GEOGRAFICKÝ ČASOPIS / GEOGRAPHICAL JOURNAL 74 (2022) 2, 159-180
DOI: https://doi.org/10.31577/geogrcas.2022.74.2.08

ANTHROPOGENIC AND ENVIRONMENTAL IMPACTS ON THE RECENT MORPHOLOGICAL DEGRADATION OF THE MEANDERING HORNÁD RIVER

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Anthropogenic and environmental impacts on the recent morphological degradation of the meandering Hornád River

In the 19th century, the Hornád River in Slovakia was an unmanaged river system with well-developed free meanders. However, there has been a significant reduction of these free meanders in the last 70 years. The aim of this paper was to evaluate the morphological response to human intervention and flood events on three types of river segments (natural, regulated and water-gap) of 72-km-long river reach of the meandering Hornád River in Slovakia over the last 197 years. Based on the dataset from the 2nd (1819 – 1827) and 3rd military survey maps (1869 – 1887), aerial photos (1949 and 1986) and orthophoto mosaics (2002, 2013 and 2016) the in-channel morphological, as well as the land cover changes, were identified. The four evolutionary periods of morphological response were identified: a pre-regulation period of 1819 – 1948, and three regulation periods with mutual effect of flood discharges of 1949 – 2001, 2002 – 2012, and 2013 – 2016. The Hornád River in the pre-regulation period was represented by a natural meandering river planform (45.8%) with a high occurrence of in-channel landforms, where the lateral bar area prevailed. The intensive anthropogenic impact in the second half of the 20th century mainly affected its planform evolution, and resulted in channel shortening and narrowing, river sinuosity index and erosion-accumulation processes decreasing and loss of free meanders. The long-term low flood magnitude series coupled with land-cover changes (increasing the built-up area and communications) during the intensive regulation period led to the simplification of river channel planform by stabilization of the erosion-accumulation processes. It caused simplification of river channel planform, mainly of the natural river segments (down to 26%). The low flood series was reversed by the flood events after the year 2004 (5 – 50-year recurrence interval), which tend to increase of the river sinuosity, channel widening as well as the migration of free meanders.

Key words: meandering, river degradation, multi-temporal analysis, river training, flood event, Hornád River

INTRODUCTION

River channel degradation is understood as a process of channel planform simplification, lateral/longitudinal connectivity loss, and channel narrowing (e.g. Kidová et al. 2016 and Lehotský et al. 2018). The anthropogenic impact channel degradation is represented by the river incision, lowering of the longitudinal channel bed slope caused by the river bed erosion commonly accompanied by bank erosion (Lehotský et al. 2015), channel narrowing and changes in channel pattern (Surian and Rinaldi 2003). Until the end of the 19th century, a moderate form of anthropogenic interference with natural river processes was observed (Kiss and Blanka 2012, Procházka and Pišút 2015 and Kiss et al. 2021). A more extensive form of anthropogenic impact within European region in relation to changing environmental conditions and the rise of more sophisticated mechanization and engineering approaches has been documented since the 20th century. Particular examples of human intervention (engineering structures, artificial meander cut-offs, channelization, gravel mining, dams and reservoirs creation) were well-marked in Hungary (Mecser et al. 2008 and Amissah et al. 2018), Italy (Surian and Rinaldi 2003), Poland (Wyzga 1993, Krzemień et al. 2015, Hajdukiewicz et al. 2017 and Hajdukiewicz and Wyżga 2019), France (Liébault and Piégay 2002), Spain (de Jalón 1987), or in England (Petts 1987 and 1988, Lambert 1988, Petts and Wood 1988 and Large and Petts 1996). In Slovakia, documented human interventions in river systems refer to bank enforcement (Rusnák et al. 2016 and 2018), floodplain and in-channel gravel extraction (Radecki-Pawlik et al. 2019), or river training impact (Kidová et al. 2021).

In this paper we focused on the meandering Hornád River. The term of meander is derived from a sinuous river system in Turkey, initially known as Maiandros (Langbein and Leopold 1966), and represents a curve in a stream longer than half the circumference of the circle above its chord, where the angle of the curve is above 180°. The channel length of a meandering river equals 1.5 times than the thalweg length (Lehotský et al. 2015). The process of meander development has first been described by Keller (1972 and 1974) using a five-stage model of its formation. Hooke (1984) classified the possible meander changes in more detail, from simple shifts (extension, translation, rotation, expansion, lateral movement and irregular changes), through their combinations (double and triple combination), up to meander neck cut-off (Fig. 1). Further studies referred to detailed development characterization and meander movement has been presented by Langbein and Leopold (1966), Brice (1974), Julien (1985) and Da Silva (2006). Understanding the erosion-accumulation processes is crucial, especially in research of lateral movement of meandering rivers. Brierley and Fryirs (2005) describe six types of erosion, distinguishing hydraulic processes, and bank failures. Stream Corridor Assessment a Process Guide (2017) describes erosion in more detail, characterizing erosion potential concerning bank height at bankfull vs. bank angle, bank root density, bank soil stratification and bank particle size. Saadon et al. (2016) focuse on the use of hydraulics, bank properties, bank geometry, grain resistance and sediment, as parameters that control riverbank erosion, which influences meandering (Hooke and Yorke 2010) and the quantity of transported sediments (Green et al. 1999). The vegetation in the riparian buffer zone provides natural stability of banks against erosion (Florsheim et al. 2008), improves water quality, in-stream and terrestrial biodiversity (Hansen et al. 2010). It also reduces the height and velocity of the flood wave, accumulates and filters flood sediments (Cebecauerová and Lehotský, 2012) etc. However, its effect is very strongly influenced by hydrological regime (river regulation, frequency and magnitude of flood waves), and by the level of vegetation fragmentation (Hansen et al. 2010). Magnitude, frequency and the duration of floods also affect the river channel's lateral migration, and thus the channel width (Kiss and Blanka 2012).

The character of meandering river planform evolution can be expressed by the sinuosity index (SI). The popular and commonly used methods for SI calculation are expressed by numerous approaches: 1) total sinuosity method; 2) Brice method; 3) inflection sinuosity method; 4) Leopold and Wolman method; 5) hydraulic sinuosity method; 6) topographical Sinuosity method (Garícia 2015). Mueller (1968) combined two sinuosity indexes by comparing the topographic area effect on water stream (Topographic sinuosity index) to the behaviour of the water stream at the bottom of the valley (Hydraulic sinuosity index). The value of the sinuosity index represents the specificity of the water stream and its adaptation to surrounding conditions. Kumar et al. (2014) present three levels of stream sinuosity: straight, sinuous, and meandering. Garícia (2015) classifies four: straight, sinuous, moderate meandering and meandering, while Lehotský et al. (2015) distinguish between five levels of sinuosity index (completely straight, straight, moderately sinuous, moderate sinuous and meandering).

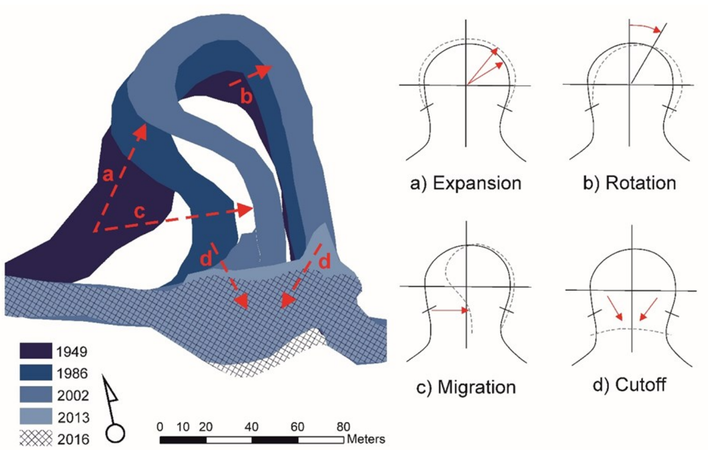


Fig. 1. Gradual process of the Markušovský meander neck cut-off from 1949 to 2016 on the Hornád River (river section no. 5) as an example of the meander evolutionary process (a, b, c, d), modified according to Hook (1984)

In Slovakia, meandering river systems were mostly studied in the context of their historical geomorphic evolution, river regulation, or the river response to flood events (e.g. Procházka and Pišút 2015, Pišút et al. 2016 and Rusnák et al. 2016). In this paper, the meandering Hornád River is presented as a typical example of anthropogenic interventions (channel regulation, weir construction and flood control management) in the context of the changing environmental conditions (flood events), which considerably altered the character of the river channel planform. The purpose of this paper is to quantify the morphological changes of the river channel and riverine landscape changes on the 72 km long river reach based on the spatiotemporal data analysis. Seven sets of data were used, including the second and third military survey maps, aerial images and ortophoto mosaics from 1819 to 2016. On the aforementioned studied river reach, we focused on the anthropogenic intervention, which has significantly influenced the former meandering planform of the Hornád River and caused its degradation.

STUDY AREA

The Hornád River, as an important left-side tributary of the Slaná River, origins near the Krahulec hill in the geomorphological division The Ridges. The length of the Hornád River in Slovakia is 178.8 km and its basin area is 4,414 km^2. The studied river reach is 72 km long, beginning in the Spiš-Gemer Karst area, where it is incised into the limestone bedrock of the Spiš-Gemer Karst, continuing through the Hornád Basin with considerable anthropogenic channel regulation and ending in

Čierna hora Mountains area by the arch of dam Ružín II water reservoir. The sub-basin has the area of 1 930 km^2 (Fig. 2).

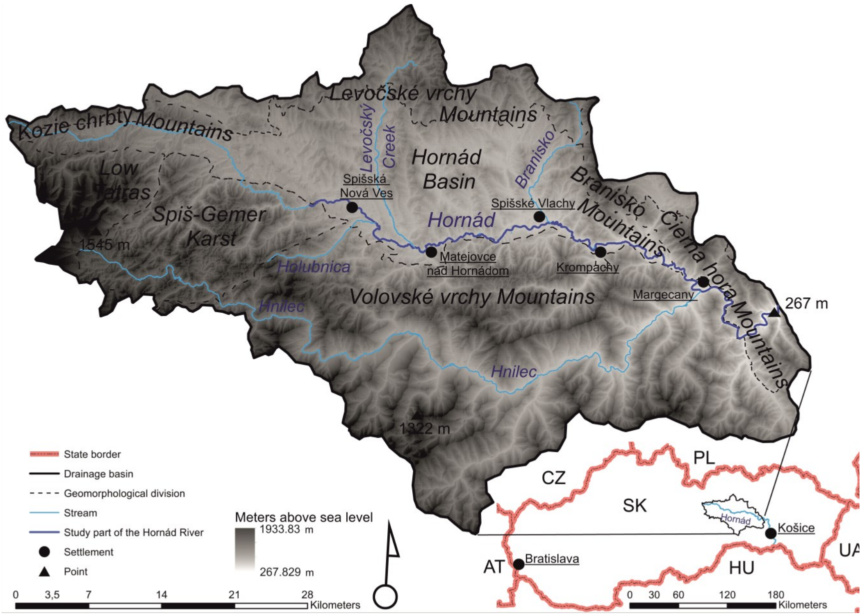


Fig. 2. Location of the studied river reach of the Hornád River within the sub-drainage area and its wider geomorphological division

The studied river reach of the Hornád River passes through a floodplain, from 50 to 1 300 m wide, 3 – 6 – 10 m thick, and with a 1 – 3° slope. In the widest sections (by the Spišská Nová Ves town), the floodplain is 600 – 1 500 m wide and 1 200 m wide by the town Spišské Vlachy (Michaeli 2001). As the Hornád River passes over the Hornád basin, it flows through wide and narrow floodplains and water gap valleys, where it is incised into the riverbed, creating cliffs in the channel. In these river segments, there is a poorly developed floodplain, and in some river reaches it is completely absent. Michaeli (2001) presents three water-gap river segments, the first in the Spiš-Gemer Karst, the second between the villages Matejovce nad Hornádom and Olcnava (7 km long) and the third dividing Branisko and the Čierna hora Mountains from the Volovec mountains, beginning downstream Spišské Vlachy and ending by the Hornád and the Hnilec River confluence. The studied section of the Hornád River flowing through the Spiš-Gemer Karst falls into the Slovak Paradise Nation Park while simultaneously belonging to Natura 2000 (SKUEV0112). It flows through middle reach of the Hornád River (SKUEV0928), Europe's Protected Area, from the Spiš-Gemer Karst to the arch of dam Ružín II dam reservoir. Despite the fact that a considerable section of the Hornád River belongs to a protected area, the anthropogenic impact is noticeable along the entire study area.

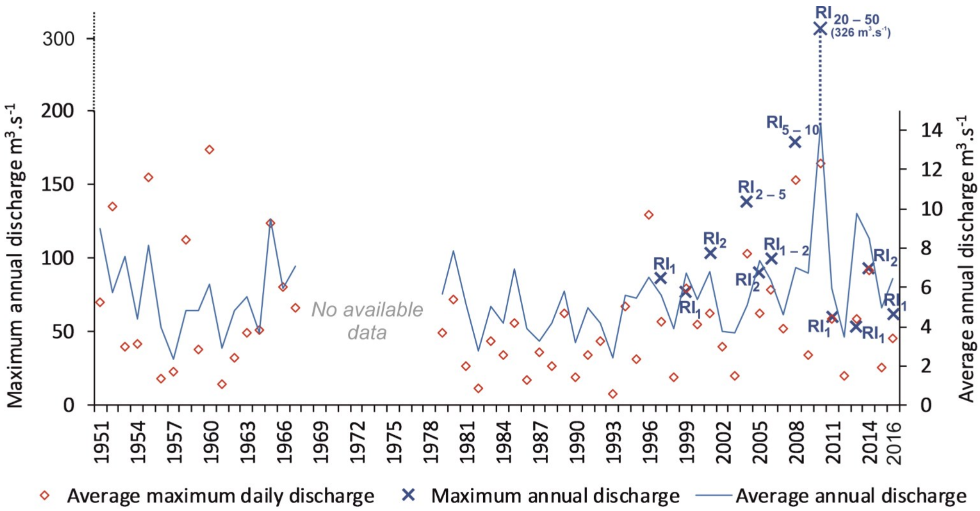


Fig. 3. Average and maximum annual discharge of the Hornád River, measured at the Spišské Vlachy gauging station (1951 – 2017)

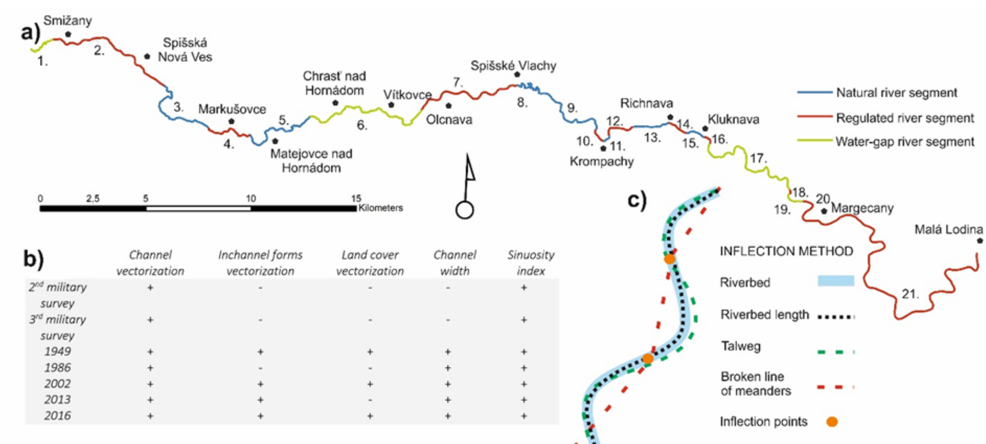
Graphical outputs compiled by the authors based on data from Slovak Hydro-Meteorological Institute (SHMI).

The study area of the Hornád River is located in a moderately warm and humid climate with an average annual temperature of 6 – 8 °C and an average annual precipitation of 550 – 800 mm (Faško and Šťastný 2002). Currently, there are three gauging stations (Spišská Nová Ves, Spišské Vlachy and Margecany) located at the studied river reach. Evaluation of the maximum and average annual discharge at the Spišské Vlachy gauging station (Fig. 3) reveals the higher values of both, the maximum (1952 – 135 m^3.s^{-1}; 1955 – 155 m^3.s^{-1}; 1958 – 112 m^3.s^{-1}; 1960 – 174 m^3.s^{-1}; 1965 – 124 m^3.s^{-1}), and average (1951 – 8.96 m^3.s^{-1}; 1953 – 7.56 m^3.s^{-1}; 1955 – 8.15 m^3.s^{-1}; 1965 – 5.97 m^3.s^{-1}; 1967 – 7.04 m^3.s^{-1}) discharges during hydrological period 1951 – 1967. The relatively low maximum discharge period after 1979 was interrupted by a flood event in 1996 with 2 – 5-year recurrence interval (RI; 129.70 m^3.s^{-1}). Hydrological data in the study period from 2002 to 2017 reveals three extreme flood events. In 2004, the maximum annual discharge reached 103.20 m^3.s^{-1} (2-5-year RI), in 2008 reached 152.45 m^3.s^{-1} (3rd degree of flood activity, 5 – 10-year RI) and in 2010, reached 163.77 m^3.s^{-1} (3rd degree of the flood activity, 20-50-year RI). In this context it should be noted that degree of flood activity in Slovakia is measured in scale from 1 to 3, where 1st degree is the lowest and 3rd is the highest level of flood activity.

METHODS

The morphological evolution of the river channel and land cover changes in its buffer zone were analysed from data consisting of the second (1819 – 1827) and third military (1869 – 1887) survey maps, two sets of aerial images (1949 and 1986), and three sets of ortophoto mosaics (2002, 2013 and 2016). The aerial images and orthophoto mosaics had been captured in regular water level and the low flow conditions. The data were chosen in such a manner, that the range of river regulation and the morphological impact of flood events could be evaluated. The second military survey (1806 – 1869) with a scale of 1:28 000 captures the territory of the eastern part of Slovakia in 1819 – 1827. The third military survey (1869 – 1887) was realized on a scale of 1:25 000. The black-and-white aerial images from 1949 with 0.5 m pixel resolution capture the river morphology before the extensive river regulation and after the river regulation in 1986. The co-loured ortophoto mosaics cover the periods of 2002 (0.5 m pixel resolution), 2013 and 2016 (both in 0.2 m pixel resolution). The State archive in Spišská Nová Ves (Ministry of Interior of the Slovak Republic, State archive in Košice, Spišská Nová Ves branch) provided historical information to understand the progress and the extent of anthropogenic intervention on the Hornád River during the 19th and at the beginning of the 20th century.

The spatial data has been processed using the ArcGIS 10.3 software in the coordinate system S-JTSK Krovak EastNorth, where the bank line, channel width, the number and area of in-channel landforms (lateral bar, mid-channel bar and island), anthropogenic intervention and land cover changes were identified and vectorised (Figure 4b). The bank line was delineated by the edge of the river bank at the bank-full stage, i.e. the line dividing the channel from the surrounding vegetation. There could be an inaccuracy in the delineation of the bank edge caused by vectorization error, shading or different stage of water level. However, the inaccuracy should be marginal and should not distort the result. Due to the unacceptable resolution quality of the aerial photos from 1986, the in-channel landforms could not be vectorised and therefore, they were not evaluated (Fig. 6). Within the river channel, we have identified several types of anthropogenic intervention (dam reservoir, stony grade-control structure, small hydroelectric power station, flood protection dike construction and bank strengthening) validated with the information provided by the Slovak Water Management Enterprise (SWME) and field survey.



	Channel vectorization	Inchannel forms vectorization	Land cover vectorization	Channel width	Sinuosity index
2nd military survey	+	-	-	-	+
3rd military survey	+	-	-	-	+
1949	+	+	+	+	+
1986	+	-	-	+	+
2002	+	+	+	+	+
2013	+	+	-	+	+
2016	+	+	+	+	+

Fig. 4. a) The study river reach of the Hornád River divided to the three types of river segments; b) Summary table of data vectorization; c) Sinuosity index calculation scheme using the inflexion points method by Garícia (2015)

For the purposes of mapping the land cover changes, we created a 50 m wide buffer zone from the edge of the riverbank line in ArcGIS software. Its final width was represented by the furthest border of four buffer lines overlay, together one over the other in four periods (1949, 1986, 2002 and 2016). Five land cover classes have been distinguished within the buffer zone: grasslands, forests and bushes, arable lands, a built-up area and communications and the other area (low flow channel, area without vegetation, quarry and reef area). However, we must point out that the land cover identification was not primarily used for the land cover changes observation, but for analysing the impact of these changes on the river channel and its surroundings (Liébault and Piégay 2002). Based on this approach, we could relatively precisely evaluate the bank stability or bank migration, or alternatively, assume its further development (Rusnák and Lehotský 2014).

In this paper, we further focused on identifying the anthropogenic changes of the river channel. The studied river reach was divided into three river segments (Fig. 4a) based on the extent of recent anthropogenic intervention (in 2016): the regulated river segment including river reach no. 2, 4, 7, 10, 12, 14, 16, 18, 20 and 21, the natural river segment including river reach no. 3, 5, 8, 9, 11, 13 and 15 with minimal anthropogenic intervention (bridges, self-help bank revetment), and the water-gap river segment including river reach no. 1, 6, 17 and 19. Overall 21 river reaches have been assorted. For every type of river segment, we identified the stream line length, the rate of lateral movement, channel width and calculated the sinuosity index. The channel width was calculated as a ratio of the channel area to its length. The changes of the channel planform representing by the sinuosity index was calculated using the method of automatic classification „Inflection sinuosity method" (Garícia 2015), which uses inflexion points as the location of angel β changes (Fig. 4c).

RESULTS

During the studied time period (1819 – 2016), the Hornád River underwent significant morphological changes due to anthropogenic interventions and the occurrence of flood events. The most extensive flood events occurred in the summers of 1813 and 1878. In the 20th century, more significant discharges (Fig. 3) contributed to the locally formation of the meandering planform of the river channel in the 1950s (1952, 1955 and 1958), in the 1960s (1960 and 1965) and in 1996. The floods from 2004, 2008 and 2010 as main factors caused the lateral bankline shift, supported the channel to widen and the in-channel morphological dynamics by the formation of new gravel bars. Based on the mutual synergy of anthropogenic intervention and flood effect on the channel of the Hornád River, we identified four evolutionary periods:

Pre-regulation period I: from 1819 (2nd military survey) to 1949

Based on the analysis of historical maps from the 19th century, it can be stated that the Hornád River was initially a meandering river, with minimal anthropogenic intervention (water mills, millraces and weirs) in the vicinity of towns (Fig. 5). The first documented river training carried out in the river reach no. 12, near the Krompachy town, dated to 1937. In the Spišská Nová Ves town (river reach no. 2), the construction of a railway bridge was dated to 1938, of weirs to 1850, and of the flood protection dike to 1886. More extensive river training took place during the forties of the 20th century. The significant factor influencing the morphological development of the Hornád River was the occurrence of flood events. The most extensive floods during 19th century have been recorded in early summer of 1813 and august 1878. In the study time period between the 2nd and 3rd military mapping, the stream line length was shortened by 4 786 m. In 1949 the stream line length increased by 3,133 m. The stream line length between 1819 and 1949 was shortened by a total of 1,653 m. The sinuosity index in both military survey maps reached the value of 1.33 and 1.32 in 1949, respectively. During the first evolutionary period, the length of natural river segment of the Hornád River was represented by 35.4 km, i.e. 45.8% of the total length of the study river reach.

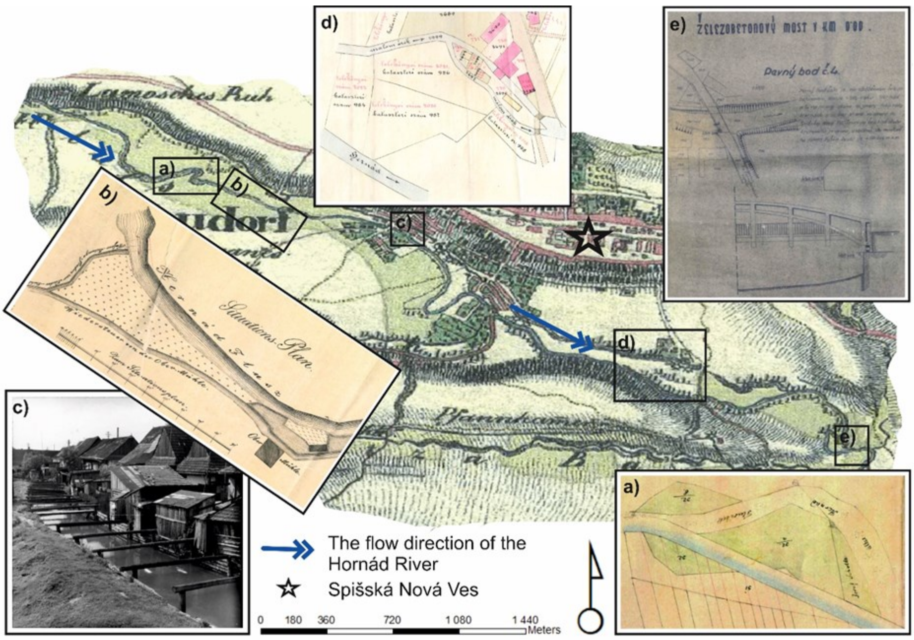


Fig. 5. Examples of anthropogenic intervention documented on the Hornád River in the Spišská Nová Ves town on the 2nd military survey map: a) river regulation plan from 1886, b) weir plan from 1850, c) millrace photo (year unknown, photo source: http://www.pamiatky.sk/Content/PZ_ZASADY/Spisska_Nova_Ves/Historicka%20fotodokumentacia.pdf), d) water mill and millrace plan from 1896, e) railway bridge construction plan from 1938.

Intensive regulation period II: 1950 – 2001

Significant anthropogenic interventions in the river channel and its buffer zone, including the riparian vegetation zone, occurred to an enormous extent in the middle of the 20th century. Flood protection and acquisition of arable land on the Hornád floodplain were the main purposes of these interventions. The channel straightening due to artificial cut-off the meanders nearby Spišská Nová Ves town and Spišské Vlachy settlement, as well as banks armouring by quarry stone nearby Spišská Nová Ves, Krompachy, Margecany, Smižany, Richňava and Kluknava settlements were recorded. In some river reaches, the banks of the Hornád River were reinforced by flood protection dike construction (e.g. nearby Smižany settlement). Reinforced banks with planted vegetation are documented nearby Spišské Vlachy and Smižany settlements as well. The most significant intervention which influenced the natural morphological evolution of the river channel was the construction of a hydroelectric power plant, the Ružín dam reservoir between 1962 and 1972. Overall, the stream line length has been shortened from 77.3 km (1949) to 72.3 km (2002). The consequence of these interventions, the initially meandering Hornád River has been straightened.

The channel width of the all study river segments had a decreasing trend from 1949 to 2002 (Fig. 6) as well. The river channel narrowed from an average of 21.9 m (1949) to 18.3 m (1986). In 1949, the channel width of the river reach no. 14 reached 110 meters, while after the river training intervention, its width is only around 20 m in 2002. In 1949, the river reach no. 2, passing through the Spišská Nová Ves town, locally reached 60 – 70 m wideness. And in 2002 we recorded the similar trend due to river regulation, when it had only 18 – 20 m. Furthermore, narrowing of the river channel also occurred in initially formed river segments without direct anthropogenic interventions (overall in 1949 – 21.6 m, in 1986 – 18.8 m, and in 2002 – 16.4 m). Between 1949 and 2002, the channel narrowing led to a decrease in the area as well as number of both lateral and mid-channel bars. Its number in regulated river segments decreased from 111 to 45, and in water-gap valleys from 64 to 22 (Fig. 6). However, in natural river segments, a slight increase was observed (from 62 to 76). In the study period from 1949 to 2002, there was a significant reduction or even disappearance of islands in the regulated river segments and water-gap valleys. On the other hand, we observed an increase in the number and the area of islands in natural river segments. The changes in the stream line length affected the values of the sinuosity index (Fig. 6). In the regulated river segment, the sinuosity index decreased from 1.21 (1949) to 1.13 (1986 and 2002). Between 1949 and 2002, the maximum sinuosity index in regulated river reach no. 7 decreased from 1.58 to 1.12. The sinuosity index in natural river segments increased from 1.25 (1949) to 1.32 (2002). The average sinuosity index in the natural river reach no. 8, nearby the Spišské Vlachy settlement, increased from 1.5 in 1949 to 1.95 in 2002. In water-gap valleys, the average sinuosity index remained unchanged.

Since 1949, there has been a gradual decline of arable land and grasslands in the buffer zone of the river channel, which have been replaced by a built-up residential area with roads, .area with roads, forests and shrubs (Fig. 7). River banks were stabilized by quarry stone as well as a tree vegetation. Natural river segments without any form of regulation were the most affected by flood effect with no more than 5-year RI, except one extreme flood event in 1996 (129.7 $m^3.s^{-1}$, with 2 – 5-year RI) between 1979 and 2002. The lack of extreme flood events led to overall stabilization of the erosion-accumulation processes and the channel planform simplification leading to the narrowing of the riverbed by an average of 4.3 m. The number and area of gravel bars and islands was reduced too.

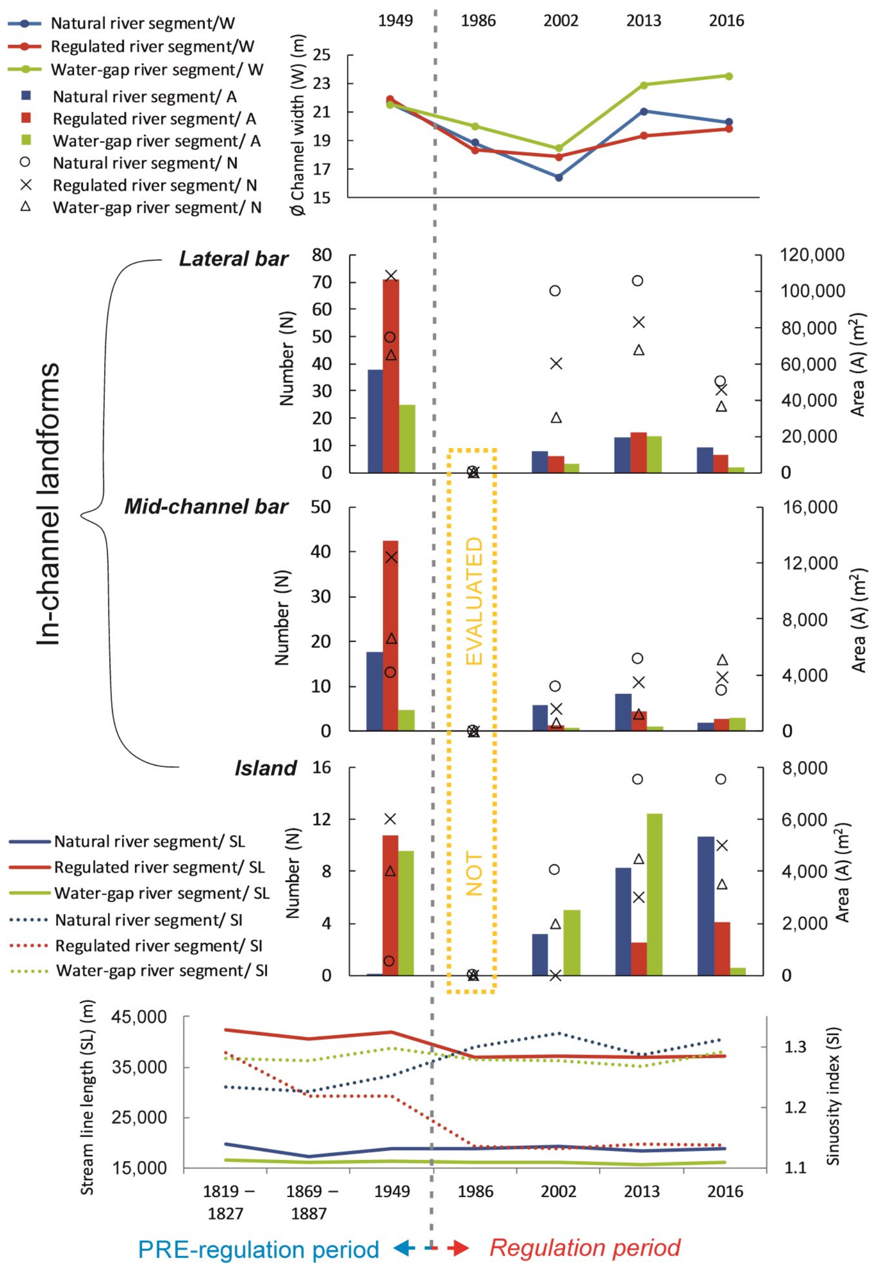


Fig. 6. Temporal evolution in the channel width, the number and area of in-channel landforms (lateral bars, mid-channel bars and islands), stream line length, and the sinuosity index on the Hornád River from 1819 to 2016, from pre-regulation to regulation period respectively

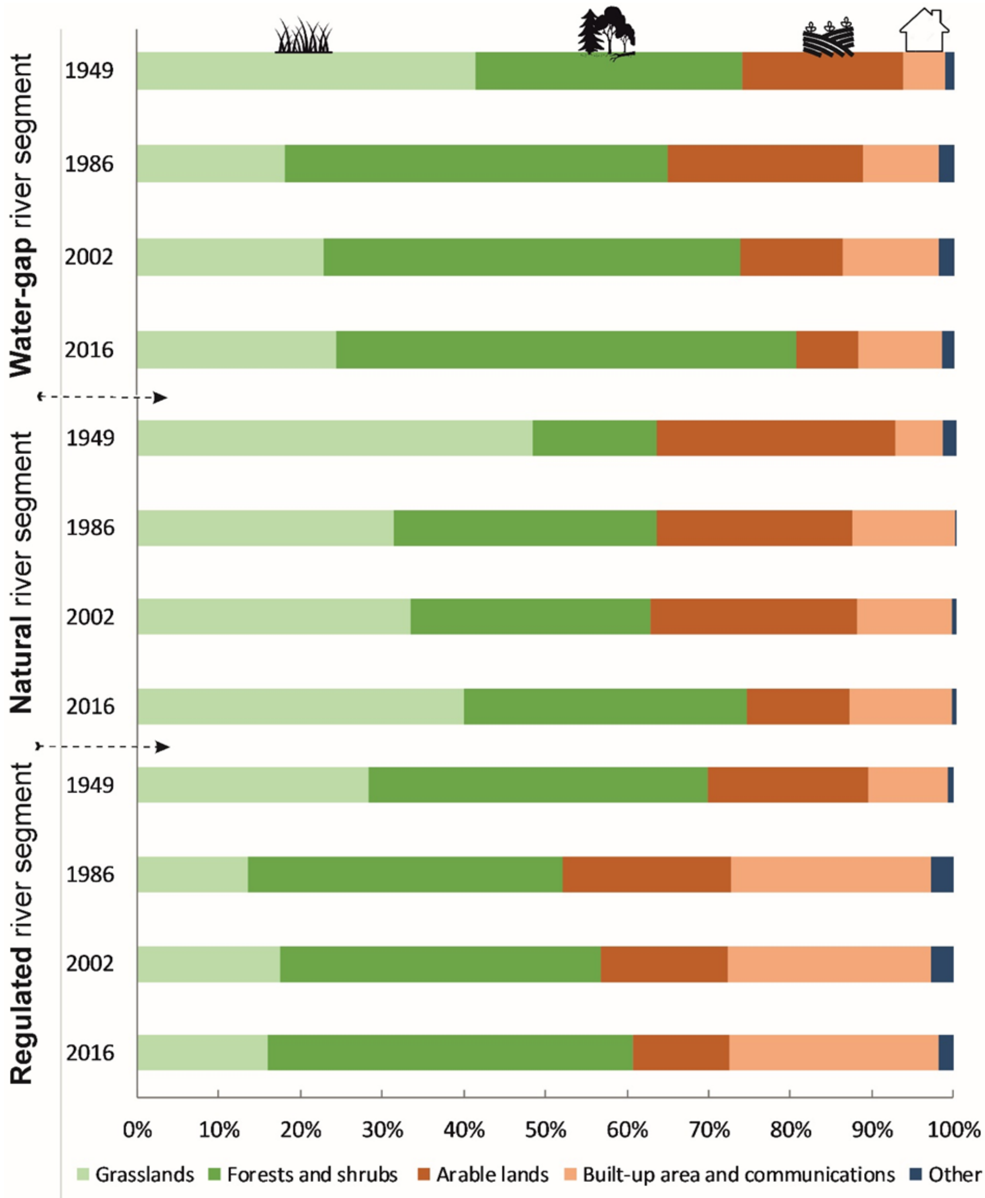


Fig. 7. Land cover changes on the delineated three types of the Hornád River segment's buffer zone in the time horizons 1949, 1986, 2002 and 2016

Local regulation period III: 2002 – 2010

By 2002, 51.4% of the 72 km long studied river reach of the Hornád River had been affected by river training presented by channel straightening, bank armoring, stony grade-control structures, constructions of weirs, and small hydroelectric power plants. Significant river channel morphological changes between 2002 and 2010 are attributed to the impact of a series of flood events (2004, 2008 and 2010) with the 5 – 50-year RI (Fig. 3). Before this flood effect, the channel width in all types of studied river segments achieved the lowest values (in 2002, Fig. 6). The lowest values were identified also for the number and the area of in-channel landforms. However, changes in discharge had a significant morphological effect mainly on freely meandering river reaches (Fig. 8). The neck of the Markušovský meander (river reach no. 5) was cut-off during the flood events series in 2008 and 2010 (Fig. 1). The value of sinuosity index in natural river segment reached 1.32 (2002). Based on the analysed of source data, we also identified 320 m long and up to 14 m wide floodplain stripping caused by washing away riparian vegetation in the river buffer zone of the river reach no. 7. The river channel widened in all river segments, from an average of 17.8 m to 19.4 m in regulated river segments, from 18.4 m to 22.8 m in water-gap valleys and from 16.4 m to 21.1 m in natural river sections.

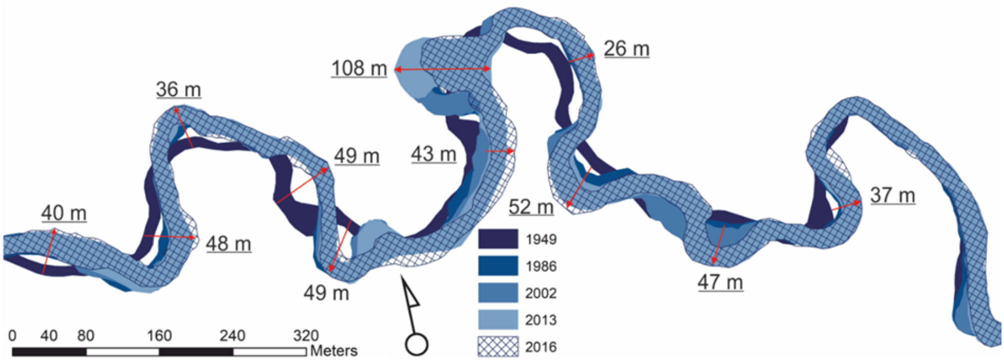


Fig. 8. Evolution of the free meanders localised in the river reach no. 8 nearby the Spišské Vlachy settlement between 1949 and 2016 expressed by overall bends shift (m).

Local regulation period IV: 2011 – 2016

The last period of morphological evolution of the Hornád River is characterized by a gradual decrease in the magnitude of flood effect (1 – 2-year RI, Fig. 3), which occurred after the year 2010. The stabilization of the river channel and increased area of tree vegetation was documented. The intensity of the changes in the channel length, channel width and sinuosity of the river channel were reduced considerably or stopped completely. Furthermore, the lack of flood events led to a decrease of the number and area of lateral bars, mid-channel bars, and islands after significant morphological effect of flood event in 2010 recorded on data set from 2013. In the natural river segment, the number of all monitored in-channel forms reached the maximum values in 2013 for the entire monitored period of 1949 – 2016. In 2016, we observed free meandering processes only on river reach no. 8 (Fig. 8) in the total length of 2,278 m. In addition, we also observed a more extensive lateral channel shift in the river reach no. 5 accompanied by extensive bank erosion on both sides of the river channel. Currently, observed natural meandering processes represent just 9.45% of the entire length of the studied Hornád River. In this period, morphological changes that occurred mainly in natural river segments were further represented by stream line extension by 310 m and growth of the sinuosity index from 1.28 (2013) to 1.31 (2016).

DISCUSSION

The Hornád River has undergone significant anthropogenic interventions from the 19th century until the present, which mainly affected its planform evolution. The second and third military surveys maps, drafted mainly the planform geometry of the studied river reach of the Hornád River. On the other hand, data on the inner dynamics of the river channel were missing. We evaluated anthropogenic interventions on the river channel indirectly, by monitoring the change in channel length (stream line), and sinusoity index changes. We were unable to accurately determine the intensity, magnitude and/or full impact of the changes in discharge or land use changes in the vicinity of the river channel, which had morphological impact on the Hornád River. A similar problem is pointed out, for example, by the work of Liébault and Piégay (2002), who in the south of France between 1830 and 1954 recorded an increase in the proportion of grassland and shrubland, and a reduction in arable land. These land cover changes caused a reduction in the amount of sediment in the river channel, which has supported the stabilization of river bars by vegetation cover. A similar change in land cover constituted by overall decreasing grassland and arable land area which was also recorded in the Hornád River (Fig. 9). Between the 2nd and 3rd military mapping, the Hornád stream line length was shortened. Subsequently, by 1949, the stream line length and sinuosity index had increased. Such significant changes in thalweg length increase had also been observed between the 19th and the first half of 20th century in Hungary on the Bodrog River by Mecser et al. (2008). They attributed these changes to the natural processes of meandering and the equilibrium theory (Brierley and Fryirs 2005) dealing with the self-regulation of river channels via negative feedback mechanisms to impacts of disturbance events.

While half of the river regulation works on the Sereď-Komárno river reach of the Váh river was completed by 1839 (Procházka and Pišút 2015), the process of river training on the Hornád River only begun during the 20th century. These human interventions corresponded to previous public requests related to flood control management and water energy supply. Therefore, aerial photographs from 1949 captured the natural erosion-accumulation processes represented by freely meandering river reaches on the Hornád River.

After 1949, there were several flood events (Fig. 3) before the extensive channel regulations. However, the period from 1979 to 2004 is noticeable by low discharges, so the flow had a very negligible impact on the river channel. Due to the lack of flood events from 1979, the river channel was narrowed. The narrowing of the Hornád River channel due to low discharge between the years 1953 and 2002 was also observed in Hungary by Kiss and Blanka (2012). It is the flood events that indicate the dynamics of the water flow, as they have a decisive effect on their behaviour (Rusnák and Lehotský 2014, Krzemień et al. 2015, Kidová et al. 2016 and Rusnák et al. 2016). Frasson et al. (2019) find strong associations between channel width and water flow slope, meander wave-length, sinuosity, and discharge.

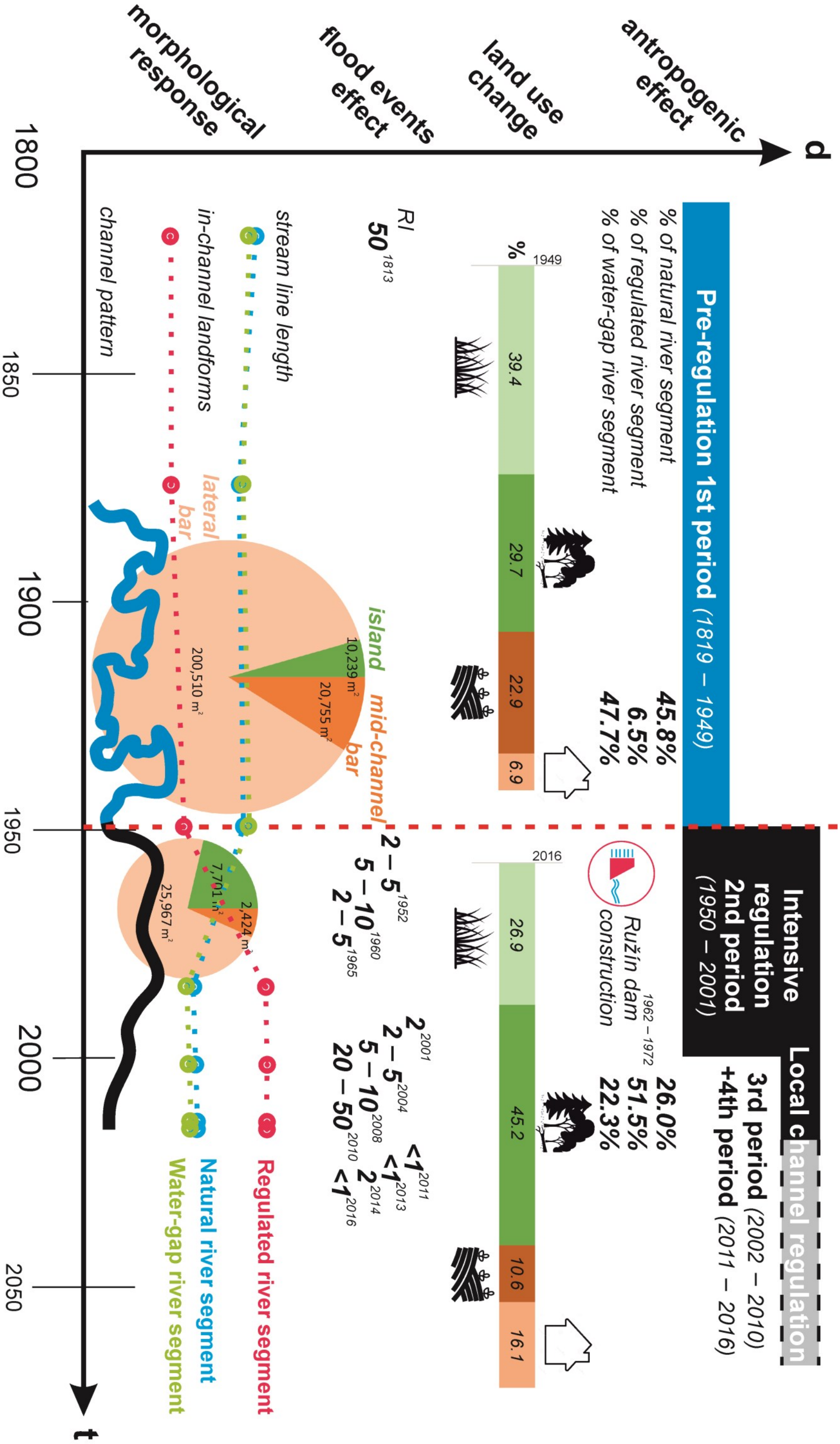


Fig. 9. The Hornád River evolutionary scheme (the pre-regulation and regulation period from 1819 to 2016)

From 2002 – 2016, the stable river channel was most significantly affected by discharge changes. Flood events in 2008 (5 – 10-year RI) and 2010 (20 – 50-year RI) contributed to a more dynamic channel evolution, by increasing the number (+40%) and area (+ 130%) of gravel bars between 2002 and 2013. The trend of channel simplification and stabilization was reversed, geomorphological structures and processes that support the natural dynamics of the river channel were restored. Another of the impacts of flood events is the widening of the river channel in all types of river sections, in the natural river segment by an average of 3.6 m, in regulated river segment by an average of 1.4 m and in water-gap river segment by an average of 4.4 m. A series of flood events in 2004, 2008 and 2010 accelerated the process of later bank erosion (Fig. 9), therefore reversing the process of narrowing. The formation of a higher point-bar surfaces and newly vegetated surfaces were found on the Hornád River in Hungary after overbank floods (after 2004) by Kiss and Blanka (2012).

The actual extent and impact of the series of flood events in 2004 (2 – 5-year RI), 2008 (10-year RI) and 2010 (in May 2 – 10-year RI and in June 20 – 50-year RI) is also evidenced by the fact that in the Spišské Vlachy settlement, a road and railway bridge was damaged by its partial demolition in river reach no. 7 during the flood of June 2010 (Fig. 10 a, b and c). In the river reach no. 8, the river channel widened by an average of 4 m and lateral channel shift reached locally up to 20 m (2.2 m/ year, Fig. 10 d). Long-term flood effect manifested itself in doubling the velocity of lateral channel movement on the Topľa River from an average of 0.8 m/ year (1987 – 2002) to 1.6 m/year (2002/2009) (Rusnák and Lehotský 2014 and Rusnák et al. 2016). The development and movements of meanders and the related bank erosion are, on the other hand, also dependent on local conditions (bank composition, bank height) and on the stage of development of a given meander (Blanka and Kiss 2011). However, the rate of erosion may also depend on the actual level of the water in the river channel and a soil consists (Mirijovsky and Vavra 2012) or on the position of the erosive bank in the meander systems (Miřijovský and Langhammer 2015).

The most significant lateral channel shift of the Hornád River was the meander neck cut-off near the Markušovce settlement (Fig. 1). Between 2002 and 2013, a shift of the right bank of the channel by 124 m was recorded and attributed to a series of flood events in 2008 and 2010. The lateral migration on free meanders near the Spišské Vlachy settlement between 2002 and 2013 reached a shift of 28 m. During flood events between 2002 and 2009, a meander neck cut-off on the Topľa River with the channel shift of 443 m was presented in the study of Rusnák and Lehotský (2014). Additionally, on the Hornád River in 2013 and 2016, the lateral bank erosion on both sides of the river channel has been identified in river reach no. 5 (Matejovce nad Hornádom settlement) and no. 8 (Spišské Vlachy settlement).

Overall, for the study river reach of the Hornád River, with a gradual decrease in the magnitude of discharges after 2010 (from 20 – 50-year RI to 1 – 2-year RI, Fig. 3), in 2016 we recorded a decrease in the number (- 38%) and area (- 52%) of lateral and mid-channel bars compared to 2013 (Fig. 6). The number of islands increased by 6% and their area decreased by 34%. However, this trend was not uniform for all types of river segments. The decreased sinuosity index of the Hornád River as a response to the flood events between 2002 and 2013 was manifested by straightening the natural river reaches. Vice-versa, due to the absence of flood events (1986 – 2002 and 2013 – 2016), the sinuosity index increased. On the Ondava River, the flood events at the turn of the 1980s and 1990s caused an increase of sinuosity of the river channel from 1.34 to 1.5. On the contrary, after the floods of 2004, 2006 and 2008, the sinuosity index decreased again (Rusnák and Lehotský 2014). Therefore, flood events may not be a decisive factor influencing the sinuosity of a river channel. Riparian vegetation, which affects the rate and extent of erosion, and thus the magnitude and direction of lateral channel migration, may be a significant factor. Bank cohesion is influenced mainly by the type and density of vegetation, while the sinuosity increases with the resistance of the banks (Ebisemiju 1994). We noticed the same continuity in river reach no. 8, where the sinuosity index increased (1949 – 1.69, 2004 – 2.08 and 2016 – 2.05) together with the increase of the area of tree vegetation (4.94 ha in 1949, 7.33 ha in 2004 and 8.46 ha in 2016).

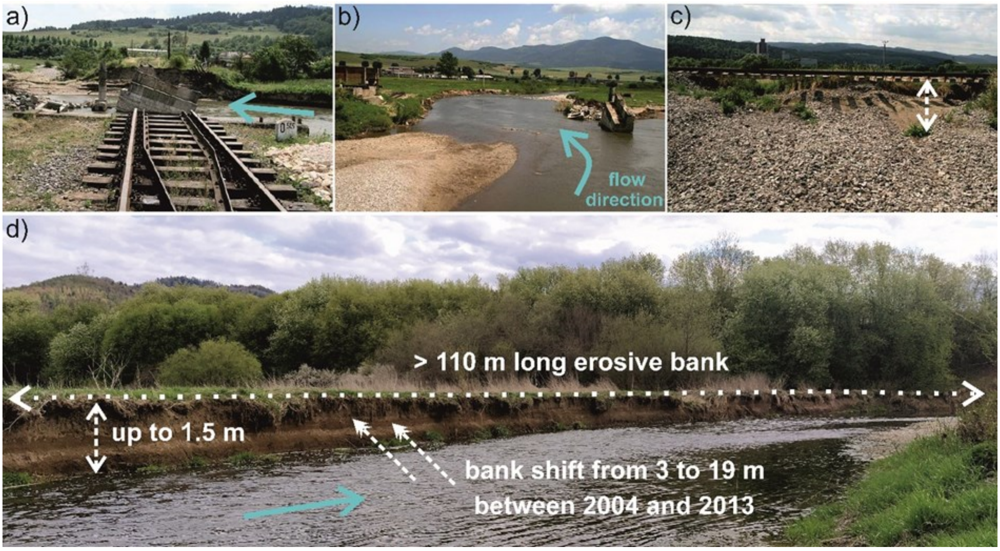


Fig. 10. a) The railway bridge on the Hornád River (the view in the cross-section direction) destroyed by an extreme flood event in 2010 near Spišské Vlachy settlement in the river reach no. 7. b) The view from the middle of the channel. c) The ground of the railway track was washed up in several places as a further consequence of the flood event in 2010 (Photos source: https://www.zeleznicne.info/pda/pdaview.php?link=2010070004&PDAkatNazev=Trate%20180-188&fbclid=IwAR119syLiJYkmUlbzJyqdx-cg6N7ja6Cmf6e3hhndeK-qsSF7TlEXq244_I). d) Erosive right-side bank of the Hornád River in a freely meandering river reach no. 8 near the Spišské Vlachy settlement (Photo: P. Labaš).

In relation to land cover changes, since 1949, the number of grassland and arable land areas have gradually decreased. The arable land near the river channel has been abandoned. These areas were gradually replaced by tree vegetation and built-up area, while increasing the proportion of tree and shrub vegetation around the stream stabilized the bank erosion. Individual trees lining the channel bank could affect the morphology of the channel and its pattern by stabilizing of the river banks (Grešková and Lehotský 2007). In addition to the remodeling of the channel planform of the Hornád River, the flood events in 2004, 2008 and 2010 also had a significant effect on the riparian vegetation in the buffer zone. In the regulated river reach no. 7, where the banks were armoured by vegetation, the extensive bank erosion and floodplain stripping in the length of 320 m and width of almost 14 m was recorded. Vegetation cover and species representation are lower in regulated river segments than in natural ones (Nilsson et al. 1991), which may have an influence on shifting the threshold value of the anti-erosion effect of riparian vegetation. The maximum annual discharge decreases after 2010 started a process of vegetation succession of in river reaches of floodplain stripping coupled with gradual bank stabilization. The impact of flood events in the studied Hornád River sub-basin could mitigate the distribution of the tree vegetation cover by the longer time discharge distribution (Bahremand et al. 2007). The suitable management of riparian vegetation could increase flood flow velocity and decrease the duration of floods (Kiss et al. 2021)

CONCLUSION

This paper analyses the identification of the key factors responsible for the morphological degradation of the meandering Hornád River over the last 197 years (from 1819 to 2016). On three types of river segments, we monitored their morphological response to human intervention and the impact of flood events. The four time periods of these responses were identified: pre-regulation period of 1819 – 1948, and three regulation periods with mutual effect of flood effect of 1949 – 2001, 2002 – 2012, and 2013 – 2016. Until the middle of the 20th century, free meanders were characteristic for the wide floodplain of the 72 km long studied river reach. From the geomorphology point of view, the engineering regulation on the river channel and the floodplain of the Hornád River caused the channel planform simplification, channel narrowing and straightening, a decrease of the sinuosity index, and loss of free meanders coupled with natural lateral shift. However, at the end of the long-term regulation period, the flood events in 2004, 2008 and 2010 reversed a declining trend of channel narrowing and planform simplifying. The high magnitude of the floods started the erosive banks expansion, floodplain stripping, the increase in the number of in-channel landforms and the disturbance of riparian vegetation.

In 2016, on the middle course of the studied Hornád River, the meandering processes occurred at a length of 2 278 m. Compared to 1949 (11 354 m of the total length of the studied river reach), a decrease of 79.54% was recorded. The Hornád River recently meandered only on two river reaches: no. 5 near the Matejovce nad Hornádom settlement with several erosive banks and potential for lateral migration, and the river reach no. 8 near the Spišské Vlachy settlement, where three active free meanders are located. Both of these sites are important from a scientific point of view, as they offer the possibility of monitoring fluvial geomorphological processes (lateral erosion, channel incision, sedimentation changes, flood impact), as well as from the protection and preservation point of view of free meandering processes. There is no anticipation of further significant interventions to the river channel, on such a massive scale as those that took place during the last century. Nevertheless, we will continue to monitor defined river reaches and make efforts to spread scientific knowledge among a wide spectre of stakeholders to support the appropriate river management measures.

This research was supported by the Science Grant Agency (VEGA) of the Ministry of Education of the Slovak Republic and the Slovak Academy of Sciences (02/0086/21). Hydrological data were provided by the Slovak Hydrometeorological Institute. Data related to river regulation were provided by the Slovak Water Management Enterprise. Historical materials were provided by the Ministry of Interior of the Slovak Republic, State archive in Košice, Spišská Nová Ves branch.

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ANTROPOGÉNNE A ENVIRONMENTÁLNE VPLYVY NA RECENTNÚ MORFOLOGICKÚ DEGRADÁCIU MEANDRUJÚCEHO VODNÉHO TOKU HORNÁD

Predkladaná práca sa zaoberá zhodnotením vplyvu antropogénnych zásahov a zmeny povodňových prietokov na morfologickú odozvu vodného toku Hornád Cieľom je kvantifikovanie morfologických zmien na 72 km dlhom riečnom úseku vodného toku Hornád od 19. storočia po súčasnosť (1819 – 2016). Pôvodne bol vodný tok do polovice 20. storočia prirodzeným (neregulovaným) vodným tokom so striedajúcimi sa úsekmi prielomových dolín a charakteristických meandrov na jeho nivách. Od polovice minulého storočia došlo k jeho výrazným reguláciám, ako je spevňovanie brehov a výstavba vodnej nádrže Ružín.

V práci sme na základe hydrologických údajov o vodnom toku, z máp a podkladov z diaľkového prieskumu Zeme (vojenské mapovanie, letecké snímky a ortofotosnímky) a informácií o antropogénnom vplyve retrospektívne zhodnotili ich efekt na morfológiu koryta. Skúmaný riečny úsek Hornádu bol rozdelený na tri typy riečnych segmentov: prirodzené riečne segmenty, zregulované riečne segmenty a prielomové doliny. Na základe ich morfologickej reakcie na zásah človeka a vplyv povodňových udalostí boli identifikované štyri časové periódy ich vývoja: prvá perióda pred reguláciami 1819 – 1948 a tri rôzne intenzívne periódy regulácií vodného toku s prihliadnutím na vplyv povodňových udalostí (druhá perióda 1949 – 2001, tretia perióda 2002 – 2012 a štvrtá perióda 2013 – 2016). Sledované boli predovšetkým zmeny vo vývoji vnútrokorytových foriem, v dĺžke, šírke a indexe kľukatosti vodného toku, ako aj zmeny v krajinnej pokrývke.

Zatiaľ čo voľné meandre a prielomové doliny boli charakteristické pre vybraný vodný tok do polovice 20. storočia, regulácie vodného toku, stavba vodnej nádrže, priečnych prahov či hatí nenávratne zmenili charakter Hornádu. Z geomorfologického hľadiska inžinierska regulácia na koryte a nive Hornádu spôsobila zjednodušenie pôdorysu koryta, zúženie a napriamenie koryta, zníženie indexu kľukatenia a stratu voľných meandrov spolu so stratou schopnosti vodného toku prirodzene laterálne migrovať. Regulácie vodného toku negatívne ovplyvnili pôdorys vodného toku Hornád zúžením koryta, skrátením dĺžky prirodzene meandrujúcich úsekov a celkovým zmenšením plochy koryta. Nízke prietoky v druhej polovici minulého storočia zastabilizovali už upravený pôdorys. Tá však bola neskôr ovplyvnená povodňovými udalosťami v roku 2004, 2008 a 2010, ktoré zvrátili klesajúci trend zužovania koryta a zjednodušovania pôdorysu vodného toku. Veľké záplavy vyvolali intenzívnu laterálnu eróziu, nárast počtu vnútrokorytových foriem koryta a narúšanie brehových porastov. Tieto povodňové udalosti mali výrazný vplyv na morfologické zmeny vodného toku predovšetkým v prirodzených, ale prekvapivo v menšej miere aj v regulovaných riečnych úsekoch. V roku 2016 na strednom toku skúmanej rieky Hornád prebiehali procesy meandrovania v dĺžke 2 278 m. V porovnaní s rokom 1949 (11 354 m z celkovej dĺžky skúmaného riečneho úseku) bol zaznamenaný pokles voľného meandrovania o 79,54 %. Vodný tok Hornád v súčasnosti meandruje len na dvoch riečnych úsekoch: č. 5 pri obci Matejovce nad Hornádom s viacerými eróznymi brehmi a potenciálom laterálnej migrácie a č. 8 pri obci Spišské Vlachy, kde sa nachádzajú tri aktívne voľné meandre. Obe tieto lokality sú významné tak z vedeckého hľadiska (ponúkajú možnosť sledovania prirodzených geomorfologických procesov – laterálna erózia, zárezávanie koryta a transport sedimentov), ako aj z hľadiska ochrany prírody v súčasnosti vzácnych a jedných z posledných takýchto riečnych úsekov. Ďalšie výrazné zásahy do koryta vodného toku v takom masívnom rozsahu, aké sa udiali v minulom storočí, sa nepredpokladajú. Na podporu vhodných opatrení pri manažmente vodného toku Hornád však budeme pokračovať v monitorovaní vybraných riečnych úsekov a vynaložíme úsilie na šírenie vedeckých poznatkov medzi čo najväčšie spektrum zainteresovaných strán.

Article first received: December 2021
Article accepted: May 2022