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RECENT CHANNEL PLANFORM EVOLUTION OF A BRAIDED-WANDERING RIVER USING MULTITEMPORAL DATA AND GIS (CASE STUDY OF THE BELÁ RIVER, SLOVAK CARPATHIANS)

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Abstract. The paper aims to the identification of the recent channel planform evolution of the braided-wandering Belá River using multitemporal data analyses of channel parameters in GIS (river active zone width, channel number, island number and mid-channel bar number) within consecutive 100-m-long channel segments (227 in total) for seven time horizons (1949, 1961, 1973, 1986, 1992, 2003 and 2009). The main types of planform (single, braided and wandering) of 227 channel segments were shown in the spatio-temporal matrix. Prevailing occurrence of a channel planform types in an individual CHS within seven time spans more than 4 times served as minimum for the discrimination of the trend of planform evolution during last sixty years. Seven evolutionary trends (B – braided, W – wandering, S – single thread, S-W – single-wandering, W-S – wandering-single, B-W – braided-wandering, W-B – wandering-braided) of planform were identified. The averages of confinement ratio were used to specify their longitudinal diversity. The largest proportion of the braided planform was identified in 1949. The stabilization of in-channel landforms and channel narrowing between years 1973 and 1992 reflect the prevailing of wandering channel planform. Situation has been changed in 2003 where the number of channel segments with braided channel planform increased. The last evolutionary period (2009) is specific by mid-channel bar stabilization and its transformation into islands as well as by significantly decrease in braided channel planform at the expense of the transitional – wandering one.

Key words: planform evolution, multitemporal, braided-wandering, GIS, Belá River

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INTRODUCTION

Using a geographical information systems (GIS) and processing relevant source data from remote sensing and historical maps plays an increasingly significant role in fluvial systems research [Gurnell et al. 2003]. GIS-oriented research provides an opportunity to quantify channel landform parameters and takes into account their relevance for the interpretation of the process-response relationship. Historical maps and remote sensing data are the key sources of spatial information, which enable study of river evolution trends and allow precise spatio-temporal analysis of landforms in river channel and on floodplain. Determination of the spatio-temporal differences of the dynamic braided-wandering river systems is strongly supported using digital/remote sensing data based on GIS techniques in order to analyse planform characteristics (e.g. channel width, braiding index), lateral migration due to erosion and deposition of sediments or in-channel forms (bar, island) changes [Zanoni et al. 2008, Surian et al. 2009, Armaş et al. 2012, Liro 2015].

In the Carpathian region, number of studies point out the channel planform changes due to impact of the long term climate (the Holocene and the Little Ice Age), land cover changes or intensive human interventions (in the channel or catchment) [Wyżga 1991, 1993, Kalicki et al. 2008, Kadlec et al. 2009, Perşoiu and Rădoane 2011, Chiriloaei et al. 2012, Rădoane et al. 2013, Stacke et al. 2014].

The aim of the paper is the multitemporal registration of in-channel form parameters (channel number, island number and mid-channel number), identification of their changes in GIS as well as the construction of the spatio-temporal matrix of planforms which allows to provide the information about trends of planform evolution of the Belá River as the longest braided-wandering river of Slovakia during last 60 years.

STUDY AREA

The Belá River with total length 23.6 km consisting of the confluence of the Creeks Tichý and Kôprovský. It is the largest right tributary of the upper Váh River and flows through the Liptov Basin in NE-SW direction (fig. 1). Most of its course is predeterminated by longitudinal tectonic faults. The river network of the Belá basin is distinctly asymmetric. The catchment area amounts to 244 km^2 with the minimum and maximum sea level altitudes of 630 m and 2.494 m respectively.

The average annual discharge (1964–2006) at the gauging station Podbanské (the confluence of the Tichý and Kôprovský Creeks) is 3.5 $m^3 \cdot s^{-1}$ and 6.8 $m^3 \cdot s^{-1}$ upstream the junction with the Váh River at the gauging station Liptovský Hrádok, respectively. The top water levels due to spring snow-melt thaw are reached from April to May and due to flash precipitation from June to July as a prevailing summer floods. The minimum water levels are reached in February. The maximum culmination discharge 180 $m^3 \cdot s^{-1}$ from summer 1958 registered at Podbanské gauging station was specified as a catastrophic flood event (RI 50-years). Magnitude of extreme flood discharges after this flood event has decreased trend (RI 2-10-years in 1968 / 68.2 $m^3 \cdot s^{-1}$, 1997 / 72 $m^3 \cdot s^{-1}$, 2001 / 45 $m^3 \cdot s^{-1}$, 2008 / 62.4 $m^3 \cdot s^{-1}$, 2010 / 63 $m^3 \cdot s^{-1}$).

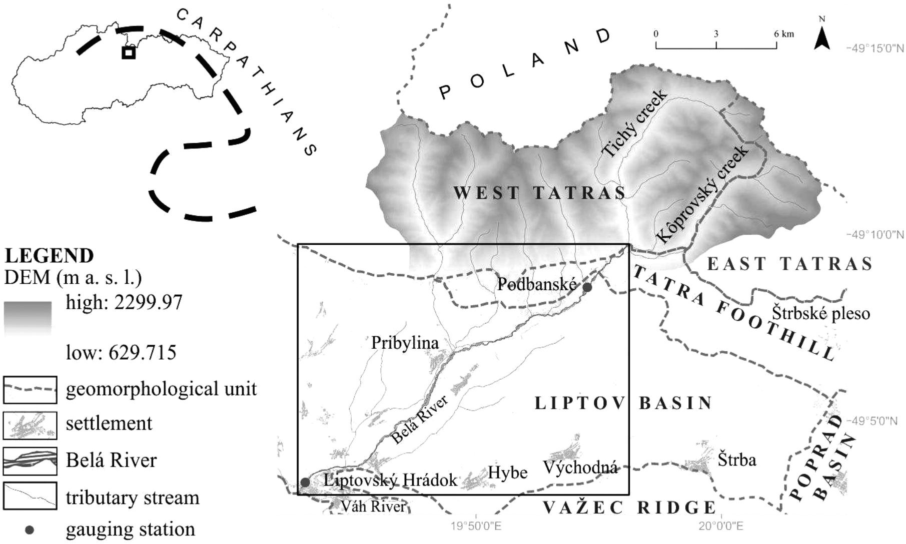


Fig. 1. Location of the Belá catchment with basic topography

DATA AND METHODS

The data gathering was based on analysis of the remote sensing data (aerial photos and orthoimages from seven time spans; 1949, 1961, 1973, 1986, 1992, 2003 and 2009) in ArcGIS environment (table 1). The aerial photos were georectified to the S-JTSK Křovák East North projection. Ground control points (GCPs) were identified for clearly distinguishable fixed points adjacent to the river active zone (corners of buildings, bridges, etc.). The orthophotos from 2003 with a pixel resolution of 1.0 m were used as the reference layer. Root mean square error (RMSE) ranged from 0.7 to 8.9 m for individual photographs.

The analysis of the aerial photos and orthoimages (1949–2009) in GIS has been used for the river active zone/braidplain delimitation, the channel landforms classification (bars, islands) as well as for the compilation of database of their parameters (fig. 2a). A border of river active zone/braidplain area for each time horizon was drawn along the outer channel bank edges whilst the bank edge was established as the border between the channel or gravel bar and the contiguous vegetation on floodplain. The maximal (reconstructed) river active zone is delimiting by the lowest Holocene terrace edges or anthropogenic (dikes) margins existed as early as 1949. An island was delimitated as a stable channel landform covered more than 90% by compact tree vegetation. Bars was digitized only when one horizontal dimension was greater than the closest active channel width and/or the area is equal or greater than 5 meters (5 pixels). In a final stage 228 transects across the river active zone spaced at 100 m intervals (fig. 2b) were automatically constructed using ArcGIS tool so 227 polygons (channel segments – CHS) were delimitated. Such a channel discrimination allowed analysis of spatio-temporal diversity of the

Table 1. Sources of data

Year	Type	Scale of photograph	Date	Agency
1949	Aerial photo	1:11000; 1:17000; 1:20000	2.8.; 8.9.; 10.9.; 27.9.	Topographic Institute
1961	Aerial photo	1:11780; 1:12360; 1:12390; 1:13014; 1:15410	21.6.; 1.7.; 20.8.; 21.8.; 29.8.	Topographic Institute
1973	Aerial photo	1:13680; 1:14270; 1:14480	7.8.; 10.8.; 28.8.	Topographic Institute
1986	Aerial photo	1:28732	21.9.	Topographic Institute
1992	Aerial photo	1:21830; 1:25420	20.7.; 21.7.	Topographic Institute
2003	Orthophoto	1m pixel	28.8.	Eurosense Slovakia
2009	Orthophoto	0.5m pixel	20.8.	Eurosense Slovakia

river. Selected parameters (perennial channel number, island number and mid-channel bar number) of in-channel forms within CHS have been used for the channel planform identification (fig. 3). Three main channel planforms were identified in the river active zone: i) single-thread (S) – from one to two perennial channels, island and mid-channel bar appearance was neglectable; ii) wandering (W) – mid-channel-island channel type with avulsion appearance, more than two perennial channels, one island occurrence at least, mid-channel bar appearance was neglectable; iii) braided (B) – mid-channel bar channel type, more than two perennial channels, one mid-channel bar occurrence at least, islands were not occurred. Graphic spatio-temporal matrix [Bertin 1981] consisting of 7 columns representing 7 time horizons and 227 rows representing longitudinal (22.7 rkm) diversity of the Belá planform was worked out. Prevailing occurrence of a channel planform in an individual CHS within seven time spans more than 4 times served as minimum for the discrimination of the trend of planform evolution during last sixty years. The averages of the valley confinement ratio was used for the interpretation of the segmental as well as longitudinal variability of evolutionary planform trends. They were calculated for each of 227 CHS as the averages of ratios of the reconstructed maximal river active zone width divided by the river active zone width [Kline et al. 2007] in each of seven time horizons.

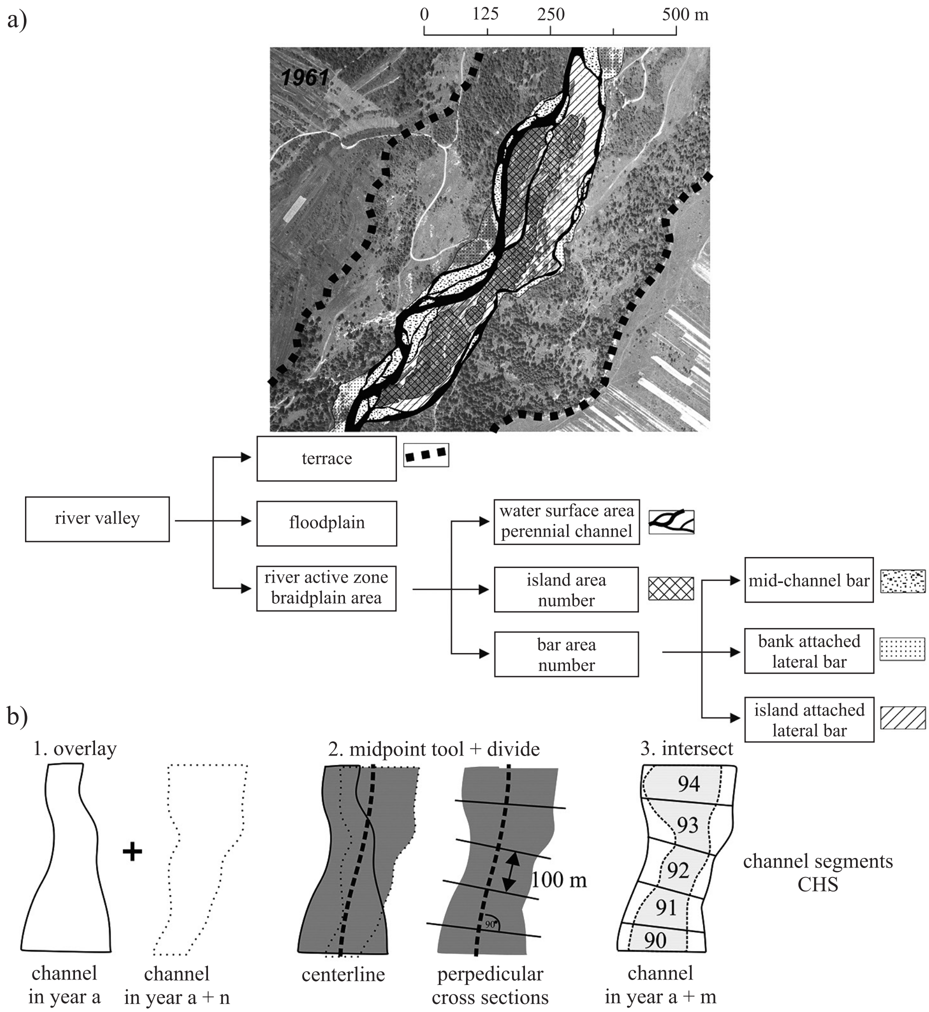


Fig. 2. (a) River active zone (braidplain) area parameters generated in GIS on the basis of data obtained from aerial photos for 100-m-long channel segments; (b) three GIS-steps for delimitation of the river active zone (RAZ) and 100-m-long channel segments (CHS) where river active zone width and parameters of in-channel landforms' properties were identified

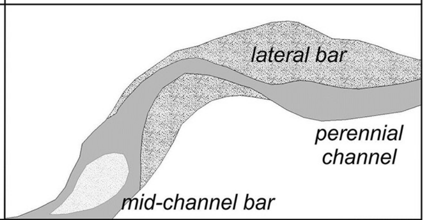
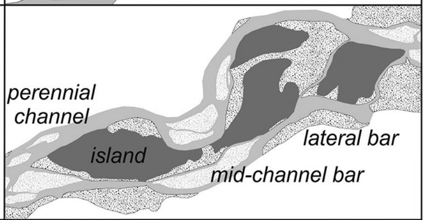
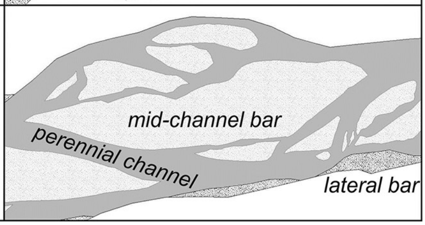
Channel planform	Number			Planform example
	Perennial channel	Island	Mid-channel bar	
Single-thread	**1–2**	**≥ 0**	**≥ 0**	
Wandering	**> 2**	**> 1**	**≥ 0**	
Braided	**> 2**	**< 1**	**> 1**	

Fig. 3. Channel planform types discrimination. One or two perennial channels, no or scarce island and mid-channel bar occurrence represent single-thread channel planform. More than two perennial channels and one island at least and scarce mid-channel bar occurrence reflect wandering channel planform. More than two perennial channels, one mid-channel bar at least and no island occurrence indicate braided channel planform

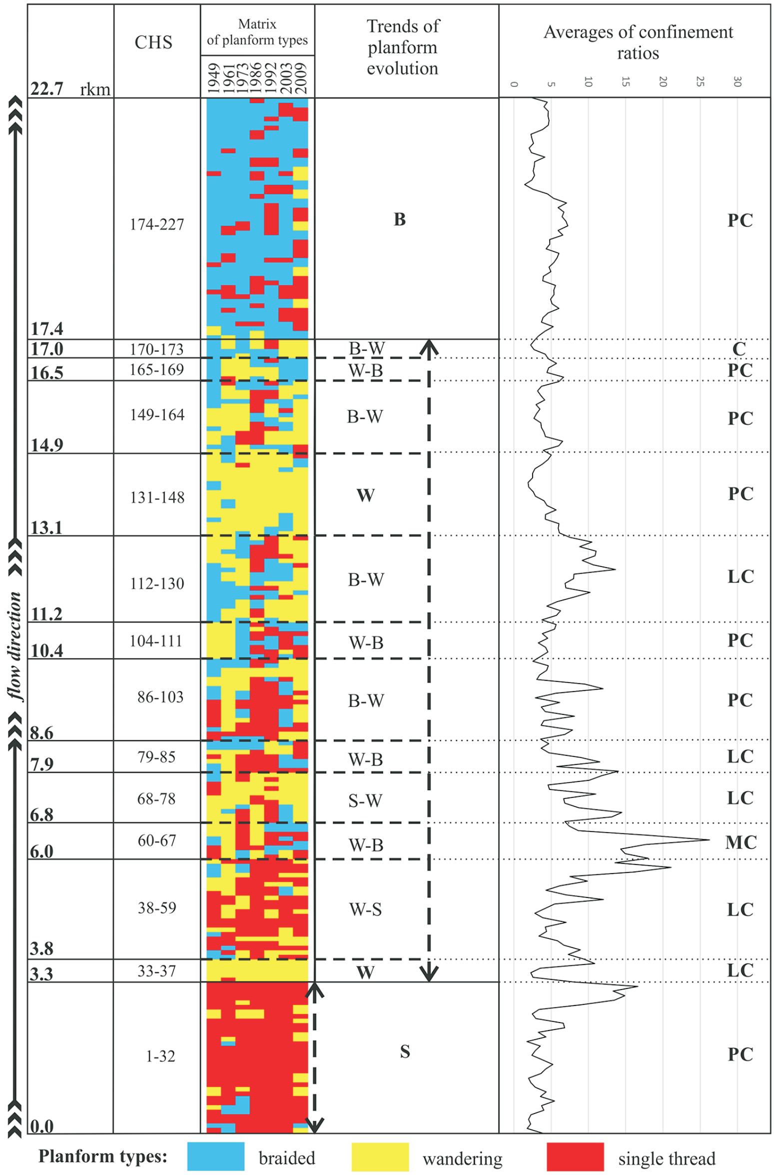
RESULT AND DISCUSSION

Based on the identification of three main kinds of planform for each of 227 individual CHS in each of 7 time horizons the matrix of planforms was compiled (fig. 4). The matrix reflects longitudinal channel planform variability within the frame of one time horizon as well as the channel planform temporal variability of the individual CHS during seven time horizons. Using the criteria of prevailing (4 times) or mixed occurrence of one planform kind seven trends (B – braided, W – wandering, S – single thread, S-W – single-wandering, W-S – wandering-single, B-W – braided-wandering, W-B – wandering-braided) of planform evolution were identified.

The 3.3 km long single-thread (S) planform evolutionary trend dominates in the most upper course of the Belá in partly confined valley setting (fig. 5a). Mixed evolutionary planform trends (W, W-B, B-W, W, S-W, W-S) were identified in the length of 14.1 km (from 3.3 rkm to 17.4 rkm) in very various valley settings from minimally confined to confined (fig. 5b). The diversity of segment planforms along the reach of wide floodplain allowing relatively free lateral channel migration and thus providing sufficient delivery of sediments to channels can be interpreted as response to local susceptibility to avulsion and braiding either in minimally and less confined segments when the river active zone is situated in central position of the valley floor or in partly confined segments with the one-sided river active zone sporadically abutted against the valley wall and restricted its lateral movement only locally. The exception are segments (No. 170–173) in the confined valley setting which maintains B-W planform due to the position on a knick point zone which is provided by sufficient sediment supply from upstream segments and thus allowing the multichannel planform development (fig. 5c). The braided planform (B) upstream the mouth of the Belá along the 5.3 km long river reach in spite of partly confined channel setting due to channelization reflects the sediment deposition area with frequent 3rd order avulsions (fig. 5d).

As to the Belá temporal planform diversity the largest proportion of the braided pattern was identified in 1949 (fig. 6). Prevailing braided planform with well developed wandering pattern indicates a morphological response of channel to destructive high magnitude flood event in 1934 (RI 50-years). After next extreme flood in 1958, number of CHS with braided pattern decreased and wandering pattern prevailed. However, in several CHS was observed opposite evolution as a transformation of single-thread channel planform to multi-thread one. These transformations are affected by local conditions (slope and input of sediments by bank erosion during floods). So, decrease of proportion of the braided pattern at the expense of wandering one in 1961 is evident. In the next time horizon (1973) the Belá maintained multi-thread channel planform but the stabilization of in-channel landforms and channel narrowing between years 1973 and 1992 reflect the prevailing single-thread channel planform. The proportion of planform types has been changed in 2003 where the number of CHS with multi-thread channel planform increased. The last time horizon (2009) is specific by mid-channel bars stabilization and their transformation into islands as well as with significantly decreasing braided channel planform at the expense of the transitional – wandering one.

Synergism effect of the flood protection works (dike, check-dam, bank stabilization) and decrease magnitude of flood events from year 1974 with dominant lateral bank accretion processes led to stabilization of in-channel landforms, channel narrowing, pattern simplification and its transition from braided to wandering one. Gravel mining and other human interventions (channelization, small hydropower plant construction, forest cover changes in the Belá River catchment) contribute to channel planform simplification [Kidová and Lehotský 2012, Kidová et al. 2016] which is in correspondence with studies [Liébault and Piégay 2002, Piégay et al. 2009, Wyżga 1991, 1993]. The reduction of active zone area over the 200-year period when recent active zone area was approximately 50% of its size from the 19th century demonstrate also Zanoni et al. [2008] on the Tagliamento River. Also according Armaş et al [2012] several factors (afforestation, riparian vegetation growth, sediment mining, upstream dams) owing to reduced natural sediment and liquid fluxes on Prahova River as well as its narrowing, incising and transition from a braided into a sinuous, single-thread planform.

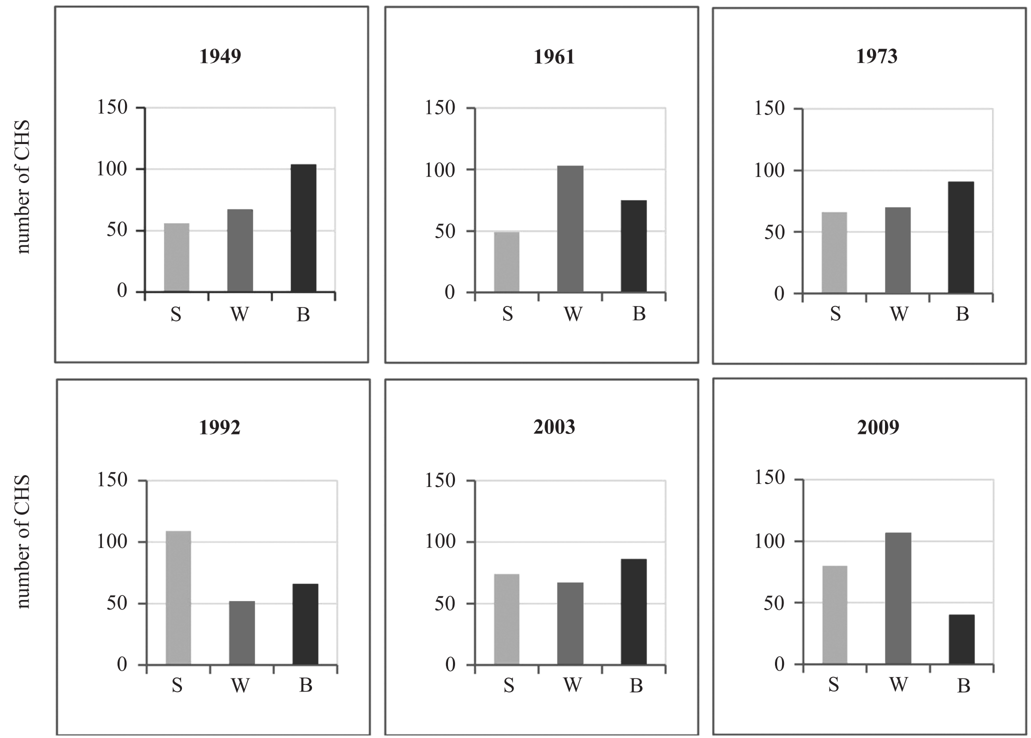


Trends of planform evolution: B – braided, **W** – wandering, **S** – single thread, **B-W** – braided-wandering, **W-B** – wandering-braided, **S-W** – single thread-wandering, **W-S** – wandering-single thread

Averages of confinement ratios: VC – very confined (1 < 2), **C** – confined (2 < 4), **PC** – partly confined (4 < 6), **LC** – less confined (6 < 10), **MC** – minimally confined (> 10)

Fig. 4. Figure shows the spatio-temporal matrix of channel planform types, evolutionary trends and averages of valley confinement ratios of the Belá River (1949–2009). The matrix presents the planform types arrangement within the frame of the whole river length in one time horizon as well as the channel planform within the frame of one CHS in each time horizon. Kinds of the planform evolutionary trend allow classify CHS into seven categories. Their relation to the valley setting is illustrated by averages of the confinement ratio

Fig. 5. Examples of the three main channel patterns of the Belá River: (a) the single thread channel in upstream channel segments, (b, c) the wandering patterns in middle part of the river and (d) the prevailing braided pattern in downstream channel segments



Year	CHS number		
	S	W	B
1949	56	67	104
1961	49	103	75
1973	66	70	91
1986	114	54	59
1992	109	52	66
2003	74	67	86
2009	80	107	40

Planform types: S – single thread, **W** – wandering, **B** – braided

Fig. 6. Proportion of main planform types by CHS in each time horizons indicates channel planform changes of the Belá River during last sixty years and its evident simplification

CONCLUSIONS

Spatial analysis and other GIS techniques presented in the paper proved their widespread availability for river changes studies. The largest proportion of the braided planform was identified in 1949. The stabilization of in-channel landforms and channel narrowing between years 1973 and 1992 reflect the prevailing of wandering channel planform. Situation has been changed in 2003 where the number of channel segments with braided channel planform increased. The last evolutionary period (2009) is specific by mid-channel bar stabilization and its transformation into islands as well as by significantly decrease in braided channel planform at the expense of the transitional – wandering one. Human interventions (channelization, small hydropower plant construction, forest cover changes in the Belá River catchment) contribute to channel planform simplification, too.

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BIEŻĄCA EVOLUCJA ZMIAN RZECZNEGO KONTURU ZATOKOWEGO-MEANDRUJĄCEGO Z UŻYCIEM DANYCH POWTARZALNYCH ORAZ GIS (STUDIUM RZEKI BELÁ, KARPATY SLOWACKIE)

Streszczenie. Celem pracy była identyfikacja bieżących zmian konturu zakoli koryta rzeki Belá z użyciem powtarzalnych analiz danych parametrów koryta w GIS (szerokość aktywnej strefy rzeki, numer koryta, numer wyspy i numer progu śródkorytowego) w kolejnych 100-metrowych odcinkach koryta (w sumie 227) dla siedmiu przedziałów czasowych (1949, 1961, 1973, 1986, 1992, 2003 oraz 2009). Główne typy konturów (pojedynczy, roztokowy, meandrujący) spośród 227 odcinków koryta zostały przedstawione w macierzy czasoprzestrzennej. Powszechne występowanie typów konturu koryta jako indywidualne CHS w obrębie siedmiu okresów czasowych więcej niż 4 razy wykorzystano jako minimum dla rozróżnienia trendu ewolucji konturu podczas ostatnich 60 lat. Zidentyfikowano siedem ewolucyjnych trendów konturu (B – roztokowy, W – meandrujący, S – pojedynczy warkocz, S-W – pojedynczy meandrujący, W-S – meandrujący pojedynczy, B-W – roztokowy meandrujący, W-B – meandrujący roztokowy). Średnie współczynniki ograniczenia zostały użyte do określenia różnorodności ich dna. Najwyższy odsetek konturów roztokowych został wykazany w 1949 r. Stabilizacja ukształtowania terenu wewnątrz koryta oraz jego zwężeń pomiędzy latami 1973 i 1992 odzwierciedla dominację meandrujących konturów koryta rzeki. Ta sytuacja uległa zmianie w 2003 r., kiedy wzrosła liczba odcinków koryta z konturami roztokowymi. Ostatni okres ewolucyjny (2009) charakteryzuje się śródkorytową stabilizacją oraz przekształceniem w wyspy, a także znacznym wzrostem roztokowych konturów korytowych kosztem pośrednich – meandrujących.

Słowa kluczowe: ewolucja konturu, powtarzalny, roztokowy-meandrujący, GIS, rzeka Belá

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