UNIVERSITY OF SZEGED
Faculty of Science and Informatics
Doctorate School of Earth Sciences
Department of Physical Geography and Geoinformatics

OVERBANK SEDIMENTATION AND ITS INFLUENCING FACTORS IN THE LOWER TISZA RIVER

Thesis of Dissertation

JUDIT NAGY

Supervisor:
Dr Tímea Kiss
Associate professor

Szeged, 2020

1. Introduction, aims

The nineteenth-century river regulation works and artificial levee constructions disrupted significantly the natural equilibrium of alluvial rivers. As a result of levee constructions, the original 5-10 km wide floodplain has been reduced to 1-4 km, thus in the Tisza river floods can occur only in this narrow floodplain. The amount of sediment transported by the river accumulates in this much narrower floodplain, which results in the gradual rising of the floodplain surface. Intensive overbank sedimentation can be a major problem from the point of view of flood protection, since as a result of sedimentation processes; the floodplain area available for flood conveyance is reduced. Flood conveyance is also affected by natural levees and point-bars, which are the most characteristic depositional features of vertical and horizontal sedimentation. These can be considered as transitory forms between the channel and the floodplain, and through their intensive sedimentation, these forms significantly influence the flow conditions in the floodplain.

In Hungary many detailed research have been conducted on the long and short-term aggradation of the floodplains of Hungarian rivers, using different methods. These researches, however, were based on point measurements, or investigated overbank sedimentation in shorter river section, then generalized these result on longer river reaches. Moreover, the spatial pattern of sedimentation has been the focus of these studies, and only a few have studied the influencing factors of overbank sedimentation processes. Besides, there is little data available on the long-term development of natural levees and point-bars, on the factors influencing their formation, and on the rate that they reflect the changes in the river system. However, the knowledge of these data could contribute significantly to the understanding of changes in river systems.

The primary aim of this research is to determine the amount of sediment accumulated on the floodplain of the Lower Tisza River since the artificial levee constructions, i.e. to determine the rate of overbank sedimentation based on non-point measurements. Since the rate of sedimentation is estimated in a longer floodplain section, my aim is to investigate the factors affecting the process of overbank sedimentation in the Lower Tisza River as well. Since natural levees and point-bars are the most characteristic features of the floodplain, thus the investigation of the development of these forms is of high priority in this dissertation. During the research the following aims have been set.

Estimation of the amount of sediment accumulated throughout the floodplain and its influencing factors

- What characterizes *the thickness and volume of accumulated sediment* in the analyzed 90-km-long floodplain section? How floodplain width, tributaries and vegetation affect overbank sedimentation?
- To what extent has the accumulated sediment reduced the *flood conveyance capacity of the floodplain*, and in which floodplain sections this reduction is the most significant?
- How the *land-cover and vegetation roughness* of the floodplain of the Lower Tisza River have been changed since the eighteenth century? To what extent has the invasive *Amorpha fruticosa* has invaded the different land-cover categories, and to what extent has the presence of this species increased the vegetation roughness of the floodplain surface?

Investigation of factors influencing the accumulation of sediments on natural levees and point-bars

- Which main factors determine the height, width, and rate of development of *natural levees*?

- How and to what extent do the type and rate of meander migration affect the morphological characteristics (height and width) of *each point-bar*?
- What types of point-bar development can be distinguished based on the changes in point-bar height in each *point-bar complex* in the direction of the channel? What are the primary factors influencing the formation of these types and what processes do they refer to?

2. Material and methods

The study area of this research is the Lower Tisza River between Csongrád and the Serbian border. Different methods were used to determine the rate of overbank sedimentation and the effects if the influencing factors.

2.1. The rate of overbank sedimentation

The rate of overbank sedimentation since the nineteenth-century artificial levee constructions was determined based on the height difference between the active floodplain and the flood-protected areas. On the active floodplain areas a high-resolution DTM (0.5x0.5 m, vertical accuracy: ±10 cm) was used based on a 2014 LiDAR survey, while on the flood-protected areas a 5x5 m DTM was used which was created based on a 1979-1985 topographic mapping (vertical accuracy: ±45 cm).

The thickness and volume of the accumulated sediment were determined on both the right and left bank of the river, in 1-km-long floodplain units bordered by lines perpendicular to the centreline of the channel.

The volume of sediment was determined also based on the height difference between the floodplain and the flood-protected areas, and these values were used to calculate the rate of reduction in flood conveyance capacity (%) in each floodplain unit.

2.2. Development of natural levees

Dimensions of natural levees (height and width) were determined also based on the DTM created from the 2014 LiDAR survey. The maximum height of the forms was determined relative to the average height of the flood-protected areas. At the same points, the width of the natural levees was also measured based on floodplain cross-sections. The edge of the forms was determined between the river bank and the point where the levee merges into the floodplain, i.e. where the slope of the surface is less than 1°. The rate of sediment accumulation (mm/y) was also determined, which was calculated for the period between the beginning of the formation of the natural levees and 2014 (LiDAR survey) based on the maximum height of the forms.

Natural levees were sampled to study grain composition, which can be used to infer spatial and temporal changes in the conditions of sediment accumulation.

2.3. Development of point-bars

Point-bars were identified based on the DTM created from the 2014 LiDAR survey, then the number of point-bars forming each point-bar complex was determined based on cross-sections, besides the height and width of the forms were measured as well. Similarly to natural levees, the maximum height of the point-bars was determined relative to the average height of the flood protected areas, while their width was defined as the distance between the deepest points of the swales bordering the point-bars on two sides.

2.4. Factors influencing overbank sedimentation and the development of natural levees and point-bars

2.4.1. Determination of channel and meander parameters

Average, right and left-side floodplain width, and average channel width were measured in different years (1784, 1861, 1890, 1929, 1976, 2014) based on channel, military, and topographic surveys. Besides the presence of revetments and their year of construction were also checked.

In the Lower Tisza River, the morphometric parameters of 39 bends were measured based on the 2014 LiDAR survey. Radius of curvature, length of arch, length of chord of meanders, and the distance of thalweg from the riverbanks were also measured based on the 1976 channel mapping, and these data were specified based on a 2017 mapping. The state of development of meanders was also determined based on the ratio of arch and chord-length of the bends.

Rate of meander development (m/y) was calculated based on military surveys (1783 and 1861), hydrographic maps (1890, 1929 and 1976), and 2014 LiDAR survey.

2.4.2. Long-term changes in land cover and vegetation roughness

To study the long-term changes in floodplain land-cover, different mappings (1784, 1861, 1881, and 1985) available from the end of the eighteenth century, and a 2017 GoogleEarth image were used. For each year the vegetation roughness (n) of the floodplain was also calculated: the mean roughness values determined in the literature (Chow 1959) were weighted by the area of the land-cover categories.

2.4.3. The impact of the invasive Amorpha fruticosa on vegetation roughness

To determine the role of *Amorpha fruticosa* in decreasing vegetation density in the floodplain, a photograph based method was used, which is suitable to calculate the area occupied by vegetation in a given volume, thus its density on a surface in downstream direction. The calculation of vegetation density was carried out for current conditions (winter of 2017/2018) in 15 plots, north of Szeged. The photographs were taken in 3 woody land-cover categories: in poplar plantations, in riparian forests, and in abandoned arable lands, meadows and pastures where *A. fruticosa* has started to spread aggressively. The photographs were taken in winter when there was no foliage on the vegetation. In order to calculate the contribution of *A. fruticosa* to vegetation roughness, it was erased from each image.

3. Results

3.1. Characteristics of overbank sedimentation and its influencing factors

3.1.1. *Since the artificial levee construction, in the studied floodplain section of the Lower Tisza River an average of 1.2 m thick sediment layer has accumulated, which corresponds to 90 million m^3 of sediment.* The thickness and volume of deposited sediment, however, vary on the right and left side of the floodplain, and also in each floodplain unit. The average thickness of sediment is 1.2 m both on the right and left side of the floodplain; however it varies between 0.4-2.6 m. The average volume of sediment is 0.35 million m^3 on the right side of the floodplain, while on the left side twice as much (0.75 million m^3) sediment has accumulated. The volume of sediment varies between 0.02-6.2 million m^3 by floodplain units.

3.1.2. *The most important result of overbank sedimentation is the gradual reduction in the flood conveyance capacity of the floodplain, which has decreased by 22.6% on average since the artificial levee constructions.* In floodplain sections characterized by the greatest loss of flood conveyance capacity, the rate of reduction is more than 40%, i.e. half as much space is available for flood conveyance than before levee constructions. These critical points are located near Csongrád. Mindszent-Mártély, Algyő, and south of Szeged, where the greatest reduction in flood conveyance affects 1-7-km-long floodplain reaches.

3.1.3. *The varying width of the floodplain determines significantly the volume of accumulated sediment (R^2=0.87).* In narrow (<700 m) floodplain sections, the maximum volume of sediment is 1.45 million m^3. A maximum of 1.5 million m^3 of sediment has been accumulated in widening but still narrow floodplain sections (700-1000 m). In broad sections (> 1000 m) 4-fold amount of sediment (max: 6.14 million m^3) has been accumulated than in the former two groups, while in narrowing but still wide floodplain units the maximum volume of sediment is half as much (3.4 million m^3) than in the broadest sections, but still nearly twice as much than in the narrowest and widening sections. The thickness of accumulated sediment, however, does not show a clear relationship with floodplain width, indicating the importance of local influencing factors, and that forms (natural levees and point-bars) associated with the river bank may have a significant influence on sediment thickness.

3.1.4. *Tributaries (Hármas-Körös and Maros River) flowing into the Lower Tisza River have different impacts on overbank sedimentation in the Tisza River floodplain, which is related to the varying slope, hydrological characteristics, and the amount* *of transported suspended sediment of the two tributaries.* Downstream of the mouth of the Hármas-Körös River, 0.6-1.1 m thinner and half the volume of sediment has accumulated in the floodplain than in the upstream sections. This is due to the two dams built in the Hármas-Körös River close to its mouth, which have reduced the sediment yield of the river. Decreased sediment yield results in the increased stream power of the Tisza River, which may shift the sediment balance from accumulation to transportation. This effect of the Hármas-Körös River occurs up to 5 km from the river mouth. Besides, this effect is also reflected in the grain size composition of natural levees along the Tisza River, since no sandy sediment occurred in the upper 5-10 cm deep layer of the natural levees, only silt (69% on average) and clay (31% on average) were found. In contrast, a 0.6 m thicker sediment layer has deposited downstream of the river mouth of the Maros River, and more intensive sedimentation occurs slightly further from the river mouth, south of Szeged. The decrease in overbank sedimentation in the floodplain reach between the river mouth of the Maros River and the section with intensive overbank accumulation is caused by the narrow floodplain, which is merely 470 m wide downstream of the river mouth.

This narrow floodplain and the great slope of the Maros River results in increased stream power, thus instead of accumulation sediment transportation occurs in a 3-km-long section. The floodplain widens in downstream direction (up to 750 m), causing the water flow to slow down on the floodplain and resulting in more intensive overbank sedimentation, which is contributed by the greatest sediment yield of the Maros River.

3.1.5. *Land-cover of the floodplain of the Lower Tisza River has changed significantly since the end of the eighteenth century, and simultaneously the vegetation roughness of the surface has increased nearly fivefold.* Before the artificial levee constructions, 83% of the present-day floodplain area was periodically or permanently covered by water. After the construction works the area of wetlands suddenly decreased, and they were gradually replaced by meadows and pastures, on which later trees started to grow. At the end of the 1800s, meadows and pastures occupied 76% of the study area, and nearly half of them were covered by sparse trees and bushes. Simultaneously, vegetation roughness doubled (from n=0.023 to n=0.048). At the end of the 1900s, however, most of the study area (61%) was covered by forests as a result of intensive forestation, thus the area of meadows and pastures significantly decreased. This process continued in the subsequent decades, and as a result the area of forest increased up to 73%, and the area of meadows and pastures decreased to 11% by 2017. Vegetation roughness followed these land-cover changes, as its value was n=0.09 estimated based on the 2017 GoogleEarth image. Field measurements, however, suggest a much greater vegetation roughness (n=0.11) due to the presence of the invasive *Amorpha fruticosa*, which started to spread aggressively in the mid-twentieth century.

3.1.6. *The invasive Amorpha fruticosa invaded the different land-cover categories by varying degrees, with the most significant populations occurring in poplar plantations and fallow lands. A. fruticosa* has invaded riparian forests to the lowest degree, where it increases vegetation density only by 3%. It is due to the fact that because of the shading effect of older trees, A. fruticosa is less able to invade the inner areas of riparian forest patches. In poplar plantations vegetation density is increased by 23% on average due to the presence of *A. fruticosa*, and the degree of invasion is dependent on the degree of undergrowth tending. A. fruticosa has invaded fallow lands (arable lands, meadows and pastures) to the highest degree, since it contributes to vegetation density by 76% on average, but at some places it can reach 100%.

3.1.7. *Based on the relationship between the thickness of accumulated sediment and vegetation roughness the n=0.08 roughness represents as a threshold value for overbank sedimentation.* As riparian vegetation becomes denser, the velocity of overbank flow increasingly decelerates, thus a greater amount of sediment accumulates near the river bank. As vegetation roughness increases (n>0.08), however, the thickness of deposited sediment begins to decrease, since at some sections of the bankline a very dense, impenetrable shrubbery grows, which acts as a filter or sponge against floods and prevents sediment to be transported to distal areas of the floodplain.

3.2. Factors influencing overbank sedimentation in the riparian zone

3.2.1. *The height of natural levees is determined by the radius of curvature of meanders and floodplain width, although the slight effect of revetments can also be demonstrated.* The effects of radius of curvature and floodplain width vary by stages of meander development. Along pseudo and undeveloped meanders, the impact of radius of curvature on the height of the natural levees is slighter (R^2=0.16), which is related to the smaller centrifugal force resulting from the great curvature, and to the narrow floodplain sections (<200 m) along these meanders, which prevents the radius of curvature to be effective. Thus, along pseudo and undeveloped meanders the height of natural levees is primarily determined by floodplain width.

Along developed and mature meanders the height of natural levees is strongly affected by the radius of curvature (R^2=0.86). This occurs along nearly half of the meanders, where the floodplain is broad enough (≥ 200 m) to allow the effect of the radius of curvature to prevail. Along the other half of the meanders, where the floodplain is narrow, the height of natural levees is affected by floodplain width. The height of the forms is also affected by revetment, although to a slighter degree. Along floodplain sections with revetments 0.2-0.3 m higher natural levees have formed than along freely developing meanders.

3.2.2. *The width of natural levees is related to floodplain width (R^2=0.65) along both pseudo-undeveloped meanders and developed-mature meanders.* However, along the former group, where the floodplain is broad enough (≥ 200 m) the effect of radius of curvature also prevails (R^2=0.5), since these meanders have small radius of curvature, thus the centrifugal force allows the sediment to be transported to distal areas of the floodplain.

3.2.3. *The rate of sediment accumulation on the surface of natural levees is closely related to the age of the forms, thus older natural levees develop slower while younger ones develop faster.* According to my results, older natural levees (> 180 years old) develop at an average rate of 21-22 mm/y, while on the surface of the youngest forms (max. 40 years old) sediment accumulation has an average rate of 83-115 mm/y. This difference suggests an acceleration in sediment accumulation, which is a primarily due to the increasing density of riparian vegetation, channel narrowing, and increased stream power of floods. The rate of sediment accumulation may be slightly reduced by thalweg being closer to the outer bankline. During floods, in my opinion, the proximity of the thalweg results in a greater stream power, and this prevents a greater amount of sediment to accumulate along the bankline. Besides, natural levees can be also eroded away, which results in a decrease of average rate of sediment accumulation on the surface of the forms.

3.2.4. *The height and width of point-bars is in direct proportion to the radius of curvature in the case of rotating meanders.* Three groups of the studied meanders along the Lower Tisza River can be distinguished: 70% of the meanders are expanding, and have a radius of curvature of greater than 750 m; 23% of the meanders are rotating, and a have radius of curvature of smaller than 750 m; while only one meander is characterized by transition. According to my results, 1.6 m higher and 20 m wider point-bars were formed along rotating meanders with the smallest radius of curvature than along expanding meanders.

3.2.5. *The width of point-bars is affected by the rate of meander migration through its impact on channel width, while the height of point-bars is related to decelerating meander migration due to revetments built on the outer banks.* Since the 1890 channel survey, the average channel width of the Lower Tisza River has decreased by 17.2% (from 192 m to 159 m), and simultaneously the average width of the point-bars has decreased from 68 m to 19 m. Due to the intensive revetment constructions between 1930 and 1960, the rate of meander migration decreased significantly, and at many channel sections it ceased, as while the average rate of migration of the outer bank was 0.5 m/y and of the inner bank was 1.1 m/y between 1890 and 1929, it decreased to 0 m/y by 2014. As a result the lateral formation of point-bars ceased, which has been replaced by the vertical accumulation of sediment resulting in a significant increase in the height of the youngest point-bars. This increase can reach 2.3-3.4 m and is observed along 70% of the studied meanders.

3.2.6. *Due to the increasing height of point-bars, sediment can accumulate on the surface of the forms during only floods with increasing return period.* While earlier the point-bars were covered by floods with a return period of 1.2-1.8 years, nowadays the forms are only flooded and built by floods with a return period of 2-4.8 years.

3.2.7. *Along the Lower Tisza River, three main types of point-bar development can be distinguished based on the height changes of point-bars towards the channel: descending, ascending, and constant.* These types are related to changes in the channel (e.g. incision), the rate of bend migration, and/or bedload and suspended sediment yield. The decrease in the height of point-bars in a given point-bar series may indicate (i) channel incision, as the point-bars have to decrease if the conditions and the time available for development do not change; (ii) accelerating meander migration, as in this case there is less time available for the formation of the point-bars, and (iii), it may indicate a decrease in sediment yield, as it would take a longer time for the point-bars to form, while no more time is available with the same rate of erosion on the concave bank.
The increase in the height of point-bars may indicate (i) decrease in the rate of meander migration, as more time is available for the formation of the point-bars; thus they became increasingly higher. Higher point-bars could also indicate (ii) an increase in bedload and suspended sediment yield, as, if the time available for point-bar formation is constant; more sediment accumulates on the surface of the point-bars, significantly increasing their height.
As descending, ascending, and constant point-bars occur adjacent to each other, the general variation in sediment yield of the Lower Tisza River cannot be the cause of their formation, since it would result in uniform changes in the height of point-bars. Thus, different types of point-bar development draw the attention to the influence of local influencing factors.

Publications used for the dissertation

Nagy Judit – Fiala Károly – Blanka Viktória – Sipos György – Kiss Tímea (2017): Hullámtéri feltöltődés mértéke és árvizek közötti kapcsolat az Alsó-Tiszán, Földrajzi Közlemények, 141/1, 44-59.

Nagy Judit – Kiss Tímea – Fiala Károly (2017): Hullámtér-feltöltődés vizsgálata az Alsó-Tisza mentén I. Hullámtér-szélesség és beömlő mellékfolyók hatása az akkumulációra, Hidrológiai Közlöny, 97/4. 59-66.

Nagy Judit – Kiss Tímea – Fiala Károly (2018): Hullámtér-feltöltődés vizsgálata az Alsó-Tisza mentén II. Folyóhátak (parti hátak) feltöltődését befolyásoló tényezők, Hidrológiai Közlöny, 98/1, 33-39.

Fabio Delai – Tímea Kiss – **Judit Nagy** (2018): Field-based estimates of floodplain roughness along the Tisza River (Hungary): The role of invasive Amorpha fruticosa, Applied Geography, 90. 96-105.

Judit Nagy – Tímea Kiss – István Fehérváry – Csaba Vaszkó (2018): Changes in floodplain vegetation density and the impact of the invasive Amorpha fruticosa on flood conveyance. Journal of Environmental Geography, 11/3-4, 3-12.

Tímea Kiss – **Judit Nagy** – István Fehérváry – Csaba Vaszkó (2019): (Mis)management of floodplain vegetation: the effect of invasive species on vegetation roughness and flood levels. Science of the Total Environment, 686, 931-945.

Judit Nagy – Tímea Kiss (2019): Point-bar development under human impact: case study on the Lower Tisza River, Hungary. Geographica Pannonica (in press).