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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

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Abstract

The quasi-natural meandering type of alluvial rivers is quite unusual in Central European watersheds. The lack of extensive regulation allows such rivers to shift along their floodplain and cause erosion of natural and agricultural lands. Description of channel morphometric parameters over decadal timescales allows a better understanding of such river systems like Sajó River (Slovakia-Hungary) where no preliminary work is available regarding channel dynamics. In addition, to just describing the geomorphic processes, the environmental management implications of these meandering rivers need to be investigated as well. Thus, this study represents a bend-scale morphological analysis on the 124 km long section of the Sajó River in the Hungarian territory in eight different periods between 1952 and 2011. Archive aerial imagery, orthophotographs and topographical maps were organized into a database, then GIS-based analyses were performed to quantify the rate and extent of channel shifts, bend development and the area of erosion/accretion. On the bend scale, we have calculated several morphometric parameters (bend length, chord, amplitude, the radius of curvature) to quantify the evolutionary trajectory of reaches. Hydrological time series data were evaluated to reveal its possible role in the processes. Based on the available GIS-data of natural elements and anthropogenic intervention, we delineated 12 different reaches showing similar characteristics, from which six reaches were defined as natural. According to the morphometric parameters of the natural reaches, channel widths became narrower and the planform became more concentrated spatially in most of the reaches while the overall sinuosity of almost all natural reaches increased. Although artificial cutoffs mainly reduced the reach complexity, in some cases, they have accelerated the bend development downstream in the following few years. Erosion and accretion activity were higher in the periods when the discharge was higher than the effective discharge but its effect became less apparent in the second half of the investigated time period. By 1980, major artificial cutoffs and bank protection works were carried out that could have an impact in reducing the potential channel shifting. Based on our results, we propose a possible preservation and some modifications along the Hungarian part of the Sajó River reaches to be carried out by the local river management authorities. We conclude that this study provides a detailed demonstration of the Sajó River morphodymanics which can be used for further land planning to avoid harmful consequences of recent bank erosion processes not only along the Sajó River, but other similar rivers in Europe.

Keywords

Meandering river; Sajó River; bank erosion; lateral channel shift; channel planform morphometry

1. INTRODUCTION

Floodplains with active river banks are characterized by dynamic landforms that affect their environment and landscapes (Hooke, 2007; Dotterweich, 2008; Yousefi et al., 2018); however, it is also essential to understand the past and recent fluvial processes at the local and global scales in order to design suitable land management plans (Lóczy et al., 2009; Cunha et al., 2017).
It is widely accepted that the meander migration processes are driven by several geological and hydrological factors, bank material (Hooke, 1980; Rhoads and Welford 1991; Konsoer et al., 2016a), changes in the frequencies of floods and water discharge (Phillips 2002; Rusnák and Lehotský 2014; Dépret et al., 2015) or land uses (Micheli et al., 2004; Gumiero et al., 2015). Therefore, the description and prediction of meander migration processes require a holistic perspective (Hooke et al., 2011; Güneralp et al., 2012). On the other hand, the transported sediment flux also shows a significant impact on natural bend evolution (Gautier et al., 2007; Xia et al., 2014); however, nowadays, its natural mechanism is increasingly affected by anthropogenic activities such as damming (Ibisate et al., 2013; Grill et al., 2015; Kiss and Balogh 2015), reservoir construction (Su et al., 2015), or gravel extraction (Richardson and Fuller 2010), which results in both channel incision and rapid lateral bank erosion on a large scale being this process constantly visible.
Lateral bank erosion is a key component of channel shifting of meandering rivers, which can cause serious problems for human activities such as for agricultural fields or river engineering (Lawler et al., 1997b; Das et al., 2012; Konsoer et al., 2016). For example, inappropriate river engineering works along with changing climatic factors are able to intensify the dynamics of channel shifting (Michalková et al., 2010; Blanka and Kiss 2011; Ta et al., 2013). Also, accelerated lateral erosion of meandering rivers endangers the surrounding landscapes by the loss of agricultural lands, disturbing the floodplain habitats and landscape structures (Ta et al., 2013). As a result, an increased flood risk, with eventual contamination spreading, could threaten populated areas (Rhoades et al., 2009; Das et al., 2012). However, without appropriate engineering, the bank erosion can be a serious threat; though, natural processes of dynamic river channels can also be a tool to maintain the health and complexity of riparian ecosystems (Micheli et al., 2004). The bank erosion is usually followed by lateral accretion that provides newly formed land for planting new vegetation and habitat development on the opposite side of the collapsing river banks. The importance of river management is related to the protection of key assets by anthropogenic intervention but it is crucial to work with the river avoiding control and protect in all the cases. It is crucial to make sure that no human actions are taken to accelerate "natural" rates of movement such as the planification of excessive land use changes or the intensification of the urban activities, which can affect water quality and soil erosion rates (Ayele et al., 2018; Challa et al., 2008). The major issue for river managers and environmental experts at the local scale is to understand the dominant erosion/accretion processes in order to prevent natural hazards, restrain the agricultural damage and allow for effective floodplain rehabilitation by working with the river without significant alteration of river processes (Piégay et al., 1997; Micheli et al., 2004; Güneralp et al., 2012; Lóczy et al., 2017). Therefore, to date, we consider that there is a need for studies that focus on channel planform dynamics in order to better understand the processes for the establishment of more effective river management.

The planform of natural bends along partly and totally unregulated meandering river channels often develop at a remarkable rate (several meters per year); thus, it is essential to detect morphological changes regularly and reconstruct the past channel dynamics (Hooke, 2008; Miřijovský et al., 2015; Bertalan et al., 2016a). Nowadays, the use of GIS (Geographic Information Systems) accompanied by remote sensing techniques and geodetic measurements can provide quick and precise opportunities for gaining datasets to reveal the river channel planform dynamics (Clerici et al., 2015; Schwendel et al., 2015; Yousefi et al., 2018). Historical maps and outlines of hydrographic surveys also serve as valuable sources for reconstructing the behaviour of past channel changes (Dort, 1978; Goudie 1990; Hudson and Kesel 2000; Słowik 2012; Dragićević et al., 2017). However, detailed quantification may be difficult to perform if we compare their content to recent cartographic or aerial datasets due to the considerable differences among scales (Li et al., 2007). The majority of studies worldwide focusing on planform channel changes are composed on the basis of military and later on civil aerial imagery from the early 1940's (Michalková et al., 2010; Nicoll and Hickin 2010; Yousefi et al., 2017; Hajdukiewicz and Wyżga 2019), topographic maps of various dates (Sarma et al., 2007; Yao et al., 2013) or even satellite imagery (Wang et al., 2014, 2016; Yousefi et al., 2016). Classic photogrammetric methods were used as a quick method for generating maps from aerial and terrestrial photographs (Pyle et al., 1997; Hughes et al., 2006).

Investigations focusing on the development of meandering alluvial rivers have a wide research background related to the alluvial regions of Hungary (Laczay, 1977; Timár 2003; Kiss et al., 2008, 2009; Mecser et al., 2009; Zámolyi et al., 2010; Blanka and Kiss 2011; Kalmár and Kozma 2012; Kiss and Blanka 2012). The channel morphodynamics of Sajó (Slaná) River, along with very high rates of channel shifting and consequently harmful land degradation, has not been explored in detail yet. However, our research provides a detailed spatiotemporal analysis of the meandering Sajó River over an approximately 60-year time series derived from aerial imagery (1952, 1956, 1975, 1988), topographical maps for reference (1980) and digital ortophotographs (2000, 2005, 2011). Most of the above listed studies in Hungary focused on one or few selected reaches while in this work we analyzed a ~125 km long section of the Sajó River which has not been studied before. Therefore, the main aims of this study were to i) perform a complex assessment of the dynamics and morphological evolutionary trajectory of Sajó River along its Hungarian section; and, ii) to explain significant spatial and temporal differences in terms of channel morphology and dynamics by a preliminary analysis of driving factors; and iii) contextualize the implications of the study findings in terms of environmental management of meandering rivers. The combined results of previous studies and recent surveys serve as necessary information for river management and restoration. We believe that our findings could provide valuable information about the evolution of channel morphodynamics of the Sajó River and the first step towards a more effective river management in the future. Our study represents an overall overview of interactions between river management and channel planform dynamics that can lead to general findings for river engineers regarding the downstream effects of construction works. This study presents a unique quasi-natural river system in Hungary, on which the knowledge of morphodynamic spatiotemporal evolution was lacking. This current paper provides a big data mining research characterized by aerial photographs, as the main dataset, which were previously inaccessible for Sajó River (Military sources). Geomorphological analyses and principles can lead to more natural and environmentally preferred designs (e.g. Hey et al., 1991). By the quantification of the erosion/accumulation rates, we provide detailed underlying analysis for river engineers, managers and watershed operation staff. Engineers can identify the thresholds for bank erosion and a number of sites where the channel was active and cutoffs occurred.

2. MATERIALS AND METHODS

2.1. Study area

The Sajó (in Hungarian) or Slaná (in Slovakian) is a Slovakian-Hungarian transboundary river with a total length of 229 km, of which 124 km is situated in the Hungarian territory (Bertalan

et al., 2018). The Hungarian section is classified as mainly alluvial meandering-type; total sinuosity is 1.78; of which one 19.8 km long section has a value of 1.99 (Mueller 1968).
The catchment of the Sajó (Slaná) River covers a total area of 5,545 km^2 from which 40.4% is situated in Hungary (Fig. 1). Topographical changes of the river vary from the highlands to valley and lowlands. The majority of the lower section is developed on the alluvium of the river. The stream gradient is relatively high upstream (50-70 cm km^{-1}) from the confluence with the Hernád River (Hungary); however, it gradually decreases downstream of that section.

 # Fig. 1. Approximately here

The yearly distribution of flow regime varies about an average 216 cm stage (discharge of 24.3 m^{-3} s-1) based on the 1950-2016 water level data of Sajópüspöki gauging station; 48°16'56.9"N; 20°20'24.3"E). The lowest level was 13 cm (1993), meanwhile, the highest one reached 416 cm (2010). The minimum discharge value was 0.75 m^{-3} s^{-1} in 1952 and the maximum one was reached 498 m^{-3} s^{-1} in 2010 (www.vizugy.hu). The main tributaries join the Sajó River in the Hungarian territory.
According to the formula of Bagnold (1977) the Specific Stream Power (SPP) of the Sajó River is 1.29 W m^{-2} at the upstream station of Sajópüspöki and 1.48 W m^{-2} at the downstream station of Felsőzsolca as the bankfull channel width range varies between 60 and 90 meters at the two gauging stations.
The total average of suspended sediment load reaches 1,927,000 m^3 y^{-1} upstream and 828,000 m^3 y^{-1} downstream while the bedload ranged up to 1,600 m^3 y^{-1} upstream and 290 m^3 y^{-1} downstream (Bogárdi 1949, 1950). The Hungarian section of the catchment has received only minor modifications of channel morphology (mostly bottom dykes, stone scatterings, bend covers, embankments).

According to the yearly Q_{min} discharge rates, incision is not relevant on the Hungarian section of the Sajó River; moreover, the downstream reaches close to the confluence of Tisza River show more accumulation processes; accordingly, this process does not affect the recent channel dynamics of the Sajó River.River regulation and adjustments could generate dramatic alterations of river morphology through a relatively short timescale; however, in general, the recovery period is a longer progress (Surian 1999). Several management plans had been established for the channelization and complex regulation of Sajó River from the beginning of the 20th century, but, finally, they were not applied due to the World Wars and economic issues (Kákóczki 2016). Even though bank protection and artificial cutoffs, mainly at the industrial zone of Kazincbarcika-Berente, are notable in terms of the regulation and channelization rates of other Hungarian rivers. Despite that, the Sajó River is one of the less modified rivers of the region (Bertalan and Szabó 2015; Bertalan et al., 2016b).

2.2. Imagery treatment

Our research focused on a spatiotemporal analysis of the active river channels over approximately 60-year time-series datasets derived from aerial imagery (1952, 1956, 1975, 1988), topographical maps (1980) and digital orthophotos (2000, 2005, 2011). The military aerial imagery was obtained from the Hungarian Military History Museum, Budapest. Therefore, our investigated time periods had been determined according to the availability of the imagery for the total Hungarian section of Sajó River (Table 1). Aerial photos and maps ranged in scale from 1:7000 to 1:12000. We selected only those aerial images as appropriate for the analysis that had been taken at low flow conditions to identify the bank edges correctly. Every black and white photograph was scanned (600 dpi) and orthorectified in ERDAS Imagine software. However, mainly orthophotographs were used as a reference (datum: Hungarian HD72/EOV), but we also included Topographical maps of 1980 as well since we have found several field objects on the aerial imagery between 1952 and 1988, that were not possible to identify on the orthophotographs of 2000, 2005 and 2011.

#Table 1. Approximately here

For each aerial photograph, 15-20 ground control points (GCP) were defined since a large number of GCPs results in more accurate georeferencing (Hughes et al., 2006). The root mean square error (RMSE) for the rectification process of the entire photoset varies between 3.4 m and 6.7 m, while the average was 4.8 m. Our results were similar to studies performed in other catchments (Michalková et al., 2010; Zawiejska and Wyżga 2010; Rusnák et al., 2016). Bank edges were manually vectorized with a scale of 1:1000 because high digitizing scale used during the analysis was essential to minimize rates of digitization errors of a channel bank (Liro 2015b; Donovan et al., 2019). Identification of bank lines was associated with the perpetual channel edges and with the contact path of the riparian vegetation of the river bank. All procedures were addressed using ArcGIS 10.3 (ESRI, USA).

2.3. Hydrological dataset

Along the Hungarian section of the river, there are three gauging stations (Sajópüspöki, Sajószentpéter and Felsőzsolca) that provide daily discharge and water level data. Discharge measurements started in 1970 at the Sajópüspöki and Sajószentpéter stations and in 1960 at the Felsőzsolca (Fig. 1).
The long-term analysis of the spatial and temporal changes in the flood intervals was a crucial step in our work. The database was the daily discharge rates at the Sajópüspöki gauging station. We compared the Q_{max} rates at all stations (Fig. 2) and between the three gauging stations more or less similar trends emerge.

#Fig. 2. Approximately here

Another issue was related to the fact that the first period of our investigations on the aerial photographs was 1952, so at the beginning, discharge data were missing for 18 years. The solution was the use of another gauging station at Bánréve (2.81 km downstream from Sajópüspöki gauging station), which had operated from 1952 to 1983. The two settlements Bánréve and Sajópüspöki are situated at the opposite side of the riverbank almost at the same river kilometre; consequently, it was assumed that the discharge data are comparable. In order to justify this issue, the overlapping discharge data were compared (5111 daily discharge values from 1970 to 1983) statistically. We applied the paired Wilcoxon test and calculated both the significance (p) and the effect size (r). We also determined the statistical relationship between the stations with linear regression (R^2) and standard error of estimate (SEE). Homoscedasticity was controlled with the Breusch-Pagan test (Hammer et al., 2001). Then, with the help of the resulting $y=0.97694x+0.53886$ equation (y: Bánréve's; x: Sajópüsöki's data; $R^2=0.983$; $p<0.001$; SEE=5.44) we calculated the missing data for Sajópüspöki station.
Based on the covered time period, the recurrence intervals of the floods and duration of discharges higher than the effective discharge (in percent of each investigated period referring to the years of the available aerial photographs), that had been defined as a flood discharge with a 1.1-year recurrence interval (Kiss and Blanka 2012), were calculated.
Notable differences can be observed in the duration of periods higher than the formative discharge on the Sajó River according to the investigated recurrence intervals calculated at the Sajópüspöki gauge station (Table 2). During the first 23 years (1952-1956, 1956-1975) of the investigated period, a minor decrease (-0.9%) was found regarding the periods higher than the effective discharge but then it was followed by a remarkable increase. The period of 1975-1980

lasted only for five years but the duration of periods higher than both the effective discharge and discharge with 2 years recurrence intervals is the highest (2%) through the ~60 years. The first period is also more intensive; however, the duration of floods higher than 2 and 5 years are less. A remarkable reduction (duration of Q=N1.1 around 0.3-0.5%) has been identified from 1980 and it lasted until 2000 when it decreased further having only 1 day in 5 years, higher than the effective discharge. The last period brought a significant intensification of discharge rates, almost reaching the initial (1952-1956) stages.

#Table 2. Approximately here

2.4. Reach segmentation

Based on the cartographic data and the river engineering, GIS datasets (bank protection locations and embankment path lines) from the North-Hungarian Water Directorate (www.emvizig.hu) and field surveys, 12 different reaches have been delineated in different spatial segments of the Hungarian section of the Sajó River that show similar characteristics according to the following factors: valley confinement, bank material, bank composition, stream gradient, levéé/embankment distance, number of artificial cutoffs, rate of channelization and bank protection. Bank composition was evaluated during the several direct field surveys and photo documentation along the Hungarian section. Stream gradient rates were identified using the longitudinal profile data given by the Water Directorate, meanwhile, the rate of bank protection was calculated as a ratio of the number of protected bends to the number of total bends at a given sub-reach. The first concept was to apply a statistical approach for the sub-reach delineation but the aim of our method was to split the sub-reaches at bend inflection points. However, difficulties arose from the fact that some of the variables, especially valley confinement or bank material could not be calculated or quantified for individual bends. Therefore, we preferred to apply a more subjective discrimination method based on the overview of the variables spatial extents and quantities. As a result, we identified the breaks between different sub-reaches at inflexion points where the channel behavior and artificiality changed undoubtedly.

2.5. Analysis of the channel planform morphometry and lateral migration

The analyses of planimetric changes were conducted to reveal the spatiotemporal tendencies and their stability through each investigated time period. At the beginning, river centerlines were generated based on the bank lines. All the morphometric variables were calculated based on these input data (Fig. 3)

#Fig. 3. Approximately here

Inflexion points, where radius of curvature tends toward infinity, were digitalized manually. Channel width was calculated as the intersection of bank edges and transects placed at every 100 m upstream from the confluence with the Tisza River. The lengths of bends were measured along the centerline as the distance between each inflexion point. The chord represents the direct distance between two inflexion points. Regarding the mean chord length, at first, the difference among values of two consecutive periods is determined then it is transformed into percentage and finally, an average is given by the number of years of the period. The amplitude (height of bends) was determined as the longest perpendicular distance between the chord and the centerline. For the calculation of the radius of curvature (radius of the greatest circle fitted into the bend) we compiled an ArcGIS 10 python script that was able to use all X, Y coordinates of each segment and calculates an average value for these coordinates (Fig. 4).

#Fig. 4. Approximately here

An optimization algorithm with the method of least squares used these points of averaged X, Y, Z coordinates for further iterations that were responsible for the approximation of fitting a circle to the bends. It should be noted that this calculation was implemented for the whole reach, consequently, straight or slightly curved bends could represent extremely high radius values. In order to prevent these issues, we numbered each individual bend backwards from the Tisza River confluence. Then, we omitted all the bends from the analysis showing low sinuosity values (SI<1.5). Sinuosity values were calculated as a ratio of centerline length and the distance between the start/end points of the channel or individual reaches considering the major changes in the channel direction. Then, the radius of curvature values were normalized (R/W) by the mean channel width of each different reach.

The characterization of intensive channel shifts was performed based on the method developed by Micheli et al., (2004). Lateral change polygons from the sets of intersecting centerlines from each consecutive period were generated. The lateral shift distance perpendicular from a given centerline year by year as the intersecting polygon area (Fig 5/a.) divided by half of the polygon perimeter was also estimated (Micheli and Larsen 2004).

Based on the relative position of each centerline, we also identified whether they shifted leftwards or rightwards. These results can reveal the main trend of channel shift dynamics but the size determination of eroded floodplain depends on the channel width as well. Therefore, the method of Rusnák and Lehotský (2014) allowed us to provide a solution to quantify the polygon areas of erosion, accretion and reworked floodplain (Fig. 5/b.) based on the overlapping river bank edges. A crucial differentiation is carried out regarding the basic terms of erosion/deposition. The investigated section of the Sajó River is affected by major human interventions; therefore, the channel replacements with natural and artificial origin have to be distinguished. In such cases, when the new channel position is the result of artificial cut-offs, we use the term 'new artificial channel' and 'abandoned natural channel' according to their positive or negative directions. The term 'erosion' and 'accretion' are used when the channel shifts resulted from bank erosion at the concave banks and accretion at the convex banks. The crosshatched areas between the rivers have both eroded and deposited in the time period (Greco et al., 2007; Hooke and Yorke 2010).

#Fig. 5. Approximately here

2.6. Statistical analysis of reach segmentation and planform changes

The correlations among the planform changes, bank erosion, channel shift rates and hydrological variability were tested by Spearman's rank coefficient. In order to reveal the possible differences between the delineated natural and artificial reaches of Sajó River based on the calculated bend- and reach-scale morphological variables, we conducted a standardized Principal Component Analysis (PCA) using the correlation matrix. The data matrix involved 11 variables in 7 time periods (1952-1956, 1956-1975, 1975-1980, 1980-1988, 1988-2000, 2000-2005 and 2005-2011) regarding each delineated reach. Basically, we obtained two types of data: values calculated at a given year like chord length; and the second type is a change between two periods like erosion rate. In this case, we omitted the year of 1952 since the first erosion rate can be used from 1952-1956 as '1956'. The investigated variables are listed in Table 3.

#Table 3. Approximately here

The data using z-scores to control outlier data were standardised, and applied Varimax rotation to ensure orthogonal and non-correlating principal components (PCs). Goodness of fit was

controlled with the Root Mean Square Residuals, which are derived from the residuals of the correlation matrix calculated from the original dataset and the PCA model (Basto and Pereira 2012). RMSR indicates good fit under 0.1. The data points in an ordination diagram were projected in a biplot where both the correlation structure of the involved variables (loadings of variables) and the distribution of the input data (PC-scores) can be analysed in the multivariate space.
We then compared the differences between the natural and artificial reaches using hypothesis testing. A robust Mann-Whitney test combined with Monte Carlo permutation, using 599 repetitions was carried out. H_0 was that the median of the two types of reaches did not differ significantly, H_1 was that reach medians differed significantly. Beside p-values, the effect sizes (r) which is a standardized method was also calculated; thus, comparable measures of the magnitude of the differences can be obtained.

The whole statistical analysis was performed in R 3.5.3 software (R Core Team, 2019) with the psych (Revelle, 2018) and WRS2 (Mair and Wilcox 2018) packages, and in Past 3.24 (Hammer et al., 2001).

3. RESULTS

3.1. Spatial variability of river segments regarding horizontal channel parameters and rate of artificiality.

The complex assessment of river morphology-affecting factors allows delineation of twelve different reaches (Fig. 6).

#Fig. 6. Approximately here

Considering the distinct variables (confinement, bank composition, stream gradient, distance of levees or embankments, rate of bank protection, previous cutoffs, tributaries) regarding each reach (Table 4), only R3, R5, R7, R9, R10 and R12 can be classified as ‘natural’ type that have minimal anthropogenic impact on the channel of Sajó River. Their total length is 51.3 km which is 41.7% of the Hungarian section of Sajó River.

#Table 4. Approximately here

R3 can be considered as completely natural; in contrast, the rate of bank protection in R2 is high (88.1%) and four artificial cutoffs are also part of this reach (R2). Both R2 and R3 have a higher stream gradient (0.64 and 0.69 m/km) then R1 and none of them has tributaries. The second most natural segment is R5 that flows in an unconfined floodplain having cohesive river banks; however, a 1.2 km long part is situated next to the village of Sajókaza. The floodplain in this reach is almost free since embankments are situated only in the last 3 km of the reach and their distance is more than 200 m. The rate of bank protection is around 1% and only one bend was cut off in the past; thus, the number of consecutive natural bends is remarkably high (36), so 97.9% of the segment length can be classified as natural with a stream gradient of 0.51 m/km. The Bán stream joins the Sajó River in this reach. One of the most natural reaches is R7, still with cohesive river banks but having the highest stream gradient (0.79 m/km) of the Hungarian section of the Sajó River. It is almost completely unconfined without levees and embankments; however, the borders of the city of Sajószentpéter are close in a 1.6 km long part. Only 4% of the river banks are protected; thus, 10 consecutive natural bends follow each other, showing that 84.8% of this 7.4 km long reach is natural. Downstream from the beginning of R8, the river banks become more composite and mainly non-cohesive and the stream gradient decreases from the beginning of R7. The stream gradient in R9 is only 0.46 m/km. However, the town of Ónod is close in a short section, but the majority of R9 is unconfined. Bank protection can be found along 21.5% of the reach without any cutoffs in the past that resulted in this reach, being the second most natural segment of the Hungarian section of the Sajó River. R10 is less natural (58.2%) with four consecutive river bends. The bank protection rate records 10.2% with one artificial cutoff. The stream gradient and bank composition are almost the same in R9 but this reach is totally unconfined. The confluence of the major tributary (Hernád River) and the small stream (Szerencs-Takta Stream) is situated in this reach. The final two reaches, R11 and R12, still have composite river banks in a totally unconfined floodplain with the lowest stream gradient rates (0.32 and 0.36 m/km) in the Hungarian section of the Sajó River. The difference is that S11 is completely unnatural regarding the previous bank protection works, while S12 is 85.3% natural.

Accordingly, these twelve reaches were classified into the following four categories with the purpose of their further joint evaluation: natural (R3), slightly modified (R5, R7, R9, R10 and R12), modified (R4 and R11) and intensely modified (R1, R2, R6 and R8).

The longitudinal profile of the Sajó River in Hungary shows a high variability in the delineated reaches regarding the different channel parameters. Stream gradient varies between 0.39 and 0.76 m/km with abrupt segment breakpoints of increase/decrease (Fig. 7a). R2, R3, R7 and R8 have the steepest slope values while R4-R6 and R9-R12 are more moderate in this case.

#Fig. 7. Approximately here

Regarding the mean chord length, mean amplitude and mean channel width, the breakpoint is the beginning of R8 from where the values of these parameters resulted in an increasing trend; however, another decreasing trend can be described in all the three parameters from R1 to R3. The increasing trend of mean amplitude (from 59.5 meters to 157.2 meters) and mean channel width (from 27 meters to 42.8 meters) values gently vary while the values of mean chord length fluctuation are more dominant (R1 – 384.1 m; R5 – 178.2 m; R8 – 421.1 m; R9 – 312.4 m). In Figure 7a, stream gradient values are referenced to the right Y-axis and the other ones plotted to the left Y-axis.

In the case of the variables referring to the anthropogenic impacts, results showed also significant differences from the longitudinal point of view. It was already discussed in Section 3.1 which reaches have been affected by anthropogenic interventions (e.g. cutoffs, bank protection, embankments). In Figure 7b, differences among natural reaches can also be noted regarding the number of maximum consecutive natural bends of a reach. In Figure 7b, sinuosity values are referenced to the right Y-axis and the other ones plotted to the left Y-axis.

#Fig. 7b. Approximately here

The highest number of consecutive bends is 36 in R5; however, the mean chord length is the lowest (178.18 m) compared to the other reaches; thus, the smallest bends are found in this reach. Taking into account the calculated sinuosity of each reach, the natural ones show the highest values (each of them is higher than 1.5, so they can be classified as meandering reaches). However, the highest sinuosity values are shown at R7 (S=1.83), R9 (S=1.73) and R12 (S=1.99), but even a few engineered reaches (R4 S=1.45; R8 S=1.44; R11 S=1.60) are also close to the meandering type.
Negative correlation had been found between stream gradient and the mean chord (r = -0.54), mean amplitude (r = -0.46) and mean channel width (r = -0.46) already presented in Fig. 7. All these three parameters also register strong positive correlations (≈0.7) with each other especially the chord length and the amplitude (r = 0.94).

3.2. Temporal variability of the planform changes

The spatial variability described above shows major differences between the reaches but the analysis of temporal variability reveals the channel dynamics. The bend length changes can represent the channel development rates (Fig. 8a). In the first investigated period, in most of the reaches, the bends have extended except R4-6-10 while R12 slightly decreased only. The largest increase is 12.7% in R3 while R10 shows the least one, attaining -14.6%. The periods of 1975-1980 and 1980-1988 are dominated by the bend length decrease of up to -12.9 and -29.1% respectively. From 2000 to 2005, the reaches downstream from R5 increase in bend length while in the last stage only three reaches exhibit a decrease.

#Fig. 8. Approximately here

The changes of mean chord length are presented in Fig. 8b. In the first period (1952-1956), mean chord length values decrease in almost all reaches except R6,7,11,12 but it is visible that reaches R1-4 and R9 show a high decrease (from -2.3 to -6.4%). The outstanding increase of 22.2% is found on R2 and 9.0% on R6. In total, it can be stated that only four reaches (R1-2-6-11) have an increase in mean chord length, of which R2 shows an outstanding 19.4% rate. The mean chord length values have decreased in the majority of the reaches, especially in R9 (-10.8%), R10 (-7.1%), R3 (-5.9%) and R4 (-5.8%), while the rest had a rate between -1 and -3.9%.

The temporal variability of mean amplitude values was calculated in the same way as the mean chord length (Fig. 8c). The first four reaches show remarkable shortening especially R3 (-14.35%) while R5-6-7-8 are more moderate and slightly increase (rates from 0.5 to 3.1%). The last three reaches show negative rates as -0.1 to -0.3% and R9 is higher at -4%. The changes increase from 2000 to 2005, especially in R1 (7.5%) and R9 (-10.4%). In the last stage (2005-2011), the highest values are connected to the decreasing R1 (-6.1%), R10 (-7.8%) and R12 (-5.7%). Based on those results, it can be stated that compared to their initial state most of the changes are negative, especially on the last six reaches.

Sinuosity values have been calculated for each reach and for the total Hungarian section as well and are shown in Fig. 8d. The temporal variability of sinuosity is moderate since the highest differences between the initial and final stages are +0.3% (R3) and -0.5 (R6). Our results show that basically, major changes have occurred between 1952-1956, 1975-1980 and 2000-2005, though in different positive/negative directions for different reaches. In the case of the overall Hungarian section of the Sajó River, the sinuosity values decreased until 1980, then a gentle increase started and it is still a meandering type of river.

Sinuosity index is suitable not only for describing the development stage of a given reach but also for each bend. The ratio of bend length and chord provides the sinuosity value for every single bend for all periods of the Hungarian section of the Sajó River. The summary of these values is shown in Table 5, where the bends are divided into four categories. It is clearly visible that significant changes occur regarding the number of bends in each category through the investigated periods. The most dominant category is the one having a sinuosity index from 1.05 to 1.25. The ‘straightest’ category (SI<1.05) is the second in the ranking with a proportion of around 25% and the highest state is registered in 1956 (30.2%). The ‘meandering’ types of bends have similar but a bit lower rate from the total and with moderate variability.

Contrary to the above-listed distribution of bend types, their total length shows some differences. The category of SI=1.05-1.5 is still the most dominant one; moreover, its proportion increases by 6.3% in 2011. However, the next large group is the ‘meandering’ category but a decrease starts in 1975 and reaches -9.6% in 2011. It has been stated that, regarding the bend number distribution, the straightest bends can be classified as the second largest proportion but it is clearly visible that their total length is not significant since the rate varies around 13-16% respectively.

#Table 5. Approximately here

It is noteworthy that major differences can be found among the temporal dynamics of reaches regarding the total length of bends in each sinuosity type. Changes in total length of meandering-type bends are summarized in Table 6. After 1975, all the meandering bends have completely ceased in R1. Moreover, their length is only around 1 km in 1952. The proportion seems to be stable in R3-7-8-11 since the rate of total changes has been considered to be around 500 meters and each change is positive. An outstanding increase is identified on R5 (4.38 km), while the rest of the reaches decrease, especially, R6 (-2.27 km), R10 (-3.38 km) and R12 (-8.13 km). Overall, the longest meandering sections are associated with R5-7-8-12, having around 4-5 kilometers respectively.
In the case of the second category (1.5 > SI > 1.25), only three reaches (R5-7-11) are more or less stable having only around 40-90 meters differences between the initial and final values (Suppl. material 1).
Our results show less variability of the temporal dynamics in the two last development categories (SI<1.25). Generally, we have not measured the outstanding increase or decrease rates, each of them is lower than 3 km. The least variability of total bend length distribution is identified in the category that has less than 1.05 value of sinuosity, which shows almost a straight planform.

#Table 6. Approximately here

Only the results of natural and slightly modified reaches can be taken into account regarding the average radius of curvature (Fig. 9) since the rest of the reaches include less curved bends (based on sinuosity values) that provide the extreme size of fitted circles. Two reaches (R5 and R9) result in a decrease in the extent of the radius of curvature especially R9 with a value of -2.32. On the other hand, the most increasing reach regarding this case is R10, showing a total increase of 2.16.

#Fig. 9. Approximately here

According to the classification system proposed by Hooke and Harvey (1983) the above-described spatiotemporal planform evolution of the Sajó River showed consistent patterns of channel migration of the natural and slightly modified reaches (i.e. Extension – Fig. 10a, 10c, Fig. 11a; Translation – Fig. 10a, Fig. 10c, Fig. 11a; Fig. 11b; Rotation – Fig. 10b, Fig. 10d; moreover, the channel evolved into compound and double headed meanders (Fig. 10b; Fig. 11a).

#Fig. 10. and Fig. 11. Approximately here

3.3. Lateral channel mobility

A detailed summary of mean lateral channel shifts is presented in Table 7. The overall trend shows us that the periods 1952-1956 and 1975-1980 are significantly active compared to the other periods. Their lateral mobility has been measured to be more than two times higher than the rest (7-9 compared to 2-4 meters/year/rkm), while in both periods the channel shifts mainly rightwards. These periods are followed by an intensive decrease (-6.69 meters/year/rkm by 1975 and -4.99 by 1988) but after 1980 this decrease lasted until 2000. In 2000-2005, the trend changed into a slight increase (~64%) then a minimal decrease (~7%) again in 2005-2011.

#Table 7. Approximately here

Considering the segmented reaches, major differences were found between their rates of lateral channel mobility. In the first period, R2-3-6-9 produce significantly higher rates (each higher than 11 m/y/km). A remarkable difference is measured between the most (R3 – 17.94 m/y/km) and the least active (R12 – 3.77 m/y/km) reaches. The final investigated stage of 2005-2011 shows only an outstanding increase in shifting activity in R3 (6.84 m/y/km as almost 2 times the mean) while R5 and R10 were also a bit higher than the rest.

3.4. Erosion/deposition

In addition to the lateral channel mobility, the exact extent of area affected by erosion and deposition has been identified based on the channel polygons. The changes in the overall rate of areas affected by erosion and deposition are presented in Table 8.

#Table 8. Approximately here

It can be clearly seen that the highest floodplain transformation activity through the whole investigated period occurred during the first phase (1952-1956). Considering that it has only a duration of four years, the 31.81 ha/year of bank erosion is a remarkable rate; moreover, the extent of the area resulting from artificial cut-offs also has the maximum proportion (5.92 ha/y) in this period. These phenomena are followed by a similar rate of accretion on the convex banks, while the channel remnants after cut-offs also have left a significant area. The second highest change in total channel area (61.88 ha/y) was found from 1975 to 1980. In the period 1980-1988, the accretion processes are considered more dominant (almost three times higher) than bank erosion , providing in total the third highest land transformation. Our results show that in the period of 2000-2005 rates of bank erosion (5.97 from 10.97 ha/y) are lower but on the other hand, the accretion has increased to almost 2.6 times (15.25 from 5.93 ha/y). The final period of investigations on this process reveals that the bank erosion is accelerated by 3.3 ha/y rate and the accretion has decreased at this stage.

The previous section gives an overview about the overall status of land transformation; while Figure 12 provides an overview about the differences between the temporal variability of bank erosion (without cut-off related changes) measured on the reaches.

#Fig. 12. Approximately here

In the majority of the reaches in the first time period (1952-1956), the highest erosion activity is measured on Sajó River downstream from R6. Intensive bank erosion has been measured between 1975 and 1980. Moreover, every reach resulted in increased activity compared to the rates measured in 1956-1975. The results of the period 1980-1988 shows that the changes are stabilized since only R7-10-12 have shown an increase in bank erosion (>0.08 ha/y/rkm). In the last period (2005-2011), the bank erosion increases in all reaches; however, the maximum increase rate is 0.13 ha/y/rkm.

The human intervention for establishing cut-offs results in new channel development as described earlier. According to Table 9, the majority of the cut-off-related land transformation or in other words, the rate of channel shortening is performed between 1952 and 1980; however, in two cases of 1988 and 2000 cutoffs also appear. Reaches R2 (0.24 ha/y), R6 (0.27 ha/y) and R8 (0.19 ha/y) show notable rate of channel shortening; while the rest are negligible. Moreover, in R7-9-11-12 they are completely missing.

#Table 9. Approximately here

3.5. Statistical differences between natural and artificial reaches

The Principal Component Analysis investigated 924 values in total (11 variables from Table 3, in 7 periods for 12 delineated reaches). PCA explained 77% of the total variance and three principal components (PC). PC1 accounted for 38% of the variance and correlated with the AM, BE, MEA, WI, MSI and TSI, PC2 accounted for 24% of the variance and correlated with the TER, TAC, SHI and PC3 explained 15% of the variance and correlated only with the NBE (Fig 13).

#Fig 13. Approximately here

The reaches of Sajó River showed differences by the naturalness of the morphometric parameters but for all morphometric variables (Table 10). In the case of MEA, WI, TSI, MSI, NBE and SHI there was significant difference ($p<0.05$) with moderate effect ($r>0.3$); however, based on the effect size (r), small effects ($0.1<r<0.3$) can be revealed, even for AM and TER, although these metrics were not of significance. The largest effect was developed in TSI (r=509). Scores of PCA aggregated the information into PCs indicating significant differences: PC1 and PC2 had significant differences, and PC1 had the second largest effect size after the TSI metric.

#Table 10. Approximately here

4. DISCUSSION

One of the aims of this study was to reveal the recent channel evolution of the Sajó River during different periods within 59 years of recorded data. The analysis of channel morphometry showed both minor and major changes in the studied parameters. According to the delineated reaches, the Hungarian section of the Sajó River has been under the influence of river engineering since 1950 except the natural-type reaches, which are situated between longer reaches that have a previous anthropogenic intervention. The spatial variability of horizontal parameters showed that the reaches have differences downstream. We demonstrated that an analysis of the temporal variability of these parameters describes the evolutionary trajectory of the Sajó River. Considering the trends of the total studied channel length, the changes of both the mean amplitude and chord values have decreased in 8 of the 12 reaches especially in R9-10 and increased only in R2-6. Consequently, the planform of bends became narrower and it suggests that the planform evolution of Sajó River cannot be characterized by the extension of bends (Hooke 1984). However, in several sub-reaches, we identified extending, translating and rotating bends. In the case of R8 and R10, the changes may be associated with larger tributaries of the Sajó River entering the system in those reaches (Phillips and Slattery 2007). Sinuosity values reflect the rate of human intervention (Timár 2003; Ortega et al., 2014; Sapkale et al., 2016). The artificial cutoffs and the later established embankments and bank protection resulted in a decrease of the sinuosity values of all the modified and intensely modified reaches while they increased in the natural and slightly modified reaches (Fig 8/d). R8 was a stable reach and the change of R1 was meagre. In the case of the rest of the artificial reaches, the river engineering succeeded in its aims as they have transformed these reaches from meandering type to sinuous (mean decrease around 0.4-0.5 in sinuosity). Regarding the channel classification of the natural and slightly modified reaches, R3 and R5 became meandering type from sinuous since their sinuosity has increased from 1.4 and 1.39 to 1.67 and 1.61 respectively. It changed in the opposite way in modified and intensely modified reaches from meandering to sinuous in R2, R4 and R6. In the cases of intensely modified R1 and R8 reaches, the sinuous type has remained; however, their values had a decreasing trend. The sinuosity values of the remaining meandering type reaches have increased except R11. However, these positive changes are not significant, though it is clearly visible that the channel morphology of reaches without human intervention tends to develop as it was found along several similar European rivers (Keesstra et al., 2005; Blanka and Kiss 2011; Dragićević et al., 2017). Previous studies revealed that stream velocities may increase downstream of channelization when the threshold for erosion is exceeded (Brookes 1987) but it is still challenging to evaluate the influence of river engineering or bank protection in the rate of planform evolution (Dépret et al., 2017) since it is an interplay between other relevant drivers (Michalková et al., 2011). The most frequent downstream effect of channelization is channel incision (Wyżga et al., 2016). Darby and Thorne (1992) described that degradation of riverbed leads to an increase in bank height that produces instability in bank material, the initial step of bank erosion and bend development. However, our study did not assess any analyses on bank heights, though it is clear from our results that the natural and slightly modified reaches, showing increased bend evolution, are found between the modified and intensely modified reaches. The total length of the intensely modified R1-2 and the modified R4 is 21.3 km and the completely natural R3 is compressed among them (Fig. 11). Furthermore, several artificial cutoffs were established along R1 and R2 (Table 2), while the rate of bank protection is the second highest in R2. These conditions could have enhanced the increased bend evolution of R3 as other studies have confirmed the development of the channel scour at the tail-end of bank protection concrete-walls (Parker and Andres 1976; Brookes 1987). A more evident consequence of human intervention was found in the slightly modified R9 where an artificial cutoff was established at the upstream part and the concerned bend was then protected (Fig. 12). This type of river management works resulted in a remarkable bend translation process shown by our study.

In Table 5a, it was observed that the total number of bends decreased by 1980 and since then it had started to increase again. The mean chord and amplitude values decreased in general; consequently, new and small bends are starting to form. River engineering works had degraded the well-developed meander loops but, especially in the natural reaches, the channel started to develop after the 1980's which can be found also in the changes of the total length of the Hungarian reach of the Sajó River (Table 5b). The proportion of meandering bends decreased continuously, while the category of having sinuosity between 1.05 and 1.25 showed an increase. It can be concluded that the bend length increase is followed by newly formed bends and not the already existing meanders developing in a significant way contrary to other findings starting from a similar initial trend observed along other rivers (Sarma et al., 2007; Yao et al., 2013; Hajdukiewicz and Wyżga 2019). The least channel activity was coupled with the less developed bends (SI<1.05) as previously found by Hickin and Nanson (1975) as the higher channel migration rates are associated with more curved bends. Regarding the normalized radius of curvature (R/w), most of the evolutionary models (Brice 1974; Hickin and Nanson 1975; Hooke 2007; Sylvester et al., 2019) show bends tightening and becoming elongated over time. These values are presented in Fig. 9 as the majority of the natural reaches show stability or slight decreasing trend except R10; therefore, the Sajó River does not represent an outstanding behaviour.

It had been argued by several authors that an effective discharge is responsible for the intensive bank erosion processes (Gautier et al., 2007; Rusnák et al., 2016), which can be enhanced by the absence of vegetation (Keesstra, 2007). However, this parameter has not reached the strong correlation (r=0.96) value measured, for example, for the intensively developing Amazonian Rio Beni (Gautier et al., 2007). Our results have shown some similarities with other European rivers. Ondruch and Máčka (2015), who worked on the Morava River (Czech Republic), found that the correlation between the duration of discharges was equal or higher than the effective discharge and the bank erosion rates, reaching 0.57. However, they investigated only a 5.5 km long reach and the meandering reaches showed a correlation of only 0.26, while along the Sajó River, it was 0.59, 0.61 and 0.59 regarding the total reach, the natural and the artificial reaches, respectively (Suppl. material 2). The mean channel shifts were higher than other rivers in Hungary and Central Europe. In Hungary, the Bodrog River produced shift rates around 2.67 m/year (Mecser et al., 2009). Rusnák et al. (2014; 2016) found the lateral shifts up to 0.8-1.5 m/year and 1.15-1.45 m/year on the gravel bed Topl'a and Ondava Rivers (Slovakia). Estimating rates of erosion has allowed us a better management of this process since it is very important to know if the process is slow or fast related to its intensity. Bank erosion can register results from a few cm/year up to several m/year. During 1952-1956, an exceptional bank erosion (32 ha/y) and accretion (45 ha/y) rate were evident. Establishments of artificial cutoffs had been stopped by 1980 (Fig. 14). However, the duration of periods higher than the effective discharge was 0.5% higher in the period of 1975-1980 but the erosion rate had exceeded it since it was accompanied by the first artificial cutoffs. After the significant channel straightening of the first investigated period, a long (19 years) and meagre dynamic period had taken place. From 1975 to 1980, the duration of N1.1 and N2 recurrence floods increased significantly, which resulted in extensive bank erosion (27 ha/y) and accretion (28 ha/y) processes again. The rest of the investigated periods had been characterized by the discharge conditions similar to those found on the tributary Hernád River (Kiss and Blanka 2012). Our results show that the flow regime does not represent a major control on the river (e.g. only minor morphological change occurred in the period of 2005-2011) while the system has become progressively less dynamic.

#Fig. 14. Approximately here

Earlier studies for the Sajó River just provided information about local cutoffs (Bertalan and Szabó 2015), engineering works (Bertalan et al., 2016b) or ecological impacts (Bertalan et al., 2018) but did not perceive the river as a continuum system. On the other hand, we distinguished twelve different river reaches not by "automatic" distance, e.g. river kilometres but reaches grow out of specific geomorphological conditions which are with or without human modifications. The PCA analysis showed clear differences exist between our subjectively delineated "natural" (natural and slightly modified types) and "anthropogenic" (modified and intensely modified types) reaches of Sajó River; however, several exceptions were noted as well (Fig. 13). The main reason for this was that we applied an overall look on the total 59 years period but several anthropogenic factors such as bank protections were established during the first periods. In contrast, we defined the rate of artificiality as a constant value through time. In few cases, anthropogenic types of reaches were found in an overlapping position with the natural ones or *vice versa*. According to Table 7, R3 reach in 1956 showed similarly high erosion and channel shift rates as it was found along R2 and R6, but this process decreased in these intensely modified reaches meanwhile it happened naturally in R3. We can assume that, in this case, the river management and bank protection may affect the erosion and later shifting processes along natural reaches as well, since R3 is situated between the modified R4 and intensely modified R2 reaches and this was observed in other rivers too (Simon and Darby 2002; Zawiejska and Wyżga 2010; Blanka and Kiss 2011; Kiss and Blanka 2012). However, in the case of Sajó River, this state was just temporary and then gently started to increase again. The main fact could be related to the poorly constructed protection works that sometimes just only reduce the effects in a short-term period, which can easily evolve later again (Surian 1999; Wang et al., 2016; Yousefi et al., 2016). Regarding the modified reaches overlapping the natural ones, as the modified R11 and the intensely modified R8, the main driving factors are now not the erosion rates but the planform variables. Both reaches were stabilized but their planform remained in a relatively developed state i.e. high sinuosity and amplitude values. In this case, their characteristics can be really similar to the natural reaches if the erosion or channel shift rates are not considered (Micheli and Larsen 2004; Mecser et al., 2009; Dragićević et al., 2017). Based on this study, we can propose to preserve the natural R3 reach and the slightly modified R5 and R7 reaches. Moreover, we state that the reaches R1, R4, R11 and R12 must not be modified. Finally, we consider it is vital the reaches R2, R6, R8, R9 and R10 to be redesigned (Fig. 15).

#Fig. 15. Approximately here

We remark that each river channel is a unique system created by distinctive composition of local and global processes in time and different connectivity processes (Cavalli et al., 2013; Poeppl and Parsons 2017). It is well-known that the reproduction of the river morphodynamics by different models is full of uncertainties (Di Silvio and Nones 2014; Rousseau et al., 2017). Therefore, the most precise approach would be to study the river as an inimitable system, needing more results at different scales (East et al., 2016; Rusnák et al., 2018; Langat et al., 2019) for example using plots with different sizes and vegetation covers close to the river or along the hillslopes in different parts of the catchment as was also tested in the Loess Plateau (China) (Feng et a., 2016, 2018). Our study confirmed the hypothesis proposed by Hooke (2004), who noted that much of the behaviour fits models of nonlinear systems patterns and system developing towards criticality, which then becomes truly chaotic. Individual meanders show remarkably consistent behaviour, although variation in detailed form.

Recent studies remind that the "Stage 3" of the Anthropocene arrives soon (Goudie 2018) where fluvial geomorphology, with studies similar to ours, will provide the necessary skillsets to reveal precisely the human impact on the floodplains (Pijl et al., 2018; Grill et al., 2019) and has to occupy a leading role in the development of effective environmental management (Słowik 2015; Brown et al., 2017). Moreover, new trends related to climate change should be also taken into account. Recent studies related to the evolution and influence of different weather types on soil erosion processes in highly anthropised territories could give new key information to foresee land degradation processes in specific eroded reaches (Peña-Angulo et al., 2019; Rodrigo-Comino et al., 2019).

The scientific community agrees that river restoration works are fundamental elements in decreasing flood risk (Dixon et al., 2016) and the riverine landscape characterization is a vital issue for effective floodplain management (Williams et al., 2013). Several former studies pointed out that local water management authorities should present detailed and complex floodplain evaluation works (McGrane 2016), and geomorphic analysis could contribute to its background (Habersack et al. 2015). However, our study highlights the issue that automated reach evaluation is not always acceptable but the long time series of morphological variables of the river channel provides the possibility to characterize the floodplain in a more effective way. Other studies discussed that it is crucial not just to investigate the recent stage of channel morphology but to understand the evolutionary trajectory of the floodplain and erosion history (Mondal and Patel 2018); otherwise, they can induce and intensify erosion processes (Nichols et al., 2018). In this case, our study gives support to the local environmental management strategies to avoid the locally induced further land degradation. We also have to keep in mind that channel shifting and, accordingly, bank erosion is not always a harmful effect. The ecological impacts have to be investigated thoroughly as well (Bertalan et al., 2018). Last but not least, humans usually tend to ignore their harmful effects on the environment and especially on riverine landscapes (Wohl 2018), but a holistic perspective and understanding of these physical and ecological phenomena could promote a better formulation of the environmental restoration goals (Pasternack 2013). Other studies stated that those restoration projects have higher success rates, which involved the preliminary analysis of the local history regarding the river channel evolutions and their adjustments (Morandi et al., 2014; Mondal and Patel 2018); therefore, our case study can serve as a guideline to local water management authorities, by showing its key issues, for future management and restoration of similar rivers.

We confirm that altogether understanding of channel planform dynamics, at the spatial and temporal scales used in this study, can be a relevant tool for managers to predict which portions of the floodplain will be likely involved river dynamics in the near future (e.g. next 30-50 years). There is still a demand for detailed geomorphological inputs for management strategies; however, many policy-makers argue with a necessary preservation of the previous channel development trajectories (Thorne et al., 1998; DeVries and Aldrich 2015; James 2015). The next step for managers would be to decide which strategy to adopt: protecting the floodplain (Piégay 1998; Morandi et al., 2014; Alber and Piégay 2017) or defining an erodible corridor where lateral shifting will not be hindered (Piégay et al., 2005; Habersack and Piégay 2007)?

5. Conclusions

The description of morphometric parameters over decadal time scales allowed us a better understanding of the Sajó River river systems and make comparable their spatiotemporal changes with other European rivers.Considering the channel forming distinct variables, twelve different reaches were delineated showing similar characteristics, from which up to six had a natural origin. We concluded that the spatial variability of channel morphometric parameters showed an increasing trend in several natural reaches by the development of bends while both hydrological conditions and anthropogenic interventions affected these processes. Although bank erosion and accretion rates were, mainly, coupled with the higher discharge periods, their key role had decreased by the last period (2005-2011). For the future, more research is needed in order to assess the seasonal variability of in-channel flow velocities and bed topography in the bends of intensely shifting natural and slightly modified reaches in order to understand the bend evolution for an extensive prevention of bank erosion processes at these localities.

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List of Figures

Fig. 1. Location of the Sajó River catchment. Study section in bold. Gauging stations: 1) Sajópüspöki; 2) Sajószentpéter; 3) Felsőzsolca

Fig. 2. Annual peak discharge rates measured at the gauging stations of Sajó River. Red arrows show dates of maps/aerial photographs

Fig. 3. Morphometric variables of the analysis

Fig. 4. Circle fitting script for calculating the radius of curvature at individual river bends of Sajó River

Fig. 5. Determination of later channel changes (A) and area of erosion/deposition (B)

Fig. 6. The delineated reach segments of Sajó River

Fig. 7. Spatial variability of horizontal channel parameters (bold numbers on the top refer to reach ID, green bars refer to the natural and slightly modified reaches)

Fig. 8. Temporal variability of the planform parameters: a) total bend length (% per year); b) mean chord length (% per year); c) mean amplitude length (% per year); d) sinuosity

Fig. 9. The changes of the mean normalized radius of curvature (R/W) values in the natural and slightly modified reaches

Fig. 10. Spatiotemporal planform evolution of the natural (R3) and slightly modified (R5, R7) reaches of Sajó River

Fig. 11. Spatiotemporal planform evolution of the slightly modified (R9, R10) reaches of Sajó River

Fig. 12. The rate of reach-averaged bank erosion (ha/year/rkm) measured on the different reaches

Fig. 13. Biplot diagram of the morphometric variables indicating the naturalness of the river bends in different dates (green circle: natural reach, black square: artificial reach; labels: IDs of reaches; arrows: loading vectors of variables)

Fig. 14. The interplay between bank erosion processes and hydrological conditions of the Sajó River

Fig. 15. Proposed management types regarding the Hungarian reach of the Sajó River

List of Tables

Table 1. The cartographic and aerial datasets used for the detailed analysis

Table 2. Duration of periods higher than the effective discharge at the Sajópüspöki gauge station

Table 3. The calculated planform and morphological variables of the Sajó River reaches

Table 4. Segmentation of the Hungarian section of the Sajó River based on different river morphology-affecting factors

Table 5. Distribution of bends based on different development categories

Table 6. Total length of meanders (km) based on different development categories in the reaches (grey bars indicate the natural reaches)

Table 7. Mean lateral channel shifts (meters/year/rkm) and their main directions (grey bars indicate the natural reaches)

Table 8. The rate of erosion/deposition and the total channel change (ha/year) in the study periods

Table 9. The rate of channel shortening (ha/year) (grey bars indicate the natural reaches)

Table 10. Differences according to the Mann-Whitney test of the morphometric parameters of reaches of Sajó River (highlighted with bold: $p<0.05$; italic: at least medium effect of r)