CHANNEL ADJUSTMENT OF A MIXED BEDROCK-ALLUVIAL RIVER IN RESPONSE TO RECENT EXTREME FLOOD EVENTS (THE UPPER TOPĽA RIVER)

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Recent increasing of magnitude and frequency of extreme flood events leads to exaggeration of the fluvial processes. Spatial and temporal aspects of extensive channel adjustment of the Topľa River in its piedmont segment are discussed. The changes of channel pattern were analyzed using remotely sensed imageries, whereas the vertical erosion was established by analysis of 78 cross-sectional profiles. Considering the relatively low size of the river (4^{th} – 5^{th} Strahler ord.), vast area was stricken with the active bank erosion during flood of June 2006 (1.42 ha) and July 2008 (3.43 ha). In addition, another flood in June 2010 occurred, but its effect was mostly vertical on average 0.33 m. Spatial distribution of the intensity of the processes of bank erosion and bed incision during these extreme events are suggested to be driven primarily by their magnitude (represented by discharge) and by channel inclination. Nevertheless, local controls such as presence of bedrock bottom or large woody debris jams bring uncertainties and contribute to nonlinear behavior of river channel during extreme events.

Key words: channel pattern, bedrock-alluvial channel, channel cross-section, extreme flood events, the Topľa River

INTRODUCTION

The climate had been changing throughout the time and so it is changing at present (BÜNTGEN et al. 2010). Apart from the causes, intensity and rate of recent climate fluctuation, which is in scope of climatologists, in geomorphology, the impact of accompanying extreme events on contemporary geomorphologic processes is the subject of interest. There are several studies assessing the geomorphologic response on historical climate changes in Central Europe (STARKEL 1995 and 2002), particularly the effect of the Little Ice Age in 16^{th} – 19^{th} centuries (STANKOVIANSKY and BARKA 2007). In last two decades, the number of case studies dealing with the geomorphological impact of extreme precipitation-runoff events on slope processes (STANKOVIANSKY et al. 2010, LIŠČÁK et al. 2010) and river channel processes (HRÁDEK 2000, KLIMEK et al. 2003, ZIELINSKI 2003, BRÁZDIL and KIRCHNER, eds. 2007, MORCHE et al. 2007, HAUER and HABERSACK 2009, TUROWSKI et al. 2009, BUCAŁA 2010, BAUCH and HICKIN 2010, RUSNÁK 2010, GALIA and HRADECKÝ 2011) is increasing. If considering these extreme events as the consequences of recent climate change, then implicitly the climate change has a profound influence on contemporary geomorphologic pro-cesses (GOUDIE 2006). The aim of this paper is to contribute to the documentation, that the recent climate fluctuations has a direct geomorphologic response.

The second aim is to outline the character of the morphological responses on extreme flood events, their magnitude/frequency distribution in both space and time and the controls driving the changing system of the Topľa River.

During last five years, the Topľa River in its piedmont reach went through significant morphologic transformation under impact of three extreme events. Summer heavy precipitation in June 2006, July 2008 and June 2010 enlarged the active river channel both in width and depth. The question is, whether this was just a fluctuation of the Topľa River behavior, or the channel went through a change in terms of BRIERLEY and FRYIRS (2005) and shifted at a different evolutionary level. A flood of similar magnitude occurred as well in the past, in

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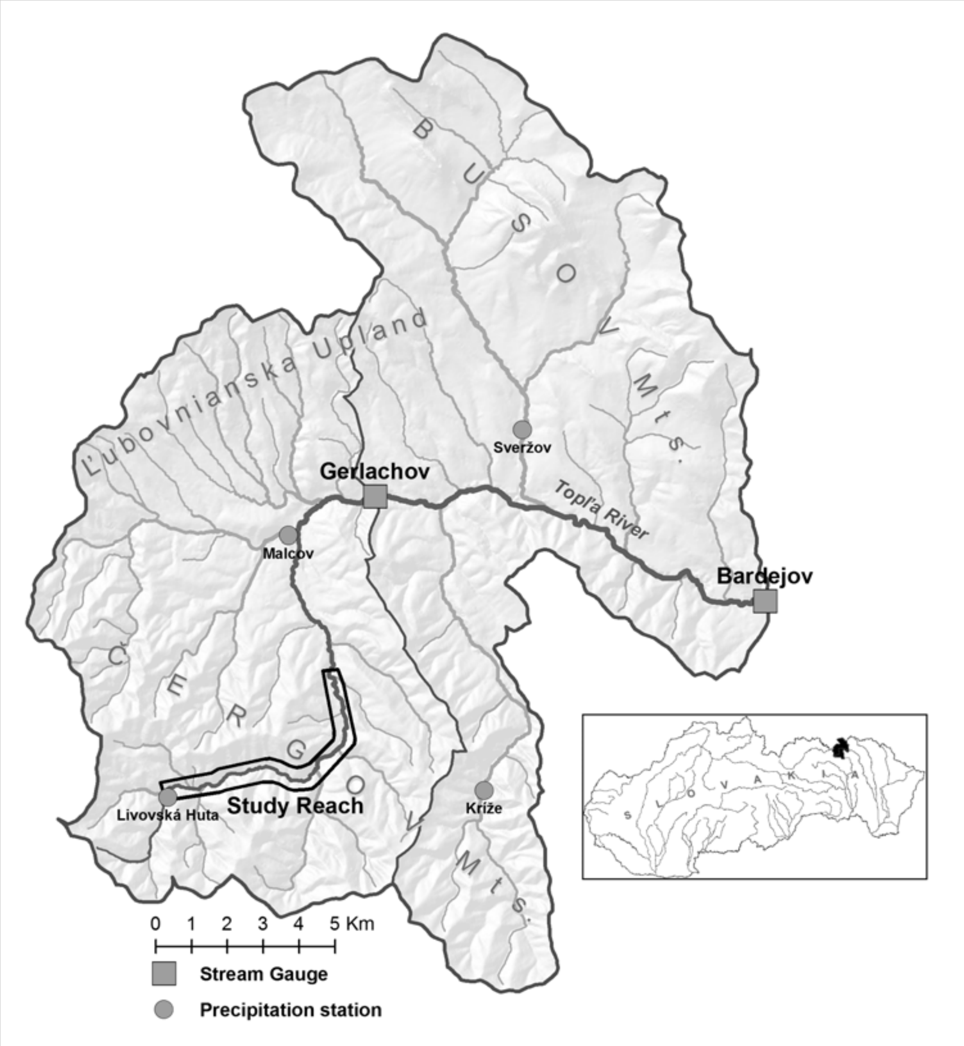


Fig. 1 Location of the study reach of the Topľa River and two closest gauging stations with their corresponding watersheds and precipitation stations

May 1987. The comparison of the rate of channel adjustment during both recent and past extreme events may bring more light into this.

STUDY REACH

The examined 8.7 km long channel reach of the Topľa River (**Fig. 1**) is located within the Čergov Mts. range, with the highest peak Minčol (1157 m a. s. l.) whereunder the river springs at the altitude of 1015 m. The mountain range is build of Magura tectonic unit flysch; more resistant coarse-grained sandstones, and less resistant sandy claystones and sandstones containing claystone galls (NEMČOK 1990). Within the Čergov Mts. the average annual precipitation at the station Livovská Huta is 830 mm, at Kríže station 822 mm, whereas at the piedmont station Malcov, declines to 700 mm. The study reach begins at the length of 3.7 km from the spring, at the altitude 675 m a. s. l., achieving the 4th order. Further downstream the river achieves 5th order, and the study reach ends at the foot of the Čergov Mts., 12.4 km from the spring, at the altitude 460 m. The nearest stream gauge is in Gerlachov, further downstream in Bardejov (**Fig. 1** and **Tab. 1**).

HYDROLOGICAL ANALYSIS AND CAUSAL PRECIPITATION OF THE EXTREME EVENTS

Climatic impact on river channel morphology is in analogy with the magnitude/frequency distribution of the extreme flood events. In the study reach area, the most effective events with highest discharges during the year emerge in summer period (**Fig. 2**). The trend of increasing magnitude and frequency of extreme events in Bardejov gauging station (**Fig. 2a**) is affected by the precipitation over the whole

Stream gauge	Distance from the spring [km]	Watershed area [km^2]	Altitude [m a. s. l.]	Gauge establishment	Average long term discharge [m^3.s^{-1}]	Maximum discharge		Culmination discharge at extreme event [m^3.s^{-1}]			
						[m^3.s^{-1}]	Date	*23.5.1987*	*4.6.2006*	*23.7.2008*	*4.6.2010*
Gerlachov	19.2	139.4	358.69	1992	1.4	90.09	23.7.2008	-	67	90.09	79
Bardejov	33.7	325.8	265.04	1967	2.96	350	4.6.2010	235	52.68	169	350

Tab. 1 Stream gauging stations relevant to the Topľa River study reach, their main characteristics and culmination discharge values during selected flood events

draining area (**Fig. 1**) and does not reflect confidently the effect of summer storms which are usually of limited area of extent and located in the source zones of the watersheds (SOLÍN and GREŠKOVÁ 1999, GREŠKOVÁ 2001). Furthermore, the same flood wave is flattening when flowing downstream; it can even have higher discharge in the station upstream then in the station downstream (**Tab. 1**, see June 2006), as well as higher N-year discharge. Therefore, in addition to its closer position, the data from Gerlachov station is more representative for our study reach hydrology. Unfortunately, the period of gauging in Gerlachov is too short (18 years) and statistically not reliable, even the N-year discharges of the floods hadn't been estimated however, the trend is evident (**Fig. 2b**) and shows significant increase in magnitude and frequency of extreme events. In addition, the last extreme event from June 2010 isn't in the graph. In the Bardejov gauging station (**Fig. 2a**), this tendency is disturbed by an extraordinary flood event that occurred in May 1987.

THE MAY 1987 FLOOD EVENT

The flood wave culminated at a record-setting discharge 235 m^3.s^{-1} in Bardejov gauging station, and last unbroken until the last event of June 2010. Unfortunately, the Gerlachov gauging station hadn't been established yet. The precipitation data from this event give some advice (**Tab. 2**, **Fig. 1**), that the discharge in Bardejov was extreme due to their approximately even distribution over the watershed. The daily cumulative precipitation at the stations across the watershed was similar, varying from 43.5 mm in Sveržov to 57 mm in Livovská Huta. Based on this distribution, the culmination discharge in Gerlachov probably wasn't higher than in July 2008, when the causal precipitation was more abundant and concentrated into the Topľa River headwater in the Čergov Mts.

THE JUNE 2006 FLOOD EVENT

At the turn of May and June 2006, in the Livovská Huta station (**Fig. 1**) 150 mm of total precipitation was recorded during five days, while in other stations (Malcov, Kríže, Sveržov) it varied from 60 to 130 mm. Immediately after the first day of abundant rain in the Topľa River watershed, the flood situation emerged, which was deteriorated by continual precipitation during the 2[nd] and 3[rd] July. On the next day in Gerlachov gauging station a record-setting culminate discharge of 67 m^3 s^{-1} was recorded, while the same flood wave culminated in Bar-

Causal precipitation	*14.-23. 5. 1987*		*26.5.-4.6. 2006*		*14.-23.7. 2008*		*26.5.-4.6. 2010*	
Precipitation station\Data type	***10-d***	***24-h***	***10-d***	***24-h***	***10-d***	***24-h***	***10-d***	***24-h***
Livovská Huta	130.6	57	170.1	48.8	253.4	97.2	207.4	63.6
Kríže	123.9	46	158.5	51	267.8	62.5	204.3	59.5
Malcov	117.3	53	111.4	26.3	174.7	42	166.6	82
Sveržov	119.2	43.5	124.9	30.3	153.9	38.2	137.2	64.3

Tab. 2 Causal precipitation of the examined flood events on the Topľa River; May 1987, June 2006, July 2008 and June 2010. 10-day totals and maximal 24-hour totals are provided for each flood event [mm]

dejov on 52.7 m^3 s^{-1} as a 2-year flood. The situation was caused by sharp extent of excessive precipitation.

THE JULY 2008 FLOOD EVENT

The flood situation was caused by extraordinary precipitation series. Three days of abundant precipitation (the 14th, 17th and 20th July 2008), each of total from 20 to 40 mm led to abnormal saturation of the watershed soil layer. Afterwards an extreme precipitation event occurred on the 23rd July, with daily total of 97 mm in Livovská Huta station, while in other stations (**Tab. 2**, **Fig. 1**), the totals were lower (62.5 mm in Kríže, 42 mm in Malcov). The resultant flood wave caused extensive damage of road passing by the Topľa River in the study reach. The culmination discharge in Gerlachov station set a new record setting discharge 90.09 m^{3}s^{-1}, the culmination discharge 169 m^{3}s^{-1} (**Tab 1**) in Bardejov was set as a 20-year flood.

THE JUNE 2010 FLOOD EVENT

The last flood in study reach was caused by extreme precipitation of great area of extent. Excessive rains over the region of eastern Slovakia caused flood situations on majority of the rivers. In the study area the daily precipitation measured in Livovská Huta station was 23.6 mm on the 31st May, 59.8 mm on the 1st June. During the crucial precipitation day on the 3rd June the precipitations were most abundant; 63.6 mm. Similarly as in July 2008 flood; the causal precipitation followed previously wet days. The culmination discharge in the Gerlachov station (79 m^{3}s^{-1}) didn't outnumber the previous record. Whilst in Bardejov station, the

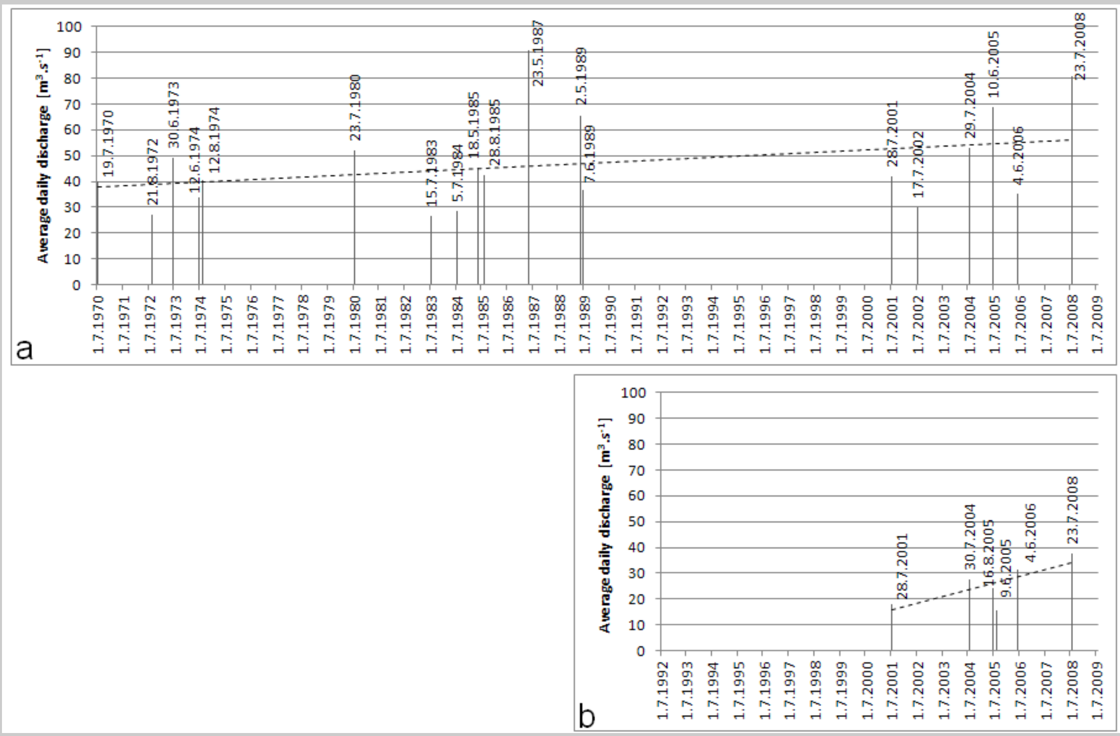


Fig. 2 The summer extreme average daily discharge values recorded in Bardejov (a) and Gerlachov (b) gauging stations from the all observation period. The dashed line represents the trendline

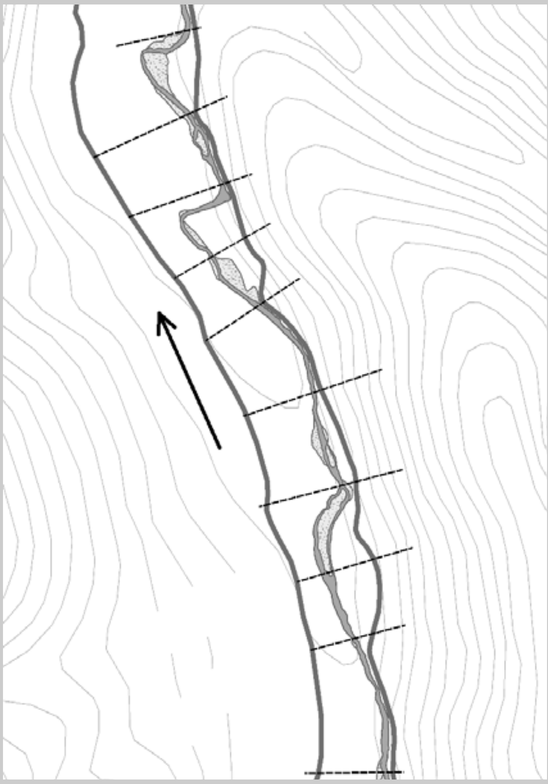


Fig. 3 A section of the study reach with the valley bottom borders and delineated channel reaches. Notice the bar emergent and channel abut as key delimitating parameter. The borders of channel reaches were specified after detailed fieldwork

role of larger contributing watershed played significant role in combination with greater area of precipitation and the result was new record setting discharge 350 m^3s^{-1} (**Tab. 1**), and estimated at over 100-year flood.

METHODS

For the purpose of spatial comparisons, the study reach had to be divided into channel reaches. The delimitation was conducted under the RMHC (River Morphology Hierarchical Classification) framework after LEHOTSKÝ (2004). The channel reach unit is the basic spatial unit of the assessment dataset. First identification and delimitation was conducted over the very actual remote sensing image from 2009 by identification of reaches with/without bars (**Fig. 3**). Next step was performed in the field; the measurement of the longitudinal stream profile for the identification of the channel slope and its inflections. Simultaneously, turning points of abuted/non abuted channel were located, and the dominant channel process types (degrading, transitional, aggrading) were identified. Analyses of these parameters led to delimitation of 78 channel reaches, quasi homogenous from the perspective of dominant fluvial processes. Finally, a representative cross-section profile was measured on each channel reach. Data processing and analyses was conducted using GIT.

ANALYSIS OF REMOTELY SENSED IMAGERY

The input data were obtained from the remote sensing imagery taken before and after

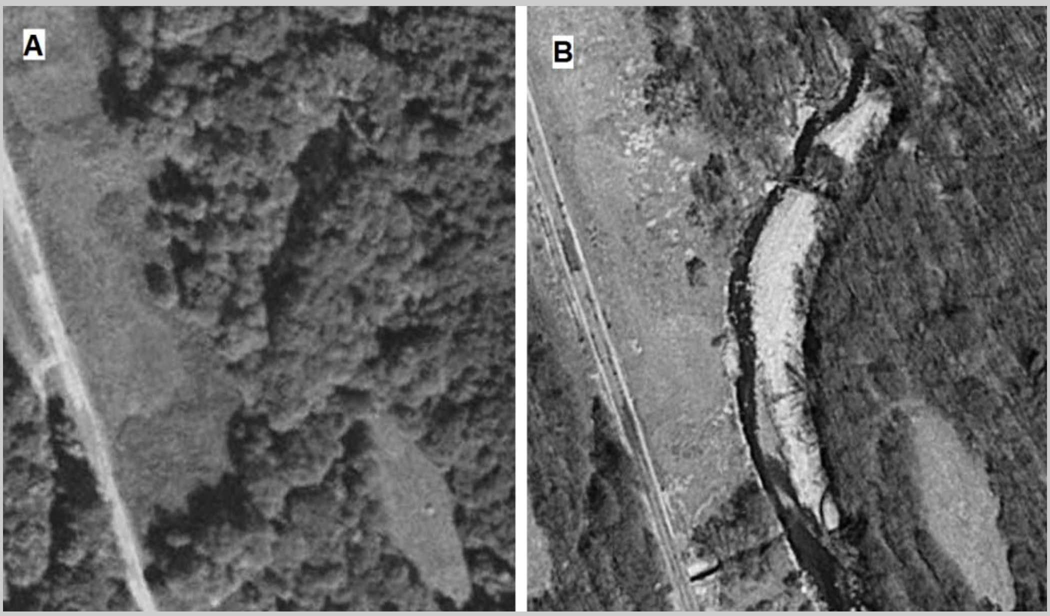


Fig. 4 Example of a sequentionary remotely sensed imageries with distinct lateral erosion. The same location captured in A - September 2006 and B—October 2009

Data type	Date	Major event effect captured	Provider	Accuracy and reliability level
color image	**10/2009**	event 7/2008	Eurosense, s.r.o.	High
color image	**9/2006**	event 6/2006	Eurosense, s.r.o.	High
color image	**5/2002**	-	Eurosense, s.r.o.	High
monochrome image	**1987**	event 6/1987	Topography Institute	Medium

Tab. 3 The remotely sensed imagery used for the horizontal dynamics analysis

the major extreme events (**Tab. 3**). Using these data only horizontal changes – the effects of bank erosion processes – could be analysed. No remote sensing has been after the 2010 event yet.

The main feature which can be clearly identifiable on a remote sensed imagery of a relatively narrow stream with mostly forested riverine is the presence and area of channel bars as a component of the active channel. Provided that in the image taken before extreme event no or small bar is visible and in the image taken after the event distinct bar area occurs, this can be assumed as the area stricken with bank erosion (**Fig 4**). Presence of the bar on the eroded area is related with the stream power decrease after the extreme event (FONSTAD 2003).

The active channel of all alluvial reaches was delimitated on all sequentional remote sensing images. Although focus is given to the most recent events, primarily to the July 2008 event, accordingly analysis of historical data is necessary to approve the outcomes. The answer to the question, whether last events on the Topľa River had extraordinary geomorphic effect, or there had been similar events and their effects in the past, is of vital importance. For this purpose, the event from May 1987 (record breaking discharge in Bardejov until June 2010 flood) was assessed.

Required attributes per channel reach obtainable from imageries were; total channel bar area, total eroded area, average and maximum bank retreat.

Analysis of Channel Cross-Section Profiles

Total of 78 cross-sections were measured after the last flood event on Topľa River without repetition. The dimensions were measured with high accuracy using laser distometer on tripod and electronic hose levelling instrument, both indicating in millimeters. Lacking of the pre-event state does not allow accurate assess-

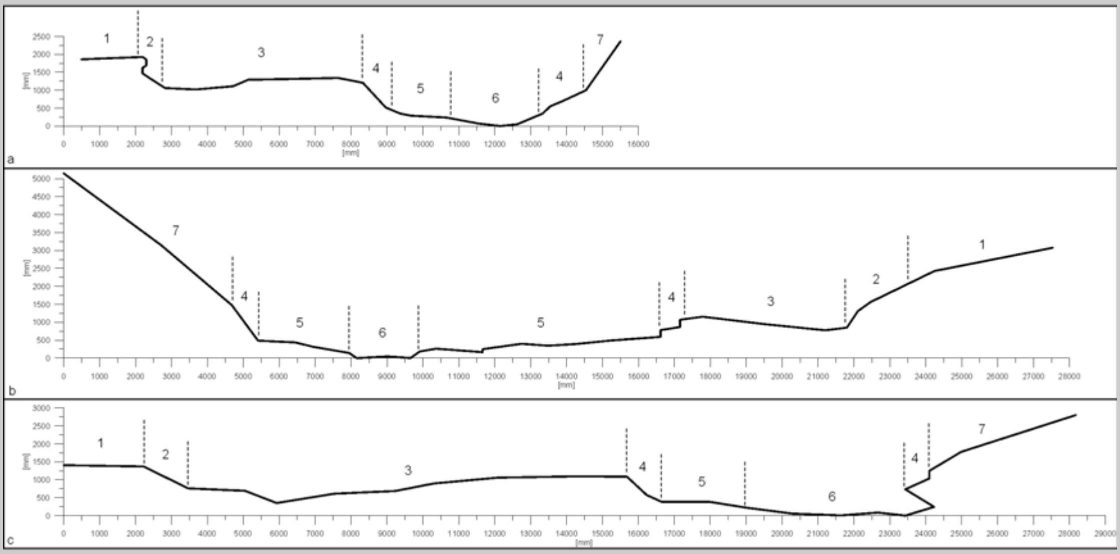


Fig 5 Examples of three (a, b, c) cross-section profiles measured after the June 2010 flood. 1 – floodplain, 2 – bank eroded by the July 2008 flood, 3 – gravel bar aggraded by the July 2008 flood, 4 – bank eroded by the June 2010 flood, 5 – flood bench of June 2010 flood, level of pre event channel bottom, 6 – contemporary channel bottom, 7 – slope

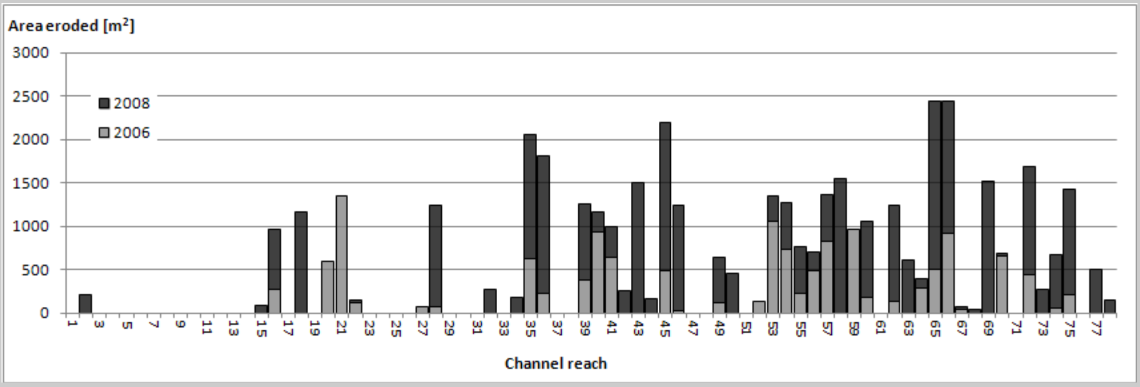


Fig. 6 Weighted area stricken by bank erosion at channel reach during flood of June 2006 and July 2008

ment however, a single-time measurement still offers some valuable information, providing the calculation of incision ratio and channel width/depth ratio. The channel width/depth ratio requires establishment of bankfull, which includes uncertainty (PYRCE 2003), therefore the channel bottom width was selected as another, more reliable parameter describing incised channel morphology. The June 2010 event had dominantly vertical effect, with degrading into material aggraded by previous event. The resultant shape is a distinct flood bench (**Fig. 5**), recognizable on majority number of cross-section profiles. We assume this vertical differentiation as the incision rate of the last flood event.

RESULTS AND DISCUSSION OF RECENT CHANNEL CHANGE

Remotely Sensed Imagery

The active channel of the Topľa River enlarged significantly during the June 2006 and the July 2008 floods. Total area eroded in the study reach during the flood of June 2006 was

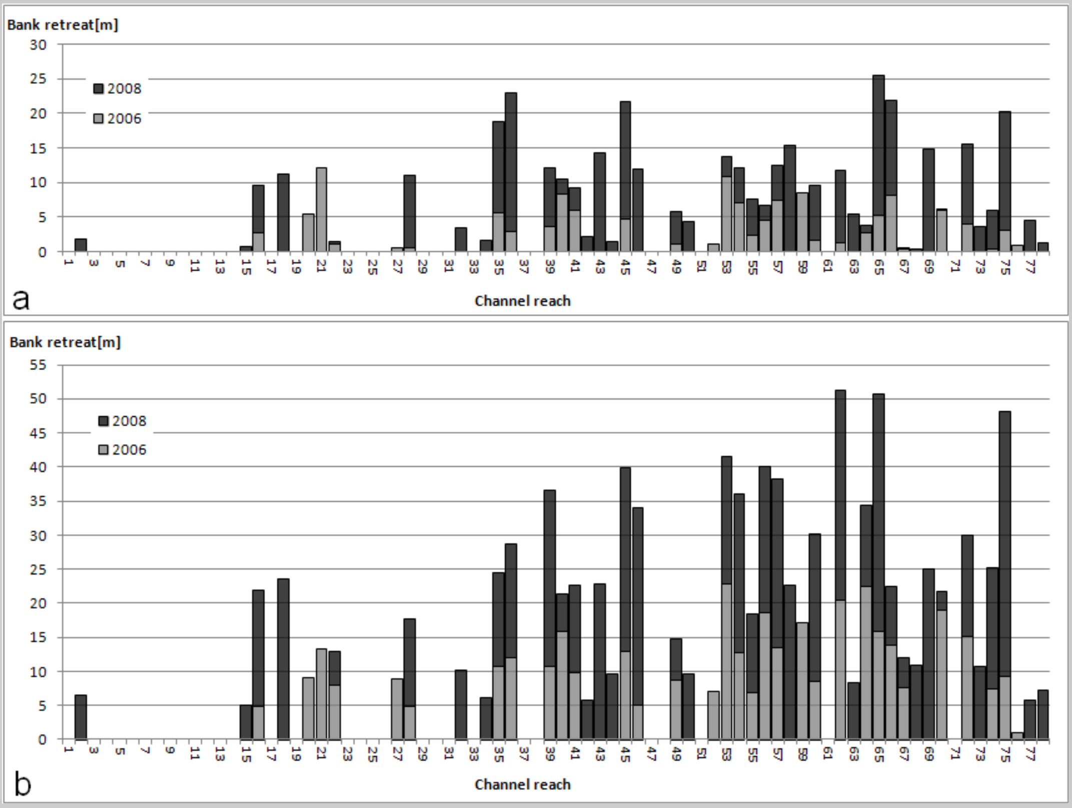


Fig. 7 Average (a) and maximum (b) bank retreat at channel reach during flood of June 2006 and July 2008

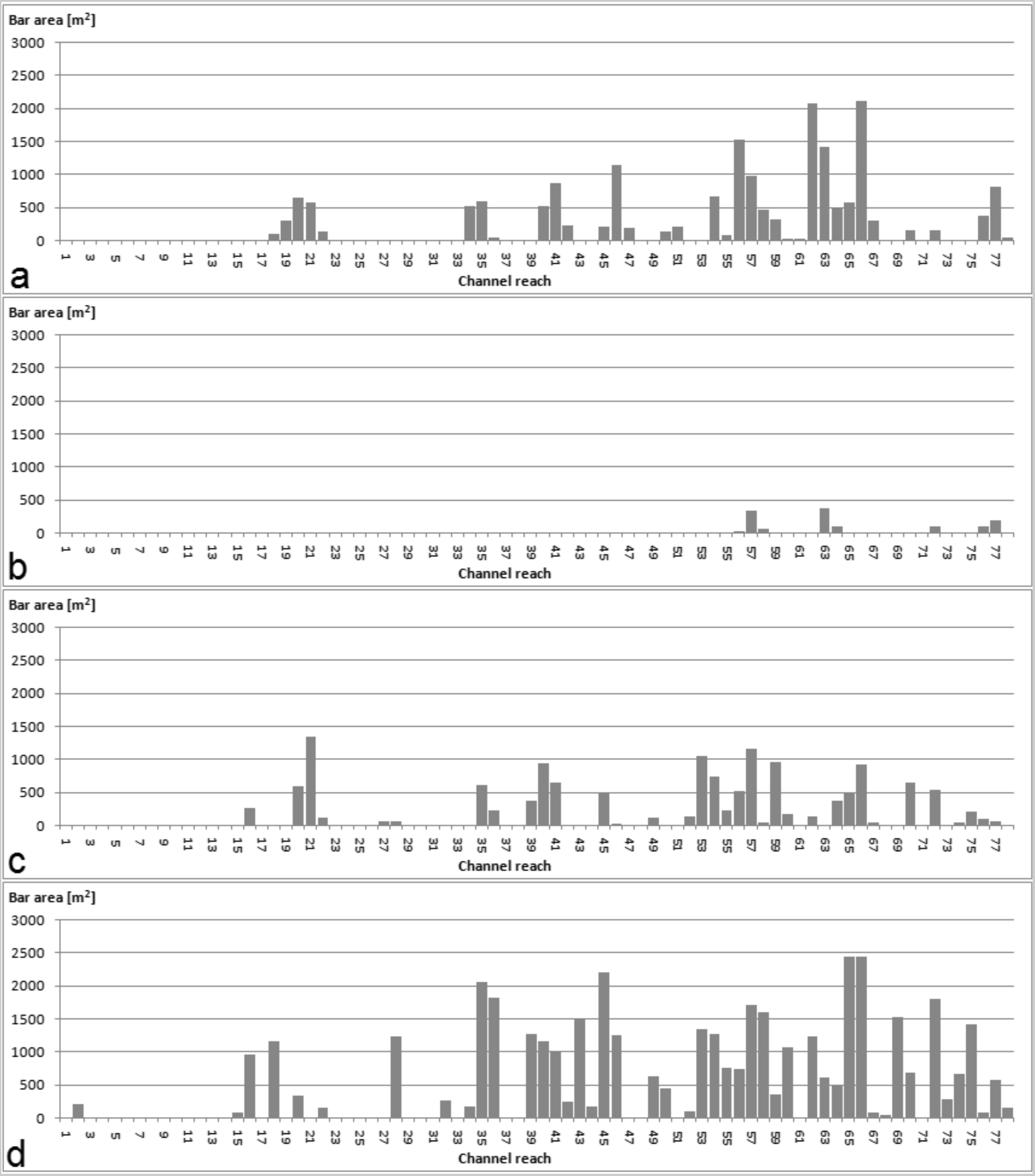


Fig. 8 Weighted bar area at channel reach deliminated from imageries (a) 1987, (b) 2002, (c) 2006 and (d) 2009

1.42 ha, while during flood of July 2008 another 3.43 ha (**Fig. 6**). The average bank retreat in reaches with floodplain pockets was 4 m (up to 23 m maximally) during 2006 flood (**Fig. 7**). Following flood from July 2008 caused average bank retreat of another 7 m (up to 39 m).

When comparing with the pre-flood state, total bar area is a parameter of higher reliability (**Fig. 8**). In imageries from the 2002, when the channel was not disrupted with extreme floods and the bars from 1987 flood event were stabilized by dense vegetation, the total bar area was only 0.16 ha. The enlargement of the bar area after the flood of 2006 was 850 % (9.5 times) to 1.52 ha. But the most extreme flood of July 2008 left bars of total area of 4.74 ha, which means 2862 % growth (29.6 times) (**Fig. 9**). In comparison with the total bar area of 2.24 ha after flood of May 1987, it is still 150 % more.

Another important result of the remotely sensed imagery analysis is the spatial distribution of the bank erosion processes; a significant repetition of reaches with/without bars (**Fig. 3**), which guided the delimitation of channel reaches described in the methods. Further field

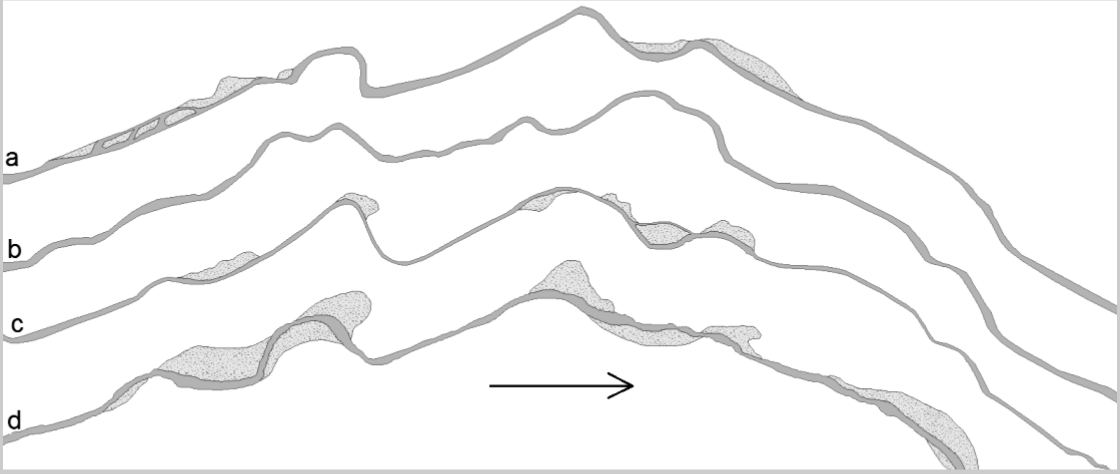


Fig. 9 A section of the study reach, with the channel bottom and bars from imageries (a) 1987, (b) 2002, (c) 2006 and (d) 2009

investigation showed that reach without bar and reach with bar creates a functional sequence. The sequences are composited rarely of one, commonly of two or three channel reaches. They were exhibited by the July 2008 flood, when the flowing water of extreme discharge was degrading the channel vertically. But in the locations of hydraulic jumps caused either by the gradient decrease or the channel bend, lateral erosion took place and widened the channel.

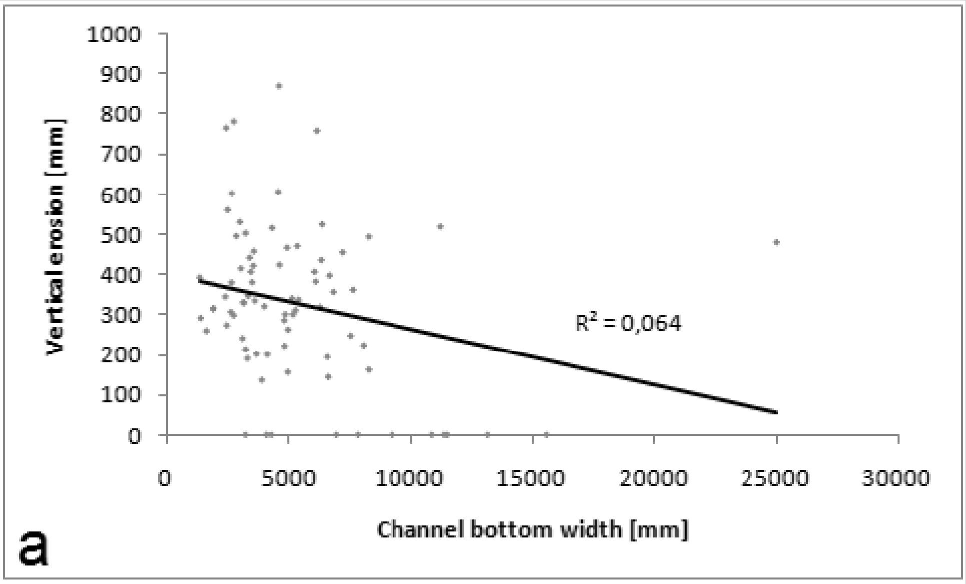
CHANNEL CROSS-SECTION PROFILES OUTCOMES

The rate of channel vertical erosion during the July 2008 flood is unknown, but based on statements mentioned in the previous text it has a considerable spatial differentiation with repetition of aggrading and degrading reaches as the result. The flood of June 2010 had lower discharge in the study reach, thus lower stream power and lower sediment load capability than the previous flood. The cobbles and boulders in the bars deposited by previous flood were more resistant against entrainment than the stream power of this second flood could entrain. This led to narrowing of the stream closer to the mid-channel position and consequently caused vertical bed erosion. Degradation took place in majority of reaches.

The average established channel vertical erosion during June 2010 flood was 0.33 m. The maximum rate was established on 0.87 m. The width/depth ratios, taken from the new bankfull level, which was reshaped by the last flood (**Fig. 5**), range from 4 to 39, with the a-

Process or landform	Weighted channel reach average	Weighted maximum	Coefficient of variation	Σ
bank erosion 2006	176 m^2	1341 m^2	176 %	14209 m^2
bank erosion 2008	379 m^2	1936 m^2	144 %	34253 m^2
bank retreat 2006	4 m	23 m	171 %	-
bank retreat 2008	7 m	39 m	147 %	-
bar area 1820	3555 m^2	21238 m^2	92 %	311412 m^2
bar area 1987	244 m^2	2104 m^2	185 %	22387 m^2
bar area 2002	17 m^2	379 m^2	380 %	1558 m^2
bar area 2006	186 m^2	1341 m^2	173 %	15223 m^2
bar area 2009	535 m^2	2445 m^2	129 %	47353 m^2
channel width/depth	14	39 (min = 4)	60 %	-
channel bottom width	5363 mm	24987 mm	51 %	-
channel vertical erosion 2010	327 mm	869 mm	67 %	-

Tab 4 Results of channel morphology and adjustment analysis. Weighted parameters were calculated per channel reach unit. High coefficients of variation demonstrate level of variability of fluvial processes and landforms in the study reach of the Topľa River



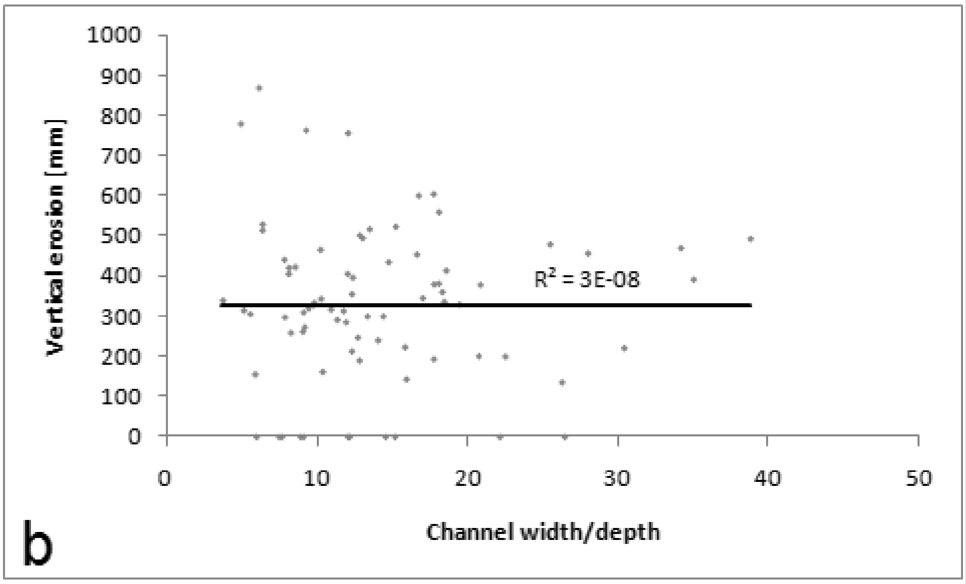


Fig. 10 The relationship between vertical channel erosion during the flood of June 2010 and (a) channel bottom width, (b) channel width/depth ratio. Nonlinearity of the process is caused by local controls, such as bedrock channel or large woody debris

verage value of 14. The average channel bottom width, also reshaped by the last flood, is 5.36 m, ranging from 1.34 m to 25 m.

RIVER BEHAVIOR UNDER FLOOD CONTROL

The resultant morphological effect of flood events in the study reach of the Topľa River is interpretable in two aspects; in temporal and spatial. In temporal aspect the crucial control is climate, particularly the occurrence of extreme precipitation and resultant extreme discharge values. The spatial distribution of the processes is controlled by the properties of valley morphology, lithological and tectonic structures with corresponding local erosional bases in the form of bedrock knickpoints, whereas the rate of these processes in time is controlled by the presence of coarse-grained sediments, distribution of large woody debris and anthropogenic activities, such as roads, bridges, regulations. We assume, that these driving controls causes variability of the processes and their corresponding landforms (**Tab. 4**), which demonstrates high level of nonlinearity in the Topľa River behavior.

For example, the shape of channel cross-section at a certain location expressed by the channel width/depth ratio at bankfull, or by the

Fig 11 Example of a log dam. Notice the significant aggradation upstream and degradation down-stream the dam

channel bottom width should correspond either with degradation/incision or aggradation process. In general, the channel with low channel width/depth ratio and narrow channel bottom should be more vertically eroded. However, the data obtained show the disconcordance (**Fig. 10**) with the presumption mentioned above. This can be explained that the reaches where the cross-section measurements were taken from exhibit in two types of vertical bed erosion; the exhaustion of the alluvium and the bedrock incision. Reaches with high channel width/depth ratio were alluvial-bedded and low channel width/depth ratio emerges in bedrock reaches. Although the resultant shape of these two processes is similar, they are quite distinct in the material matter. During the June 2010 flood, at locations, where the channel cross-section dimensions were favorable for vertical erosion, bedrock channel already had been present, but at those locations, where the channel was wide, the bottom was alluvial. Unfavorable channel morphometric conditions for vertical erosion were compensated by presence of relatively entrainmentable sediments and conversely, favorable morphometric conditions were constrained by presence of bedrock channel. Thus, the process of vertical bed erosion was strongly affected by local influence of bedrock channel. Another agent of significant local effects is supposed to be the effect of large woody debris (GREŠKOVÁ 2005, MALIK 2007, KREJČÍ 2008). The most significant way in which the wood in channel can affect aggradation/degradation processes is a transversal log damming, with aggradation upstream and degradation downstream (**Fig. 11**).

CONCLUSIONS

Recent channel morphology of the study reach of the Topľa River is primarily result of extreme flood events caused by summer torrential precipitation. Rising intensity of the extreme events is reflected in the effect of fluvial processes. The flood of June 2006 initiated lateral erosion in reaches of the highest susceptibility. Following flood of July 2008 had great morphological effect, more extensive than the flood of May 1987. Based on precipitation and hydrological data, we suppose, that the sedimentological threshold conditions set by the July 2008 flood hadn't been overcome by the flood of June 2010, which had lower culmination discharge. Consequently the last flood acted as "hungry water" and the effect was primarily vertical erosion.

The channel pattern, morphology and adjustments are determined by the valley thalweg gradient distribution and valley confinement which could be, on higher level, controlled by lithologic and tectonic structures. After the flood of July 2008 the whole study reach consisted of repetition of **a)** relatively high gradient, degraded bedrock reaches, explicitly single threat, that were abutted to valley slope with channel incision as dominant erosion process and **b)** relatively low gradient, aggraded alluvial reaches, susceptible to bifurcation, with low or no channel abut and the dominant erosion process was bank erosion (**Fig. 3**). The periodicity was disturbed only in the middle part of the study reach, where the Topľa River confluences with the Vlčí potok Stream and the Noriče Stream, consequently higher sediment load results into domination of alluvial channel. The flood of June 2010 degraded the channel at several previously alluvial reaches up to bedrock, straightened the channel and shifted it to the abut position.

The rate of the channel processes in the study reach of the Topľa River shows high variability, controlled by local morphological-sedimentological conditions as well as by presence of large woody debris in the channel.

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