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FLOODPLAIN LEVEL DEVELOPMENT INDUCED BY HUMAN ACTIVITY – CASE STUDY IN THE LOWER MAROS/MUREŞ RIVER, ROMANIA AND HUNGARY

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Abstract: Multiple human impacts affect the development of the lowland section of the Maros/Mureş River. Extensive channel and floodplain regulations implemented during the nineteenth century resulted in considerable shortened and straightened channel, and formation of a narrow artificial floodplain. Later, in the twentieth century, the construction of revetments and groynes, and in-channel gravel and sand mining influenced the channel morphology. These human activities triggered an increase in channel slope and stream power, thus significant incision took place. This paper aims (1) to determine the incision rate of the channel along the Maros/Mureş River, and (2) to characterize the newly formed floodplain sections. The incision process varied temporally and spatially. The first stage of channel incision occurred between 1876 and 1912, and it was driven by channel regulation works. It was replaced by an aggradation stage (1913-1981), and finally, in the second half of the 20th century a new incision stage has started in connection with in-stream gravel mining. The incision rate was the highest upstream of Arad. The incision resulted in the development of floodplains levels, which have 65-644 cm height difference. Under these circumstances, the duration of floods decreased to one fifth of the original length.

Keywords: incision, floodplain development, river regulation, gravel mining, water stage

1. INTRODUCTION

Rivers response to environmental changes by changing their slopes, regime and sediment load. As the result of hydrological changes the channel pattern and the fluvial morphology could be altered (Kiss & Andrási 2013), the rate of meandering might increase or decrease (Blanka & Kiss 2011), or the riverbed could be filled up or incised (Rădoane et al., 2010).

The most common natural cause of incision is increased slope, triggered by tectonic movements or sink of the erosional base (Csoma 1987). The water and sediment discharge and regime, the grain-size of the transported material could be altered by change of climate, vegetation and run-off conditions (Lenzi et al., 1999). These natural triggering forces are slow, thus the resulted incision develops for centuries (Morisawa 1985).

River incision triggered by human activity usually propagates faster than natural processes, because usually the rate of human impact is greater. Incision could be induced by land-use change or soil erosion control (Rinaldi & Simon 1998, Antonelli et al., 2004). However, the most common cause is the river regulation, affecting the channel directly and generating considerable downstream scouring (Graf 2005). Such regulation works are meander cutoffs, construction of dams, groynes, diverter structures and bank protections. Besides, sand and gravel mining from the channel can also cause narrowing and incision (Uribelarrea et al., 2003, Antonelli et al., 2004). These human impacts increase the channel slope and decrease the channel roughness, thus the flow velocity rises (Brookes 1985, Yates et al., 2003), the specific stream power (Laczay 1977) and the sediment discharge increase (Biedenharn et al., 2000), and the channel geometry and the slope of the river bed alter (Smith & Winkley 1996). As a result, man-made structures in the channel (e.g. foundations of bridges, water pumps) will be undermined, and they get instable (Lenzi et al., 1999).

Though incision mainly affects the channel, it also generates environmental changes in the neighboring riparian areas. The altered regime is in the background of these changes, as in the incised channel low stages become more common and the duration of floods decreases (Kiss & Andrási 2013). After the incision overbank floods became rare, but if any develop, it usually has higher energy (Lenzi et al., 1999, Wyzga 2001). The groundwater level and its flow direction could also change as the result of stage drops and the lack of floods (Bravard et al., 1997). These processes affect the hydrological conditions of the floodplains (Werners et al., 2010), resulting in alteration of wetlands and habitat loss of several species (Dévai 2000, Lóczy & Kiss 2008).

Most lowland meandering rivers of the Carpathian Basin were straightened and their floodplains were artificially confined during the nineteenth-twentieth centuries river regulation works (Ihrig 1973, Tóth 2000). The slope of the rivers was doubled by cutoffs, causing measurable incision almost immediately (Lászlóffy 1932, 1934, Károlyi 1960, Kiss et al., 2008, Kiss & Sipos 2007, Lóczy et al., 2009), the decrease of low water stages and the transformation of wetlands (Félegyházi 1929, Dévai 2000). Decreasing riverbed elevation is still common phenomena in the Carpathians (Wyzga 2001, Rădoane et al., 2010) and elsewhere in Europe (Bravard et al., 1997, Rinaldi et al., 2005).

The Lipova – Szeged section of the Maros/Mureş River was one of the most dramatically regulated rivers in the Carpathian Basin, since the originally meandering – anastomosing channel was almost completely straightened and its slope doubled (Urdea et al., 2012). In the late twentieth century, intensive sand and gravel mining started on the lowland section of the river, triggering incision The most obvious evidences on incision are (1) the remnants of cut-offs on the higher floodplain levels, which nowadays are rarely flooded; and (2) the development of the lower floodplain levels, which are inundated regularly. These low floodplain areas developed of sand-bars and islands, after vegetation could stabilize their surface (Blanka & Kiss 2011).

The aims of the present paper are (1) to estimate the spatial and temporal differences in the incision rate along the Maros/Mureş River, (2) to describe the characteristics of the newly formed low floodplain sections, and (3) to give an evolutionary model on the recent development of the channel–floodplain system. The timing and the scale of the incision will be evaluated based on the analysis of water stage and discharge values, while the propagation of the process will be studied by measuring the height differences between the floodplain levels.

2. STUDY AREA

The Maros/Mureş River is the largest tributary (L: 789 km; A: 30.322km²) of the Tisza River, collecting the waters of southern Transylvania (Konyecsny 2010). The research was carried out on the lowland section of the river, between the Lipova Gorge (where the river enters to the plain from the Apuseni Mountains) and Szeged, at the junction of the Maros/Mureş and Tisza Rivers. Based on the data of the Makó gauging station, the lowest water discharge is 21 $m^3 s^{-1}$, the mean discharge is 161 $m^3 \cdot s^{-1}$, and the greatest flood discharge is 2420 $m^3 \cdot s^{-1}$ (measured in 1974; Urdea et al., 2012). The slope of the river varies between 13–47 $cm \cdot km^{-1}$ (average: 27 $cm \cdot km^{-1}$) and the mean flow velocity is $0.6 m \cdot s^{-1}$ (Csoma 1975). The great slope predicts that the channel formation is intensive (Kiss & Sipos 2007), which is further stressed by the high sediment transport. The Maros/Mureş carries significant amount of suspended load (average: 650 $g \cdot m^{-3}$), but it can be 15-times more (ca. 10,000 $g \cdot m^{-3}$) during floods, while the bed-load discharge is 0.9 $kg \cdot s^{-1}$ or 28,000 $t \cdot yr^{-1}$ (Bogárdi 1974).

Altogether 33 cutoffs were made in the nineteenth century, thus the original length (260 km) from Lipova to Szeged was reduced to 145 km (Laczay 1975, Török 1977). The downstream section of the Maros/Mureş is intensively narrowing since the 1950's (Kiss & Sipos 2007), which was interpreted as a morphological return of the Maros/Mureș to its original meandering pattern (Sipos 2006).

The studied 145 km-long reach was divided into four sections based on the channel processes and morphology (Fig. 1). The upper section stretches from Pauliş to Fântânele (145-105 fluvial km), it has a sinuous–meandering pattern and the channel was strongly affected by in-stream gravel mining. The second section from Zădăreni to Semlac (105-57 fluvial km) has similar channel pattern, but the mining activity does not affect the channel directly. The third, anastomosing section between Şeitin and Makó (57-22 fluvial km) was almost straightened during the nineteenth–twentieth century's river regulation works, but it developed without direct human influence in the last almost 100 years, because it constitutes the border between Romania and Hungary. The section between Makó and Szeged (22-0 fluvial km) had a meandering channel before nineteenth century's regulation works, but after the numerous cutoffs it became straight–sinuous, and in the twentieth century the channel was stabilized by revetments and groynes (Kiss et al., 2011). Along the studied reach double floodplain levels were identified at 53 sites. On the most characteristic 13 sites detailed survey was carried out to map the different floodplain levels.

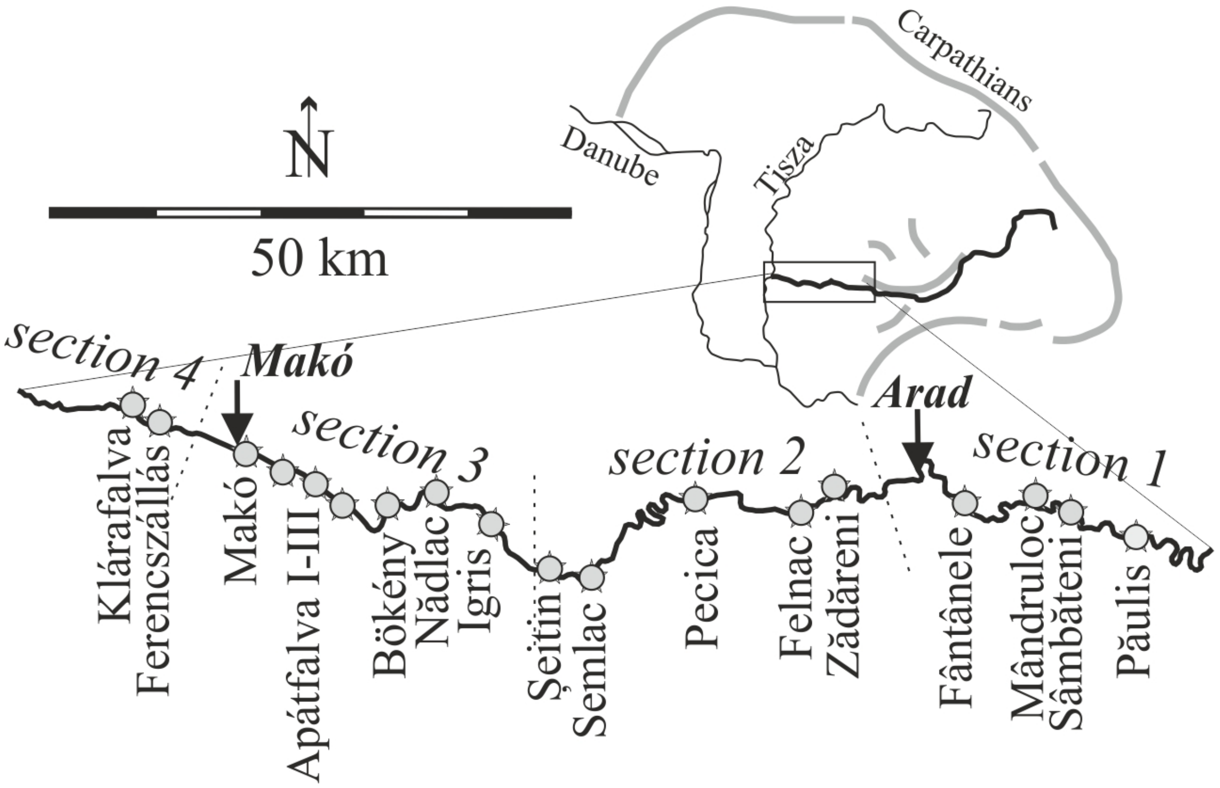

Figure 1. The studied section of the Maros/Mureş River was divided into four morphologically uniform sections, where 18 sites were chosen for detailed morphological study. The locations of the two gauging stations are marked by arrows.

3. METHODS

The water stage and discharge data of Arad (97 fkm) and Makó (24.5 fkm) gauging stations were analyzed to determine the rate and time of incision. The Makó gauging station has long (1876-2011) and continuous daily water stage record, whilst at the Arad gauging station the stage record is discontinuous (existing data: 1876-1916, 1971-1975, 1980-1985 and 1991-2010). Discharge data are available from Makó since 1960 and from Arad since 1970. Based on the data set the yearly lowest water stages were analyzed in detail, as they reflect riverbed erosion or aggradation. The decadal hydrological changes of the Maros/Mureş were described based on stage durability curves (applying daily data). The discharge and the associated stage data were also analyzed to determine whether the drop in low stages was generated by incision or decreased run-off. The spatial propagation of incision (towards downstream or upstream) was determined by the comparison of the data sets of Makó and Arad gauging stations.

The incision and narrowing of the channel result in the development of double leveled floodplains. Those areas were identified as low floodplain surfaces, which were sandbars in the 1950-60s (according to aerial photos and maps) and later they were stabilized by vegetation. The area and geomorphological forms of these low floodplain sections were determined based on topographical maps (in Romania at 1:20,000 scale; in Hungary at 1:10,000 scale), aerial photos (2000), Google Earth images (2004, 2007 and 2012) and LiDAR images (2014; in Hungary). The geo-referencing of these data was made under ERDAS IMAGINE 9.1, and the analysis of the landforms was carried out under ArcMap 10.2 software.

The geomorphology of 18 selected study sites was mapped in detail by field surveys using Topcon Hiper Pro RTK-GPS (its horizontal accuracy is 10±5 mm and the vertical is 15±5 mm).

4. RESULTS AND DISSCUSION

4.1. Hydrological changes

The yearly lowest stage values reflect the incision quite well. Based on the continuous data-set at Makó four channel incision stages could be identified (Fig. 2).

During the first period (1876−1912), the yearly lowest water stages varied between -139 cm and 19 cm. The water stage durability curves (Fig. 2B) shows that during 75% of the period water stages were higher than -10 cm, in half of the period the stages exceeded 30 cm, and only 25% of the period was characterized by stages higher than 105 cm. As the bankfull stage is 300 cm, floods were quite rare.

During the next period (1913−1950) the level of yearly lowest waters increased by 6-78 cm. It also appears on the durability curves, as they shifted upwards by 5-10 cm (75%: 0 cm; 50%: 30 cm; 25%: 110 cm).

The previous hydrological processes continued in the third period (1951−1981), as the yearly lowest stages increased further on, though the increase became smaller (5-23 cm). The stage durability curves also shifted upwards by 5-20 cm (75%: 5 cm; 50%: 50 cm, 25%: 130 cm).

In the latest period (1982−2011) the yearly lowest water stages dropped considerably. The decrease of water level is reflected by descending water durability curves (75%: -15 cm, 50%: 25 cm, 25%: 100 cm), which refer to 20-30 cm decrease in stage values.

The datasets of Makó and Arad were compared to reveal the spatial differences in the hydrological parameters (Fig. 2A). Between 1876 and 1912 the decrease of yearly lowest stages appeared at both sites, but the rate of water-level drop is greater at Arad (143 cm) than at Makó (75 cm). There is a lack of data at the Arad gauging station between 1913 and 1950, thus the hydrological changes could not be evaluated. Between 1970 and 1981 the yearly lowest values of Arad reflect considerable stage drop (by 195 cm), which became even more pronounced between 1982 and 2010 (by further 161 cm).

These data suggest that in the area of Makó river-bed incision was characteristic in two periods, (1) before 1912 and (2) since the beginning of 1980's, whilst an aggradational period appeared in between. In the late 19th and early 20th century similar incision characterized the sections of the two gauging stations. However, the second incision stage started (at least) as early as the 1970s at Arad, and in the 1980s at Makó, and the rate of incision was greater upstream, than along the lower section.

The decreasing level of yearly low stages could be explained not only by incision, but also by climate change (decreasing precipitation and run-off). To separate the two causes, the discharge–stage relationship was also analyzed. At Makó gauging station (Fig. 3A) the mean discharge related to -50 cm-stage increased by 106% (1960-1981: 36 $m^3 \cdot s^{-1}$ and 1982-2011: 75 $m^3 \cdot s^{-1}$). At the same period the discharge of the 0 cm-stage has increased by 82% (from 74 $m^3 \cdot s^{-1}$ to 134 $m^3 \cdot s^{-1}$) and by 57% of the 50 cm-stage (from 124 $m^3 \cdot s^{-1}$ to 195 $m^3 \cdot s^{-1}$). As the stage values got higher, the discharge increase becomes less pronounced, as there was just 32% increase of 100 cm-stage (from 193 $m^3 \cdot s^{-1}$ to 255 $m^3 \cdot s^{-1}$), and only 17% increase was measured of the 150 cm-stage (from 277$m^3 \cdot s^{-1}$ to 325 $m^3 \cdot s^{-1}$). From the level of the near-bankfull discharge the processes alter, as their discharge decreases: at 200 cm-stage by 7% (from 370$m^3 \cdot s^{-1}$ to 343 $m^3 \cdot s^{-1}$) and by 9% of the stages higher than 300 cm (from 560 $m^3 \cdot s^{-1}$ to 513 $m^3 \cdot s^{-1}$). Finally, higher stages almost disappeared since 1982.

At the Arad gauging station (Fig. 3B) no discharge measurements were made below 50-cm stage before 1980. But the discharge of the 100 cm-stage increased by 201% (in 1970-1981:74 $m^3 s^{-1}$, and in 1982-2010: 150 $m^3 \cdot s^{-1}$). Thus, the change is similar as at Makó, but at Arad with a much greater degree. At higher stages similar trend is shown at Arad as at Makó: at Arad the discharge increase was 74% (from 137 $m^3 \cdot s^{-1}$ to 238 $m^3 \cdot s^{-1}$) in case of 150 cm-stage, and 58% (from 217 $m^3 \cdot s^{-1}$ to 344 $m^3 \cdot s^{-1}$) at the 200cm-stage respectively. However, whilst at Makó the near-bankfull (over 250 cm water level) and overbank flood stages have a decreasing discharge, at Arad the tendency of the increase remain the same: at 250 cm-stage by 41% (from 325 $m^3 \cdot s^{-1}$ to 458 $m^3 \cdot s^{-1}$), at 300 cm-stage by 36% (from 435 $m^3 \cdot s^{-1}$ to 591 $m^3 \cdot s^{-1}$) and at 350 cm-stage by 27% (from 559$m^3 \cdot s^{-1}$ to 710$m^3 \cdot s^{-1}$). Probably it is connection with the incision itself, namely, due to the incision only higher stages reach the bankfull level.

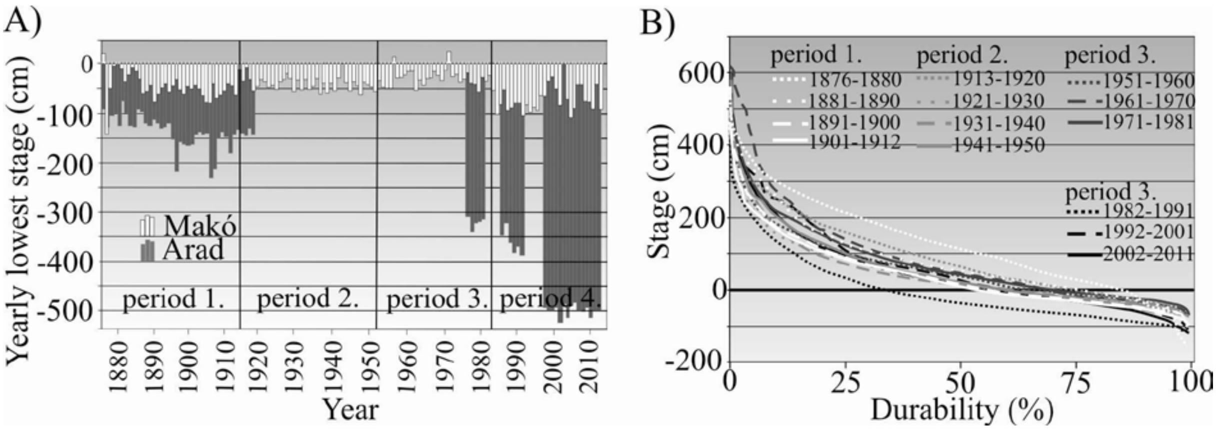

Figure 2. (A)Yearly lowest water stages at Makó and Arad gauging stations. (B) Stage durability curves at Makó gauging station between 1876–2011 (Data source: Hungarian Hydrological Year Books).

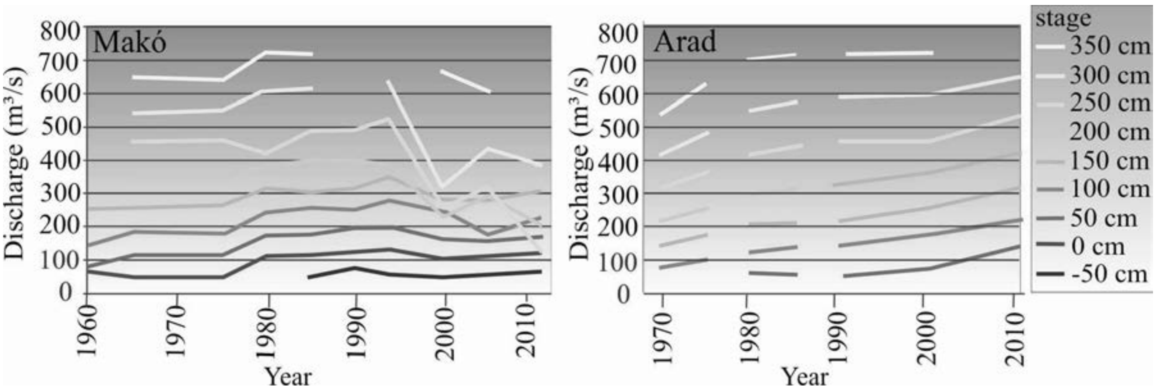

Figure 3. Discharge changes of given stages at Makó and Arad gauging stations between 1960–2011 (data source: Hungarian Hydrological Year Books).

4.2 Development of low floodplain levels

Along the Maros/Mureș artificial levees were built in the nineteenth century as flood protection measures. The levees were not built parallel to the river, but along the cut off meanders, therefore the width of the artificial floodplain varies: at some places it is only 17 m wide, whilst at others it is over 0.5 km. The incision and narrowing (see Sipos 2006) of the Maros/Mureș channel resulted in the development of new, lower lying floodplain surfaces. According to our spatial analysis, such low floodplain areas developed at 53 sites along the studied reach. As a consequence, the nineteenth century floodplain became relatively higher, and it is flooded less frequently. The two floodplain levels are divided by an escarpment. The studied low floodplain sections were classified based on their geomorphologic features and the characteristics of the river section they are situated by.

4.2.1. Floodplains along the meandering section influenced by gravel mining (145-105 fkm)

The most upstream studied section of the Maros/Mureș is characterized by sinuous–meandering channel. In-channel gravel mining was intensive until recently, affecting ca. 62 % of the section-length.

Along this section of the Maros/Mureș wide artificial floodplain areas were created at 12 sites, but low floodplain levels developed only at seven of them. These newly developed low floodplain surfaces are 32-384 m wide and 0.2-3.4 km long, their total area is 1.5km². The height difference between the lower and higher floodplain levels varies between 1.5–6.6m. The most characteristic geomorphologic features on the higher level are the abandoned channels of the nineteenth century cut-offs, their point-bar systems, and the quarries of abandoned or active gravel mines.

A good example on the section is provided at Mândruloc (Fig. 4). On the higher floodplain level, the remnant of a cut-off is visible, even its in-channel bars, riffles and pools are identifiable, referring to very rapid cut-off and incision of the main channel, thus overbank aggradation could not cover the former channel forms. On the floodplain the point-bar system and the natural levee of the former channel are well visible. On the lower floodplain level the channel forms of the Maros/Mureș were not preserved, because the mining destroyed the fluvial forms.

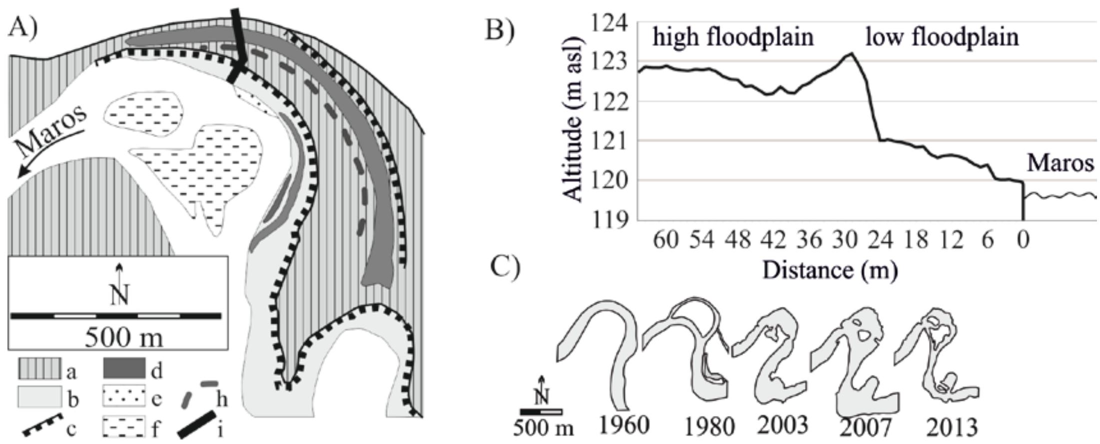

Figure 4. The uppermost (No.1) section of the Maros/Mureș characterized by double floodplain levels and meandering channel pattern. (A) Geomorphologic map of Mândruloc site. a: high floodplain, b: low floodplain, c: escarpment, d: abandoned channel, e: lateral-bar, f: active island, h: point-bar, i: surveyed profile. (B) Profile across the floodplain. (C) The planimetric changes of the Maros/ Mureș at Mândruloc (1960-2013).

Based on the height conditions of the higher floodplain level and the gauging station, it is probable, that until the late 1970s the higher level was inundated for at least one day per year, but since the incision became so great no flood could reach it. Similar trend characterizes the lower floodplain level, which could be inundated for at least a month in each year, but recently it is flooded just for two weeks in average. It reflects that incision is still an active process, and the hydrological connection between the different floodplain levels is getting worse.

As along its lowland section of the Maros/Mureș it has high slope (28 cm·km^{-1}), and wide (150-200 m) channel and considerable bedload discharge, in the over-widened sections (≥300 m) large quantity of gravel deposited. These sections offered good opportunity for in-channel gravel-mines, which were active until the early 2010s (Urdea et al., 2012). To interpret the direct effect of mining on channel development, a study area at Mândruloc was chosen (Fig. 4). Here, in the nineteenth century a narrow (30-70 m) meander developed. By 1960 the channel shifted southward, and it had almost a uniform width (average: 117 m). However, between 1960 and 1980 the mining probably had begun, thus the channel shift became more intensive (357 m), chute-cutoffs were formed, and the deterioration of the channel started, as due to the mining activity started the bankline became irregular. Between 1980 and 2007 the river shifted towards NE by 234 m (average migration rate: 5.3 m·y^{-1}), and the channel width doubled (333 m), and to compensate the widening mid-channel islands formed. Between 2007 and 2012 the channel became narrower (317 m), the islands extended, and the rate of migration decreased to 0.9 m y^{-1}.

Unfortunately the map series does not provide vertical elevation data along the river, thus the rate of incision could not be followed. However, the surveyed profile reflects the development of two floodplain levels. The higher level was formed in the nineteenth century, whilst the lower developed in the second half of the twentieth century. The mean height difference between them is 2.6 m, referring to similar rate of incision.

4.2.2. Floodplains along the meandering section, without mining (70-105 km)

The No. 2 section of Maros/Mureș has also meandering pattern, but mining activity was not typical. In the nineteenth century the artificial levee was built in irregular distance from the channel, thus here 13 floodplain sections were created. In the territory of these floodplain sections lower-lying floodplain areas developed as the result of modern incision, thus, by some larger high floodplain surfaces several smaller (not continuous) lower surfaces could be found. The low floodplain sections are smaller (width: 79-524 m; length: 0.1-4.6 km), than in the No. 1. section of the Maros/Mureş, but their total area is higher (2.6 km²). The height difference between the two floodplain levels varies between 1.4 and 2.9 m. The geomorphology of the higher floodplain is similar to the upstream section. Lower floodplain sections are characterized by point-bars and swales, which slope towards the riverbank (Fig. 5).

Between the 1950s and 1970s the higher floodplains were probably inundated for four days per years in average, whilst the lower floodplains for almost 2 months. However since the 1980s the number of overbank floods reduced drastically, as it became only one day and 18 days per year respectively, referring to the importance of incision.

The slope of this section of the Maros/Mureș is 44cm·km^{-1} (Andó 2002), the average channel width is 180 m, however there is a tendency of narrowing. For example, in 1960 the Maros/Mureș was the widest (324 m) at a straight section near Pecica (Fig. 5), but in 2011 this section was just 219 m wide, thus the rate of narrowing (3.2 m·y^{-1}) was considerable, and the lateral channel migration terminated. The low-lying floodplain surfaces developed on the bars of the narrowing and slightly incising channel.

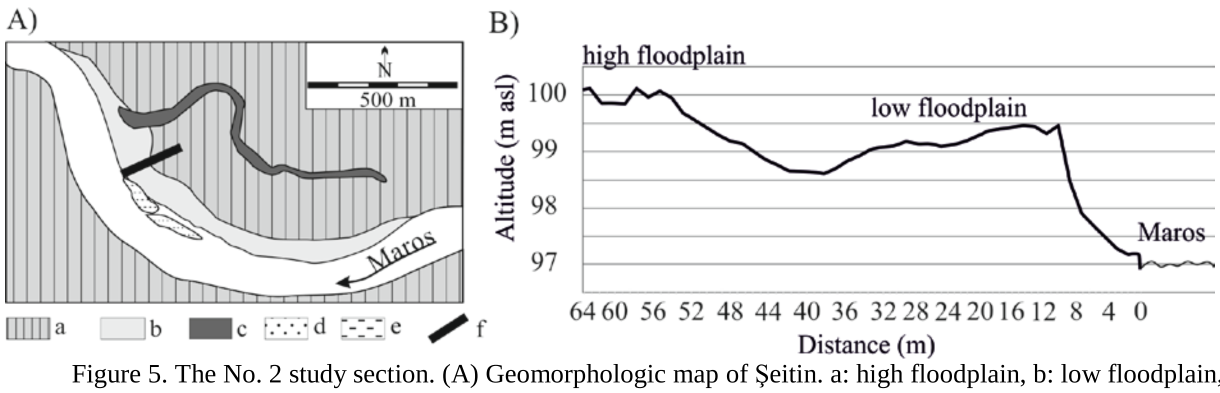

Figure 5. The No. 2 study section. (A) Geomorphologic map of Șeitin. a: high floodplain, b: low floodplain, c: abandoned channel, d: sand bar, e: active island, f: surveyed profile. (B) Profile across the floodplains.

4.2.3. Braided section (22-70 km)

The No. 3 section runs along the Romanian–Hungarian border. It became braided after the nineteenth century river regulation works, when the originally meandering– anastomozing channel was straightened to shorten the shipping route. Altogether 12 higher and 21 lower floodplain areas were identified. The width of the lower floodplain segments varies between 92 and 391 m, and their length is 0.3-7.6 km, their total area is the greatest (4.9 km²) along the whole lowland section of the Maros/Mureș. The height difference between the two floodplain levels is the smallest (0.6-2.3 m) of the study sites. Along this section at certain sites the lower floodplain sections have even two levels separated by natural levees, their elevation difference is only 0.5-1.9 m.

On the highest floodplain level the remnants of cut-offs, point-bars and sand-pits could be found (Fig. 6). On lower floodplain the geomorphological forms are in relation with the braided channel, as former sand-bars, islands and side-channels could be identified, though the deeper-lying forms are covered by deep overbank sediments (Oroszi & Kiss 2010).

Along this section the higher floodplain was flooded for two weeks per year in average until the late 1970s, whilst the number of flood days was over three weeks on the lower floodplain. However since the early 1980s the length of inundation decreased to a week and two weeks on the floodplain levels respectively.

The average slope of the channel along this section is 28 cm·km^{-1}, the average width of the braided channel was 180 m (Urdea et al., 2012). However, significant channel narrowing was observed sine the 1950's (Sipos et al., 2007). For example, at Bökény study site, the original width of the channel was 281 m (Fig. 6), nowadays it decreased to 186 m, suggesting an intensive narrowing rate of 4.3 m·yr^{-1} between 1960–1980, and a low rate of 0.2 m·yr^{-1} by 2012.

4.2.4. Artificially stabilized lowermost section (0-22 km)

The closest, No. 4 section to the Tisza–Maros/Mureș conjunction was canalized during the nineteenth century regulation works, resulting in an artificial channel with low sinuosity bends. In the twentieth century revetments and bank protections were created to stop the channel migration. Along this section of the Maros/Mureș altogether six wide high floodplain surfaces were created, along which 7 lower floodplain sections developed. Here the low floodplain surfaces are narrower (17-157 m) and shorter (313-2033 m) than along the upstream sections, and their total area (1.1 km²) is also the smallest. All the low floodplains were formed of the point-bars of the bends, and their surface became stabilized by riparian forests after 1953. Between the higher and lower floodplain levels the height difference varies between 1.4 m and 2.4 m.

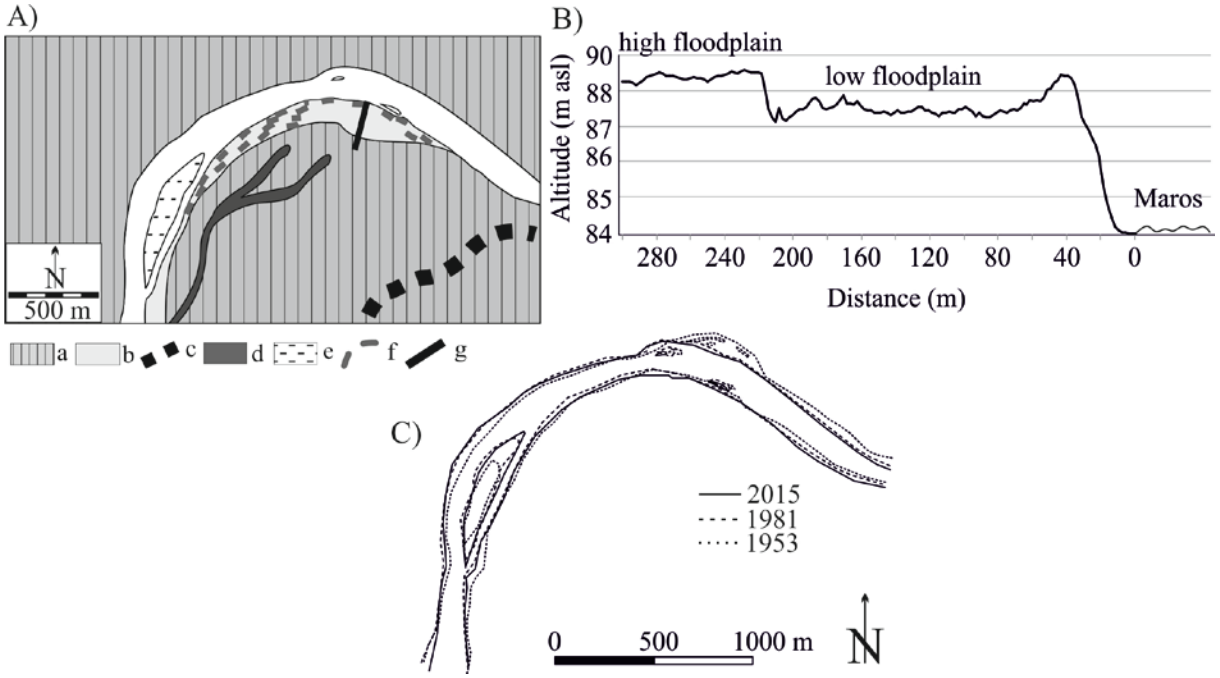

Figure 6. The No. 3 study section. (A) Geomorphologic map of of Bökény site. a: high floodplain, b: low floodplain, c: artificial levee, d: abandoned channel, e: active island, f: point-bar, g: surveyed profile. (B) Profile across the floodplains. (C) The planimetric changes of the Maros/Mureș at Bökény (1960-2012).

The surface of the high floodplain is poor in geomorphic forms because it was a flat area before the canalization, only some cut-offs, sand-pits and low artificial levees remained (Fig. 7). On the lower floodplain level point-bars, side-bars and filled-up side-channels could be identified. The lower floodplain could be divided into two levels, similarly to the upstream, No. 3 section. Based on the aerial photos the date of their formation could be estimated, as the upper part of the low floodplain was formed after 1953, and the lower part developed since 2000. The analysis of the aerial photos proved, that their formation is strongly related to channel narrowing.

Between 1951 and 1982 the high floodplain was flooded for a week during a year and the lower for almost four weeks. Here the length of inundation also decreased similarly to the upper sections, as since the early 1980s it is only three days and two weeks per year respectively.

The slope of the lowermost channel section is 13 cm km-1 (Andó 2002). The average width of the channel is 100 m, though it shows a decreasing trend. For example at the Ferencszállás study site the channel was originally 237 m wide (1953) and by 1980 its width decreased to 106 m (rate of narrowing: $3.5 m \cdot y^{-1}$; Fig. 7). Between 1980 and 2000 further channel narrowing was not measurable, but since 2000 the channel narrowed by further 10 m. The narrowing resulted in the development of the lowest floodplain level of point-bars (Sipos et al., 2007). Meander migrating is not characteristic, since the bends are stabilized by bank protections (Blanka & Kiss 2011).

4.3 Height differences between the floodplain levels

Along the 145 km-long reach of the Maros/Mureș double or multiple floodplain levels were detected at 53 different sites. The total area of lower-lying levels is 11 km², representing ca. 4% of the whole floodplain area.

Table 1: Main characteristics of 18 studied floodplain sites on the lowland section of the Maros/Mureș River. The height difference refers to the elevation difference between the high and low floodplain levels, whilst the area refers to the size of the low floodplain.

Study site	km	Height difference (cm)		Area (ha)
		at-a-site	section average	
Pauliş	133-135	680	461	6.2
Sâmbăteni	120-122	620		22.6
Mândruloc	110-112	260		12.8
Fântânele	105-107	285		13.6
Zădăreni	78-80	291	208	5.6
Felnac	76-78	211		7.8
Pecica	75-76	195		6.8
Semlac	70-71	203		6.8
Seitin	60-62	140		10.8
Igriş	55-57	74	123	63.1
Nadlac	53-54	110		25.9
Bökény	40-42	124		19.8
Apátfalva I.	34-36	65		8.9
Apátfalva II.	33-34	238		16.7
Apátfalva III.	31-32	93		21.7
Makó	27-29	155		12.6
Ferencszállás	16-18	139	191	16.5
Klárafalva	11-13	243		3.9

As these lower floodplain levels originally belonged to the channel, it means that the area of the floodplain increased by 3.5% and the area of water surface decreased by 27%. The low and high floodplains are separated by escarpments with total length of 131 km.

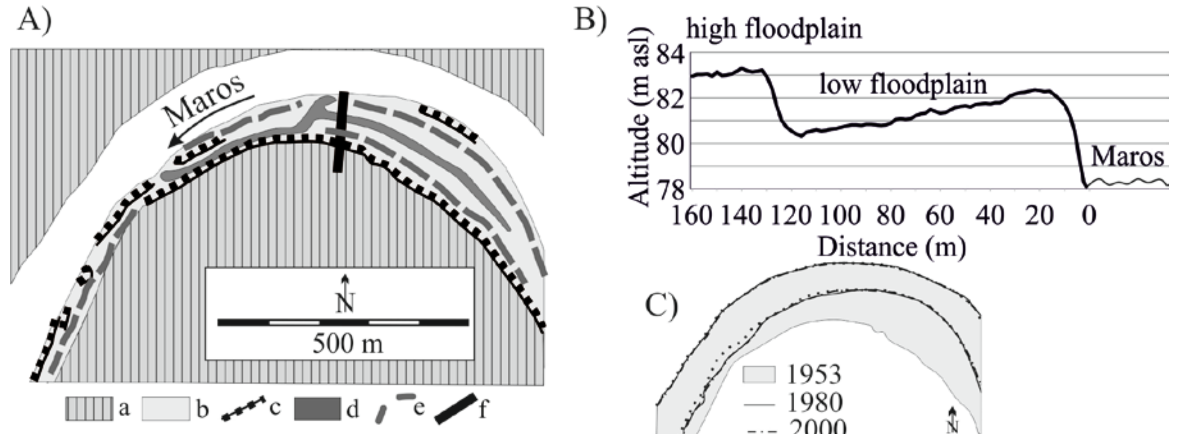

Figure 7. The No.4 study section. (A) Geomorphologic map of Ferencszállás site. a: high floodplain, b: low floodplain, c: escarpment, d: abandoned channel, e: point bar, f: surveyed profile. (B) Profile across the floodplains. (C) The planimetric changes of the Maros/Mureș at Ferencszállás (1953-2013).

In order to study the height differences in detail, the floodplain levels were surveyed along cross-sections at 18 sites (Table 1). The height difference between the high and low floodplain levels was the highest at Pauliş and it decreased downstream. The greatest incision was measured at the most intensively mined area. Downstream of the in-channel gravel mines (No. 2 section) the height difference gradually decreases from 2.8 m to 0.7 m until Apátfalva I. study area. From Apátfalva III. study site the height difference (0.9 m) increases again downstream, as it reaches 2.4 m at Klárafalva.

This tendency in the height difference suggests, that at least two incision processes played role in the channel development of the Maros/Mureș, one started upstream from the mined area, while the other from the conjunction at Szeged.

5. CONCLUSIONS

The yearly lowest water stages and the stage durability curves reflect that at the Makó gauging station incision was the dominant channel process between 1876 and 1912, then it was replaced by an aggradational period (1913-1981), finally since 1982 a new incision stage has started. Based on the yearly lowest stages, the estimated absolute incision at Makó (24.5 fkm) was 74 cm, whilst upstream, at Arad (97 fkm) the incision was more intensive (499 cm).

The stage durability curves reflect that the duration of floods has decreased (from 22.1 days/year to 14.7 $d \cdot y^{-1}$), and low stages (under 0 cm) became more frequent (from 84.6$d \cdot y^{-1}$ to 182.3$d \cdot y^{-1}$). The increasing frequency of low stages and the ascending discharge-stage curves were published by Konyecsny (2010) too, but he explained it by the construction of upstream reservoirs, and did not mention the incision as a possible reason.

The discharge data of the Makó and Arad gauging stations suggest that the water level drop was a real incision process rather than just a discharge and stage decrease due to drier climate or run-off control, as the discharges of stages lower than the bankfull level increased. The discharge-stage curves suggest that the active incision has started upstream on the river in the 1970s, and it probably propagated downstream.

Based on the yearly lowest water levels the amount of incision was 74 cm at Makó and 499 cm at Arad, which it well supported by the differentiation of floodplain levels, as it is 123 cm along the No. 3 section (upstream of Makó) and 461 cm upstream of Arad.

The present-day high floodplains were wetlands and active floodplains before the nineteenth century river regulations, and they were inundated for ca. 1-5 weeks. As the result of incision the length of inundation decreased to days. Nowadays the lower floodplain levels are the scene of active overbank processes, as they are inundated for similar duration (1-4 weeks per year) as a century ago the high floodplain was.

The remnants of the cut-offs (made in the nineteenth century), their point-bars and revetments can be found on the high floodplain level, indicating that ca. 150 years ago these floodplain areas were really active. The lower floodplain sections have more diverse form-assemblage, reflecting the channel pattern and the human impact of their reach. The uppermost mined No. 1 section is poor in forms, as most of them were destroyed by gravel-mining. Here some abandoned channels and point-bars remained. Similar forms, but in greater density are typical on the floodplains of No. 2 meandering section, where channel widening is also typical (Urdea et al., 2012). The No. 3 studied section of the Maros/Mureș was straightened and became braided, thus on the lower floodplains mid-channel bars and the fragments of side-channels could be identified. Some point-bars can be found along the lowest, stabilized No. 4 section.

The maximum height difference (680cm) between the two main floodplain levels was measured on the uppermost section and it decreases downstream (65 cm) until Apátfalva I. study site, then it increases (243 cm) again towards the conjunction.

The spatial and temporal pattern of the incision could be reconstructed based on the yearly lowest stage data-set and the height difference between the high and low floodplains. The height differences are the greatest at the first and fourth sections of the Maros/Mureș, referring two incision processes: one started from upstream and another from downstream. An evolutionary model for the channel changes and floodplain development of Maros/Mureș could be set up based on the available data:

1) The analysis of the stage data of Makó and Arad gauging stations reflect that the first phase of the incision (1876–1912) affected the whole reach of the Maros/Mureș, resulting in approx. 0.5-1.5 m channel lowering. It is probably connected to the river regulation works, as the lowland reach of the Maros/Mureș was shortened considerably (from 260 km to 170 km; Urdea et al., 2012). It resulted in doubled slope and increased erosional capacity, leading to incision and intensive bank erosion along the third, braided section (Sipos et al., 2007). This incision was probably intensified by the 3.0-4.6 m incision of River Tisza (Kiss et al., 2008), which could have affected the lower sections of the Maros/Mureș, since Tisza is the erosional base of the Maros/Mureș River.

2) General deposition was typical in the next

period (1913–1981), though it could be detected just at Makó, where the average yearly lowest stage increased by 17cm. Similar processes at the Arad gauging station could not be detected because of the discontinuous data-set.

3) Finally, a new incision process started in the late 20th century. New, low floodplain levels formed with great height differences (max. 6.8 m) on the upper section, but as the process propagated downstream, its magnitude decreased. This incision is also proven by the changing stage-discharge curves. The direction of the incision (from upstream to downstream) is marked by the decreasing height differences of the two floodplains. This incision is probably in connection with the intensive in-stream gravel-mining, construction of reservoirs, and upland river regulation works (Konyecsny 2010, Urdea et al., 2012). As the result of the second incision, double-leveled lower floodplains formed along the lower sections (0-70 km). Similar phenomenon does not detectable on the low floodplain level of the upper sections (70-145 km); probably because the incision was continuous or bank erosion was intensive and destroyed the former low floodplain sections.

Similar channel degradation processes were studied on the tributaries of Rhone (Bravard et al., 1997), on the Skawa and Wisloka Rivers in the Northern Carpathians (Wyzga 2001), on the streams of the Eastern Carpathians (Radoane et al., 2010), and on the Hernád River (Blanka & Kiss 2011). All these incision processes were in connection with human activity and resulted in the disappearance or area-loss of wetlands (Kovács 2013), ground-water level decrease, or alteration of vegetation (Bravard et al., 1997).

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