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MŰSZAKI
KATONAI
KÖZLÖNY

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Investigation of the Spatial Changes in Overbank Floodplains and Sedimentations on the Study Site of the Middle Tisza

River systems and their floodplains can be studied and evaluated according to different aspects. The natural processes of the Tisza were mostly influenced by the river training and levee construction works named after Vásárhelyi, as well as the main channel regulation works. After the construction of the embankments, the fluvial formation of the natural floodplains ceased, as these processes limited it to areas of the floodplain along the main channel. Another consequence of the river regulations is that the river is forced to deposit the sediment transported during the floods in this narrow floodplain causing increased filling up, so the role of floodplains in flood conveyance has increasingly been reduced. In this study, the author aimed to investigate the bed changes that occurred as a result of the river regulation works, as well as the sediment accumulation in the flood plain, focusing on a typical section of the Middle Tisza.

Keywords: *Tisza, geomorphology, sedimentation, digital elevation model, floodplain*

Introduction

At the turn of the millennium, the Tisza River repeatedly showed that significant changes had occurred in the flow conditions. The previous record water levels in the most important water gauge sections of the river have fallen successively, which drew the attention of the country's leadership to the flood protection problems of the Tisza Valley. Looking for the causes, the process can be partly explained by changes in land use in the catchment area, or by the effects of climate change. The floods, which start from heavy, suddenly heavy rains, arrive at the domestic river section with a high concentration of sediment, where compared to the slope conditions of the foreign river bed, the speed of the flow slows down, so the transported sediment[2] builds up the bed and narrowed floodplains due to the surrounding,

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[2] Stelczer 1973.

anthropogenic effects. Regarding the floodplains, the situation was further worsened by the fact that they were not adequately managed and maintained from a water point of view, so impenetrable "living walls" were created in places, decreasing their water conveyance capacity. Consequently, the flood of the river is sometimes forced to flow down a section of a floodplain with extremely poor hydraulic conditions, so it overcomes the loss of kinetic energy by increasing its potential energy, which results in a further increase in peak water levels.

Literature review

The rate and tendency of the Tisza river bed changes have been examined more seriously since the major river regulation works, since the middle of the 19th century in most published literature, since the bed development in the cut sections of the river bed was the most intensive in this period due to the increased slope conditions. According to Jenő Kvassay's[3] study, as a result of the regulation works that took place in the middle of the 19th century, there were significant changes in the levels and duration of high and low waters. In case of large waters, an increase of 147 cm was observed in Szolnok between the years 1830 and 1895, while in case of low flow conditions, the water levels dropped by 100 cm, which was attributed to the higher energy of the river.

Additionally, he numerically confirmed that due to the increased slope of the main channel, the durability of the flood waves significantly decreased on the section between Vásárosnamény and Szeged, the period for the flood wave decreased from 52 days to 6–10.

Fekete[4] analysed the cross-sections of the main channel based on three bed surveys taken at different times. According to his findings, the average depth of the bed in the Polgár–Szolnok river section increased by about 0.8 m during this period, while the section area expanded by an average of 140 m^2.

Károlyi[5] was one of the first to give a numerical estimate of the filling up of the floodplains along the Tisza, but according to him, this has no significant effect on the rise of floods. Since that time, research by other authors has proven that the effect of reducing the wetted cross-section (A_w)[6] of sediment deposition has a significant effect on flood levels.[7]

In Hungary, sediment accumulation came to the forefront of research within the water sector after the record floods of the turn of the millennium, 1998–2000. The research was aimed at discovering the deposition processes that took place during a flood or during the period since the regulation works, using various measurement methods. In the early phase of the research, the level of filling up was determined by comparing the height data of the

3 Kvassay 1902: 8–27.
4 Fekete 1911: 141–152.
5 Károlyi 1960.
6 Aw: Wetted Area – author's note.
7 Gross 2003: 115–121.

VO[8] profiles, and later with more serious sedimentological and chemical analysis as well as pollen analytical tests.

In his study, Dombrádi[9] analysed the water level and water flow data series of the Szolnok section and also pointed to the phenomenon of changes in the riverbed, which can be detected mainly in the high water regime. In recent decades, the large-scale development of geo-informatics systems has made it possible to estimate the level of accumulations by comparing digital terrain models.[10]

Short description of the study area

A typical section of the Middle Tisza (Szolnok and its surroundings) was delineated as the study area of the following research. Based on the results of several previous studies and publications, it can be stated that the geomorphological and accumulation processes in this section of the Tisza have a significant (typically negative) influence on the discharge of the floods. A part of the Middle Tisza between 345 and 325 fluvial kilometres was selected as the study area. The section considered is problematic as it affects the city of Szolnok and its surroundings, where it has been proven that serious problems are caused by the filling up of floodplains and the accumulation of sediment. In their study, Nagy[11] and his colleagues pointed out that the conveyance capacity of the river and its floodplain had significantly deteriorated, which was derived from the analysis of the loops of rating curves compiled from the series discharge measurements during floods.

We can divide the river section into a narrowing and widening section and there are three oxbow lakes in the examined section. These are the Holt-Tisza of Alcsi, the Holt-Tisza of Feketeváros and the Holt-Tisza of Szajol (see Figure 1 below). These oxbow lakes were created as a result of the regulation works of the Tisza through the cut offs carried out between the 1840s and 1850s.

The section is characterised by a relatively small water surface slope (2–3 cm/km). There is a gauging station at Szolnok (334.6 fluvial km) and water flow measurements are also regular here. In the section, the velocity of water 0.2–0.4 m/s at low water conditions, 0.5–0.8 m/s at mean flow conditions, and around 1.4–1.5 m/s may occur in the event of a flood. The hydrological regime around 13.0 meters (LKV:[12] –291cm; LNV:[13] 1041cm). The minimum discharge detected so far is 68 m^3/s, while the maximum reached 2,640 m^3/s, i.e. the difference between the discharges is almost 40x.

8 Reference section designated by the Hydrographic Department – author's note.
9 Dombrádi 2004: 57–62.
10 Gábris et al. 2008: 65–71.
11 Nagy et al. 2001: 539–564.
12 LKV: lowest water level detected so far.
13 LNV: highest water level detected so far.

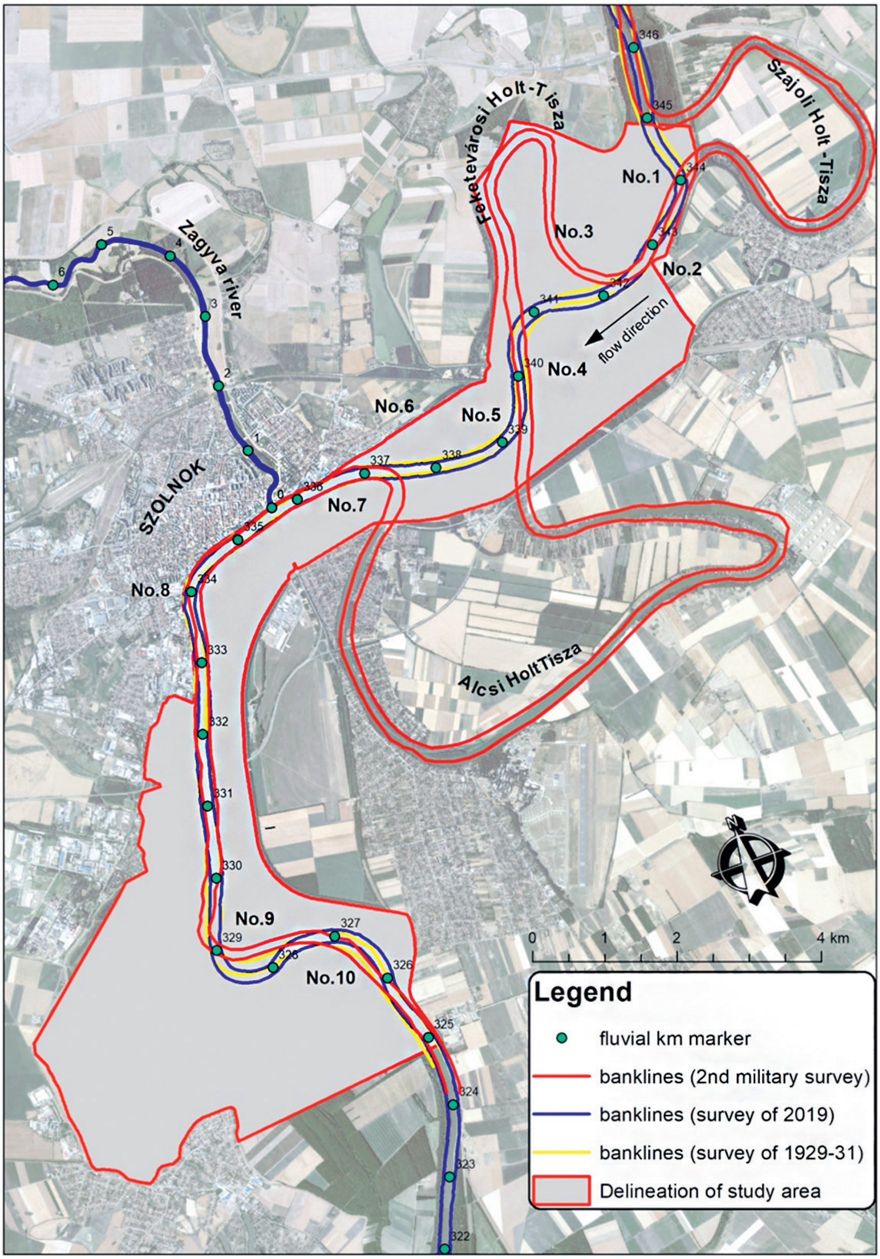

Figure 1: Presentation of the examined study area (between 345.0 and 325.0 fluvial km)
Source: Compiled by the author.

Material and methods

For the investigation, I have used the hydrological surveys of the Tisza, which are based on field measurements and were made according to uniform principles, so the parameters of the bed and floodplain could be determined more precisely. Since the regulations of the 19th century, such maps have been produced 6 times, for the current work the basic information for the calculation was based on the 1929–1931 survey and the recent aerial photographs and terrain models of 2019. This nearly 100-year period is long enough for the investigation of main channel migration and morphological processes[14] taking place in the section. The banklines, centrelines and inflexions have been digitised in GIS environment for the whole section under study.

With the help of the completed digital files, the following bend parameters (Figure 2) were determined for the section:

- section length: the total length of the centre line
- main channel width: the distance between the banks
- arc length (L): distance between two inflexion points measured along the centre line
- chord length (H): the distance between two adjacent inflexions
- amplitude (A): the greatest perpendicular distance between the chord and the arc
- the radius of curvature (R): the radius of the largest circle that can fit into the curve
- sinuosity index: parameter based on the coefficient between the length of the riverbed and the shortest distance between its beginning and end of studied river reach[15]

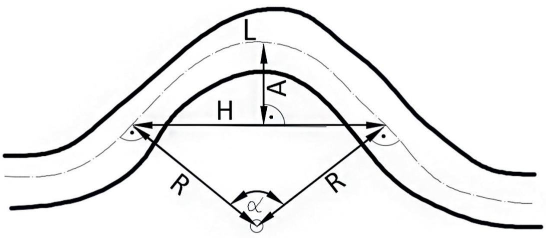

Figure 2: Interpretation of parameters of bends
Source: Compiled by the author based on Zorkóczy–Károlyi 1985.

In the section, I distinguished between curves and meanders with free development and those influenced/regulated by anthropogenic effects/activity. The total length of the section today is 18,221 m, of which the length of the sections stabilised by stone scattering (on one of the banks) is a total of 8,617 m, which represents a ratio of about 47%. These embankments and stone works were built in the period from 1930 to 1960 to stabilise the bends.

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[14] Fiala–Kiss 2006.
[15] Horacio 2014.

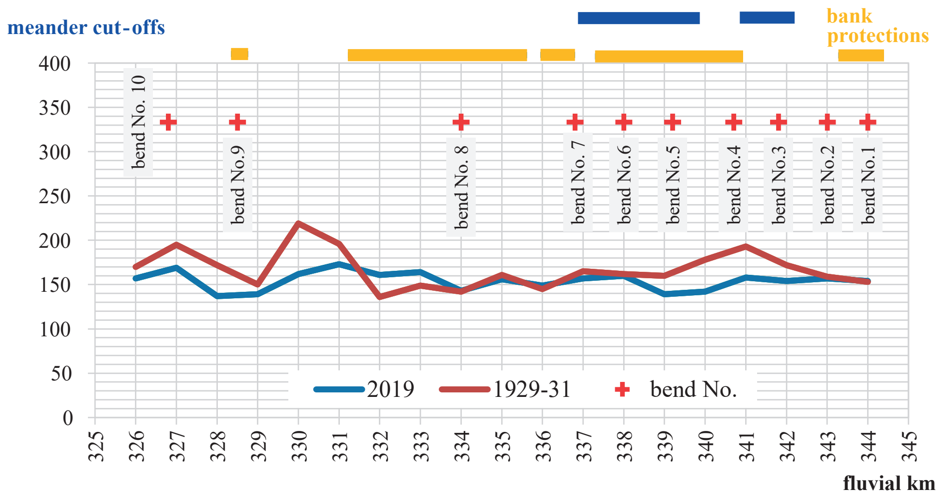


Figure 3: Development of the latitudinal conditions of the examined river section
Source: Compiled by the author.

Between the two examined periods (1929–1931 and 2019), the width of the main channel decreased by an average of 7–8% (0.14 cm/year), the more detailed time course of this can be determined by analysing the additional recordings related to the test phase (Figure 3) (by evaluating additional mapping and surveys). The decrease in width is related to the fact that, as a result of the bank protections built between the two surveys, the point bar shifted towards the centre line. A good example of this is the case of bend No. 4 (which is located north of Szolnok), where the outer bank of the bend was stabilised with a stone surfacing, but the inner bank was able to develop further. Furthermore, this bend started to develop after the crossing of the Holt-Tisza in Feketeváros, before that there were no bends on the river here.

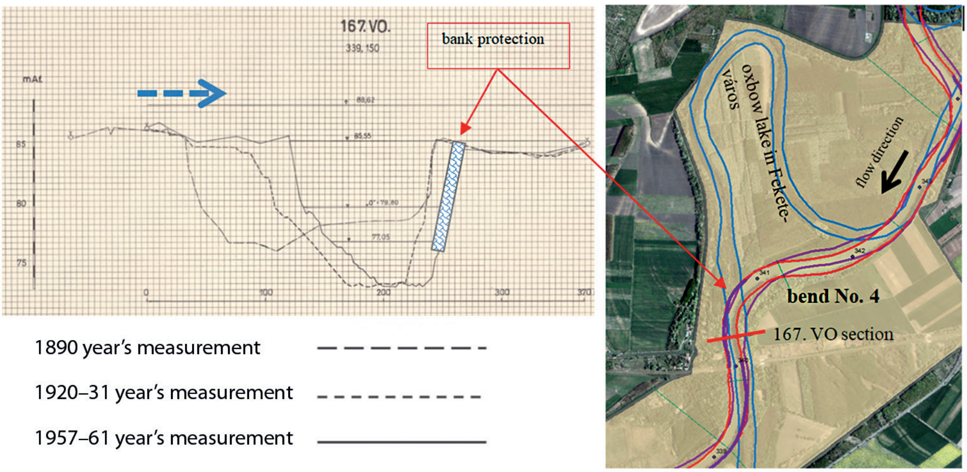
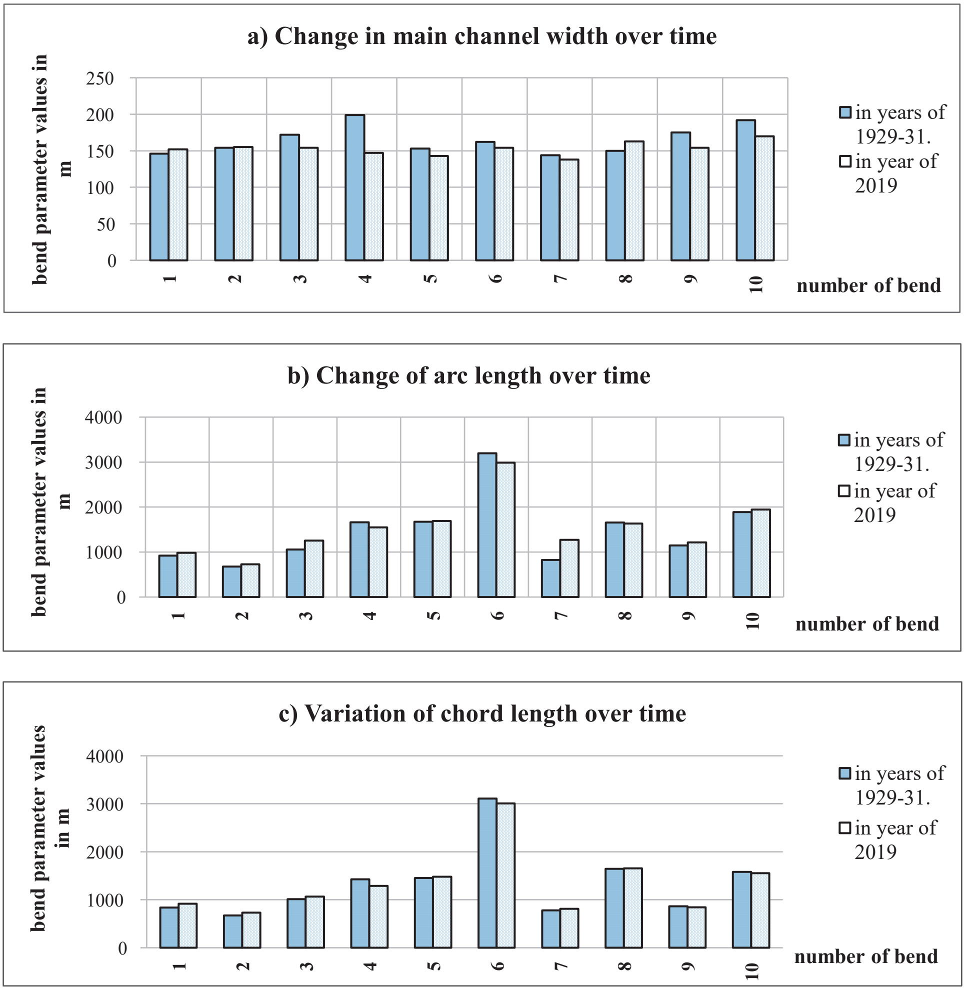


Figure 4: Horizontal development of the meander concerned by the bank protection (comparison of previous surveys)
Source: Compiled by the author based on Stelczer *1973.*

In Figure 4, I have depicted the development of the above-mentioned bend No. 4, on which the changes between 1890 and the periods 1929–1931 and 1957–1961 can be traced. The bend was created by connecting the Feketevárosi Holt-Tisza, apparently between the surveys of 1890 and 1929 it developed significantly as a result of the new bend created, the left bank shifted almost 80–90 m towards the right bank (nearly 2.0 m/year rate). The position of the right bank did not change significantly, as the river deepened its bed and in the following period the bank on the right began to be demolished as well. After that, the necessary bank protection works were carried out, as a result of which the rate of river bed development slowed down significantly, the left bank migrated 30–40 metres, while the right bank moved 10–20 metres until the 1957–1961 survey.

I have presented the changes that occurred between the test periods of the individual curves in the series (a–e) of Figure 5.



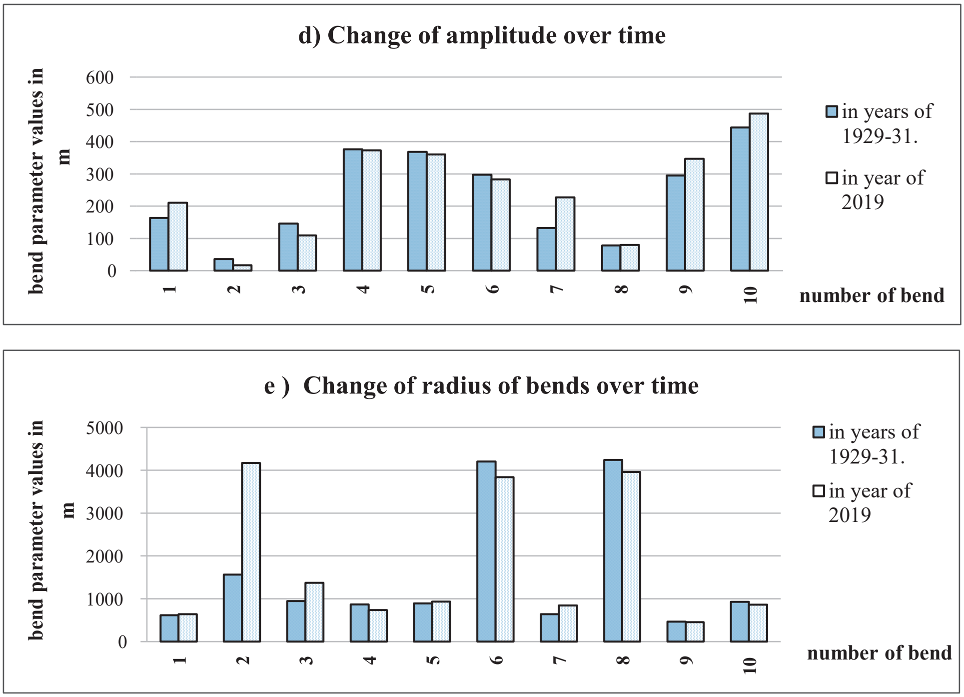


Figure 5: Evolution of cornering parameters between the two test periods
Source: Compiled by the author.

Regarding the length of the river section, the length of the centre line increased by 1.3% in proportion to the development of the bends, the average value of the amplitude and the radius of the bend (2.76 m/year) and the development of the bend also showed an increase of nearly 10–15% during this period. The summary diagram of the horizontal turning parameters is shown in Figure 6. The numerical data shown here are to be interpreted as the average value of the given parameter per bend, of course more marked changes than these values can be detected at certain bends.

As an excellent example of this, I have analysed the changes to the last bend number 10, which was not equipped with bank protection, so it can continue to develop without anthropogenic influence. Figure 7 shows the parameters of the No. 10 freely developing bend. The development of the bend is clearly shown by the data presented below, and the retreating of the bank reached 70–80 metres over nearly 100 years.

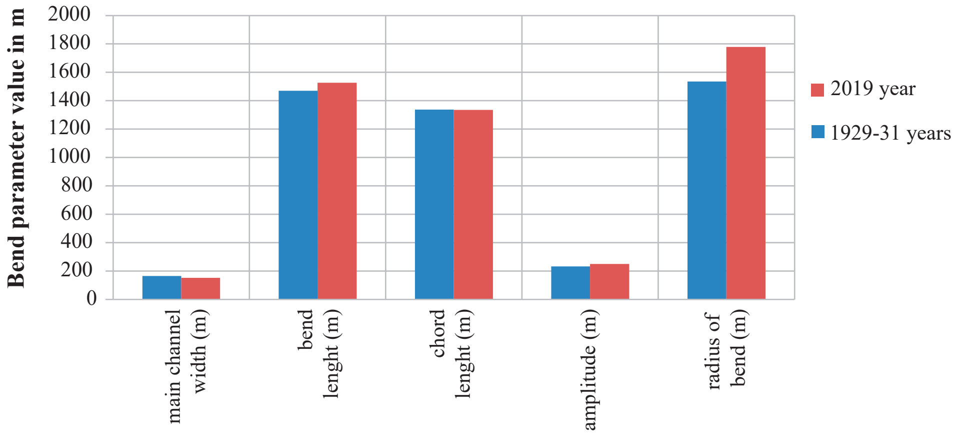
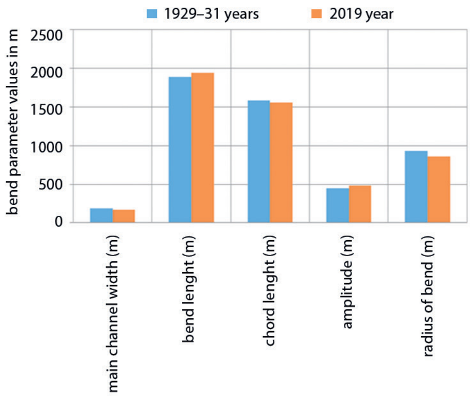


Figure 6: Average change of the bend parameters during the examined periods
Source: Compiled by the author.



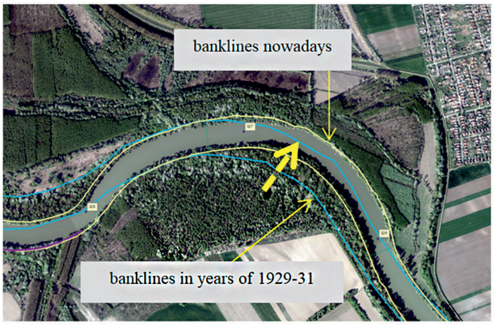


Figure 7: Change of the parameters of the bend No. 10
Source: Compiled by the author.

Estimation of floodplain accumulation based on digital terrain models

To quantify sediment deposits in the sample area presented above, I used the digital terrain models created by EUROSENSE in 2001 and the LiDAR[16] surveys in 2014 as basic data. Several people have already investigated the filling up of the floodplains in this section.

[16] Light Detection and Ranging – author's note.

After the big floods of 2000, the floodplain deposits were indirectly deduced from the investigation of the flood loop curves, with the conclusion that the increase in the difference between the rising and falling limb of floods is attributable to the increasingly poor water conveyance capacity of the floodplain. In addition, they were able to estimate the amount and thickness of suspended sediment deposited during each big flood based on the research carried out in the Szolnok floodplain. The developing of natural levees was also investigated, based on this the estimated accumulation could be reached 10–45 cm per flood.

The width of the floodplains in the area is quite variable, in general, it can be said that it is a narrowing and then widening section, where the average width of the floodplain is around 2.0 km. The narrowest part of the study area is located in the downtown section of Szolnok, which is about 160 m wide. It can reach 5.0 km in the widest parts, which is important because I have assumed that there will be less sediment deposition in narrower floodplains, while larger, thicker sediment deposition will be experienced in wide, spreading slow water flow floodplain areas.

The spatial resolution of the digital floodplain models used differs in magnitude due to the technical development of the time between the two surveys. The 2001 stock has a resolution of 5 × 5 m, while the laser-based digital map of 2014 has a spatial resolution of 0.5 × 0.5, which means that it is capable of mapping the surface in more detail, which is well illustrated in Figure 8.

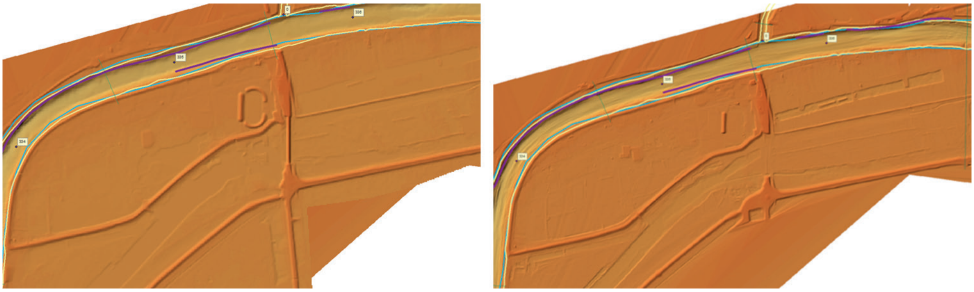


Figure 8: Digital model of the given area made using two different methods (on the left: from 2001, on the right from 2014)
Source: Compiled by the author.

With the tools of GIS software, it is possible to extract these terrain models from each other, thus it will be possible to determine the amount of sediment deposited on the floodplain in the period between the two recordings and to quantify its thickness. I presented the thickness of the sediment deposited on the floodplains in two characteristic cross-sections, one narrowing above Szolnok and one expanding below Szolnok. The examination of the cross-sections reveals the extent to which the test cross-sections have been modified.

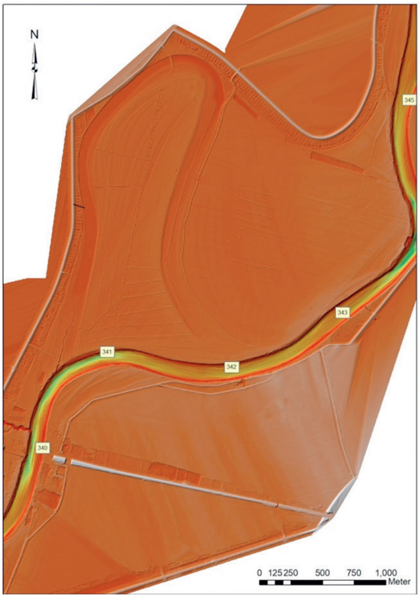
The sections clearly show that e.g. intensive accumulation occurs near the bank due to the effect of summer dykes and natural levees (see Figure 9). Regarding both profiles, a level increase of up to 1.0–2.0 metres can be observed near the banks, while in the rest of the floodplain, moving away from the main channel the amount of deposited material decreases markedly. The average accumulation per section can be estimated at around 0.2 m during 13 years.

Regarding the entire section, I examined the left and right bank floodplains separately. Similar to the previous ones, I used the difference between the two terrain models as a basis. By dividing the floodplains into sections, the average filling up level can be determined for both the left and right bank floodplains. The results are summarised in a table (Table 1).

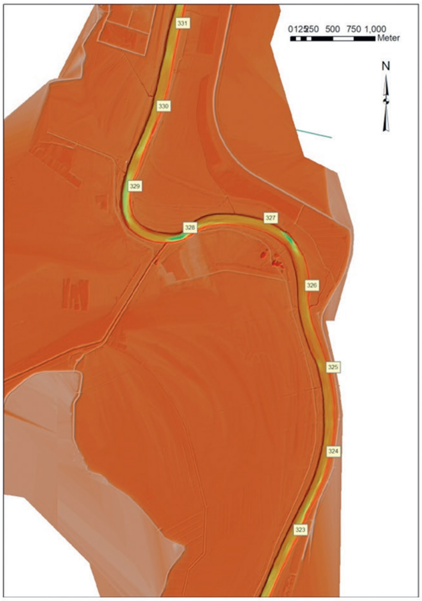
Table 1: Data on the rate of filling up of the floodplain on the examined section

	Left bank floodplain	**Right bank floodplain**
Average value of accumulation [m]	0.25	0.21
Total area (km^2)	11.8	21.5
Estimated amount of alluvial deposits (1,000 m^3)	2,950	4,515
Average accumulation rate (cm/year)	1.9	1.6

Source: Compiled by the author.



A-A section above Szolnok



B-B section under Szolnok

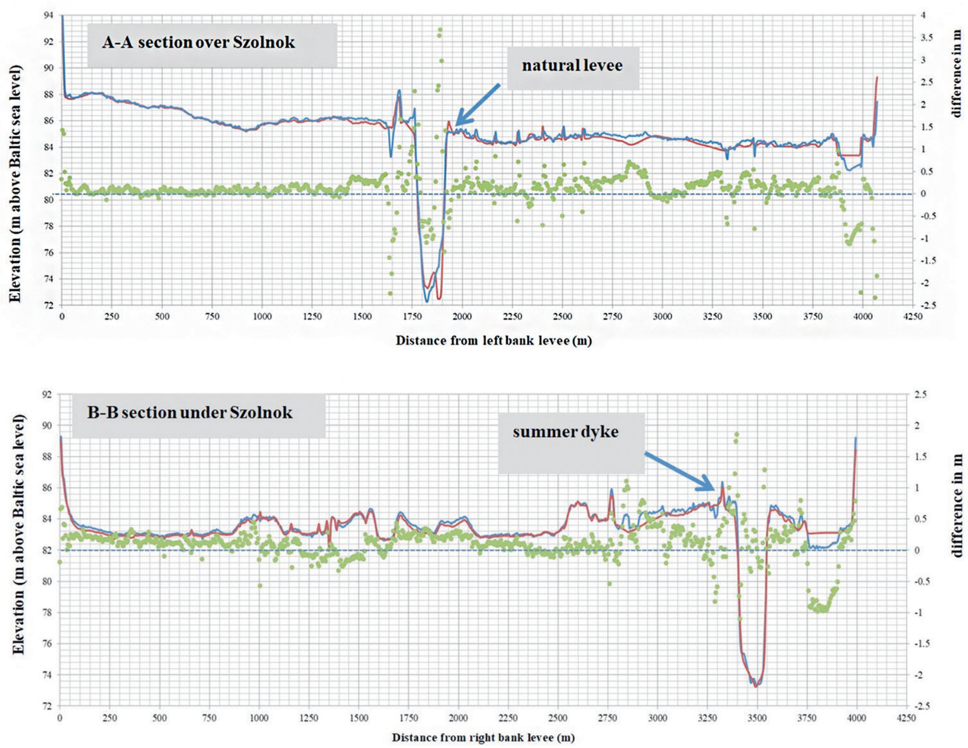


Figure 9: Investigation of floodplain sediment accumulation in two typical sections
Note: Blue line – DTM 2014; red line – DTM 2001; the points represent the difference between the two terrain models (DTM 2014 – DTM 2001) at that point.
Source: Compiled by the author.

Summary

The major regulation works of the Tisza began more than 150 years ago, but their impact is still felt in some cases to this day. By cutting the overdeveloped bends, our predecessors increased the slope of the river, reducing its length by 400 km. The river, which once roamed the entire Great Hungarian Plain, was squeezed between embankments, as a result of which serious changes occurred in its hydrological regime. The levels of the low flows were almost 1.0 m lower in Szolnok. A 1.5 m rise in flood peaks was experienced until the end of the 19th century. New bends developed in place of the intersected bends, and the old ones continued to develop due to increased erosion. Starting from the 1930s, bends were stabilised with bank protection, which in many cases only meant securing the outer curve of the bend. In the study, I have presented the effect of river regulation works (significant anthropogenic effects), based on the surveys between 1929–1931 and the 2019 recordings. It can be concluded that, overall, the river regulation works achieved their goal, the river is almost in a state of equilibrium, although the free developing bends continue to show further progress.

Another main result of the study is that it provides a numerical estimate of the floodplain siltation that occurred in the study area in the period since the turn of the millennium. After the big floods that took place between 1998–2000, the water sector realised that greater emphasis should be placed on the correct management and maintenance of the river's floodplains. Several studies have been conducted to estimate the amount of deposited sediment. The accumulation can be estimated well based on the digital elevation models available in the examined section. The digital model created by EUROSENSE in 2001 and by the ÁKK project[17] in 2014 with laser-based remote sensing provided the basis for the tests. After analysing the base data, it can be concluded that the degree of accumulation is the most intense near the main channel of the river, which can reach 1.0–2.0 metres in some places. The negative effect of summer dams can also be demonstrated. Based on the 13 years that have passed between the two digital models, they can be characterised by an accumulation rate of 1.9 cm/year in the left bank floodplains and 1.6 cm/year in the right bank floodplains. The tests carried out in the Lower Tisza showed a slower rate of accumulation (0.8 cm/year), but it should be noted that those tests were intended to show changes over 100 years.[18]

Based on the above data, if this pace continues, a further increase in flood levels is expected. In order to ensure satisfactory flood safety and to keep flood risks at a tolerable level, comprehensive, complex flood protection strategies are necessary, and it is essential to develop systemic water management at the sectoral level. In addition, the measurement of the suspended sediment and bedload carried by the river needs to be concentrated in space and time, using the appropriate instrumentation and methodology of the time.

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