0.5 km. In the case of the Lower Tisza 51.4% of the banks are protected by revetments, most of which were constructed between 1930 and 1960. Extensive groyne installation also took place, as 80% of the total 30 groynes were built at this time. Since 1971 there has been very limited engineering work and only a few hundred metres of bank were stabilised. At the studied reach the total length of revetments is 9270 m. This means that in 37% of the reach one or both banks are protected.

2.2. Hydrology

The Tisza River and its tributaries are mostly fed by overland flow. The first, and normally the largest flood

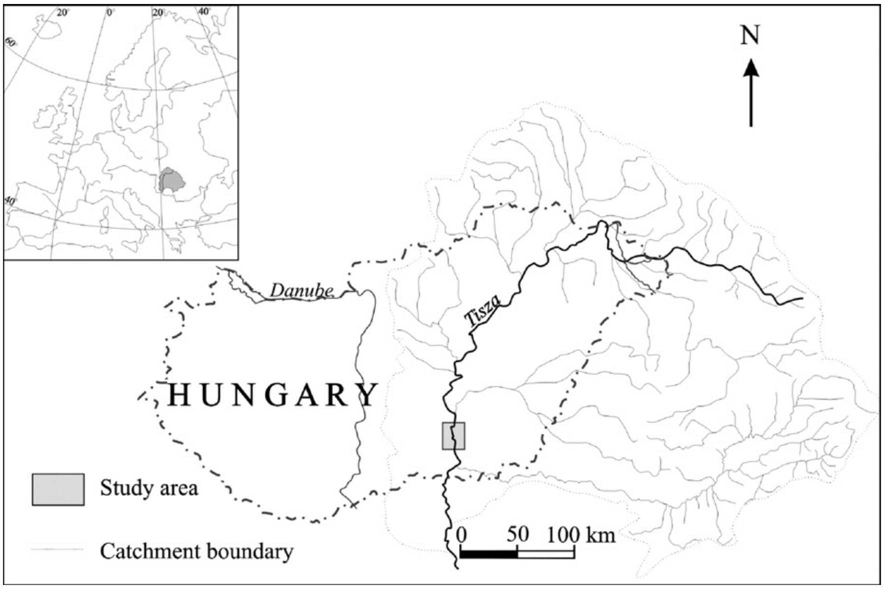

Fig. 1. The catchment of the Tisza River and the location of the study reach.

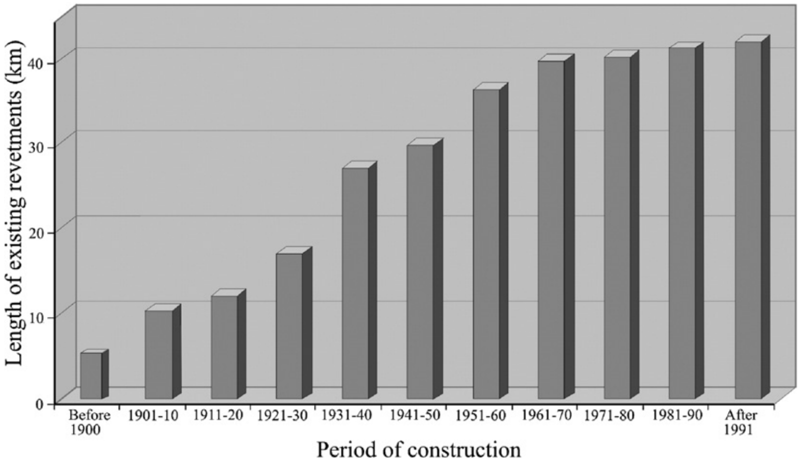

Fig. 2. Revetment constructions along the 88 km long Hungarian section of the Lower Tisza River.

of the year is due to snowmelt in early spring. The second is caused by early summer rainfall. The period between August and December is characterized by low stage. The mean discharge at low stage is 115 m^3/s, but at peak floods it exceeds 3600 m^3/s. As a result of the cut-offs, the present slope of the studied reach is 0.000029 while the mean velocity during mean discharges is 0.7 m/s (Károlyi, 1960). The annual suspended sediment yield is 18,700,000 t/year, and only 9000 t/year is transported in the form of bed-load (Lászlóffy, 1982).

Since 1901 (the establishment of fluvio-metres), floods occurred in every second year on average, though distinct periods characterized by high and long floods can be distinguished in every decade (Fig. 4). During flood years the river inundates the floodplain for 2–3 months, though in 1941, 1945, 1970 and 2006 the flood lasted for 4–5 months. Since 1901 the level of record floods has increased by 150 cm in the study area, but the peak discharge remained the same. This flood level increase is slight compared to other sections of the Tisza River, where it can exceede 350 cm (Kiss et al., 2004).

3. Methods

3.1. Measuring planform parameters

In order to measure planimetric changes along the studied reach, a series of hydrological survey maps was used. As they are based on very detailed field surveys, these maps give more precise and uniform data on the boundary of the channel and the floodplain than ordinary topographic maps. Since the regulation works in the beginning of the 19th century, the floodplain and the channel were mapped 6 times (1842, 1890–1891, 1929–1931, 1957–1961, 1976 and 1999). The maps were made at different projection systems. Therefore, all map sheets were geocorrected by AutoDesk Land Desktop 2004 software, and transformed into the Unified Hungarian

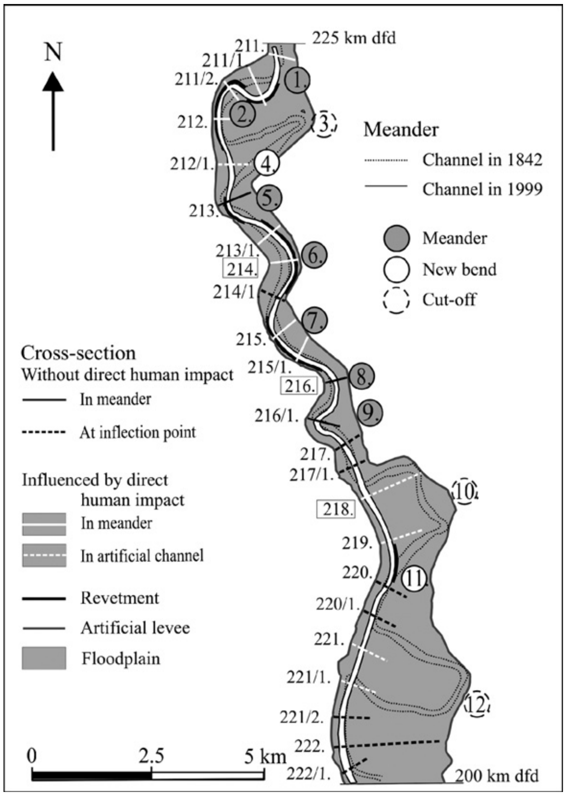

Fig. 3. The course of the study reach in 1842 and 1999, and the location of the studied meanders, cross-sections and revetments. Note the irregularity in floodplain width, and the meanders advancing towards artificial levees (dfd: distance from the downstream river outlet).

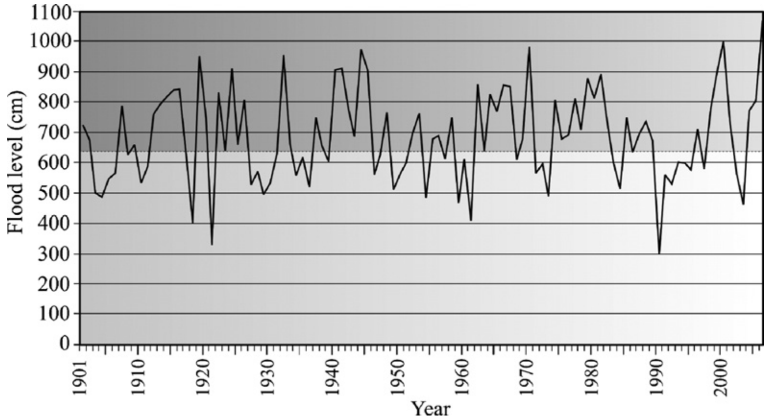

Fig. 4. Annual highest water level (cm) recorded at the Mindszent fluvio-meter station. The river overflows its banks if water level exceeds 630 cm on the fluvio-meter.

Projection System (EOV). Calculations were performed following the digitisation of bank-lines.

The centre-line and inflection points of the studied reach were determined by measuring and halving the distance between bank-lines at every 100 m. Theoretically, the inflection point is at the intersection of the centre-line and the thalweg, but on the maps it was determined as the mid-point of straight sections. During the evaluation a number of planform parameters were studied (Table 1).

3.2. Measuring cross-section parameters

The Hungarian Hydrological Institution established a reference-point system along the Tisza River in the late 1890s. These fixed survey points were installed within a 100 m distance from the banks and on the levees, with a spacing of 0.5–1.0 km along the river. They make it possible to re-survey cross-sections at the same locations. As their geographical coordinates are known they can be fitted into different projection systems.

The depth of the channel along a cross-section was measured every 2 m within a 30 m distance from the banks, and at every 5 m in the middle of the river. During early surveys the depth was determined along a steel wire. More recently, ultrasonic sonar was used, and the exact position of each depth measuring point is determined by measuring tape or (laser) theodolite. The cross-sections were mapped 6 times (1890, 1929, 1957, 1976, 1999 and 2001). We evaluated depth data using AutoDesk Land Desktop 2004 software: values were transformed into absolute height (above sea level), then the cross-sections were overlapped using the fixed survey points.

The changes in the cross-sections were evaluated using different parameters of the bankfull channel. Bankfull channel is a theoretical notion, and geometrically it was determined by the brink point between the channel and the floodplain. Normally, at a section the brink points of the two banks are at different elevations, thus always the height of the lower point was used to determine the bankfull level. Geometric cross-sectional parameters which have the most important influence on the height of floods were calculated (see Table 1). However, the effect of individual flood events in cross-sectional changes was not possible to evaluate precisely, since their length, height and discharge were very different between the surveys.

4. Results

4.1. Change in planform parameters

The most general index describing the whole study reach at the survey dates is its length (Table 2). Pre-regulation conditions are reflected by the 1842 survey, at that time 12 meanders existed along the study reach (Fig. 3) and the length of the centre-line was 37.9 km. As a result of the cutting off of three meanders the reach length decreased by 35% to 24.6 km. Following that time the length increased by 0.35 km (1.4%) until 1999; however, the rate of the increase was uneven. Until the establishment of bank stabilising structures, it reached 6 m/year, then the process slowed down and between 1976 and 1999 it was just 0.8 m/year. Length increase was expressed in continuous meander growth and the initiation of two new bends.

The lateral shift of banks has varied between 25 and 347 m since 1842 (0.16–2.4 m/year). However, this migration was uniform neither in space nor in time. As a result of 19th century cut-offs the slope was doubled and

Table 1
Description of investigated (a) planform and (b) cross-sectional parameters

	Parameter	Symbol	Units	Description
a)	Reach length	L_R	km	Total length of the centre-line.
	Width	w	m	Distance between the bank-lines, measured along sections perpendicular to the centre-line. Width measurements were made at every 100 m.
	Bend length	L	m	Length of centre-line between two inflection points.
	Chord length	H	m	Straight distance (chord) between two neighbouring inflection points.
	Amplitude	A	m	Greatest perpendicular distance between the chord and the centre-line.
	Radius of curvature	R_c	m	Radius of the largest circle, which can be fitted into the bend. The centre of the circle is at the intersection of lines perpendicular to the centre-line at the bend's inflection points.
	Meandering index	M_i	–	Ratio of amplitude and chord length. It reflects the evolutionary state of a meander, as the index grows the bend is maturing.
b)	Maximum width	w_{max}	m	Width of cross-section at bankfull level.
	Mean width	w_{mean}	m	Ratio of cross-section area and maximum depth.
	Maximum depth	d_{max}	m	Deepest point measured from bankfull level.
	Mean depth	d_{mean}	m	Arithmetical mean of all depth data.
	Cross-sectional area	A	m^2	Area of cross-sections up to bankfull level.
	Shape index	Sh	–	Ratio between maximum width and maximum depth. If the ratio is increasing by time, the cross-section tends towards a trapezoidal or U-shape, whilst if it is decreasing a rather V-shape develops.

in the lack of artificial bank protection the rate of migration between 1842 and 1890 was 0.7 m/year. The most intensive migration rate (2.4 m/year) was measured at sharp meander bends with sandy bank material. The meanders with greater radius or resistant bank material (clayey) migrated more slowly (0.4 m/year). As a result of 20th century bank protection works the shift of bank-lines became slower, even in the case of non-stabilised meanders (0.6 m/year). However, the process has continued and has not stopped even at protected meanders where concave, stabilised banks remained unchanged but convex banks have advanced towards the centre-line (at a rate of 0.4 m/year) in the form of point-bars. The length of straight sections within the study reach increased due to cut-offs (their proportion was 4% in 1842 and 24% in 1999), but since then these sections have developed without direct human impact. Bank-line migration in their case is small (0.3 m/year), as thalweg shifts are insignificant.

The mean width of the river has decreased since 1842 by 16% (Table 2); however, this change was not uniform in time. Narrowing was greatly influenced by the place and time of cut-offs (Fig. 5), as the technique of 19th century engineers was to create only a small, 8–11 m wide and 5–6 m deep pre-channel, which was adjusted to the desired size by the river itself after blocking the meander (Lászlóffy, 1982). The outcomes of this practice are reflected on the hydrological survey maps and the 8% width decrease measured between 1842 and 1890 is in connection with the existence of undeveloped artificial pre-channels. By 1929 the width of the reach was almost the same as it had been prior to the cut-offs. Later as a result of artificial bank stabilisation the channel started to narrow down intensively, and by 1957 its width was just 154 m, which means a 12% (0.7 m/year) reduction since 1929. These changes were related to the advance of convex banks towards the centre of the river. Since 1957 the width conditions can be considered stable, as by 1999 the average width decreased by only 2 m. A reach scale tightening is evident, the narrowing (180–190 m) at artificially stabilised sections is much greater than at naturally developing sections (100–140 m).

The geometric parameters of meanders changed simultaneously with the centre-line and bank-line changes. In 1842, before the cut-offs, bends were sharp (Table 2), had a short bend and chord length. By the end of the 19th century, the sharpest bend (No. 3) and those meanders which were compound (No. 11 and 12) were cut-off. The remaining bends developed naturally until 1910, when the first revetment was constructed in the study reach. Most of the revetments were completed after the 1929 survey, thus, to date the

Table 2
Mean planform parameters of the studied reach between 1842 and 1999 (see Table 1 for symbols and units)

	L_R	W_{mean}	L	H	A	R_c	M_i
1842	37.9	182	937	828	193	600	0.24
1890	24.6	169	1230	1057	247	785	0.21
1929	24.7	174	1266	1121	260	820	0.22
1957	24.9	154	1124	971	203	809	0.19
1976	24.9	156	1112	973	208	806	0.20
1999	25.0	152	1139	990	221	800	0.21

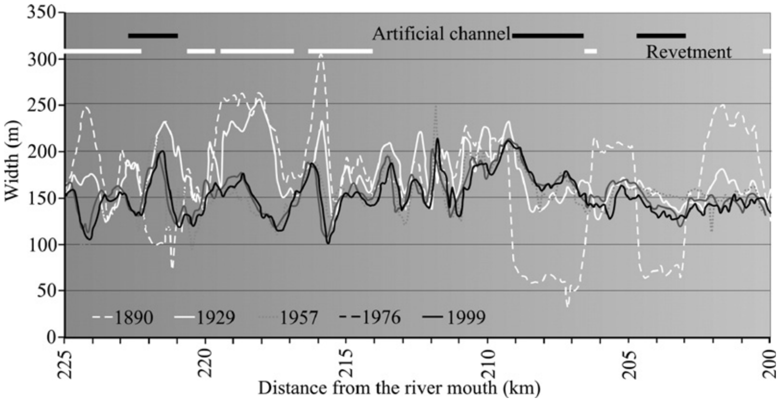

Fig. 5. Width conditions of the studied reach between 1890 and 1999, and the location of artificial channels (cut-offs) and revetments.

size of meanders has continuously increased at a 0.9–3.9 m/year rate. By 1957 the most intensive period of artificial bank stabilisation ended. Therefore, the direction and rate of changes in mean values shifted. Between 1929 and 1957 the mean chord length decreased by 13%, bend length and amplitude showed similar changes, though these processes terminated by 1999. The radius of curvatures also decreased after 1957 by 2.4% but this process has not stopped and continues at a very slow rate (0.17–0.24 m/year).

The data above represent the mean values of the whole reach. In the meantime, existing meanders can be classified into three groups, representing different rates of change: (1) meanders without artificial bank

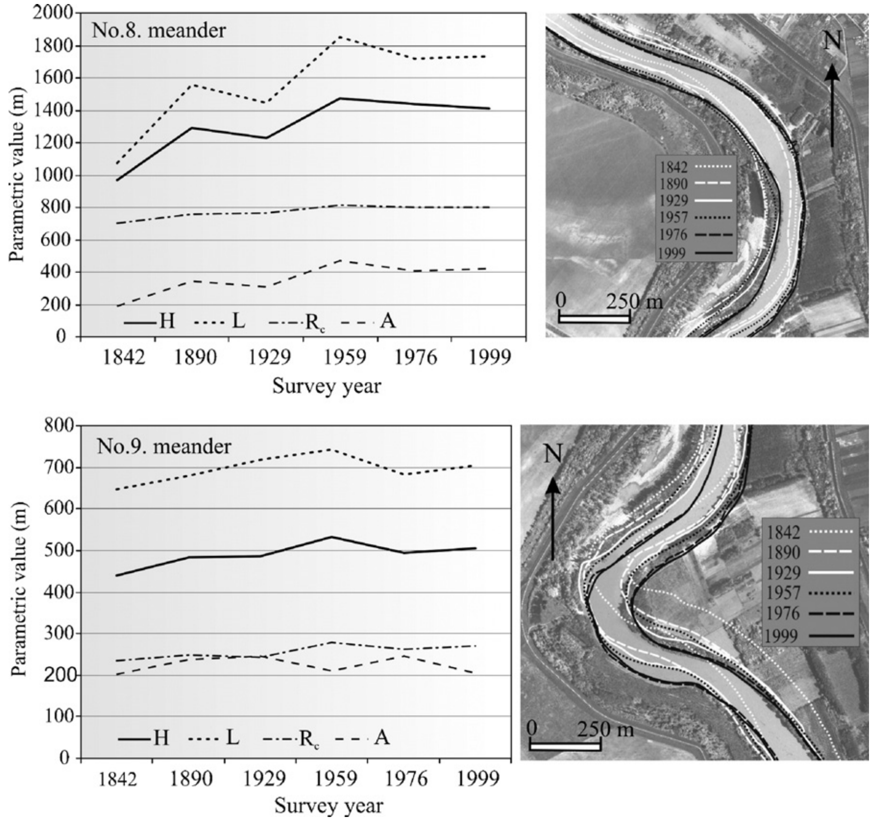

Fig. 6. Development of meanders without direct human impact (Nos. 8 and 9). Subsequent to artificial cut-offs all of the parametric values increased due to doubled slope.

Table 3
Mean planform parameters of meanders developing with or without direct human impact (see Table 1 for symbols and units)

	Meander development without direct human impact								Development under direct human impact			
	Meander				New bend				Meander			
	L	*H*	R_c	M_i	*L*	*H*	R_c	M_i	*L*	*H*	R_c	M_i
1842	860	702	467	0.33	–	–	–	–	–	–	–	–
1890	1120	887	503	0.37	–	–	–	–	1476	1268	926	0.24
1929	1018	856	503	0.27	–	–	–	–	1347	1184	823	0.28
1957	1217	964	531	0.36	1211	1113	1456	0.06	1061	919	675	0.23
1976	1153	942	523	0.32	1229	1123	1454	0.06	1053	929	671	0.24
1999	1160	926	425	0.36	1302	1188	1445	0.06	1080	952	661	0.25

protection; (2) new meanders developing on the artificially straightened sections; and (3) meanders with artificial bank protection. The development of these types will be introduced by describing some representative examples of each type:

(1) Only two meanders are developing without artificial bank protection (Nos. 8 and 9). The bank material of meander No. 8. is silt and clay, but the bank of No. 9. consists of loose sandy deposits. The planimetric values increased in both cases since 1842, but they developed in a different way (Fig. 6). The position of meander No. 8. did not change, but the meander became wider, as it is reflected by the 45–61% increase of chord length and bend length, the 13% increase in radius of curvature and the growth of the meandering index to 0.3 by 1999, which denoted a 51% increase. At the same time the parameters of meander No. 9. can be considered constant, representing only a 1–8% change. The planimetry and the meandering index (0.4) of this bend remained stable, though the meander migrated downstream by 165 m. Thus, meander No. 8. can be characterised as extending, while meander No. 9. as translating.

(2) Recently initiated bends (Nos. 4 and 11) have developed without direct human influence, though they have been formed on artificially created straight sections (Table 3). As they are fresh bends, their meandering index is very low (0.1), far less than that of the real meanders (0.2–0.4). They appear first on 1959 maps. Their parameters have slightly changed (max. 1% increase) but their development reflects continuous bend formation. Bend No. 4. is situated between two meanders with bank protections, thus the thalweg is forced towards the banks and parameters have changed 2–3 times faster than in case of bend No. 11 (Fig. 7), which is situated at the end of a long straight section, i.e. the thalweg is not forced for curvature.

(3) Most of the meanders in the study reach are affected by revetment establishment (Nos. 1, 2, 5, 6 and 7). Meander development before and after the regulation works will be introduced using the example of meander No. 6 (Fig. 8). During the period of natural development (between 1842 and 1929) the bend and the chord length increased by 43% (485 m) and 11% (308 m), respectively, as well as the radius of curvature (by 11%, 108 m). The meander grew relatively quickly in size (L increased at 4.3–6.6 m/year); however, its meandering index remained constant (0.2). Due to bank retreat the meander advanced too close to the artificial levee, therefore, in 1932 its concave bank was stabilised along a 2.35 km long section. By 1999 following the establishment of the revetment parametric values *L*, *C* and R_c decreased by 21%, 18% and 10%, respectively. The rate of these changes was the same as before human impact,

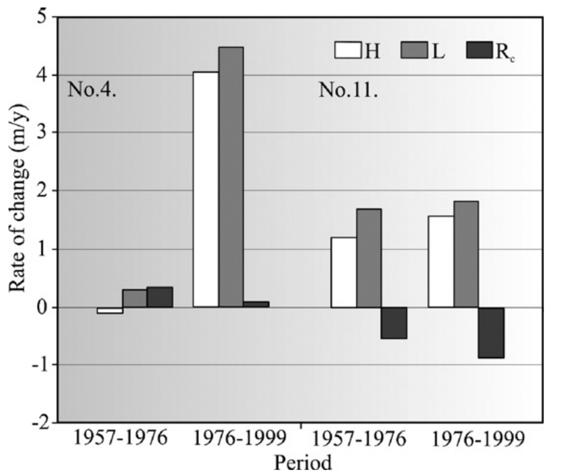

Fig. 7. Change of planform values at newly developing meanders (Nos. 4 and 11) located on artificially created sections.

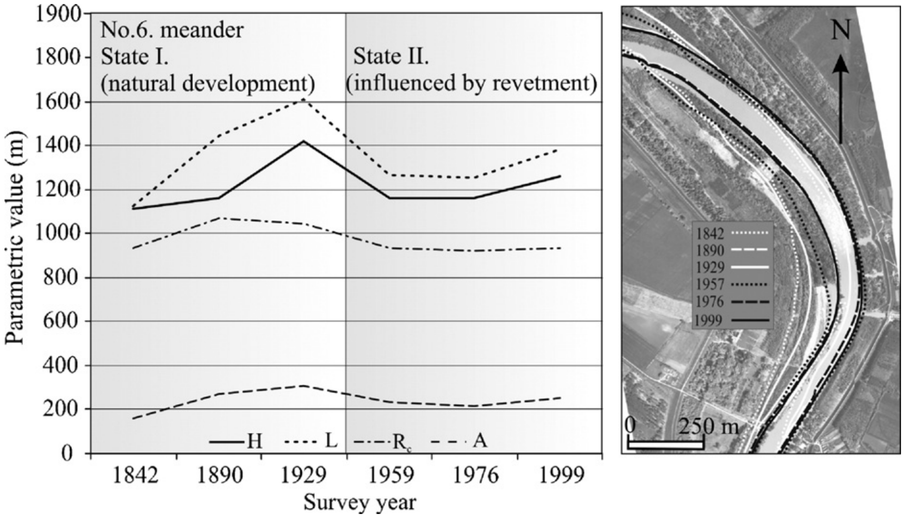

Fig. 8. Change of planform values at meander No. 6, influenced by revetment construction in 1932. Note the decrease of values, which reflects a sharper bend.

but with an opposite direction. Other stabilised meanders show very similar processes; however, there are certain differences depending on the time of revetment establishment. In the case of meanders which were fixed in the 1920–1930s, tightening seemingly came to an end by 1999, while those stabilised later (between 1940 and 1966) still represent decreasing values. The most intensively tightening meander is No. 2, where all planimetric values have decreased by 67–75% since 1890, and the meandering index has grown to 0.3 making it the sharpest bend of the reach.

4.2. Change in cross-sectional parameters

During the analysis of changes in vertical parameters cross-sections were viewed based on their exposure to human impact and their geomorphological situation, which naturally defines flow conditions, the location of the thalweg and thus the rate and form of channel development (Fig. 3). Based on these, cross-sections were classified into the following groups: (1) cross-sections without direct human impact, in straight reaches (1a) or in meanders (1b); and (2) cross-sections affected by artificial cut-offs (straight reaches, 2a) and by revetment constructions (meanders, 2b).

(1a) At the study reach altogether eight such cross-sections can be found (Nos. 214/1, 217, 217/1, 220, 220/1, 221/2, 222 and 222/1). In 1890 the greatest width of a single cross-section was almost 250 m (No. 217), but by nowadays it has decreased by 10% (Fig. 9). The mean width decrease has been even greater, being 15–19% on average (Table 4), but at some cross-sections reaching 35%. The greatest depth has also changed considerably, and increased by 3–4.6 m since 1890 (45% greater values at some cross-sections). This suggests an intensive incision. Altogether, the simultaneous narrowing and deepening have

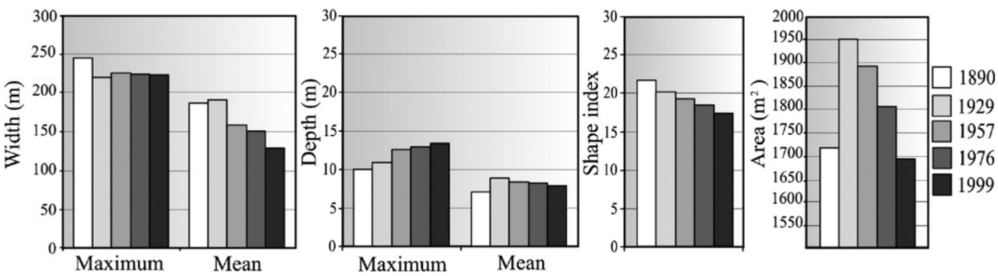

Fig. 9. Cross-sectional changes of an originally straight reach (No. 217). The cross-section became narrower but deeper, thus only minor changes occurred in its area during the last 100 years.

Table 4
Cross-sectional values of sections influenced by natural processes or human activity (see Table 1 for symbols and units)

	Without direct human impact												Under direct human impact					
	Meanders						Inflection points						Meanders					
	w_{max}	w_{mean}	d_{max}	d_{mean}	Sh	A	w_{max}	w_{mean}	d_{max}	d_{mean}	Sh	A	w_{max}	w_{mean}	d_{max}	d_{mean}	Sh	A
1890	115	110	11.0	9.8	11.2	1741	218	196	7.0	6.8	25.2	1674	163	124	7.5	6.7	18.3	1474
1929	125	103	11.1	9.1	11.3	1667	191	164	10.0	9.1	16.8	1752	115	100	9.8	8.5	11.9	1566
1957	110	107	9.9	9.2	11.6	1568	168	145	9.5	9.0	14.7	1763	100	97	10.1	9.1	10.7	1360
1976	133	119	9.9	9.8	12.1	1651	174	144	10.8	9.4	14.4	1743	114	102	11.0	10.1	10.3	1370
1999	125	111	10.6	10.4	10.7	1767	173	140	10.0	8.9	16.3	1710	123	103	11.1	9.8	10.7	1321

caused only minor cross-sectional area decrease (3.5% in average). These changes on the other hand have significantly affected the shape of the channel. Values of shape indices have decreased by 34% from 21.0–28.0 to 12.9–20.4, indicating the deformation of the trapezoidal channel shape.

(1b) Meander development at the studied reach is greatly influenced by revetment construction, therefore, only 3 cross-sections are located at "human impact-free" meander sections (Nos. 213, 216 and 216/1). The best example is cross-section No. 216 (Fig. 10), where the greatest width has decreased by 16.2% since 1890 as the convex bank has migrated 57 m towards the concave bank. At the same time, the mean width has increased by 19.7%. The maximum depth has changed slightly, becoming deeper only by 0.26 m, though the mean depth has become greater by 22.1%. The increasing mean width and depth values denote a continuously deforming cross-section, transforming from V-shape to U-shape, which is also reflected by the 18% decrease of the shape index. However, these changes have not affected the cross-sectional area considerably, which has become only slightly (2.3%) greater.

(2a) Cross-sections of the straight reaches created by cut-offs reflect a characteristic form of development (Nos. 212/1, 218, 219, 221 and 221/1). The most typical example is cross-section No. 218 (Fig. 11). In its 1929 state it represented a wide and incised channel. Incision terminated by 1957 and accumulation took place in the channel, making it 14.3% shallower. Only record floods between 1998 and 2001 caused channel deepening again. The width of

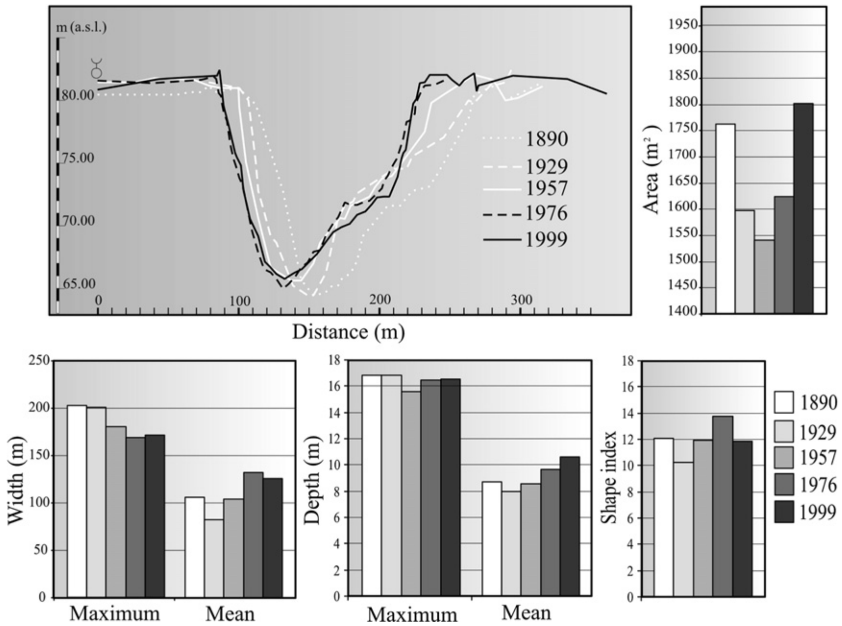

Fig. 10. Cross-sectional changes of a non-stabilised meander (No. 216). Lateral migration was intensive; however, cross-sectional parameters varied only slightly.

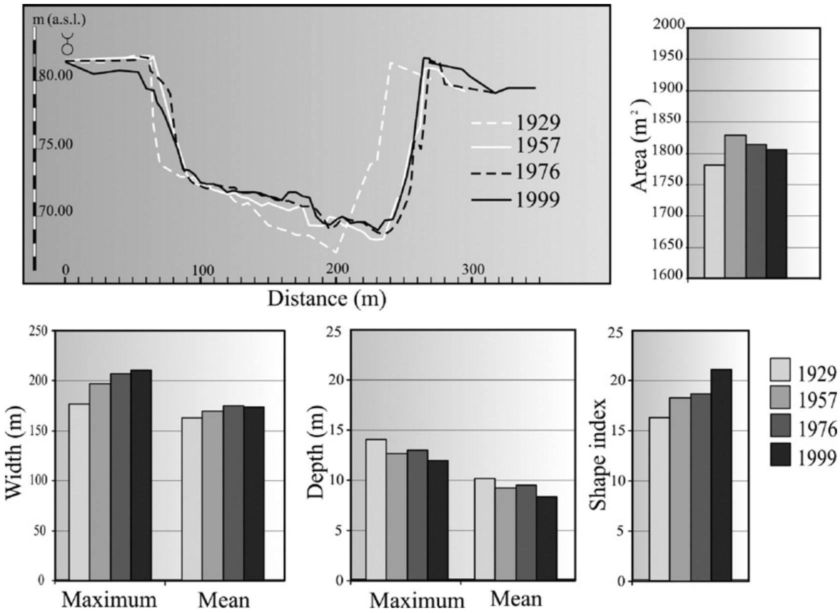

Fig. 11. Cross-sectional changes of an artificial, straight, inflection section (No. 218). The first survey was made 60 years after the cut-off, therefore, the channel parameters and their changes are very similar to human impact-free sections.

the cross-section has been continuously increasing (since 1957 by 7%), though at a lower rate than before. The area of the cross-section has changed only slightly, as it was 1827 m^2 and 1804 m^2 in 1957 and 2000, respectively, which equates to only a 1.2% area decrease.

(2b) In the 20th century river management concentrated on meanders in order to stop bank retreat. Works resulted in permanent concave banks. Altogether 8 cross-sections are located at stabilised meanders (Nos. 211/1–2, 212, 213/1, 214, 215 and 215/1). The evolution of cross-section No. 214 (Fig. 12) reflects their common characteristics. Following the establishment of revetments (1932) the greatest width of the cross-section has decreased by 45.3% up till now. Due to point-bar formation, the mean width has also decreased, but only by 29.9%. As the bank protection disabled lateral erosion, intensive incision started, which is reflected by the 3.2 m (30.9%) increase of the maximum depth. In the meantime the deepest point (thalweg) gradually moved closer to the protected bank: in 1890 and 1957 it was 27.5 m and 17.2 m away from the concave bank, respectively. However, due to the constant tightening of the channel between these dates, if the thalweg's distance from both the convex and concave bank is considered, its relative position remained constant. At both dates the ratio of the two distances was 1:3.6. Nevertheless, during the last 50 years the thalweg certainly has got as close to the protected bank as possible, because its absolute position has not changed recently. On the other hand, by 2001 the cross-section has become even narrower, and the ratio of its distance from the concave and the convex bank has changed to 1:3.1. This process can result in a truly deformed channel shape and a decreased cross-sectional area. The most distorted shapes were observed at this group of cross-sections. The deformation is well represented by the change of the cross-sectional shape index as well. This has decreased from 1890 (13.9–24.5) to 1999 (7.7–14.7) by approximately 40%. The decrease in cross-sectional area is also significant, and it is at least 25% in the case of meander cross-sections under human impact.

4.3. Changes in flood conductivity due to the altered parameters of cross-sections

Cross-sectional area is fundamental in determining the water stage produced by a specified amount of water passing through the given cross-section. This is very important from the point of view of floods because any change in the area will influence the maximum stage at peak discharge. Flood conductivity was defined as the discharge associated with bankfull water level and was calculated for each cross-section at all survey dates by applying mean velocity and mean slope.

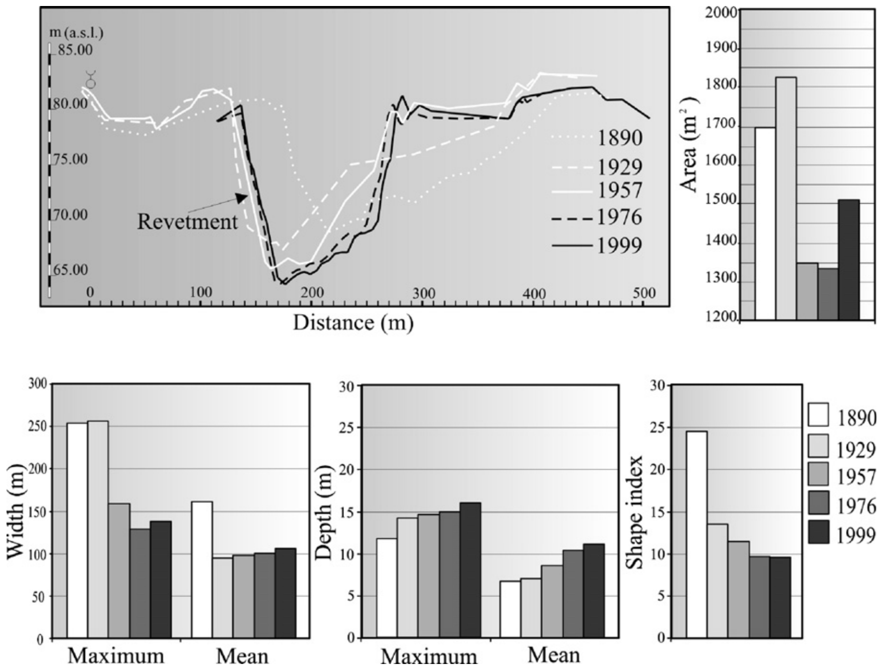

Fig. 12. Cross-sectional changes of a meander (No. 214), where the artificial bank stabilisation was created in 1932. After the revetment construction the channel form became deformed and the flood conductivity decreased considerably.

Until 1929 the area and thus flood conductivity of cross-sections were mostly influenced by cut-offs, which caused the enlargement of the channel (Fig. 13). The flood conductivity became better at straight sections by 38% and at meanders by 8%. By 1929 conditions became uniform along the whole reach, and the calculated conductivity value was 1100–1200 m^3/s.

Flood conductivity changes between 1929 and 2001 were due to the response of the river to artificial bank stabilisation. The average flood conductivity of cross-sections without bank protection changed slightly (1.1%), as it decreased by 4.3% at straight sections but increased by 12.9% at the two freely developing meanders. At the same time the flood conductivity of stabilised cross-sections became much worse, and decreased by 15.6% on average, with a 24.9% maximum decrease. In other words the calculated discharge became 171 m^3/s lower on average, and 318 m^3/s lower at the most tightened cross-section. As a result of the divergent development of protected and non-protected sections, flood conductivity conditions became highly uneven between 1929 and 2001. In the case of revetment free cross-sections it grew slightly to 1160–1240 m^3/s, but decreased to 850–950 m^3/s at stabilised ones.

The change in flood conductivity shows a temporal pattern as well. Its deterioration is almost continuous at protected sections; however, some variation can still be detected. This is illustrated best by cross-section No. 214. Here the bank was protected in 1932, and up to this date its conductivity increased by 7.5%; though, subsequent to bank stabilisation it decreased by 26% till 1999. Perhaps by this time the channel got close to the minimum sustainable value of flood conductivity, and that is how the record floods of 1999 and 2001 resulted again the increase of the parameter. This signifies the end of unidirectional changes and the development of an equilibrium state.

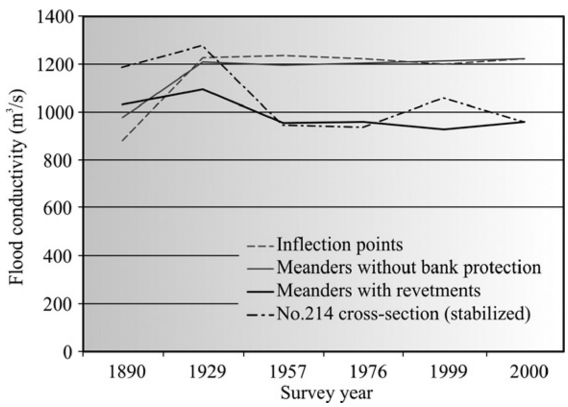

Fig. 13. Mean flood conductivity changes of cross-sections influenced by revetments and of cross-sections not affected by direct human impact at inflection points or in free meanders. Temporal changes of flood-conductivity on the example of cross-section No. 214.

Similar processes can be recognised at many other cross-sections, suggesting that the self adjustment of the fluvial system to the effects of revetment construction took approximately 60–70 years.

5. Discussion

Spatial and temporal changes in planform and cross-sectional values are mainly determined by the geomorphological position of a section and the local regulation works affecting it. The rate of these changes might also be influenced by the material of the river bank and the riparian vegetation colonising the banks.

The analysis of the planimetry and the cross-sectional parameters of sections which have been developing without direct human impact implies that they are in a dynamic equilibrium. Their parameters have changed only slightly during the last 150 years (Fig. 14) and correspond well with parameters of meanders under natural evolution, reported for example by Hickin (1974). If a geometrical parameter changed, then its complementary value was also adjusted but in an opposite direction (e.g. mean depth versus mean width). As the result of this process the cross-sectional area hardly changed (± 1–3%) and the flood conductivity of the channel could be permanently sustained by the river. However, the shape of these cross-sections altered considerably and the original trapezoidal shape (mean Sh = 25.2) was replaced by a more U-like shape (mean Sh = 16.5) at inflections. In the meantime, neighbouring cross-sections have started to represent more and more similar shapes. The altered but more uniform shape conditions suggest that these seemingly "human impact-free" reaches were also affected by regulation works, though, just indirectly. Gilvear (1999) has detected similar translational processes. Depth changed due to cut-offs increasing slope, and channel deformations have probably been induced by stabilised upstream sections, which determine the course of the thalweg. At the same time the initiation of new bends and the growth of free meanders indicate that the natural process of channel development continues.

The parameters of sections influenced by direct human activity have changed considerably. As a result of cut-offs, long straight reaches evolved. Their distinct development lasted until 1929–1957, as by this time their width conditions and cross-sectional parameters became similar to those of "human influence-free" sections. This process is very similar to the development of natural cut-offs, reported for example by Hooke (1995). Since then, affected and non-affected straight sections show a similar evolution, suggesting that these sections have adapted to the channel forming discharge and the hydrology of the river. The rate of change in the case of meanders influenced by bank protection suggests that they have reached a disequilibrium

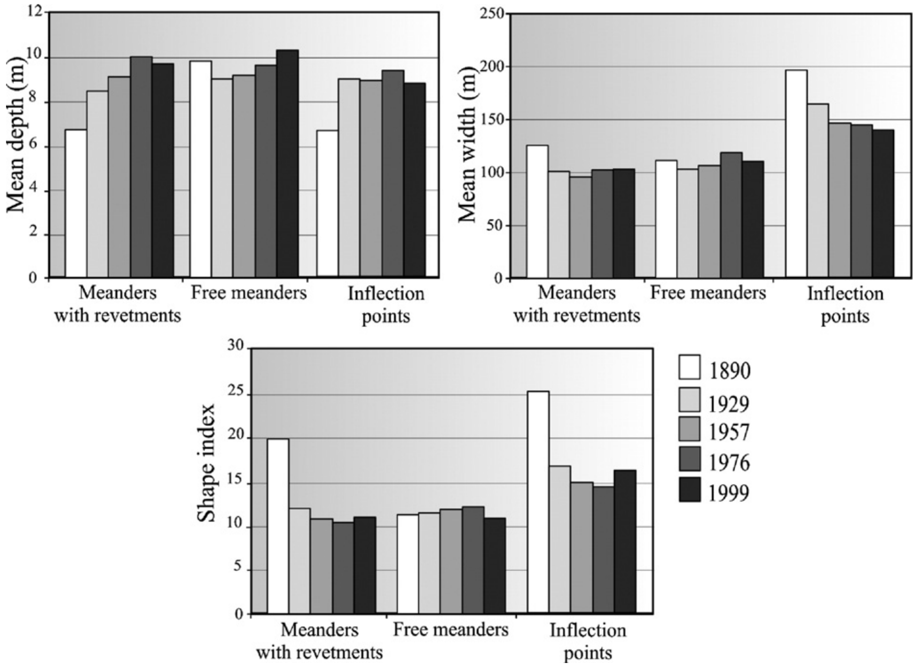

Fig. 14. Comparison of mean depth, mean width and shape indices of meanders and inflection points. Note the complementary characteristics of the values and the intensive incision of the river bed.

state due to the construction of revetments. The planform of bends has become sharper and narrower, and cross-sections representing them have turned to be tighter. As the retreat of the concave bank was stopped but point-bar formation on the convex bank continued, the thalweg has been squeezed to the concave bank. The deformed cross-sectional shape (mean shape index decreased from 18.3 to 10.7) reflects intensive incision. Despite the incision, the cross-sectional area decreased by 4–19%, resulting in a fall in flood conductivity. In the most outstanding case the area calculated for bankfull stage has decreased from 1004 m^3/s to 868 m^3/s during the past 110 years. Considering each cross-section of human influenced meander type, flood conductivity has decreased by 6.2–13.5% since 1890. A similar phenomenon was found on the Missouri River by Pinter and Heine (2005), who also pointed out the resultant increase in flood stages. As the tightening process has probably reached the hydrological limits of the Tisza River, by the last survey greater flood conductivity was detected at some cross-sections (e.g. 214, 215 and 215/1). An observed process, which has increased cross-sectional area recently, is when freshly deposited material from the banks and point-bars slides into the channel especially in case of rapid water level drop.

The decreased flood conductivity of bank protected sections has even greater importance, if it is considered that 37% of the 25 km long study reach is directly affected by bank protection. Taking into account that protected sections are alternating with non-protected ones, they should have an overall influence on the whole reach by determining the line of the thalweg and sediment transport processes. The decreasing flood conductivity of the channel necessarily increases peak water stages, and can be one factor behind the occurrence of record floods recently. The problem is especially severe, if we consider that 75–80% of the flood discharge used to be drained within the channel, and the floodplain has only a subordinate role in flood passage (Szlávik, 2000).

The temporal variation of cross-sectional parameters refers to the length of geomorphic response of the river to cut-offs or the establishment of revetments. Cross-sections on straight, artificial sections have reached an equilibrium in 60–70 years. During this period their geometrical parameters became very similar to those of unaffected straight (inflection) reaches (differences are 2.4–6.0%). The parameters of those cross-sections which were affected by bank stabilisation changed radically following the intervention. However, the tendency of their development changed between 1999 and 2001. This suggests that the period of channel tightening was 60–70 years long and might be followed by widening, a process which is highly limited due to stabilisation works.

6. Conclusions

Based on the evaluation of horizontal and vertical parameters, four stages of channel development can be distinguished along the study reach since 1842. The first is the period of natural development prior to extensive river training works. This stage is represented by only one survey (1842), which reflects a highly sinuous river, characterised by sharp bends and a wide channel.

The second development stage (1890–1929 surveys) was determined by the first phase of river regulation works. The 1890 survey was made right after the meanders were cut-off, while the 1929 survey was just before the start of artificial bank stabilisation works. Therefore, these helped in the study of the river's natural response to shortening. As a result of cut-offs, the length considerably decreased and due to the existence of artificially created "pre-channels" the average width of the reach also decreased. However, by 1929 all parameters reached almost the same value as before (just a slight incision and cross-sectional area increase was detected).

The third stage of development (between 1957 and 1976 or in some cases until 2001) represents the period of revetment constructions and responses to it. As more than one third of the reach length is artificially stabilised, this type of intervention had a great impact on the channel. The total length of the centre-line increased, whilst lateral migration was disabled, thus the meanders became sharper. Furthermore, point-bar formation on the convex banks continued. Therefore, the channel became narrower, cross-sectional area decreased, flood conductivity conditions became worse, thus flood hazard increased. These changes influenced the development of non-stabilised sections as well. Therefore, the way of their development has also changed.

The fourth stage can be identified only at those reaches where revetment constructions took place at least 60–70 years ago. By this stage the meanders have grown wider, as the narrowing cannot be sustained due to the given hydrological conditions of the river. The width of the channel and the area of cross-sections are increasing due to bank collapse on the convex, non-stabilised bank. Although this process is localised, it plays an important role in the improvement of flood conductivity.

Acknowledgements

The investigation was sponsored by the Hungarian Research Foundation (OTKA 037414 and 62200). The cross-sectional data were measured by the Directorate for Environmental Protection and Water Management of Lower Tisza District (ATIKÖVIZIG). We are very grateful for the two anonymous reviewers for their useful advice. We also thank Vary Thorndycraft for commenting and handling our manuscript, and Colin Klotzbach for improving the English of the text.

References

Antonelli, C., Provansal, M., Vella, C., 2004. Recent morphological channel changes in a deltaic environment. The case of the Rhone River, France. Geomorphology 57, 385–402.

Arnaud-Fassetta, G., 2003. River channel changes in the Rhone Delta (France) since the end of the Little Ice Age: geomorphological adjustment to hydroclimatic change and natural resource management. Catena 51, 141–172.

Biedenharn, D.S., Thorne, C.R., Watson, C.C., 2000. Recent morphological evolution of the Lower Mississippi River. Geomorphology 34, 227–249.

Bridge, J.S., 2003. Rivers and Floodplains. Forms, Processes, and Sedimentary Record. Blackwell, Oxford.

Brookes, A., 1985. River channelization: traditional engineering methods, physical consequences and alternative practices. Progress in Physical Geography 9, 44–73.

Brookes, A., 1997. River dynamics and channel maintenance. In: Thorne, C.R., Hey, R.D., Newson, M.D. (Eds.), Applied Fluvial Geomorphology for River Engineering and Management. Wiley, Chichester, pp. 293–309.

Brooks, G.R., 2003. Holocene lateral channel migration and incision of the Red River, Manitoba, Canada. Geomorphology 54, 197–215.

Chin, A., Gregory, K.J., 2005. Managing urban river channel adjustments. Geomorphology 69, 28–45.

Downs, P.W., Gregory, K.J., 2004. River Channel Management. Towards Sustainable Catchment Hydrosystems. Arnold, London.

Dunka, S., Fejér, L., Vágás, I., 1996. A verítékes honfoglalás—A Tisza szabályozás története (The New Concquest—History Of The Regulation of Tisza River). Vízügyi Múzeum és Levéltár, Budapest.

Gilvear, D.J., 1999. Fluvial geomorphology and river engineering: future roles utilizing a fluvial hydrosystems framework. Geomorphology 31, 229–245.

Hey, R.D., 1997. River engineering and management in the 21st century. In: Thorne, C.R., Hey, R.D., Newson, M.D. (Eds.), Applied Fluvial Geomorphology for River Engineering and Management. Wiley, Chichester, pp. 3–13.

Hickin, E.J., 1974. The development of river meanders in natural river channels. American Journal of Science 274, 414–442.

Hooke, J.M., 1995. River channel adjustment to meander cutoffs on the River Bollin and River Dane, northwest England. Geomorphology 14, 235–253.

Ihrig, D., 1973. A magyar vízszabályozás története (History of the Hungarian River Regulations). Akadémiai Kiadó, Budapest.

Károlyi, Z., 1960. A Tisza mederváltozásai - különös tekintettel az árvízvédelemre (River-Bed Changes of the Tisza River, with Special Attention to Flood Protection). VITUKI, Budapest.

Kiss, T., Sipos, Gy., Fiala, K., Oroszi, V., 2004. Different geomorphic and hydrological response to river regulation—comparative study on Maros and Tisza Rivers, Hungary. Joint International Geomorphology Conference, Glasgow, Abstract, vol. 20.

Knighton, D., 1998. Fluvial Forms and Processes. A New Perspective. Arnold, London.

Kondolf, G.M., Piégay, H., Landon, N., 2002. Channel response to increased and decreased bedload supply from land use change: contrasts between two catchments. Geomorphology 45, 35–51.

Laczay, I.A., 1977. Channel pattern changes of Hungarian rivers: the example of the Hernád River. In: Gregory, K.J. (Ed.), River Channel Changes. Wiley, Chichester, pp. 185–192.

Lászlóffy, W., 1982. A Tisza (The Tisza River). Akadémiai Kiadó, Budapest.

Liébault, F., Piégay, H., 2001. Assessment of channel changes due to long-term bedload supply decrease, Roubion River, France. Geomorphology 36, 167–186.

Newson, M.D., 1997. Land, Water and Management. Sustainable Management of River Basin Systems. Routledge, London.

Newson, M.D., Hey, R.D., Bathurst, J.C., Brookes, A., Carling, P.A., Petts, G.E., Sear, D.A., 1997. Case studies in the application of geomorphology to river management. In: Thorne, C.R., Hey, R.D., Newson, M.D. (Eds.), Applied Fluvial Geomorphology for River Engineering and Management. Wiley, Chichester, pp. 311–365.

Pinter, A., Heine, R.A., 2005. Hydrodynamic and morphodynamic response to river engineering documented by fixed-discharge analysis, Lower Missouri River, USA. Journal of Hydrology 302, 70–91.

Richard, G.A., Julien, P.Y., Baird, D.C., 2005. Statistical analysis of lateral migration of the Rio Grande, New Mexico. Geomorphology 71, 139–155.

Rinaldi, M., 2003. Recent channel adjustments in alluvial rivers of Tuscany, Central Italy. Earth Surface Processes and Landforms 28, 587–608.

Rinaldi, M., Simon, A., 1998. Bed-level adjustments in the Arno River, Central Italy. Geomorphology 22, 57–71.

Schumm, S.A., 1977. The Fluvial System. Wiley, New York.

Smith, L.M., Winkley, B.R., 1996. The response of the Lower Mississippi River to river engineering. Engineering Geology 45, 433–455.

Stover, S.C., Montgomery, D.R., 2001. Channel change and flooding, Skokomish River, Washington. Journal of Hydrology 243, 272–286.

Surian, A., 1999. Channel changes due to river ragulation: the case of the Piave River, Italy. Earth Surface Processes Landforms 24, 1135–1151.

Surian, N., Rinaldi, M., 2003. Morphological response to river engineering and management in alluvial channels in Italy. Geomorphology 50, 307–326.

Szlávik, L., 2000. Az Alföld árvízi veszélyeztetettsége (Flood hazard of the Hungarian Great Plain). In: Pálfai, I. (Ed.), Role and Importance of Waters on the Hungarian Great Plain. Nagyalföld Alapítvány, Békéscsaba, pp. 64–85.

Tiegs, S.D., Pohl, M., 2005. Planform channel dynamics of the lower Colorado River: 1976–2000. Geomorphology 69, 14–27.

Uribelarrea, D., Perez-Gonzaleza, A., Benito, G., 2003. Channel changes in the Jarama and Tagus rivers (central Spain) over the past 500 years. Quaternary Science Reviews 22, 2209–2221.

Xu, J., 2002. River sedimentation and channel adjustment of the lower Yellow River as influenced by low discharges and seasonal channel dry-ups. Geomorphology 43, 151–164.

Yates, R., Waldron, B., van Arsdale, R., 2003. Urban effects on flood plain natural hazards: Wolf River, Tennessee, USA. Engineering Geology 70, 1–15.