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Point-bar Development Under Human Impact: Case Study on the Lower Tisza River, Hungary

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Abstract

Point-bars are the most typical forms of floodplains; therefore, any change in the fluvial environment is reflected in their formation. We aimed to analyse the morphological characteristics and influencing factors of their formation along the Lower Tisza River (Hungary). Before the 1930-60s the morphological characteristics of point-bars were affected primarily by natural factors. However, after revetment constructions, the lateral migration of meanders ceased and channel became significantly narrower, therefore point-bar widths have decreased from 68 m to 19 m. Besides, vertical accumulation became dominant, thus, the youngest active point-bars are narrow and high.

Keywords: point-bar; meander migration; human impact; revetment; channel narrowing

Introduction

Point-bars are the most characteristic depositional features of meandering rivers. These quasi-regular ridges parallel to the river bank are formed along the convex banks as a result of secondary flows in a meander (Hooke, 1975): the decreased flow velocity along the convex bank results in sediment deposition (Dietrich & Smith, 1983). As a result of lateral meander migration, new point-bars are developed, forming point-bar complexes (Nanson & Hickin, 1983).

The mechanism of point-bar formation has been the subject of numerous researches (Hickin, 1969; Hickin & Nanson, 1975; Jackson, 1976; Hooke & Harvey, 1983; Hooke 2007, Hagstrom et al., 2018, Hagstrom et al., 2019, Moody, 2019, Wang et al., 2019); however, the fact that how various human impacts affect their formation is a rarely posed issue. The factors influencing the morphological characteristics (e.g. height, width, and spacing) of point-bars have been the subject of some research, but the combined effects of these factors are rarely studied (Strick et al., 2018). However, research on the influencing factors is essential, as the formation and characteristics of point-bars are affected by several factors that are parts of the complex fluvial systems. The morphology of point-bars is influenced by the radius of curvature of meanders, which is closely related to meander migration rate (Hickin, 1974, Nanson & Hickin, 1983). Besides, the influence of the type of meander migration (Strick et al. 2018), the channel width (van de Lageweg et al., 2014), and the resistance of channel material (Nanson & Hickin, 1983; Thorne, 1991; Motta et al., 2014) are also important. Human impacts also probably have significant effect on point-bar formation, however it is rarely studied. Exceptions are the studies of Biedenharn et al. (2000) and Zinger et al. (2011), who evaluated the role of cut-offs and revetment constructions on point-bar formation, stating that these are the major influencing factors in regulated rivers, and if the revetments were built in different years, they influence point-bar development differently.

River dynamics can be significantly altered by human impacts (Romanescu et al., 2011; Djekovic et al., 2013; Tarolli et al., 2019), such as channelization works and cut-offs (Kiss, 2014) alter the stream gradi-

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ent which leads to channel incision (Surian & Rinaldi, 2003), the construction of artificial levees accelerates overbank sedimentation (Sándor & Kiss, 2006), the construction of revetments and groynes cease lateral erosion which causes channel narrowing (Kiss, 2014; Bertalan et al., 2019), furthermore dam constructions and sediment extraction from the channel modify sediment supply (Surian & Rinaldi, 2003). The Lower Tisza River has been a subject to significant human impacts (artificial levee constructions, cut-offs, and revetment constructions) since the nineteenth century. These impacts have led to a transformation in channel pattern from meandering equilibrium to meandering-incising (Kiss et al., 2018, 2019a), and as a response, the formation of point-bars has changed as well. The number of active point-bars has decreased by half (from 47 to 20), and their total length by 90% (from 52.3 km to 4.7 km), besides, their surface is eroded as a result of channel incision (Kiss et al., 2018, 2019a). The effects of natural influencing factors thus can be overrun by human factors in many sections.

The fundamental aim of this study is to analyse the natural and anthropogenic factors that affect the morphological characteristics of the older inactive and the youngest, active point-bars. Our aims are (1) to distinguish different meander-migration types along the Lower Tisza River, (2) to analyse the spatial characteristics of the height and width of point-bars, (3) to determine the different types of point-bar development based on their width and changes in height in the direction of the channel, and finally, (4) to analyse the primary factors that influence point-bar morphology.

Study area

The Tisza River is the second-longest river in Hungary (length: 962 km, catchment area: 157,000 km^2). Our measurements were carried out along the 90-km-long Lower Tisza River, between Csongrád and the Hungarian-Serbian border (Figure 1).

During the nineteenth century, the Tisza River was heavily regulated. As the result of meander cut-offs the length of the entire river decreased by 32% (by 467 km), and the width of the original 5-10 km wide floodplain was narrowed down to 1-4 km by the artificial levees. Along the Lower Tisza River, 10 meanders were cut off between 1855 and 1889 (Pálfai, 2001), which decreased the length of the reach by 19 km (Ihrig, 1973). In the 1930s revetment construction started on the concave banks (but a few had been already built at the end of the 1800s), which aimed to stop meander migration (Kiss et al., 2008). Intensive lateral channel migration caused significant problems, primarily on the western part of the floodplain, as on this side, the artificial levees were constructed closer to the channel than on the eastern part of the floodplain (at some sections the distance between the artificial levee and the channel was merely 50 m), thus artificial levees were more endangered by lateral erosion. Therefore, revetments were constructed primarily on the western side of the river channel, and today 51% of the Lower Tisza River is stabilised by revetments.

The Tisza River is usually characterised by two floods every year, as a result of early-spring snow melt and early-summer rainfalls (Lászlóffy, 1982; Kiss et al., 2019c). After the river regulation works flood stages increased by 200-350 cm (Rakonczai & Kozák, 2009), in the last few decades, however, record-high floods have become more frequent. The record flood stage (982 cm) of 1970 was exceeded twice in the Lower Tisza River in the twenty-first century, as at Mindszent the flood stage was 1000 cm in 2000, and 1062 cm in 2006. The duration of floods is 54 days/year on average (Kiss et al., 2019c), but if the flood of the Tisza coincides with the flood of the Danube, several months long floods could occur due to the impoundment effect of the Danube (e.g., in 2006). The mean discharge of the Tisza River at Szeged is 810 m^3/s, and here, the greatest measured discharge was 4346 m^3/s (Lászlóffy, 1982). The average flow velocity is 0.10-0.15 m/s, while during floods, it is 1 m/s (Kiss et al., 2019c).

The average channel width is 160 m, and the average depth is 14 m, but during floods, the channel can reach a depth of 19-22 m (Kiss et al., 2019a). The stream gradient is small (1.5-2 cm/km), while downstream of the confluence of the Maros River it increases to 5 cm/km (Lászlóffy, 1982). The Tisza River transports fine suspended sediment of 12.2 million m^3/year (Bogárdi, 1971).In the studied river reach the Körös River increases the sediment yield of the Tisza River by a smaller extent (by 0.4 million m^3/year), while the Maros River transports a considerable amount of coarse sediment (4.3 million m^3/year) into the Tisza River (Bogárdi, 1971).

The development of point-bars was studied along the whole Lower Tisza River. In this reach of the river, there are 39 bends (Fig. 1), which have a wide variety of morphological characteristics, and due to river regulation works they develop for a different time.

Data and Methods

Point-bars were studied based on a high-resolution (±10 cm) DEM which was derived from a 2014 LiDAR survey (provided by the ATIVIZIG Lower Tisza District Water Directorate). Though 39 bends are in the Lower Tisza River, point-bars could have been studied only along 33 bends, since there are some bends where no LiDAR survey is available (No. 31 and 32);or point-bars could not have been identified due to the excessive disturbance of the surface (No. 36 and 37); and there are two bends (No. 12 and 39) which started to develop after the river regulation works, and their development is so slow that no point-bar could have formed yet.

The number of point-bars forming each point-bar complex was determined based on cross-sections of the floodplain (Figure 2). The cross-sections were made perpendicular to the highest point of the youngest point-bar (the youngest point-bar is the one that is formed nearest the river channel). The height of each point-bar relative to the flood protected areas was determined, besides, their width and spacing were measured too. During the analyses ArcGIS 10.1 software was used.

The influence of meander migration types, the radius of curvature of bends, channel width, and the presence or lack of revetments on the height and width of point-bars were studied. The meander migration types (Figure 3) were determined following Daniel (1971), which suited the most in the study area. The effect of meander migration types was analysed on all point-bars of each point-bar complexes, as each meander migration type have developed over a long period, and their effect could be reflected on the older point-bars as well. The youngest forms were omitted from the analyses, because in their cases, the effect of human impacts may be more significant. As the last point-bars were formed after the construction of revetments (from the 1930s), these structures may have a greater influence on point-bar formation than natural factors. Similarly, the effect of channel width was also studied on the older point-bars. In this case, we calculated the number of point-bars formed in each period between two channel surveys, and the height and width of these point-bars were compared to the channel width measured at the end of each period. For each period, the mean channel width was determined as the ration of the area of channel surface and the length of its centreline. For example, the width of point-bars formed between 1976 and 2014 was compared with the channel width of 2014, as these forms had not been affected by the channel width of 1976 because they formed only afterwards. For this analysis the surveys made in 1783, 1861, 1890, 1929, 1976 and 2014 were applied.

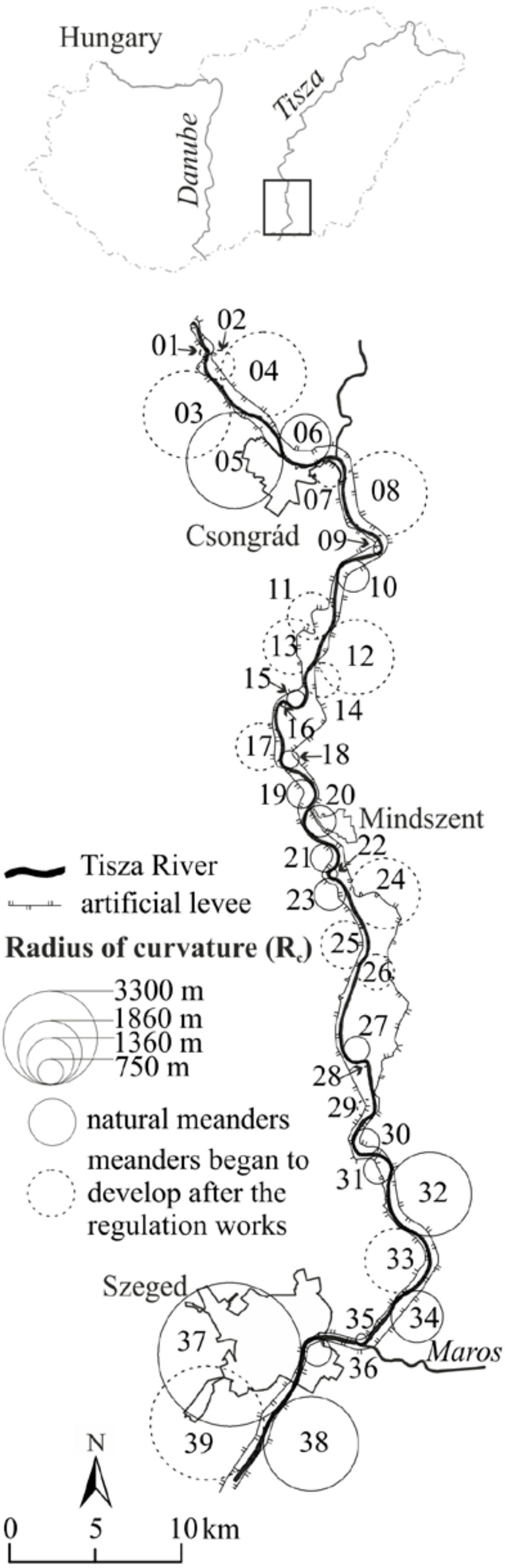


Figure 1. Point-bars were studied in 39 bends in the Lower Tisza River. The radius of curvature and age of the meanders and bends are very diverse

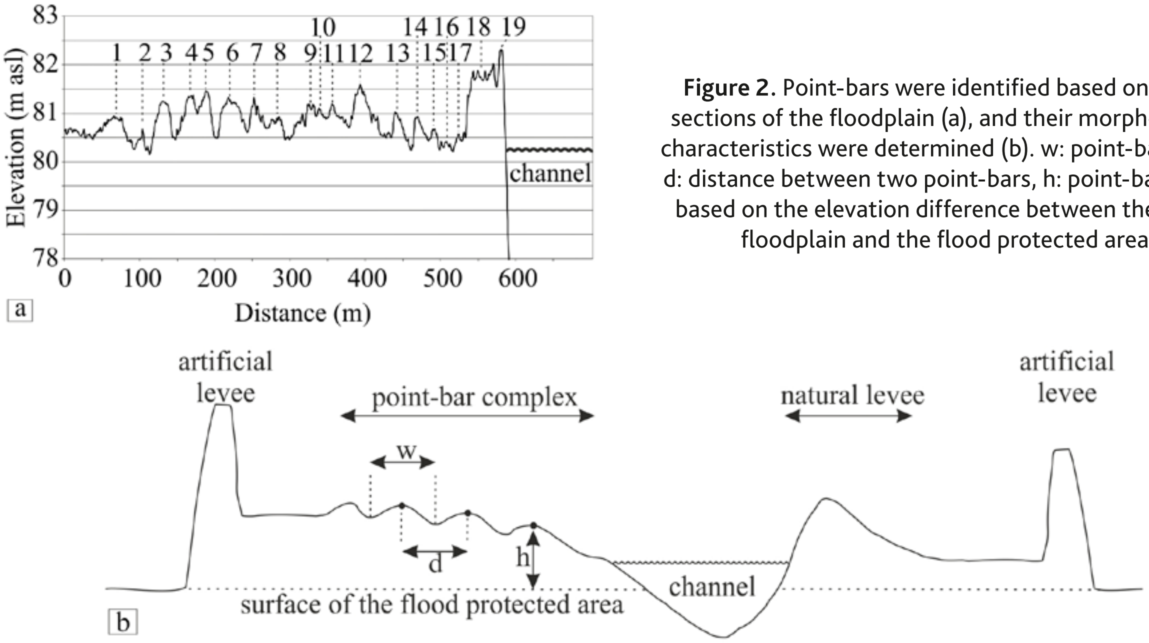
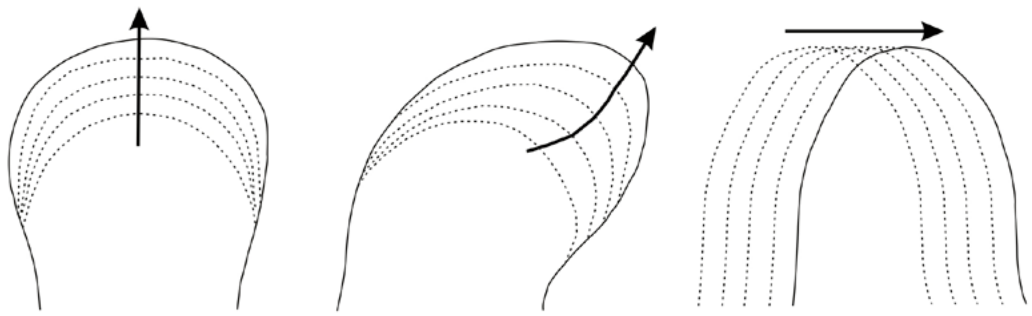


Figure 2. Point-bars were identified based on cross-sections of the floodplain (a), and their morphological characteristics were determined (b). w: point-bar width, d: distance between two point-bars, h: point-bar height based on the elevation difference between the active floodplain and the flood protected areas



a) Expansion

The position of inflection points are constant, thus the length of centerline increases.

b) Rotation

The direction of the bend axis and the position of one of the inflection points changes.

c) Translation

The bend moves downstream, without changing centerline length and the direction of the axis.

Figure 3. Meander migration types (after Daniel, 1971)

The effects of the radius of curvature of meanders (R_c) and revetments on point-bar characteristics were studied on the youngest point-bars, as only the present radius of curvature of the meanders can be determined. The radius of curvature was determined as the radius of the largest circle which can be best fitted into the bend (Kiss et al., 2009). The majority of the revetments were built in the second half of the 1900s; thus revetments have an explicit impact only on the formation of the last point-bars in each point-bar complexes.

During the research, after the determination of the bend-migration types, we analyse the point-bar complexes, and then the morphology of individual point-bars.

Results

Meander migration types

In the Lower Tisza River, three meander migration types were identified (Figure 4). Expanding meanders are the most common, as among the 33 meanders 23 were classified as expanding. They are usually large ($R_c \geq 750$ m), and mostly they are located in those river sections that were straightened during the river regulation works (except No.19 and 20).

Nine rotating meanders were identified, and each has small radius ($R_c \leq 750$ m). Rotating meanders are mostly located in those sections that remained intact during the channel regulation works, but cut-offs were made upstream or downstream of these meanders.

Only one freely translating meander was identified (No. 22) along the entire studied Lower Tisza.

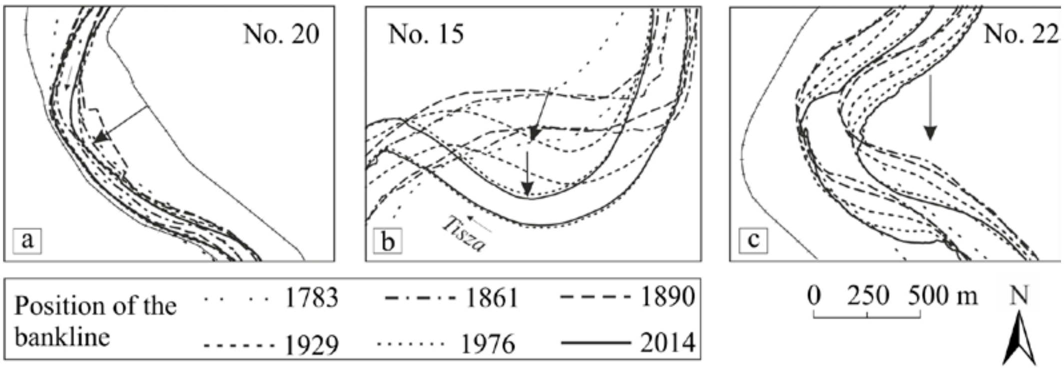


Figure 4. Examples of meander migration types from the Lower Tisza River. a: expansion, b: rotation, c: translation

Height and width conditions of point-bar complexes

Types of point-bar complexes based on their height characteristics

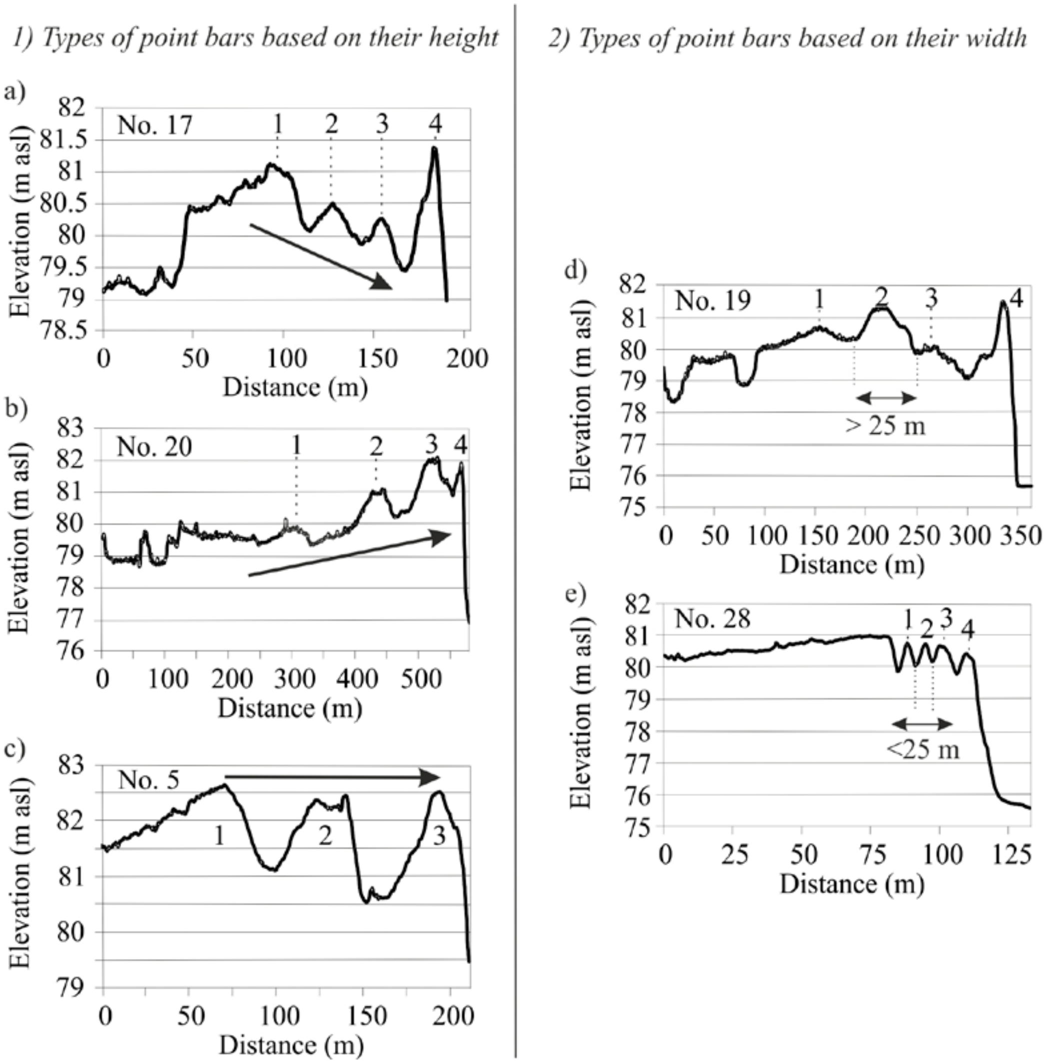
Based on the height characteristics of point-bar series, four main development types were distinguished (Figure 5). It is important to emphasise that the four types were defined without the youngest point-bars, as they are mostly affected by human impact.

In case of the descending point-bar complex, the height of point-bars gradually decreases towards the channel (Figure 5a). This type was identified at 36% of the studied meanders. The average height drop between point-bars is 0.9 m (0.2-1.4 m). The second point-bar complex type is ascending, as the height of point-bars gradually increases towards the channel (Figure 5b). This development type occurs in 39% of the meanders. The average height increase between the point-bars is 1.2 m (0.2-3.4 m). The height of point-bars does not change significantly in 15% of the meanders: here the height difference was under 0.1-0.2 m, and the height of bars showed no continuous decrease or increase (Figure 5c). In the remaining 10% of the bends, only one point-bar has formed; thus the direction of development cannot be determined. This type is located in artificially straightened river sections, where the bend development could begin just after the river regulation works; therefore the development of multi-member point-bar complex had not been allowed due to the short time and as the thalweg is located at the centreline of the channel.

Majority (8) of the 12 descending point-bar complexes are located in the western part of the floodplain, therefore along meanders which migrate eastwards. In contrast, two-third (8) of the 13 ascending point-bar complexes is located in the eastern part of the floodplain, i.e., point-bar heights increase along meanders migrating westwards.

Types of point-bar complexes based on their width characteristics

Two main types of point-bar complexes can be distinguished based on their width conditions (Figure 5). In case of 21% of the meanders, point-bar complexes consist of wide (>25 m) point-bars (Figure 5d), while 39% of the point-bar complexes has narrow (< 25 m) members (Figure 5e). In the rest of the meanders (40%), however, a mixture of wide and narrow point-bars can be observed. In some cases, at the beginning of the development of a point-bar complex the point-bars were broad, then they became narrower by time, or wide and narrow point-bars alternate in a point-bar complex.



1) Types of point bars based on their height

2) Types of point bars based on their width

Figure 5. Examples of different types of point-bar development in the Lower Tisza River. a: descending, b: ascending, c: constant point-bar heights, d: wide point-bars, e: narrow point-bars within a complex

Height and width characteristics of individual point-bars

Along the Lower Tisza River, the height and width of point bars within a point-bar complex is not a function of downward direction. In the northern and southern parts of the study area where the river is less sinuous, the average height (north: 1.5-2.1 m; south: 2.3-2.6 m) and width of point-bars in a point-bar complex is similar (12-20 m and 38-42 m, respectively). However, in the middle section of the river point-bar heights (0.8-4.1 m) and widths (8-58 m) vary in a large scale.

Within point-bar complexes a sudden rise in the height of the last (youngest) point-bar was observed. This is typical for 70% of the studied point-bar complexes, but in the case of descending point-bar complexes, this increase (0.6 and 2.3 m) is more significant since the increase of the last point-bar is more striking and different from the normal development of the point-bar complex. The increase of the last point bar in ascending point-bar complexes is between 0.4 and 2.2 m.

Factors influencing the height and width of individual point-bars

The effect of meander migration type on the height and width of older point-bars

As only one translating meander (No. 22) was identified on the Lower Tisza, the analysis was carried out for the expanding and rotating meander migration types (Figure 6). Along rotating meanders the mean height of point-bars is 2.3 m (1.1-3.3 m), while along expanding meanders their average height is only 2 m (0.5-3.5 m). This 0.3 m difference between the two types is not too definite, in some cases there are very high (≥3 m) point-bars in expanding meanders as well (e.g. meanders No. 19 and 20).

The relationship between point-bar width and meander migration type suggests that the mean width of point-bars in a point-bar complex is very similar in both migration types. The mean width is 33 m (6-93

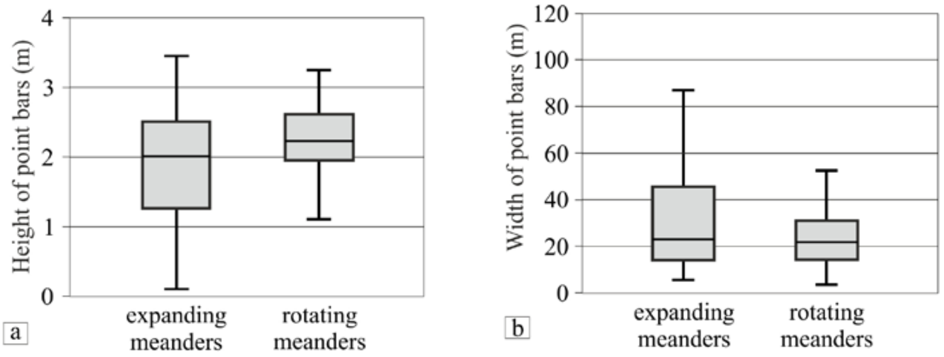


Figure 6. The impact of different meander migration types on the height (a) and width (b) of point-bars

m) in expanding meanders, while it is slightly narrower, only 27 m (4-114 m) in rotating bends.

The effect of radius of curvature on the height and width of point-bars in rotating meanders

Relationship between the morphological characteristics of the last point-bars and the radius of curvature of meanders is found only in rotating meanders (Figure 7a). Results suggest that the height of the last point-bars changes logarithmically with the radius of curvature (R^2=0.74), i.e., in meanders with small radius higher point-bars are formed. Similar relationship was observed between the Rc and the width of the point-bars (R^2=0.72), i.e., the last point-bar is wider where R_c is greater (Figure 7b).

The effect of channel width on the height and width of older point-bars

Since the end of the nineteenth century, the channel width of the Lower Tisza River has been continuously narrowing which is also reflected by the width of the point-bars (Figure 8). At the time of the 1783 survey the channel was broad (197 m on average), and the mean width of the point-bars at that time was 68 m. By 1861, the channel narrowed by 20 m (to 175), and simultaneously, the point-bars became significantly narrower (mean width: 34 m). Then, the channel broadened, as in 1890 its mean width was 192 m. Thus, the width of point-bars increased to 48 m on average. In the twentieth century, the channel was narrowing steadily. In 1929 its mean width was 178 m, in 1976 and

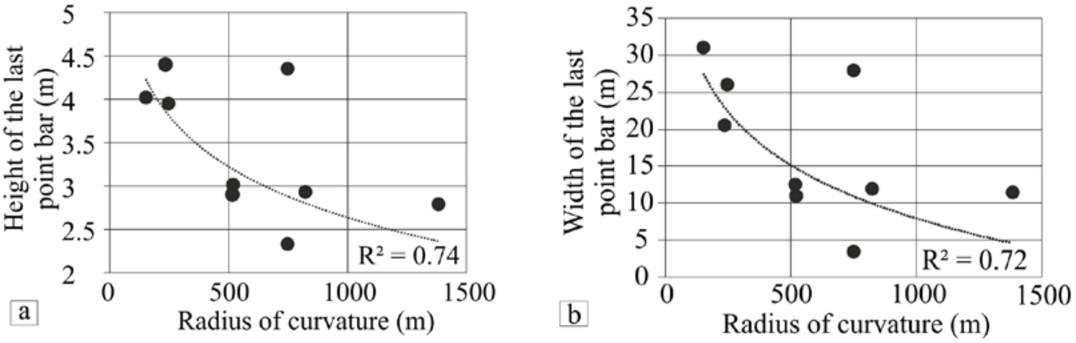


Figure 7. The impact of the radius of curvature of meanders on the height (a) and width (b) of the youngest point-bars of point-bar complex

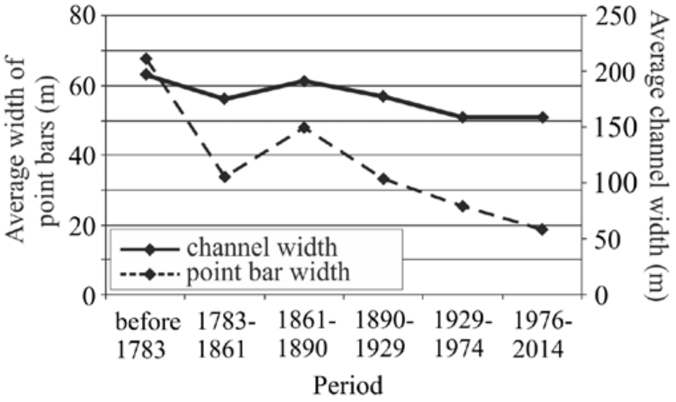


Figure 8. Mean width changes of point-bars as a function of channel width since the end of the eighteenth century

2014 it was only 159 m; therefore, the point-bars became narrower too (1929: 33 m; 1976: 25 m; 2014: 19 m). Thus, during the last centuries the point-bars became significantly narrower.

The effect of revetments on the height and width of point-bars

According to the results, the revetments built on the concave banks slightly influence the height and width of point-bars forming on the opposite bank (Figure 9). In meanders where there are revetments, the mean height of the active point-bars is 3.1 m, and their mean width is 19 m. In contrast, in meanders where there is no bank protection, the youngest point-bars are slightly lower (2.5 m) and wider (22 m).

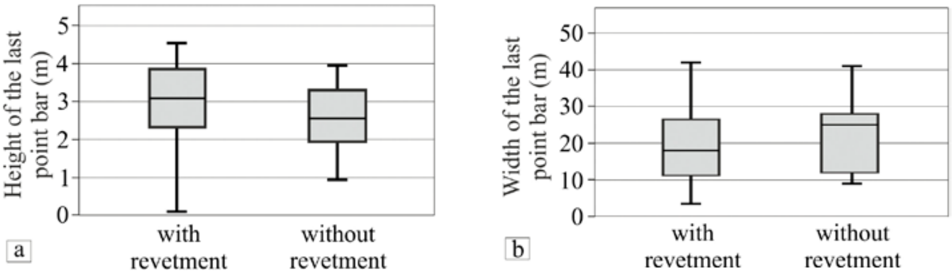


Figure 9. The impact of revetments on the height (a) and width (a) of the youngest point-bars

Discussion

Meander migration types in the Lower Tisza River

The type of meander migration has a significant impact on the formation and morphological characteristics of point-bars; thus identification of the different types is essential (Hickin & Nanson, 1975; Nanson & Hickin, 1983; Russell et al., 2018; Strick et al., 2018). Along the Lower Tisza the abundance (70%) of expanding meanders could be explained by human impact: most of them began to develop on river sections that were straightened during the river regulation works in the second half of the nineteenth century. These meanders are therefore at the beginning of their development.

In some of the bends (e.g., No. 19 and 20) that had already existed before the regulation works, the more consistent bed material (Hernesz, 2015) is the cause of the rotating movement of the meanders. In the Lower Tisza River, however, the consistency of bed material varies, thus expanding meanders are likely to become rotating as they develop (Daniel, 1971). Cut-offs upstream of the rotating meanders can contribute to the development of rotation. Since rotating bends originally had a great radius of curvature, the accelerated water flow in the upstream straightened sections struck against the outer bank in the lower third of the meander; thus the outer bank eroded more rapidly.

The formation of the only one translating meander (No. 22) is due to local causes, as in this section, the channel is enclosed in the homogenous bed material of a paleo-channel (Hernesz, 2015).

Development and spatial characteristics of different types of point-bar complexes

In general, the height changes of point-bars towards the channel (descending or ascending) are related to changes in the channel, the rate of bend migration, and/or bedload and suspended sediment yield. Based on our results, we assume that the decrease in the height of point-bars in a given point-bar complex may indicate (1) channel incision, as the point-bars have to decrease if the conditions and the time available for development do not change; (2) accelerating meander migration, as in this case there is less time available for the formation of the point-bars, thus each form became lower and lower; and (3), 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.

In contrast, we assume that the increase in the height of point-bars may indicate (1) decrease in the rate of meander migration, as more time is available for the formation of the point-bars; thus they became increasingly higher. Slower migration of the river bank may be due to the achievement of more consistent bed materials (silt and clay), and as a result, the channel is more resistant to lateral erosion and incision (Thorne, 1991). Besides, our study proved that revetments built on the outer bank of meanders cause the deceleration and/or cease of meander migration. Higher point-bars could also indicate (2) 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.

The constancy of the height of point-bars in some meanders, however, may indicate the role of local influencing factors; thus the change in sediment yield in the Tisza River cannot be an explanation, as it would result in a change in the height of all point-bars.

In the eastern part of the floodplain, there are mainly ascending point-bar complexes, while in the western part primarily descending ones are found. One of the reasons may be the fact that the consistency of the sediment varies on the two sides of the floodplain. The majority of the paleo-channels remained on the eastern side of the Tisza River, which indicates that the river constantly migrates westwards. On the western side, however, the channel runs very close to the edge of the alluvial fan of the Danube, which is composed of older and more solid sediments, which are harder for the Tisza River to erode (Hernesz, 2015). As a result, slowly developing and ascending point-bar complexes are found in meanders migrating westwards. Another reason for the development of ascending point-bars on the western side may be the fact that on this side of the channel runs very close the artificial levee; thus meander migration has been ceased by revetments on the concave bank. As a result, on the opposite, convex bank the lateral development of point-bars is decelerated, then ceased (Kiss et al., 2018), thus point-bars become increasingly high.

Factors affecting the morphology of point-bars

The effect of meander migration type on the height and width of older point-bars

According to our results, older point-bars in each point-bar complex are slightly higher (by 0.3 m) along rotating meanders. It corresponds with the findings of Strick et al. (2018), as rotating meander rotate back on themselves (in the downstream part), which increases the height of the forms. At some places, it can be exceeded by the effect of bed-material consistency. We identified very high point-bars in some expanding meanders, where the bed materials are more consistent. The migration of the bank line is slower where bed material is silt or clay (even at the end of the 1800s, in this meanders the rate of channel migration was less than 1 m/year), which cause the increase of point-bar heights.

No evidence was found that the type of meander migration would influence the width of point-bars, as point-bars of very similar mean widths (27 m and 33 m) have formed in both meander migration types. This result, however, does not correspond with the findings in the literature (Strick et al., 2018) that under natural conditions, wider point-bars are formed in rotating meanders. In our opinion, the effect of channel narrowing in the past 250 years, primarily due to human activity, exceeds the influence of the type of meander migration; therefore point-bars of very similar, but increasingly narrowing width are formed in both expanding and rotating meanders.

The effect of radius of curvature on the height and width of youngest point-bars

The radius of curvature influences the morphology of the last (youngest) point-bars in each point-bar complex. The effect of curvature primarily influences point-bar formation in bends that are characterised by rotational movement, as these bends have the smallest curvature (Rc<750 m). In meanders with small radius, higher and broader point-bars have developed. It could be explained by the fact that the small radius of curvature usually results in narrower channel width; thus the thalweg is relatively closer to the convex bank, therefore, greater amount of sediment could be deposited along the inner side of the bends. It is further enhanced by the type of meander migration, because of the rotational movement meanders rotate back on themselves, which increases the height and width of the forms (Strick et al., 2018).

Effects of channel width and revetments on point-bar formation

Channel narrowing and revetment constructions are closely linked. Revetments were built (the first was built in 1886) after the river regulation works, and has since been built along almost all bends. Revetments stopped the lateral erosion of the concave bank, but meander migration may have continued due to channel narrowing, as the convex bank continued to develop. Due to the lack of migration in the outer bank, the formation of point-bars has significantly changed. Channel narrowing is well indicated by the decrease in point-bar widths (van de Lageweg et al., 2014; Strick et al., 2018). In case of the Lower Tisza the mean width of the channel has decreased from 197 m to 160 m over the last 250 years, and as a result the mean width of point-bars has decreased too from 68 m to 19 m. Initially, channel narrowing was caused by cut-offs, as the slope and stream power of the river suddenly increased, which temporarily resulted in channel incision and narrowing (Károlyi, 1960; Ihrig, 1973). Later, however, revetments caused the rapid narrowing of the channel.

Not only the width of the point-bars changed, but their height conditions also altered. In 70% of the meanders, the last point-bar in each point-bar complex is higher than the preceding one. It is undoubtedly the result of revetment construction, as the lateral development of point-bars has become limited or stopped in the narrowing channel. As a result, the lateral development of the forms has been replaced by the vertical accumulation of sediment, thus point-bars become increasingly higher. Riparian vegetation, which is becoming denser (Kiss et al., 2019b), may also contribute to the development of higher point-bars, as vegetation prevents sediment from reaching distal parts of the floodplain; thus sediment is deposited in a narrow zone adjacent to the channel.

Conclusions

Point-bars are the most striking features of floodplains and they are mainly the sites of lateral sediment accumulation; therefore any change in the factors influencing point-bar development is also reflected in their formation. As the Lower Tisza River has been a subject to various types of intensive human impacts over the past centuries, these human activities have affected point-bar morphology and development too.

Under natural conditions, point-bar morphology was primarily affected by the type of meander migration, the radius of curvature of meanders, and the distance of thalweg from the bank line. However, the processes in the channel and point-bar formation have fundamentally changed as a result of human interventions. On the one hand, in the second half of the nineteenth century, artificial cut-offs caused an increase in water slope; thus the channel incised (Kiss et al., 2008). Channel incision is indicated by the decrease in the height of the point-bars in a given point-bar complex. On the other hand, downstream of cut-offs meanders with a small radius of curvature developed. As a result, more intensive accumulation occurred in the convex banks; thus higher and wider point-bars have developed.

However, the most intensive intervention in point-bar formation was revetment construction, which aimed to prevent the concave bank from erosion. As a result, the channel incised and narrowed more intensively (Kiss et al., 2019a) as point-bar formation continued, but it was limited horizontally. As a result, the vertical sediment accumulation has become more intensive, resulting in an increase in point-bar heights, which affects primarily the last (youngest) members of the point-bar complexes.

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References

Bertalan, L., Rodrigo-Comino, J., Surian, N., Šulc Michalková, M., Kovács, Z., Szabó, Sz., Szabó, G., & Hooke, J. (2019). Detailed assessment of spatial and temporal variations in river channel changes and meander evolution as a preliminary work for effective floodplain management. The example of Sajó River, Hungary. *Journal of Environmental Management 248C*, 109277. https://doi.org/10.1016/j.jenvman.2019.109277

Biedenharn, D.S., Thorne, C.R., & Watson, C.C. (2000). Recent morphological evolution of the Lower Mississippi River. *Geomorphology*, 34, 227-249. https://doi.org/10.1016/S0169-555X(00)00011-8

Bogárdi, J. 1971. Vízfolyások hordalékszállítása [*Sediment transport of rivers*]. Budapest: Akadémiai Kiadó (In Hungarian)

Covasnianu, A., & Tudose, O. (2013). Airborne LiDAR data and GIS technique outputs over Romanian Danube Plain with a special attention on geomorphology. *Carpathian Journal of Earth and Environmental Sciences*, 8(1), 117-126.

Daniel, J.F. (1971). Channel movement of meandering Indiana streams. *USGS professional paper* 732, 1-18.

Đieković, V., Anđelković, A., Milošević, N., Gajić, G., & Janić, M. (2013). Effect of reservoir on floodwave transformation. *Carpathian Journal of Earth and Environmental Sciences*, 8(2), 107-112.

Dietrich, W. E., & Smith, J. D. (1983). Influence of the point-bar on flow through curved channels. *Water Resources Research*, 19, 1173-1192. https://doi.org/10.1029/WR019i005p01173

Hagstrom, C. A., Leckie, D. A., & Smith, M. G. (2018). Point bar sedimentation and erosion produced by an extreme flood in a sand and gravel-bed meandering river. *Sedimentary Geology*, 377, 1-16. https://doi.org/10.1016/j.sedgeo.2018.09.003

Hagstrom, C. A., Hubbard, S. M., Leckie, D. A., & Durkin, P. R. (2019). The effects of accretion-package geometry on lithofacies distribution in point-bar deposits. *Journal of Sedimentary Research*, 89(5), 381-398. https://doi.org/10.2110/jsr.2019.23

Hernesz, P., 2015. *Késő-pleisztocén és holocén ártérfejlődés az Alsó-Tisza mentén* [Late Pleistocene and Holocene floodplain development in the Lower Tisza River]. Doctoral dissertation, University of Szeged, Department of Physical Geography and Geoinformatics, Szeged (In Hungarian)

Hickin, E.J. (1969). A newly-identified process of point-bar formation in natural streams. *American Journal of Science*, 267, 999-1010. https://doi.org/10.2475/ajs.267.8.999

Hickin, E.J. (1974). The development of meanders in natural river-channels. *American Journal of Science*, 274, 414-442. https://doi.org/10.2475/ajs.274.4.414

Hickin, E.J., & Nanson, G.C. (1975). The character of channel migration on the Beatton River, Northeast British Columbia, Canada. *Geological Society of America Bulletin*, 86(4), 487-494. https://doi.org/10.1130/0016-7606(1975)86<487:TCOCMO>2.0.CO;2

Hooke, J.M. (2007). Complexity, self-organisation and variation in behaviour in meandering rivers. *Geomorphology*, 91(3), 236-258. https://doi.org/10.1016/j.geomorph.2007.04.021

Hooke, J.M., &Harvey, A.M. (1983). Meander changes in relation to bend morphology and secondary flows. In Collinson, J., & Lewin, J. (Eds.), *Modern and Ancient Fluvial Systems* (pp. 121-132). International Association of Sediment Special Publication. https://doi.org/10.1002/9781444303773.ch9

Hooke, R.B. (1975). Distribution of sediment transport and shear stress in a meander bend. *Journal of Geology*, 83(5), 543-565.

Ihrig, D. (1973). A *magyar vízszabályozás története* [The history of river regulation works in Hungary]. Országos Vízügyi Hivatal, Budapest (In Hungarian)

Jackson, R.G. (1976). Depositional model of pointbars in the lower Wabash River. *Journal of Sedimentary Research*, 46(3), 579-594. https://doi.org/10.1306/212F6FF5-2B24-11D7-8648000102C1865D

Károlyi, Z. (1960). A Tisza mederváltozásai, különös tekintettel az árvízvédelemre [Channel changes in the Tisza River, with special regard to flood protection]. VITUKI 8, Budapest. (In Hungarian)

Kiss, T. (2014). *Fluviális folyamatok antropogén hatásra megváltozó dinamikája: egyensúly és érzékenység vizsgálata folyóvízi környezetben* [Changing dynamics of fluvial processes under human impact: investigation of equilibrium and sensitivity in river]. Academic dissertation, Szeged (In Hungarian)

Kiss, T. Fiala, K., & Sipos, Gy. (2008). Alterations of channel parameters in response to river regulation works since 1840 on the Lower Tisza River (Hungary). *Geomorphology* 98(1-2), 96-110. https://doi.org/10.1016/j.geomorph.2007.02.027

Kiss, T., Horváth, R., & Fiala, K. (2018). Szabályozások hatására megváltozó medermintázat az Alsó-Tiszán: El fognak tűnni az övzátonyok? [Changing channel patterns due to river regulation in the Lower Tisza River: Are point-bars disappearing?] In Fazekas I., Kiss E., & Lázár I. (Eds.), *Földrajzi Tanulmányok 2018* (pp. 259-262), Debrecen. (In Hungarian)

Kiss, T., Amissah, G.J., & Fiala, K. (2019a). Bank processes and revetment erosion of a large lowland river: Case study of the Lower Tisza River, Hungary. *Water*, 11(6), 1313. https://doi.org/10.3390/w11061313

Kiss T., Nagy J., Fehérváry I., & Vaszkó Cs. (2019b). (Mis)management of floodplain vegetation: The effect of invasive species on vegetation roughness and flood levels. *Science of the Total Environment* 686, 931-945. https://doi.org/10.1016/j.scitotenv.2019.06.006

Kiss, T., Fiala, K., Sipos, Gy., & Szatmári, G. (2019c). Long-term hydrological changes after various river regulation measures: Are we responsible for flow extremes?. Hydrology Research, 50(10), 417-430. https://doi.org/10.2166/nh.2019.095

van de Lageweg, W.I., van Dijk, W.M., Baar A.W., Rutten, J., & Kleinhans, M. G. (2014). Bank pull or bar push: what drives scroll-bar formation in meandering rivers?. Geology, 5(42), 319-322. https://doi.org/10.1130/G35192.1

Lászlóffy, W. (1982). *A Tisza. Vízi munkálatok és vízgazdálkodás a Tisza vízrendszerében* [The Tisza River. Regulation works and water management in the Tisza water system]. Budapest: Akadémiai Kiadó (In Hungarian)

Moody, J. A. (2019). Dynamic relations for the deposition of sediment on floodplains and point bars of a freely-meandering river. *Geomorphology*, 327, 585-597. https://doi.org/10.1016/j.geomorph.2018.11.032

Motta, D., Langendoen, E.J., Abad, J.D., & García M.H. (2014). Modification of meander migration by bank failures. *Journal of Geophysical Research: Earth Surface*, 119, 1026-1042. https://doi.org/10.1002/2013JF002952

Nanson, G.C., & Hickin, E.J. (1983). Channel migration and incision on the Beatton River. *Journal of Hydraulic Engineering*, 109, 327-337. https://doi.org/10.1061/(ASCE)0733-9429(1983)109:3(327)

Pálfai, I. (2001). *Magyarország holtágai* [Oxbow lakes in Hungary]. Budapest: Közlekedési és Vízügyi Minisztérium (In Hungarian)

Rakonczai J, & Kozák P. (2009). Az Alsó-Tisza-vidék és a Tisza [The Lower Tisza Basin and the Tisza River]. *Földrajzi Közlemények*, 133(4), 385-395. (In Hungarian)

Romanescu, G., Jora, I., & Stoleriu, C. (2011). The most important high floods in Vaslui River Basin – causes and consequences. *Carpathian Journal of Earth and Environmental Sciences,* 6(1), 119-132.

Russell, C.E., Mountney, N.P., Hodgson, D.M., & Colombera, L. (2018). A novel approach for prediction of lithological heterogeneity in fluvial point-bar deposits from analysis of meander morphology and scroll-bar pattern. In Ghinassi, M., Colombera, L., Mountney, N.P. & Reesink, A.J.H. (Eds.), *Fluvial Meanders and Their Sedimentary Products in the Rock Record* (385-418). International Association of Sedimentologists Series Special Publication

Strick, R.J.P., Ashworth, P.J., Awcock, G., & Lewin, J. (2018). Morphology and spacing of meander scrolls. *Geomorphology*, 310, 57-68. https://doi.org/10.1016/j.geomorph.2018.03.005

Tarolli, P., Cao, W., Sofia, G., Evans, D., Ellis, & E. C. (2019). From features to fingerprints: A general diagnostic framework for anthropogenic geomorphology. *Progress in Physical Geography: Earth and Environment,* 43, 95-128. https://doi.org/10.1177/0309133318825284

Thorne, C.R. (1991). Bank erosion and meander migration of the Red and Mississippi Rivers, USA. In Van-de-Ven, F.H.M., Gutknecht, D., Loucks, D.P., & Salewicz, K.A. (Eds.), *Hydrology for the Water Management of Large River Basins* (pp. 301-313) (Proceedings of the Vienna Symposium, August 1991). International Association of Hydrological Sciences

Wang, J., Chen, L., Zhang, W., & Chen, F. (2019). Experimental study of point bar erosion on a sand-bed sharp bend under sediment deficit conditions. *Sedimentary Geology,* 385, 15-25. https://doi.org/10.1016/j.sedgeo.2019.03.008

Zinger, J.A., Rhoads, B.L., & Best, J.L. (2011). Extreme sediment pulses generated by bend cutoffs along a large meandering river. *Nature Geoscience*, 4, 675-678.