GEOMORPHOLOGICAL PROCESSES ALONG THE LOWLAND SECTIONS OF THE MAROS/MUREŞ AND KÖRÖS/CRIŞ RIVERS

György Sipos, Tímea Kiss, Viktor Oroszi

Introduction

The historical and economic importance of the Maros/Mureş and Körös/Criş Rivers is unquestionable. For a long time they had provided a direct link between Transylvania and the Great Hungarian Plain. This connection was however broken during the most of the 20th century, but can be and should be revitalized by mutual Romanian-Hungarian efforts.

Due to frequent and highly destructive floodings and intensive channel formation both rivers were regulated in order to protect settlements and agriculture. Regulation works started gradually in the mid 19th century according to the most up-to-date river management schemes of the time, but the great scale measures and aims remained unfinished due to historical and political reasons. Nevertheless, as a consequence of channel regulation, the alienation of settlements and people from the river unstoppably began, and thus the common knowledge about their behaviour and the processes forming their channel become relevant for the public only during great floods or disastrous events.

Meanwhile, as a consequence of continuous measurements since the end of the 19th c. the hydrology of Hungarian rivers is fairly well known. Numerous authors have studied the hydrological characteristics of the floods occurring on the Tisza and Maros/Mureş Rivers (Bogdánfy 1906, Károlyi 1960a, Bezdán 1998, 1999, Vágás 2000, 2001, Illés *et al.* 2003). As the water level of peak stages shows an increasing tendency on the Tisza, recently the development and reasons of extreme floods, affected greatly by the tributaries, have drawn the attention of researchers. Several studies have been written on the climatic and hydrological causes, and the changes experienced on the catchments (Nováky 2000, Rakonczai 2000, Somogyi 2000, Bodolainé Jakus 2003, Gönczy *et al.* 2004), while other studies have emphasized the significance of floodplain aggradation (Nagy *et al.* 2001, Gábris *et al.* 2002, Kiss *et al.* 2002, Sándor and Kiss 2006). The morphological processes acting in the river bed during floods have rarely been analysed even though these can also influence stages experienced at a given hydrological situation (Starosolszky 1956, Károlyi 1960ab, Sipos *et al.* 2007).

In the present study we aim to provide an overview of the main morphological and hydrological features of both rivers. However, in terms of morphological change River Maros/Mureş will be considered, as it is more actively responding to anthropogenic effects and interventions. The key processes that will be analysed are contemporary riverbed formation, channel pattern change and floodplain sedimentation.

The Maros/Mureş catchment

In terms of its shape the catchment of the Maros/Mureş River can be divided into two parts. The upstream part is square shape (approximately 250×100 km), while the downstream 200 km section with an E-W axis, starting from Deva, has only a width of 20-40 km (Laczay 1975). In all the shape of the catchment is elongated (Fig 1.). This feature slightly tempers the ferocity of floods developing on the mountainous sections as the flood wave flattens on the elongated lowland section (Boga and Nováky 1986). The Transylvanian catchment has a significantly higher density of valleys than that of the lowland parts, the Maros/Mureş river system is built up by 430 permanent waterflows (Laczay 1975), the registered total length of which is 11 189 km (Andó 1993, 2002).

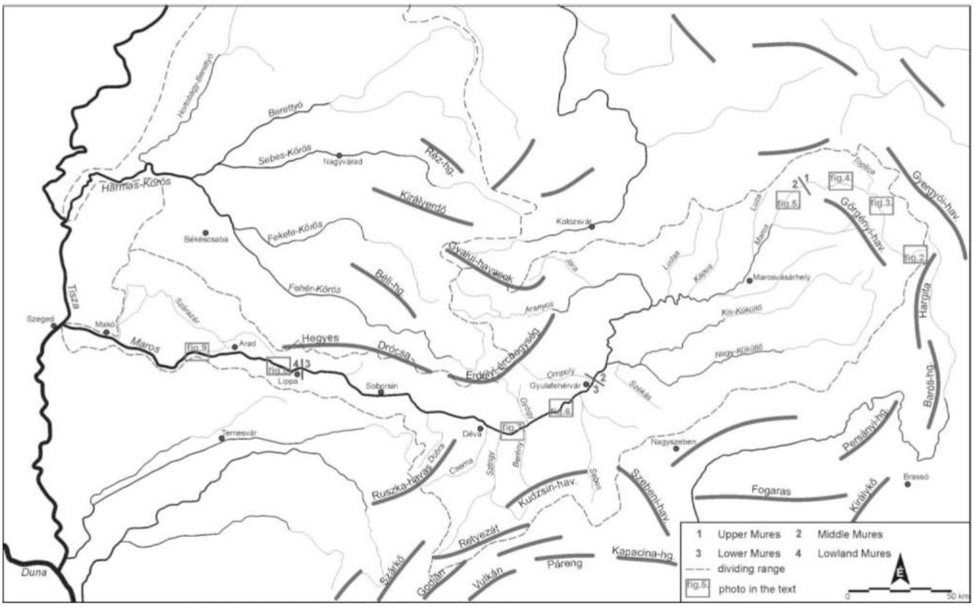

Figure 1. The catchment of the Maros/Mureş and Körös/Criş river systems by unifying several maps. Numbered rectangles mark the place of photographs shown taken on different sections of the Maros/Mureş River.

Figure 2. The so called "touristic" source at Izvoru Mureşului (Marosfő) (850 m), and the "real" source 4-5 km to the N (1350 m).

Figure 3. The Upper Maros/Mureş close to Toplita (Maroshévíz). It passes the Depresiunea Giurgeului (Gyergyói-medence) with mild bends (flow from left to right)

Figure 4. Channel with gravel bars in the Topita-Deda (Maroshévíz–Déda) gorge (flow from left to right).

Figure 5. Braided pattern Middle Maros/Mureş leaving the gorge (flow towards the front).

The highes point of the catchment is 2511 m asl. high Retezat (Retyezát), while the lowest point is at 81 m asl. at the outlet of the river (Boga and Nováky 1986). The source of the river is located on the northern slopes of the Hargitha Mountains at Izvorul Mureşului (Marosfő) (Fig. 2). From the source to the outlet the river can be divided into four different reaches on the basis of slope conditions. The almost 110 km Upper Maros/Mureş passes through the Gyergyó Basin and in between the Giurgeului and Harghita Mountains (Gyergyói-havasok, Hargita) it reaches to the Toplita-Deda (Maroshévíz-Déda) gorge (Fig. 3-4.). The slope of this reach is very high, in average 369 cm/km (Török 1977). The next reach is the Middle Maros/Mureş, which has a length of 266 km. It passes the Câmpia Transilvaniei (Erdélyi Mezőség), the forelands of the Gurghiu Mountains (Görgényi-havasok) Târnava Hills (Küküllő hátság). Here the river flows in a valley as wide as 15 km at certain sections and built up by sedimentary rocks. Its slope is 50 cm/km on this reach. The 225 km long Lower Maros/Mureş is stretching between Alba Julia (Gyulafehérvár) and Lipova (Lippa) along a tectonic fult line separating the Apuseni Mountains (Erdélyi-érchegység) and the Southern Carpathians (Fig. 1). Its slope decreases to 30 cm/km. The Lowland

Maros/Mureş reaches from Lipova (Lippa) to the outlet, has a length of 162 km and a slope of 20-10 cm/km (Fig. 1).

Figure 6. Meandering section of the Lower Maros/Mureş at Alba Julia (Gyulafehérvár) (flow from left to right).

Figure 7. The river at Folt. At certain sections braided pattern with bars and islands appears again (flow from left to right).

Figure 8. The Lowland Maros/Mureş at Paulis (Ópálos). The river actively forms its channel which is proved by gravel bars and bank erosion (flow towards the front).

Figure 9. Widened channel of the river at Pecica (Pécska) with a gravely sand bar, and small in-channel islands.

The Körös/Criş catchment

The catchment of the Körös/Criş river system has a fan shape,. The area of the catchment is 27 537 km2, and thus it is the second largest tributary of River Tisza. As a consequence of the shape of the catchment flood waves arriving from the different sub-catchments reach the lowland almost simultaneously, and thus very severe floods can develop (Fig. 1). The Körös/Criş river system is composed of five main tributaries: Fehér-Körös/Crişul Alb (L=236 km, A=4275 km^2), Fekete-Körös/ Crişul Negru (L=168 km, A=4645 km^2), Sebes-Körös/ Crişul Repede (L=209 km, A=9309 km^2), Berettyó/ Beretău (L=204 km, A=6095 km^2) and Hortobágy-Berettyó (L=163 km, A=5776 km^2) (Andó 2002). The Körös/Criş system has its sources in the Bihor Mountains (Bihar) and the Apuseni Mountains

(Erdélyi-érchegység). The source of the Fekete-Körös/Crişul Negru is at 1460 m asl, the source of the Fehér-Körös/Crişul Alb is at 980 m asl. The slope of valleys in the upland catement can reach 100-500 cm/km, while it is well below 20 cm/km, at the Hármas-Körös it is only a few cm/km.

Hydrology of the Maros/Mureş River

The Maros/Mureş and its tributaries are mostly fed by overland flow. Floods rise quickly, and last for only a short time, because of the geology (overwhelmingly crystalline rocks) of the catchment area and the high proportion of very steep slopes. Two floods are common during the year; the first is due to snowmelt in early spring, the second is caused by early summer rainfall. The rest of the year is characterized by low stages. By analysing the annual change of monthly mean discharges Boga and Nováky (1986) has shown that the maximum water delivery is usually at April (15 % of the total amount of water). Others also emphasize the importance of spring floods and point out that June rainfall may cause only a secondary flood wave (Csoma 1975). The minimum water delivery is at October, equalling 4.5 % of the total mean annual discharge (Boga and Nováky 1986).

Table 1. Characteristic stage, discharge and sediment load values at the Makó (Maros/Mureş) gauge stations*, Maximum and minimum discharges at Gyoma (Körös/Criş)

		Maros/Mureş (Makó)	Körös/Criş (Gyoma)
Stage (cm)	maximum (1976-2000)	624	928
	mean (1976-2000)	36	
	minimum (1976-2000)	-104	-116
	bankfull	310	
Discharge (m^3/s)	maximum (1976-2000)	2 420	1 684
	mean (1976-2000)	161	
	minimum (1976-2000)	34	4.5
	bankfull	850	
Sediment load (t/y)	suspended load	8 300 000	
	bed load	28 000	
Specific sediment load** (t/m^3)	suspended load	1,6x1012	
	bed load	5,5x109	

* source: http://www.vizadat.hu and Bogárdi 1955, 1971)

** values of sediment load (t/y), divided by the mean discharge (m3/s)

At present, the slope of the studied lowland reach is 0.0028 while the mean velocity during mean-discharges is 0.6 m/s. The greatest flood on record was in 1970 with a peak discharge (Q_{max}) of 2420 m^3/s and a water level (H_{max}) of 624 cm. Nevertheless, the mean discharge (Q_m) is just 161 m^3/s, while the minimum recorded discharge (Q_{min}) is 34 m^3/s (H_{min}= -104 cm, 2003). Thus, the ratio between maximum and minimum values is 70 (Table 1).

Compared to other rivers of the region the Maros/Mureş transports a huge amount of sediment. The mean discharge of suspended load (0.05-0.02 mm) is 263 kg/s (8.300.000 t/y), but it may increase up to 10 kg/s during floods. The volume of the bed load (0.3-0.4 mm) is 0,9 kg/m^3 (28.000 t/y) (Bogárdi, 1974). The amount of the annually transported suspended load and bed load matches to similar values of the Tisza at Tápé and the Danube at Nagymaros, respectively. This fact also underlines the high sediment transport rate of the Maros/Mureş River.

Hydrology of the Körös/Criş River

Prior to the regulation works the hydrology of the river was determined natural factors, such as climate, geology and shape of the catchment. Human interventions however resulted an almost completely regulated river, with artificial channels and reservoirs, thus the river has lost its natural character. Floods however rise quickly due to the relief and shape of the catchment, and last for a long time on the lower reaches due to the impounding effect of the Tisza (Szlávik 1981). The development of severe floods is also facilitated by the fact that temporal differences might be significant in rainfall quantity and intensity, and the 25-30 % of the annual rainfall may occur within only 2-3 weeks (Szlávik 1981, Andó 2002). Flood waves may arrive as fast as 24-36 hours to the lowland sections, which makes flood prevention a difficult task.

As a consequence of the above the hydrograph of the Criş system is highly fluctuating. Similarly to the Maros/Mureş system floods related to snow melt are the most significant, and there can also be secondary early summer floods related to rainfall. Besides, the role of Mediterranean airmasses durin autumn rainfall and floods is also emphasised by some authors (Andó 2002). The highest water level was measured at Gyomandrő in 1970 (928 cm), while the lowest in 1935 (-116 cm), during the later the river almost entirely dried up. Therefore, the variability of discharges is much greater than in case of the Maros/Mureş (Table 1).

As a matter of its hydrology and catchment geology it manly transports suspended sediments on the lowland reaches. The greatest sediment concentration measured was 833 g/m^3.

Regulation works

The direction of the Maros/Mureş and the Körös/Criş changed frequently during the Quaternary, which is reflected by the large symmetrical alluvial fan of the Maros/Mureş and the great number of abandoned Holocene-Pleistocene paleochannels of both rivers (Mike 1991). Meandering reaches were surrounded by extensive swamps and wetlands (Fig. 10-11), and the rivers flooded vast areas every year. Inundation lasted for months, since point-bars and natural levees hindered the drainage of excess water.

Figure 10. Map of the I. Military Survey (1784) showing Apátfalva (Col.: 20, Sect.: 30)

During the 18-19th centuries unified regulation works attempted to make huge flood endangered lands suitable for agriculture all over the lowlands of the Carpathian Basin (Fig. 10-11). The large-scale works, including channelisation and the construction of 4220 kms of artificial levees (Dunka *et al.* 1996), resulted in the protection of 21,200 km^2 of land, a significant achievement in Europe. In the case of the Maros/Mureş levee construction started in 1752 and followed the banks of the river, in case of the Körös/Criş these works started a little later, in the beginning of the 19th century. Channel adjustments were carried out mostly between 1847 and 1872 on the Maros/Mureş and between 1855 and 1879 on the Körös/Criş. These measures reduced channel length significantly.

Due to the drastic decrease in length, the slope of the Maros/Mureş doubled (from 0.0014 up to 0.0028) and the river incised approximately 1.0 m (calculation based on decreasing lowest water stages; Rakonczai 2000). As a result of the closeness to the rim of the lower segment of the alluvial fan and the additional slope increase, the sediment transport has become more intensive and a down fan shift of the locus of deposition can be observed. Therefore, aggradation increased, and led to the appearance of new bars and islands in the river bed and the disappearance of ox-bow lakes on the active floodplain (Gazdag 1964, Ihrig 1973). Traditionally the Maros/Mureş was an important shipping route for salt and timber from Transylvania to the lowlands but, by the end of the 19th century, navigation was virtually impossible due to extensive mid-channel bar formation. River regulation therefore restarted in 1899. The existing bends were preserved, however, the low-stage channel width of the river was adjusted to 70 m at bend apexes and 40 m at crossovers. For training the river revetments were used on the concave and groins on the convex banks.

Figure 11. Hydrological map of the Maros/Mureş at Apátfalva, made by Vertics József (1796).

In case of the Körös/Criş the aim was not only increasing slope by cut-offs, but by deepening the channel itself. The maximum delivery rate was determined for each tributary, and channel dimensions were developed in harmony with these calculations. As a result the longest sections of artificial channels were made along this river in Hungary during the regulation works, actually a new river network developed on the lowlands.

After World War I. the history of regulations split up on the studied Maros/Mureş reach. On the lower, 28 km long Hungarian section (between the outlet and Makó) river training continued. All together 21.4 km long revetments and 53 groins were built, and the radius of the bends was adjusted to 500-800 m. However, at the same time the upper section between Makó and Nagylak became a border between Hungary and Romania. As no regulations were subsequently carried out on this reach it has been unmanaged for almost 90 years. Through the lack of bank protection, and due to the formerly straightened channel, the river bed of the Maros/Mureş widened (up to 300 m at some places), and new braids were born with islands and several different bar types, resulting in frequent thalweg shifts (Kiss and Sipos 2003). Aerial photographs and modern maps also show island braided reaches. The length of these on the managed 28 km long section is only 1 km; however on the unmanaged 22 km upstream, it increases to 6.6 km. Channel pattern changes were evaluated as a sensitive response to channelisation works (Sipos and Kiss 2003).

Hydraulical and sedimentological data of the Maros/Mureş plot the river to the meandering region on either the Leopold and Wolman (1957), Parker (1976) or van der Berg graphs (1995) (Sipos and Kiss 2004). However, the width/depth ratio of some sections exceeds the value of 50, determined by Fergusson (1987) as a threshold for braiding. These cross-sections correspond well to that of sand-bedded rivers with high bed-load discharge (Schumm 1985, Bridge 2003)

Geomorphological issues related to channel formation

Riverbed development on the Maros/Mureş at different water stages

Preliminaries

The role of different water stages in the river-bed dynamics of braided and slightly sinuous rivers is rarely discussed in geomorphological research. Most investigators concentrate on the effect of a single flood event when studying changes in channel pattern, bar-formation or bed-load processes (e.g. Borsy 1972, Wolman and Gerson 1978, Osterkamp and Costa 1987, Kochel 1988, Magilligan 1992; etc.).

A common difficulty in such investigations is the collection of precise and both spatially and temporally high density data. In most cases the solution to this problem is the restriction of data collection to short river sections, rivers of relatively low discharge, or to a short period of time. Another problem, which is emphasized in Whiting's (1997) study on flow fields, water and bed surface topography at two different water stages, is in relation to the relative depth of flow, which significantly influences the various terms in governing equations, and leads different researchers to a variety of conclusions. The measurements of Ryan *et al.* (2002) also support this idea. In addition, they emphasize that a shift from low to moderate transport of bed load occurs typically at about 80 per cent of bankfull discharge. Inevitably, this data should be important in terms of the character of bed topography changes at different discharges. In all, the role of different stages must be considered when channel geometry and bed topography are investigated (Jackson 1975, Dietrich *et al.* 1984).

Channel parameters and bed forms are studied most frequently in connection with floods, since dune and bar formation is the most dramatic and spectacular at the high stage (Bridge *et al.* 1986, Ham and Church 2000). Meanwhile, the investigation of a longer river reach has proved that the growth, decay and migration rates of dunes during floods are dissimilar at various sections during varied flood episodes (Lane and Richards 1997, Wilbers and Brinke 2003). In another case Eaton and Lapointe (2001) found that two floods of very different parameters did not cause qualitative changes in channel morphology. The importance of relatively low-magnitude floods in the development of disequilibrium state was also proved (Fullera *et al.* 2003). In the absence of large floods, bed-material transport rates decline over time, and material is mainly transported by higher stages which occur several times a year (Mosley and Jowett 1999, Ham and Church 2000). Based on Madej's research (1999), during a flood-free period subsequent to a great flood, the distribution of residual water depths may alter significantly. Mean residual water depth and depth variability increase over time, while the length of channel occupied by riffles decreases, resulting in an increase in the degree of bed heterogeneity relative to the time since the disturbance.

On a few occasions, rising and falling stages have also been investigated. Bridge and Jarvis (1982) found no evidence for the alteration of hydraulic geometry at the falling or rising stages, and no tendency was discovered in terms of the various cross-sections at any of the measuring stations. According to Carling *et al.* (2000), during the rising river stage, dunes tend to grow in height. However, during steady or falling stages the diminishing dunes actually increase in unit bed-load volume by a process of increased leeside accumulation.

In considering the role of low stages in channel development, it is nevertheless accepted that even low discharges should be considered in terms of bed formation (Bridge,, 2003). Different authors have different views on the active processes in braided rivers during low stages. According to Friedman *et al.* (1996), as a result of sediment input during high flow, the bed level rises; at lower stages the narrowing channel incises and thus high portions of the former river bed are left behind. On the other hand, some other studies report aggradation in the river bed during low stages (Owens *et al.* 1999, Ashworth *et al.* 2000). The model of Nicholas (2000) suggests that braided rivers may transport a significant proportion of their annual bed load during lower discharge periods.

In order to study bed evolution we have chosen the Maros/Mureş River, which is the second largest sand-bedded river on the Hungarian Great Plain. During the 19th century river regulation works, the meanders were cut off, the river bed was straightened and bars and islands started to develop. The lower 30 km section of the studied reach is still managed, but the upper 20 km has developed without human intervention since World War I.

One aim of the investigation was to determine the role of different stages on the cross-sectional channel geometry of a large river, with special attention to low-stage processes. A further aim was to locate braids, which are suspected to be the most significant zones of sedimentation along the river channel, and to determine their function in river-bed development (deposition – erosion).

Study area

The Maros/Mureş River is the second largest river of the Eastern Carpathian Basin. It is 749 km long with a catchment area of some 30 000 km^2, mostly situated in Romania. The lowest, 50 km section of the river was chosen as a study area. Of this a 28 km long reach is located entirely in Hungarian territory, while the remaining 22 km is part of the border between Hungary and Romania.

Hydrological events

Since the middle of the 19th century, hydrological measurements have been taken continuously on Hungarian rivers. On the reach studied, the daily stage and discharge data measurements at the Makó gauging station date back as far as 1876. Stage data are measured from the "0" point of the fluvio-meter, which was set to the level of the lowest water observed prior to 1876.Since then due to the decrease of low water levels, negative values have also appeared in records.

At the beginning of the period studied (from 1940 to 1981), floods (stages higher, than 350 cm) were common almost every year (Fig. 12). After 1981 several flood-free years followed. The durability of floods on Maros/Mureş is much shorter than on other rivers in the Carpathian Basin. The floodplain is inundated by the river on average 6 days a year; however, during the record flood of 1970 stages remained above bankfull for 81 days.

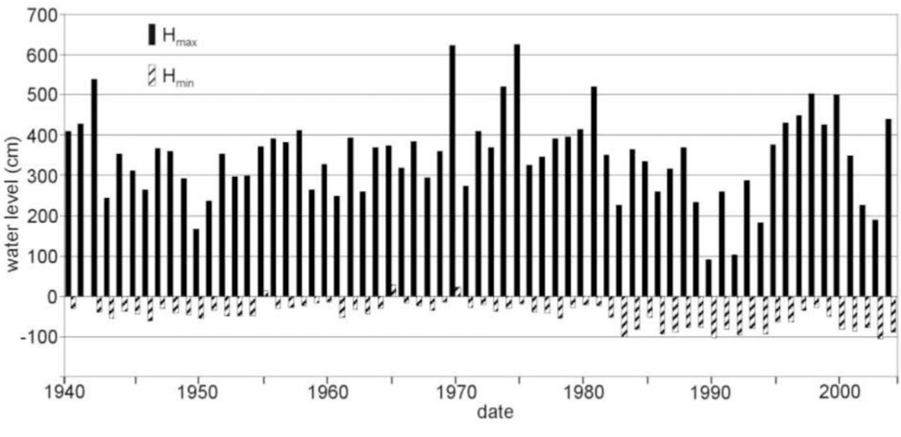

Figure 12. Annual maximum (H_{max}) and minimum (H_{min}) stages on the Maros/Mureş River at the Makó gauging station (1940-2004).

Based on the analysis of the 65 year gauging data set, the mean stage is approximately 54 cm, while the mode of the data set is at -10 cm, suggesting the importance of low stages. Between 1940 and 1981 the lowest stage never dropped below -50 cm, but since 1981 it has been between -50 and -104 cm. The lowest stage on record was observed at the start of our investigation in 2003. The period of low stages lasts approximately 10 months starting in June and terminating in March. The decreasing values of H_{max} and H_{min} during the last 20 years suggest a climatic change in the catchment area, which may be the reason for such extremely low stages.

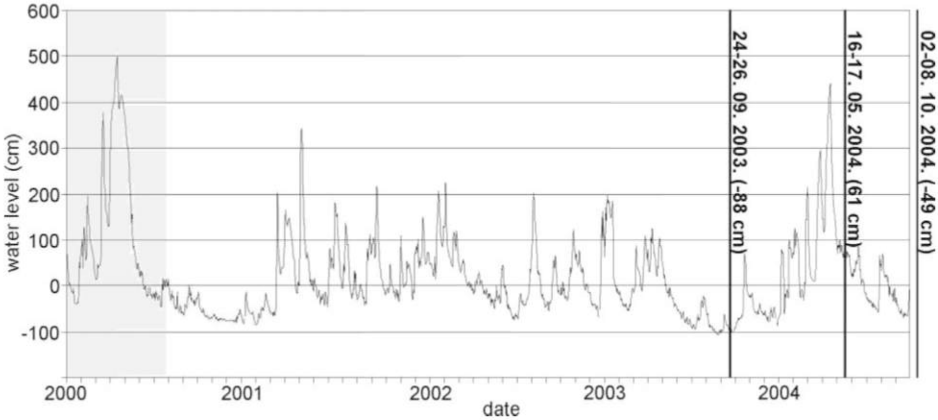

Figure 13. Hydrograph showing daily gauging data received at the Makó station from 2000 to 2004.

The extreme low-stage period followed a medium sized flood in 2000 (H_{max} = 500 cm Q_{max} = 1170 m^3/s) lasting for 2 weeks. For the rest of the year an unusually long low-stage period followed, when the water level never exceeded 0 cm (Fig. 13). The period between 2001 and 2003 was also characterised by low discharges, the water level hardly reaching the level of half bank height. However, daily stage fluctuations have been significant, occasionally exceeding 20 cm/day. At the beginning of 2004 a small flood was observed (H_{max} = 440 cm), but since then the stage and the rate of water-level changes have corresponded well to usual seasonal tendencies. The mean water stage for the past 5 years was 10 cm, while the most frequently occurring stage was –16 cm.

Methods

Data collection was undertaken at different spatial and temporal scale. Width measurements were done along the whole 50 km long section, cross-sections were surveyed in five braids, and at-a-station data were gained from the Makó gauging station. The longest period was covered by width measurements (from 1953), at-a-station data are available since 1988, and the cross-sectional measurements within braids started in 2003. Here data collected between 2003 and 2004 are analysed.

Before studying the role of different stages, their definition is necessary. Based on the long-term data set, those stages were considered low, which did not exceed "0" cm on the fluvio-meter (Q = 150 m^3/s). According to the calculations made by Török (1977), the channel forming discharge is at 248 cm (Q= 553 m^3/s). The bankfull level is at 310 cm (Q = 850 m^3/s). Water levels above this are considered as floods.

At-a-station cross-sectional measurements

Data were collected by the Hungarian Hydrological Service (ATIKÖVIZIG) between the same fixed points every month at the Makó gauging station. During certain hydrological periods (floods, extreme low waters) the measurements were more frequent, sometimes repeated daily or even as often as every eight hours. The depth was measured every 2 m to an accuracy of 1.0 cm. At the same time, discharge and velocity were also measured, but not bed-load transport rate.

From 1988 on, 365 at-a-station cross-sectional data sets are available. These sets represent different water stages and so, the relationship between water stages and different cross-sectional parameters can be studied. Maximum and mean depths and depth variability were determined. Depth variability is the difference between the maximum and mean depth, and refers to the shape of the river bed, as increasing difference implies a deeper thalweg, thus greater heterogeneity of bed topography.

Width measurements on the whole reach

In order to identify long-term width changes on the 50 km river section and the place of potentially braided structures, measurements were done on aerial photographs and map series from five dates (1953, 1973, 1981, 1991 and 2000) using Erdas Imagine 8.4 and Arc View 3.1 software. On the geo-corrected layers the bank-lines were digitized and a centreline was drawn for each date. On the basis of individual centrelines a line was interpolated, along which the width of the channel was measured every 100 m for each date.

The location of potential braids was determined by the average difference of maximum and minimum values per km (ad value). Those sections were considered braids where the difference between a section of peak width and the oncoming narrowest section exceeded the ad value for a given date.

Downstream cross-sectional measurements in braids

The underwater parts of downstream cross-sections at the chosen braids were surveyed with sonar equipment and a measuring rod. The width of the sections and height data of the emerged bars were determined with Total Station. The geographical position of cross-section end points was measured with GPS. Perpendicular cross-sections were made approximately every 100 m or, if the diversity of bed forms required, the distance between sections was decreased. Between the end points of neighbouring sections, diagonal sections were also sampled to increase the reliability of mean depth data. In all, 122 sections were made per survey. Data were gained from every 2.0 meters of the sections. Depth and height values were normalized to the water level of the channel forming discharge (248 cm).

Measurements were performed on three different dates over the course of a year. Low water measurements were made in September 2003 (H = -88 cm) and October 2004 (H = -49 cm), while after the falling stage, cross-sections were made in May 2004 at around the 65 year mean water level (H= 61 cm) (Fig. 13). Flood-stage measurements have not been made yet due to flashy and fierce waters making movement on the river almost impossible.

Results

Long term bar scale changes

The graph of average at-a-station cross-sectional parameters plotted against water stage shows that, as the water level rises, cross-sections become more asymmetric, because the thalweg is better defined though, average maximum depths do not change significantly. The average maximum depth is 5.15 m and 5.43 m at low and at flood stages, respectively, and this increases slightly by stage (Fig. 14). However, during low stages the mean depth values are greater, and the river becomes shallower on average by 0.6 m when water level reaches the highest category. This suggests that, during floods, large amounts of sediment are accumulated in the river bed, but that this will erode during low stages.

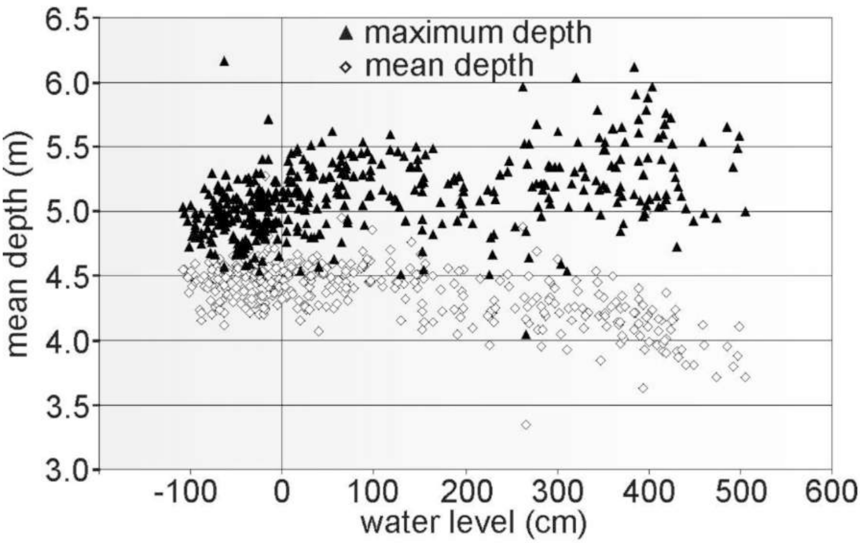

Figure 14. At-a-station mean depth and maximum depth values (m) plotted against water stage (cm) (from 1988 to 2004)

In order to reinforce this, 171 low-stage cross-sections were evaluated. Here the longest low-stage data set (18 measurements) from the period of July 1990 and April 1991 is analysed, when water stage never exceeded the "0" level (Fig. 15a). In the summer of 1990 water stages varied between –75 and -100 cm (Q = 35-51 m^3/s). The mean and maximum depth increased by 20 cm and 28 cm, respectively, equalling a 26 m^2 cross-sectional area increase. In the autumn the water stage rose by 50 cm (Q=65-100 m^3/s), resulting in an aggradation of 22 cm thick sediment in the cross-section. During the winter the water level fluctuated between -25 and -75 cm and thus the erosion of the river bed restarted with simultaneous thalweg shifts. A slight increase in maximum and mean depth was measured, though depth variability was no greater, than 0.4. Across all low-stage periods the maximum increase in cross-sectional area was 28%. The data proved that the dominant process during low stages is erosion, which is intensified by frequent thalweg changes.

Bed processes related to channel-forming discharge were studied at periods when stages varied between 250 and 350 cm (Q = 550-850 m^3/s), nearing flood discharges, but with a water level below bankfull. The longest channel-forming period was in March-April 1988, when three smaller flood-like waves succeeded (Fig. 15b). During the first wave, which was the highest (H_{max}=369 cm) and brought the greatest discharge (Q_{max}= 765 m^3/s), the value of maximum and mean depth changed cyclically by 1.0 m within 1-2 days. Consequently, during this period a great amount of sediment was transported through the cross-section. The change of bed topography suggests that the transport was maintained in the form of mid-channel bars and dunes. During the falling stage the maximum depth was reduced to 450-500 cm, and the mean depth decreased simultaneously. Therefore the surface of the bed became more even and elevated due to aggradation and frequent thalweg shifts.

Since 1988 only two floods have occurred on the Maros/Mureş (1998 and 2000). To show the role of floods in bed formation, the spring flood of 2003 (March-May) was chosen (Fig. 15c), as it provided the longest cross-sectional data set (27). Until the peak stage was reached, the maximum depth increased twice (up to 5.9 and 5.5 m). However, in-between the two dates it varied around 5.0 m. Meanwhile, the mean depth continuously decreased, which meant that a great amount of sediment reached the section, though it was transported away. During the falling stage, the maximum depth changed slightly, but mean depth increased further on. This should mean that the transport rate became smaller than it was during the rising stage. A comparison of the cross-sections before and after the flood shows that the depth variability decreased to 0.85, and their area was reduced by 14 m^2 (15%), suggesting river-bed aggradation during the falling stage, though the transport rate remained significant. The phenomenon is also shown by the discharge vs. water-level curves (Fig. 16) of greatest floods (1938, 1970, 1998, 2000). The water-level values belonging to the same discharge at the falling stage (upper section of the curve) are always higher by 0.7-1.0 m, than at the rising stage, implying a similar aggradation rate.

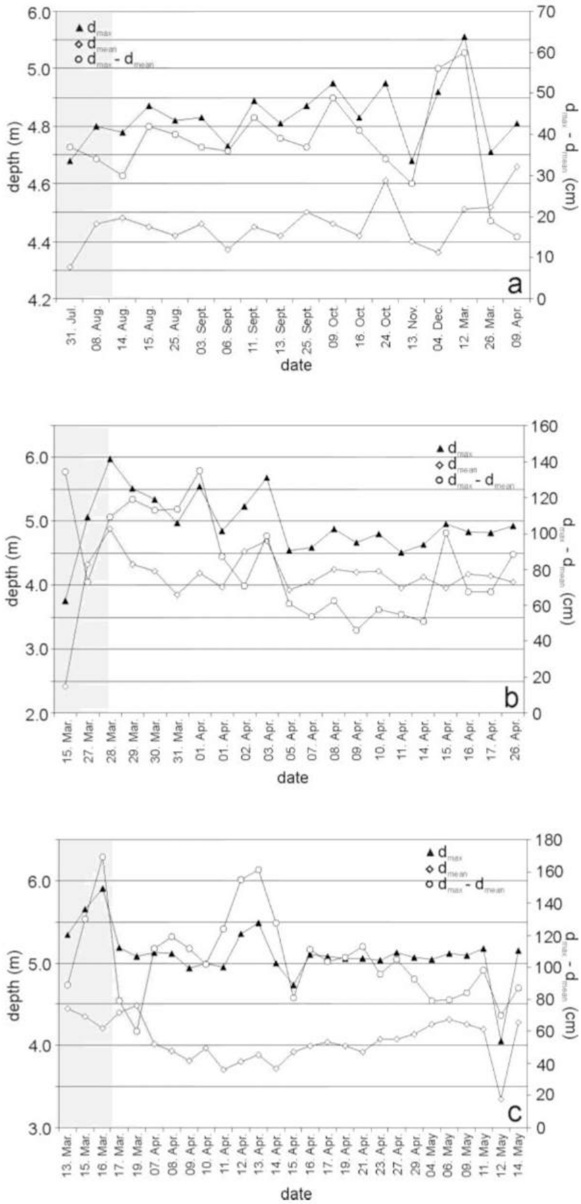

Figure 15. Changes of cross-sectional parameters during different stages: (a) low- stage period in 1990-91; (b) bankfull and channel-forming period in 1988; and (c) the flood of 2003.

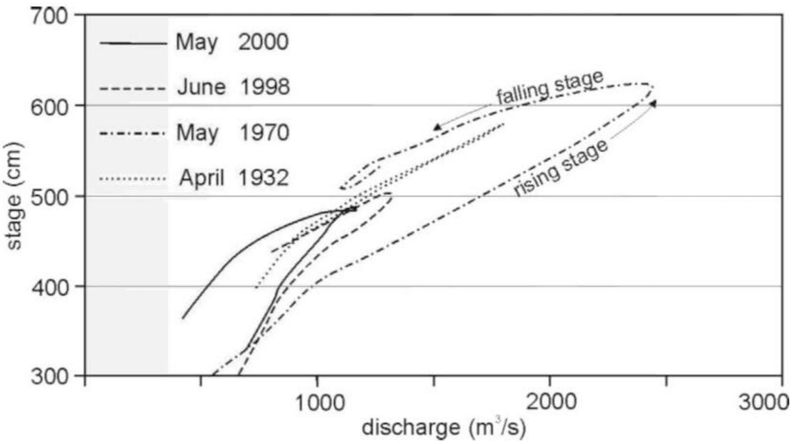

Figure 16. Water-level vs. discharge curves of the greatest floods at Makó.

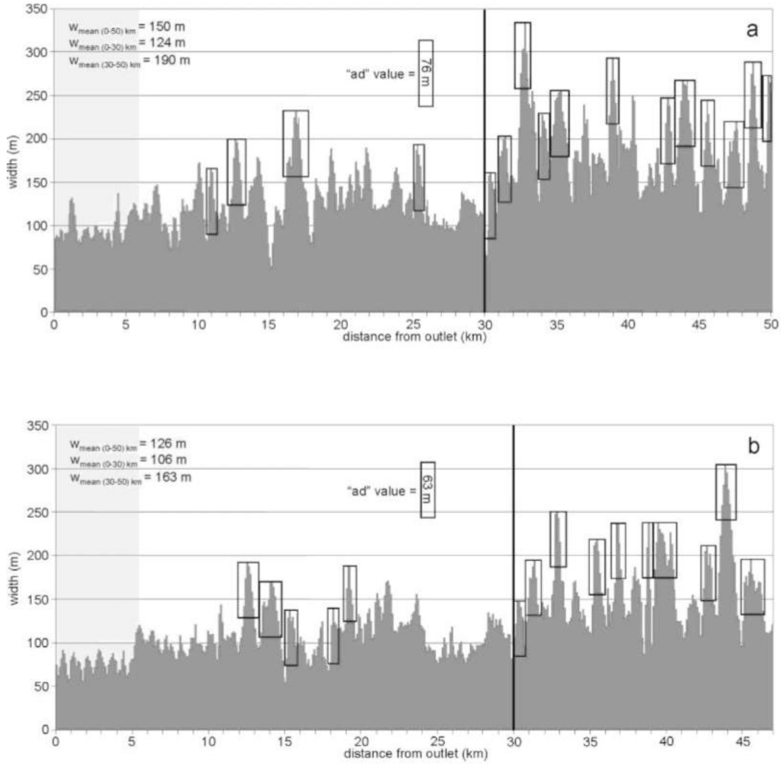

Figure 17ab. Width conditions of the studied 50 km long reach and the position of braids in (a) 1953 and (b) 1991.

Downstream width change, and identifying braids

The available geo-informatical database on channel width enabled detailed planimetric analysis from 1953 till 1991. In case of the first date, the mean width of the whole reach was 150 m. However there is a sharp fall in width data at around 30 km from discharge (Fig. 17ab, Fig. 18). Upstream from this point 190 m and 114 m were the mean and the minimum width, while downstream they were 124 m and 53 m, respectively (Table 2). The difference between the two identified sections was characteristic in all periods, as the upper part was consequently wider than the lower section. The shift in mean width data coincides with the limit of the length along which the river is managed with revetments and groins (Fig. 18).

Table 2. Changes in maximum and mean width values on narrow sections and in braids between 1953 and 1991.

	managed reach (0-30 km)				unmanaged reach (30-50 km)			
	1953	1973	1981	1991	1953	1973	1981	1991
w_{max} (m)	231	219	197	191	333	304	288	304
w_{min} (m)	53	70	65	55	114	111	95	87
braid wmean (m)	161	150	141	135	229	209	200	190
narrow section wmean (m)	118	115	109	101	171	166	153	147
wmean (m)	124	121	114	106	190	180	167	163

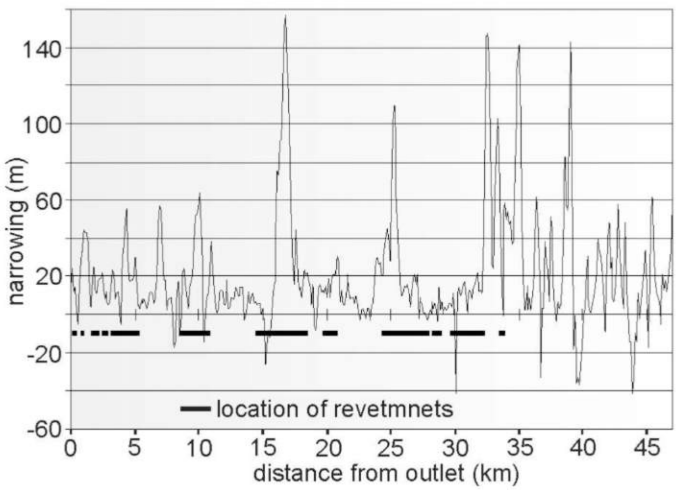

Figure 18. Width changes between 1953 and 1991, and the position of revetments and groins.

As mean data was calculated from a great diversity of widths at the different dates, the calculation of frequencies concerning widths was necessary in order to shed light on the changeability of channel width. Frequency calculations were made separately for the upstream and downstream reaches (Fig. 19). Downstream curves are narrower, implying that width values are more homogenous, while upstream curves are more asymmetric and show a great heterogenity of widths, with several peaks. When considering the peak of the curves on different dates, there is a move toward lower width values on both sections.

This tendency is also reflected in maximum, minimum and mean values (Table 2). Mean width decreased by 15 % from 1953 to 1991 (Fig 18.), while maximum values decreased by 9 % and 18 % on the upstream and downstream sections respectively. In relation to minimum values, there is a drop from 114 m to 87 m on the upstream section, while in terms of the downstream section there is almost no difference (Table2). There are two possible causes for the changes, both occurring in the 1940s. At the beginning of the decade bankfull and flood stages were frequent and so a great number of large bars developed. The cutting of riparian vegetation for war purposes coincided with this process, and resulted in bank erosion and thus channel widening. From then on, as flood frequency dropped, and low-stage periods lengthened, vegetation could colonise the banks and extensive side-bar surfaces (Kiss and Sipos 2003).

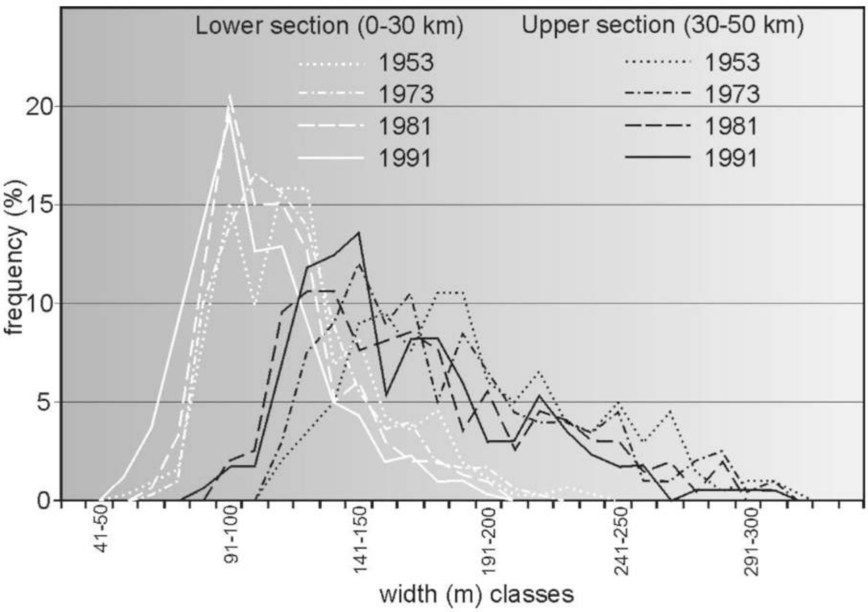

Figure 19. Frequency of width classes on the unmanaged (30-50 km) and the managed (0-30 km) reaches at the different dates.

Table. 3. Position, number and average spacing of braids on the study reach.

	1953	1973	1981	1991
ad value	76	75	69	63
Position of braids on the managed reach*	10.9	-	-	-
	12.6	12.7	12.6	12.6
	-	14.2	14.2	14.1
	-	-	15.4	15.4
	16.8	-	-	-
	-	-	-	18.2
	-	-	19.2	19.2
	25.3	-	-	-
Position of braids on the unmanaged reach *	30.4	30.4	30.3	30.3
	31.4	31.4	31.4	31.4
	32.5	-	-	-
	-	33	32.9	32.9
	34	-	-	-
	35.3	35.6	35.5	35.5
	-	37	36.8	36.8
	-	-	38	-
	38.9	39.1	38.9	38.9
	-	-	-	39.5
	-	-	40.3	-
	-	42.1	-	-
	42.8	42.9	42.8	42.7
	43.8	44	44	43.9
	45.5	-	-	45.6
	47.5	47.5	47.5	47.5**
	48.7	48.7	48.7	48.7**
	49.8	49.9	49.9	49.9**
No. of braids lower section	5	2	5	5
No. of braids upper section	12	12	14	13
average spacing upper section	1.76	1.77	1.68	1.7

*position: distance of the braid's peak width from the outlet (km)
** aerial photographs did not cover the uppermost 3 km. Supposed location, based on the constant position of braids.

Short term braid scale changes

In the last fifty years the width of the river has varied significantly and the presence of widened, braid-like structures is obvious. Their identification was based on the ad value, which varies between 63-76 m/km over the four dates and thus represents 50-52 % of the average width at each period (Fig 17ab). In terms of the upstream region, differences are even more emphasized and the ad value can rise to 185 m/km (in 1981). This is due to the presence of areas where the channel significantly widens then narrows. These units are island and bar braided or potentially island braided structures. The number of identified braids is varying between 14 and 19 on the whole reach at the four dates. The place of braids on the managed section was changing continuously, which was due to river management affecting channel width. However, the position of 3 braids seems to be constant from 1953. The number of upstream, unmanaged braids is between 12 and 14. From them 8 braids were stable during the investigated period. The most changes on this section can be related to widened straight reach between 35-42 km from the outlet, in which the place of braids can change easily (Table 3). The position of stable braids may slightly change over time mainly through narrowing at their downstream end, and the widening of upstream sections. Braids upstream are much wider, with an average maximum width of 230-250 m as opposed to the 160-180 m value of downstream braids, which only develop where no revetments or groins hinder the evolution of the river bed.

Due to slight changes in their position, necessarily, the spacing of braids is quite constant at the four dates, and resembles a riffle-pool sequence on the upstream reach. The wavelength of the riffle-pool sequence is approximately 1.7 km. However the distance between braids can be different (Table 3).

Cross-sections made at braids were used for investigating changes in channel geometry at different stages, and defining the function of braids in sediment transport in time and space. Braids were chosen in order to represent the upstream, unmanaged reach (site No. 1-3) and the downstream, managed reach (site No. 4-5), too (Fig. 20). An important characteristic of the selected braids is that those upstream contain islands, while those downstream do not.

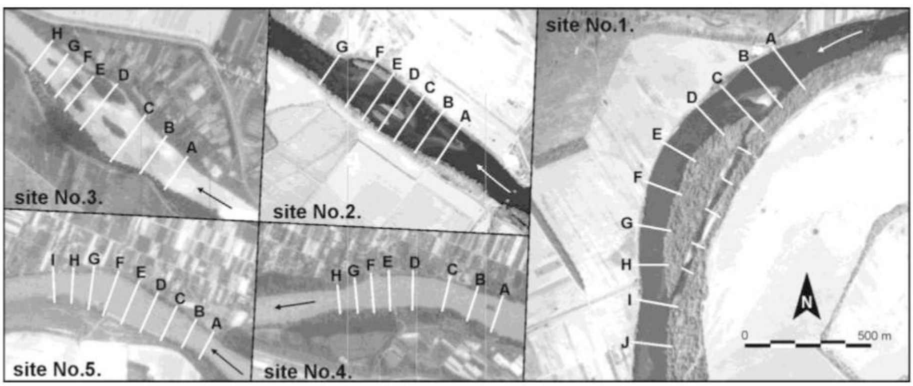

Figure 20. The studied braids (sites No.1-5) and the location of perpendicular cross-sections, along which depth measurements were done in 2003 and 2004.

The mean depth value for a whole braid was calculated as a sum of all depth data, and it was evaluated as a value resembling sediment storage, since the density of sampling was relatively high. Change in the mean depth was well observable in terms of the braids on the upstream reach. At study site No.1 the difference between the low-stage and the falling-stage values was 9.6 % and 8.0 %, however, going downstream these differences faded first to 6.6 % (site No. 2.), then to values around 4-5 % (site No. 3) (Table 4). The smallest changes (0 and 2.1 %) were observed in terms of study site No. 4, which is managed by both groins and revetments. In case of study site No. 5 the differences were similar to those of at site No. 3, even though the previous is located on the managed reach (but without groins or revetments), and the later one at the lower end of the unmanaged reach. This implies that both sections experienced similar changes in terms of the summed cross-sectional mean depth data, however, upstream braids (site No.1-2) were seemingly more variable in this respect.

The tendency of change is also obvious. The two autumn data in 2003 and 2004 represented almost the same values, the difference between these was lower, than 2 %; and seemingly 2003 low-stage data were higher than those measured in 2004. Falling-stage mean depths were always lower, than low-stage mean depths. Thus, at low stage each braid, except the managed one, experienced net sediment loss that was resulted by the out-washing of previously deposited sediment and bar forms. The sediment or bed-load input therefore, is due to floods and high water stage periods at springtime. The difference of the two autumn surveys suggests that the longer the low-stage period is the more sediment is removed from the channel.

Table 4. Summed mean depth data of the studied braids at dates of investigation.

	site No.1	site No.2	site No.3	site No.4	site No.5
d_{mean} 2003 low stage (m)	4.05	n.d.	4.06	4.20	4.20
d_{mean} 2004 falling stage (m)	3.66	3.54	3.88	4.11	4.04
d_{mean} 2004 low stage (m)	3.98	3.79	4.07	4.11	4.14
Difference of 2003 low stage and 2004 falling stage (%)	9.6	n.d.	4.4	2.1	3.8
Difference of 2004 low stage and 2004 falling stage (%)	8.0	6.6	4.7	0.0	2.4

By comparing individual perpendicular cross-sections at different dates, we can receive information on the location of accumulation and erosion at the braid scale during different water stages. Change of cross-sectional mean depths at the three dates (representing two typical water stages) are shown in Fig. 21a-d. In case of study site No.1 upstream sections experienced accumulation during the falling stage of the 2004 flood; e.g. the mean depth of section A at spring in 2004 was shallower, than at the previous and subsequent low water surveys by 0.90 and 0.53 m, respectively (Figs. 20 and 21a). Downstream sections represented continuously decreasing accumulation, and there was a change from section H, where falling-stage data were higher, thus net erosion could be suspected at the lower end of the braid compared to autumn data. The depth values of the cross-section series at the two low water stages represented an almost even distribution of mean depths in the braid during these periods, while the shape of the 2004 spring line resembles a sediment plug in the upstream half of the site, which might represented a local and temporal riffle-pool setting within the braid (Fig. 21a). The maximum depth variability of the braid was different after falling (2,9) and during low stages (1,5) referring to the decrease in river-bed heterogeneity and the dominance of sheet erosion.

At site No.3 the maximum difference in mean depth at the same section was 0.97 m (section C). This site showed a similar process concerning the location of accumulation and erosion (Fig. 21b), i.e. during falling stage accumulation occurred predominantly at the upstream end. The difference compared to the previous site was that the local riffle-pool system in the braid was apparent at low water stages, too.

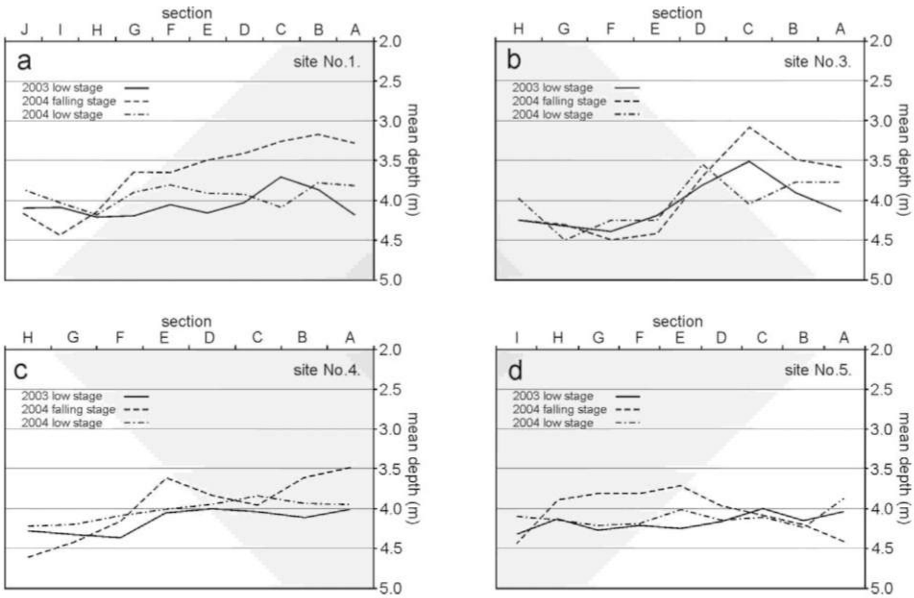

Figure 21. Mean depth changes at cross-sections of the studied braids at different stages.

On the managed reach, braid at site No.4 also represented increased sedimentation upstream, however the difference in mean depth data was much less, than at other places (0.39 m at section E), and cross-sections resembled an almost even bed surface at each dates (Fig. 21c). Site No.5, which is neighboured by trained reaches but itself is not managed neither by groins nor revetments, represented different accumulation processes, than any other braids analysed before. Increased sedimentation subsequent to the falling stage could be observed in case of downstream sections within the braid (0.45-0.55 m), while upstream sections experienced erosion from autumn 2003 to spring 2004, which means that the evolving sediment plug was positioned downstream (Fig. 21d). Maximum depth variability after falling stage was lower (1.9), than in upstream braids, suggesting that floods formed smaller bars in height, and the main thalweg was blocked, decreasing the heterogeneity of the bed. During low stage, as opposed to other cases, the value increased (2.8) probably due to the more stable position and less diversion of the thalweg, which resulted a more pronounced linear erosion.

Discussion and conclusions

The role of stages in bed formation

Results on mean depth and cross-sectional measurements have shown that each stages have their own function in transportation processes on a sand-bedded river like Maros/Mureş, where discharge and water level change rapidly and frequently during the year.

During floods, bankfull and channel forming discharges a great volume of sediment may be transported through cross-sections of the channel in the form of sediment pulses day by day. Thalweg shifts are frequent, and most of the sediment is carried in dunes the height of which can reach at least 1 m, thus depth variability may reach quite high values, e.g. in 1998 during the peak discharge it was 1.7 at narrow sections.

After floods or any cases when the water level falls at least 50 cm at a rate of 10 cm/day, accumulation will be the dominant process. However, the amount of deposited sediment differs greatly if straight and braided sections are considered. The at-a-station data and the discharge vs. water-level curves suggest that in straight reaches the decrease of depth, i.e. aggradation can be 0.7-1.0 m, which means a 10-15 % (10-14 m^2) decrease in the cross-sectional area. In the braids the values of aggradation can reach up to 22 % (140 m^2) at certain cross-sections, however, in average a 15 % cross-sectional change was measured here, too. The way of sedimentation differs in the narrow, straight and in the braided sections, as it is shown by depth variability values. In the narrow sections the surface during falling stages becomes even (depth variability = 0.85), but in the braids the accumulation forms large bars and depth differences are greater (depth variability = 1.9-3.0).

Aggradation at falling stage will provide deposits for low water sediment transport. During long-lasting low-stage periods most of the accumulated sediment is relocated. Therefore, in narrow reaches cross-sectional area increases, which means net erosion and an increase in mean depth. Braids experience similar transportation processes, when the mean of all cross-sections is considered however, there are well separable functional and morphological zones within one braid structure. In case of some individual cross-sections aggradation can also be observed, as a result of relocation. In cases of upper braids and narrow sections by the end of the low-stage period depth variability values decrease to 1.6 and 0.4, respectively, and cross-sections reflect more homogeneous river-bed topography, suggesting rather sheet than linear erosion during low-stage transport. In the lower braids depth variability increased by low stage, implying the importance of a single thalweg in linear erosion. The effectiveness of low-stage periods in transporting bed load is even more significant, if there are frequent 50-100 cm fluctuations in the water level, which act like small floods, and deposit further sediment ready to be relocated.

Function and characteristics of braids

Concerning total amount of sediment deposited during falling stage, braids store overwhelmingly more, than straight, narrow reaches. Therefore, their role must be significant in influencing transportation processes, through the storage of large volumes of sediment subsequent to floods and the continuous release of them during low stage.

The difference in location of sedimentation in braids is mainly reasoned by the structure of these units. At those braids, which are characterised by islands the sediment plug of the falling stage is deposited at their upstream end, because islands, usually located at the braids' lower end, increase stream power by decreasing channel width. Thus, they create a transportation zone in the downstream end. Braids with no islands are more likely to experience deposition at their downstream end during falling stage. However, increased bar formation due to extreme floods might create surfaces for vegetation to colonise, which after all, may lead to the development of islands and finally the shift of transportation zone (Fig.22). Thus, concerning braids two types of general setup can be separated: a pre-island-formation and a post-island-formation state. These states basically determine the locus of deposition.

In upstream braids with islands usually more sediment is accumulated. The change in the average cross-sectional area is the greatest in the uppermost braid (10 %), going downstream on the unmanaged reach the value decreases (6%), while concerning the managed reach in braids without islands it falls to 3 % and 4 %, meaning a one half reduction in the storage function of the braids.

Difference in braids also appears when taking a look at their width conditions, namely braids on the unmanaged reach are wider, than those downstream. However, a constant tightening of braids was observed during the last fifty years, and the rate of narrowing was identical, 28 % at both reaches. At the same time, the mean width of the whole river has decreased only by 15 %, showing that braids are more prominent places of narrowing. Changes in the regime of the river, and altered land-use can be placed in the background of this process. As it can be seen on the hydrograph of the last sixty years the frequency of floods has decreased, while that of extreme low waters increased. Therefore, the need for the sediment storing function of braids is less necessary, which leads to their tightening. The process is carried out by vegetation colonising side-bars.

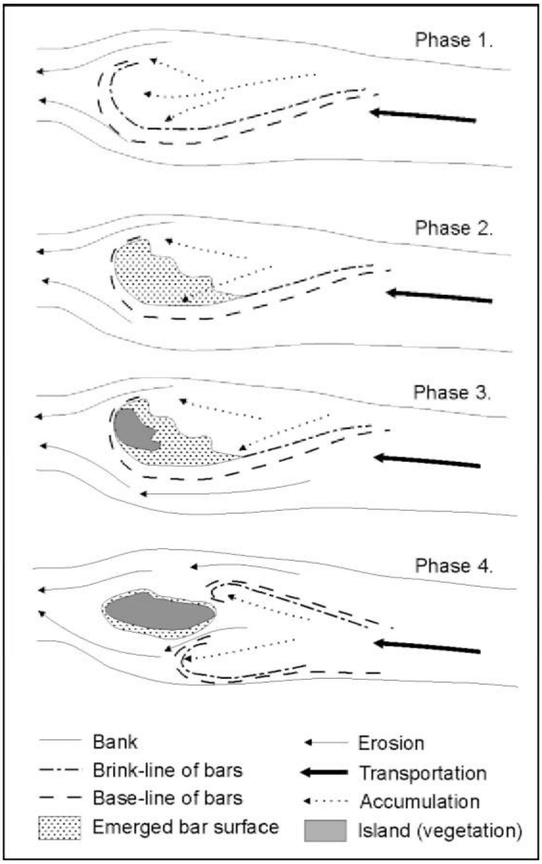

Figure 22. Hypothetical model of the relocation of accumulation and erosion during the evolution of a braid.

Finally, the significant role of low stage in channel forming seems to be well supported from two aspects. First, low waters are proved to be important in sediment transport by eroding and relocating sediments deposited during the falling stage of yearly reoccurring high stages. On the other hand, the long-term increase in the length of low-stage periods results channel narrowing and the decline of braids.

Long term geomorphological changes

Preliminaries

The horizontal and vertical parameters of channels (channel pattern), affected by several factors, are broadly discussed in different geomorphological and hydrological texts (Schumm 1977, Knighton 1998, Bridge 2003, Richard *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 increased flood hazard (Tiegs and Pohl 2005, Pinter and Heine 2005).

Human activities affecting channel morphology and fluvial processes can be quite varied. Indirect influences, including changes of land-use and management on the catchment, urbanisation and land drainage, can alter run-off and sediment yield. A wide range of direct impacts influence the channel itself: e.g. dams, reservoirs and grade-control structures, channelization, 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).

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 (1945–60) was the result of instream gravel mining and construction of upstream dams (Rinaldi and Simon 1998). The same phases were divided by Antonelli *et al.* (2004) on the Rhone River, though they describe 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 altered human activities (Xu 2002).

Direct anthropogenic interventions on lowland alluvial rivers primarily aim at ensuring navigation and enhancing flood control. However, measures may lead to long profile degradation, channel narrowing (Liébault and Piégay 2001), or to incision (Rinaldi and Simon 1998, Arnaud-Fassetta 2003, Surian and Rinaldi 2003). Channelisation is one of the typical approaches during river training. Its effects were studied by Brookes (1985) and Yates *et al.* (2003). Both of them found that channelisation resulted an increase in slope and a decrease in roughness. The use of artificial cut-offs is another frequent method of training, especially in case of large alluvial rivers. Investigations show that it 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 the rapid changes of the first 2–3 years, the channel needs an additional few years to relax and to become stable (Hooke 1995).

Study Area

The Maros/Mureş River is the second largest river of the Eastern Carpathian Basin. It is 749 km long with a catchment area of some 30 000 km2, mostly situated in Romania. The lowest, 50 km section of the river was chosen as a study area. Of this a 28 km long reach is located entirely in Hungarian territory, while the remaining 22 km is part of the border between Hungary and Romania.

Methods

On the Maros/Mureş hydrological survey maps were not made, thus a regulation map series (1829), military survey maps (1865) and aerial photographs (1950, 1973, 2000) were used for the analysis. The earliest map series had a very good resolution, still, because of accuracy problems it was only used for the determination of relative indices.

Maps of different projection systems and aerial photographs were geocorrected by AutoDesk Land Desktop 2004 and Erdas 8.4 softwares, and transformed into the Unified Hungarian Projection System (EOV). Subsequent to this 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. Based on this planform parameters, such as sinuosity (S), meander arc length / meander chord length (a/c) and total sinuosity (ΣP) evaluated. Based on the a/c values meanders were categorised according to the classification of Csoma (1973) and Laczay (1982)

Results

Channel pattern change prior to the regulation works

The planform of the pre-regulation river was investigated with the help of two map series. The base map series was originating from 1829 and made by Szathmáry. This was compared to the maps of the II. Austrian military survey, made around 1865 right during the regulation works. The original course of the river could be unambiguously identified on this map series as well. On the investigated reach the average sinuosity of the river was 2.09 and 2.16, however, based on the direction of flow, morphology of meanders the investigated reach can be divided into four sections. If these are compared, than morphological factors show significant differences (Table 5).

Table 5. Morphological parameterson the lower 50 km of the river prior to the regulations.

	1829			1865			
	S	ΣP	i/hátl	S	ΣP	i/hátl	p (m)
Section 1.	1,32	1,74	1,24	1,46	1,66	1,17	8537
Section 2.	2,23	2,76	1,68	2,17	2,91	1,70	32027
Section 3.	2,01	2,01	1,63	2,05	2,20	1,40	29048
Section 4.	2,58	2,58	1,68	2,71	2,71	1,65	26532
Entire section	2,09	2,31	1,64	2,16	2,48	1,57	96144

The most upstream section was characterised by meanders dissected by islands, the sinuosity of the main channel was the lowest here. The a/c ratio was right at the limit of well developed meanders according to the classification of Csoma (1973) and Laczay (1982) (Table 5, Fig 23). The width of islands on this section did hardly exceed the double of the net channel width, suggesting that these forms are reflecting a braided pattern. As a consequence Section 1. represented a transitional state between meandering and braided patterns.

Section 2 was characterized firstly by a main channel with well developed and mature meanders, and subchannels which themselves were meandering too. Sinuosity and the a/c values were considerably higher here (Table 5, Fig. 23). In 1829 and 1865 52 % and 43 % of meanders were falling to the mature category and first one, later two over-mature meanders could be identified on this section. Section 2. also contained islands, but the maximum width of these was approximately 4.5 times greater than the net width of the channel, thus these islands were probably dissected from the floodplain. the more detailed 1829 maps show in channel bars primarily at inflection points. Based on these morphological features this section had also a transitional pattern, however, in all it can be considered an anastomosing river reach. Meanwhile sub channels are also in between meandering and braided patterns.

Concerning the next section meandering was dominant, however sinuosity and meander curvature decreased here. In terms of planform Section 3. was similar to Section 1., though here, mature meanders were present in a higher proportion (47 and 53 %).

On Section 4., close to the outlet, meanders were jammed, providing a compound and in certain cases distorted pattern for the river. Although Section 4. represented only 10 % of the entire studied reach, 40 % of the meanders were identified here. As a consequence sinuosity was the highest here, its value was almost double of the values of Section 1. (Table 5, Fig. 23). No islands were identified on the reach. The proportion of mature meanders was still around 50 % but a/c values were higher even than on Section 2. Based on these Section 3-4. can be regarded unambiguously meandering before the regulations.

It is obvious that both map series clearly show the spatial change of channel patterns and meander curvature. There can be several causes in the background, such as different slope, the fining of the material of the river bed and the banks, or the impounding effect of the Tisza. It must also be emphasized, that according to the digital terrain models made by Botlik (2005) the edge of the Maros/Mureş alluvial fan is situated at Makó, which also coincides with the border between Section 2. and 3., meaning that braided like transitional patterns are rather characteristic on the alluvial fan, while truly meandering patterns appear only downstream of the fan edge.

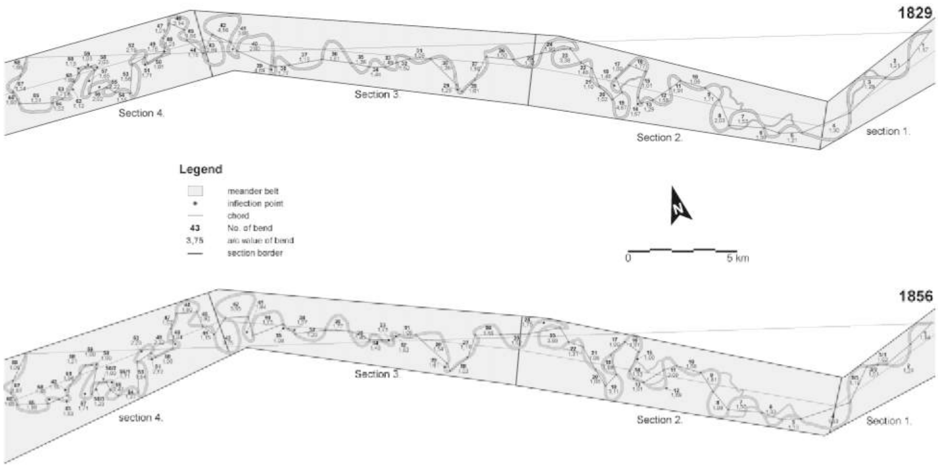

Figure 23. Morphology of the Maros/Mureş River prior to the regulations, based ont he map series of Szathmáry Sámuel (1829) and the II. Military survey (1865).

Beside spatial changes temporal differences can also be investigated with the help of the two map series, reflecting the natural pace of river development. The sinuosity and thus the length of the main channel increased, while average meander curvature values decreased. Sinuosity increase was resulted by the development of new bends (e.g. meander 3 on Section 1., and meander 58 on Section 4.). Decreasing a/c values were due to several reasons. Firstly the curvature of the newly developing bends is naturally lower, secondly two meanders were cut-off naturally between the two mapping (meander 14. and 39.), thirdly in case of certain bends the changing position of the inflection points resulted an increased chord length which in turn lead to a decrease in the a/c ratio (e.g. meander 21.). The temporal change of the a/c ratio can be seen on Fig 24., where positive values stand for the increase of curvature or to the development of new bends, while negative values represent cut-offs and replacement of inflection points.

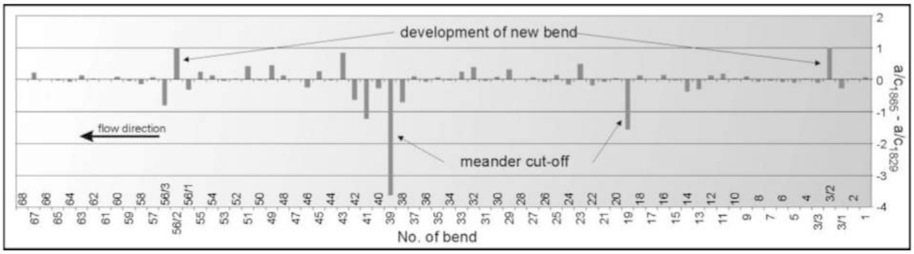

Figure 24. Difference of 1865 and 1829 a/c values of bends ont he studied section.

The analysis above clearly show that the river prior to the regulations was developing actively, its average morphological parameters significantly changed due to the development of new bends and the natural cut-off of others. It is also clear that in between the two mapping dates considerable changes occurred on each section, and the difference between average morphological parameters could be as much as 8-10 %, suggesting intensive processes, especially in the light of the changes in the past 50 years.

Channel pattern change in the past 50 years

The planform change of the Maros/Mureş was analysed with the help of aerial photo series from 3 dates (1953, 1973, 2000). On the basis of earlier results very slight changes were expected, and thus very precise measurements were necessary to detect changes. Measurements were made following uniform principles, width was measured at the same locations on each photo series, and the centreline was drawn by using the halving points of these cross-sections. When making average calculations for different sections, in each date the earlier demonstrated natural border lines were considered.

In all Section 1. was affected the least by regulation activities. Here the sinuosity values of the past 50 years fall close to that of the natural state (Table 6). The total sinuosity of the reach has increased according to the changes in the size and number of in-channel islands, however its maximum value was always the highest on this section. Meander curvature values have also increased (Table 6). Besides, the apex of meander 2. and 4. shifted 190-200 m from 1865 to 1953 and further 50-60 m from 1953 to 2000 (Fig. 25). Shifting can be explained by the maturing of the meanders and their slight downstream migration. As a conclusion however, this section has preserved its transitional state between meandering and braided patterns.

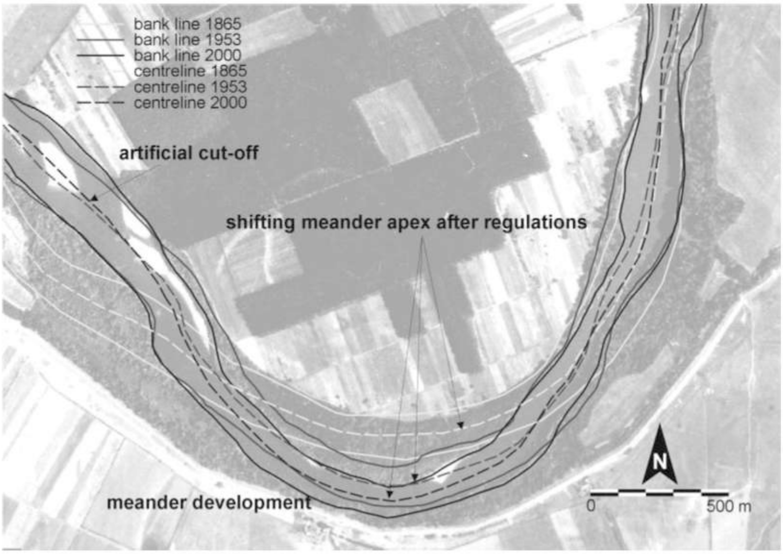

Figure 25. Shifting meander apex, and meander development at bend 4. (2000 aerial photo in the background).

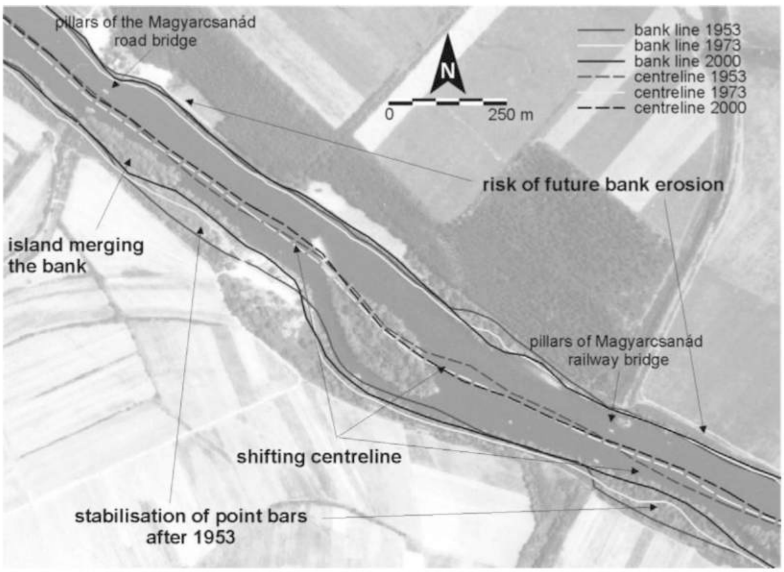

Figure 26. Shifting centreline at a straightened section (2000 aerial photo in the background).

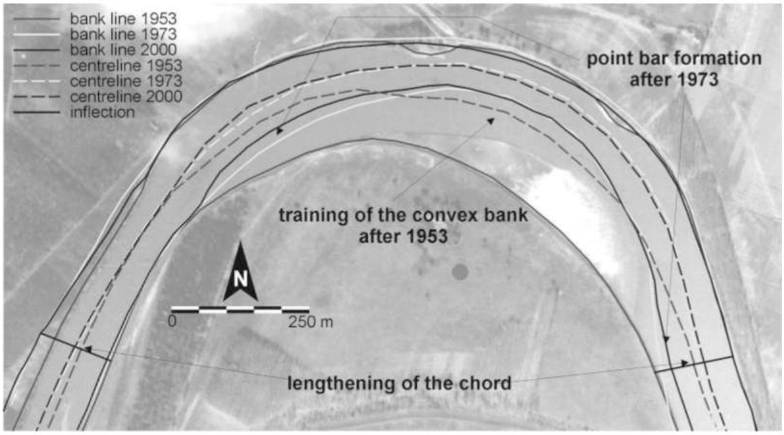

Figure 27. Development of a mature meander (bend 29) on Section 3. (2000 aerial photo in the background).

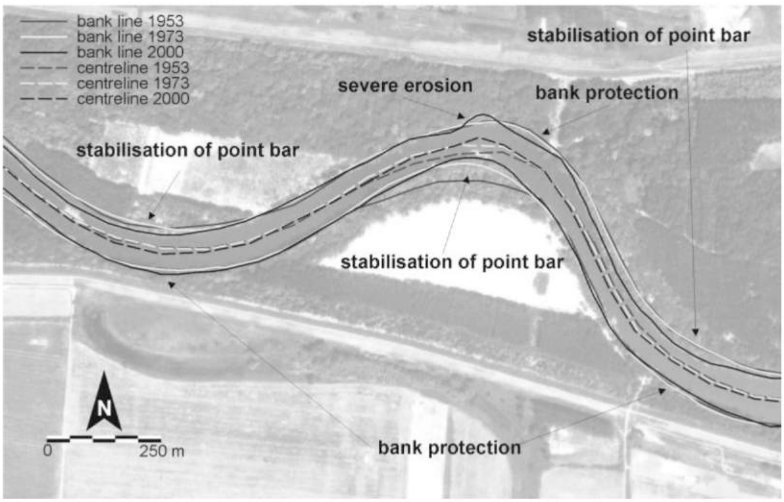

Figure 28. Shifting of centreline due to point bar formation on Section 4. (bends 40., 41. and 42.) (2000 aerial photo in the background).

In case of Section 2. the length of the centreline decreased by 56 % from 32-14 km (Table 6). Due to increasing slope the channel slightly incised, later at certain sections it widened and braided units of islands and bars developed. The significant shifting of the centreline (occasionally 60-70 m between 1953-2000) underlines the changing character of straightened Section 2 (Fig. 26). As a consequence centreline length has also varied significantly, however a/c values are far less than the threshold value (a/c = 1.1) for undeveloped bends. Based on the above, Section 2. has turned to be a truly braided reach due to the regulations.

Table 6. Change of morphological parameters determining channel pattern (length of centerline: p, sinuosity: S, total sinuosity: ΣP, meander curvature: a/c)

p (m)	1953	1973	2000
Section 1.	9205	9292	9312
Section 2.	14364	14326	14340
Section 3.	16613	16716	16775
Section 4.	9132	9168	9212
Entire section	49314	49502	49639
S	1953	1973	2000
Section 1.	1,3770	1,3900	1,3921
Section 2.	1,0213	1,0186	1,0196
Section 3.	1,1794	1,1867	1,1909
Section 4.	1,0862	1,0905	1,0957
Entire section	1,1404	1,1448	1,1478
ΣP	1953	1973	2000
Section 1.	2,0539	2,0103	1,9317
Section 2.	1,5877	1,5289	1,4737
Section 3.	1,2544	1,3052	1,2966
Section 4.	1,0862	1,0905	1,0957
Entire section	1,4537	1,4452	1,4134
a/cmean	1953	1973	2000
Section 1.	1,3187	1,3304	1,3245
Section 2.	1,0121	1,0091	1,0104
Section 3.	1,1345	1,1413	1,1449
Section 4.	1,0601	1,0633	1,0668
Entire section	1,0869	1,0897	1,0917

The length and sinuosity of the earlier meandering Section 3. has also decreased (by 43 %) due to the regulations. Nevertheless, here a slight increase can be detected between 1953 and 2000, but these changes were also caused by human intervention, namely the training of certain meanders in the 1950s. The best example in this respect is meander 29. (Fig 27), where the a/c value increased from 1.42 to 1.50 due to regulation activities (revetments). Later, from the 1980s due to the formation and stabilisation of 40-50 m wide point bar surfaces (Blanka *et al.* 2006) inflection points were replaced, chord length increased and thus the a/c value decreased (a/c = 1.48). As opposed to the slight overall increase of curvature values on Section 3. 45 % of the reach still dose not meet the threshold morphological parameters of river bends.

Section 4. is outstanding in terms that its length decreased the most drastically due to the regulations, by 65 %. This is still the "most managed" reach of the river, as the concave bank of almost each meander is fixed by revetment structures. On the contrary, the sinuosity of the section slightly though, but continuously increased between 1953 and 2000 (Table 6). Centreline increase is mainly resulted by changes on the meanders closest to the estuary. Here point bar formation gradually pushes the centreline towards the protected bank (15 m in average). Still, only 4 bends can be classified as well developed on this section (Table 6). Based on the above it is obvious, that changes on Section 4. are the most significant in terms of a pattern rearrangement, though this is inhibited by bank protection structures (Fig. 28).

Conclusions

In all it turned clear that due to the regulation works the rate of morphological development has slowed down on both managed and unmanaged sections (Fig 29). Although on certain reaches there are obvious signs of channel pattern rearrangement, during the assessed 50 years the length of the centreline increased only by 325 m, while sinuosity increased by only 6 ‰, and the values of average meander curvature increased even more slightly, by 4.4 ‰. The decrease of total sinuosity is clear however (2.9 %), which is in close relation with the decreasing number of in-channel islands.

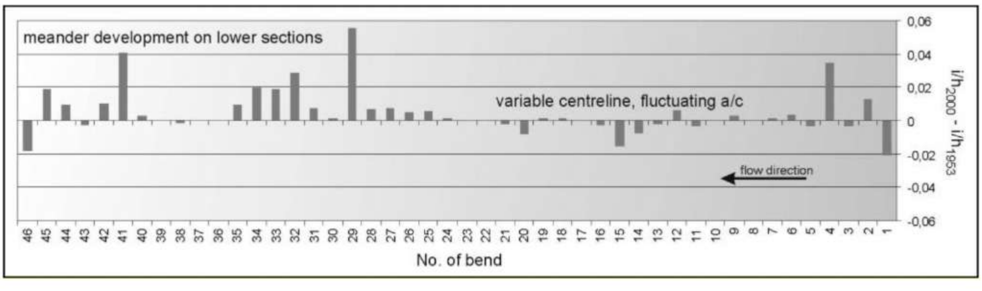

Figure 29. Difference of 1953 and 2000 a/c values of bends ont he studied section. If compared to Fig. 24, significantly smaller changes

Floodplain aggradation and floodplain geomorphology

Preliminaries

Extended floodplain areas were formed by the rivers of the Carpathian Basin, however as the consequence of mid-19th century river regulation works the area of floodplains were drastically decreased. The levee constructions split the uniform floodplain to an active artificial and an inactive protected floodplain which developed in different ways.

The development and geomorphological processes of floodplains are widely studied. According to early researches the dominant process on floodplains is lateral accretion in connection with channel migration (Friedkin and Lászlóffy 1949, Wolman and Leopold 1957, Károlyi 1960). According to Wolman and Leopold (1957) 80-90 % of the floodplain-material is derived from lateral accretion and only insignificant amount (10-20 %) is from vertical accretion deposited during floods. However, the latest one might be even missing in case of some floodplains (Allen 1965). Later, the researches emphasised the role of vertical accretion in floodplain processes, highlighting overbank aggradation, island and ox-bow lake sedimentation (Chorley *et al.* 1985). Factors influencing the development of floodplains were divided into two groups by Nanson és Croke (1992), where the main factors are (1) lateral point-bar accumulation; (2) vertical accretion of floodplains in the form of natural levees, sand sheets and fine floodplain sediments; and (3) channel aggradation of braided rivers. In their classification secondary processes are (1) silting-up of concave banks; (2) aggradation of convex banks of wide rivers and (3) accretion of oxbow lakes.

The overbank sedimentation on natural floodplains is a very complex process influenced by numerous factors, therefore its spatial and temporal pattern is quite uneven. The overbank accumulation is greatly dependent on the gemorphological features and micro-topography of the floodplain (natural levee, back-swamp, drainage ditches and abandoned channels etc.), which control overbank hydraulics (Nicholas and Walling 1997). Other factors, as riparian vegetation (Steiger *et al.* 2001, Kiss and Sándor 2009), distance from the active channel (Walling and He 1998, Oroszi 2008) and width of the floodplain (Gábris *et al.* 2002) also influence the sedimentation.

The natural floodplain development might be altered by human impact. Here the key factor is the sediment discharge modification, which was detected on each continent during the last 200 years (Owens *et al.* 2005), thus the rate of floodplain aggradation was increased by one order approximately (i.e. Knox 1987, Florsheim and Mount 2003, Benedetti 2003). Most studies explain it by catchment-scale human induced changes, like mining (Knox 2006), land conversion (Florsheim and Mount 2003), intensifying agriculture (Mücher *et al.* 1990, Lecce and Pavlowsky 2004, Knox 2006, Owens and Walling 2002), timber harvest (Constantine *et al.* 2005) and anthropogenically induced changes in fluvial dynamics (Hohensinner *et al.* 2004, Owens *et al.* 2005). Local human impact also can cause accelerated floodplain aggradation, like revetment construction (Károlyi 1960, Brown 1983), river regulation (Ten Brinke *et al.* 1998) and creation of narrow artificial floodplain (Gábris *et al.* 2002).

However in some cases the overbank sedimentation was reduced in response to better land management and soil conservation practices (Knox 1987, Benedetti 2003), forestation due to depopulation and socio-economic changes (Keesstra 2007). Besides, the impact of river incision in response to channelisation can decelerate overbank sedimentation, since incision can raise the relative elevation of the floodplain above the river bed, thereby the frequency of overbank flows and the overbank aggradation can be reduced considerably (Wyzga 2001).

Table 7. Overbank sedimentation on the artifical floodplain of the Tisza River since the 19th century regulation works

Author	Location	Method	Period	Total amount (and rate) of overbank sedimentation
Károlyi (1960)	Along the Tisza River	compariso n of elevations	1838-1957	Narrow floodplains: 0.8-1.6 m (0.6-1.3 cm/y) Wide floodplains: 0.2-0.5 m (0.1-0.4 cm/y)
Gábris *et al.* (2002)	Tiszadob	DTM	1846-1983	Floodplain: 0.15-0.59 m (0.1-0.4 cm/y)
Szabó *et al.* (2008)	Gulács	heavy metal markers	1946-2008	Floodplain: 0.58-0.60 m (0.9-1 cm/y)
Balogh *et al.* (2005)	Vezseny	pre-regulation buried paleosoils	1857-2005	Floodplain: 0.4-0.75 m (0.2-0.5 cm/y) Point bar: 1.70-1.83 m (1.1-1.2 cm/y) Ox-bow lake: over 1.5 m (over 1.0 cm/y)
Sándor and Kiss (2006) Sándor and Kiss (2008)	Nagykörű, Szolnok, Mártély	magnetic susceptibility, heavy metal markers	1856-2005	River bank: 0.60 m (0.4 cm/y) Point-bar: 0.92 m (0.6 cm/y) Floodplain: 0.35 m (0.2 cm/y) Before 1975: 0.5-0.6 cm/y After 1975: 1-1.5 cm/y
Szlávik (2001)	Middle and Lower Tisza	cross-section surveys	1976-1983	Riverbank: 0.35 m (5 cm/y) Point bar, natural levee: 0.70 m (10 cm/y)

Overbank sedimentation plays important role in the floodplain development of the Tisza and Maros/Mureş Rivers (Table 7), since they transport considerable amount of suspended sediment and their floodplain became significantly narrower after 19th century levee constructions. Nevertheless researches were carried out just on the Tisza River. However, the geomorphological setting of the Maros/Mureş River promotes overbank sedimentation, because its short lowland section is situated in the front of an extended alluvial fan and the regulation work was quite drastic, as the meandering river became almost totally straightened. These factors altered the rate of overbank deposition by means of increased slope and channel erosion, which increased sediment discharge. Besides, the land-use of the floodplain was also changed, as wetlands and meadows were replaced by dense forests increasing the roughness of the floodplain (Kiss and Sándor 2009).

The present study aimed to (1) determine the rate and longitudinal variations of overbank sedimentation on the lowland section of the Maros/Mureş River since the mid-19th century regulation works, and to (2) evaluate the rate of accumulation in relation to geomorphological setting and forms of the floodplain. The rate of overbank aggradation has key aspect in flood hydrology and flood forecast, as the elevated floodplain is able to transport less amount of water (Keesstra 2007), thus even levee heightening might be necessary in accordance with the amount of aggradation. According to the calculations of Gábris *et al.* (2002) and Kiss *et al.* (2002) the cross-sectional area of the floodplain was already reduced by 5-16 % due to overbank deposition along the River Tisza playing important role in the development of record floods betewen 1998 and 2006.

Methods

To determine the spatial and temporal pattern of overbank sedimentation along the Maros/Mureş River two approaches were applied. The amount of sedimentation and its longitudinal characteristics were calculated based on elevation difference of the active and protected floodplain areas using DTM. The temporal changes in sedimentation rate were determined by sediment and pollen analysis. As the aim of the study was to specify the overbank sedimentation of the active artificial floodplain since the regulations, the number of applicable dating methods was limited, therefore the pollen grains of invasive plants appearing at known date were applied.

Digital Terrain Modelling

The DTM represents the area (250 km^2) of 4 km buffer zone along the 34 km long lowland section of the Maros/Mureş River (Fig 30B). Between the 28-34 fluvial km only the northern zone was modelled because no maps were accessible for the southern, Romanian section.

The DTM was created in ArcGIS 8.2 applying 10 m pixel size, using topographical maps (scale: 1:10,000) made in 1983. The whole area was divided by cross-sections spaced in 1 km distance parallel with each other and near-perpendicular to the Maros/Mureş River. The measurements were made for the areas bordered by the cross-sections and the levees. In order to determine the amount of floodplain aggradation since 1880 differences in mean elevation data between the artificial (active) floodplain and the flood-protected (inactive) floodplain areas were calculated.

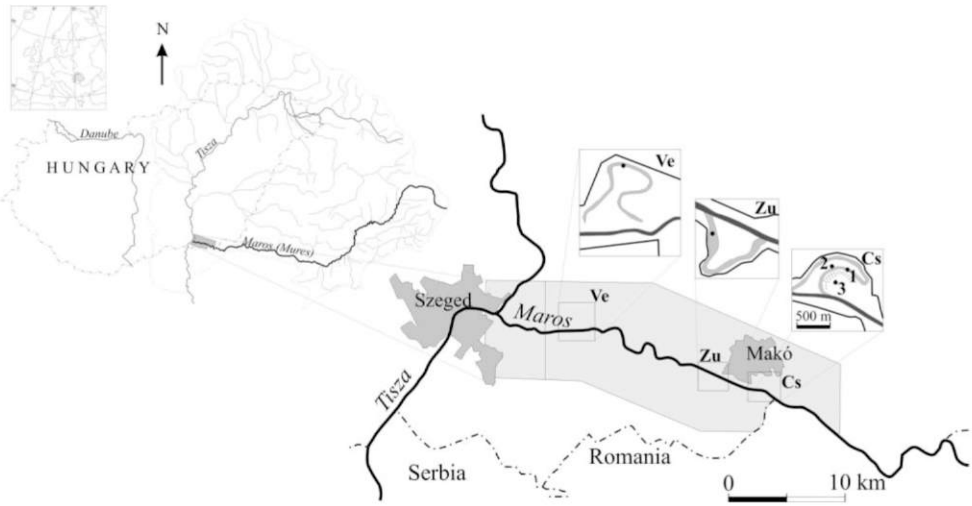

Figure 30. The study area is located on the Maros/Mureş River. The digital terrain model represents the 4 km buffer zone of the lowland section of the river. Sediment samples were taken at three sites (Ve, Zu. Cs) from cut-offs, and at Cs site from different geomorphological units (1-3).

Sedimentological and palynological analysis

The temporal variation of overbank accumulation was determined applying sedimentological and pollen analyses. Samples were collected at sites (Fig 30C) where (1) the grain size distribution changed sharply after the cut offs due to the increased distance from the active channel (e.g. the sandy deposits on the pre-regulation natural levee were covered by finer floodplain sediments, or in the cut-offs silt and clay were deposited over the coarse sand of the channel bed) and (2) always fine floodplain sediments were deposited, e.g. in a back-swamp (Table 8). Cut-offs (Cs1, Zu, Ve) were sampled from boreholes (5 cm interval), while at other sites (Cs2 and Cs3) sampling pits were established (2 cm sampling interval).

Table 8. Main characteristics of the sampling sites

Sampling site	Unit	Date of cut off	Distance from the active channel (m)	Floodplain width (m)	Vegetation	Sampled form	Elevation (m asl)
Csordajárás (Cs)	alluvial fan	1846	840	1700	meadow, plough field	cut-off (Cs1)	83.0
						natural levee (Cs2)	83.9
						back-swamp (Cs3)	83.2
Zugoly (Zu)	secondary alluvial fan	1864-72	450	2100	forests, orchards	cut-off	81.5
Vetyehát (Ve)	floodplain	1858	1740	2200	plough fields replaced by forests	cut-off	78.0

Grain size distribution of the samples was determined by Köhn-pipetten method and wet sieving, the organic content (%) was measured following Tyurin's method.

Pollen extraction followed the method of Zólyomi-Erdtman, the sporomorpha were studied under a 400-600× magnification, and identification was carried out on species, genus and family levels. Pollen diagrams were drawn under Tilia and TiliaGraph softwares. The arbour (AP) species were divided into allochthonous species representing upstream catchment areas and autochthonous species reflecting the local environment. The allochthonous pollen were used to identify greater floods (see Weninger and McAndrews 1989, Xu *et al.* 1996, Constantine *et al.* 2005).The herbaceous (NAP) species were also divided as above, but the autochthonous species were grouped into associations as pondweeds (*Lemnetea*), reed (*Phragmitetea*), wet meadows (*Molinio-Juncetea*), dry meadow and ruderal weeds (*Festuco-Brometea+Chenopodietea*), herbs of willow stands (*Salicetea* NAP) and other herbs. As introduced invasive species were used to date the sediment, they got into a separate group. The appearance date of an invasive species on the floodplain of the Maros/Mureş River was determined based on herbariums and descriptions. Those species were used for dating, which have well documented history and no close native relatives.

Spatial pattern of aggradation based on DTM

The reach can not be considered as one entity, as it can be divided into five geomorphological units (Fig. 31).

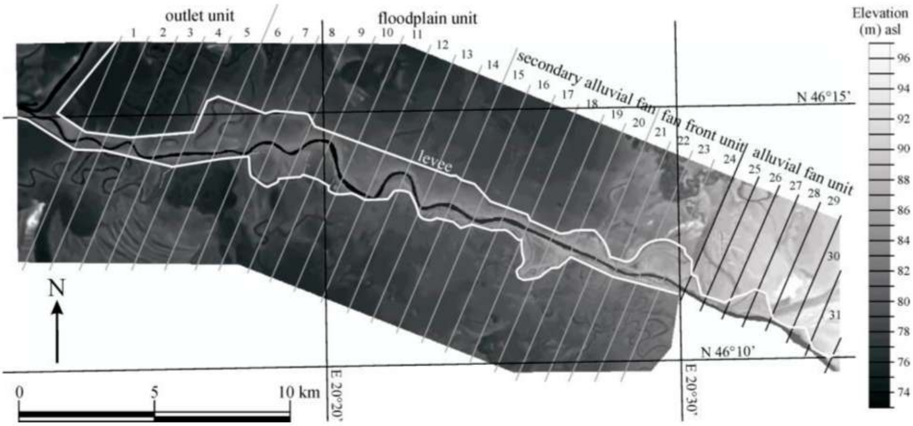

Figure 31. The digital terrain model of the study area represents the active floodplain bordered by levees, the lines frame the areas which were the basis of the height calculation. Based on the amount and pattern of aggradation the area was divided into five geomorpological units.

The alluvial fan unit is the highest characterised by Pleistocene sand ridges and shallow valleys dissecting the alluvial fan. In this unit the pre-regulation Maros/Mureş River had meandering-anastomosing pattern and slightly (0.3-1.5 m) incised floodplain. The levee was built on the edge of this lower floodplain section (Fig. 32). During the regulations this section of the Maros/Mureş River was totally straightened, thus the channel became deeper and much wider, the pattern changed into braided (Kiss and Sipos 2007). These changes affected the floodplain development, as along the regulated channel another lower floodplain was developed, therefore the artificial floodplain can be divided into a higher and a lower part (their difference is 0.8-1.1 m). Therefore, the duration of floods is not even on the artificial floodplain, the lower floodplain is inundated more often. Because of these terrace surfaces, it is not possible to calculate the aggradation using the DTM.

The southern segment of the fan front unit is characterised by abandoned meanders and point-bar remnants, whilst the higher northern part (by 1.2-1.9 m) is dissected by deep valleys and covered by sand dunes. In this unit the whole active floodplain is quite aggraded especially the areas near the active channel, though some pre-regulation forms are still visible. Comparing the mean elevations the amount of overbank accumulation is 1.62±0.27 m. Since the elevation of the protected floodplain segments differs considerably, it is also possible to calculate the amount of aggradation compared just to one flood protected segments. The amount of overbank aggradation is 0.89±0.45 m compared to the northern side, but 2.34±0.11 m compared to the southern one.

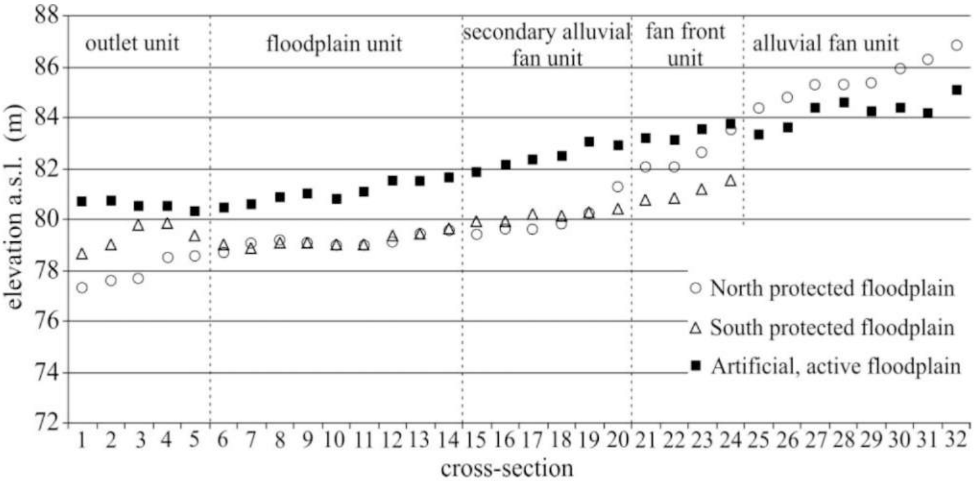

Figure 32. Elevation differences between the northern and southern flood protected areas and the elevation of the artificial (active) floodplain

The next unit can be considered as a secondary alluvial fan, which was developed after the levee constructions, as the form is limited to the artificial floodplain and it is much higher than the protected pre-regulation floodplain areas. The flood-protected area is characterised by breaches, crevasse-splays of the former meanders and back-swamps. In this unit the accumulation is the greatest (2.44±0.24 m), being the most intensive along the river in the form of natural levees. The aggradation shows an increasing tendency towards downstream, which suggest the active development of the secondary alluvial fan. Its northern and southern segments are nearly at the same elevation (height difference 0-0.8 m), therefore there is no significant difference in the amount of accumulation comparing the active floodplain height to these protected areas (North: 2.54±0.42 m; South: 2.35±0.27 m).

On the classical floodplain unit the fluvial form assemblage is the same as it was in the previous unit, but here the intensive aggradation is limited along the active channel in the form of point bars and natural levees, the further areas are characterised by moderate aggradation. Since the post-regulation aggradation did not bury the former geomorphological features, it can be seen that the former floodplain was also convex. The protected former floodplain areas are almost at the same elevation (their difference: 0.3-0.1 m). In this unit the overbank sedimentation of the artificial floodplain is 1.96±0.23 m. The sedimentation shows a decreasing tendency downstream (Fig. 33). As the elevation of the two protected sides is almost the same, here the calculated aggradation data is probably the most precise (North: 2.01±0.26 m; South: 1.91±0.23 m).

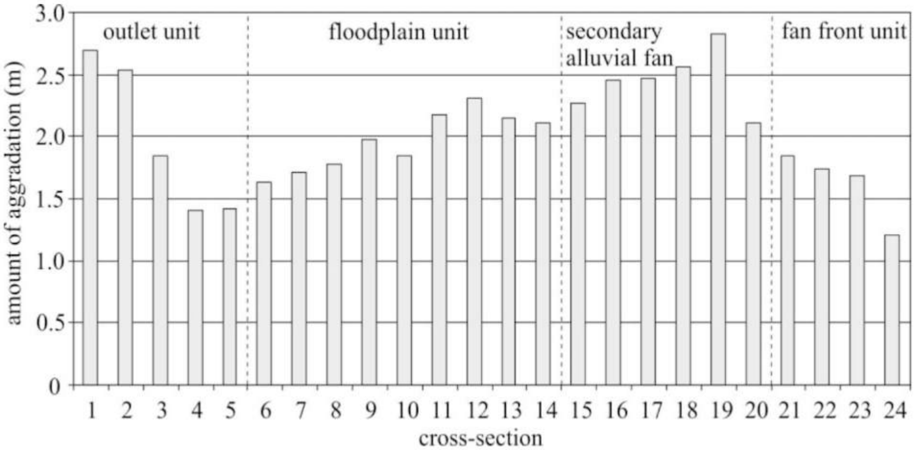

Figure 33. Amount of aggradation on the active floodplain since levee construction (1880-1983)

The outlet unit of the reach differs from the upstream units in its regulation history, because here the long cut-off section of the Maros/Mureş River got outside of the artificial floodplain, thus the post-regulation sediments were deposited on a flat surface instead of a convex one. The elevation difference between the northern and southern flood-protected area is the greatest (0.8-2.1 m) of all units. Before the regulations the northern area was a flat back-swamp with shallow breaches, but the southern area is characterised by a great paleo-channel with high point-bar system. The amount of aggradation is greater (1.98±0.60 m) than it was before showing an increasing tendency towards the outlet of the Maros/Mureş River. The pattern of the accumulation is also different, as it is the greatest in the back-swamp area instead of near the channel. In this unit the calculated accumulation data could be distorted by the high elevations of the southern paleo-point-bars, therefore compared to the southern inactive floodplain segment it is only 1.25±0.61 m, but compared to the deeper northern part it is 2.70±0.70 m m.

Temporal pattern of aggradation: analysis of sediment profiles

Sediment and pollen profile of a cut-off (Cs1) located on the fan front unit

The sediment record of the almost totally filled up cut-off was divided into three zones and the middle zone into two sub-zones based on the physical and palynological character of the samples (Fig. 34).

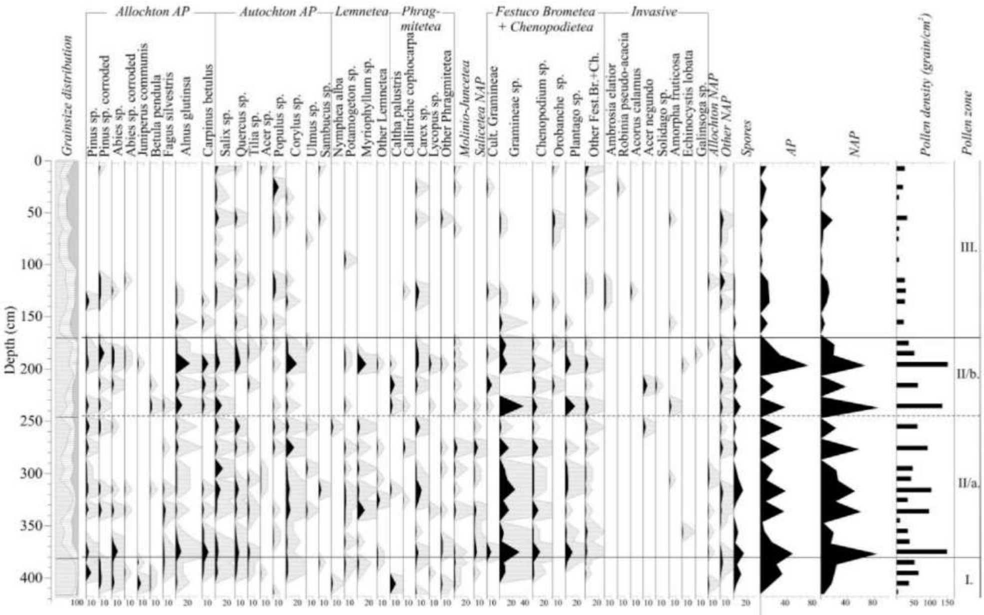

Figure 34. Sediment and pollen profile of a cut-off (Cs1) located on the fan front unit. The proportion (%) of pollen grains is exaggregated (10x) for better visualization, AP: arbour species, NAP: herbaceous species.

In the lowest zone (I. 380-420 cm) the samples contain high proportion (77-92 %) of sand. The coarse sand fraction (0.1-0.32 mm) represents the bed-load material of the river. The proportion of allochthonous pollen grains (*Pinus, Abies, Juniperus*) is high and because they were transported from the upper part of the catchment, very often the grains are corroded and broken. The pollen spectrum also reflects the environment of the site, where *Salix* and *Quercus* were the dominant species of the riparian forest. The samples of the zone were deposited before the cut-off (1846) when the channel was still active.

The samples of the middle zone (II. 170-380 cm) contain more clay and silt (25-50 %) and organic material, but sandy layers are intercalated in between them. In the II/a sub-zone (245-380 cm) pondweed species (*Myriophyllum*, *Potamogeton* and *Nymphea*) appear and *Carex* indicates the expansion of the marshland. The higher surfaces were covered by riparian forest (*Salix*, *Quercus*, *Populus* and *Ulmus*), pastures and plough-fields. This sub-zone represents an ox-bow lake in its juvenile stage with deep open water. Sand and allochthonous pollen from the catchment were washed into the lake during floods. The sandy layers are covered by finer, organic rich sediments deposited during falling stage or smaller floods. The pollen of *Amorpha fruticosa* were found in the 300-310 cm sample, the plant appeared in the area in 1884 (Tímár 1948), whilst the *Acer negundo* was found in the 250-260 cm sample and was discovered in 1889 (Prisztcr 1960).

The pollen spectrum of the II/b sub-zone (170-245 cm) reflects mature state of the ox-bow which most of the time was wetland and open water appeared just temporally in the deepest part during floods when allochthonous pollen were also transported to the site. The decreased amount of sand suggests that flood velocity decreased as the cut-off was gradually filled up. After floods pondweeds appeared, though the plants of wetland associations (i.e. *Caltha*, *Carex* and *Lycopus*) are continuously represented. These changes reflect the rapid sedimentation of the cut-off. Pastures and cultivated areas extended in the close vicinity of the site (reflected by cult. Gramineae, *Chenopodium*, *Orobanche*, *Plantago* and *Artemisia*). The pollen of the invasive *Solidago* sp. (at 210-220 cm) and *Galinsoga* sp. (at 180-190 cm) were found, however we could not identify them on species level, but their different species appeared in the area between 1870 and 1902 (Tímár 1948).

In the upper zone (III. 0-170 cm) the higher clay content of the samples indicates the exclusive deposition of suspended sediment. By this time the cut-off became aggraded in such extent, that it did not play role in water conductivity during floods, so the sediment could reach this point just in suspension. The wetland almost disappeared, hygrophilous species appeared temporally during floods. The riparian forest was driven back and near the site pasturing and ploughing became dominant. For dating the sediment the pollen of *Ambrosia artemisiifolia* (115-135 cm) can be applied, which appeared on the floodplain in 1955 (Prisztcr 1960).

Sediment profile of a natural levee (Cs2) on the fan front unit

The natural levee became inactive after the meander became cut off in 1846 (Fig. 30C). The sediment profile was divided into two zones (Fig. 35). Because the form is elevated its material is drier, therefore no pollen gains were found.

In the lower zone (I. 35-138 cm) the proportion of sand fraction is very high (80-85 %), but it is slightly finer (0.1-0.2 mm) than the present-day bed-load (0.2-0.3 mm) of the Maros/Mureş River. Between the sandy sediments silty (40 %) and clayey (20 %) layers rich in organic material are intercalated, which were probably deposited during falling stage of floods. These characteristics suggest that this zone represent the period of active natural levee formation.

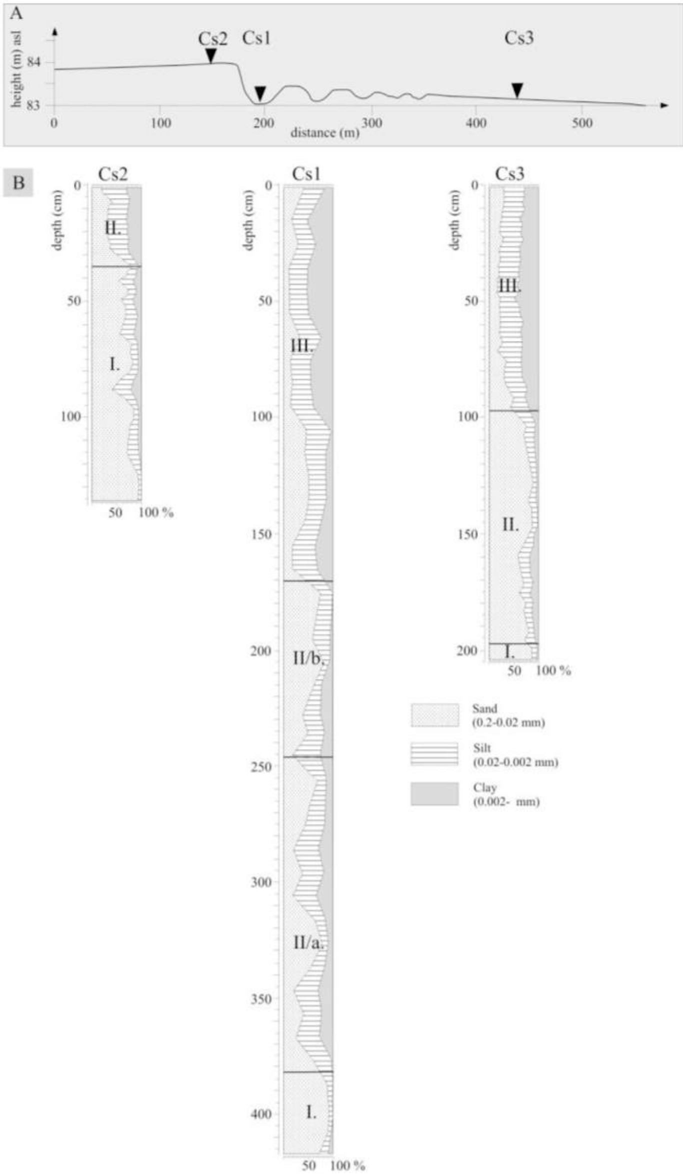

Figure 35. Sediment profiles of the Csordajárás (Cs) site, on the fan front unit. A: The Cs1 coring was made in a cut-off, the Cs2 on its natural levee and Cs3 in the backswamp area, behind the point-bars. B: Grain-size distribution (%) of the profiles.

The proportion of sand decreased to 30-40 % in the upper zone (II. 0-35 cm), and it is mostly consists of very fine sand. The proportion of silt and clay increases to 40 % and 20-30 % respectively. These samples correspond to the post-regulation period, when only suspended sediment could be transported and deposited at the site.

Sediment profile of the back-swamp (Cs3) on the fan front unit

The site is situated near the cut-off and natural levee described above. It was enclosed by the meander just behind its point-bar system and it was always a back-swamp (Fig. 30C). Unfortunately its samples are pollen sterile.

In the lower zone of the profile (I. 198-206 cm) the sand fraction is dominant (90 %), the proportion of medium sand is 60 % (Fig. 35). Finer fractions are underrepresented and the organic content of the samples is very low. These samples probably represent a point-bar and they were deposited when the meander was developing and the site was at the channel. In the middle zone (II. 98-198 cm) the amount of sand fraction decreases (60-80 %) and the medium sand fraction is replaced by finer sand. The sediments are getting finer (154-198 cm), but then they become coarser again (98-154 cm) as the proportion of sand reaches 90 %. The finer sediments of the upper zone (III. 0-98 cm) sign that the active channel got far from the site, thus just suspended sediment (silt and clay 40-40 %) was deposited.

Comparing the profile to the Cs2 sediment record it becomes possible do determine the age of the zones. Probably the lower and middle zones were deposited when the meander was still active, and gradually finer material was deposited as the channel migrated away from the site. The sediments of the upper zone were deposited after the regulation, when only final material could be transported here.

Sediment and pollen profile of the cut-off (Zu) located on the secondary fan unit

The lowest zone (I. 170-400 cm) consists of high proportion of sand (90-100 %), and the amount of medium sand representing the bed-load material is 10-35 % (Fig. 36). As these samples are almost pollen sterile it is difficult to reconstruct the environment. The bottom sample (390-400 cm) contains some pollen (9-23 grain/cm^2), whilst in the upper samples pollen density increases simultaneously with silt and clay content (310-350 cm: 5-8 grain/cm^2; 230-240 cm: 9-12 grain/cm^2). The pollen spectrum dominated by allochthonous, mostly broken pine pollen grains, but some autochthonous pollen also appeared (*Populus*, *Carex*, *Phragmites*, Gramineae and cultivated plants).

The middle zone (II/a. 170-90 cm) contains very fine material, since the proportion of silt increases to 45 % and the clay to 25 %. Though some sandy layers also appear, e.g. between 160 and 130 cm depth the sand fraction (0.2-0.1 mm) has double peak. These sediment property changes reflect that the channel was not active any more and sandy material was transported into the cut-off just during floods. The zone is rich in pollen, though the pollen density decreases upwards (130-160 cm: 54-154 grain/cm^2; 90-130 cm 3-54 grain/cm^2).

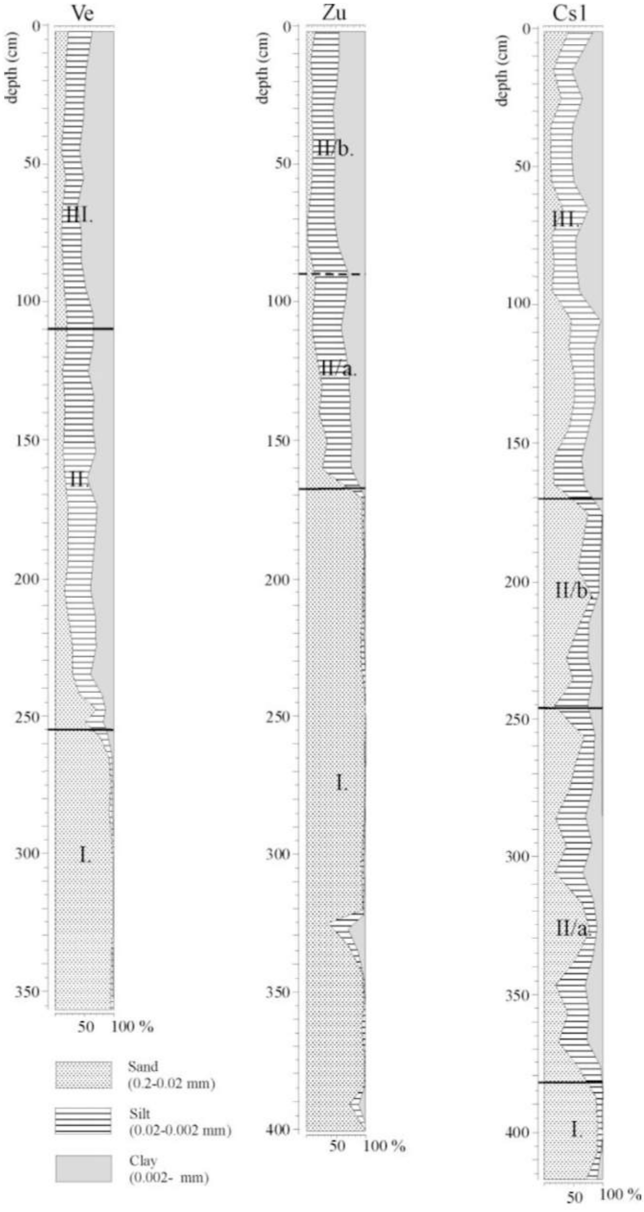

Figure 36. Sediment profiles of the studied cut-offs: Ve is located on the floodplain unit, Zu is on the secondary fan unit and Cs1 is situated on the fan front unit.

This zone contains considerable amount of alochtonous grains, like *Pinus* (very often broken), *Fagus* and *Alnus*. The pondweeds (*Nymphaea*, *Myriophyllum* and *Potamogeton*) indicate deep water in a juvenile stage ox-bow, which was surrounded by reeds. The riparian forest was dominated by willow and poplar species mixed with *Quercus*, *Fraxinus* and *Ulmus*. Some lands were cultivated nearby as it is indicated by cereals and weeds. The *Amorpha fruticosa* was introduced in 1885 to stabilise the riverbanks (Tímár 1948, Priszter 1960) and its pollen appeared in the 130-140 cm sample.

In the upper zone (II/b. 0-90 cm) the sediment is getting even finer, as the proportion of clay increased to 50 %. As the cut-off was aggrading and getting shallower the velocity of the flood water decreased considerably, therefore just suspended material was deposited. The intensive sedimentation is also reflected by a 1914 map, which show a filled-up cut-off covered by wet meadow. The pollen density of the samples is low (1-20 grain/cm^2). The environment of the cut-off did not change significantly, as still mixed willow stands are nearby. The species of the *Phragmitetea* are continuously represented, while the *Molinio-Juncetea* association reflect the existence of wet meadows. In the area the first appearance of the *Ambrosia artemisiifolia* was detected in 1955 (Priszter 1960), and its pollen grains were found in samples between 70 and 80 cm. In the upper samples (0-30 cm) the proportion of arboreal pollen decreases, though the *Populus* sp. becomes dominant in connection with the intensive poplar forest plantations in the 1960's. The cut-off became drier as only *Carex* sp. could grow, but the grasses, cereals and other cultivated plants and their weeds became more abundant. The pollen grains of the *Ambrosia* are represented in great number indicating its intensive spreading, which is also proven by the air pollution data of the last few decades (Makra *et al.* 2005).

Sediment and pollen profile of a cut-off (Ve) located on the floodplain unit

The lowest zone (I. 255-360 cm) contains mostly sand (90 %), where the high proportion (20-40 %) of medium sand represents the bed-load of the pre-regulation channel (Fig. 36). The pollen density of the samples is quite low (0-15 grain/cm^2), except a silty sample (330-340 cm: 77 pollen grain/cm^2). Besides of the great number of allochthonous pollen grains (*Pinus*, *Fagus* and *Alnus*) the local vegetation is also represented. Near the channel riparian forest dominated (*Quercus*, *Salix* and *Populus*) whilst the deeper areas were covered by marshes and wetlands.

In the middle zone (II. 110-255 cm) the grain-size and the proportion of sand decreases (20 %). Similarly to the site at Zugoly (Zu II/a zone) a double peak of 0.1-0.2 mm sandy deposits can be identified at 255-230 cm depth. Based on its pollen content the zone can be divided. In the lower sub-zone (II/a 180-255 cm) the pollen density is high (maximum 282 grain/cm^2 at 250-255 cm). There are numerous allochthonous pollen and their broken fragments (*Pinus*, *Fagus*). The local forest was dominated by oak, poplar and hazel. In the ox-bow lake *Myriophyllum* was typical, while many marshland species also occurred (eg. *Callitriche*, *Lycopus* and *Carex* sp.). The elevated surfaces were cultivated as it is reflected by the corn pollen and some weeds (*Chenopodium*, *Plantago*).

In the upper sub-zone (II/b 110-180 cm) the pollen density decreases (0-14 grain/cm^2). The pollen spectrum is similar to the previous sub-zone, though the proportion of hygrophilous plants decreased. Probably it is in relation with the rapid aggradation of the cut-off which was probably dry most of the time, only great floods could supply some water and allochthonous sediment to the depression.

In the upper zone of the sediment profile (III. 0-110 cm) is getting finer, as the silt content decreases (30-35 %) and the clay content increases (50-60 %), indicating the increasing importance of suspended sediment in overbank sedimentation. Riparian forest is still dominant, but in the upper part of the zone (0-50 cm) *Populus* sp. becomes dominant in connection with the intensive forest plantation between 1953 and 1964. The increasing proportion of open-water pondweeds and wetland species indicate permanent water supply, which can be explained by the artificial modern water-retention of the cut-off.

Discussion

The average sedimentation rate of the studied area was 1.2 cm/y based on DTM, while the sedimentological and palynological data suggest 0.2-2.4 cm/y aggradation rate. These data are higher than the sedimentation rate measured on the Tisza River (Table 7), which can be explained by the different hydrological characteristics of the two rivers. The Maros/Mureş River has higher sediment discharge and slope, less intensive lateral migration, more irregular and narrower floodplain and the outlet of the river is very close to the margin of the alluvial fan. The rate of accumulation was not uniform in space nor in time, as it changed downstream and on the different fluvial forms.

Spatial changes

Aggradation rate along the river

First of all, a relation between the active artificial floodplain-width and the accumulation rate was analysed (Fig. 37). No unambiguous link was established between the parameters, though on the Tisza River Károlyi (1960) found negative, while Gábris *et al.* (2002) found positive relationship between them.

However, the geomorphological units of the studied reach presented characteristic tendency in the aggradation rate (Fig. 33). The overbank sedimentation was the most intensive in the secondary alluvial fan (2.44±0.24 cm/y), whereas in the outlet unit (1.98-0.6 cm/y) and in the floodplain unit

(1.96±0.23 cm/y) it was moderate, and low in the fan front (1.60±0.27 cm/y). The greatest difference between these units is slope, therefore the relation between the aggradation rate and slope was analysed (Fig. 38). These are directly proportional on the secondary alluvial fan and on the floodplain units, though as the slope decreases the standard deviation increases suggesting the influence of other factors (i.e. micro-relief or vegetation). In the case of the fan front and outlet units this relationship could not be found.

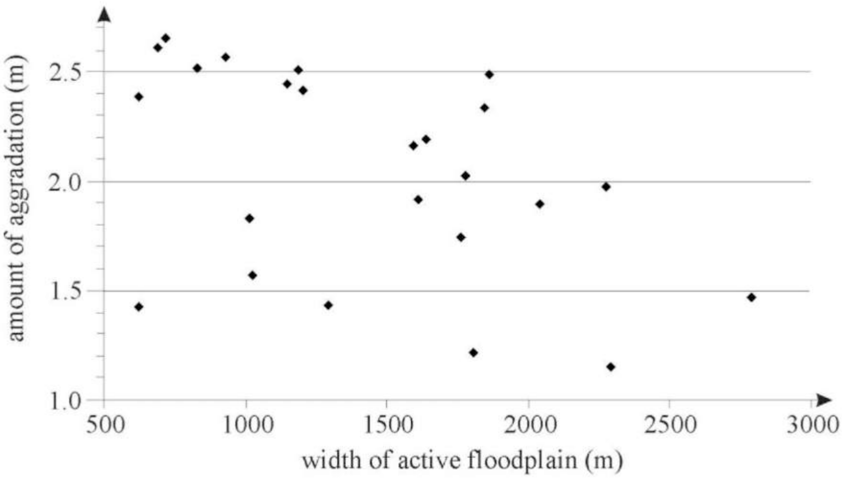

Figure 37. Relationship between the width of the artificial floodplain (m) and the amount of aggradation (m).

On the outlet unit the slope of the river plays secondary role in aggradation, as here the drain back effect of the Tisza is probably the major control on sedimentation. It can be proven by the increasing tendency (Fig. 33) of the aggradation towards the outlet (it is almost doubled) and by the pattern of the accumulation (Fig. 32). Here the greatest amount of aggradation is not along the active channel, but in the back-swamp area indicating the importance of particle settling from suspension in still water. The situation is totally different in the fan front unit, where the greatest slope and the smallest aggradation rate were measured. This phenomenon can also be explained by the velocity conditions (Fig. 39): here the velocity of the flood on the floodplain is quite great (0.3-0.5 m/s) due to the great slope of the floodplain and the low vegetational roughness (dominance of pastures and plough-fields). At this velocity the suspended sediment is in transportation according to the calculations of Bogárdi (1974), resulting smaller rate of aggradation.

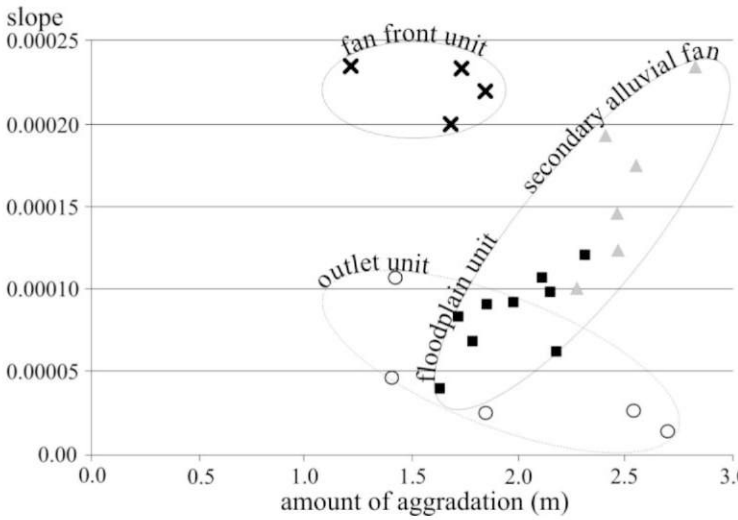

Figure 38. Relationship between the amount of aggradation (m) and the slope of the artificial floodplain on the different units of the study area.

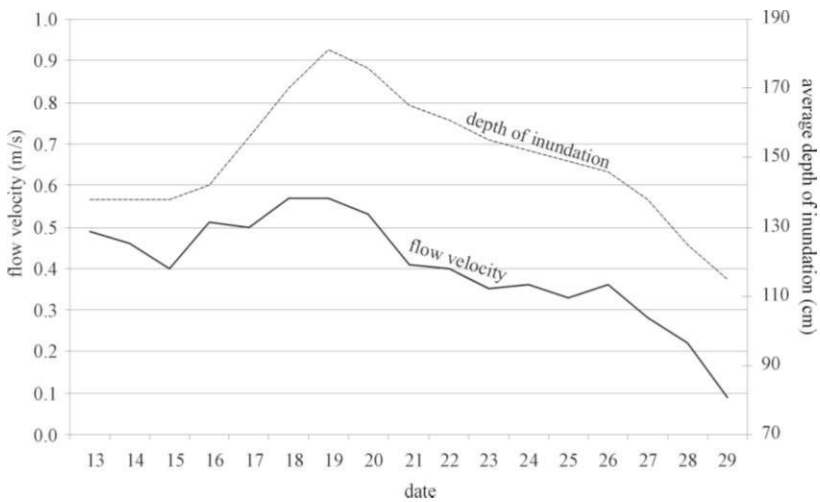

Figure 39. Average flood flow velocity and the depth of the inundation on the floodplain of the fan front unit in April, 2006.

Aggradation rate on different forms

The role of micro-topography was evaluated in the area of the fan front unit, where the sites (Cs1-3) were close to each other, but far from the present-day active channel (ca. 840 m) and the only one difference between them was elevation (Table 3). The average rate of overbank sedimentation was 0.2 cm/y on the former natural levee (Cs2) at the highest elevation, while it was tripled (Cs3 site: 0.6 cm/y) on the lower back-swamp area. The deepest part of the floodplain is the cut-off where the average rate of aggradation was the greatest (Cs1: 2.4 cm/y). Thus the elevation of the different geomorphological forms influences the aggradation rate via the duration, depth and energy of the inundation. Similar results were found by Benedetti (2003) and Walling and He (1998). Besides, these data derived from the sediment profiles correlate well with the average aggradation rate (0.9 cm/y) calculated for the whole floodplain applying the DTM.

The sedimentation was the most intensive (1.3-2.4 cm/y) in the low lying cut-offs, but its rate was different as a result of variation in the (1) date of the cut off, (2) duration of floods, (3) distance of the site from the active channel. According to earlier measurements on active overbank sedimentation, beyond the 250 m buffer zone of the channel only suspended sediment is transported and deposited on the floodplain of the Maros/Mureş River (Oroszi 2008). Since all investigated cut-offs are 450 m further than the active channel, therefore nowdays only suspended sediment reaches these sites by diffusion. However in their earlier development phase the flood velocity in the cut-off was probably greater, thus coarser material was also transported into them. The accumulation rate in Cs and Ve sites was higher than it was calculated for the whole floodplain based on the DTM (Table 9), which is acceptable, as deeper surfaces has higher accumulation rate. However, at Zu site the rate of sedimentation was lower than it was calculated applying the DTM. It can be explained by the date of the regulation, as this was the last meander cut off. According to some descriptions (Iványi 1948) during the regulations the bed-load transport of the straightened Maros/Mureş River had increased in such an extent that the originally 4-5 m deep channel became quickly extremely shallow (0.1-0.5 m) due to intensive bar development. Therefore, the older cut-offs were the scene of greater aggradation just because they acted longer as sediment trap during the regulation.

Table 9. Main characteristics of the sampled cut-offs

Site	Year of cut off	Distance from the active channel (m)	Mean aggradation rate (cm/y) based on sediment analysis	Mean aggradation rate (cm/y) based on DTM
Cs1	1846	840	2.4	0.9
Ve	1858	1700	1.8	1.2
Zu	1872	450	1.3	2.1

Temporal changes

The results above suggest that the rate of aggradation could not be even during the last approximately 150 years (Fig. 40). Subsequently of the regulations, in the 19th century (between the date of the cut-off and 1884/89) the oxbow lakes in the cut-offs were in their juvenile development phase: they were deep and the sedimentation rate was high (1.9-2.4 cm/y) due to increased sediment load after the disturbance caused by the regulations. In the first half of the 20th century (1884/89-1960's) the sedimentation rate decreased (1.4-.2.1 cm/y). It can be explained by the decreased sediment input since the bank erosion and incision terminated in the straightened sections and the sediment trap function of the cut-offs gradually became less effective. The sedimentation rate became even smaller (0.5-0.9 cm/y) since the 1960's. This decreasing tendency is similar to the deposition history of other owbow-lakes (Tamás and Kalocsa 2003; Félegyházi 2009). However sedimentation rate became greater (2.6 cm/y) since the 1960's in the cut-off (Cs) situated in the fan front unit, which can be explained by local factors. The cut-off became so shallow that it was ploughed and due to soil erosion and the planation effect of ploughing more material was transported into it even during flood-free periods.

Conclusion

Accelerated overbank aggradation was measured along the Maros/Mureş River as a result of mid 19th century regulation works. It was so rapid, that within 50 years the cut-offs were filled up by sediment and lost their water cover. The accelerated sedimentation was in relation not just with the establishment of the narrow artificial floodplain, but also with channel adjustments. The artificial floodplain gave the spatial framework, but the real explanation of the accelerated aggradation is channel regulation. Due to these works the meanders of the lowland Maros/Mureş River were cut off, the channel became straightened. Since natural widening became dominant, it produced extra amount of sediment input for the Maros/Mureş River which is characterised by great sediment discharge in its natural state. The accelerated sedimentation was especially intensive in front of the alluvial fan, where a secondary alluvial fan was built.

The amount of sedimentation is unique in Hungary. Especially, if we consider, that the floods on the Maros/Mureş River are quite short compared to the Tisza River, thus the duration of at least 1.0 m deep floods is only one day in a year (Csoma 1975), and the return period of floods deeper than 2.0 m is 30 years (Boga és Nováky 1986). According to our calculations the floodplain was covered by at least 1.0 m deep flood for only 88 days during 105 years. This means, that the rate of accumulation is 1.5-2.7 cm/day during floods! Due to the aggradation the cross-sectional area of the active floodplain decreased by 19-35 %, therefore, the levees should be heightened to keep the flood hazard on its previous low level.

The original floodplain of the Maros/Mureş River was asymmetrical, therefore the calculation of overbank accumulation using DTM could be imprecise depending on the degree of asymmetry. Besides, the calculation probably overestimates the aggradation of the last 150 years, as the Maros/Mureş River always had convex, elevated floodplain near the active channel. Despite of these difficulties, the rate of overbank aggradation was similar by calculations based on the DTM and by analysing sediment profiles.

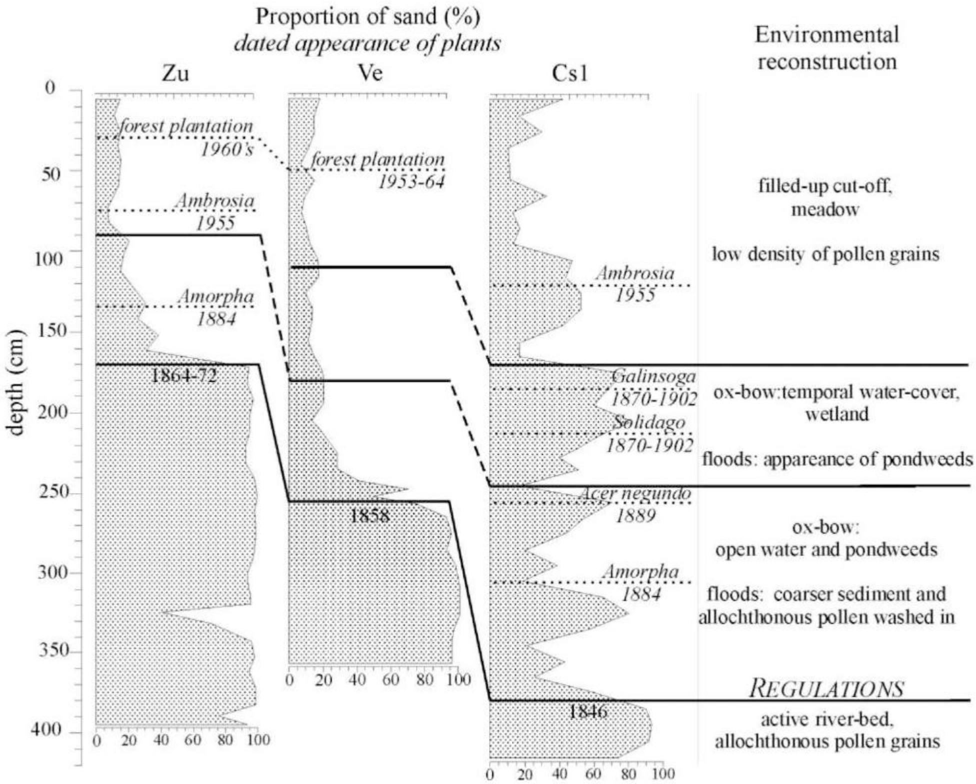

Figure 40. Comparison of the profiles of the cut-offs, paying special attention to the proportion of sand fraction in the sediment and the dated appearance of introduced plant species. Based on the pollen profiles environmental reconstruction was made for the sites indicating rapid aggradation of the cut-offs.

References

Allen, JRL. 1965. A review of the origin and character of recent alluvial sediments. Sedimentology 5: 89-191.

Andó, M. 1993. The geography of the Mureş River. Acta Geographica Szegediensis 31: 1–9.

Andó, M. 2002. A Tisza vízrendszer hidrogeográfiája. SZTE Természeti Földrajzi Tanszék, Szeged.

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.

Ashmore, P. E., 1991. How do gravel-bed rivers braid? Canadian Journal of Earth Sciences 28, 326-341.

Ashworth, P. J., Best, J. L., Roden, J. E., Bristowá, C. S. Klaasen, G. J. 2000. Morphological evolution and dynamics of a large, sand braid-bar, Jamuna River, Bangladesh. Sedimentology 47, 533-555.

Balogh, J, Nagy, I, Schweitzer, F. 2005. A Közép-Tisza mente geomorfológiai adottságainak és a hullámterek feliszapolódásának vizsgálata mintaterületeken. Földrajzi Értesítő 54/1-2: 29-59.

Benedetti. MM. 2003. Controls on overbank deposition in the Upper Mississippi River. Geomorphology 56: 271-290.

van der Berg. J.H., 1995. Prediction of alluvial channel pattern of perennial rivers. Geomorphology 12, 259–279.

Bezdán, M. 1998. Kölcsönhatások a Tisza-vízgyűjtő folyóin. Hidrológiai Közlöny 78/4: 247-249

Bezdán, M. 1999. A Tisza balparti mellékfolyóinak hatása az árhullámokra. Hidrológiai Közlöny 79/2: 89-99

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

Bodolainé Jakus, E. 2003. Az 1998. évi őszi tiszai és más nagy árhullámok időjárási okairól. Vízügyi Közlemények 85, Különszám I: 21-33

Boga, L, Nováky, B. (edts) 1986. Magyarország vizeinek műszaki-hidrológiai jellemzése. A felszíni vízkészlet mutatói: Maros. Vízgazdálkodási Intézet, Budapest: 32.

Bogárdi, J. 1954. Hordalékméréseink eddigi eredményei. Vízügyi Közlemények 36/2: 135-146.

Bogárdi J. 1974: Sediment transport in alluvial streams. Budapest, Akadémiai Kiadó, 826.

Bogdánfy, Ö. 1906. A természetes vízfolyások hidraulikája. Budapest: Franklin Társulat.

Borsy, Z., 1972. Sedimentological and geomorphological investigation on the Szatmár Plain after the record flood of 1970. Földrajzi Közlemények 21, 38–42.

Bridge, J.S., 2003. Rivers and floodplains: forms, processes, and sedimentary record. Balckwell, Oxford, pp. 141–214.

Bridge, J. S., Gabel, S. H., 1992. Flow and sediment dynamics in a low sinuosity, braided river: Calamus River, Nebraska Sandhills. Sedimentology 39, 125–142.

Bridge, J.S., Jarvis, J., 1982. The dynamics of a river bend: a study in flow and sedimentary processes. Sedimentology 29, 499–541.

Bridge, J.S., Smith, N.D., Trent, F., Gabel, L., Bernstein, P., 1986. Sedimentology and morphology of a low-sinuosity river: Calamus River, Nebraska Sand Hills. Sedimentology 33, 851–870.

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

Brown, AG. 1983. An analysis of overbank deposits of a flood at Blandford-Forum, Dorset, England. Revue de Geomorphologie Dynamique 32: 95-99.
Carling, P.A., Golélz, E, Orr, H. G., Radecki-Pawlik, A., 2000. The morphodynamics of fuvial sand dunes in the River Rhine, near Mainz, Germany. I. Sedimentology and morphology. Sedimentology 47, 227–252.
Chin, A., Gregory, K.J. (2005) - Managing urban river channel adjustments. Geomorphology 69, 28–45.
Chorley, RJ, Schumm, SA, Sugden, DE. 1985. Geomorphology. Methuen, London
Church, M., Jones, D., 1982. Channel bars in gravel bed rivers. In: Hey, R. D., Bathurst, J. C., Thorne, C. R., (Eds.), Gravel-bed rivers. John Wiley and Sons Ltd., Chichester, pp. 291-338.
Constantine, JA, Pasternack, GB, Johnson, ML. 2005. Logging effects on sediment flux observed in a pollen-based record of overbank deposition in a northern California catchment. Earth Surf. Process. Landforms 30: 813-821
Csoma, J. 1975. A Maros hidrográfiája. In Vízrajzi Atlasz sorozat 19. Maros. VITUKI Budapest: 7-12.
Dietrich, W.E., Smith, J.D., Dunne, T., 1984. Boundary shear stress, sediment transport and bed morphology in a sand-bedded river meander during high and low flow. In Elliot, C.M. (Ed.), River Meandering: Proceedings of the Conference. Rivers '83, American Society of Civil Engineers. New York. pp. 632–639.
Downs. P.W.. Gregory, K.J. (2004) - River channel management. Towards sustainable Catchment Hydrosystems. Arnold, London.
Dunka, S.. Fejér. L., Vágás, I., 1996. History of the regulation works on River Tisza. Vízügyi Múzeum, Budapest.
Eaton, B.C., Lapointe, M.F., 2001. Effects of large floods on sediment transport and reach morphology in the cobble-bed Sainte Marguerite River. Geomorphology 40, 291–309.
Félegyházi, E. 2009:Ártéri lapályok elhagyott meder- és morotvatavainak feltöltődési sebessége. In: Kiss T. – Mezősi G. (edts): Recens geomorfológiai folyamatok sebessége Magyarországon. Földrajzi Tanulmányok 2, Szeged, 55-65.
Fiala, K., Sipos, Gy., Kiss T. 2006. Szabályozások hatására bekövetkező morfológiai változások a Tisza és a Maros alsó szakaszán. In Kiss A. – Mezősi G. – Sümegi Z. (szerk): Táj, környezet és társadalom. Ünnepi tanulmányok Keveiné Bárány Ilona professzor asszony tiszteletére.203-213.
Fergusson, R.I., 1987. Hydraulic and sedimentary control of channel pattern. In: Richards, K.S., (Ed.), River channels: environment and process. Blackwell, Oxford, pp. 129-158.
Florsheim, JL, Mount, JF. 2003. Changes in lowland floodplain sedimentation processes: pre-disturbance to post-rehabilitation, Cosumnes River, CA. Geomorphology 56: 305-323.
Friedkin, JK, Lászlóffy, W. 1949. A folyómedrek vándorlása. Vízügyi Közlemények 31/1-2: 98-116.
Friedman, J.M., Osterkamp, W.R., Lewis, W.M., 1996. The role of vegetation and bed-level fluctuations in the process of channel narrowing. Geomorphology 14, 341–351.
Fujuta, Y., 1989. Bar and channel formation in braided streams. In: Ikeda, S., Parker, G., (Eds.), River Meandering. American Geophysical Union, Washington DC, pp. 417–462.
Fullera, I. C., Largeb, A.R.G., Milan, D. J., 2003. Quantifying channel development and

sediment transfer following chute cutoff in a wandering gravel-bed river. Geomorphology 54, 307–323.
Gazdag, L., 1964. River system of the Száraz-ér. Földrajzi Értesítő 13. 367–374.
Gábris Gy, Telbisz T, Nagy B, Belardinelli E. 2002: A tiszai hullámtér feltöltődésének kérdése és az üledékképződés geomorfológiai alapjai. Vízügyi Közlemények 84/3: 305-318.
Gillyén, J., 1912. A Maros-szabályozás mai állása. Vízügyi Közlemények 1912/1, 63–64.
Gilvear D.J. (1999) - Fluvial geomorphology and river engineering: future roles utilizing a fluvial hydrosystems framework. Geomorphology 31, 229–245.
Gönczy, S., Molnár, J., Szabó, G. and Sándor, A. 2004. Az erdőirtások hatása az árvízi vízhozamokra a Felső-Tisza kárpátaljai mellékfolyóin. Földtani Kutatás 41/3-4: 52-56
Gurnell, A. M., Petts, G. E., Hannah, D. M., Smith, B. P. G., Edwards, P. G., Kollmann, J., Ward, L. W., Tockner, K., 2001. Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. Earth Surface Processes and Landforms 26, pp. 31–62.
Ham, D.G., Church, M., 2000. Bed-material transport estimated from channel morphodynamics: Chilliwack River, British Columbia. Earth Surface Processes and Landforms 25, 1123–1142.
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, 3–13.
Hohensinner, S. Habersack, H. Jungwirth, M. Zauner, G. 2004. Reconstruction of the characteristics of a natural alluvial river-floodplain system and hydromorphological changes following human modifications: the Danube River (1812–1991). River Res. Applic. 20: 25-41.
Hooke, J.M. (1995) - River channel adjustment to meander cutoffs on the River Bollin and River Dane, northwest England. Geomorphology 14, 235– 253.
Howard, A.D., 1996. Modelling channel evolution and floodplain morphology. In Anderson, M.G., Walling, D.E., Bates, P.D. (Eds.), Floodplain Processes. John Wiley and Sons, Chichester, pp. 15–61.
Ihrig, D. (edt) 1973. A magyar vízszabályozás története. VÍZDOK Budapest: 356-361.
Illés, L., Konecsny, K., Kovács, S., Szlávik L. 2003. Az 1998. novemberi árhullám hidrológiája. Vízügyi Közlemények 85, Különszám I: 47-76
Iványi, B. 1948. A Tisza kisvízi szabályozása. Vízügyi Közlemények 30/2, 131-304.
Jackson, R.G., 1975. Velocity–bedform–texture patterns of meander bends in the lower Wabash River of Illinois and Indiana. Geological Society of America Bulletin 86, 1511–1522.
Jiongxin, X., 1997. Evolution of mid-channel bars in a braided river and complex response to reservoir construction: an example from the Middle Hanjiang River, China. Earth Surface Processes and Landforms 22, pp. 953–965.
Károlyi, Z. 1960a. A Tisza mederváltozásai – különös tekintettel az árvédelemre. Tanulmányok és kutatási eredmények 8. Budapest: VITUKI.
Károlyi, Z. 1960b. Zátonyvándorlás és gázlóalakulás - különös tekintettel a magyar Felső-Dunára. Hidrológiai Közlöny 40/5: 349-358
Keesstra, SD. 2007. Impact of natural reforestation on floodplain sedimentation in the Dragonja basin, SW Slovenia. Earth Surface Processes and Landforms 32/1: 49-65.

Kiss, T., Sipos, Gy., 2003. Investigation of channel dynamics on the lowland section of River Maros. Acta Geographica Szeged. 39, 41-49.
Kiss, T. – Sipos Gy. 2007: Braid-scale geometry changes in a sand-bedded river: Significance of low stages. Geomorphology 84, 209-221.
Kiss, T, Sipos, Gy, Fiala, K. 2002. Recens üledék-felhalmozódás sebességének vizsgálata az Alsó-Tiszán. Vízügyi Közlemények 84/3: 456-472.
Kiss T. – Sándor A. 2009: Land-use changes and their effect on floodplain aggradation along the Middle-Tisza River, Hungary. Landscape and Environment 3/1, 1-10.
Kochel, R.C., 1988. Geomorphic impact of large floods: review and new perspectives on magnitude and frequency. In: Baker, V.R., Kochel, R.C., Patton, P.C., (Eds.), Flood Geomorphology. Wiley-Interscience, New York, pp. 169–187.
Knighton, D. 1998. - Fluvial forms and processes. A new perspective. Arnold, London.
Knox, JC. 1987. Historical Valley Floor Sedimentation in the Upper Mississippi Valley. Annals Ass. of American Geographers 77/2: 224-244.
Knox, JC. 2006. Floodplain sedimentation in the Upper Mississippi Valley: Natural versus human accelerated. Geomorphology 79: 286-310
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.
Kvassay, J. 1902: A szabályozások hatása a folyók vízjárására Magyarországon. Vízügyi Közlemények 15: 7-27.
Laczay, I. 1975: A Maros vízgyűjtője és vízrendszere. A Maros szabályozása és kanyarulati viszonyai. Vízrajzi Atlasz sorozat 19. Maros. VITUKI, Budapest: 4-6, 20-23.
Laczay I. (1977): Channel pattern changes of Hungarian rivers: the example of the Hernád River. In: Gregory K.J. (ed) River channel changes. Wiley, Chichester. 185–192.
Lane, S.N., Richards, K.S., 1997. Linking river channel form and process: time, space and causality revisited. Earth Surface Processes and Landforms 22, 249–260.
Lecce, SA, Pavlowsky RT. 2004: Spatial and temporal variations in the grain-size characteristics of historical flood plain deposits, Blue River, Wisconsin, USA. Geomorphology 61/3-4: 361-371.
Leopold, L.B., Wolman, M.G., 1957. River channel patterns: braided, meandering, and straight. US Geol. Survey Prof. Paper 282.
Liébault, F., Piégay, H. 2001. - Assessment of channel changes due to long-term bedload supply decrease, Roubion River, France. Geomorphology 36, 167–186.
Madej, M.A., 1999. Temporal and spatial variability in thalweg profiles of a gravel-bed river. Earth Surface Processes and Landforms 24, 1153–1169.
Makra, L, Juhász, M, Béczi, R and Borsos, E. 2005: The history and impacts of airborne Ambrosia (Asteraceae) pollen in Hungary. Grana 44: 57-64.
Magilligan, F.J., 1992. Thresholds and the spatial variability of flood power during extreme floods. Geomorphology 5, 373–390.
Márton, Gy., 1914. A Maros alföldi szakasza és fattyúmedrei. Földrajzi Közlemények 52, pp. 282-301.
Mezősi, J, Donáth, É. 1954: A Tisza és Maros oldott és lebegtett anyagának vizsgálata. Hidrológiai Közlöny 34/3-4: 140-148.

Mike, K. 1991. Magyarország ősvízrajza és felszíni vizeinek története. Aqua Kiadó, Budapest.
Morisawa, M., 1985. Rivers: form and process. Longman, London.
Mosley, P., Jowett, I., 1999. River morphology and management in New Zealand. Progress in Physical Geography 23, 541–565.
Mücher, HJ, Slotboom, RT, ten Veen,. WJ. 1990: Palynology and micromorphology of a man-made soil. A reconstruction of the agricultural history since late-medieval times of the Posteles in the Netherlands. Catena 17: 55-67.
Nagy, I., Schweitzer, F., Alföldi, L. 2001. A hullámtéri hordaléklerakódás (övzátony). Vízügyi Közlemények 83/4: 539-564
Nanson, GC, Croke, JC. 1992: A genetic classification of floodplains. Geomorphology 4: 459-486.
Nelson, J. M., 1990. The initial stability and finite-amplitude stability of alternate flows in straight channels. Earth Science Reviews 29, 97–115.
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, 311–365.
Nicholas, A.P., 2000. Modelling bed load yield in braided gravel bed rivers. Geomorphology 36, 89–106.
Nicholas, AP, Walling, DE. 1997. Investigating spatial patterns of medium-term overbank sedimentation on floodplains: a combined numerical modelling and radiocaesium-based approach. Geomorphology 19: 133-150.
Nováky, B. 2000. Az éghajlatváltozás vízgazdálkodási hatásai. Vízügyi Közlemények 82/3-4: 418-448
Oroszi, VGy. 2008. Egy árvíz okozta ártérfeltöltődés - esettanulmány a Maros 2006 évi áradása kapcsán. In: Kiss T., Mezősi G. (edts) Recens geomorfológiai folyamatok sebessége Magyarországon; Szeged: 73-83.
Osterkamp, W.R., Costa, J.E., 1987. Changes accompaying an extraordinary flood on a sand-bed stream. In: Mayer, L., Nash, D., (Eds.), Cathastrophic flooding. Allen and Unwin, London, pp. 201–224.
Owens, PN, Batalla, RJ, Collins, AJ, Gomez, B, Hicks, DM, Horowitz, AJ, Kondolf, GM, Marden, M, Page, MJ, Peacock, DH, Petticrew, EL, Salomons, W, Trustrum, NA. 2005. Fine-grained sediment in river systems: environmental significance and management issues. River Res. Applic. 21: 693-717.
Owens, PN, Walling, DE. 2002. Changes in sediment sources and floodplain deposition rates in the catchment of the River Tweed, Scotland, over the last 100 years: the impact of climate and land use change. Earth Surf. Process. Landforms 27: 403-423.
Owens, P.N., Walling, D.E., Leeks, G.J.L., 1999. Deposition and storage of fine-grained sediment within the main channel system of the River Tweed, Scotland. Earth Surface Processes and Landforms 24, 1061–1076.
Parker, G. 1976. On the cause and characteristic scales of meandering and braiding in rivers. Journal of Fluid Mechanics 76, 457-480.
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.
Priszter Sz. 1960. Adventív gyomnövényeink terjedése. A Keszthelyi Mezőgazdasági Akadémia Kiadványai 7, Budapest; 3-34.
Rakonczai, J., 2000. Hydro-geographical consequences of environmental change on the Hungarian Great Plain. In: Pálfai, I.. (Ed.), Role and importance of surface waters on the Hungarian Great Plain. Nagyalföld Alapítvány, Békéscsaba, pp. 16–27.
Rakonczai J. 2000. A környezet hidrogeográfiai összefüggései az Alföldön. In A víz szerepe és jelentősége az Alföldön, Pálfai I (ed). Békéscsaba: Nagyalföld Alapítvány. 16-27
Repetto, R., Tubino, M., Paola, C., 2002. Planimetric instability of channels with variable width. Journal of Fluid Mechanics 457, 79–109.
Richards, K.S., 1982. Rivers: Form and Processes in Alluvial Channels. Methuen, London.
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., Simon A. (1998) - Bed-level adjustments in the Arno River, Central Italy. Geomorphology 22, 57– 71.
Ryan, S.E., Porth, L.S., Trondele, C.A., 2002. Defining phases of bed load transport using piecewise regression. Earth Surface Processes and Landforms 27, 971–990.
Sándor A, Kiss T. 2006. A hullámtéri üledék-felhalmozódás mértékének vizsgálata a Közép- és az Alsó-Tiszán. Hidrológiai Közlöny 86/2: 58-62.
Schumm S.A. 1977. - The fluvial system. Wiley. New York
Schumm, S.A., 1985. Patterns of Alluvial Rivers. Annual Review of Earth and Planetary Sciences 13, 5-27.
Schweitzer F. 2001. A magyarországi folyószabályozások geomorfológiai vonatkozásai. Folyóink hullámtereinek fejlődése, kapcsolatuk az árvizekkel és az árvízvédelmi töltésekkel. Földrajzi Értesítő 50/1-4: 63-72.
Sipos, Gy., Kiss, T., 2003. Formation and evolution of fluvial islands on the border section of River Maros. Vízügyi Közlemények 85/4, 225-238.
Sipos, Gy., Kiss, T., 2004. Island development and morphological stability on the lowland reach of River Maros, Hungary. Geomorphologia Slovaca 4, 52-62.
Smith L.M., Winkley B.R. (1996) - The response of the Lower Mississippi River to river engineering. Engineering Geology 45, 433– 455.
Somogyi S. (edt) 2000. A XIX. századi folyószabályozások és ármentesítések földrajzi és ökológiai hatásai Magyarországon. Budapest
Steiger J, Gurnell AM, Ergenzinger P, Snelder DD. 2001. Sedimentation in the riparian zone of an incising river. Earth Surf. Process. Landforms 26: 91-108.
Starosolszky Ö. 1956. Az emberi beavatkozások hatása a vízfolyások morfológiai viszonyaira. Vízügyi Közlemények 38/2: 248-252
Stover, S.C., Montgomery, D.R. 2001. - Channel change and flooding, Skokomish River, Washington. Journal of Hydrology 243, 272– 286.
Surian, N., Rinaldi, M. 2003. - Morphological response to river engineering and management in alluvial channels in Italy. Geomorphology 50, 307–326.
Szabó, Sz, Molnár, LSz, Gosztonyi, Gy. Posta, J, Prokisch, J. 2008. A nehézfém-szennyezettség vizsgálata egy felső-tiszai holtmeder környezetében. In: Szabó J,

Demeter G. (edts): Geographia Generalis et specialis. Debrecen: 255-260.
Szlávik, L. 2001. A Tisza-völgy árvízvédelme és fejlesztése. In: I. Magyar Földrajzi Konferencia CD-kiadványa, Szeged: 52.
Tamás EA, Kalocsa B. 2003. A Rezéti-Duna feltöltődésének vizsgálata. In: Somogyvári O. (edt) Élet a Duna-ártéren. Pécs: 43-49.
Ten Brinke, WBM, Schoor, MM, Sorber. AM, Berendsen, HJA. 1998. Overbank sand deposition in relation to transport volumes during large-magnitude floods in the dutch sand-bed Rhine River system. Earth Surface Processes and Landforms 23: 809-824.
Tiegs, S.D., Pohl M. 2005. - Planform channel dynamics of the lower Colorado River: 1976–2000. Geomorphology 69, 14– 27.
Tímár, L. 1948. A Tisza- és Marosmente új növényei. Acta Soc. Bot. Hungaricae, Sep. Borbasia: 8-61.
Török, I. 1977: A Maros folyó 0-51,33 fkm közötti szakasza általános szabályozási terve. Alsó-Tisza Vidéki Vízügyi Igazgatóság. Szeged.
Uribelarrea D., Perez-Gonzaleza A., Benito G. (2003) - Channel changes in the Jarama and Tagus rivers (central Spain) over the past 500 years. Quaternary Sci. Reviews 22, 2209–2221.
Vágás, I. 2000. A Tisza és árvizei. Hidrológiai Tájékoztató 40/1: 45-50
Vágás, I. 2001. Az ezredforduló árhullámai a Tiszán. Magyar tudomány 48/8: 958-866
Walling, DE, He, Q. 1998. The spatial variability of overbank sedimentation on river floodplains. Geomorphology 24: 209-223.
Wathen. S. J., Hoey, T. B., 1998. morphological controls on the downstream passage of a sediment wave in a gravel-bed stream. Earth Surface Processes and Landforms 23, 715–730.
Weninger, JM, McAndrews, JH. 1989. Late Holocene aggradation in the lower Humber River valley, Toronto, Ontario. Canadian Journal of Earth Sciences 26: 1842-1849.
Whiting, P.J., 1997. The effect of stage on flow and components of the local force balance. Earth Surface Processes and Landforms 22, 517–530.
Wilbers, A.W.E., Brinke, W.B.M.T., 2003. The response of subaqueous dunes to floods in sand and gravel bed reaches of the Dutch Rhine. Sedimentology 50, 1013–1034.
Wolman, M.G., Gerson, R., 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surface Proceesses and Landforms 3, 189–208.
Wolman, MG, Leopold, LB. 1957. River Flood Plains: Some observation on their formation. U.S. Geological Survey Professional Papers 282-C: 85-107.
Wyzga, B. 2001. Impact of the channelization-induced incision of the Skawa and Wisloka Rivers, Southern Poland, on the conditions of overbank deposition. Regul. Rivers: Res. Mgmt. 17: 85-100.
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.
Xu, Q, Yang, X, Wu, C, Meng, L, Wang, Z. 1996. Alluvial pollen on the North China Plain. Quaternary Research 46: 270-280.
Yates, R., Waldron, B., van Arsdale, R. (2003) - Urban effects on flood plain natural hazards: Wolf River, Tennessee, USA. Engineering Geology 70, 1 –15.