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1 Introduction

Central European rivers have been the subject of intensive river regulation works in the past, which caused a dramatic decrease in the physical and biotic complexity of riverine landscapes [1, 2]. Lowland meandering rivers were the most affected as they were systematically engineered from the nineteenth century in order to acquire new arable land, maintain flood protection, and enhance river navigation. The traditional empirical approach towards the understanding of meandering rivers focused primarily on determination of the variables which control planform geometry and the evolution of their channels [3–6]. Later, theoretical approaches dealing with the numerical modelling of the physical basis of meandering [7–10], and physical laboratory experiments [11–13] complemented empirical studies.

A substantial body of knowledge on the dynamics of meandering rivers is now available. Nonetheless, as indicated by [14], many gaps in research still exist, and thus new research themes have arisen as well in meandering river research. In Europe and North America, considerable effort has been put into establishing linkages between the knowledge gained on the dynamics of meandering rivers and river management and restoration practices. Just as empirical research into meandering river dynamics focused, in the past, primarily on natural rivers, it is now evident that attention should also be paid to meandering systems affected directly or indirectly by human intervention.

Understanding the dynamics of quasi-natural (artificially influenced) meandering rivers is one of the key prerequisites for the development of appropriate strategies targeting the restoration of artificially controlled river reaches to attain an ecologically favourable state in accordance with the European Water Framework Directive (2000/60/EC)[1]. Therefore, traditional research of meander-

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[1] European Parliament and Council, Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a Framework for Community action in the Field of Water Policy, 2000.

ing rivers is receiving new impulse from river managers who demand models of possible development trajectories of newly formed (revitalised) meandering channels where only straightened channelized streams existed for many decades. In this context, with regard to meandering river research, the key questions that need to be addressed are: (1) how do bank erosion and channel migration affect production of aquatic and semi-terrestrial habitats in floodplains (e.g. through cut offs and oxbow lake formation) [15–17]?; (2) how should channel migration zones be delimited to mitigate the conflicts between the dynamic changes of meandering channels and economic activities, typically arable land erosion and disruption of transportation infrastructure [18–20]?; (3) what controls channel migration rates of meandering rivers [21–23]?

In the Czech Republic, as a consequence of river-straightening practices, meandering reaches of large lowland rivers have almost completely disappeared. Examples of the last river reaches with a spontaneous development of meandering can be found on the middle and lower course of the Morava River in the Litovelské Pomoraví (40 km in length) and the Strážnické Pomoraví (13 km in length) regions. The latter region represents an interesting example of the quasi-natural development of meandering river reaches after significant channel and floodplain engineering adjustments were undergone in the 1930s. The aim of this paper - with special focus on Strážnické Pomoraví - is to: (1) quantify the spatio-temporal evolution of channel migration rates and related changes in channel geometry; (2) test the relationships between the pattern of channel migration and environmental and geometric variables; and (3) characterise the influence of channel engineering adjustments on the channel migration rates. Our contribution brings further information about the behaviour of a medium-sized meandering river flowing through a highly transformed settlement-agricultural landscape with various lithologies, land use categories and a complicated history of river-engineering practices.

2 Geographical setting

The Morava River drainage basin is the largest fluvial system in the eastern part of the Czech Republic. Above the confluence with the Danube, the Morava has a length of 353 km with a catchment area of 26,578 km^2. The Morava rises in the Králický Sněžník Mountains close to the Czech-Polish border at an altitude of 1,371 m and leaves the territory of the Czech Republic in the lowlands of south Moravia after 269 km of its course and has catchment area of 25,273 km^2 at an altitude of 148 m. The lower reach of the river forms a natural border between the Czech Republic and Slovakia, and further downstream between Slovakia and Austria. Among the most important tributaries are the Bečva River (1,626 km^2), draining the eastern part of the catchment, and the Dyje (Thaya) River (13,419 km^2), draining half of the whole catchment.

The study area is a small segment of the floodplain stretched along the 5.5 km long reach of the River Morava between the Strážnice, Bzenec-Přívoz and Rohatec settlements in south-eastern Czech Republic. It is located in the Dolnomoravský úval Basin (northern tip of the Vienna Basin, altitude between 150-200 m), where the Morava River floodplain is on average 3.5 km wide (Figure 1). Sedimentary infill of the Dolnomoravskýúval Basin consists of claystones, siltstones, and sandstones of Miocene age. Overlying Quaternary sediments are represented by Upper Pleistocene sands of the so-called Moravian Sahara on the western side side of the floodplain. These deposits are originally of lacustrine origin, however they have been extensively reworked by wind action and moulded into the form of sand dunes [24]. These sands are eroded by lateral erosion of the Morava and form unstable concave banks reaching a height of up to 15 m (Figure 2). Alluvial sediments are formed by a layer up to 10 m thick of sandy gravels of Upper Pleistocene to Holocene age that are covered by Holocene flood loams. Uplands adjacent to the alluvial valley are composed of flysch sediments of the Magura Nappe unit of the Western Carpathians, whose thrust fronts are oriented from SE to NW [25].

The Strážnice stream flow-gauging station (river 133.5 km, drainage area 9,145.8 km2, mean annual discharge 59.6 m^{3}s^{-1}), operated by the Czech Hydrometeorological Institute since 1940s, is located at the upstream end of the study reach. The history of water level and discharge measurements extends back to 1886. Discharges with N-years recurrence intervals are summarised in Table 1. Since the 1920s, discharges have reached Q_{100} once, Q_{50} twice, Q_{50} once, Q_{10} six times, Q_5 eighteen times, and Q_2 twenty-eight times (Figure 3). Among the highest frequencies of floods are decades 1961-1970, with eleven events, and 2001-2010, with seven events [26]. So far the highest peak discharge at Strážnice, a flow of 901 m^{3}s^{-1}, was recorded on 10 July 1997, during the 'flood of the 20th century' which exceeded the value of Q_{100}.

Today, the Morava River in the Strážnické Pomoraví region has a meandering pattern with a sinuosity of 1.53, the width of the meander belt reaches 700 m, the channel bed has a very gentle slope of 0.36‰, and mean channel width is 69 m. The river bed is formed mainly by sand and gravel, whereas the river banks are mostly formed by cohesive ma-

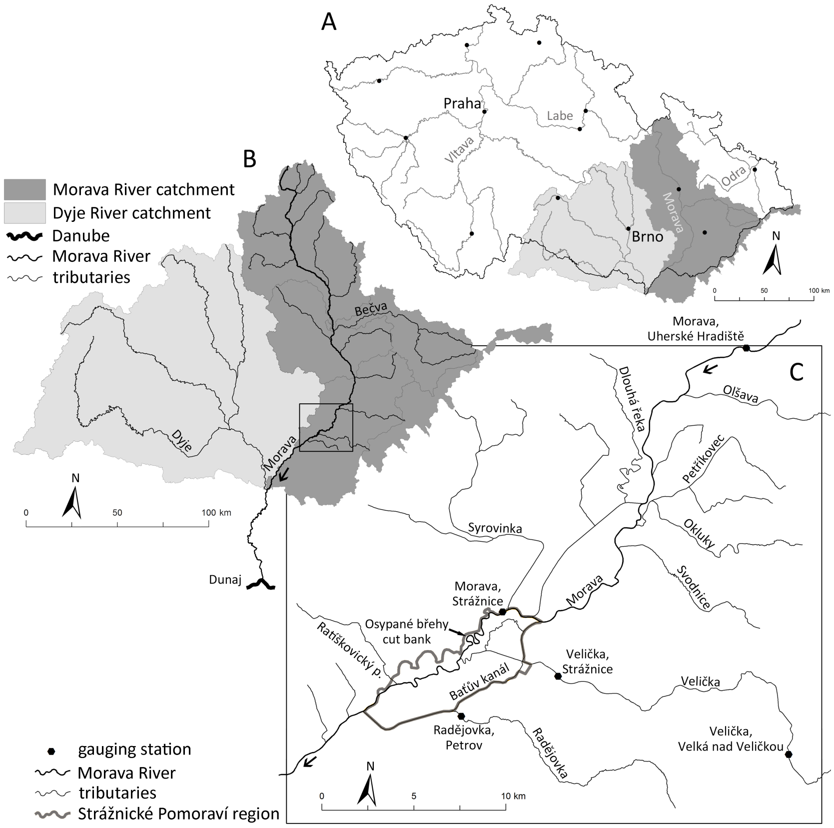

Figure 1: Study reach of the Morava River within the Czech Republic (A), the whole drainage (B), and the Strážnické Pomoraví region (C).

Figure 2: High river bank formed by aeolian sands of the Moravian Sahara in the locality of Osypané břehy, Strážnické Pomoraví region. Note the contact of flood loams and aeolian sands on the left-hand side of the image. (Photo by J. Ondruch, 2011).

terial of flood loams with a thickness of up to 6 m. In some bank profiles unconsolidated sand material prevails [27].

Until the 1920s, an anabranching pattern with straight as well as meandering river channels was characteristic of the study river reach (Figure 4). As a consequence of river regulation works starting in the 1920s, the functionality of smaller anabranching channels had weakened and the flow was progressively concentrated into a single dominant channel. Tributaries and side channels were progressively channelized and a network of drainage ditches was built in order to increase the area of arable land. The length of the dominant channel was shortened by the artificial cut off of two sequences of meanders. A significant reduction in the connectivity between channels and floodplain emerged with the construction of flood-defence dykes, which completely obstructed the overbank flows of the Baťa channel (former Morávka side channel) and the Radějovka River and partly of the Morava River itself, and the inundation area dropped to 20% of its original extent [28]. River regulations in 1920s-30s triggered the incision of a dominant channel. Currently, the river bed is approximately as low as 6 m beneath the floodplain. As a consequence, the frequency of overbank flows has significantly decreased and the floodplain has gradually become hydrologically disconnected; where, at the end of the nineteenth century, the overbank flows occurred even several times a year, today the bankfull stage is reached only with five years recurrence interval [29].

3 Material and methods

A GIS analysis of the lateral migration of the Morava channel in the period 1938-2012 was conducted for the 5.5 km long river reach (upstream most part of the 13 km long (quasi)natural course of the Morava River). Available aerial images were provided by the Military Geographical and Hydrometeorological Institute (VGHMÚř) and the Czech Office for Surveying, Mapping and Cadastre (ČÚZK). The first aerial images were taken in this area shortly after significant river regulation works of the Morava were made in the 1930s.

First, georeferencing of aerial images was done in ArcMap 10.0 software. All images were georeferenced according to the orthophotomap produced by ČÚZK from the aerial images taken on 20 October 2012 on a scale of 1:1,000. Polynomial transformation of first order was employed with the use of at least 18 reference points and a polynomial transformation of second order with 25 points. As reference points, corners of buildings, engineering constructions on drainage ditches, crossings of roads or drainage ditches, margins of distinctive land cover patches, and solitary trees, were used. If the mean square errors were lower than 5 m, georeferencing was accepted and an aerial image was rectified with a grid resolution of 0.1 m.

For a quantification of spatio-temporal variability of the channel migration rates, seven periods were used (1938-1953, 1953-1963, 1963-1973, 1973-1982, 1982-1993, 1993-2003, 2003-2012). These intervals result from the availability of aerial images enabling document channel changes with a relatively high temporal resolution. For every respective year, bank lines were digitalised from georeferenced images on a uniform scale of 1:1,000. In non-forested segments, where the floodplain was covered by grassland or arable land, the bank line on the concave side of meander bends was clearly visible in the incised channel. On the convex sides of meander bends the floodplain was distinguished from point bars by vegetation cover. In forested segments, bank lines were delineated by connecting visible fragments of bank lines with the central points of treetops that were the most adjacent to the water surface. This approach assumes a circular shape of treetops and vertical position of trees growing directly on the bank line. However, this is not always the case in the study area and therefore an error could arise. Nonetheless, the river channel is deeply incised into the floodplain and furthermore many aerial images were taken in the winter season when leaves were missing. Even in forested segments, there were many stretches with clearly visible bank lines, substantially decreasing the possibility of this type of error occurring. Due to the incision of the Morava into the floodplain, delineation of both bank lines was not affected by the differences in the water level in the years when aerial photographs were taken. Despite discharge data not being available for the situations caught on aerial images, bankfull discharge was not reached in either year, thus even the inner banks were clearly visible and possible to delineate.

Based on the methodology of [30], lateral migration polygons (polygons delineated by the position of the bank line in times t and $t + 1$) were constructed for every respective period for both bank lines (Figure 5). In previous studies, authors used either bank lines or centrelines for describing the pattern of lateral channel migration. Hooke and Redmond [31] found that maximum values of migration are higher for polygons constructed from bank lines than for those from centrelines. Nonetheless, they are both of the same order. The advantage of the approach based on bank lines is that it provides the possibility to also study spatio-temporal changes in channel width and thus to cal-

Table 1: The list of the N-years discharges of the Morava River at the Strážnice gauging station (133.5 river kilometre, drainage area 9145.84 km^2) for 1940-2014. (Source: [26])

	Q_1	Q_2	Q_5	Q_{10}	Q_{20}	Q_{50}	Q_{100}
Q (m^3/s)	375	440	525	588	649	730	790

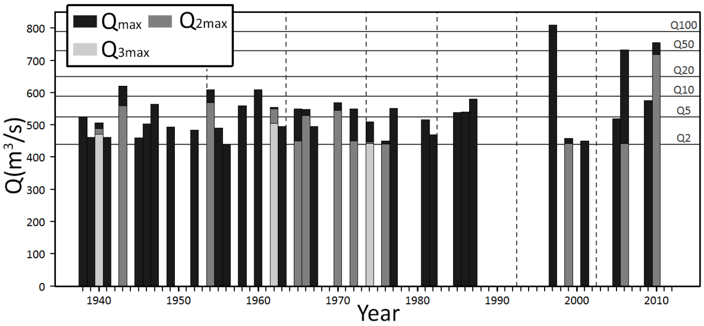

Figure 3: Magnitude of floods with a recurrence interval equal to or higher than Q_2, which were documented at the gauging station Strážnice, the Morava River, between 1938 and 2012. If more than one flood with a recurrence interval equal to or higher than Q_2 occurred,all events are differentiated by colour (Q_{max} represents the largest, Q_{2max} the second largest, and Q_{3max} the third largest flood for particular year). N-years discharges are highlighted by horizontal solid lines. Years when aerial images were taken are highlighted by vertical dashed lines.

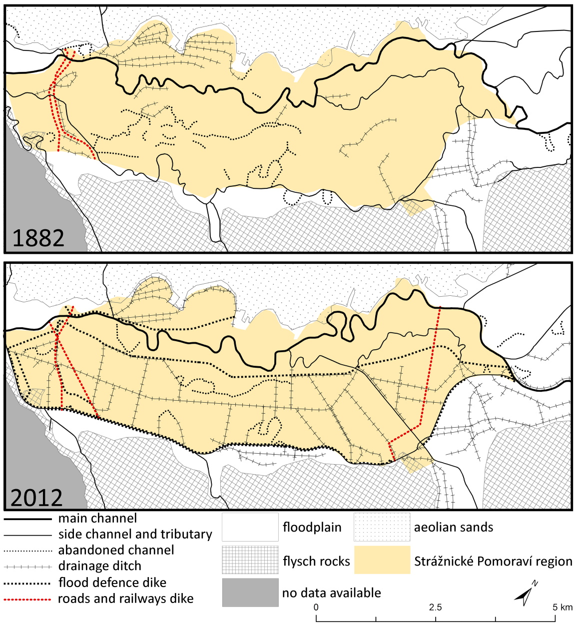

Figure 4: Drainage system and flood defence of the Morava River in Strážnické Pomoraví region in 1882 and 2012. Note that roads and railways are delineated only in Strážnické Pomoraví region for better clarity of the figure.

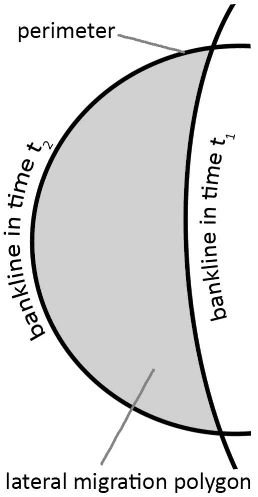

Figure 5: (A) Methods for quantification of lateral channel shifts utilising the lateral migration polygons approach. An average migration for the whole polygon is calculated as a polygon area divided by its perimeter.

culate the differences between the rates of erosion and accretion on opposite channel banks.

Employing the technique of lateral migration polygons, we quantified the rates of erosion (Er), accumulation (Ar), and channel width change (ΔW). Mean channel shift for the period analysed is then calculated as a polygon area divided by half of its perimeter [30]. For a detailed description of spatio-temporal changes of Er, Ar and ΔW, lateral migration polygons were further divided into 25 m long segments, similar to the studies of [21, 32, 33], representing in the case of the Morava approximately half of the channel width. For every segment, a mean channel shift was calculated as its area divided by a half of the bank line length in times t and $t+1$.

Patterns of channel migration rates were visualised by cumulative curves of Er, Ar and ΔW plotted against a distance from the beginning of the study reach. The construction of such curves for different time periods enables the determination of laterally active and stable river reaches and their comparison in time.

On three spatial scales (reach, segments, and individual meanders), relationships between measures of lateral channel migration (Er and Ar) and anticipated explanatory variables, bank material, floodplain land cover, flood frequency and magnitude, and channel geometry (radius of curvature, sinuosity, channel width), were tested employing non-linear correlation and Kruskal-Wallis nonparametrical ANOVA.

Eroded floodplain material was identified from aerial images and verified by the field validation exercise. Information on flood frequency and magnitude in the studied period was supplied by the Czech Hydrometeorological Institute (the Strážnice gauging station). Floodplain land cover for the respective years was delineated from aerial images on a scale of 1:1,000. Land cover patches were delineated only if their area exceeded 100 m^2. Only one, prevailing, land cover category was further assigned to migration polygons.

4 Results

4.1 Changes in the overall channel planimetry

The channel of the Morava River in the Strážnické Pomoraví region has experienced significant changes to its planform in the past 75 years (Figure 6). As a consequence of erosion, 60.43 ha of river floodplain were removed between 1938-2012. Accumulation on the convex bank was lagging behind the erosion with 44.12 ha of new floodplain developed in the same period. The most dynamic evolution of the channel was recorded in the first time interval, 1938-53 (floodplain erosion EF = 1.37 ha/year; floodplain accretion AF = 0.69 ha/year). In the following period, 1953-63, the rate of erosion decreased (EF = 1.07 ha/year), whereas the rate of accumulation rate increased (AF = 0.90ha/year). Both processes were, nonetheless, still reaching relatively high values in comparison with the remaining periods. For the period 1963-2012, the stabilisation of rates of lateral channel migration is characteristic of the fluctuation between 0.43-0.79 ha/year for erosion and 0.31-0.62 ha/year for accumulation. Of key importance regarding the planform changes of the channel documented for the period 1938-53 is the fact that 34.1% (20.62 ha) of the total eroded area of the floodplain falls within the opening time period. Similarly, in this relatively short time, 23.5% (10.38 ha) of total newly formed floodplain area was formed here (Table 2). Differences between erosion rates in concave banks and accumulation rates on convex ones caused an increase of the active channel area by 16.31 ha, while the most rapid increase was also documented in 1938-53 (10.28 ha, i.e. 63% of total area).

The reach average rate of bank line retreat (river bank erosion) for a whole studied period was 1.04 m/year; the average accretion rate was 0.75 m/year. The average river bank erosion rate (Er) reached maxima of 2.19 m/year in the opening time period (standard deviation (SD) = 2.1 m/yr). Maximum erosion was documented in the area of meander M7, where local Er reached 9.8 m/year in the first

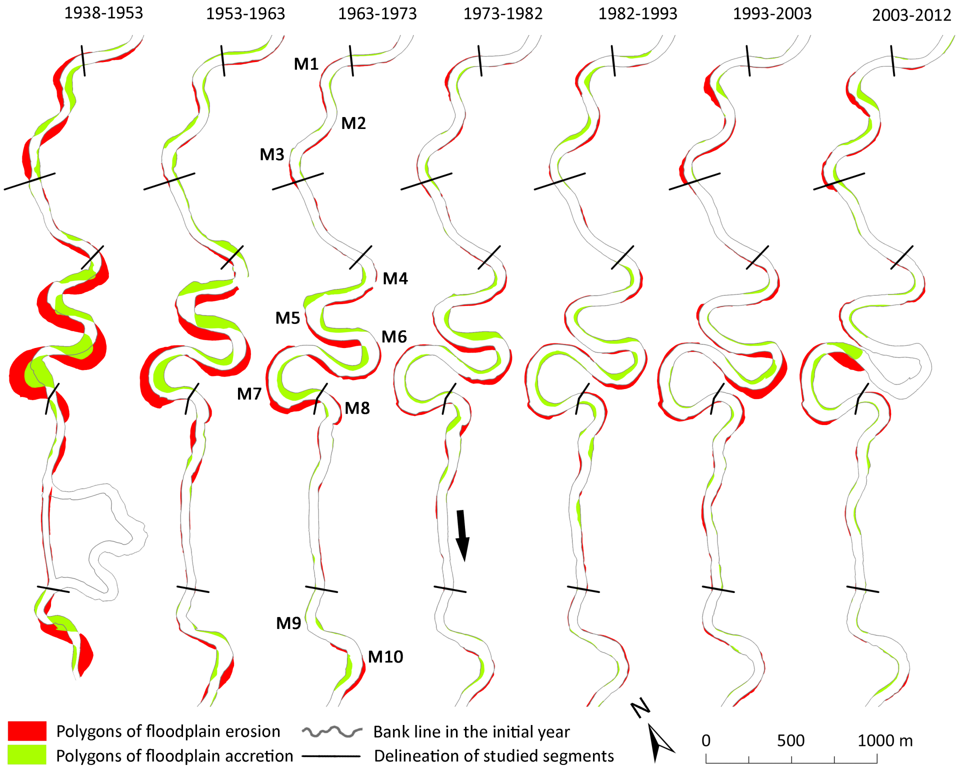

Figure 6: Changes in the planform pattern of the channel in the 5.5 km long study reach of the Morava River in the Strážnické Pomoraví region for selected periods between 1938 and 2012. M1-M10 addresses the codes for meanders which were selected for the detailed study of the relationships between spatio-temporal variability of the migration rates (Er and Ar) and selected controlling variables. Note the artificial cut off of 6 meanders, which took place in 1930s just before the aerial image in 1938 was taken.

Table 2: Area of eroded (EF) and accreted floodplain (AF), difference in rate of floodplain erosion and accumulation (ΔEAF = EF – AF), erosion rates Er, accumulation rates Ar, and rates of the channel width changes (Δw/Δt) along a 5.5 km stretch of the Morava River in the Strážnické Pomoraví region for the periods between 1938 and 2012. An average and median (in brackets) is given in the table for Er, Ar, Δw/Δt.

Period	EF (ha)	ΔEF (ha/year)	AF (ha)	ΔAF (ha/year)	ΔEAF (ha)	Er (m/yr)	Ar (m/yr)	Δw/Δt (m/yr)
1938-1953	20.62	1.37	10.38	0.69	10.24	2.19 (1.5)	1.43 (0.7)	0.75 (0.6)
1953-1963	10.67	1.07	9.02	0.9	1.64	1.47 (0.8)	1.35 (0.9)	0.04 (-0.1)
1963-1973	6.72	0.67	6.2	0.62	0.52	0.87 (0.6)	0.89 (0.5)	-0.16 (0.0)
1973-1982	5.06	0.56	4.81	0.53	0.25	0.69 (0.6)	0.77 (0.5)	-0.08 (0.1)
1982-1993	4.7	0.42	5.56	0.51	-0.86	0.53 (0.5)	0.70 (0.5)	-0.26 (-0.1)
1993-2003	7.86	0.79	3.13	0.31	4.73	0.83 (0.6)	0.39 (0.0)	0.50 (0.3)
2003-2012	4.81	0.53	5.03	0.56	-0.22	0.71(0.4)	0.91 (0.7)	-0.09 (-0.2)
total	**60.43**	**0.77**	**44.12**	**0.59**	**16.31**	**1.04**	**0.92**	**0.1**

15 year and the concave bank moved laterally by 147 m. The period 1938-53 also experienced the maximum accretion rates (Ar), although the rate was significantly lower (1.43 m/year, SD = 2.12 m/year). High values of SD result from alternating channel segments with low and high lateral mobility, causing considerable scatter of Er and Ar values for the entire river reach. An absolute local maximum of Ar was reached 100 m downstream from the local erosional maximum with a value of 11 m/year that caused a shift of the inner bank by 165 m. Minimum Er falls within 1982-93 (Er = 0.53 m/year, SD = 0.50m/year), whereas the minimum accretion rate (Ar = 0.39 m/year, SD = 0.61) occurred one period later (1993-2003).

The channel length of the study reach was 4,978 m in 1938. During the first fifteen years, an increase in length reached 830 m (on average increasing by 56.7 m/year). After this, the increase was relatively stable until 2003, with an average of 26.1 m/year, the length of the channel reaching 7,111 m in 2003. During the final period, 2003-12, local shortening took place as a consequence of a natural cut off (meander M6) in 2006. In 2012, the study reach was 6,459 m in length. Changes in channel sinuosity are related to length development. Average reach sinuosity with the value of 1.31 in 1938 increased, in the opening period, to 1.47. In the following 50 years, sinuosity slowly increased to 1.80 in 2003. A neck cut off caused a decrease in sinuosity that subsequently reached 1.63 in 2012.

Average channel width was 57.1 m (SD = 15.8) in 1938. During the opening period the channel widened, on average, by 19% to 67.9 m (SD = 14.4). In the remaining periods, only slight variations in width took place (66–68 m).

In the study reach, spatial variability in erosion and accretion is evident. Figure 7 depicts cumulative values of Er, Ar and ΔW for the whole reach. Based on the shapes of the depicted curves in the charts, the reach was subdivided into six segments. Laterally stable segments are located between 0-500 m, 1250-1900 m, and 3400-4800 m. Between these segments with minimal channel planform changes, segments with a relatively dynamic development are located, which are related to meander bends consisting of 2 to 5 meanders. On average, we characterised laterally dynamic segments by three to fourfold higher rates of lateral shifts (Er, Ar). Figure 8 summarises the descriptive statistics of Er and Ar for stable and dynamic segments.

it Segment 1 (stable), 0-500 m. The first segment represents a relatively stable bend situated immediately downstream from the bridge that divides the freely meandering reach from the channelized one. Values of Er varied between 0.15-0.80 m/year for all periods with a maximum in the opening period 1938-1953, and then a minimum in 1982-93. In all periods, values of Er were lower than reach average. Sediment accretion rates varied between 0.10-1.07 m/year; with the maximum in 1953-63 and the minimum in 1993-2003. Extreme values of Ar are, then, delayed by one decade behind the Er extremes. Similar to the case of Er, in all periods Ar reached below-average values. Channel narrowing (Ar>Er) was documented in periods 1953-63 and 1982-93 with rates of 0.52 and 0.42 m/year, respectively. Remaining periods experienced channel widening (with the highest rate of 0.34 m/year in the opening period 1938-53).

Segment 2 (dynamic), 500-1250 m. Stable segment #1 is followed by the sequence of three bends (M1-M3). Values of Er ranged from 0.50-2.11 m/year; with the maximum in 1938-53 and the minimum in 1953-63. Above-average values in comparison with the whole reach in the segment were documented in all periods from 1973. Significant reduction of erosional activity occurred in 1953-63, when Er of the segment reached as low as 34% of reach average. Sediment accretion rates (Ar) varied between 0.49-1.54 m/year; with the maximum in the opening period. Minimum Ar was reached in the two periods; 1963-73 and 1993-03. The minimum documented in 1993-2003 was still higher than reach average, but the other minimum of Ar had a value that represented only 56% of the reach average. Except for the latter period, all time intervals were characterised by above-average values of Ar. As a consequence of secondary maximum and minimum in 1993-2003, significant channel widening occurred, at a rate of 1.32 m/year. Considerable widening also occurred between 1938-53, at a rate of 0.56 m/year. Periods 1953-63 and 1982-93 documented channel narrowing by 1.09 m/year and 0.37 m/year, respectively.

Segment 3 (stable), 1250-1900. This segment represents the most stable part of the study reach. Values of Er varied in the range of 0.16-0.61 m/year, with two maxima in 1938-53 and 1953-63. In all periods, the values of Er moved within the below-average interval. Sediment accretion rates ranged between 0.04 and 1.39 m/year. The most important period for new floodplain establishment was 1953-63, when a side bar, located by the downstream end of the segment, was attached to the floodplain. This period also represents the only period when Ar exceeded, slightly, the average reach value. As a consequence of meander (M3) downstream translation, the closing period (2003-12) experienced relatively higher Ar (0.59 m/year). Channel widening occurred in 1938-53 (0.45 m/year) and 1963-73 (0.33 m/year). Significant channel narrowing (0.75 m/year) was documented in 1953-63.

Segment 4 (dynamic), 1900-3400 m. This highly dynamic segment is represented by four mature bends (M4-M7). Values of Er varied in the range of 0.78-4.27 m/year. Maximum was reached in the opening period and even

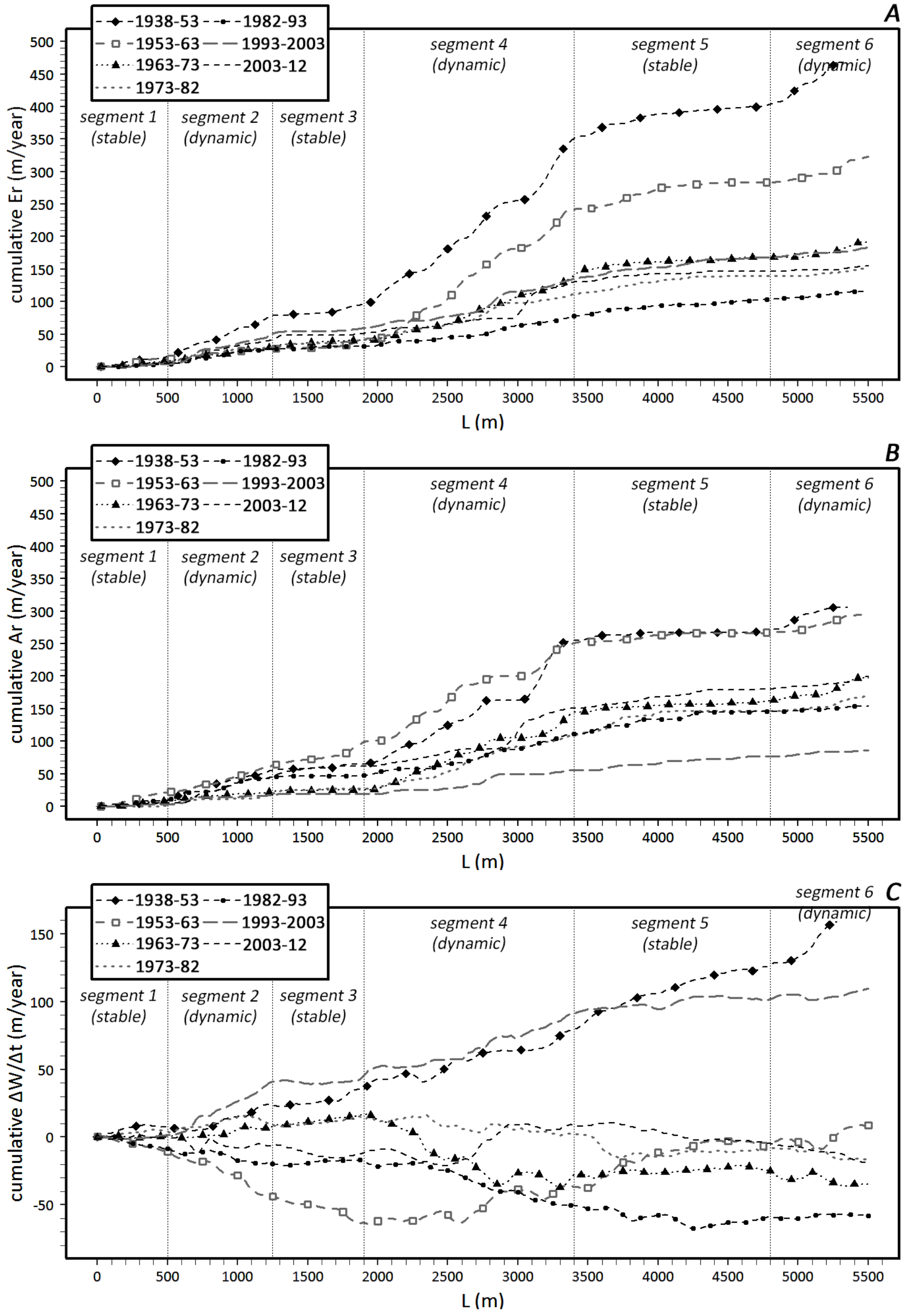

Figure 7: Cumulative erosion rates (A), accretion rates (B) and rates of the channel width change (C) in the 5.5 km long study reach of the Morava River in the Strážnické Pomoraví region for selected periods between 1938-2012. Dashed lines divide the reach into individual dynamic and stable segments.

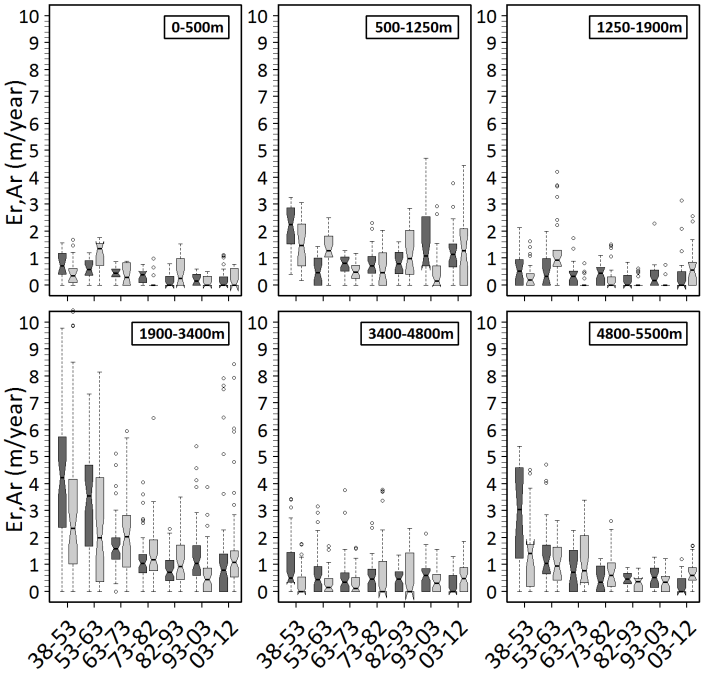

Figure 8: Box plots of erosion (Er) and accretion (Ar) rates for individual segments in the 5.5 km long study reach of the Morava River in the Strážnické Pomoraví region for selected periods between 1938 and 2012. Median value is highlighted by the line, the upper and lower margin of the box represent 1st and 3rdquartile and whiskers explains the 1.5 times of IQR. Empty circles depict extreme values.

the following period preserved very high values, with Er >3 m/year. The minimum was documented in 1982-93 (the only period with Er < 1 m/year). All periods exceeded the reach's average Er values. Three intervals delimited by the years 1938 and 1973 were characterised by Er as high as twice the reach average. Values of sediment accretion rates ranged between 0.61 and 3.17 m/years. In contrast with the first dynamic segment (500-1250 m), the maximum was documented in the opening period (1938-53). The maximum was followed by a gradual decrease to 0.61 m/year in 1993-2003, which represented the only period with Ar < 1 m/year. Similarly, in comparison with Er, values of Ar exceeded reach average; the first two periods reached double the average reach values. Channel widening occurred in 1938-53 at a rate 0.73 m/year and 1953-63 (0.55 m/year). The following three periods experienced channel narrowing at the rate of 0.75, 0.19, and 0.55 m/year, respectively, which balanced the previous channel widening. In 1993-2003 and 2003-12, subsequent widening occurred at the rate of 0.77 and 0.34 m/year, respectively.

Segment 5 (stable), 3400-4800 m. This segment is characterised as being very stable and with both its Er and Ar values being gradually increased by meander M8, which was formed during the opening period at the most upstream part of the segment and which immediately follows meander M7. Development of the segment was significantly influenced by river regulation works that took place in the 1930s (immediately before the time when the aerial photo was taken in 1938), which cut off the meander bend compound of six meanders. Values of Er ranged from 0.31-0.95 m/year (lower than the reach average for all periods) with the maximum in 1938-53 and the minimum in 2003-2012. Sediment accretion rates (Ar) varied between 0.30 and 0.68 m/year, with the maximum in 1973-82 and the minimum in 1953-63. All time intervals until 1973, as well as the closing one, documented values of Ar that was significantly lower than reach average. Between 1973 and 2003, values were comparable with the reach average. The first two periods experienced channel widening, at a rate of 0.86 and 0.57 m /years respectively, which was followed by a stabilised channel width for remaining periods.

Segment 6 (dynamic), 4800-5500 m. The study reach of the Morava River is closed by two meander bends (M9 and M10), which are situated downstream from the confluence with the Velička River and the artificially cut off meander bend. Erosion rate (Er) varied in the range 0.26-2.87 m/year with the maximum in the opening period (1938-53) and the minimum in the last period (2003-12). Since 1973-82, Er stabilised at low values (0.26-0.55 m/year). Above-average Er was reached only in the opening period. Sediment accretion rates fell into the range of 0.31-1.50 m/year with the maximum in 1938-53 and the minimum in 1982-

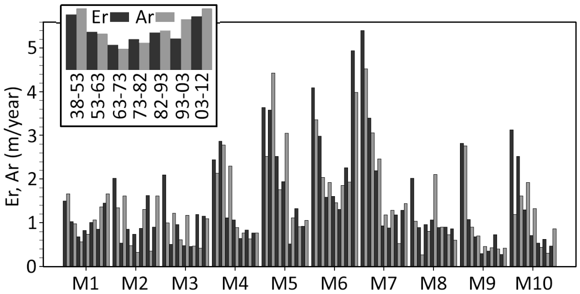

Figure 9: The evolution of the erosion (Er) and accretion (Ar) rates for individual meanders in the 5.5 km long study reach of the Morava River in the Strážnické Pomoraví region for selected periods between 1938 and 2012.

93. In 1938-53 and 1963-73, above-average values of Ar were documented, and in 1973-82 sediment accretion rates equalled the reach average. Significant channel widening took place in 1938-53 and 1953-63 at a rate of 1.69 and 0.46 m/year, respectively. Channel narrowing was documented in the segment in 1963-73 (0.35 m/year) and 2003-12 (0.53 m/year).

4.2 Temporal changes of selected meanders

Special focus was paid to ten meanders (M1-M10) that are situated in the study reach. The bends were used to test the effects of channel geometry, flood plain land cover and hydrology (flood frequency and magnitude) on lateral migration rates (both Er and Ar). The average length of the bends varied between 277 and 739 m with the average width being between 55 and 70 m. All meanders, excluding meander M7, are classified (*sensu* [34]) as simple symmetric (M3-M6, M8-M10) and simple asymmetric (M1, M2). In the time period 1963-73, the straight segment in the apex of meander M7 was formed and the meander transformed from simple symmetric to compound symmetric. For the study meanders, an evolution of erosion rate (Er) and accretion rate (Ar) is depicted in Figure 9.

During the opening period (1938-53), apparent extension and downstream migration took place on all meanders except for M7, which experienced extension complemented by rotation in the downstream direction. In the period that followed, substantial translation was documented on meanders M4-M6, which, on meander M6, was supplemented by extension. Meander M7 was characterised by an intensive extension. The other meanders remained more or less stable, and experienced slight extension and downstream translation, respectively. The same pattern of meander development was preserved in 1963-73. On meander M7, significantly higher dynamics in terms of planform development was apparent on the downstream bend, which caused a formation of the straight segment and compound meander. This process also conditioned the lateral translation of meander M8. The time intervals 1973-82 and 1982-93 documented a decrease to a cessation of meander translation (except for meander M6) and a slight extension on meanders M1-M8. Between 1993 and 2003, more intensive extension occurred on meanders M1-M8. In the closing period, a cut off of meander M6 took place, which conditioned the development of meanders M6 and M7 (upstream bend). In this period, meanders M1-M3 experienced a relatively significant extension and downstream translation. Meander M8 also experienced extension, but without translation.

4.3 Determination of controlling factors

The control of geometrical variables on changes in channel planimetry (Er, Ar, and ΔW) of the whole reach, dynamic segments, and selected meanders, was tested employing non-parametric correlation. Geometrical variables were represented by channel width (W), sinuosity (SI) and radius of curvature divided by channel width (Rc). Results are summarised in Table 3.

On the reach scale, moderate correlation was ascertained between Er and sinuosity ($r = -0.69$; $r^2 = 0.48$), Ar and sinuosity ($r = -0.79$; $r^2 = 0.62$) and no significant correlation was found for rate of channel width change. For dynamic segments (i.e. segments 2, 4, and 6), correlation was ascertained between Er and channel width ($r = 0.37$; $r^2 = 0.14$) and Ar and channel width ($r = 0.46$; $r^2 = 0.21$). Rate of width change did not correlate with geometric variables. On the scale of individual meanders, positive correlations were found between Er (Ar) and channel width and sinuosity, and negative correlation was found between Er (Ar) and radius of curvature divided by channel width.

As hydrological variables, we determined the number of floods with a recurrence interval equal to or higher than $Q_2 (n \geq Q_2)$ and magnitude of the largest flood (Q_{max}). On the whole reach scale, equally tight correlation was ascertained between Er and Ar, respectively, and $n \geq Q_2$ ($r = 0.57$; $r^2 = 0.32$). Er also correlated with Q_{max} ($r = 0.32$; $r^2 = 0.10$). Rate of channel width (ΔW) change correlated negatively with Q_{max} ($r = -0.60$; $r^2 = 0.36$). If only dynamic segments were taken into account, moderate correlation was found only between Ar and $n \geq Q_2$ ($r = 0.41$; $r^2 = 0.17$), and a negative correlation between ΔW and Q_{max} ($r = -0.51$; $r^2 = 0.26$). On the scale of individual meanders, a positive correlation was ascertained between Ar and $n \geq Q_2$ ($r = 0.30$; $r^2 = 0.09$) and ΔW and Q_{max} ($r = 0.42$; $r^2 = 0.18$).

Employing the non-parametric Kruskall-Wallis test as an alternative to ANOVA for the dataset possessing other-than-normal distribution, the control of floodplain land cover on the lateral dynamics of the channel was tested. The land cover was categorised into three categories; (1) arable land (and the area of open-pit sand mining); (2) cultivated meadows and clearings; and (3) forest. A statistically significant difference was proven (α=0.05) between the first and second category for Er (p = 0.00602), and not proven for Ar (p = 0.0893). Further, the difference between arable land and forest was proven for both Er and Ar (p = 0.00014 resp. p = 0.0066). For ΔW, a statistically significant difference between categories was not proven for any variables (p = 0.065).

In the Strážnické Pomoraví region, two lithological facies are eroded by the Morava River; flood loams and aeolian sands. The control of river bank material on the planform evolution of the channel is not statistically significant for the whole reach (p = 0.4625 for Er, p = 0.6041 for Ar, and p = 0.6599 for ΔW). Nonetheless, local influence of the bank material is apparent from a visual comparison of aerial images. The control of material on Er could be proven, to a certain level, when only meanders M1, M3, M5, and M7 entered the analysis. These meanders partly eroded along their course both flood loams and aeolian sands, in the periods since 1973. Meanders were divided into 25m long segments and information about river bank material was obtained for all. With the use of the Mann-Whitney test, differences between Er for flood loams and aeolian sands were tested. A statistically significant difference for Er was proven for the periods 1982-93 (p = 0.00001647) and 1993-03 (p = 0.02233). In the closing period (2003-12), erosion rates are comparable for flood loams and aeolian sands without proven difference (p = 0.9733).

5 Discussion

5.1 Planform changes

The study reach of the Morava River is characterised by an alternating pattern of segments with a high and low dynamics of planform channel development. High rates of lateral shifts are focused into three segments with developed meanders (sinuosity 1.17-2.37), whereas intervening segments with very low rates are straight or formed into slightly curved bends (sinuosity 1.05-1.18). Such a spatial pattern remained unchanged for all studied periods. Before the river regulation works in the first half of the twentieth century, the Morava River in Strážnické Pomoraví region had been characterised as an anastomosing river. The study reach is situated on the former dominant anastomosing arm, which has preserved, according to evidence from old maps, its meandering pattern since at least the second half of the eighteenth century. The current spatial pattern of dynamic and stable segments distribution had already been documented by [26] who employed visual analysis of old maps from the second half of the nineteenth century. While the channel migration rates varied significantly in that time and were conditioned primarily by river engineering, the spatial pattern was rather persistent. A similar pattern of spatio-temporal relationships in the development of a meandering channel was described on the river Dane by [35].

Rates of the planform evolution of the Morava River in Strážnické Pomoraví in the nineteenth century were studied by [36] and [37] with the use of GIS analyses of maps from the second and third Austrian Military Survey on a scale of 1:28,800 and 1:25,000, respectively. The results of [36] suggest that between 1841 and 1938 an average meander migration rate varied between 0.35 and 1.09 m/year, while values for meanders eroding the floodplain with arable land were twice as high as meanders in the forest or permanent grassland. Our results show that during the first 25 years, after river regulation works, lateral migration rates (both Er and Ar) reached 1.5 to 2.5 times higher values in comparison with the nineteenth and beginning of the twentieth centuries. In the following period, lateral migration rates significantly decreased and equalled values from the nineteenth century. We estimate the response time to accommodate the disturbance caused by river regulation was approximately 25 years.

Methods for the quantitative description of erosion (accretion) rates differ in individual studies, therefore it is relatively difficult to compare the erosion rates of the Morava River with other rivers. Nonetheless, it is evident that in the period immediately following the river regulation works (1938-53), the whole reach was developing with significantly higher erosion rates compared to rivers of the same size order; e.g. Big Fork River: Er = 0.72 m/year [38], Beaver River: 1.41 m/year [39], Swan River: 1.52 m/year [39]. The most dynamic segment of the Morava River (segment 4) reached lateral migration rates of the same order of magnitude as substantially larger rivers (e.g. the Sacramento: 5.5 m/year [30], Prophet River: 2.34 m/year [39], the Fort Nelson: 4.44 m/year [39], the Brazos River: 3.28 m/year [40]). Similar behaviour was documented by [35] on the Dane River, which reached local maxima of Er of around 3 m/year and likewise exceeded the average rates of rivers of the same order.

Table 3: Correlations between geometrical (W, SI, and Rc) and hydrological variables ($n \geq Q_2$, Q_{max}) and variables describing lateral dynamics (Er, Ar, and ΔW) for whole reach dynamic segments and selected meanders.

	Reach				
	W	SI	Rc	$n \geq Q_2$	Q_{max}
Er	0.07	**-0.69**	-	**0.57**	**0.32**
Ar	0.21	**-0.79**	-	**0.57**	0.06
ΔW	-0.21	-0.29	-	-0.19	**-0.60**

	Dynamic segments				
	W	SI	Rc	$n \geq Q_2$	Q_{max}
Er	**0.37**	0.14	-	0.2	0.24
Ar	**0.46**	0.14	-	**0.41**	-0.05
ΔW	-0.04	-0.07	-	-0.08	**-0.51**

	Meanders (M1-M10)				
	W	SI	Rc	$n \geq Q_2$	Q_{max}
Er	**0.5**	**0.4**	**-0.47**	0.26	0.18
Ar	**0.54**	**0.43**	**-0.43**	**0.3**	-0.08
ΔW	-0.09	-0.07	0.01	-0.11	**0.42**

5.2 Variables controlling planform changes

We discuss here several controlling variables, which were determined to play a key role in studies of other authors. Correlations of tested variables with erosion rates are, in general, rather weak, which might be due to limited range of values (studied reach is 5.5 km in length) as well as the fact that several variables appears to play an important role, which, in turn, decrease the strength of correlation for individual variables.

Channel width was described as an important factor for comparison of lateral migration rates between particular reaches as well as rivers [41, 42]. Our results prove a spatial pattern with wider channels in meander bends as well as dynamic segments with higher Er and Ar, and narrower channels in sites with lower values of Er and Ar. This pattern could be explained by the larger difference between Er and Ar in the more dynamic meander bends, where accretion lags more behind erosion. Such spatial distribution was also referred to by other studies [e.g. [41, 43, 44]. In the case of study reach of the Morava River, we conclude that channel width reflects differences between Er and Ar rather than acts as controlling variable determining rates of erosion and/or accretion.

Before artificial shortening in the 1930s, reach sinuosity was as high as 1.59 and such value was reached again in the period 1973-82, in comparison with 1.31 after cut off. In the opening studied period, rate in sinuosity increase doubled in comparison with other periods before cut off (with 1.47 in 1953). The neck cut off event in 2006 led to the decrease in sinuosity from 1.80 to approximately 1.63 (real sinuosity right after cut off was slightly lower as meanders underwent development between 2006 and 2012). Assuming that river development is controlled by self-organisation processes (e.g. [45, 46]) we can estimate that the Morava River within the study reach attains contemporary (quasi)equilibrium state around a sinuosity of 1.60.

Sinuosity belongs to features commonly used as a descriptor of channel planform. A general theory for sinuosity was recently proposed by [47]. On the reach scale, sinuosity correlates negatively with both Er and Ar. This is mainly due to low sinuosity values in the opening two periods (1938-63). We argue that acceleration of erosion occurs when sinuosity suddenly decreases, thus sinuosity could partly describe the lateral dynamics of the Morava River in the study reach. Similar conclusions could be drawn from the works of [45, 46, 48].

The correlation could also explain the difference in the extent of the accelerated erosion as a consequence of artificial and natural cut offs. Whereas the decrease in sinuosity related to artificial cut off (which was followed by extended acceleration of erosion) reached 0.27, a natural cut off (with rather local acceleration of erosion as a consequence) caused a decrease in sinuosity only by 0.17. On the other hand, on the scale of individual meanders, sinuosity correlates positively with both Er and Ar. This fact can be understood as sinuosity explains both spatial and temporal variability (as opposed to only temporal variability in the case of the reach scale) and adds information about the differences in the curvature of individual meanders. Correlation between sinuosity and radius of curvature recalculated to channel width is -0.55 ($r^2 = 0.30$).

Radius of curvature divided by channel width ratio (Rc) is generally understood as an important control variable determining lateral migration rates [49–51]. Along the study reach of the Morava River, a negative correlation between the radius of curvature of selected meanders and the measures of channel migration rate (Er and Ar) was found ($r = -0.47$; $r^2 = 0.22$ for Er and $r = -0.43$; $r^2 = 0.18$ for Ar). Thus we can conclude that Rc is among important factors in the Morava River. Meander M6 serves as an example. Substantially accelerated lateral erosion occurred as the Rc dropped from 2.20 to 1.54. The natural neck cut off of meander M6 that took place in 2006 shortened the study reach by 827 m. Local sinuosity was preserved at relatively high values (decreasing from 2.9 to 2.1). Hooke [52] tested a possible explanation for cut offs on the Bollin River. The case of a natural cut off on the Morava River supports the statement that cut off occurred as a consequence of high flow (during the flood with Q50 discharge). As mentioned above, our findings suggest that the behaviour of the study river reach resembles a self-organising system and thus the cut off could also occur as a consequence of increasing sinuosity that reached critical value. Nonetheless, more cut offs need to be analysed to convincingly prove our presumption.

Furthermore, maximum rates of Er were documented on meanders with Rc of 1.5-2.2 and 2.9-3.2 that correspond with the values presented in studies on English, Canadian [53], and American [54] rivers.

We assume that another important geometric variable controlling erosion rates of meanders is river bed slope. Although longitudinal profiles for the selected years are not available, our conclusion comes from indirect evidence from the artificial channel straightening that was immediately followed by maximal values of erosion rates. Artificial channel shortening, apparent on the aerial photo from 1938, caused cut off of six meanders (see Figure 6). The channel length was reduced by 1.1 km and local sinuosity (in segment 5) from 3.0 to 1.0. In the Strážnické Pomoraví region, the upstream propagation of knick points after artificial cut offs appears to be a primary controlling factor of spatio-temporal variability in channel migration rates. This conclusion does not fully correspond to previous findings; for example [55] addressed, in a sand-bed channel with cohesive river banks, a change in river bed slope as a factor subordinate to alterations of hydrological conditions. A model of channel incision and subsequent widening after river engineering was advocated by [56]. Rapid channel widening in the period following artificial cut off may be most probably attributed to such a channel incision resulting in bank destabilisation.

The temporal variability of channel migration rates since 1938 also partly corresponds with the magnitude (Q_{max}) and the frequency of floods ($n \geq Q_2$). The highest frequencies were documented in the period 1953-63, when frequency was 1.00 flood/year. Relatively high frequencies were also documented in 1938-53 (0.87 flood/year), 1963-1973 (0.90 flood/year), and 1973-82 (0.89 flood/year). Minimum frequency occurred between 1982-93 (0.27 flood/year). The final two periods also documented low frequencies (0.40 and 0.67respectively). On the reach scale, $n \geq Q_2$ appears to be an important controlling factor in determining both Er and Ar. That is consistent with results found e.g. by [21, 35], or [43]. In a detailed scale of (dynamic) segments and individual meanders, $n \geq Q_2$ does not seem to influence Er and Ar. Anthropogenic activity seems to play more important role. This suggests that controlling factors differ with scale. Such findings were also documented in the works of [6, 46].

The contribution of flow magnitude to the explanation of the temporal variability of lateral erosion rates could be found on the reach scale. On the segment and meander scale, other variables appear to play a more important role. Our finding stands in contradiction with results from other rivers, where flow magnitude was a factor of key importance [e.g. [40, 57–60]. Further, we found that flood magnitude could belong to the controlling variables influencing rate of channel width change, as there was a positive correlation on the meander scale between Q_{max} and ΔW. This suggests that, in general, during large floods, in meander bends erosion surpasses accretion more than during floods of moderate magnitude. As this finding could not be proved on other scales, we argue that this controlling variable is of rather secondary importance.

We also argue that specific conditions occurring in the study reach before and during floods can play an important role in the determination of the erosion capability of the flood. This could be seen in last two studied periods. During 1993-2003, one flood with a magnitude exceeding Q100 occurred in the study reach. Three small floods with a magnitude of Q_2 occurred later in the period. The erosion rate was, nonetheless, slightly higher than during the following period that experienced six floods, two of them exceeding Q_{50} and one with a magnitude slightly below Q_{50}. Our finding stays in agreement with the works of many authors [e.g. [61–64] that emphasized the importance of local and/or temporal specifics on pattern of river bank erosion.

An assessment of the control of the magnitude and frequency of floods over channel migration rates is, obviously, influenced by the fact that during the twentieth century, the value of bankfull discharge substantially increased. Whereas, even in the beginning of the twentieth century, overbank flow was reached, on average, once a year, nowadays, bankfull discharge occurs, on average, once in five years [26, 29]. The cause of the change was a progressive increase in the channel capacity - degradation and widening [36, 37]. Today, bankfull discharges exert higher shear stress on the wetted perimeter than did the considerably lower bankfull flows at the beginning of the twentieth century. When considering twofold widening of the channel in comparison to pre-engineered conditions, the mean shear stress induced by full channel discharge is estimated to rise approximately from 4 to 13.5 N/m^2. Assuming a higher erosional potential of smaller discharges during the early periods (1938-63) of channel adjustment to river regulation, then the magnitude of floods is no doubt a more important controlling variable of channel change than was ascribed to by our statistical analysis. This may be supported by comparing stream power between 1938 and 2012. Although the bankfull discharge stage multiplied at least 1.2 times, and values of stream power per unit length of the channel rose from approximately 1380 to 1646 W/m), specific stream power stayed virtually the same (24.2 W/m^2 in 1938 and 24.6 W/m^2 in 2012) because of considerable channel widening.

Lithology was determined as an important factor in controlling erosion rates in many studies [e.g. [8, 65, 66].These authors ascribe key control to river bank properties as an explanation of the lateral erosion rates. The results from non-parametric analysis of variance in the study reach found a role of the material only at a local scale (recent acceleration of Er and Ar in meandersM1 and M3, which started to erode aeolian sand facies). Nonetheless, lithology were not capable of satisfactory explanation of the spatio-temporal variability of lateral erosion for the whole reach nor for individual meanders that eroded sand facies in the past 75 years. A similar conclusion was mentioned in the study of [21] on the Sacramento River.

Land cover belongs to the group of controlling factors that influence erosion rates in the study reach of the Morava River. Statistical testing proved higher erosion rates in meanders eroding arable land (Er = 2.67 m/year, SD = 1.45 m/year) in comparison with ones with forest cover (Er = 1.05 m/year, SD = 0.58 m/year), and, respectively, meadows and clearings (Er = 1.24 m/year, SD = 0.80 m/year). In the Strážnické Pomoraví region, [36] studied the influence of land cover on channel migration rates, and documented, for the time period 1841-2007, erosion rates that were approximately twice as high for meanders eroding arable land than those of deciduous forest and grassland. In this study we proved a statistical difference between arable land and forest and arable land and meadows and clearings. No statistical difference was ascertained between forest and meadows and clearings. Similar findings concerned in controls of land cover on erosion rates were described in another studies, for example [22, 67, 68]. On the other hand, the findings on the Sacramento River [21] did not ascribe a significant influence on erosion and accretion rates to the land cover.

Land cover influences the erosion rate mainly by increasing the shear strength of river banks, which is dependent on root density. Although this might be the case in flood loams, trees covering dunes of aeolian sand could accelerate the erosion by the gravity exertion of unconsolidated sedimentary bodies. Among the indirect influences of land cover observed in the study reach is the import of woody debris into the channel and the formation of wood accumulations. In turn, woody debris protects bank material from entrainment, resulting in a deceleration of river bank erosion. However, wood accumulations can also divert the flow towards the bank and thus increase the rate of erosion. Both effects of woody debris were observed in the study reach. The effect of woody debris only started to occur in recent years as large wood ceased to be removed from the channel by river managers. Although the effect of trees and woody debris is apparent from aerial photos, it belongs to the secondary control variables. Even a fully mature poplar forest could not substantially mitigate the accelerated erosion that occurred as a result of the meander cut off in spring 2006. In the area of the breached meander neck, the accelerated erosion took place despite eroding the floodplain with mature forest, which caused a substantial input of large woody debris and subsequent wood accumulation development.

Analyses of the influence of river regulation works suggest that the most important human-induced factors are engineering activity affecting (1) flow conditions and (2) changes in geometric parameters such as river bed slope and radius of curvature. This is apparent from the patterns of planform shifts of ten analysed meanders that are situated at different distances from the segments that were affected by direct engineering alterations (channelization of segment 5). Meanders M1-M3, situated at the furthest distance from the artificial cut off, experienced, immediately after the alterations, substantially lower rates of erosion and accretion in comparison with meanders M4-M10. Channel destabilisation induced by local shortening did not, apparently, reach such remote distances. Despite this fact, the rate of erosion of meanders M1-M3 in the years 1938-1963 was substantially higher than in the following periods. During the first 25 years, the effect of engineering adjustments and relatively high flood frequencies jointly influenced erosion rates. Besides the artificial cut off, acceleration of the erosion was conditioned by the channelizing of side arms and tributaries and channel clearing of sediment and large wood [26], which supported the concentration of run-off in the main channel of the Morava River and its bed degradation and channel widening. In the middle part of the reach (meanders M4-M8), the influence of channel shortening (slope) and other abovementioned adjustments was the most apparent, thus resulted in the largest, dynamic lateral movements.

6 Conclusions

Detailed analysis of spatial and temporal patterns of lateral movement rates (both erosion and accretion) was per-formed on the 5.5 km long reach of the Morava River in the Strážnické Pomoraví region for a period delineated by the years 1938 and 2012. Our results demonstrate that bank erosion and accretion rates differed substantially among river segments and time periods even within such a short river reach. Rates of erosion and accretion were controlled by the simultaneous effect of several factors. Among the controlling variables, which were identified as key ones, are: (1) engineering works causing changes in channel geometry (mainly river bed slope) and channel hydraulics; (2) frequency and magnitude of floods; and (3) radius of curvature. Local influence is also ascribed to river bank lithology and vegetation. The relative importance of the above-mentioned factors varied with time and scale.

As a key factor, engineering works were identified (especially the artificial cut off and straightening of segment 5). This action induced a dramatic increase in bank erosion rates. Approximately 25 years went by before the erosion rates returned to the values documented before the river engineering adjustments. This dynamic period was characterised by bank erosion rates reaching 2.19 (1938-53) and 1.47 (1953-63) m/year. It was possible to detect the reaction of the channel to the shortening as far as 2,000 m upstream from the cut off and at least 500 m downstream from the cut off. The influence of the artificial channel adjustment was supplemented by the relatively high flood frequency. Another substantial acceleration of river bank erosion was induced by the natural neck cut off of one mature meander during the spring flood in 2006, with a magnitude of Q_{50}. In the first five years after the event, local values of erosion rates varied between 5.7 and 7.9 m/year. The spatial extent of the influence of the natural cut off was more localised. The influence of other factors (flood magnitude, land cover, bank material properties, radius of curvature) was identified as being of rather secondary importance.

Another characteristic feature documented in the study reach was the different erosion and accretion rates. In periods with higher dynamics of planform changes (1938-53, 1953-63, 2003-12), erosion rates substantially exceeded accretion rates, resulting in channel widening (in the first 15 years, at a rate as high as 0.75 m/year). Channel width in the remaining periods remained more or less stable. In general, a substantial increase in channel capacity took place in the study reach. The same trend was also documented by [26, 29], who showed a decrease in bankfull flow frequency from occurring every year to occurring once every five years. Besides the shortening of the channel, other artificial activities such as side arms and tributaries channelization (transformation from anastomosing to single-thread meandering pattern), sediment dredging, and removal of large woody debris contributed to the increase in river bed and river banks erosion (incision, widening).

References

[1] Kiss T., Fiala K., Sipos G., Alterations of channel parameters in response to river regulation works since 1840 on the Lower Tisza River (Hungary), Geomorphology, 2008, 98, 96-110.

[2] Gregory K.J., The human role in changing river channels, Geomorphology, 2006, 79, 172-191.

[3] Allen J.R.L., A review of the origin and characteristics of recent alluvial sediments. Sedimentology, 1965, 5, 89-191.

[4] Hansen E., On the formation of meanders as a stability problem. Reports on Progress in Physics 13, Coastal Engineering Laboratory, Technical University of Denmark, Lyngby, 1967.

[5] Langbien W.B., Leopold L.B., River Meander - Theory of Minimum Variance. USGS Professional Paper, 1966, 422-H, H1-H15.

[6] Leopold L.B., Wolman M.G., River meanders. Geol. Soc. Am. Bull., 1960, 71, 769-794.

[7] Camporeale C., Perona P., Porporato A., Ridolfi L., Hierarchy of models for meandering rivers and related morphodynamic processes. Rev. Geophys., 2007, 45, 1, RG1001.

[8] Ikeda S., Parker G., Sawai K., Bend theory of river meanders. Part 1. Linear development, J. Fluid Mech., 1981, 112, 363-377.

[9] Johannesson H., Parker G., Linear theory of river meanders, In: Ikeda S., Parker G. (Eds.), River Meandering, Water Res. M., 1989, 12, 181-214.

[10] Zolezzi G., Seminara G., Downstream and upstream influence in river meandering. Part 1. General theory and application to overdeepening, J. Fluid Mech., 2001, 438, 183-211.

[11] Rüther N., Olsen N.R.B., Modelling free-forming meander evolution in a laboratory channel using three-dimensional computational fluid dynamics. Geomorphology, 2007, 89, 308-319.

[12] Tal M., Paola C., Effects of vegetation on channel morphodynamics: results and insights from laboratory experiments. Earth Surf. Proc. Land., 2010, 35(9), 1014-1028.

[13] Nardi L., Rinaldi M., Solari L., An experimental investigation on mass failures occurring in a river bank composed of sandy gravel. Geomorphology, 2012, 163-164, 56-69.

[14] Güneralp I., Abad J.D., Zolezzi G., Hooke J., Advances and challenges in meandering channels research. Geomorphology, 2012, 163-164, 1-9.

[15] Florsheim J.L., Mount J.F., Chin A., Bank erosion as a desirable attribute of rivers. BioScience, 2008, 58(6), 519-529.

[16] Camporeale C., Perucca E., Ridolfi L., Gurnell A.M., Modeling the interactions between river morphodynamics and riparian vegetation, Rev. Geophys., 2013, 51(3), 379-414.

[17] Greco S.E., Patch change and the lifting mosaic of an endangered bird's habitat on a large meandering river. River Res. Appl., 2013, 29(6), 707-717.

[18] Rapp C.F., Abbe T.B., A framework for delineating channel migration zones. Ecology Final Draft Publication #03-06-027, Washington State Department of Ecology, 2003, 52 p.

[19] Piégay H., Darby S.A., Mosselmann E., Surian N., The erodible corridor concept: applicability and limitations for river management. River Res. App., 2005, 21, 773-789.

[20] Larsen E.W., Girvetz E.H., Fremier A.K., Landscape level planning in alluvial riparian floodplain ecosystems: using geomorphic modelling to avoid conflicts between human infrastructure and habitat conservation. Landscape Urban Plan., 2007, 79, 338-346.

[21] Michalková M., Piégay H., Kondolf G.M., Greco S.E. Lateral erosion of the Sacramento River, California (1942-1999), and responses of channel and floodplain lake to human influences. Earth Surf. Proc. Land, 2011, 36, 257-272.

[22] Micheli E., Kirchner J., Larsen E., Quantifying the effect of riparian forest versus agricultural vegetation on river meander migration rates, Central Sacramento River, California, USA. River Res. App., 2004, 20, 537-548.

[23] Wallick J.R., Lancaster S.T., Bolte J.P., Determination of bank erodibility for natural and anthropogenic bank materials using a model of lateral migration and observed erosion along the Willamette River, Oregon, USA. River Res. App., 2006, 22, 631-649.

[24] Kadlec J., Kocurek G., Mohrig D., Shinde D.P., Murari M. K., Varma V., et al., Response of fluvial, aeolian and lacustrine systems to Late Pleistocene to Holocene climate change, Lower Moravian Basin, Czech Republic. Geomorphology, 2015, 232, 193-208.

[25] Havlíček P., Kučera Z., Vachek M., Přírodní park Strážnické Pomoraví-Osypané břehy: zkrácení toku Moravy. Zprávy o geologických výzkumech v roce 2007, 2008, 91-92.

[26] Brázdil R., Máčka Z., Řezníčková L., Soukalová E., Dobrovolný P., Grygar T.M., Floods and floodplain changes of the River Morava, the Strážnické Pomoraví region (Czech Republic) over the past 130 years, Hydrolog. Sci. J., 2011a, 56(7), 1166-1185.

[27] Kadlec J., Grygar T., Světlík I., Ettler V., Mihaljevic M., Diehl J.F. et al., Morava River floodplain development during the last millennium, Strážnické Pomoraví, Czech Republic. Holocene, 2009, 19, 499-509.

[28] Grygar T., Sětlík I., Lisá L., Optíková L., Bajer A., Wray D.S. et al., Geochemical tools for the stratigraphic correlation of floodplain deposits of the Morava River in Strážnické Pomoraví, Czech Republic from the last millennium. Catena, 2010, 80(2), 106-121.

[29] Brázdil R., Řezníčková L., Valášek H., Havlíček M., Dobrovolný P., Soukalová E., Řehánek T., Skokanová H., Fluctuations of floods of the River Morava (Czech Republic) in the 1691-2009 period: interactions of natural and anthropogenic factors. Hydrolog. Sci. J., 2011b, 56, 468-485.

[30] Micheli E.R., Larsen E.W. River channel cut off dynamics, Sacramento river, California, USA, River Res. App., 2010, 27(3), 328-344.

[31] Hooke J.M., Redmond C.E., Use of Cartographic Sources for Analyzing River Channel Change with Examples from Britain. In: Petts G.E. (Ed.), Historical Change of Large Alluvial Rivers: Western Europe. John Wiley & Sons, Ltd., Chichester, 1989, 79-93.

[32] Richard G., Quantification and prediction of lateral channel adjustments downstream from Cochiti Dam, Rio Grande, NM. Dissertation thesis. Colorado State University. Fort Collins, Colorado, 2001, 244 p.

[33] Shields F.D. Jr., Simon A., Steffen L.J., Reservoir effects on downstream river channel migration. Environ. Conserv., 2000, 27, 54-66.

[34] Brice J.C., Air Photo Interpretation of the Form and Behavior of Alluvial Rivers, Final Report to the U.S. Army Research Office–Durham, Washington University, St. Louis, 1975, 10 p.

[35] Hooke J., Spatial variability, mechanics and propagation of chase in an active meandering river. Geomorphology, 2007, 84, 277-296.

[36] Smetana M., DynamikakorytaMoravyvevztahu k příbřežní vegetaci na základě studia historických map a současných měření: případová studie ze Strážnického Pomoraví. Geologické výzkumy na Moravě a ve Slezsku, 2011, 18(2), 58-63.

[37] Stehlík F., Analýza polohových změn koryt řeky Moravy ve Strážnickém Pomoraví: vliv regulace na dynamiku toku. In: Roszková A., Vlačiky M., Ivanov M. (Eds.): Sborník příspěvků ze semináře 14. kvartér 2008.Ústav geologických věd PřF MU. Brno., 2007, 24-25.

[38] MacDonald T.E., Parker G., Luethe D.P., Inventory and analysis of stream meander problems in Minnesota. Master Thesis, University of Minnesota, 1991.

[39] Nanson G.C., Hickin E.J., A statistical analysis of bank erosion and channel migration in western Canada, Geol. Soc. Am. Bull., 1986, v97, 497-504.

[40] Giardino J.R., Lee A.A., Rates of Channel Migration on the Brazos River, Final Report No. 0904830898, Texas Water Development Board, Texas, 2011.

[41] Lagasse P.F., Spitz W.J., Zevenbergen L.W., Zachmann D.W., Handbook for Predicting Stream Meander Migration. Transportation Research Board, Washington D.C., 2004, 107 p.

[42] Richard G.A., Julien P.Y., Baird D.C., Statistical analysis of lateral migration of the Rio Grande, New Mexico, Geomorphology, 2005, 71, 139-155.

[43] Brice J.C., Stream Channel Stability Assessment, Federal Highway Administration Report, 1982, 42 p.

[44] Luchi R., Hooke J.M., Zolezzi G., Bertoldi W., Width variations and mid-channel bar inception in meanders: River Bollin (UK), Geomorphology, 2010, 119, 1-8.

[45] Stolum H.H., River meandering as a self-organization process. Science, 1996, 271, 5256, 1710-1713.

[46] Camporeale C., Perucca E., Porporato A., Ridolfi L., On the long-term behavior of meandering rivers, Water Resour. Res., 2005, 41, 1-13.

[47] Lazarus E.D., Constantine J.A., Generic theory for channel sinuosity, PNAS, 2013, 110(21), 8447-8452.

[48] Constantine J.A., Dunne T., Meander cut off and the controls on the production of oxbow lakes, Geology, 2008, 36(1), 23-26.

[49] Heo J., Duc T.A., Cho H.S., Choi S.U., Characterisation and prediction of meandering channel migration in the GIS environment: A case study of the Sabine River in the USA. Environ. Monti. Assess., 2009, 152, 155-165.

[50] Hickin E., Mean flow structure in meanders of the Squamish River, British Columbia, Can. J. Earth Sci., 1978, 15, 1833-1849.

[51] Hooke J., River meander behaviour and instability: a framework for analysis. T. I. Brit. Geogr. 2003, 28(2), 238-253.

[52] Hooke J., Cutoffs galore!: occurrence and causes of multiple cutoffs on a meandering river, Geomorphology, 2004, 61, 225-238.

[53] Hooke J.M., Interaction of sediment dynamics and channel morphology. In: Wang S., Langendoen E.J., Shields F.D. (Eds). Management of Landscapes Disturbed by Channel Incision. Mississippi, University of Mississippi, Oxford, 1997.

[54] Hudson P.F., Kesel R.H., Channel migration and meander-bend curvature in the lower Mississippi River prior to major human modification, Geology, 2000, 28(6), 531-534.

[55] Darby S.E., Thorne C.R., Modelling the sensitivity of channel adjustment in destabilized sand-bed rivers. Earth Surf. Proc. Land., 1996, 21, 1109-1125.

[56] Schumm S.A., Harvey M.D., Watson C.C., Incised channels: morphology, dynamics, and control. Water Resources Publications, Littleton, Colorado, 1984, 200 p.

[57] Buer K., Eaves N., Scott R., McMillan J., Enlarged Shasta Dam, Downstream Geomorphic Changes - Preliminary Report. DWR-ND Memorandum Report, California Department of Water Resources, Sacramento, 1983, 50 p.

[58] Hooke J.M., An analysis of the processes of river bank erosion. J. Hydrol., 1979, 42, 39-62.

[59] Miller J.R., Barr R., Grow D., Lechler P., Richardson D., Waltman K. et al., Effects of the 1997 flood on the transport and storage of sediment and mercury within the Carson River valley, west-central Nevada. J. Geol., 1999, 107(3), 313-327.

[60] Carroll R.W.H., Warwick J.J., James A.I., Miller J.R., Modeling erosion and overbank deposition during extréme flood conditions on the Carson River, Nevada, J. Hydrol., 2004, 297, 1-21.

[61] Beschta R.L., Conceptual models of sediment transport in streams. In: Sediment transport in gravel-bedrivers, Thome C.R., Bathurst J.C., Hey R.D. (Eds.), John Wiley & Sons, Inc., Chichester, 1987, 387-420.

[62] Luppi L., Rinaldi M., Teruggi L.B., Darby S.E., Nardi L., Monitoring and numerical modelling of river bank erosion processes: a case study along the Cecina River (central Italy), Earth Surf. Proc. Land., 2008, 4, 530-546.

[63] Marren P.M., Smith H.G., Erosion and Channel Changes on Corryong Creek, NE Victoria Following Drought-Ending Floods: Implications for Channel and Riparian Vegetation Management. In: 6th Australian Stream Management Conference, Canberra, 2012, 31-38.

[64] Newson M.D., The geomorphological effectiveness of floods - A contribution stimulated by two recent events in mid-Wales. Earth Surf. Proc. Land., 1980, 5, 1-16.

[65] Constantine C., Dunne T., Hanson G.J., Examining the physical meaning of the bank erosion coefficient used in meander migration modeling. Geomorphology, 2009, 106, 242-252.

[66] Mossa J., Coley D., Planform change rates in rivers with and without instream and floodplain sand and gravel mining: assessing instability in the Pascagoula River and tributaries, Mississippi, Report No. 04HQGR0178, USGS, 2004.

[67] Smith D.G., Effect of vegetation on lateral migration of anastomosed channel of a glacier melt-water river. Geol. Soc. Am. Bull, 1976, 87, 587-860.

[68] Gyssels G., Poesen J., Bochet E., Li Y., Impact of plant roots on the resistence of soils to erosion by water: a review. Prog. Phys. Geog., 2005, 29, 189-217.