Channel migration inferred from aerial photographs, its timing and environmental consequences as responses to floods: A case study of the meandering Topľa River, Slovak Carpathians

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Abstract

The bank erosion area, rate of bank retreat and overall geomorphological and financial effects of channel migration due to recent flood events (over the time span 1987–2009) are identified using remotely sensed data and GIS. A 39 km-long reach of the meandering, gravel bed Topľa River (Flysch Slovak Carpathians) was selected as the study area. Based on the analysis of culmination discharges, two different flood periods are identified. The first one (1987–2002) is characterised by the dominance of low magnitude flood events, compared to the second one (2002–2009) with higher magnitude floods. Aerial photographs from 2002 and 2009 were chosen as a way to capture the morphological changes that occurred after the flood periods, while those from 1987 served as the reference point. In total, an area of 85.2 ha was eroded and 60.1 ha were deposited. The average channel shift per year doubled from 0.8 m/year (1987–2002) to 1.6 m/year (2002–2009). The most eroded land cover category in the riparian zone is floodplain forest, followed by arable land, grasslands and pastures and shrubs. From an economic point of view, the eroded floodplain with arable land and grassland (€ 29,924.02 in total) is a negative consequence of channel migration.

Key words: river channel migration, flood, bank erosion, land cover, erosion risk, Slovakia

1. Introduction

Most river channels develop bends in reaches with erodible materials and low gradient. Flow energy in such sinuous channels is concentrated along the concave bank in bends, while deposition occurs at the convex one. Fast-moving water on the outside bend erodes the bank, picks up the sediment and drops it when the water slows at the inside of the next downstream bend. This increases the length of the channel, which helps dissipate the energy of the flowing water over a longer distance. Streambank retreat, frequently called streambank erosion, occurs by a combination of three processes: subaerial processes, fluvial entrainment and mass wasting. To provide clarity for the remainder of the article, the authors have adopted the terminology proposed by Lawler et al. (1997). Specifically, the terms "fluvial erosion" and "fluvial entrainment" are used to describe the detachment, entrainment and removal of individual soil particles or aggregates from the streambank face by the hydraulic forces occurring during flood events. The terms "bank failure" or "mass wasting" denote the physical collapse of all or part of the stream banks as a result of geotechnical instabilities. Bank erosion and bank failure commonly work in concert to produce bank retreat.

Thus, bank erosion on one hand and deposition/ reworking of bank-attached geomorphic units along the convex bank on the other hand, promote lateral migration of the channel. Studies have shown that the sediment from stream banks counts for as much as 85% of watershed sediment yields and bank retreat rates as high as 1.5 m^{-1},100 m/year (Simon et al., 2000). In addition to water quality impairment, stream bank retreat impacts floodplain residents, riparian ecosystems, bridges and other stream-side structures. River bank erosion is seen as a part of long-term channel change, meander migration and floodplain development and destruction.

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In recent years, floods following heavy precipitation have occurred with increasing but unpredictable frequency in many European countries. Many authors (e.g. Bronstert, 2003; Brázdil et al., 2006; Langhammer, 2010; Pekárová et al., 2003, 2010) point out the cyclical character of flood events and have identified several dry and wet periods during the last century in many world and Slovak rivers. Dry and wet periods are likely to be conditioned by the North Atlantic Oscillation (NAO) phenomenon (Pekárová, et al., 2010).

Hence, understanding streambank erosion hazards in response to recent floods calls for analyses of the links between floods and river behaviours at the regional to local scale (Langhammer and Vilímek, 2008; Brázdil et al., 2011). The long-term response to a series of flood events manifests itself first in the inner-channel organisation of landforms. The temporal distribution of flood events reflects the overall climatic conditions of the region and responds to the precipitation regime. The impact of floods depends on the morphological state of the channel (sinuosity, pattern, gradient) during high flow events, and the geological and morphological (topographical) conditions of the river catchment (Hooke, 2015). Further variables which affect the response of the channel system to floods, are changes in vegetation cover (succession, seasonality and land use), as they partially influence the sediment supply or flood capacity of the channel. Similar floods in terms of magnitude and frequency, however, can produce dissimilar morphological responses (Fuller, 2008). Michalková et al. (2011) point out the significant geomorphological effect of a critical shear stress, which is recorded under the influence of more frequent and prolonged floods. Hickin and Sichingabula (1988) highlight the importance of the flood duration. In general, they consider that smaller but longer duration floods are more constructive, while high magnitude floods are destructive. The effects of small magnitude and frequent floods are constructive and contribute to accretion of sediments and stabilisation of the channel (Corenblit et al., 2007).

Bank erosion is closely connected with flood events characterised by the increase of stream power. It leads to an increased rate of erosion/deposition processes in the channel (Hooke, 1979; Miller, 1990; Hrádek, 2000; Richard et al., 2005; Larsen et al., 2006; Kiss et al., 2008; Pišút, 2008). Bank erosion processes depend on the size of the discharge and the interactions between the ever-changing hydrological conditions (the flow velocity, local hydraulics, floods and their magnitude, frequency, duration and timing) and other factors contributing to bank erodibility (initial bank geometry, planform geometry, height and density of vegetation, volume of accessible sediments, sediment grain size) (Knighton, 1998; Russell et al., 2004; Luppi et al., 2009), as well as floodplain land cover and overall riverine landscape management.

The successful and sustainable management of rivers requires awareness of which river reaches are prone to bank destruction and any subsequent lateral shifts (Brierley and Fryirs, 2005; Richard et al., 2005; Fryirs and Brierley, 2013). Piégay et al. (2005) report several ways of delimiting the erodible corridor. Historical analysis based on data obtained by remote sensing and historical maps, offers an ideal source for the definition of river channel mobility and the identification of both stable and unstable reaches. It is less applicable, however, for the prediction of future instability and lateral shift.

Aerial photos capture high-resolution details of the changing fluvial landscape (Bryant and Gilvear, 1999). The greatest advantage though, is their temporal and spatial flexibility in the mapping of changes. Their benefit lies in the accessibility of dense and highly accurate information (dependent on resolution), which allows relatively precise quantification of morphological processes (bank erosion, planform changes, bar accumulation, etc.). The accuracy and precision of spatial data, methods for calculating lateral movement of the channel and the selection of consistent rules for identifying landform dynamics and delimiting the features of interest, significantly affect geomorphological interpretations (Zanoni et al., 2008). Not only do historical data serve to identify lateral migration (Hooke, 1979; Pišút, 2002; Gilvear and Bryant, 2003; Michalková et al., 2011), but they also contribute to the study of changes of channel and riparian zone patterns (Bryant and Gilvear, 1999; Gilvear and Willby, 2006). Floods and their erosional power affect the overall ecological diversity in the riparian landscape by eroding channel landforms or vegetation in the riparian zone, by depositing sediments and seed dissemination (Ward et al., 2002; Gurnell and Petts, 2002, 2006; Corenblit et al., 2007; Opperman et al., 2010; Corenblit et al., 2010; Erskine et al., 2012).

The aim of this paper is to identify bank erosion areas, the rate of bank retreat and its financial consequences. The paper also investigates the links between bank erosion and land cover categories in the riparian zone, and the overall geomorphological effects of channel migration and its timing, due to recent flood events between 1987 and 2009 in a gravel bed, minimally regulated and laterally partly-confined meandering watercourse.

2. Study area

The research has been carried out over a 39 km central reach of the Topľa River, a gravel-bedded, non-regulated channel (Fig. 1) in the outer Carpathians flysch setting in Eastern Slovakia (Central Europe). The river springs at an altitude of 1,015 m a.s.l. in the mountain range of Čergov. It is 115 km long before it reaches the point of confluence with the River Ondava. The area of its basin is 1,506.4 km^2; the long-term daily average discharge at the Bardejov gauging point oscillates at a level of $Q = 3.018$ m^3.s^{-1} ($Q_{max} = 350$ m^3.s^{-1} (17. 05. 2010)). The Topľa River in the study reach is a 6th order stream (Strahler order). The catchment is built by Eocene claystones, sandstones and conglomerates. The floodplain of the Topľa River is filled with Holocene gravels and sandy gravels and the valley slopes are affected by landslides. The thickness of the layers varies between 2–8 m (Kováčik et al., 2011).

The river basin is considerably forested with a total cover of 52% (CORINE land cover 2006). Agricultural landscape is represented by the category of arable land, concentrated along the valley bottoms, and covers 24.4% of the catchment. Dikes are built on the left bank near the town of Giraltovce (length 670 m) and in the town of Bardejov (length 150 m). A small hydropower plant was constructed between 1987 and 2002 in a meandering reach of the river south of Bardejov. Stony bank revetments were built in several places (to a total length of 1,990 m) where the river threatened roads, bridges or arable land. These bank protection practices were mapped: the longest bank revetment is 300 m long. These works only have a very local effect, however, and the Topľa preserves its natural state.
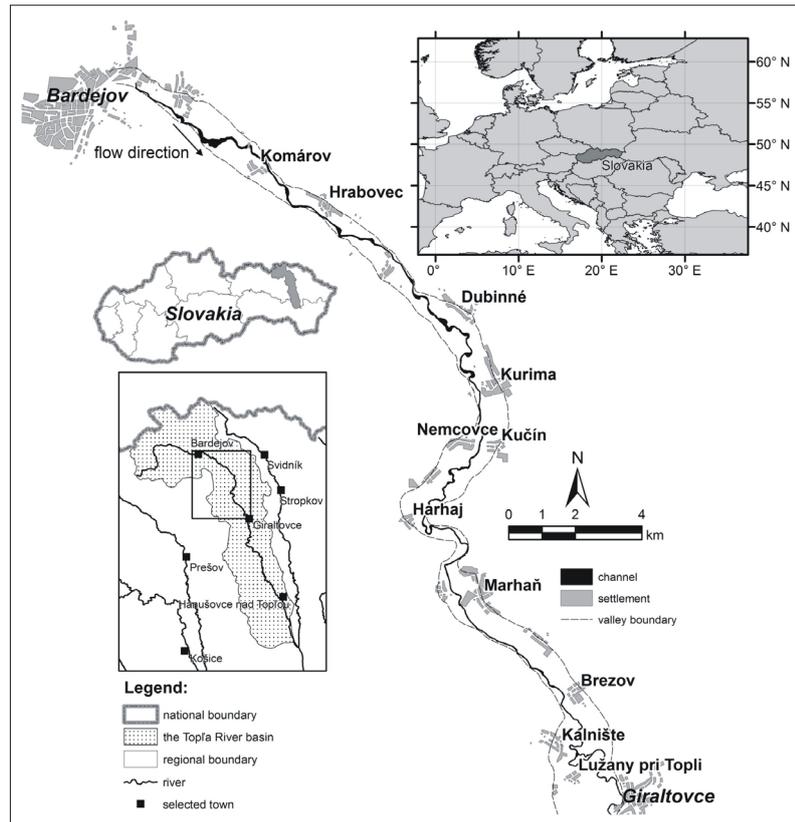
Fig. 1: Location of the Topľa River catchment and the study reach. Source: GIS data: Geodesy, Cartography and Cadastre Authority of Slovak Republic (122-24-99-2012); authors´ elaboration

3. Methods

The post-flood period serial geomorphic analysis (POPSEGA, Kidová et al., 2016) approach has been used as the methodological template. The analysis of daily average discharges (data provided by the Slovak Hydrometeorological Institute (SHMÚ) from the Bardejov gauging station located immediately upstream from the study reach) and the analysis of culmination discharges (which were defined as the 3rd level of flood alert declared by the SHMÚ), allowed us to identify two different flood periods. The first one (1987–2002) is characterised by the dominance of low magnitude events, whilst during the second one (2002–2009) higher magnitude floods are typical.

Spatial data about the channel, the in-channel landforms and the riparian zone land cover were generated from remote sensing images (aerial photographs and orthophotographs). The photographs were chosen in such a way that the morphological changes that occurred after flood periods were captured. They were analysed in three time horizons (1987 as reference, and 2002 and 2009 as the post-extreme flood events) applying ArcGIS in the S-JTSK (Krovak East North)

coordinate system. Black-and-white aerial photographs (taken on July 7, 1987 and August 23, 1987, pixel resolution 0.5 m) and colour orthophotos (second half of June 2002 with pixel resolution 1 m, and from April 15, 2009, pixel resolution of 0.89 m), were the sources of spatial data. Aerial photographs were taken at similar low flow conditions, which is important to minimize differences caused by varying water levels during vectorisation of channel landforms (mainly gravel bars, Tab. 1). Discharges at the time of imagery were similar to the average daily discharges. A limitation of the method is that the images capture the state of the channel at the moment of imaging and do not record the process of changes that take place between individual events; this leads to a problem with the assessment and definition of changes and the identification of the contribution of individual change attractors (Hooke and Redmond, 1989; Draut et al., 2011).

The raster sources obtained were used to identify the bank edge (channel); the in-channel forms (bars) and the land cover structures of the riparian zone. The bank edge was traced either along the visible bank line or, in the case of the canopy cover impeding its distinct position, it

	Daily average Qa (1967–2009) Hd (1987–2009)	Date of aerial photograph					
		1987		2002 (15.–30. 6.)		2009	
		7/7/1987	23/8/1987	max.	average	15/4/2009	26/8/2009
discharge Qa [m³.s⁻¹]	3.017	1.975	1.439	2.259	1.465	4.078	1.485
water level Hd [cm]	155.1	155.3	151.54	156	150.76	159	149

Tab. 1: Hydrological characteristics of the River Topľa at the Bardejov gauge station (daily average discharge (Qa) and daily average water level (Hd) on the date of aerial photographs. Spatial data were recorded during similar flow conditions. Source: Data (Slovak Hydrometeorological Institute)

was drawn in an approximate position based on the field survey of the treetop size. Bank erosion was assessed by overlapping bank positions in three time horizons according to the methodology of Lehotský et al. (2013) and Rusnák and Lehotský (2014). The spatial aspect of the individual parameters of the lateral shift, gravel bars and bank erosion was expressed for 250 m segments (154 up-stream numbered segments in total). During the field research trips (2011–2014), individual morphological forms and processes were identified. Thus, data were gained about the erosion and the deposition area, as well as the direction and the size of the individual bank shifts. As for in-channel landforms, four types of channel landforms were identified: a) lateral bars, b) point bars, c) central bars, and d) islands. The main criterion for distinguishing between bars and islands was vegetation cover. Bars were identified as landforms without vegetation or low vegetation cover of less than 25%, and islands with a tree vegetation cover of more than 70%. The resolution of raster data influenced the amount of detail and the size of interpretation objects. The limit for identification of lateral shift was 1 m (1 pixel) and the landforms were digitised if one dimension exceeded 3 m (3 pixels).

The land cover of the riparian zone was investigated in the buffer zone of 20 m away from the bank lines obtained for 1987, 2002 and 2009. Its width, 20 m, is considered the floodplain space sufficient to capture bank line shift during the study time span. In total, five land cover categories were defined:

1. riparian forest (tree cover more than 70%) as a mature stage of the development in the riparian vegetation;

2. shrubs;

3. grassland and pastures;

4. arable land; and

5. urbanised areas (built-up surfaces, among which gardens, urban greenery or other man-made technical structures can be found).

The social aspect of bank erosion was assessed according to the monetary value of destroyed plots, which is defined by the Decree of the Ministry of Agriculture and Rural Development of the Slovak Republic about prices of plots and growths on such plots for the purpose of land consolidation (Decree No. 38/2005). This Decree contains prices set by the Government. The prices are based on the soil quality of plots classified by the so-called bonity soil-ecological units. The values of plots were established only for categories 3 and 4 (grassland and arable land). Forests in the buffer zone (categories 1 and 2) were excluded because they are not economically exploited. The economic value established by this method reflects the prices set by the Government, which differ from market prices.

4. Results

4.1 Analysis of flood events

Mean daily discharges oscillate around 3.018 $m^3.s^{-1}$, but the maximum discharge in the relevant period of 1987–2009 was 235 $m^3.s^{-1}$ in May 1987 (20-year recurrence interval, RI20). After the distinct flood event of 1987 and the flooding in 1989 (with a 5-year recurrence interval, RI5), there was a period of reduced flood activity with the maximum discharge corresponding to a 1 or 2-year recurrence interval (Fig. 2). Flood events of greater importance appeared after the year 2000 and particularly in 2004 (Q_{dmax} = 207 $m^3.s^{-1}$ [20-year recurrence interval]), 2006 (Q_{dmax} = 160 $m^3.s^{-1}$ [10-year recurrence interval]) and 2008 (Q_{dmax} = 218 $m^3.s^{-1}$ [20-year recurrence interval]). Larger floods also appeared in 2000 (Q_{dmax} = 92 $m^3.s^{-1}$ [from 2 to 5-year recurrence interval]), 2001 (Q_{dmax} = 76 $m^3.s^{-1}$ [2-year recurrence interval]), 2002 (Q_{dmax} = 82,1 $m^3.s^{-1}$ [from 2 to 5-year recurrence interval]) and in 2005 (Q_{dmax} = 103 $m^3.s^{-1}$ [from 2 to 5-year recurrence interval]). Based on the above, two different flood periods, i. e. 1987–2002 and 2002–2009 were identified. The first flood period (1987–2002) is characterised by the occurrence of the floods from a 1 to 2-year recurrence interval. The second flood period (2002–2009) represents a series of high magnitude and high frequency flood events with a recurrence interval from 5 to 20 years. The periods correspond to wet and dry periods identified by Pekárová et al. (2010).

4.2 Bank lateral shift and changes in bedforms

A typical feature of the Topľa River channel is its lateral dynamics and distinct bank erosion. In total, an area of 85.2 ha was eroded and 60.1 ha was deposited (the area of the former channel which became a part of the floodplain) in the period 1987–2009 (Tab. 2).
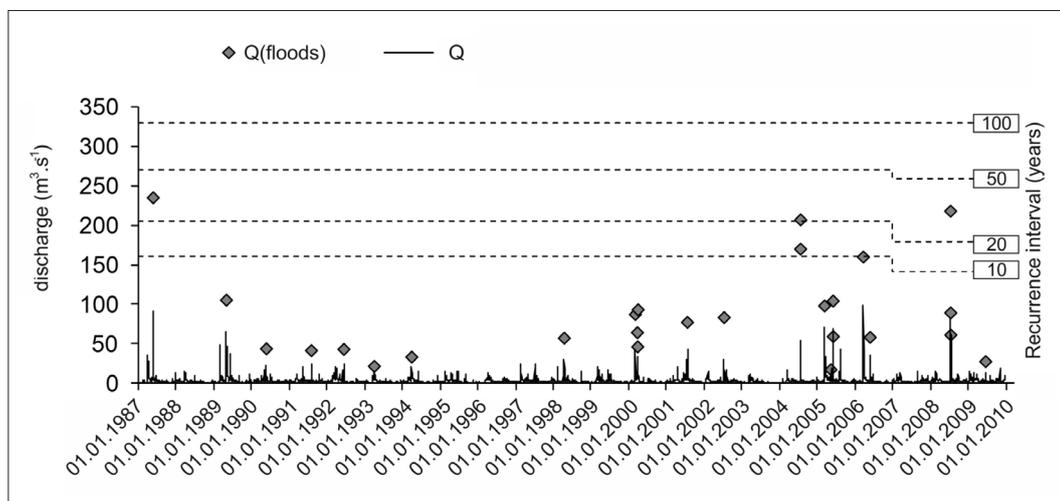
Fig. 2: Variability of daily average discharges (Q) in the period 1987–2009 on the Topľa River recorded at the Bardejov gauge station, discharge of flood events and recurrence interval over the same period
Source: Data (Slovak Hydrometeorological Institute); authors´ elaboration

Flood period	Area of erosion total [m²]	Area of deposition total [m²]	m²/year	
			erosion/year	deposition/year
1987–2002	318,047	424,204	21,203	28,280
2002–2009	534,063	176,951	76,295	25,279

Tab. 2: The area of erosion and deposition and the rate of erosion/deposition per year in the periods 1987–2002 and 2002–2009. Source: authors' calculations
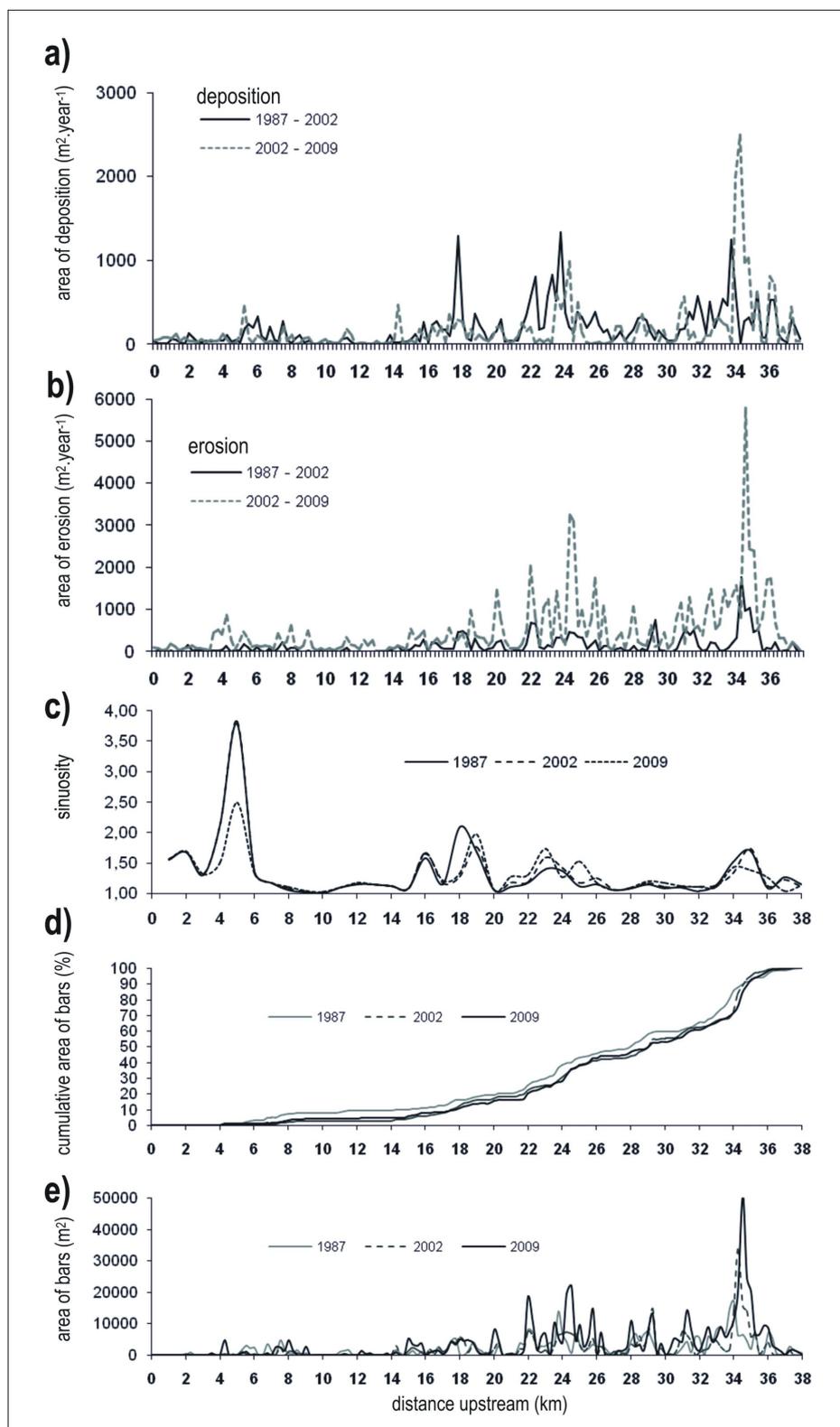
Fig. 3: Longitudinal evolution of (a) deposition, (b) erosion, (c) sinuosity, (d) cumulative area of bars, and (d) area of bars in the study reach of the Topľa River. Source: authors' calculations

The increase of erosion was particularly visible between 2002 and 2009. It increased up to 7.6 ha per year which is almost 3.6 times more than in the previous period (1987–2002). Reaches manifesting distinct instability of the channel were identified in the longitudinal direction (Fig. 3). The first and the smaller one (km 4–8) is linked with the system of meanders north of the town of Giraltovce (Fig. 4). Other similar locations are identifiable between the villages of Harhaj and Kučín (km 15–20), between kilometres 21–26 (in the cadastral territory of the villages Kurima and Dubinné) and north of the village of Hrabovec (km 30–36). They are linked to the reaches with a higher degree of sinuosity (Fig. 3c), where the planform pattern changed in the period 2002–2009.

The average channel shift in the study reach is 12.4 m (flood period 1987–2002) and 11.3 m (flood period 2002–2009) (Tab. 3). The average channel shift per year doubled from 0.8 m/year (1987–2002) to 1.6 m/year (2002–2009). A similar development is observable in bedforms where the area of gravel bars almost doubled in 2009. In 1987, they covered an area of 32.7 ha, which represented 26.9% of the overall channel area, and in 2002 they occupied a comparable area of 31.4 ha (28.2% of the channel area). Their representation increased in 2009 to 37.3% corresponding to an area of 54.8 ha. This phenomenon is most conspicuous north of Hrabovec (between kilometres 34 and 36), where the area of gravel bars increased from 5.7 ha in 1987 to 16.2 ha in 2009 (in 2002 the area was 9.7 ha) along the 2 km reach.
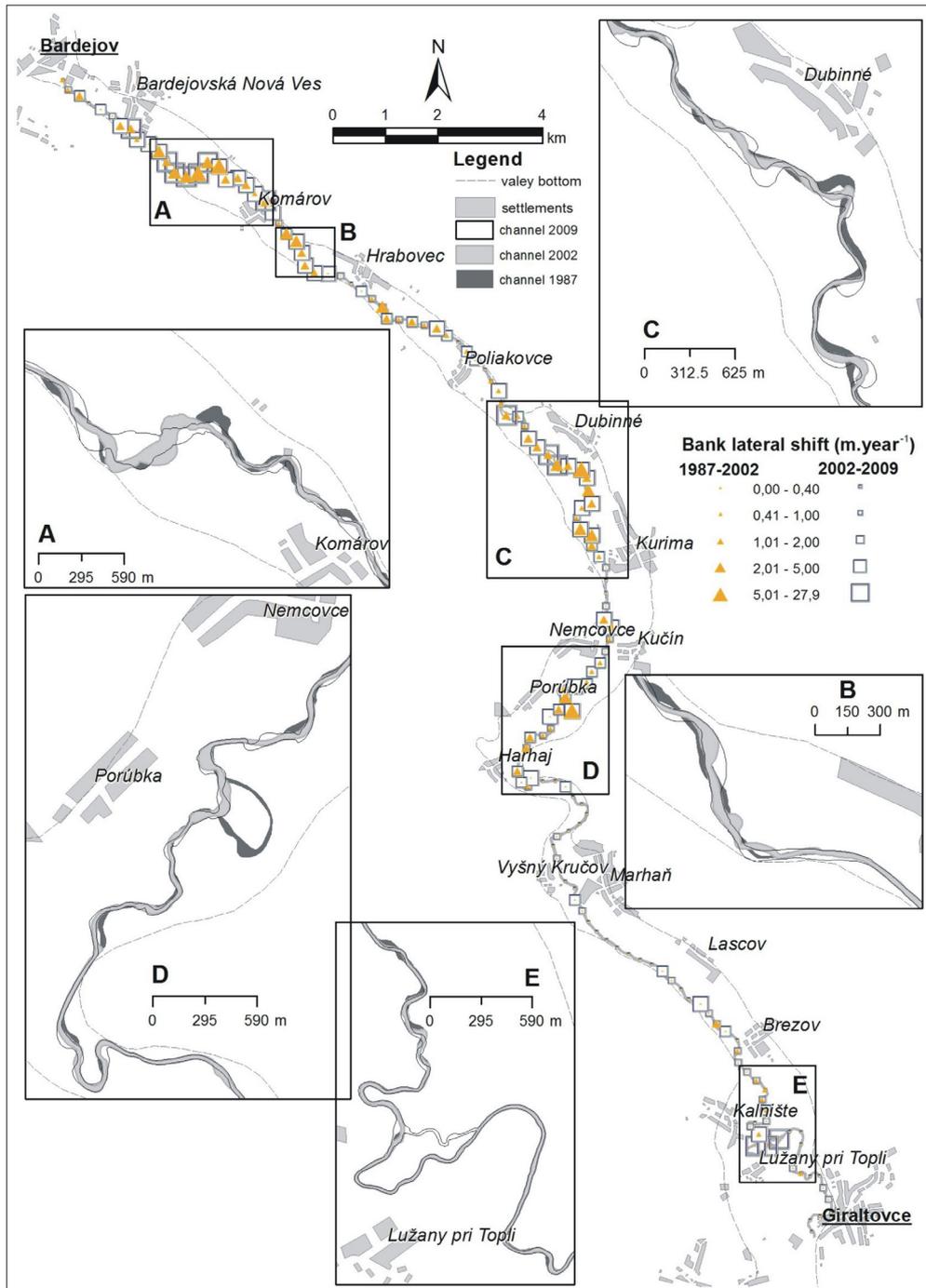
Fig. 4: The spatial distribution of lateral movements of bank line in the two study periods, and locations (A–E) with high lateral instability. Source: authors' calculations; Settlements layer (Geodesy, Cartography and Cadastre Authority of Slovak Republic (122-24-99-2012))

Flood period	Lateral shift [m]				Rate of shift [m.year^{-1}]		
	total	left bank	right bank	max. shift	total	left bank	right bank
1987–2002	12.4	11.4	13.5	260	0.8	0.8	0.9
2002–2009	11.3	10.7	12.0	445	1.6	1.5	1.7

Tab. 3: Lateral shift of banks and rate of shift per year in the periods 1987–2002 and 2002–2009
Source: authors' calculations

	Lateral bars		Point bars		Mid-channel bars		Islands		Σ
	[ha]	[%]	[ha]	[%]	[ha]	[%]	[ha]	[%]	[ha]
1987	22.8	69.8	6.7	20.5	3.2	9.7	0.0	0.0	32.7
2002	24.6	78.4	3.1	9.8	3.5	11.3	0.2	0.5	31.4
2009	39.7	72.5	9.0	16.4	4.0	7.3	2.1	3.9	54.8

Tab. 4: Changes in in-channel landforms of the Topľa River expressed by areas and percentage. The greatest intensity in bars changes and islands development was registered in 2009. Source: authors' calculations

The change of structure of individual gravel bars is negligible and is local (Tab. 4).

The most threatened reaches of the Topľa River are identifiable based on the average lateral bank shift in individual 250 m long segments (Fig. 4). The most dynamic reach is located south of the town of Bardejov, where the lateral shift reaches several hundreds of metres and threatens the wastewater treatment plant. The lateral shift also forms extensive gravel bars with the transition of the channel to a wandering river. Several dynamic reaches (located between Bardejov and Dubinné) are bound to points where water course transformation occurs from the abutted to the transversal (free) reaches. Three other very unstable reaches (Fig. 4: detail in C, D and E) are linked to the sinuous channel located in the centre of the valley characterised by typical chute offs and the formation of avulsive channels during floods.

4.3 Land cover changes in the riparian zone and bank erosion risk

Between 1987 and 2009, a total of 58.2 ha of riparian forest was eroded in the study reach (Tab. 5). The second most-eroded types of riparian landscape were arable land (19.4 ha) and grasslands and pastures (6.8 ha). The remaining two land cover types (shrubs and urbanised area) were only slightly affected by erosion. The erosion of forest, a result of their dominating representation in the delimited riparian zone, prevails in the reach. From an economic point of view, large destroyed farmland areas are a negative phenomenon (Fig. 5). The resulting damage in the area calculated according to

Decree No. 38/2005 was € 29,924.02 in total; for the period 1987–2002 it was € 13,619, and in the period 2002–2009 it was € 16,304.33 This calculated value of destroyed areas does not reflect the real market prices of the land.

Erosion of built-up surfaces occurred in two places in the study reach of the Topľa. The first is erosion of part of a garden adjacent to an old homestead south of Hrabovec. The second is the destruction of a part of the wastewater treatment plant protective dike, located beyond the city of Bardejov, and disablement of the small hydropower station built in the meander bend (Fig. 6) due to its improper siting. The wastewater treatment plant was again threatened and the bank further eroded during the extreme flood of 2010.

Newly-formed deposition areas, which are created in the space of the old channel after its shifting by erosion, are progressively covered by natural succession. The result is a visible increase of the proportion of the riparian forest, which gradually replaces other eroded landscape structure types in the riparian zone (such as arable land or grassland): see Table 5.

5. Discussion

The channel's lateral shift, its width and the bedforms area of the reach studied, are affected by discharge in the short term, as they are controlled by the magnitude and frequency of floods and by the duration of low-stage periods. The increase of bank erosion after 2002 in the reach studied is obvious. In the first period, the rate of erosion and deposition were in approximate balance with

Flood period	Process	Land cover category [ha]				
		1	2	3	4	5
1987–2002	erosion	20.1	0.3	3.9	7.5	0.1
	deposition	40.9	0.3	1.2	0.0	0.0
2002–2009	erosion	38.1	0.5	2.9	11.9	0.1
	deposition	16.8	0.0	0.7	0.1	0.0

Tab. 5: Erosion of land cover categories in the riparian zone (ha) and the area of new land cover categories formed on the deposition areas after the lateral movement of the channel in the two study periods. Land cover categories: 1) riparian forest, 2) shrubs, 3) grassland and pastures, 4) arable land, 5) urbanised area.
Source: authors' calculations
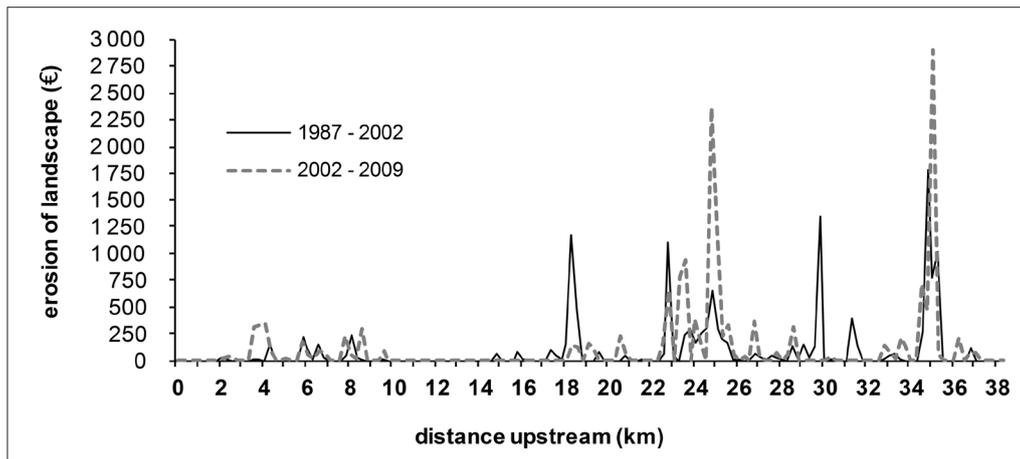
Fig. 5: Longitudinal evolution of the erosion of grassland, pastures and arable land in monetary terms (€)
Source: Authors' calculations
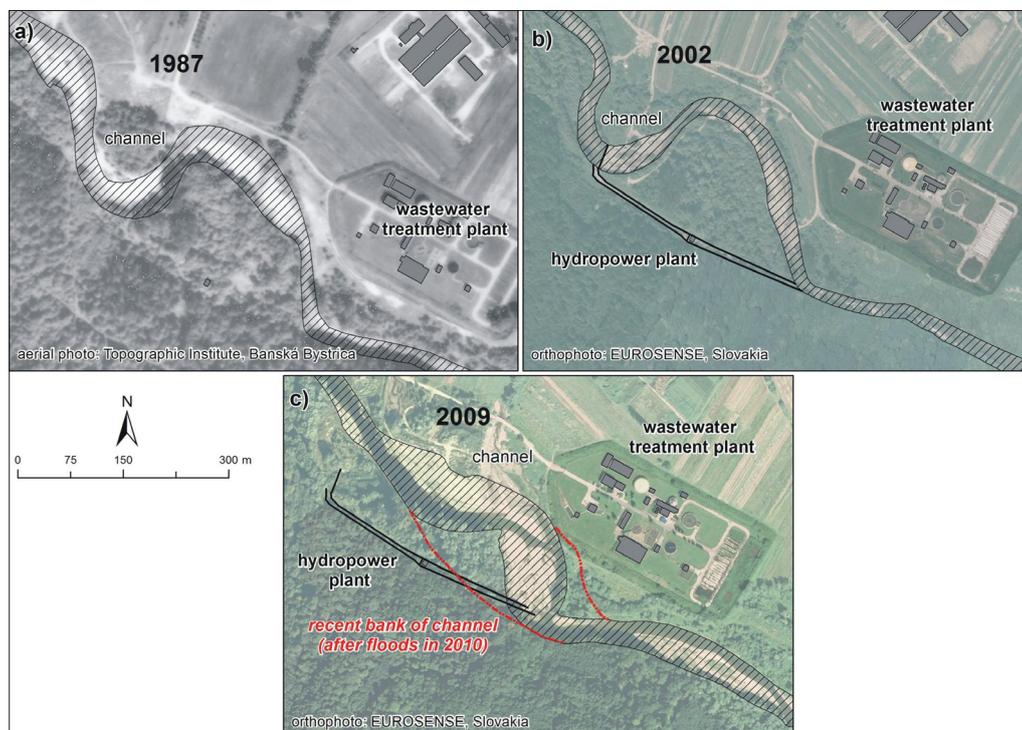
Fig. 6: a) Channel position in 1987; b) The channel position in 2002 with the small hydropower plant constructed in the meander loop in 2000; c) The changed channel planform in 2009 due to flood events in the second flood period leading to the dike's destruction close to the wastewater treatment plant, and the disablement of the hydropower plant as the consequence of its improper siting at the laterally active meander loop
Source: authors' elaboration; aerial photo (Topographic Institute, Banská Bystrica and EUROSENSE, Slovakia)

a slight prevalence of deposition. Due to the response of the river to the phase of low magnitude floods after events in 1987 and 1989, the channel narrowed from the average width of 31.4 m to 28.7 m and stabilised. Small discharges with a recurrence interval 1 or 2 years, which occurred in the reach between 1989 and 2000, did not exert larger destructive effects. On the contrary, in accord with Corenblit et al. (2007) and Phillips (2002), their effect was constructive and contributed to the stabilisation of the system. On the other hand, high magnitude and frequent floods after 2002 (and especially in 2004, 2006 and 2008) intensified erosion processes – the area of erosion compared to the area of deposition increased 3.6-fold and the average shift of the bank doubled. The result was widening of the channel to an average width of about 38 m.

Some authors (Bertoldi et al., 2009, or Hickin and Sichingabula, 1988) emphasise the predominant role of the channel-forming discharge or relatively smaller but long-duration floods in bank or floodplain erosion. As Lehotský et al. (2013) or Phillips (2002) point out, it is precisely the smaller discharge that leads to channel and planform formation and relatively slower bank erosion, which is connected with the overall behaviour of the river in the stage of dynamic equilibrium and hydraulic flow in the river bend (Hickin and Nanson, 1984). High magnitude floods lead to sudden and significant bank erosion, destruction of the planform and to partial or total rejuvenation of the stream, accompanied by channel and gravel bars expansion, and the destruction of old and formation of new stands for vegetation.

While bank erosion in bends is more or less continuous, its rate depends on the discharge régime. Therefore, channel shifting changes rhythmically; because of the lateral erosion, the channel widens and creates favourable conditions for the formation of large bar surfaces. This process is more pronounced if floods return frequently, enhancing bank erosion, and the stabilisation of the vegetation is limited. If years characterised by low discharges occur, however, the arboreous vegetation can stabilise the bar surfaces, leading to channel narrowing (Kiss and Blanka, 2012). Consequently, the changes in the characteristic stages and frequency of floods since 1987 can highly influence the long-term tendencies of channel migration and bedforms evolution. Individual landforms are formed and reformed in new locations, but they retain their generic identity as part of a landform assemblage. Thus, the Topľa as a meandering river is deemed to be "robust" if, over decades, it steadily migrates creating bars/point bars, which, in turn, are incorporated into a new floodplain, but yet retains its characteristic morphology of pools, riffles, undercut banks and bars/point bars. This can be described as "robust" behaviour within existing intrinsic thresholds, rather than "responsive" behaviour crossing extrinsic thresholds (Werritty and Leys, 2001). Not only does bank erosion lead to the development of new geomorphic diversity of a river, but it also provides several ecosystem services (Cebecauerová and Lehotský, 2012). Bank erosion may also have a psychological effect (Piégay et al., 1997).

The majority of eroded banks are located in less valuable places than settlements or arable land. The monetary expression of the damage caused by the bank erosion of arable land and pastures normally concern the unstable stretches (Fig. 7). The attention of water authorities or managers should focus precisely on these dynamic reaches, along with those where the stream directly threatens human activities.

The calculated prices of eroded agricultural land reflect the prices set by Slovak law, which differ from those of the market. The actual market price of a plot of arable land in this area is two to three times higher. Ignorance of stream dynamics and behaviours often leads to the application of expensive and inappropriate interventions, which do not respect the natural development of the channel (Langhammer, 2010) (Fig. 8). An example of such inappropriate intervention is the location of the above-mentioned small hydropower plant. For a natural and healthy river state, the self-regulatory mechanism which leads to spontaneous self-organisation into a quasi-new balanced status is important.

Extreme discharges cause considerable bank erosion and the formation of new bar areas, which lead to a loss of arable land and the destruction of buildings. Bank failure occurrence indicates potential erosion in future years because they are not fixed by vegetation (Grešková and Lehotský, 2007), indeed even minor bank erosion related to the growth of channel loops leads to bank migration, but over a longer time frame.

6. Conclusions

Understanding the dynamics and behaviour of rivers in their natural environment and in the context of other components of landscape, makes it possible to predict the future development of the stream and its environs. It may simplify the co-existence of humans and the river and limit negative man-made interference with streams.

The Topľa River reach, as an unconfined gravel-bed river system, is typical for its migratory behaviour and obvious bank erosion. It is still one of the few minimally trained river reaches in the Slovak Republic and, therefore, ideal for contemporary monitoring of the dynamics of a river system. Gradual loss and bank destruction along the concave banks and deposition of material on the opposite
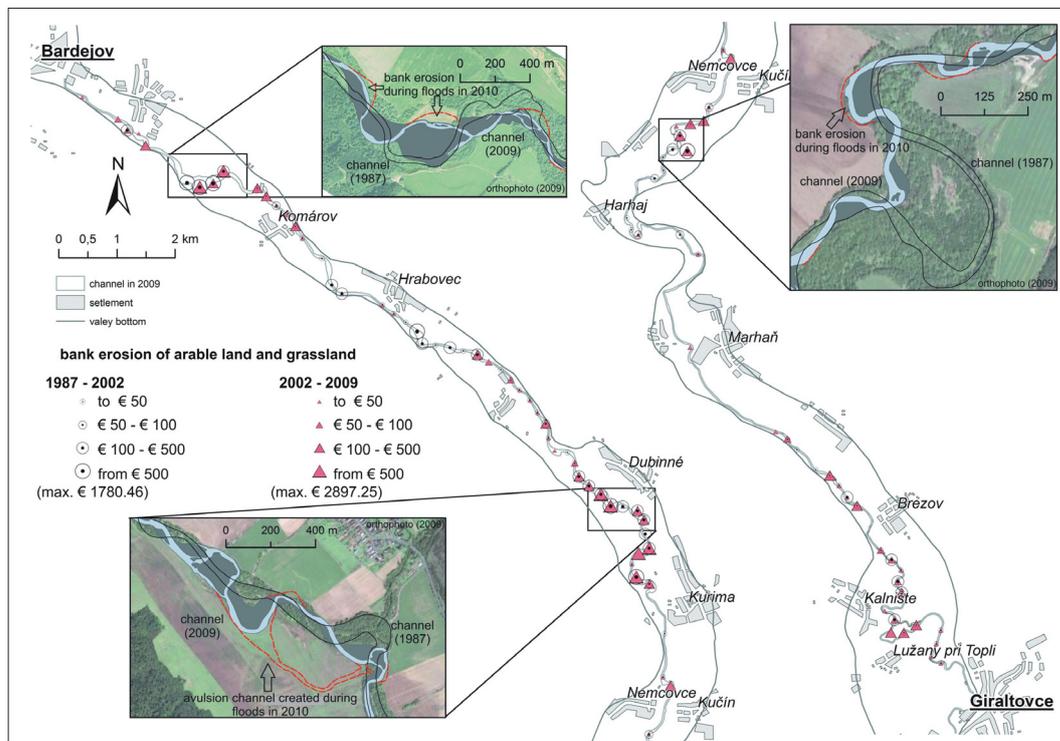
Fig. 7: Localities of grassland, pasture and arable land plots destroyed by bank erosion, and expressed by value (€) according to state-determined prices
Source: authors' elaboration; Settlements layer (Geodesy, Cartography and Cadastre Authority of Slovak Republic (122-24-99-2012)); aerial photo (EUROSENSE, Slovakia)

Fig. 8: An example of non-environmentally friendly river management. Channel lateral movement and bank erosion in the meander loop was stopped by the dike and the channel was shifted to the position before the flood event (left image). The inter-dike area close to the eroded bank was filled downstream by construction waste (right image). Despite these measures, channel migration continues. Photo: M. Rusnák

banks, are the processes that take place along the stream. The size of the shift itself is considerable – it moves about one metre per year and more than 10 m per year in the most dynamic reaches. The shift of the channel manifests itself by the formation of cutting banks and undercutting former floodplain and slope terraces. The channel shift is responsible for the change and destruction of the existing landforms and the deposition of new ones, followed by succession of vegetation and overall land cover changes in the riparian zone. Two different flood periods (1987–2002 and 2002–2009) with two different channel behaviours have been identified. The average channel shift per year doubled from 0.8 m/year (1987–2002) to 1.6 m/year (2002–2009). In total, an area of 85.2 ha was eroded and 60.1 ha was deposited. The most eroded land cover category in the riparian zone is floodplain forest, followed by arable land, grasslands and pastures and shrubs. From an economic point of view, the eroded floodplain with arable land and grassland (€ 29,924.02 in total) are negative consequences of channel migration. It is also necessary to bear in mind that channel migration and bank erosion are natural processes. A "green" approach is now preferred worldwide, one which avoids technical interventions into the channels and rivers are left to meander freely in certain areas (Piégay et al., 2005) or in certain reaches (Piégay et al., 1997). Piegay et al. (1997) also point out that active restrictive interventions in channels are expensive and result in a spiral effect leading to the degradation of streams and increased flood risk. Fortunately, the study river reach is a good example of a situation where the channel migration, bank erosion and bank destruction processes are not given much attention by local authorities.

Acknowledgments

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