UNIVERSITY OF SZEGED
FACULTY OF SCIENCE AND INFORMATICS
DOCTORAL SCHOOL OF GEOSCIENCES
DEPARTMENT OF PHYSICAL GEOGRAPHY AND GEOINFORMATICS

CHANNEL PROCESSES OF A LARGE ALLUVIAL RIVER UNDER HUMAN IMPACTS

PhD Dissertation

Gabriel Jonathan Amissah

SUPERVISORS:

DR. TÍMEA KISS (DSc), Associate Professor

DR. GYÖRGY SIPOS, Associate Professor

SZEGED
2020

1. INTRODUCTION

Rivers all over the world have been subjected to various forms of human alterations and engineering constructions which have altered their equilibrium states and their morphological evolution. The Lower Tisza River (Hungary) has been the subject of various engineering interventions including the construction of levees to protect settlements, artificial meander cutoffs to improve navigation, and the construction of revetments and groynes to stabilize banks. These interventions have however had various adverse effects on the river. These include the disconnection of the river from its distal floodplains due to the construction of the levees; the shortening of the length of the river by one third by the artificial meander cutoffs, thus, increasing slope and stream power; and the rapid incision due to bank stabilization methods.

Although the effects of these human interventions have been investigated on the Lower Tisza, they were done over short sections of the river, thus, the parametric connections between various sections of the river do not exist. To have a comprehensive understanding of the effects of the regulation works on the Lower Tisza River, an assessment of the spatial and temporal variations of longer river reaches are needed to reveal the spatial connections of the parametric changes over various temporal dimensions for the river since it is critical for effective and sustainable river management. The changes are controlled by the in-channel processes; hence, they must also be studied to reveal their connections as drivers of morphological changes. The aim of the research therefore was to assess the morphological changes of the Lower Tisza channel to understand the long-term changes in a large alluvial river channel which has been subjected to various form of human interventions, emphasizing the roles played by the various interventions over the last century; to assess the in-channel processes as drivers of morphological changes; to analyze near-bank processes; and finally, to apply models in predicting sediment transport and morphology.

The main study focused on the Lower Tisza to establish the evolution of the river from 1891 to 2017 by emphasizing on changes in the vertical channel parameters and changes in the equilibrium state of the river. The in-channel processes of the Lower Tisza were also assessed together with near-bank processes as drivers and indicators of the channel's evolution. The flow characteristics were measured together with detailed channel morphology at four selected sites within the most sinuous middle reach of the river which represented revetted sections and a freely developing meandering section. The revetted sections were made of different types of revetments with some sections having different stages of revetment collapse. The changes in point-bar elevation and bank erosion were also measured as indicators of the equilibrium state; thus, the evolution pattern of the river. To understand the sediment transport dynamics which forms part of the drivers of morphological change, the Maros River was selected since the Lower Tisza has a low bedload sediment transport making it difficult for bedload to be effectively monitored and analyzed; moreover, at the Makó gauging station, a mechanized steel-cable monitoring station exists, which is suitable for detailed bedload measurements.

2. METHODS

2.1 Centurial changes in the morphological evolution of the Lower Tisza

To analyze the changes in the Lower Tisza channel from 1891 to 2017, I employed a dataset of hydrological surveys provided by the ATIVIZIG. The data included survey data of 36 fixed cross-sections (VO) for the years 1891, 1931, 1961, 1976, 1999 and 2017; data on the artificial meander cutoff sections and revetments; and the Hydrological Atlas of the Lower Tisza (1976) which provided the plan-form of the river showing the banklines in 1891, 1931 and 1976, and the locations of cross-sections (VO), artificial cutoffs and revetments. Based on the hydrological survey data, the cross-sectional area, thalweg depth, mean depth, bankfull width and mean width were calculated and analyzed.

2.2 Detailed channel morphology and flow velocity

To measure the flow characteristics of four selected sites, a boat mounted River Ray ADCP (by Teledyne RD Instruments) with a GPS device were used to survey transects spaced at 40-105 m (approximately half of the channel-width at the surveyed locations), and also along longitudinal directions. The field data were analyzed using the WinRiver software, and the mean discharge and wetted width (at actual water level) determined for each cross-section. The velocity distribution across the sections, mean velocity for each cross-section and the specific stream power (stream power per unit width) were also calculated. The detailed channel morphology was determined from a DEM database (developed by ATIVIZIG) created from a detailed survey of the Lower Tisza channel made at approximately every 100 m interval (using a Sonar Mite Echo Sounder by Ohmex Instruments in 2017), and an airborne LiDAR survey of the floodplain (from 2014) with a 10 cm vertical resolution. For every location of the flow survey, the channel cross-section was determined; the thalweg depth and the bankfull width were then calculated.

2.3 Changes in point-bar evolution and bank erosion

Hydrological analysis of the Lower Tisza using stage data of the Csongrád gauge station between 2011 and 2019 was made to understand how it affected changes in point-bar development and bank erosion. The frequency of low stages, overbank stages at the measured banklines, and the inundation of the point-bar were determined.

The changes in the elevation of the point-bars and bank erosion were measured using the Topcon GNSS RTK Hiper Pro system (horizontal and vertical accuracy: ±1 cm). The measurements for the point-bars spanned 2012-2019, while the monitoring of the bank erosion covered 2011-2019. On the point-bars cross-sectional profiles were surveyed, thus, 850-1600 points were measured at each location. There was an average interval of 4 m between successive points in the transverse direction and 10 m in the longitudinal direction. Based on the data, digital elevation models (DEM) were created (in ArcGIS 10.3) using the Kriging interpolation method at a resolution of 1 m. The volume of the bar at a given survey was measured from 73.5 m a.s.l (lowest elevation of the DEM) at Csongrád, while at Ányás it was measured from 74 m a.s.l (lowest elevation of the DEM). To evaluate the changes in sediment dynamics, the subsequent DEMs were extracted from each other, and longitudinal and cross-sectional profiles were analyzed. Similarly, the banklines were analyzed using ArcGIS 10.3. The mean bank erosional rate was calculated based on the mean width of the polygon between two bank-lines.

2.4 Modelling the channel morphology of the Lower Tisza

The morphological changes of the Lower Tisza were modelled using the Delft3D FLOW model to predict the evolution of the river. The model uses both sediment transport and bed updating to show morphological changes of the river. The 2017 bathymetry of the Lower Tisza was applied in the model had fixed water discharge as the forcing on the open boundaries at the upstream section and at the confluences with the Körös and Maros.

2.5 Bedload discharge measurement of Maros

The bedload transport of the Maros was determined based on sediment sampling at the Makó gauge station with a 76 mm Helley-Smith bedload sampler between 2015 and 2017. The flow conditions were also measured along the same transect using an ADCP. The measurements were repeated at the same location due to a fixed cable across the Maros at the gauge station with a motorized system to move the sampling instrument at 10 m intervals where samplings were made. The recovered samples were dried, weighed and analyzed to obtain bedload rate (using sampling times). The grain size distribution of the sediment samples was also analyzed using dry sieving.

2.6 Estimating the bedload transport

The bedload transport on the Maros was estimated using six bedload formulae: Meyer-Peter Muller (1948), Einstein-Brown, Brown (1950), Rottner (1959), Bagnold (1980), Wong and Parker (2006) and Bathurst (2007) to determine the predictability of bedload transport of the Maros at Makó.

3. RESULTS

3.1 Centurial (1891-2017) morphological evolution of the Lower Tisza channel

Based on the results of the research, I established that the morphological evolution of the Lower Tisza is driven by the planform (indicated by the sinuosity) and the various engineering constructions. The evolution is reflected in the changes in the vertical channel parameters (cross-sectional area, depth and width) as indicated by my conceptual model of the morphological evolution of the Lower Tisza (Fig. 1).

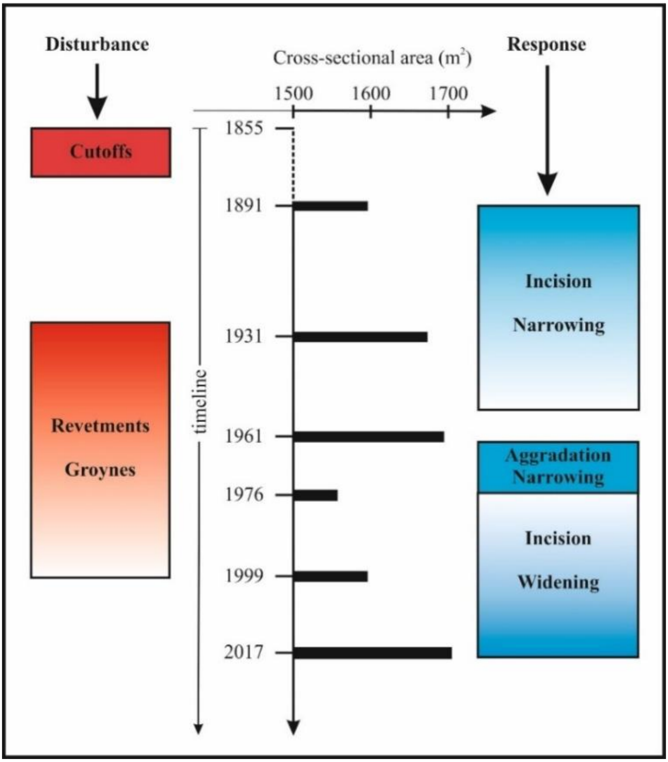

Fig. 1: Conceptual model of the morphological evolution of the Lower Tisza River (1891-2017).

3.1.1 Responses to artificial meander cutoffs (1891-1961)

The Lower Tisza channel experienced incision and narrowed in response to artificial meander cutoffs with a resultant increase in its mean cross-sectional area; the changes were however not uniform within the period, rapid initially but slowed down in the latter part due to the decreased influence of the cutoffs. The artificial meander cutoffs which were made in the second half of the 19th century reduced the length of the Lower Tisza by one third and increased the slope. As pilot channels were created during the cutoffs and allowed to evolve using the energy of the river, there were some sections of the channel which were narrow with small cross-sectional areas. The cutoffs increased the cross-sectional area by 9.5% between 1891 and 1931 (22% in cutoff sections and 4.9 % in non-cutoff sections); however, by the period 1931-1961, the increase was only 1.1%. The differences were due to the decreased influence of the artificial meander cutoffs in the river's evolution in the latter part of the period as indicated by a similar rate of increase of the cross-sectional area for both cut and non-cutoff sections (0.6 m^2/y). Thus, the non-cutoff sections had similar evolution patterns as the cutoff sections, and the increase in cross-sectional area and the changes in the other vertical channel parameters became asymptotic. The increase in cross-sectional area was due to incision (4.1 cm/y) and narrowing (21.7 cm/y) within the period. In the latter of the period, the channel attained a quasi-equilibrium as the influence of cutoffs became negligible as the rate of change in the channel reduced.

3.1.2 Distortion in quasi-equilibrium state (1961-1976)

The initial response of the Lower Tisza channel to the construction of the revetment overlapped the initial evolution pattern creating a distortion of the initial quasi-equilibrium state, characterized by in-channel aggradation and narrowing resulting in a drastic reduction in the mean cross-sectional area of the channel. The next period (1961-1976) was marked by the distortion in the morphological evolution of the Lower Tisza channel as the quasi-equilibrium was lost. The originally increasing cross-sectional area reduced by 8% over a 15-year period (ca. 9.0 m^2/y). As the channel responded to the effects of the construction of the revetments and groynes (mainly in the 1930s), the channel experienced both aggradation (6.5 cm/y) and narrowing (0.49 m/y) which contributed to the drastic reduction in the cross-sectional area. The reduction in the cross-sectional area within the revetted and non-revetted sections of the river also differed (10.5% and 6.5% respectively).

3.1.3 Channel response to the construction of revetments (1976-2017)

The Lower Tisza channel's evolution due to the revetments was marked by incision and widening which increased the mean cross-sectional area of the channel; however, contrary to the response to the cutoffs, the increase in the mean cross-sectional area of the channel was initially slow but became faster in the latter part of the period. After the initial distortion in the evolution of the Lower Tisza, the channel began a new pattern of morphological evolution within this period with an increase in cross-sectional area (3.6 m^2/y). The initial half of this period was marked by a slower rate of increase (1.6 m^2/y), less than the rate for 1931-1961; with channel incision (4.3 cm/y) and narrowing (0.14 m/y). However, the final half of this period was characterized by a faster rate of increase of the cross-sectional area (6.5 m^2/y). With negligible change in the depth conditions of the river, this increase is due to channel widening (0.60 m/y) due to the dominance of bank erosion in the Lower Tisza (Kiss et al., 2019).

3.1.4 Spatial patterns of the morphological evolution

The spatiality distribution of the changes in the channel was controlled by the density of engineering construction with most intense changes occurring in the upper reach which had the highest density of human interventions. Although the timing of the engineering works affected the general evolution of the Lower Tisza, the intensity of the various engineering works, especially the revetments, affected the spatial patterns of morphological evolution. The upper reach which had the highest density of engineering constructions had the greatest changes in vertical channel parameters. In the middle reach, the channel generally had the least density of engineering interventions and with a cross-sectional area less than 1300 m^2 for all surveyed years with the exception of 2017. The lower reach was more stable, having the largest cross-sectional area (>2000 m^2) for all surveyed years due to its proximity to both the Maros and Danube. As the pattern of the channel was divided into bends and meanders, the change in cross-sectional area in the bends and meanders differed over the 126-year period (15.9% and 5.3% respectively), thus the bends responded with greater degree.

3.2 In-channel processes related to channel morphology

The velocity distribution of flow within the Lower Tisza was related to channel morphology, bank characteristics and the presence of revetments.

3.2.1 Influence of morphology and the revetment on velocity profiles

The mean flow velocity and the velocity distribution of the studied Lower Tisza was influenced by the channel morphology, and the type and state of revetment present (if any). Within the studied sections of the Lower Tisza, the straightened sections which were revetted had relatively uniform velocity which were high. The revetment created the high velocities while the morphology influenced their uniformity. At the revetted meander had the smallest mean flow velocity. Although the revetments will ordinarily contribute to high velocities, the complex nature of the morphology deflected the flow at the meander apex causing non-uniformity of flow velocity. Downstream of the apex however, the velocity distribution was more uniform. The highest mean velocities were generated at the freely developing meander. However, the presence of a sequence of riffles and pools created a non-uniformity of flow velocities.

3.2.2 Collapse of revetments

The collapse of the placed-rock revetment in the more sinuous middle reach of the Lower Tisza occurs in two ways: through landslides, and through the erosion of the individual rocks as a result of favourable conditions downstream of the revetments due to the high erosivity of the channel. The studied sites had two different types of revetment: the placed-rock type along the along the banks at Csanytelek North and Mindszent, and the stepped-block type at Csanytelek South. The revetment at Csanytelek South did not experience any type of erosion although the point-bar on its opposite bank eroded due to a transfer of the erosive energy. The placed-rock revetments at Csanytelek North and Mindszent however are at different stages of collapse as indicated by my conceptual model of revetment collapse within the studied sites (Fig. 2). The high incision rates of the channel after the regulations (Amissah et al., 2017) created suitable conditions for the collapse of parts of the revetments at Mindszent to fail through landslides. At Csanytelek North, similar conditions coupled with the high erosivity of the channel due to high velocities generated close to the revetment caused the non-revetted banks downstream of the revetment to fail at high intensities. This creates conditions suitable for the collapse of the stones at the end of the revetment. This allows for both lateral and vertical erosion which threaten the levees which are as close as 50-100 m at some sections.

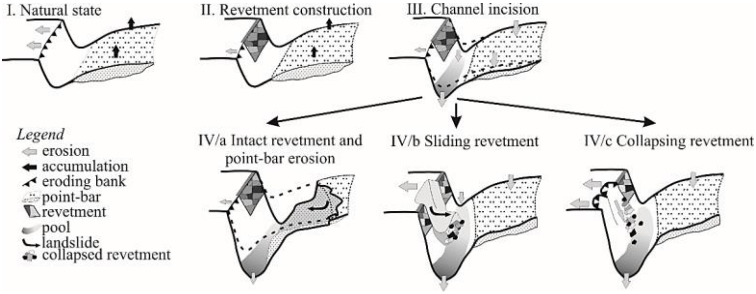

Fig. 2: Conceptual model of revetment collapse based on the case studies in the Lower Tisza

3.3 Changes in point-bar evolution and bank erosion

The changes in point-bar development and bank erosion determine the equilibrium conditions of a river as the two processes complement each other in a typical channel in equilibrium.

3.3.1 Changes in the point-bar evolution

The contemporary evolution of the studied point-bars indicated erosion as the dominant channel process. However, the factors influencing their development differed. While the Csongrád point-bar was influenced by human interventions, the Ányás point-bar developed freely. The relative changes in the elevation of the two point-bars were not very different. The change at Csongrád was 0.20 m (2012-2019), while that at Ányás it was 0.28 m (2013-2019). However, since the relative height at Csongrád was only 2 m compared to 11.5 m at Ányás, the change was more pronounced at Csongrád which was inundated between 2-3 months per year. At

Csongrád, the presence of a confluence may as well influence the sediment dynamics on the bar.

3.3.2 Bank erosion along the Lower Tisza channel

Although the Lower Tisza channel is generally erosion dominant, the measured erosion rates are different based on the morphology and state of revetment (if present). At the revetted meander, the stepped block revetment protected the bank from erosion. However, at the revetted section upstream with placed-rock revetments, there was a mean bank erosion rate of 0.79 m/y. This rate was higher at the collapsed placed-rock revetment downstream of the revetted section. At the freely developing meander, the rates of erosion were high (1.29 m/y), with the highest rates at the downstream section where the high steep banks provided favourable conditions for slips.

3.4 Modelling the morphology of the Lower Tisza

The morphological evolution of the Lower Tisza can be adequately modelled although exaggerated due to input schematization. The morphology of the Lower Tisza was modelled based on the natural evolution of the river without any revetments using the 2017 bathymetry and 1976 river pattern. The model employed discharge as the forcing on the open boundaries except the downstream boundary which utilized water level. The model shows that the channel will evolve with further incision of the channel bed and narrowing with sedimentation along most of the banks if no bank stabilization is present. This evolution pattern is similar to the evolution of the Lower Tisza before the effects of the construction of revetments and groynes.

3.5 Bedload transport on the Maros River

My analysis indicates that bedload rates are highly variable across the cross-section due to differences in the in-channel bed morphology arising from changing bedforms (a characteristic of the river), and how the Helley-Smith bedload sampler is positioned on the streambed. Furthermore, the optimum time for bedload sampling on the Maros was determined to be 60 s for low flows. The bedload transport measured at Makó had both high temporal and spatial variability. The recovered sediment yields. Although three sampling times were used (30 s, 60 s and 90 s), the 60 s sampling time was found to be optimum. The samples were recovered at low water flows

(< 300 m^3/s). The variations in the bedload transport may be due to differences of in-channel morphology, changing bed forms and the positioning of the Helley-Smith sampler on the channel bed. In the same sampling day, changes of up to 60 cm were recorded along the channel bed. As indicated by Sipos et al. (2007), the Maros has sediment pulses which may affect the temporal variability of bedload transport. The bedload rating curve showed a strong correlation between the bedload rate and the water discharge.

3.6 Estimating the bedload transport on the Maros

The bedload transport rate of the Maros can be estimated within a margin of 20% of measured bedload rates using the Bathurst formula although estimates using the Wong and Parker formula result in better consistency. The bedload transport rate was estimated using six different equations: Meyer-Peter Muller (1948), Einstein-Brown (Brown, 1950), Rottner (1959), Bagnold (1980), Wong and Parker (2006) and Bathurst (2007). The estimations were based on low discharges (<300 m^3/s) and a mean sediment size of 0.3 mm. Apart from the Einstein-Brown and Rottner formulae which were based on statistical theories, the other formula were based on flow characteristics. Based on the results, Bathurst's formula (0.18 kg/s/m) yielded the closest to the sampled bedload (0.15 kg/s/m) although Wong and Peter's formula generated the least standard error (0.011) of all the applied equations.

PUBLICATIONS IN RELATION TO THE DISSERTATION

Amissah, G. J., Kiss, T., Fiala, K. (2019). Active point bar development and river bank erosion in the incising channel of the lower Tisza river, Hungary. *Acta Geographica Debrecina Landscape & Environment*, 13(1), 13-28. DOI: 10.21120/LE/13/1/2

Kiss, T., Amissah, G.J., Fiala, K. (2019). Bank Processes and Revetment Erosion of a Large Lowland River: Case Study of the Lower Tisza River, Hungary. *Water*, 11, 1313. DOI: 10.3390/w11061313

Amissah, G.J., Kiss, T. (2019). The morphological evolution of a large alluvial river channel under human impacts: A case of the Lower Tisza River, Hungary. Carpatho-Balkan-Dinaric Conference on Geomorphology 2019, Szeged, Hungary (Abstract).

Amissah, G.J., Kiss, T., Fiala, K. (2018). Morphological evolution of the Lower Tisza River (Hungary) in the 20th century (1891-1999) in response to human interventions. *Water*, 10, 884. DOI: 10.3390/w10070884

Amissah, G.J., Kiss, T. (2018). The effect of point-bar formation and bank erosion on the morphology of the Tisza River, Hungary. *CAG State of Geomorphological Research in 2018 Conference*, Vilanec, Czech Republic (CD Abstract).

Amissah, G.J., Kiss, T., Fiala, K. (2017). Centurial changes in the depth conditions of a regulated river: Case study of the Lower Tisza River, Hungary. *Journal of Environmental Geography* 10 (1–2), 41–51. DOI: 10.1515/jengeo-2017-0005.