UNIVERSITY OF SZEGED

Faculty of Sciences and Informatics

Doctoral School of Geosciences

Department of Physical Geography and Geoinformatics

CHANNEL-FLOODPLAIN (DIS)CONNECTIVITY OF THE LOWLAND SECTION OF RIVER MAROS

Theses of Dissertation

MÁRTON BALOGH

Supervisor

Dr. Tímea Kiss

Associate professor

Szeged

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1. Introduction and aims

Rivers response to environmental changes by adjusting their slopes, regime and sediment load. As a result of these hydrological changes the channel pattern alters, the in-channel and floodplain morphology could be changed, the rate of meandering might increase or decrease, or the riverbed could be aggraded or incised.

Floodplain forms are dominantly the result of fluvial processes, and they play a key role in the water and sediment budget of river systems. Floodplain forms influence the height of floods by controlling the hydraulic conductivity of the floodplain (Schweitzer et al. 2002), as well as they act like fluvial archives, because their morphology, material and spatial characteristics refer to the hydro-morphological changes of the river and (dis)connectivity of the alluvial system. Two main processes contribute to the evolution of floodplain forms: lateral and vertical accretion. The comparative intensity of these processes is primarily determined by stream power and sediment transport (Nanson 1986, Brierley and Hickin 1992). The lateral accretion mainly connected to lateral channel shift (Nanson and Croke 1992), or to channel narrowing caused by decreasing discharge or sediment flux (Kiss and Blanka 2012). Vertical accretion is connected to overbank floods, when usually coarse grains accumulate along the banks forming natural levees (Dufour and Piégay 2005, Steiger et al. 2005), while fine grains are deposited on the entire floodplain creating sediment sheets (Cazanacli and Smith 1998, Kiss et al. 2004, 2011). The development of floodplain forms is greatly dependent on the hydrological characteristics of the river, as vertical accretion occurs during floods, while lateral accumulation could be continuous, independently of the water stage (Lóczy 2013).

Very intensive accumulation processes characterize the floodplain of the Maros River, which is related to its considerable sediment discharge and slope (Kiss et al. 2011). However, the processes of vertical and horizontal aggradation are spatially limited by artificial levees, recent channel narrowing and incision (Blanka and Kiss 2006, Kiss et al. 2017, 2018). The spatial and temporal changes in accumulation are known from sedimentary analysis (Kiss et al. 2011), but the various floodplain forms created by the intensive accumulation were unknown due to the missing spatial data. However, the floodplain forms refer to the lateral connectivity between the channel and the floodplain, it was not studed in detail, though it refers to the spatio-temporal changes in active fluvial processes. A new LiDAR dataset provided an opportunity to study the connectivity of the Maros and its floodplain, and to identify and evaluate the floodplain forms created by

vertical accretion on the floodplain of the 53.7 km long lower reach of the Maros.

The aims of this research are

1) to determine the main hydrological characteristics of the River Maros between 1901 and 2017;
2) to identify the spatial and temporal characteristics of the morphology of the channel;
3) to identify and analyze the floodplain levels developed along the river;
4) to identify the natural levees, crevasses and point-bars on the floodplain and to quantify their horizontal and vertical parameters;
5) to reveal the spatial characteristics of the floodplain forms and to evaluate their changes during the last ca. 150 years in connection with human impact;
6) to evaluate the connectivity between the channel and the floodplain.

2. Study area

The research was carried out on the lowland section (176.1 km) of the River Maros, between Lipova Gorge (where the river enters to the plain) and Szeged. Most of this section (124.8 km) is located in the territory of Romania; only 25.7 km long section constitutes the state border between Romania and Hungary, then it flows entirely (28 km) in Hungary until its confluence with the Tisza River. The Maros has a considerably high slope which decreases from 0.00060-0.00030 to 0.00004 along the studied section (Kiss et al. 2011). It has considerable sediment discharge: the average amount of suspended load is 265 kg/s (8.3 million t/y), and of the bed-load is 0.9 kg/s (28,000 t/y; Bogárdi 1954). The great slope combined with the high sediment load predicts intensive channel formation (Kiss and Sipos 2007),

The discharge of the Maros at the Makó gauging station varies between 21-2450 m^3/s (Sipos et al. 2007). In the 19-20th centuries floods lasted for 6-21 days/y, however, in recent decades floods were missing or lasted just for 1-1.5 days/y (Kiss 2014), which could be explained by upstream water-retention and in-channel gravel mining (Urdea et al. 2012). The Tisza River also influences the duration of floods on the Maros, as the Tisza impounds the floods from the confluence up ca. 28 km (to Makó).

On the River Maros channel regulation works started in the 1850s (Török 1977). Continuous artificial levee system was built in the downstream part of the study area (between Felnac/Fönlak and Szeged), but along the upstream reach the levee system is not continuous, as the villages were established on terraces. The river was shortened (from 249.5 km to 165.6 km)

by 33 artificial cut-offs between Lipova and Szeged (1846-1872), thus the mean channel slope doubled Török 1977). The increased slope resulted in accelerated bank erosion and channel incision (ca. 1.0 m), thus the amount of transported sediment greatly increased (Kiss 2014), causing accelerated island and bar formation, which led to the development of island-braided channel pattern in the border section (Sipos 2006). The overbank aggradation was the most intensive (1.2-2.5 cm/y) at the time of channel and floodplain regulations as a consequence of increased sediment transport (especially after cut-offs), narrowed floodplain and frequent floods (Kiss et al. 2011).

In the 19-20th centuries the floodplain aggradation rate was outstanding compared to other rivers of the Carpathian Basin (Kiss et al. 2011), however, nowadays the role of floods is minor in the formation of floodplains, due to the decreased length of floods in connection with water retention and channel incision (Kiss et al. 2017). The lower section downstream of Makó was designed to have a sinuous pattern, and later, in the 20th c. this section was fixed by groynes and revetments. Since the 1950s the width of the channel decreases (Sipos 2006) in connection with revetment constructions, water retention, water withdrawal (which caused flood duration decrease), and in-channel gravel mining (Kiss et al. 2017). The channel narrowing was the most intensive (12-15 m/y) in the 1950-1960s, then its rate decreased (Blanka et al. 2006). The narrowing of the upper (island-braided and meandering) section was greater by 40% that of the lower sinuous section (Sipos 2006). The process created new low-lying floodplain sections along the entire studied reach of the Maros (Kiss et al. 2017).

However, longitudinal measurements were made on the whole section (from Lipova to Szeged), the Hungarian section of the Maros floodplain was studied in detail, between Nagylak and Szeged (53.7 km). The LiDAR survey covers just the northern part of the floodplain along the upstream border section, whilst at downstream (where Maros is no longer the country border) both floodplain sides were analyzed.

3. Methods

In order to understand the morphological changes of the Maros, it is necessary to understand its *hydrology*, because the alterations of hydrological parameters can have a great impact on the rate of the erosional and aggradational processes which are forming the river bed and the floodplain. The water stage and discharge data (1901-2017) from Makó (24.5 rkm) gauging station were analyzed to determine the hydrological characteristics of the river. The annual minimum, mean and maximum stage and discharge values were calculated, the number of overbank flood days, the number of days with low water stages, and the return period of overbank floods. Based on their changes 5 periods were distinguished: 1901-1911; 1912-1944; 1945-1969; 1970-1994; 1995-2017. The annual lowest water stages and discharges must be highlighted, as they reflect riverbed erosion or aggradation (Sipos and Kiss 2004). The discharge and the associated stage data were also analyzed to determine whether the drop in low stages was generated by incision. Return intervals of floods were calculated applying the Gringorten formula, to determine the frequency of the highest floods and those floods which could cover (and thus aggrade) various floodplain forms.

The *long-term changes of the river bed and its forms* were analysed along the entire alluvial section of the Maros (176.1 km). For the longitudinal measurements the *Third Military Survey of Hungary* (1:25,000; 1881) and *Google Earth satellite images* (2017) were used. Measurements were performed with ArcMap 10.0, while for the comparison between the data sets were made in MS Excel. Though precise measurements could not be made on the maps of the *First* (S = 1:28,800; 1783-1784) and *Second Military Surveys* (1:28,800; 1860-1865) *of Hungary*, however to trace the channel migration I have used them.

The entire studied section was split into 114 units along its inflexion points. Units with similar morphological characteristics and slope, analogous anthropogenic alterations, and similar development type were grouped into continuous sections.

As the dimensions of floodplain features are quite variable, their survey by classical topographical mapping is difficult with sufficient accuracy, besides the field survey of large floodplain areas could be laborious and time-consuming due to the dense vegetation. A digital terrain model (DTM) that was based on a LiDAR survey (provided by the Lower Tisza District Water Directorate) was applied to identify and measure the *morphometric parameters of the islands and the floodplain forms*. This LiDAR survey was conducted in the winter of 2014 to minimize the effects of vegetation on the resulting elevation data. The vertical accuracy of the

DTM is ±0.1 m based on the resurveying of 525 points along the entire floodplain. The DTM covers an area of 96 km^2 and has a resolution of 4 m^2. The morphological measurements were performed with the ArcMap 10.0 software.

To analyze the *buried, inactive forms of the floodplain and the channel*, I used a GSSI Ground Penetration Radar with 200 MHz and 270MHz antennas. The depth of the GPR profiles were 5-6 m along the measured cross sections, with a resolution of 0.1-0.3 m. During the measurements, height profile was recorded with Topcon HyperPro RTK GPS along the path of the GPR section. The raw data was loaded into Radan 6.6 software and the whole section got corrected by the height profile. With the identified bounding surfaces and fine sediment structures, buried forms became visible and measurements could be done on them. Using the collected dataset, the evolution of the form could be determined.

To investigate the *downstream alteration of natural levees' material*, sediment samples were collected along the studied section. Sediment cores were sampled at every 10 cm, until I reached the sandy material of former river bed. Grain size analysis of the collected, dried-out samples was made with the Malvern Mastersizer 3000 and its Hydro LV extension module. The measurable particle range of the instrument is 0.01-3500 µm. Wentworth-scale was used for grain size classification.

The *evolution of point-bars* was investigated on the basis of dendrological survey. The method allows to determine the minimum age of the surface which can be used to specify the rate and spatiality of meander development. Number of annual rings were counted using microscope. To obtain height profile along the sampled section, I used a LEICA-total station.

4. Results

4.1. Hydrological analysis

Based on the changes of annual water levels and annual discharges (minimum, mean, maximum) the years between 1901 and 2017 were separated into 5 periods. These periods influenced the development of the river bed and the floodplain, however due to the great slope of the river they could be applied just in the close vicinity of the Makó gauging station.

The calculations revealed major changes in the regime during the investigated 117 years. In the first period (1901-1911) there were only two short floods. The second period (1912-1944) was the most optimal considering the development of the floodplain, because the Maros has large floods in almost every second years, which had lasted for 21 d/y in average. Thus, the vertical development of the floodplain could be intensive. The ascending low and mean water stages between 1945 and 1970 imply to the slow aggradation (8-15 cm/y) of the river bed. At the same time, the durability of low water stages increased, which means that the development of the river bed became slower. In contrary, between 1971 and 1994 the level of low water stages decreased, which imply the incision of the river bed (19-24 cm). While the level of low water stages was decreasing, extremely high water stages and discharges were contributed in the development of the floodplain, but at a deliberate pace (16 d/y). In the last few decades (1995-2017) moderate incision (12-15 cm), and gentle development of the floodplain was characterizing the hydrological environment of the river. Floods became rarer and shorter in time, which is implied by the decrease of the number of overbank flood days (14 d/y).

4.2. Characteristics of the studied river reach

The most upstream, *excavated section* was heavily influenced by in-channel gravel mining (units 1-37, 52.6 km). Downstream of this section the river has a *meandering and incising section* (units 38-50, 17.3 km), as the upstream mining resulted in an increased rate of bank erosion and incision. Several cut-offs were made and revetments were built on the *regulated and straightened section* (units 51-59, 12.2 km). On the *highly sinuous section* (units 60-68, 14.5 km) several confined meander developed closely spaced to each other, upstream of a weir. The *fan-front section* (units 69-87; 38.9 km) is located on the Quaternary alluvial fan of the Maros, and here the width of the channel is the highest. Due to the increased slope and sediment discharge of the upstream section, in front of the alluvial fan a *secondary alluvial fan* (units 88-95; 12 km) has developed. After leaving the area of the alluvial fan, the river flows across its natural *floodplain* (units 96-104; 15.4 km). On the most downstream section, the Maros finally reaches the *outlet section* (units

105-114; 13.2 km) near the confluence with the Tisza River. The outlet section is highly regulated by revetments and several cut-offs shortened its length in the past centuries.

4.3. Changes in channel parameters of the Maros between 1881 and 2017

The morphology and the alignment of the river bed had been changed intensely due to meander cut-offs and the anthropogenic alterations. The reach length of the Maros between Lippa (Lipova) and Szeged has been already decreased by 83.9 km (from 249.5 km to 165.6 km) by the time of the Third Military Survey (1881). Since then, the centerline had been elongated by 9.5 km between 1881 and 2017. However, only 6% (0.6 km) of this increase had affected the Hungarian and the border sections, the rest (8.9 km) was observable on the Romanian reach of the river.

The channel of the Maros became considerably narrower during the studied 136 years, as in 1881 the average width was 183 m (max: 1704 m; min: 31 m) while in 2017 it reduced to 116 m (max: 493 m; min: 41 m). Thus, the average rate of narrowing was 0.5 m/y, and it affected 80% of the studied reach. The most intensive narrowing characterized the meandering and braided sections, while the channel width of the slightly sinuous downstream section remained the same, or at the apex of some bends, it even increased. The process of intensive channel narrowing enabled the development of point-bars and created new floodplain surfaces suitable for natural levee accumulation, though at a lower elevation.

The decreasing number of the islands on the investigated section does not necessarily mean that they cease to exist, but they could be merged and developed together by filling up the side-channels among them. Floodplain development by islands merging into the floodplain were general on the following sections: between Păuliș/Ópálos and Arad (units 8-37), between Zădăreni/Zádorlak and Pecica/Pécska (units 45-60), and between Șeitin/Sajtény and Magyarcsanád (units 76-89). The islands of the Maros generally developing downstream.

4.4. Characteristics of the floodplain levels

There is a strong connection between the rate of the recent incision and the height difference of the floodplain levels which became inactive due to the incision and the new lower-lying floodplain levels. From Păuliș/Ópálos to Mândruloc/Mondorlak (units 6-21), where the in-channel gravel mining was the most intensive, the elevation difference between the active and inactive floodplain levels, and the rate of the recent incision have increased. This means that the upstream section of the mined section incised, moreover recently there is a head-ward incision, because the river is trying to form a

more balanced longitudinal slope-profile. This process has influence on the downstream section as well, but the development of the floodplain levels and the rate of the recent incision is varying. The height difference of the investigated floodplain levels is intensively decreasing (by 42%), between Mândruloc (unit 21; *excavated section*) and the weir, because the weir has a mitigative effect on the slope of the river, which causes a gentle decrease in the rate of the river bed erosion as well. However, on the downstream section of the weir clear water erosion occurs, thus the height difference between the floodplain levels become higher. Meanwhile, the rate of the recent incision still decreasing. Near Zădăreni (unit 44; *meandering, incising section*), the height difference of the floodplain levels is almost 4 m again, but the recent incision is still decreasing. On the *regulated and straightened* and the *highly sinuous sections* there were no identifiable new, low-lying floodplain levels; however, the rate of the recent incision is still decreasing downstream. On the upstream part of the *fan-front section* both the height difference and the rate of the recent incision are slightly decreasing, but on the downstream part (near the common border) the rate of the recent incision became 12 times higher. Downstream from here the, the height difference and the rate of the recent incision are decreasing uniformly until Cenad/Csanád (unit 90; *secondary alluvial fan*), but then they become slightly higher towards the confluence of the Maros.

4.5. Characteristics of natural levees

On the Hungarian and the common border section, where the floodplain forms were mapped in detail, 32 active and 20 inactive natural levees were identified. In 16 units only active natural levees developed, however in 15 units both active and inactive natural levees appeared, thus in some places double or triple natural levee systems developed as the bankline was removed from the forms due to channel narrowing or river training.

The widest (1022 m) natural levee is located along a meander on the upstream section (unit 84), where the floodplain is wide (3400 m) and the rate of lateral channel shift is low (0.3 m/y). The height of this particular natural levee (1.7 m) is the same as the average, thus its slope is very low (0.0005). The tallest (3.1 m) natural levee developed along the straight section (unit 98) and it is relatively narrow (71 m), therefore it has greater slope (0.0436). In general, the narrowest natural levees have the greatest slopes (mean: 0.0428), while the wider forms have gentle slopes (mean: 0.0052), thus a negative correlation was found between these parameters.

The narrowest active natural levee (width: 18 m; height: 1.8 m) developed on the new floodplain surface created by channel narrowing (unit 92). Here, a double natural levee developed, as along the inactive bankline

the formation of the older natural levee terminated, and by the actual bankline a new, active form is evolving.

The size of the natural levees is influenced by the sinuosity of the channel. Usually, the natural levees along sharp meanders (sinuosity over 1.4) are 1.7-2.5 times wider, however no clear correlation exists between the height of the forms and channel sinuosity. Usually the steepest natural levees are located along slightly sinuous sections.

As the locations of 19th c. artificial cut-offs and 20th c. channel narrowing are known, it is possible to evaluate their role in natural levee development. No cut-offs were made on the upstream section (units 84-89), thus here the natural levees are along three large meanders and they develop continuously (at least) from the 19th c. These old, and still active natural levees are wide (max: 1022 m), and they have low slopes (max: 0.0076). On the downstream part of the study area (units 90-114), several meander cut-offs were made, so those natural levees which belonged to them became inactive, and new forms started to develop along the new artificial channel. Thus, these young natural levees have been evolving just for ca. 150 years, therefore they are narrower (max: 768 m), though they mean height is almost at the average of all levees (mean 1.7 m), as a consequence, they have steeper slopes (max. 0.0420) than of the natural levees along the upstream section. The youngest natural levees evolved on the new, low-lying floodplain sections created by channel narrowing, resulting in the inactivity of the previous natural levees. Altogether, they appear in 12 channel units. These young levees are narrow (max: 79 m), but they are the highest (max: 3.1 m) forms, thus they have the steepest slopes (max: 0.0991). As channel narrowing is a quite new process, behind these new natural levees additional older and nowadays inactive natural levees could be identified, creating levee-series.

4.6. Characteristics of crevasses

Crevasse systems developed just along such sections where no meander cut-off was made and the channel remained almost in the same position due to low (≤0.3 m/y) lateral erosion (units 3-4, unit 15, and units 18-19). The lateral shift of the channel along these sections is inhibited by cohesive bank material (No. 1. study site) or revetments (No. 2-3 study sites). Identifiable crevasses did not appear along other sections.

The uppermost crevasse system developed along with a meander (No. 1 study site; units 86-87), where the slope of the Maros is great (0.00038). The mean depth of these crevasses is 0.7 m (max: 0.8 m) at 20 m far from the bankline, and towards the distal parts (50-500 m from the bankline) it decreases to 0.4 m in average. The deepest crevasse (max: 0.8 m)

developed at the apex of the meander. In this study area, the crevasses are generally short (400-600 m) and they terminate at the rim of the natural levees, because here the agricultural activity already levelled all fluvial forms. In the study area, the total length of the crevasses is 6.6 km, thus their mean density is 2.2 km/km^2, and they are not segmented (1.0 junction/km^2), probably because they stretch just to the edge of the natural levees. The mean slope of the crevasses is 0.00015. The longest (max: 1.6 km) and the steepest (max: 0.00030) crevasse developed behind a point-bar in the southern part of the study area, thus during floods it could act as a chute channel.

On the lower section of the Maros crevasses developed along a slightly bending section (No. 2 study site; unit 98) with 0.00012 mean water slope; and along a meander (No. 3 study site) with 0.00005 slope. In No. 2. study site the crevasses are easily identifiable, as their mean depth is 1.5 m (1.0-1.8 m) at 20 m far from the bankline. Farther from the bankline, at 50 m distance, their mean depth reduces to 0.8 m, and their distal sections become even shallower (at 250 m: 0.6 m; at 500 m: 0.4 m). The density of the crevasse system is 2.7 km/km^2, they have more junctions (4.0 junctions/km^2), and their mean slope is 0.00017, thus all parameters are greater than in the No. 1. study site. Here the steepest crevasse (max: 0.00041) also developed at the apex of the bend.

The No.3 study site is also located on the downstream section of the Maros (units 100-101), but in contrast to the previous site, it is located at a meander. Here the crevasse system is the most complex, as its density (8.4 km/km) is 2-4 times higher than of the upstream areas. The crevasses terminate in artificial clay pits in front of the constructed levees. The crevasses are quite shallow (0.1-0.3 m) near the bank (at 20 m), but they are getting deeper towards the distal part of the floodplain (50-500 m zones), as their mean depth increases to 0.4 m (max: 1.0 m). The crevasses create a complex system, as it is reflected by their high segmentation (21 junctions/km^2). However, the mean slope of the crevasses (0.00015) is similar to the other study areas, but considerably higher than the mean water slope of the main channel. The steepest crevasse (max: 0.00032) is located at the apex of the meander, where the thalweg is probably situated closest to the bank.

4.7. Characteristics of point-bars

Point-bars were identified at 26 bends, but only 18 point-bars are actively forming, while at 9 meanders the point-bar systems became inactive as the result of 19th c. artificial cut-offs.

The inactive point-bar systems are different on the upper and lower units. In the upper units (units 92-94) the point-bar systems are wide (524-1133 m) containing 11-34 ridges. The width of the individual point-bars is

63-79 m. In contrary, in the lower units (units 100-107) the point-bar systems have only 5-22 ridges, and they are narrower (172-921 m), but the width (50-115 m) of individual point-bars is higher. Though the maximum height of the point-bars (0.3-1.0 m) does not reflect a downstream trend, but within the point-bar systems the ridges have characteristic height changes. In the upper units the highest point-bars are located in the youngest third of the point-bar system, whilst in the downstream units, the highest ridges are always located right on the banks of the cut-off meanders.

The active point-bar systems are less developed, as in the upper units (units 84-87) they have only 6-11 members and their width changes between 265 and 926 m. Their height is 0.9-1.4 m (mean: 1.2 m), and it decreases downstream. In contrast, in the downstream units (units 96-114) the number of point-bars is more variable (4-13), but the width of the point-bar system is only 96-709 m, and they are slightly lower (0.4-1.5 m; mean. 0.8 m).

4.8. GPR analysis and grain size analysis

Based on the GPR cross-sections, two separate development cycles were identified in the evolution of the floodplain.

Several hundred years old, already buried point-bar series show that formerly active point-bars were declining towards the direction of the former bankline, for example: near Păuliş (unit 6), Sâmbăteni (unit 15) and Mândruloc (unit 21). The incision of the river is reflected by the vertically layered point-bar members (e.g. O1 GPR cross-section), the point-bar series declining in the direction of the former bankline, and the stratal surfaces of negative forms, which are getting closer as they are getting shallower. This means that the former incision process resulted in weakening the connectivity between the river bed and the floodplain, and low energy floods were altering the floodplain.

This erosional cycle was followed by an aggradation period, when the members of the point-bar series were heightening and the depression among them were getting shallower also. This is corroborated by the multiple times layered point-bars (e.g. M4 cross-section) which are describing the process of long-term point-bar series development. The spatiality of the point-bars presumes trend-like decreasing in the rate of vertical aggradation. Areas where there are just a few forms (near Zădăreni and Pecica: units 44-46 and unit 65) GPR cross-sections shows that a 1.5-2.0 m thick, homogeneous sediment layer has been deposited during a single (or low number of) high flood(s), resulting intense vertical aggradation. However, despite the lack of floodplain forms in these areas, crevasses implying the formerly close connection between the river bed and the floodplain.

4.9. Evaluation of channel-floodplain connectivity on the Maros

Accelerated incision (662 cm) is the main indicative of weakening connectivity, along the studied section of the Maros. As a result of incision, overbank floods became rarer, which issues in the ceasing of vertical sedimentation and the terminated development of floodplain forms.

Intensively developing floodplain sections, where the connection is the strongest, located at between Zăbrani/Temeshidegkút and Fântânele /Angyalkút (units 10-29), and Şeitin and Munar (units 59-76). On these floodplain sections the bank erosion rate and the rate of channel narrowing is the highest, and the number of islands melted into the floodplain is high as well. This can correlate with the well-developed meanders and with the loose material of the floodplain sections which can be eroded easier. However, the rate of incision is also the highest on these sections, which will result in intensifying disconnectivity in the future.

Among local anthropogenic disturbances, there are catchment-size effects which cannot be ignored, like climate change (Sipos et al. 2014), and the changes in land usage (Oroszi and Kiss 2006). The incising level of annual water stages and the reduced number of floods resulted in 20-38 years recurrence time of overbank floods which can reach the level of recently developing natural levees. If this trend continues, the development of active natural levees may become more restricted spatially, thus the channel and the floodplain will become more disconnected.

5. Theses

1) Since 1901 the development of the floodplain was probably the most intensive between 1912 and 1944 and also it was considerable during the high floods of the 1970s. In the period of 1912-1944 considerably long (mean: 21 d/y) overbank floods developed and formed the floodplain in almost every second year, while in 1970-1994 also long floods (mean: 16 d/y) appeared. The relatively long overbank floods created favorable conditions for vertical floodplain aggradation.

2) ***Only 6% of the total length increase of the Maros' centerline took place on the common border and the Hungarian section between 1881 and 2017.*** The more intensive length increase along the Romanian reach could be explained by its greater slope and higher sediment transport (Právetz 2018), which created advantageous circumstances for more intensive channel formation. Besides, on the Romanian section of the river less revetments were constructed and no continuous embanked levee system were built. As a result, the river has considerably wide floodplain to develop further on, while along the lower, Hungarian sections these circumstances are not provided.

3) ***The channel narrowing affected 80% of the section between Lipova and Szeged, creating favorable conditions for horizontal floodplain aggradation.*** The channel narrowing is the result of the intensive incision and the that the islands merge to the banks. The increase in the minimum channel widths and the decrease in the maximum channel widths imply the termination of former braids, and that the river channel became more uniform. This trend had already been stated by Sipos (2006); however, only on border and Hungarian section of the Maros, and not along the entire lowland section of the Maros from Lipova.

4) ***According to the downstream alteration of the recent incision and the height difference between the inactive- and the newly developing floodplain levels, there were two different incision processes with reverse direction.*** The starting point of one of the incision processes is located in the vicinity of Mândruloc (unit 21), and it affects both the upstream and the downstream sections. The downstream effect is pronounced until Cenad and Apátfalva, with a length of almost 110 km. However, this process is not continuous, as in unit 24, the weir breaks the continuity of the process. On the upstream section of the weir decreases the slope, and accumulation became the dominant process. In contrary, on the downstream section of the weir clear water erosion is controlling the incision process.

The other incision process propagates from the direction of the confluence, as the Tisza River incised by 3-3.6 m (Kiss et al. 2008) as a result of the 19th century cut-offs. This incision process affects the outlet and floodplain sections of the Maros as the headward erosion propagates upstream. The inflexion point of the two separate incision processes is located between Apátfalva and Makó (units 91-95).

5) ***The recent incision cycle is not unique in the history of the Maros River.*** The GPR cross-sections suggest that erosional and accumulational cycles were following each other in the past. The deeper buried floodplain forms which are declining towards the direction of the former river bed presume increased channel erosion. This was followed by an accumulational cycle, which heighted the floodplain forms and caused increased vertical aggradation. Recently a new erosional cycle prevails.

6) New, low-lying floodplain level developed in the narrowing channel, and the former floodplain (active in the 19th c.) became flood-free and inactive. As a result of the meander cut-offs, the formerly active floodplain forms moved horizontally further from the active bankline, thus only higher floods could reach their level. Because of the channel narrowing and incision, the forms' distance from the bankline lengthened further, not just horizontally, but vertically as well. As a consequence of these processes, the formerly active floodplain became inactive, because nowadays even the highest floods can't reach their level. Meanwhile, on the low-lying surface between the former and the recent bankline a new floodplain level is developing.

7) The morphology of the floodplain forms is highly dependent on the quantity and quality of the anthropogenic interference (e.g. meander cut-offs, revetments and artificial levee building, gravel mining) affecting the river bed and the floodplain. As the result of these human activities new floodplain forms can develop (e.g. oxbow-lake, floodplain levels), development of formerly active forms can cease (e.g. natural levees, crevasses, point-bars), and development of active forms can be altered compared to the naturally developing forms.

8) The natural levee series could be considered as very special floodplain forms, which are mainly developed as the result of human activity. As a result of the meander cut-offs, the formerly active natural levees moved further from the active bankline and became inactive. Meanwhile, new natural levees developed along the new bankline. However, due to the channel narrowing and incision, these new forms got gradually further from

the bankline as well, and became inactive. These days, the 3rd generation of natural levees are developing on the lower-lying floodplain levels.

9) Crevasse systems remained only at sections not affected by cut-offs, and new ones are not developing any more. While crevasses along the sections not affected by cut-offs could develop for a long time, resulting in deep negative floodplain forms with own natural levees, crevasses of the cut-off sections moved further from the recent channel, lost their water supply, and faded into the floodplain. Nowadays, no crevasses could develop due to the short and rarefying floods, because the river does not have enough energy the break through the material of the natural levees.

10) The river bed and the floodplain is increasingly disconnected. Recent incision (max. 662 cm) caused by the river regulation works and gravel mining are the main causes of disconnectivity. As a result of the incision overbank floods became less frequent and their duration decreased, which leads to the termination of vertical floodplain aggradation. On the inactive floodplain the water supplement of oxbow lakes and crevasses is terminated, thus they dry out, and these processes can lead to serious alterations in the ecology of the environment.

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7. Publications related to the dissertation

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