INTERNATIONAL SCIENTIFIC JOURNAL
GEOGRAPHICA PANNONICA
Volume 28, Issue 3, 169–181 (September 2024)
Journal homepage: http://www.dgt.uns.ac.rs/en/homepage/pannonica/

Lateral Meander Migration of a Medium-sized Lowland River: Case Study on the Rába River, Hungary

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KEYWORDS

meandering
lateral channel migration
human impact
QGIS
topographic maps

ABSTRACT

Engineering works greatly influence the lateral channel migration (LCM) of meandering rivers. We aimed to characterise the spatiotemporal characteristics of LCM during the last 174 years of the almost freely meandering Upper Rába (Hungary) and to identify units with distinctive LCM histories. The studied Rába's reach has been regulated just at some points. Due to the free meandering, its length varied between 119 and 133 km. The most intensive length increase (+291 m/y) took place between 2005 and 2008, and by the end of the process, the sinuosity had reached its historical maximum (SI_{2018}= 1.93). The mean LCM was 3.3 m/y (1844–2018). The periods with intensive channel migration (max: 24–27 m/y) were followed by periods with low migration rates. Based on local channel morphology and LCM rates, 14 units were identified. The highest LCM rate was measured in the freely migrating units (R5: 5.8 m/y; R3: 4.4 m/y and R6 4.0 m/y).

Introduction

Lateral channel migration (LCM) is a fundamental process governing the channel dynamics of meandering rivers (Blanka & Kiss, 2008; Bertalan et al., 2016) and contributing to the sediment budget (Nagy & Kiss, 2020; Kiss et al., 2022, 2024). However, bank erosion can cause severe damage to agricultural lands, settlements, or infrastructure, depending on its extent and intensity (Lawler et al., 1997; Das et al., 2012; Bertalan et al., 2019; Langović et al., 2024). The horizontal channel shift of free or partially controlled meandering rivers could have a significant LCM up to several meters per year. Therefore, monitoring the spatiotemporal extent and driving factors of channel changes is crucial, especially along some highlighted reaches and sections (Blanka & Kiss, 2008; Hooke, 2008; Mirijovsky et al., 2015; Bertalan et al., 2016; Bertalan et al., 2019), allowing the prediction of the lateral migration process, providing a basis for sustainable channel and floodplain management, e.g., to determine the necessary floodplain width (Sipos et al., 2022).

Historical maps of the last two to three centuries and modern sources provide valuable sources for analysing past processes and could be used to determine the direction and rate of channel development (Goudie, 1990; Hudson & Kesel, 2000; Dragicevic et al., 2017). Geoinformatics completed by remote sensing methods and field geodetic measurements allow fast and accurate data collection and systematization to reveal the characteristics of horizontal channel development (Clerici et al., 2015; Schwendel et al., 2015; Yousefi et al., 2018; Bertalan et al., 2019). The increasing availability of remotely sensed and topographic

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doi: 10.5937/gp28-49989
Received: March 22, 2024| Revised: June 26, 2024| Accepted: August 29, 2024

databases has significantly boosted spatiotemporal studies with increasingly smaller errors (Blanka & Kiss, 2008, 2011; Michalková, 2009; Michalková et al., 2011; Bertalan & Szabó 2015; Pavlek, 2023; Langović et al., 2021).

Meandering is a common channel pattern of alluvial rivers (Rhoads & Welford, 1991; Thorne, 1997; Hooke, 2007; Blanka, 2010). Especially in the middle of the Carpathian Basin, where most rivers are embedded into alluvial deposits, their slope and discharge characteristics allow the development of a meandering channel pattern (Timár & Telbisz, 2005). Although most meandering rivers in Hungary have been regulated, there are sections where the channel is still unregulated. The intensive meander development is the main problem, often endangering settlements and infrastructure (Laczay, 1972), justifying the need for comprehensive studies.

The Rába River is a tributary of the Danube. Formerly, its lower reach (downstream of Sárvár) was studied in detail from a hydro-morphological point of view (Károlyi, 1962; Laczay, 1972). However, no mapping or morphometric study has been conducted on the upper Hungarian reach. The main problem is that the free meander migration erodes arable lands and destroys roads and infrastructure. Thus, to carry out sustainable floodplain and channel management, it is necessary to understand the characteristics of the long-term channel evolution. Therefore, we aimed to collect spatial data over a long time (1844–2018) and to identify the most intensively migrating sections of the Upper Rába River in Hungary. The following research questions were raised: (1) What were the main spatial and temporal characteristics of the LCM during the last 174 years? (2) Could the studied reach be divided into smaller units with distinctive LCM histories? (3) How did the local engineering works influence the long-term evolution of the river?

Study area

The Rába River (length: 287 km) is one of the main rivers in Western Hungary (Bergmann et al., 1996). The Upper Rába (from its source in Austria to Sárvár) has been regulated only at a few points, mainly at settlements; thus, it meanders freely on its floodplain. The local works aimed to protect the settlements, transport infrastructure, and flood defence works from flooding and lateral erosion. Besides, five dams were built on the Upper Rába (Bergmann et al.,

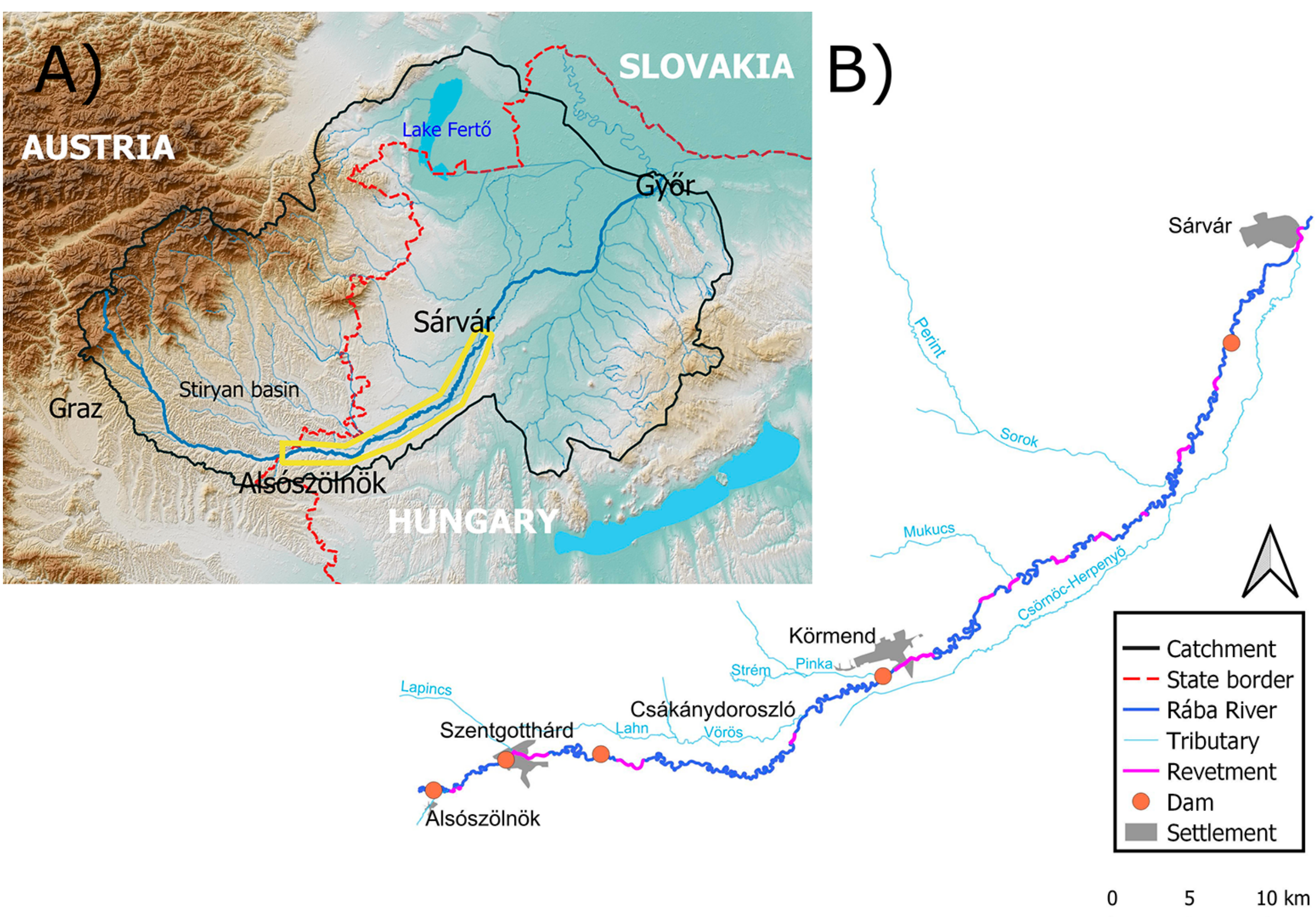

Figure 1. The catchment of the Rába River is located in Austria and Hungary (A). The upper part of the Hungarian reach was studied in detail (B)

1996). On the contrary, the Lower Rába is confined by artificial levees, and its channel is regulated by cut-offs and revetments to a large extent (Laczay, 1972). This study aimed to analyse the channel development of the Hungarian Upper Rába reach (Figure 1).

The catchment of the Rába River (10,113 km^2) is shared by Austria and Hungary. The Alpine sub-catchments have a key influence on the regime of the Rába. The first flood of the river in March is initiated by snowmelt and rainfall, then heavy rainfalls trigger rapid floods in July. In November, a smaller flood is related to Mediterranean cyclones. Based on the characteristic discharge values (Q_{min}= 2.6 m^3/s and Q_{max}= 471 m^3/s measured at Szentgotthárd), the Rába River is a medium-sized river. It contributes to the mean discharge of the Danube by 1.3% (Bergmann et al., 1996).

The hydrology of the Hungarian Upper Rába is determined by the tributaries draining the mountainous sub-catchments in the Eastern Alps (Figure 1). On the other hand, the Upper Rába has no significant right-side tributary (Laczay, 1972). The Lapincs Brook has the greatest influence on the water and sediment transport of the Upper Rába since the mean discharge of the Lapincs is three times greater than the mean discharge of the Rába, and its coarse sediments also have a major influence on the formation of the riverbed (Károlyi, 1962).

The Hungarian Upper Rába is located in a 2–3 km wide valley, influenced by tectonic displacements. The mean gradient of the upstream part of the Upper Rába valley is 1‰, then decreases to 0.85‰, and finally increases to 0.90–0.86‰ in the downstream section (Bergmann et al., 1996).

The large amount of sediment transported by the Rába decreases significantly along the studied reach (Bogárdi, 1971). Bedload transport starts at Q ≥12 m^3/s, reaching its maximum at 30 m^3/s (EDUVIZIG, 2024). Large amounts of the bedload and suspended sediment are deposited on the valley floor during floods (Bergmann et al., 1996).

Materials and Methods

Data sources

Military maps, civilian maps, and orthophotos were used to analyse the horizontal channel shift (Table 1). They have different sources with different formats and projections; thus, they had to be integrated into the same projection system (EPSG:23700–HD72/EOV) using QGIS (3.28/Firenze). Georeferencing was performed using control points (e.g., bridges, road crossings, and churches).

The error in georeferencing (Table 1) of the Second Military Survey (1844–1855) (Timár et al., 2006) was greater than that of the Third Military Survey (1878–1880) (Biszak et al., 2007; Jankó, 2007). The military maps of the 20th century (made in 1951, 1955–1956, and 1983–1984) were provided by the Hungarian Military History Institute and Museum. To create the 1951 map, the sheets of the Third Military Survey were re-edited based on field survey data or by visual interpretation of aerial photographs (Jankó, 2007; Hegedüs, 2007). The next detailed survey of the Rába valley was completed in 1955–1956, so it became the next accurate mapping after the Third Military Survey. In or-

Table 1. Main characteristics of maps and orthophotos used in the present study

Source	Survey date	Scale	Resolution (m/px)	Horizontal error (m) of the original source		Mean error (m) after georeferencing
				Mean	Maximum	
Second Military Survey	1844–1855	1: 28,800		70–80*	200** / 140–300*	2.2±1.3
Third Military Survey	1878–1880	1: 25,000		5–10***	80–120***	1.8±0.9
Military Topographical Map	1951	1: 25,000		5–10***		0.8±0.4
Military Topographical Map	1955–1956	1: 25,000		5–10***		0.8±0.4
Civil topographical map	1960–1961	1: 10,000		neglible		
Military Topographical Map	1983–1984	1: 25,000		neglible		
Civil topographical map („EOTR”)	1983, 1996–1998	1: 10,000		neglible		
Orthophoto	2000		0.5	neglible		
Orthophoto	2005		0.5	neglible		
Orthophoto	2008		0.5	neglible		
Orthophoto	2012		0.4	neglible		
Orthophoto	2015		0.4	neglible		
Orthophoto	2018		0.4	neglible		

*Source: * Kovács, 2010; **Timár & Molnár, 2003; ***Kovács et al., 2024a* der to avoid the horizontal errors of the various maps, the method proposed by Timár & Molnár (2003) was followed, and control points (100 points/survey) were applied for each map sheet. Topographic maps (1960–1961, 1983, and 1996–1998) have also been produced for civilian purposes. These map series were optimised for the territory of Hungary, so their projection inaccuracies are neglectable.

The projection inaccuracies of the orthophoto images (taken in 2000, 2005, 2008, 2012, 2015, and 2018) are negligible; they were orthorectified by the provider (Lechner Knowledge Centre).

The main error of the remotely sensed dataset originates in the canopy cover of deciduous trees, as the woody riparian vegetation could hide the bankline during digitisation. To solve the problem, the image processing method *Classification* (plugin) within QGIS was used to classify the pixels of a given orthophoto. The created pixel classes with the same or similar properties supported the separation of the land from the water so that the bankline of the channel could be delineated (Pusztai-Eredics et al., 2024).

Calculation of sinuosity and lateral migration rate of the bankline

The banklines and the centre line were determined (midpoints of the distance between the banks) on each map and orthophoto. The Sinuosity Index (SI) was calculated as the ratio of the length of the centre line and the length of the meander belt (Brierley & Fryirs, 2005).

The vectorized banklines were overlapped in QGIS using the NNjoin module. The new polygon between two subsequent banklines in the direction of the displacement indicates the area eroded from the floodplain by the channel. In contrast, the polygon on the other side refers to the area of accumulation.

Geometrical and statistical methods were used to determine the extent of the LCM rate. First, a perpendicular line was constructed on a digitised bankline every 2 m all along the studied reach (Figure 2A). Along these lines, the lateral channel shift was measured. The annual LCM rate (m/y) was expressed as the ratio of the length of perpendicular lines and the years between two surveys.

To determine the maximum LCM rates, circles with a diameter of 500 m were placed along the centre line. The circles overlap by 90 m, approximately equal to the doubled channel width (Figure 2B). The maximum LCM rates within the circles were determined by applying a moving average.

Delimitation of the units of the Upper Rába section in Hungary

Based on the LCM rate and the degree of human influence, 14 units with similar channel characteristics were identified on the Upper Rába. The unit boundaries were set at inflexion points (following Bertalan et al., 2019), where the channel evolution rate showed a clear shift. The unit length, the proportion (%) of bank protection, and average and maximum LCM rates (m/y) were calculated in each unit. The joining tributaries were also considered, as they could substantially influence the water and sediment dynamism of a unit. The slope of each unit was determined based on the longitudinal profile provided by the Water Directorate.

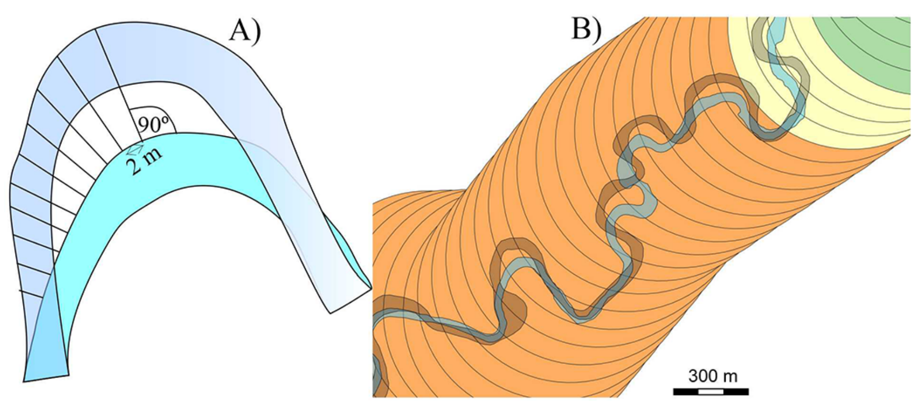

Figure 2. The method used to quantify lateral channel changes in every 2 meters (A) and to identify the rate and location of the greatest lateral erosion

Results

Based on the spatial data, the LCM of the Hungarian Upper Rába was studied in detail over 174 years.

Changes in river length

The length of the centre line of the Upper Rába was 127.5±4.5 km during the studied period (Figure 3). The reach length has changed dramatically in some periods due to natural or artificial cut-offs. The most extensive shortening was observed between 1844 and 1879, as the river was shortened by 7.7 km or 6% (–266 m/y) by artificial cut-offs. Therefore, its originally high sinuosity (SI_{1844}=1.84) decreased (SI_{1878}=1.73). By the 1960s, the original length of the channel had almost recovered, as well as its sinuosity (SI_{1960}=1.84). However, several meanders were artificially cut off between 1968 and 1977, and some natural meander cut-offs also happened. Thus, by the early 1980s, the 24 cut-offs had shortened the Hungarian Upper Rába by about 2.7 km, or 2% (–117 m/y). Since the late 1990s, the reach length increased again (by 2.6%, +235 m/y) as intensive meander development started, as reflected by the increasing sinuosity (SI_{1996}=1.85). The most intensive length increase (+291 m/y) took place between 2005 and 2008, thus in 2018 the sinuosity had reached its historical maximum (SI_{2018}= 1.93).

Temporal changes in lateral channel migration (LCM) rate

The regulation works were very limited along the studied reach of the Upper Rába; therefore, the channel could almost freely develop by bank erosion and point-bar accumulation. As a result, the mean LCM rate over the entire studied period (1844–2018) was 3.3 m/y.

However, the LCM showed considerable spatiotemporal variability (Figure 4). During the 1950s (1951–1959) and late 1990s (1996–1999), the LCM was high and changeable compared to other periods (Figure 5), as reflected by the box plots with many outliers and a wide range between extreme values. In these periods, the mean LCM was 4.1–4.9 m/y; however, it was as high as 15–20 m/y at some bends. The lateral channel shift was especially intensive in the late 1990s, as some meanders were displaced by 24–27 m/y, reaching the maximum values of the entire studied period. The direction of the LCM is also interesting, as in the 1950s, the channel mostly migrated towards its left bank (west), but later, in the late 1990s, the channel shifted towards the right bank.

The periods of intensive LCM were always followed by periods when the LCM became moderate or slow (Figure 5). Low LCM rates (2.2–2.8 m/y) were measured in five periods (1878–1950, 1960–1982, 2000–2004, 2005–2007 and 2015–2018). During these periods, the box plots reflect that the individual bends migrated almost uniformly, as the boxes are narrow and outliers are almost missing.

The periods with intensive LCM were preceded by periods with gradually increasing values. For example, the 20th century started with a very limited LCM rate (mean: 2.1 m/y). However, after 2005 a gradually increasing trend is visible until 2012–2014 (mean: 3.5 m/y). Then, the cycle started again, as moderate LCM (mean: 2.6 m/y) between 2015 and 2018 followed the last intensive migration phase.

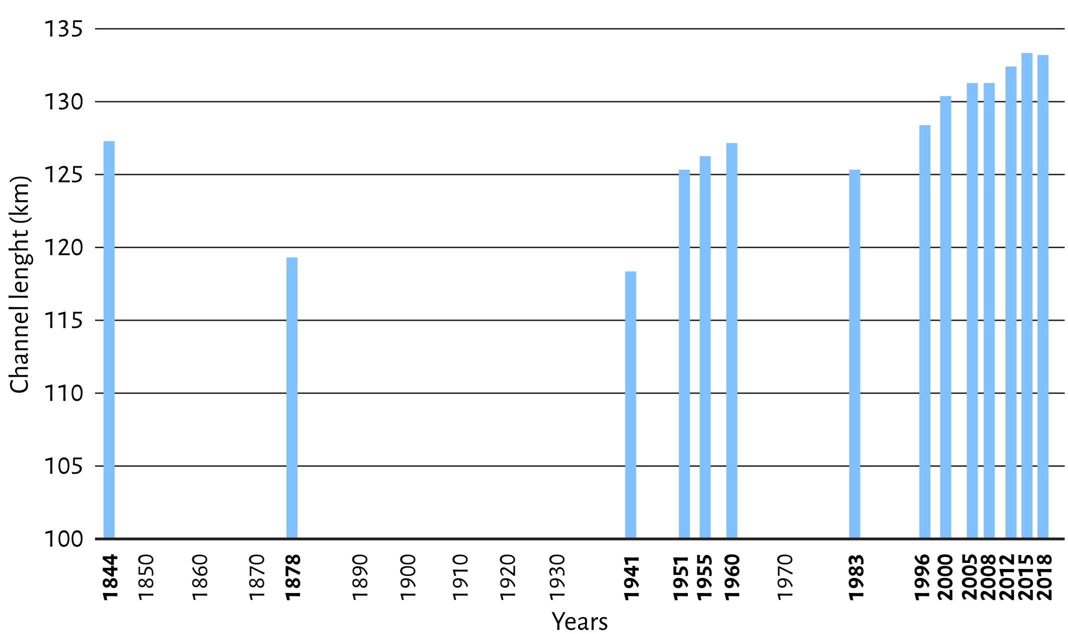

Figure 3. Changes in reach length (km) of the Hungarian Upper Rába between 1844 and 2018

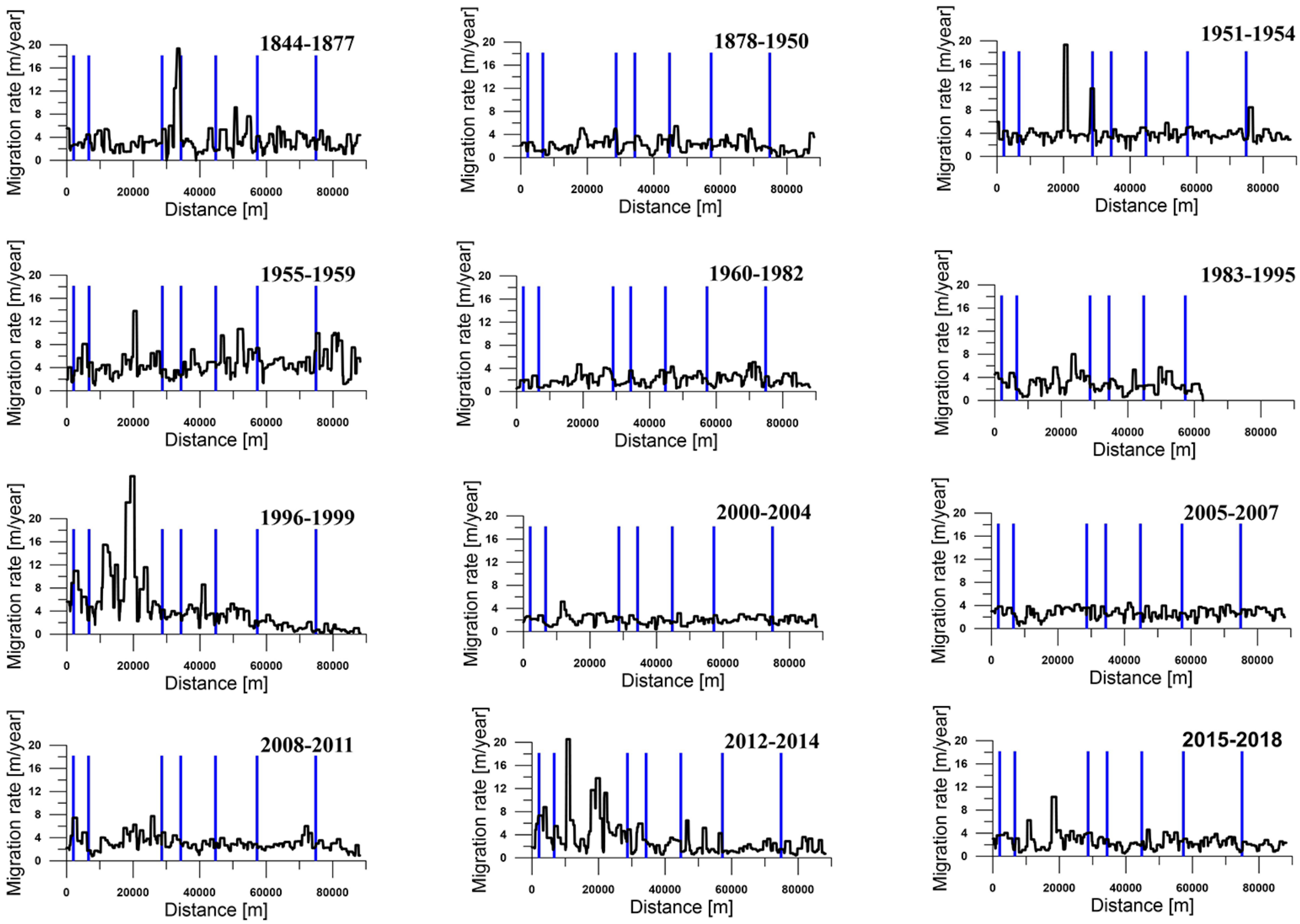

Figure 4. Changes in lateral channel migration rate between subsequent surveys along the Hungarian Upper Rába. Blue bars indicate the location of confluences. On the horizontal axis, the distance refers to the distance from the Austro-Hungarian border, where the Rába enters Hungary

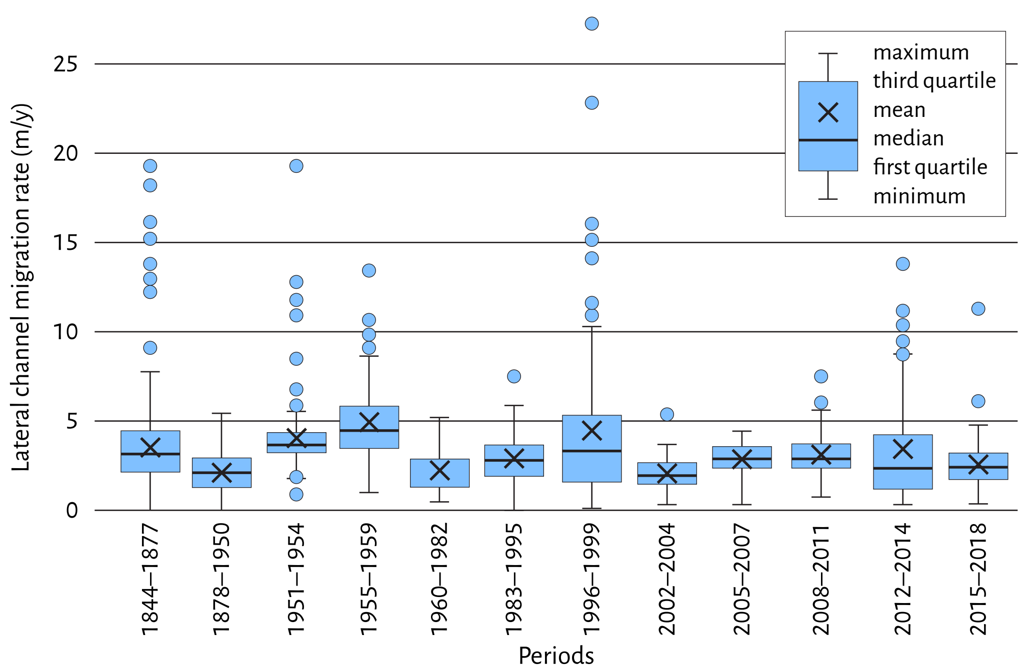

Figure 5. Temporal characteristics of the LCM of the Upper Rába. The input data of the box plots are the LCM of single bends

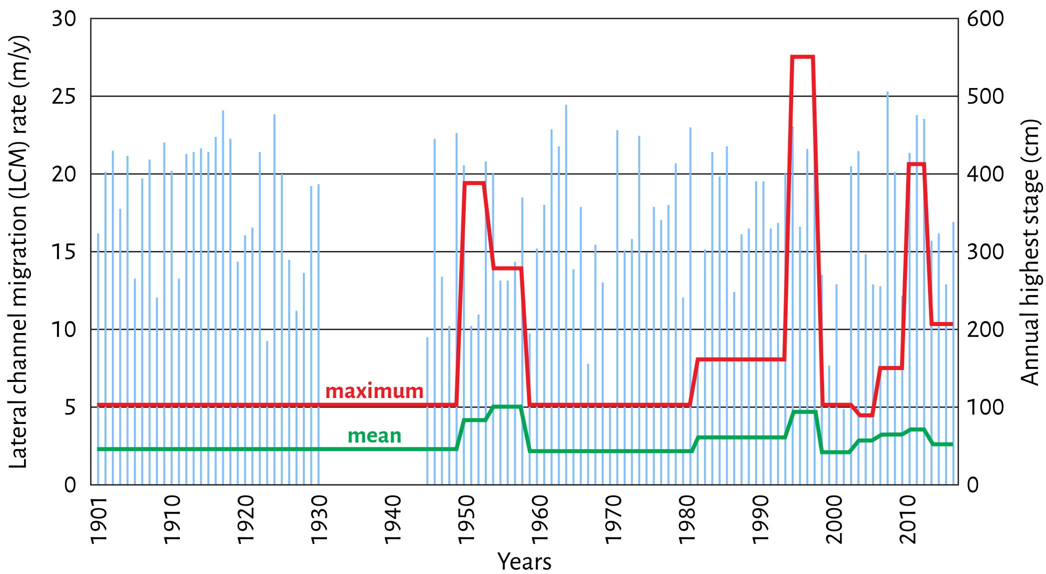

Figure 6. Connection between mean and maximum lateral migration rate and annual highest water levels measured at Körmend gauging station

Hydrological background of the lateral channel migration

The occurrence of floods was compared to the channel shifts of the Upper Rába. Four major floods occurred in 1883, 1900, 1910, and 1925; however, their effects on LCM were unclear (Figure 6), as the LCM rates were probably levelled during the long interval (72 y) between the subsequent surveys. The next major flood was registered in 1963, and another large flood followed it in 1965 when the highest water level on record was measured. However, despite the two consecutive floods, there was no evidence of more intensive LCM between 1960 and 1982 (22 y).

However, since 1996, more frequent spatial data on LCM have been available. Thus, the effect of floods in 1996, 2009, and 2013 could be identified on lateral erosion. After the 1996 flood, the maximum LCM rate was 27.3 m/y for the four years (1996–1999). The 2009 flood resulted in a maximum displacement of 7.7 m/y (for 2008–2011), while after the 2013 flood the maximum value was again quite high, as it was 20.5 m/y (2012–2014).

These contradictory results suggest that a long period between surveys could hide the effects of hydrology on LCM. In contrast, if the surveys were made with shorter intervals, the effects of floods could be detected. Besides, the LCM seems to have a cyclic pattern: it gradually increases until it reaches a peak value, and then – regardless of the floods – a relaxation period comes with low bank erosion rate.

Spatial changes in lateral channel migration (LCM) rate

The detailed analysis of the temporal variations in LCM rate revealed periods with intensive or moderate channel changes. However, it was hypothesised that there were spatial variations, as local variables influence the bed morphology (e.g., confinement, slope, revetments, and tributaries). Based on local variables and LCM rates, 14 units with similar meander characteristics were identified on the Upper Rába (Figure 7; Table 2).

Some units could be considered as "near-natural" ones (R3, R5, R6, R8, and R13), as they experienced no or minimal human impact. However, even these units could not develop naturally, as the effects of upstream or downstream human impacts might propagate toward them. These units represent 84% (111.5 km) of the studied Upper Rába. They are far from settlements, and the valley sides do not impede meander development. Therefore, these units had the highest LCM (Figure 8). The Unit R5 had the highest LCM rate (5.8 m/y) with the greatest variability (from 2.6 m/y to 27.5 m/y). Also, a high average migration rate was measured in Units R3 (4.4 m/y) and R6 (4.0 m/y).

The "heavily modified" group of units (R2, R4, R7, R9, R11, and R14) have been affected by human interventions to a great extent. In several bends, the concave bank was stabilised by revetments between 1968 and 1977, and many meanders were artificially cut off. Before these engineering works, these meanders also developed freely (Figure 8). Thus, they had intensive LCM (1844–1959: 2.5-3.6 m/y). However, LCM became negligible after the bank stabilisation and cut-offs, the (1983–2018: 1.6-2.6 m/y). Consequently, the long-term average LCM rate of these units with bank stabilisations became low (2.0-3.0 m/y).

The third group of units belongs to the "slightly modified" class (R1, R10, and R12). These units had moderate LCM rates, as the long-term average varied between 2.9 and 3.6 m/y. Due to their medium character, these units had significant variations in LCM between the lowest (1.7–1.9 m/y) and highest (5.4–7.8 m/y) rates.

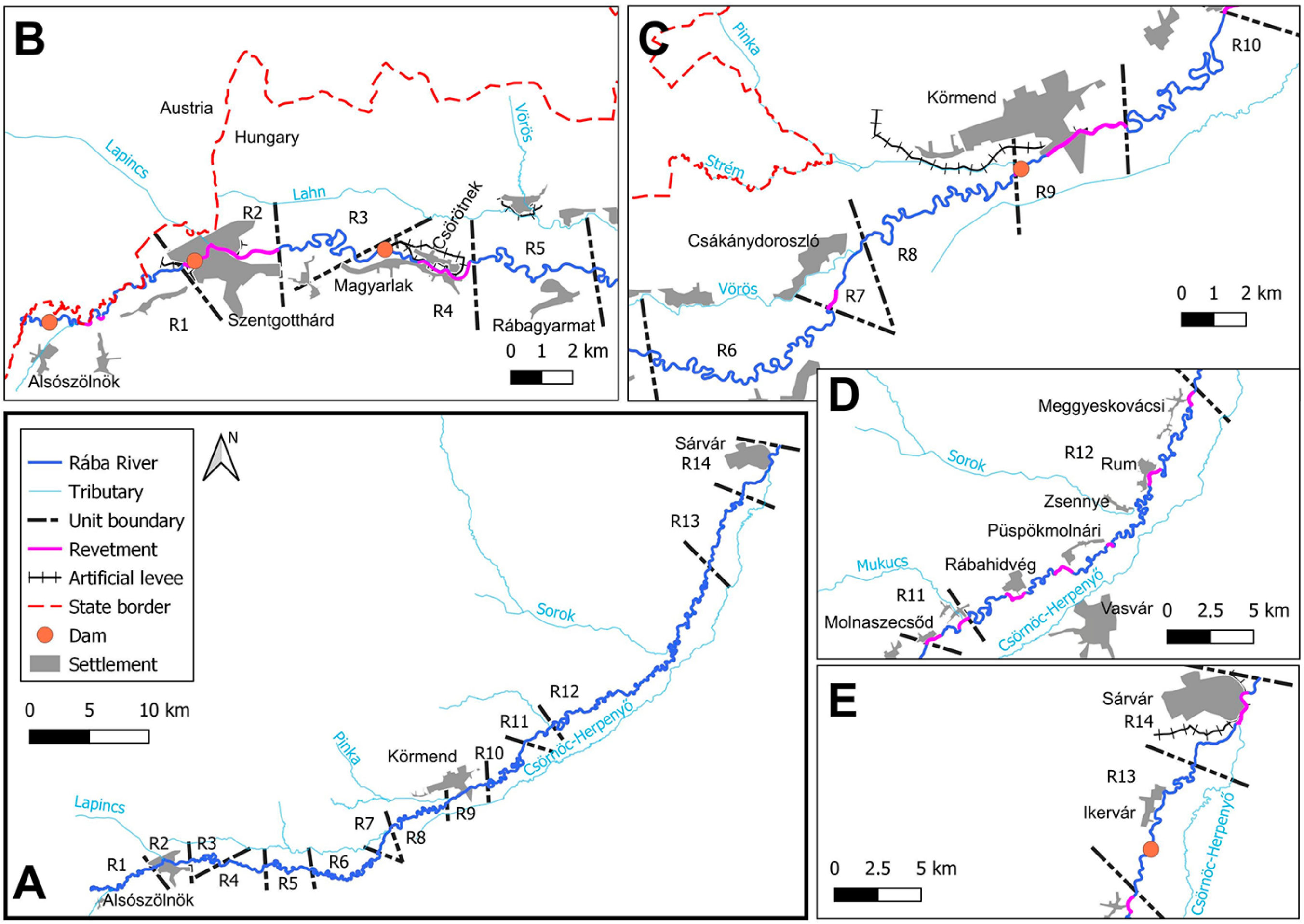

Figure 7. Fourteen morphologically uniform units were identified along the Hungarian reach of the Upper Rába (A). Some units have higher sinuosity, greater lateral migration, and more human impact than others (B–E)

Table 2. Main characteristics of the units identified along the Upper Rába

Unit (river km)	Length in 2018 (km)	Confinement	Slope in 2023 (m/km)	Number of bends	Proportion of revetments (%)	Migration rate (m/y) (1844-2018)	
						mean	max.
R1 (216.3-207.5)	8.8	none	1.06	40	5.7	3.6	10.9
R2 (207.5-203.7)	3.8	great	1.32	8	95	2.1	5.6
R3 (203.7-197.9)	5.9	none	0.58	14	0	4.4	20.5
R4 (197.9-193)	4.9	great	0.9	14	44.9	2.6	12.0
R5 (193-186.2)	6.8	none	0.76	22	0	5.8	27.3
R6 (186.2-173.6)	13.9	none	0.56	48	0	4.0	11.8
R7 (173.6-171.1)	2.5	none	0.52	6	24	2.1	9.3
R8 (171.1-160.8)	10.7	partial	0.46	36	0	3.3	19.4
R9 (160.8-156.7)	4.1	great	0.73	9	75.6	2	12.8
R10 (156.7-145.2)	11.9	none	0.4	31	0	3.0	9.6
R11 (145.2-141.6)	3.6	none	0.64	12	47.2	3.0	17.6
R12 (141.6-102.9)	39.2	none	0.42	125	13.3	2.9	10.7
R13 (102.9-93.1)	10.3	none	0.93	29	0	2.8	10.0
R14 (93.1-86.6)	6.5	great	0.58	18	29.2	2.2	7.5

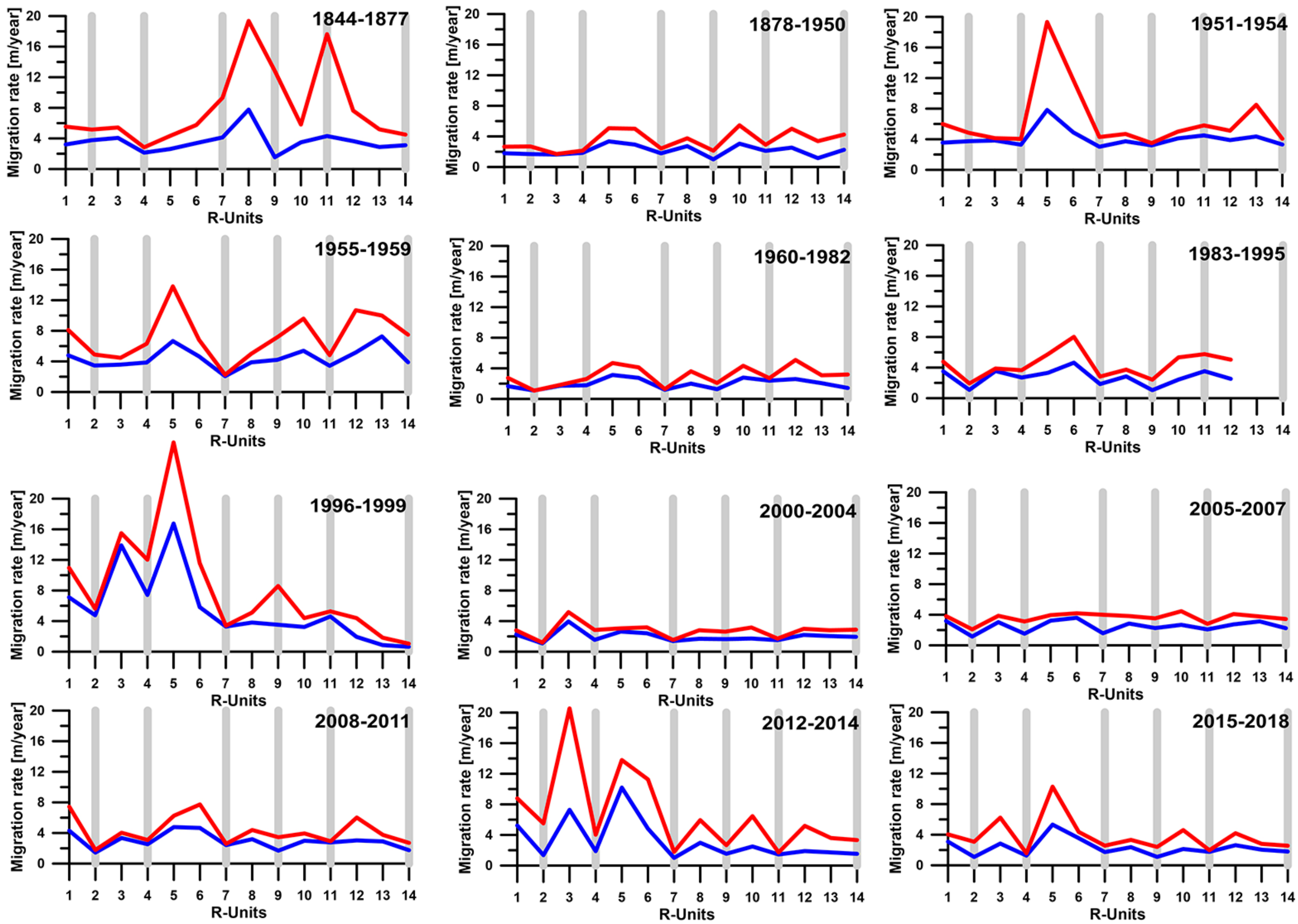

Figure 8. Mean (blue) and maximum (red) lateral channel migration rates of the units during the studied periods. (Grey bars indicate "heavily modified" units)

It is also interesting to note that, in terms of LCM direction, units directly affected by human interventions tended to move towards the right bank, while naturally developing stretches tended to migrate towards the left bank.

Discussion

Significant lateral erosion and LCM have been detected along the bends of the Hungarian Upper Rába reach over the last 174 years. However, their magnitude and direction were not uniform, neither in space nor in time, as there are significant differences between the different periods and between the identified units of the studied reach.

The studied reach has been significantly shaped by local river management works, particularly between 1968 and 1977, highlighting the substantial role of human intervention. Based on the extent of this influence and meander migration characteristics, 14 units were identified and later classified into three groups (Figure 9).

Most of the reach develops without direct human impact (84% of the total length) or with limited human impact (16%). However, these bends could not have developed completely freely either, as these units are located between units that have been heavily modified by direct interventions (e.g., cut-offs, revetments, dams). The cut-offs increase the slope, the revetments increase the flow velocity by reducing the channel friction, and dams could impound the channel. These effects propagate both upstream and downstream. Thus, they may also have affected the flow and sediment transport conditions of the freely developing units.

Spatiotemporal changes in reach length and lateral migration rate

The studied parameters reflect intensive LCM, especially in naturally developing units. The most intensive increase in reach length was observed between 2005 and 2008 (291 m/y). However, this lengthening varied in space, as the

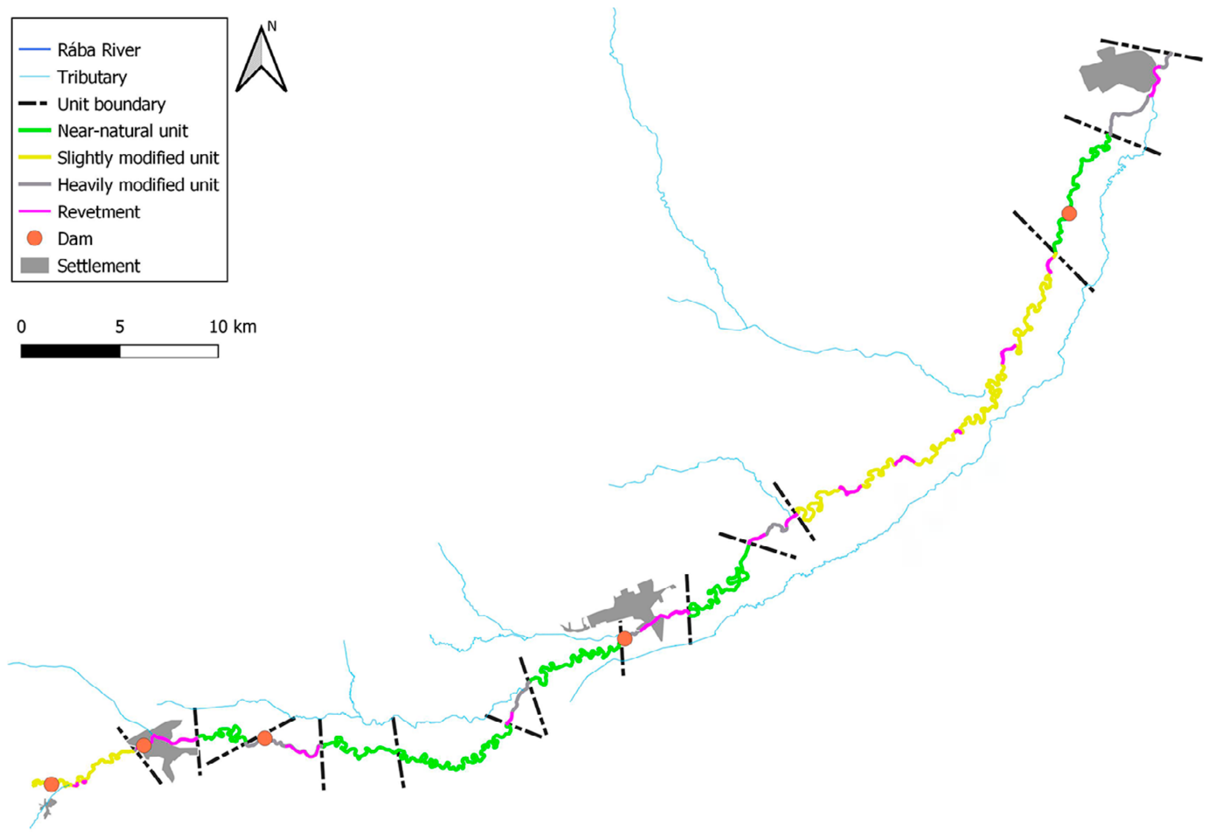

Figure 9. Based on the human impact and the lateral channel migration three types of units were identified along the Hungarian Upper Rába

units without direct human impact (e.g., R3, R5, and R6) had a markedly higher centre line increase than the units with human impacts. In the naturally developing units, nothing impeded the lateral erosion. Thus, the meanders could migrate freely, and the sinuosity increased.

The fluvial evolution and LCM were particularly active in the 1950s and the late 1990s. An average LCM rate of 4.1 to 4.9 m/y was measured in these active periods, whereas the long-term mean LCM rate was 3.3 m/y. These values are considerably higher than observed along other rivers in the Carpathian Basin. For example, along the Tapoly and Ondava Rivers (Slovakia), the LCM ranged between 0.8–1.5 m/y and 1.15–1.45 m/y, respectively (Rusnák et al., 2014; 2016). Though, along the Sajó River in Hungary the LCM was higher, reaching 5-7 m/y (Bertalan et al., 2019). It must be noted that along the Upper Rába, exceptionally high maximum rates were detected, especially in Unit R5, where the maximum LCM rate was 27.5 m/y, and the greatest variability in channel shift was also found. This value is much higher than the maximum LCM (17.9 m/y) measured on the Sajó River (Bertalan et al., 2019). During the intensively forming periods, the LCMs were widely changeable, referring to some individual meanders with very high migration rates. According to our hypothesis, in these meanders and these periods, all environmental parameters were favourable for the rapid migration (e.g., loose bank material, sparse vegetation, thalweg diverted to the bank). In contrast, other meanders reached areas with dense vegetation or compacted bank material. Besides, the collapsed bank material at the foot of the bank could also slow down the erosion at some points.

Spatiotemporal changes in sinuosity

Human interventions could also affect a river's sinuosity (Timár, 2003). Along the Upper Rába reach, cut-offs made in the late 19th century resulted in a significant decrease in sinuosity along the entire reach until 1878. As a result of these engineering works, the length of the river decreased by 6%. Thus, the sinuosity was reduced (SI_{1844}=1.84; SI_{1878}=1.73). Similar changes in sinuosity were detected later on because 24 artificial or natural meander cut-offs occurred (1960–1982). They shortened the reach by 2%, so the sinuosity of the channel decreased again from 1.84 to 1.80.

The effects of human impacts were also evident in the unit scale. The "heavily modified" units had lower sinuosity (SI: 1.04–1.30) than the "near-natural" and "slightly modified" units (SI: 1.54–2.53). Usually, the human impact decreases the sinuosity of a channel. Thus, the channel pattern of the heavily modified units (e.g., R2, R7, and R9) changed from meandering to slightly sinuous (SI: 0.3–0.4). Conversely, the channel pattern of the almost natural and slightly modified units (e.g., R1 and R6) changed from slightly sinuous to meandering as their sinuosity index increased from 1.3 and 1.5 to 1.6 and 2.4, respectively.

Thus, all the studied parameters indicate that there is a gradual evolution along the units with little or no human disturbance, as has been shown in other studies of similar European rivers (Keesstra et al., 2005; Blanka & Kiss, 2011; Dragicevic et al., 2017; Bertalan et al., 2019).

Effect of slope conditions and tributaries on lateral channel movements

The Rába River's unique characteristics, such as its high sinuosity and free meander development, are key to understanding its high LCM rates. As Schumm (1985) pointed out, the moderate slope (0.5-0.9 m/km) is a crucial factor in supporting the formation of high sinuosity. This specific slope range is found along the Upper Rába, which in turn promotes high sinuosity and intensive LCM, making the Rába a fascinating subject of study.

In Unit R3, the accelerated meander migration might also be influenced by the confluence of the largest tributary of the Rába River. The Lapincs Brook has higher discharge than the Rába, as their mean discharge ratio is 3:1; besides, it transports large amounts of bed load. Thus, the erosion accelerated downstream of the confluence, especially because here, meanders develop freely; thus, nothing impedes the LCM. The other tributaries have no similar effect on the LCM of the Rába, as they have very low discharges.

Conclusion

The study has revealed significant LCM of the Hungarian Upper Rába during the last ca. 180 years. Some extremely migrating meanders have been eroded at 20-27 m/y, indicating significant floodplain reworking. This does not imply that bank erosion was always significant in a given area, as periods of intensive LCM (e.g., 1950s) were interspersed with periods (e.g., 1960s) when LCM became slower in the whole system. The temporal pattern shows that the LCM gradually gets more and more intensive until reaching its maximum. Then, a period of relaxation appears with very limited bank retreat. Then the cycle starts again. However, this natural cycle is influenced by various human impacts in some units, while the meanders freely develop in other units.

However, further research will be needed to investigate the driving factors of the intensive changes in sinuosity and LCM rate. Thus, the effects of hydrological changes, influence and dynamism of tributaries, and bank material should be studied in greater detail. In addition, the channel evolution of the Rába is probably influenced by active tectonism, which changes the slope and the flow velocity (Miall, 1996; Keller & Pinter, 2002; Timár, 2003), and influences sinuosity (Blanka, 2010). Therefore, the LCM should be compared with available tectonic data in the future.

The identified units with characteristic LCM rates could be applied to develop effective solutions for sustainable channel and floodplain management for the Upper Rába. Preserving freely developing banks is important to maintain the natural bank processes, which contribute to the healthy sediment budget of the river and provide valuable habitats. In the case of artificially modified channel sections, the hydro-morphological consequences of interventions should be carefully considered. As revetments could lead to incision and channel narrowing, they could increase flow velocity and greater flood risk (Kiss et al., 2019).

Acknowledgement

The acquisition of the 2012 orthophotos was supported by the ELTE BDPK Institutional Excellence Framework Programme in 2021.

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