A Unique Braided-Wandering River in Slovakia: Recent Development and Future of the Belá River

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Anna Kidová, Milan Lehotský, Miloš Rusnák, and Peter Labaš

Abstract

The Belá River represents a reference braided-wandering river system to observe natural, or semi-natural, forms and processes in the mountain environment. In this chapter, human impact and spatio-temporal bio-morphological evolution of the Belá River from the second half of the twentieth century are described. For the high-energy Belá River, new gravel bar formation as well as their re-formation due to frequent channel avulsion is typical. An overall trend of simplification of the braided and wandering river planform, narrowing of the river active zone and vegetation succession on in-channel landforms with an increased island area was registered. However, in-channel landforms and processes typical for the braided rivers are still prevailing in some river reaches, and these represent unique natural entities. Additionally, the Belá River is included in the network of protected areas Natura 2000, with habitats of European importance.

Keywords

Braided river • Morphology • River active zone • Floods • Human impact • Vegetation dynamics

15.1 Introduction

Natural processes and processes caused by human activity affect river corridors and can act in isolation, but more often they do so simultaneously, in mutually reinforcing interactions. The disruption of the original structure of the river systems is accompanied by a causal chaining effect that permanently weakens their basic ecological functions. Ongoing processes in the river system can be seen as changes at two levels, at the floodplain and river channel level. High-energy braided rivers are characterized by frequent changes in the riverbed position. It can be stated that lateral channel migration is a measure of the dynamics of processes taking place in braided and wandering river systems. The morphological changes are caused by disruption of the river banks and bars by erosion processes (Charlton 2008). At the same time, during channel migration, numerous bars are formed, and abandoned channels are filled with river sediment (Nordseth 1973). Channel migration or shifting within the river active zone according to Bertoldi et al. (2009) represents a specific change in the position, size and arrangement of an individual part (channel element) of a river system over time while maintaining a constant number of channels. High-energy multi-thread river systems often re-occupy abandoned channels, where bar formation or transformation is supported in the river active zone. Channel avulsion such as relocation or shifting of the channel to the lower part of the floodplain is considered to be a sign of lateral channel instability (Schumm 1985) and exceedance of the equilibrium thresholds. Natural processes mostly operate within the range of states of dynamic equilibrium of the river system and have some self-regulating potential for restoration and return to the original form, while changes caused by human activity very often require revitalizing respective renaturation measures. Over the last decades to hundreds of years, river dynamics in many fluvial systems worldwide have been greatly influenced by human intervention in the form of land-use change and urbanization (Surian and Rinaldi 2003).

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Understanding these changes requires data collection to explain local geographic and historical impacts. When disrupting the natural development of a river active zone as a result of anthropogenic influences, there is a certain sequence of morphological changes in the river channel in the process of adaptation to changed conditions, according to which we can define its current state of development and predict its development in the future (Halaj 2004). In terms of hydromorphological evaluation, the Water Framework Directive proclaims indicators and significance criteria for their impact (Pedersen et al. 2004), which interpret the disturbance of the lateral and longitudinal continuity of a river system. The study of geomorphological processes has an irreplaceable role in such an evaluation, including the determination of the current state of the river system. It needs to be acknowledged that landscape systems do not evolve gradually and linearly, but non-linearly, i.e. through fluctuations manifested by new system properties (emergencies) causing the system to go into a new state. The theory of complexity (Nicolis and Prigogin 1977; Jantsch 1980) points to a higher level of organization, with "special attractors" as influences and impulses playing an important role.

Several authors pointed to changes in river behaviour at the end of the nineteenth century, associated with the end of the cooler period, a decrease in the humidity and intensity of meteorological and hydrological processes, and thus to a change in morphological processes in the river systems (Kotarba 1989; Surian 1999; Liébault and Piégay 2002). Bauch and Hickin (2011) emphasized the correlation between climate change, hydrological regime, and geomorphology of the river channels. The increase in the size and duration of floods is a major factor in the acceleration of riverbed changes. Pekarová et al. (2003, 2010) pointed to the cyclical nature of flood discharges, their occurrence in periods with more intense floods. Gurnell and Petts (2002) pointed to the shift of several river systems in Europe from gravel-bed, braided and wandering rivers to a stable single-thread channel as a result of climate change (the end of the Little Ice Age) and intensive human intervention in the river landscape. Wyżga (1991, 1993, 1996, 2001), Lach and Wyżga (2002), and Zawiejska and Wyżga (2010) explained riverbed degradation and channel incision in the Polish Carpathians as a consequence of river basin reforestation, river channel engineering, and gravel mining. In the North-Eastern Italy, there is a visible trend of narrowing and incision of the originally wide braided rivers and its conversion into a wandering or single-thread channel due to anthropogenic interventions and river sediment extraction (Surian et al. 2009; Rinaldi et al. 2005; Surian and Rinaldi 2003). In France (Liébault and Piégay 2002), the transformation of rivers (the conversion trend from braided rivers through wandering to meandering ones accompanied by narrowing of the riverbed) is explained by climate change at the end of the Little Ice Age when the afforestation of river basins and construction of dams led to sediment input reduction. In the Czech Republic, changes of river systems were identified in the Moravian-Silesian Beskydy (Hradecký 2002, 2007; Hradecký et al. 2012; Škarpich et al. 2012, 2013, 2016; Galia et al. 2012). Škarpich et al. (2013) pointed to significant channel incision and degradation of the former multi-thread Morávka River due to anthropogenic interventions and river regulation, resulting in channel incision rate achieving 8 m over the past 40 years. Škarpich et al. (2016) reported the lithological structure (flysch), anthropogenic impacts (river regulation, construction of stony grade-control structures, dam construction), absence of regular floods as well as acceleration of channel incision by concentration of the flow into a narrow and deep channel be the main factors of the Ostravice River transformation.

The occurrence of river systems with braided and wandering pattern in Slovakia in the period 2006–2009 represented approximately 0.2% of the total length of national river network (49,774.8 km, Fig. 15.1). Recognizing the fact that most of the major Slovak rivers (Danube, Váh, Hron, Ondava, Laborec, etc.) had a former multi-thread pattern (documented since 1949 on the first aerial photos of Slovakia), we are entitled to consider the current 95.1 km of such river systems as unique and rare (Kidová and Lehotský 2012). At the same time, they provide opportunities for seeking and interpreting the environmental causes of their changes, which naturally implies not only the need for their research but also their protection. Only several of them, e.g. Mútňanka River, Jakubianka River, Torysa River, Topľa River or Sveržovka River exceed 5 km in their multi-thread pattern length. The longest river (14.3 km) with the multi-thread river pattern is distinctly the Belá River.

15.2 The Belá River as a Study Area

The Belá River represents a unique morphological and ecological water body in Slovakia. Its multi-thread river pattern and typical gravel-bed character represent a near-natural braided and wandering river system (Kidová and Lehotský 2012; Kidová et al. 2016, 2017; Lehotský et al. 2017; Rusnák and Kidová 2018). The Belá River is the largest right tributary of the upper Váh River and flows through the Liptov Basin (Fig. 15.2), whose origin can be dated back to the Sáva orogenesis that followed the Palaeogene. During this period, layers of flysh slate and sandstone were deposited. Through the mountain-forming processes, the strata were deformed into megatinclinals (Fatra Mountains, Tatras Mountains, Chočské vrchy Mountains) and intervening megasynclinals (Liptov and Spiš Basin) formed (Kontriš 1981). The depression of the Liptov Basin is filled with Tertiary flysch layers of cumulative

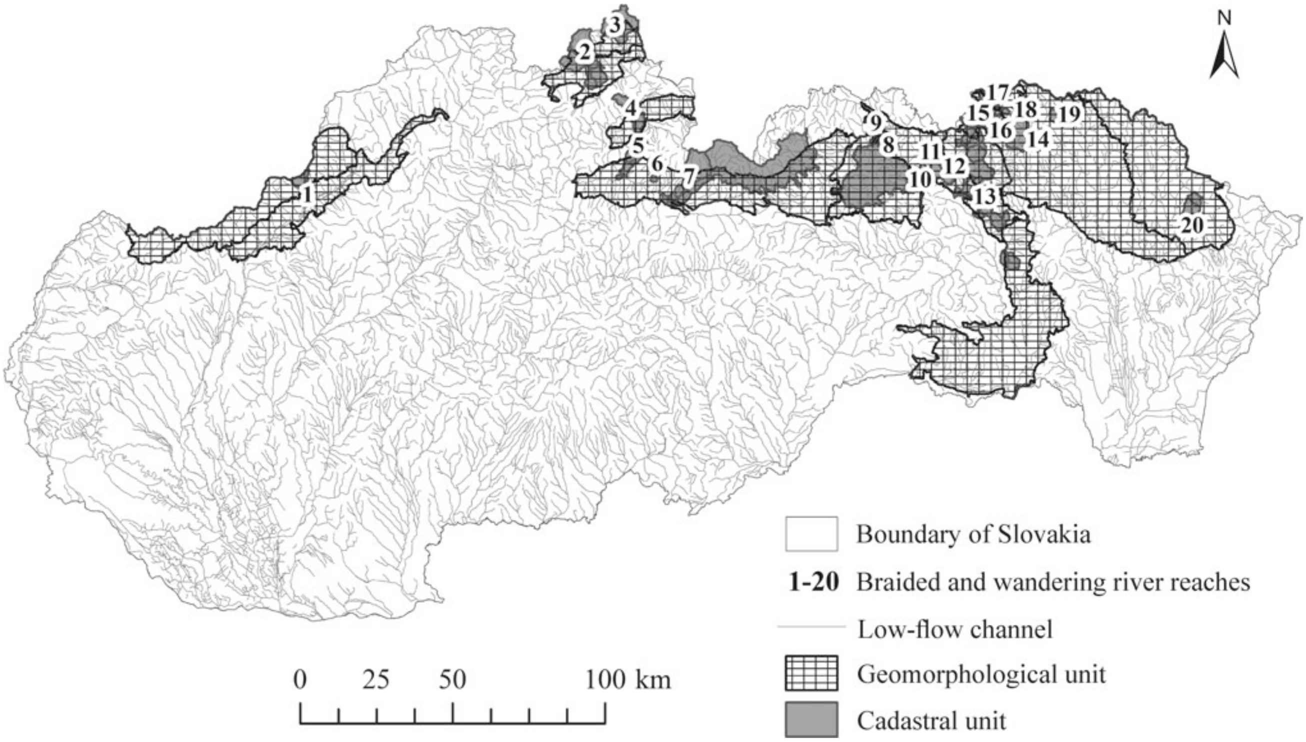

Fig. 15.1 The map illustrates the occurrence of river systems with braided and wandering pattern in Slovakia within its geomorphological (GU) and cadastral (CU) unit (modified according to Kidová and Lehotský 2012). The length of braided and wandering river reaches was identified based on the orthophotomaps of Slovakia in GoogleEarth at a scale of approximately 1:1000 from 2006 and 2009. The criterion for the classification of river sections was the width of the stream greater than 2 m and the exclusion of areas with forest cover. Published with permission of Geografický časopis (Kidová and Lehotský 2012). (Legend: 1—Vlára River in GU Biele Karpaty, Považské Podolie and CU Horné Srnie; 2—Mútňanka River in GU Podbeskydská vrchovina, Podbeskydská brázda and CU Mútne, Novoť, Beňaďovo, Krušetnica, Breza; 3—Suchý creek in GU Podbeskydská brázda and CU Oravská Polhora; 4—Studený creek in GU Skorušinské vrchy and CU Nižná, Oravský Biely Potok; 5—Suchý creek in GU Podtatranská kotlina and CU Kvačany, Liptovské Matiašovce, Liptovská Sielnica; 6—Smrečianka River in GU Podtatranská kotlina and CU Smrečany; 7—Belá River in GU Podtatranská kotlina and CU Podtureň, Liptovský Hrádok, Liptovský Peter, Vavrišovo, Pribylina, Liptovská Kokava, Vysoké Tatry; 8—Jakubianka River in GU Spišsko-šarišské medzihorie, Levočské vrchy and CU Nová Ľubovňa, Jakubany, Javorina; 9—Kolačkovský creek in GU Spišsko-šarišské medzihorie, Levočské vrchy and CU Kolačkov, Nová Ľubovňa; 10—Torysa River in GU Levočské vrchy, Spišsko-šarišské medzihorie, Košická kotlina and CU Tichý potok, Brezovica, Torysa, Krivany, Lipany, Jakubova Voľa, Pečovská Nová Ves, Sabinov, Šarišské Michalany, Ostrovany, Veľký Šariš, Kendice, Petrovany; 11—Kučmanovský creek in GU Spišsko-šarišské medzihorie and CU Šarišské Dravce, Torysa; 12—Lúčanka River in GU Spišsko-šarišské medzihorie and CU Lipany; 13—Ľutinka River in GU Čergov, Spišsko-šarišské medzihorie and CU Pečovská Nová Ves, Ľutina, Olejníkov; 14—Topľa River in GU Čergov, Ondavská vrchovina and CU Gerlachov, Malcov, Lukov, Livov, Bardejov, Komárov, Hrabovec; 15—Kamenec River in GU Ondavská vrchovina and CU Petrová, Gaboltov, Sveržov; 16—Sveržovka River in GU Ondavská vrchovina, Busov and CU Nižný Tvarožec, Sveržov, Tarnov; 17—Oľchovec River in GU Ondavská vrchovina and CUPetrová; 18—Kamenec River in GU Ondavská vrchovina and CU Chmeľová, Zborov, Bardejov; 19—Ondava River in GU Ondavská vrchovina and CU Dubová, Nižný Mirošov; 20—Udava River in GU Laborecká vrchovina and CU Nižná Jablonka, Papín, Zubné)

thickness in excess of 1500 m. Below the flysh are fragments of carbonate nappes and deeper beneath them are Paleozoic crystalline rocks. Within the geotectonic units, the bedrock formation at the bottom of the Liptov Basin is the youngest and least resistant. Faults trending in two directions occur in the vicinity of the basin: the older one's trend East–West and the younger ones follow North–South. The most famous representative of the East–West system is the Podtatranský Fault that stretches along the foot of the High Tatras and its activity is responsible for uplift of the Tatras to their present form. The formation of floodplains and their subsequent re-division to a system of river terraces and alluvial fans is evident in the Quaternary (Kontriš 1981). The original depositional morphology of fans and terraces was remodelled through subsequent fluvial incision. Quaternary sediments in the form of fluvioglacial gravels extend throughout the fore-mountain part of the Belá drainage basin. For the most part, they are non-carbonate. The material of river sediments is generally well sorted (Kontriš 1981).

According to the River Morphology Hierarchical Classification (RMHC) approach (Lehotský 2004), the Belá River is divided into the source, transfer, and the response zone (Fig. 15.3). The Belá River originates as a confluence

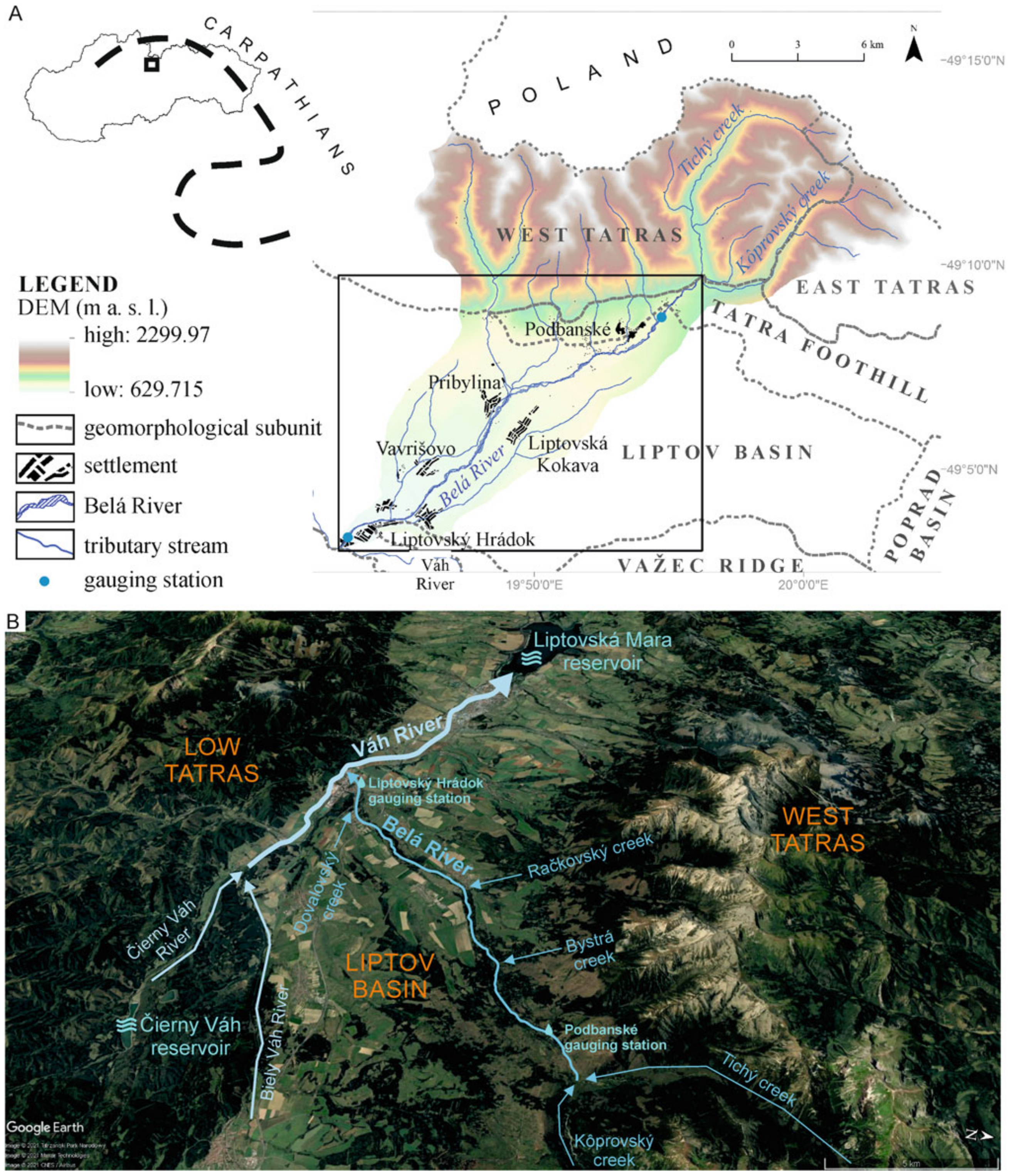

Fig. 15.2 The Belá River location with wider geomorpological division (**a**) and basic river network ordering (**b**). The (**a**) section published and coloured with permission of Acta Scientarium Polonorum (Kidová et al. 2017)

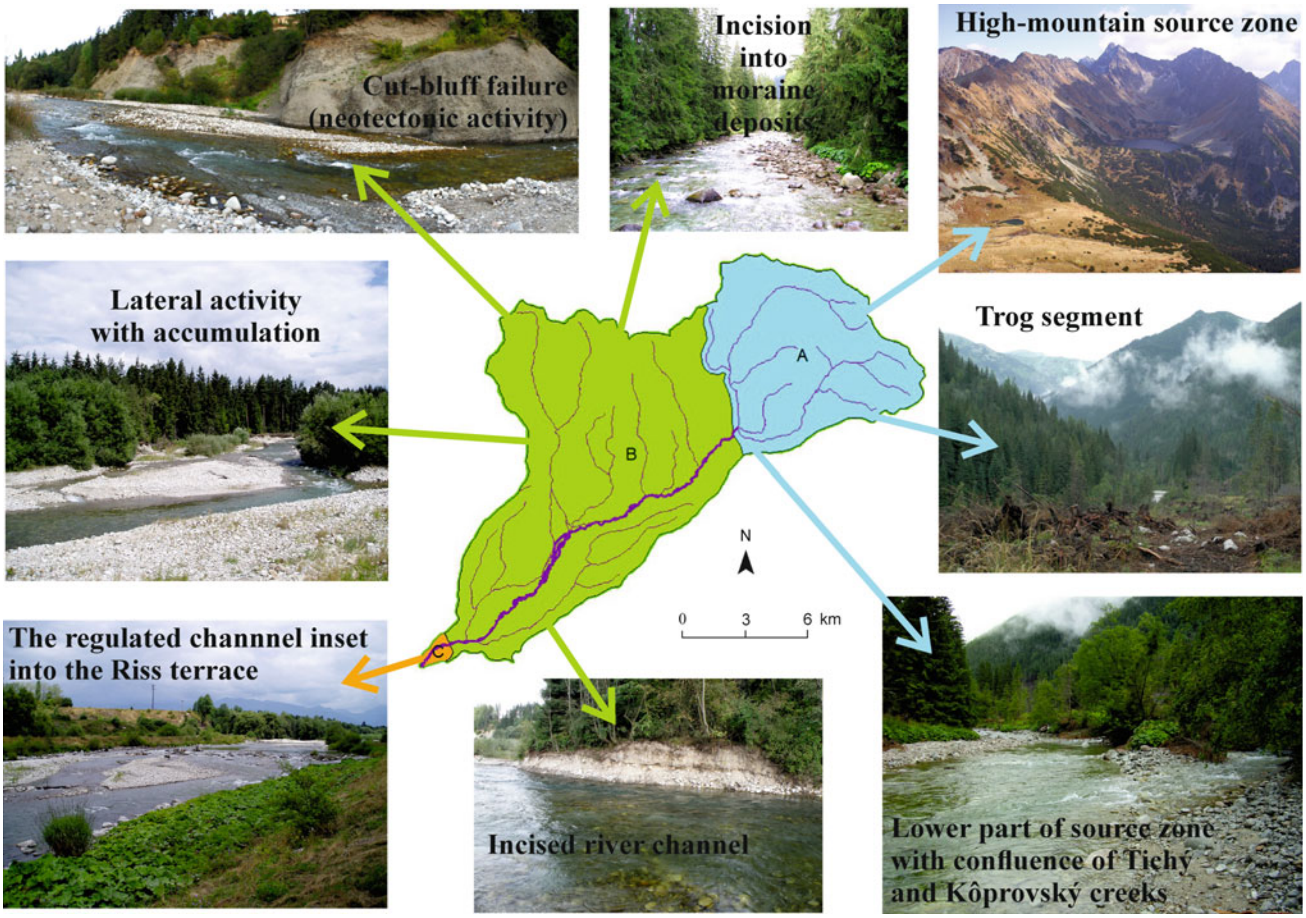

Fig. 15.3 The specific examples of fluvial landforms along the Belá River drainage basin: the source zone - A, the transfer zone - B, and the response zone - C. *Photos* A. Kidová, M. Lehotský

of the Kôprovský creek and Tichý creek in the source zone (A), situated in the High Tatras mountain area. Its higher segments are found in the alpine and subnival environment, characterized by many elements of fossil glacial relief, especially in the form of cirques with several mountain lakes. Geomorphologically, the high-mountain area is characterized by a fluvially dissected highland and moraine and glacial-fluvial piedmont. From a geological point of view, its peaks are built by granitoids and crystalline slates. The low-lying segments of the source zone have the character of a typical glacier valley (trog), with a U-shaped cross-section (Kotarba 2004; Hreško et al. 2005). The bottom of the valleys is usually without floodplain, with channel-bed and bank erosion on some river reaches.

In terms of recent fluvial processes, the transfer zone (B) is the most dynamic. It is represented by the high-mountain, glacial relief, and the fluvially dissected highlands of the Kamenistá, Bystrá, Račková, and Jamnická valleys as a part of the Western Tatras, and the proluvial cones and the proluvial undulate plain (Liptovské nivy) of the Liptov Basin. The presence of the simple-thread, meandering as well as braided-wandering planform of the Belá River is a typical sign for transfer zone. The relief of this zone is a complex of slightly undulating, hilly terrain landforms in Tatras foreland as well as dissected in the mountainous terrain, which is built by granitoids and crystalline slates. The typical flysch of the intra-Carpathian Palaeogene (claystones, siltstones and sandstones) crops out in several places in the Liptov Basin part. However, younger glacifluvial and fluvial sediments dominate (Gross et al. 1979). In the upper part, below the confluence of the Kôprovský and Tichý creeks, there are outcrops of granitoids and crystalline slates of Palaeozoic age. The middle and upper parts of the Belá River from Podbanské to Dovalovo are bordered from the right by the Würm-age terrace, which is connected to proluvial and eluvial-deluvial sediments higher upslope. On the left side, the Belá River is bordered by the Mindel Terrace, with numerous landslides in the flysch lithofacies of a typical intra-Carpathian Palaeogene.

The extent of the response zone (C) is limited to the alluvial fan developed above the confluence of the Belá and Váh River. The massive terraced alluvial fan of Belá spread from Važec to Jamník and Podtureň (Lucerna 1972) overlaid on glacifluvial sediments originating from upper parts of the river catchment. At present, we can identify its right-side border by a Pleistocene Riss terrace created by glacifluvial sediments. Its left-side border, we can find in the interface of basal transgressive lithophace and Hronicum nappe in Liptovský Hrádok settlement. Channel regulation for flood protection purposes is characteristic for the response zone as well.

The hydrological regime is influenced by spring snow melting in higher source zone and heavy rainfall during the summer period. On the Belá River, there are currently two gaging stations (Podbanské and Liptovský Hrádok) and one precipitation station (Liptovský Hrádok). The Belá River reaches an average annual discharge at Podbanské gauging station of 3.5 $m^3 s^{-1}$ (Majerčáková et al. 2007), and 6.8 $m^3 s^{-1}$ at the mouth in Liptovský Hrádok gauging station for the period 1964–2006 (Šipikalová 2006), respectively, 6.56 $m^3 s^{-1}$ for the period 1931–1974 (Hlubocký 1974). Minimum discharges are recorded mainly in winter (February), when precipitation occurs in the form of snow. Flood discharges are related to spring snow melting (May), when they are up to 8–9 times higher than in the months with low discharges (Majerčáková et al. 2007), and to summer storms (June, July) reflecting the mesoclimatic conditions of the river basin. The average annual rainfall is 1590 mm (at 1544 m above sea level) near the Podbanské gauging station. At Liptovský Hrádok precipitation station, the average rainfall achieved is 680–685 mm. From the geomorphological point of view, it is interesting that according to Majerčáková et al. (2007), the hydrological regime of the Belá River has not changed significantly over the last 80 years, i.e. it appears homogeneous (the average annual discharge in the period 1931–1980, it was 3.54 $m^3 s^{-1}$, and in the second monitored period 1961–2006, it was 3.47 $m^3 s^{-1}$).

The Belá River together with its riparian zone creates a biocorridor of supra-regional importance and thanks to its habitats of European importance (SKUEV0141), it is included in the Natura 2000 network. The following habitats are subject to protection: floodplain willow-poplar and alder forests, mountain streams and their woody vegetation with *Myricaria germanica* (Fig. 15.4), mountain streams and their woody vegetation with *Salix eleagnos*, hygrophilous

Fig. 15.4 Exposed gravel bars of the Belá River disturbed by frequent flood events preferred by *Myricaria germanica*. *Photo* A. Kidová

marginal communities on floodplains, lowland and piedmont meadows, beech and fir flowering forests as well as animal species of otter (*Lutra lutra*) and common bat (*Myotis myotis*).

15.3 Anthropogenic Impact

Anthropogenic processes associated with channelization cause disturbance of the dynamic structure of in-channel landforms and lead to degradation of river systems. On the Belá River, we can observe anthropogenic interventions in the form of changes in channel direction, which disrupts the hydrodynamic uniformity of the flow, accelerating erosion processes of the bottom and river banks. These interventions also include fragmentation of the channel and its separation from the surrounding area through the construction of bypass channels of small hydropower plants and transverse structures disrupting the connectivity between the channels, the banks and the floodplain. In addition, it leads to reduced sediment transport and disruption of the homogeneity and structure of the river system. Brierley and Fryirs (2005) classified direct changes affecting the river bed character, distinguishing regulation, river sediment extraction, removal of large wood debris and riparian vegetation, construction of dams and reservoirs, water drainage to other systems (e.g. irrigation). Indirect changes are linked to land cover structure changes, techniques applied in agriculture, forestry, urbanization, construction of buildings, infrastructure and navigation systems.

The Belá River was affected by human activity in several places. The river mouth into the Váh River is regulated in the length of 4 km, where the channel is led in the inter-dam area to protect the urban areas of Liptovský Hrádok and Dovalovo. This downstream area is regulated by five stony grade control structures and in the period from 1950 to 2000, more or less 140,000 m^3 of gravel in total was extracted as the flood protection measure for Liptovský Hrádok and Dovalovo settlements and for the protection of road and railway bridges (Kidová et al. 2016). In other parts of the Belá stream from 7th river km, the channel is regulated only at the four bridges over the Belá River and at the river reach where the small hydropower plant (SHP) was built. There are four small hydropower plants between 5,5 and 11,5 river km (one SHP in Vavrišovo settlement and four SHPs in Pribylina settlement), using abandoned side channels of the Belá River.

Kidová (2010) distinguished three specific phases (from 1925 to 2010) in the evolution of anthropogenetic influence on river channel morphology, where six attractors were identified: flood protection measures, agriculture, building-up, leisure activities, mobility of people, and nature protection policy.

The first evolutionary phase (1925–1948) was characterized by water energy utilization as well as the commencement of the flood dam system, thus reducing the area of the river active zone. The urban area of Liptovský Hrádok and other villages near the Belá River were attacked by several significant floods, where the maximum discharge achieved $Q_{max} = 180\ m^3\ s^{-1}$ with recurrence interval (RI) 50 years in Podbanské gauging station in 1934, respectively $Q_{max} = 60–100\ m^3\ s^{-1}$ in 1925, 1930, 1931, 1948 with RI 5–10 years. Due to the protection of this area, human activities were concerned with reducing the degradation of banks by lateral erosion, the admixture of the river gravel in the agricultural soils and channel avulsions in the inundation area. The great energy potential of the river was exploited as early as the first half of the twentieth century for the benefit of those who lived nearby. However, structures (a mill, groynes, a saw) introduced in this period were also aimed at the elimination of unfavourable runoff conditions, which were supposed to fulfil the function of protection of agriculturally utilized landscape. In the State District Archives in Liptovský Mikuláš, five disused water structures are registered in total. The main reasons for anthropogenic interventions in the first period were flood protection measures and improvement of agriculture.

In the second evolutionary phase (1949–1975), channel modifications due to human intervention focused mainly on how to ensure riverbed stability during further floods (RI 10 years in 1949, 1951, RI 50 years in 1958, and RI 5–10 years in 1960, 1965, 1968, 1970, 1973). Changes in the degree of protection of the surrounding area associated with the establishment of the Tatra National Park (in 1948) reflected decreasing human intervention related to river regulation. Among the attractors, flood protection measures, agriculture, building-up and nature protection policy were dominated.

According to the history of measurements of the Slovak Hydro-Metorological Institute (SHMI), the 20-year period from 1976 to 1996 was extremely dry at the Belá River gauging stations, and big floods with RI more than 5 years did not occur. The first major flood in the third evolutionary phase (1976–2010) occurred only in 1997 (RI 7 years). The series of maximum annual flow rates Q_{max}, despite the occurrence of some floods (RI < 5 years) in the Belá River in 2001, 2006, and 2008, had a downward trend. The Belá drainage basin was least affected by human activity in the upstream part of the Podbanské area. For these reasons, the Belá River in this area was, according to Pekárová et al. (2010), particularly suitable for studying the natural hydrological regime. In addition, in 2002, the Belá River was established as an area of European importance within Nature 2000 network (§27 Act No. 543/2002). It is assumed that after 1989 (change of political background), there was also a change in the social way of life in the studied area. Attention was focused on leisure activities and recreation. Flood

Fig. 15.5 The concrete grade control construction as a solution for the decreased groundwater level in 2003. The water marks on bridge pillar indicate the increased water level after channel regulation in 2006 during the third evolutionary phase. *Photos* A. Kidová, M. Lehotský

protection aimed at eliminating flood damage leads to an improvement in the level of sanitary, aesthetic, urban and cultural requirements of the population. A decrease in the depth of groundwater level necessitated the regulation of an incised channel beneath the bridge between the settlements of Liptovský Peter and Liptovský Hrádok in 2006, resulting in an increase in groundwater reserves by building a grade control structure on the river bottom, whereby the morphological diversity of the channel was lost and the hydraulic flow cross-section changed (Fig. 15.5). The exploitation of water energy potential remains attractive, as proved by active operation of four SHPs. In this phase, flood-protection measures, building-up, leisure activities, mobility of people, and nature protection policy are considered as the main attractors.

The period from 2011 to 2020 can be additionally distinguished as the fourth evolutionary phase. From the hydrological point of view, flood events with RI < 5 years are typical for this period, except floods in 2014 and 2018, with 5–10 years RI. After the flood event during summer 2018 (RI 5–7 years), gravel extraction (46,600 m^3 planned in total), relocation of river sediment (24,000 m^3 planned in total), and redirection of the channel course of the Belá River were carried out within the river training (Kidová et al. 2021). Specific morphological processes typical for the multi-thread Belá River were suppressed to a minimum on several river reaches. The new 2 m high artificial banks created by heavy machinery caused a very recent isolation of the floodplain from low-flow channels (Radecki-Pawlik et al. 2019). Although the Belá River belongs to the protection area of Natura 2000, these river training represent the only ones carried out to this extent, except of river regulation within the residential area in the third phase. Thus, the fourth phase could be undoubtedly characterized by contradiction between river training measures and nature protection policy.

15.4 Recent Bio-morphological Evolution of the Belá River's Active Zone

The recent evolution of the Belá River is linked to floodplain creation, i.e. accumulation (accretion) of the sediments and floodplain transformation, i.e. channel lateral migration, avulsions, and channel widening, respectively. To investigate spatio-temporal geomorphic changes resulting from these recent processes, the Post-flood Period Serial Geomorphic Analysis (POPSEGA) approach developed by Kidová et al. (2016) was applied. The whole river active zone was divided into 227 river segments, 100 m long each, analyzed in seven-time horizons for the study period 1949–2009. The decreasing trend in geomorphic diversity and the results of erosion–deposition index (comparison of the areas of erosion and deposition in two successive time series of floods) calculation reveal that the contraction phase (channel narrowing, straightening, incision, mid-channel bar stabilization, island development) currently prevails for the whole river active zone of the Belá River. It is linked with the decreasing long-temporal trend in the magnitude of flood events occurrence (from 1974 with prevailing only with RI 2–5 years) as well as with anthropogenic interventions (flood protection, gravel mining) and reduction in catchment sediment supply due to expansion of forest cover in headwater river reaches.

Despite the general tendency to a decrease in braiding intensity, the opposite process (bank erosion, avulsion, chute cut-offs, lateral and vertical accretion), i.e. expansion phase, in the downstream river reaches was registered. The node density analyses confirmed the very highly dynamic cores (mid-channel forms change constantly under the domination of braiding processes) in the downstream river reaches. Although there is a continuation of braiding processes in some river reaches, the progressive reduction of braidplain width (by about 44% from 1949 to 2009) shows that the Belá River is in a threshold phase, characterized by channel narrowing and incision and increase in island area (Fig. 15.6). The transformation from the type with prevailing bars (braided) to the one typified by bars and islands (braided-wandering) was recognized as an outcome of the study (Fig. 15.7).

The distribution of the observed in-channel landforms (perennial channels, lateral bars, mid-channel bars, islands), which form the channel platform monitored by Kidová et al. (2017), led to the compilation of the spatio-temporal matrix of channel planform types (Fig. 15.8). It includes the channel planform typology based on the number of perennial channels, islands, and mid-channel bars. It consists of single-thread (S), wandering (W), and braided (B) channel planform. The matrix accounts for longitudinal channel planform variability within one-time horizon as well as for channel planform temporal variability of the individual channel segments during the whole study period. According to the authors' findings, the largest proportion of the braided pattern with a well-developed wandering one was identified in 1949, due to high magnitude flood event in 1934 (RI 50 years). In 1958, the next extreme flood event caused probably many channel avulsions, which decreased the number of channel segments with braided pattern and the wandering pattern prevailed. Transformation of the single-thread channel planform to the multi-thread one was observed as well. The Belá River maintained its multi-thread channel planform in 1973. The in-channel landform stabilization as well as channel narrowing between years 1973 and 1992 led to the predominant single-thread channel planform. In 2003, the number of channel segments with the multi-thread channel planform increased due to a flood event with RI 7 years that occurred in 1997. Vice-versa, the mid-channel bar stabilization and their transformation into islands represented the last study horizon (2009). The results confirmed the findings in Kidová et al. (2016) where the simplification of the Belá River´s braided pattern was declared. These conclusions were also confirmed by the application of the original methodology of Postflood Period Sediment Connectivity Assessment (POPSECA) on the connectivity of the coarse sediments of the Belá River (Lehotský et al. 2018). Eight types of potential functional connectivity were identified by interpreting balance connectivity indices at the floodplain–channel, channel–bar, and bar–bar levels. By linear trend analysis of the Integral Connectivity Index (IIC) and the flood periods, it was found that all river reaches show a decreasing trend of IIC values, i.e. a decrease in transport of coarse sediments and thus a decrease in the formation of bars and reduced geodiversity.

The vegetated patches within the river active zone (gravel bars and islands) with a different state of succession phases affect the morphological channel change (stabilization/rejuvenation). The bank and in-channel landforms stabilization by vegetation support the planform simplification process. The size and structure of the vegetated in-channel landform react dynamically by positive feedback to flow discharge changes and directly affect the local variability of sedimentation rate as well as the in-channel landform formation. These reciprocal processes markedly affect the multi-thread planform of the Belá River. Clarification of the role of vegetation cover evolution is essential for detailed detection of vegetation on in-channel forms and was attempted using Braun-Blanquet (1921) approach, based on both abundance and dominance of plant species. An assessment of vegetated patches from remote sensed data (1949–2009) of the Belá River was based on a combined scale of coverage and abundance. Bar and island areas involved in analyses were evaluated in terms of

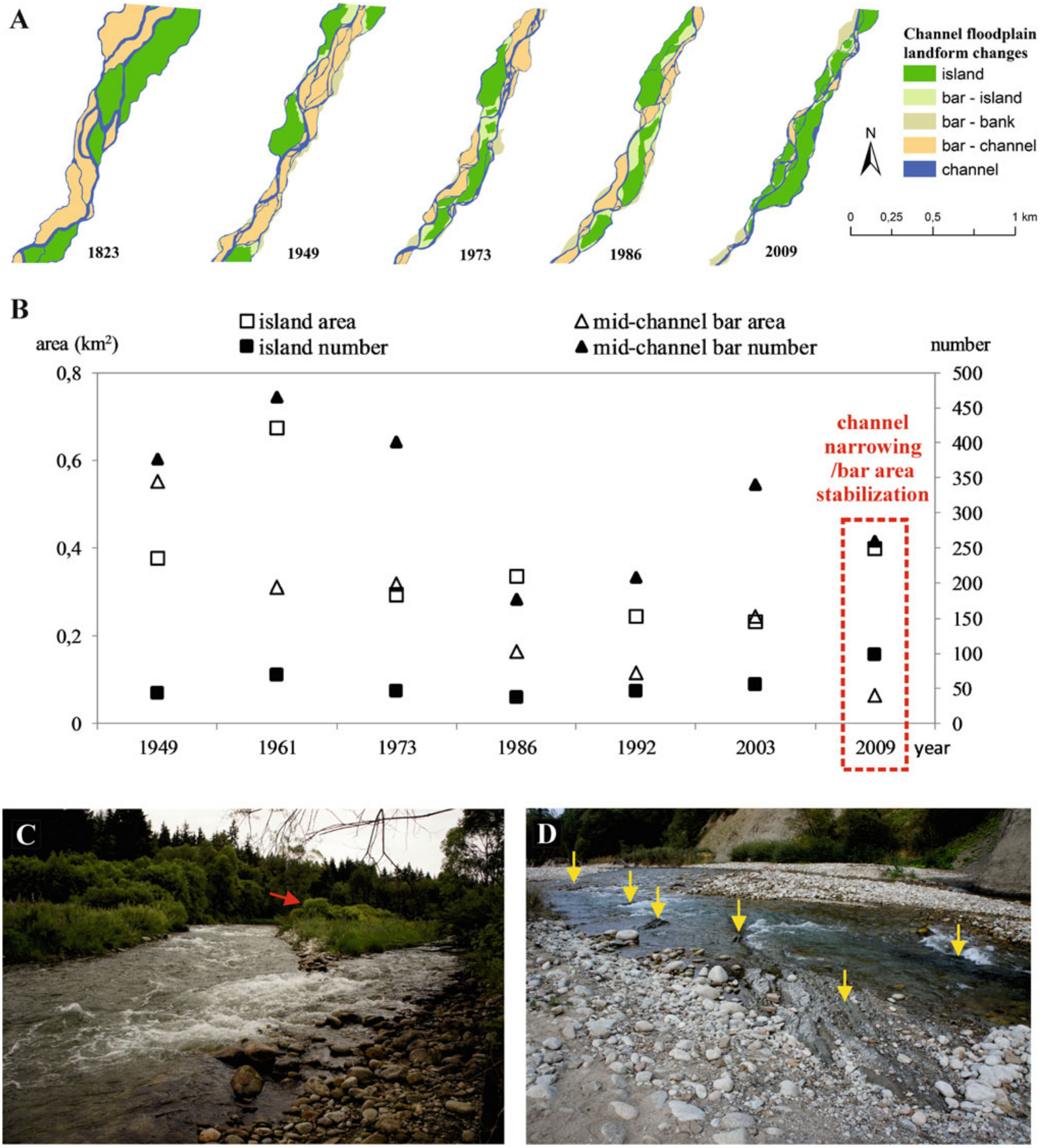

Fig. 15.6 In-channel landform changes from 1823 to 2009 within the river active zone of the Belá River (**a**). Differences between island and mid-channel bar number/area changes during the timespan 1949–2009, where islands represent the most stable in-channel landforms, while the mid-channel bars represent the most unstable ones, are presented on (**b**) section. The *Salix eleagnos* mixed up with *Myricaria germanica* self-sowing in front of the mid-channel bar. Behind the shrub, very well established *Salix* trees (marked with a red arrow) indicate ongoing mid-channel bar stabilization, and its gradual modification to the island (**c**). Channel incision due to progressing backward erosion has created in-channel flysh outcrops, mainly in the downstream river reaches of the Belá River (**d**). *Photo* A. Kidová

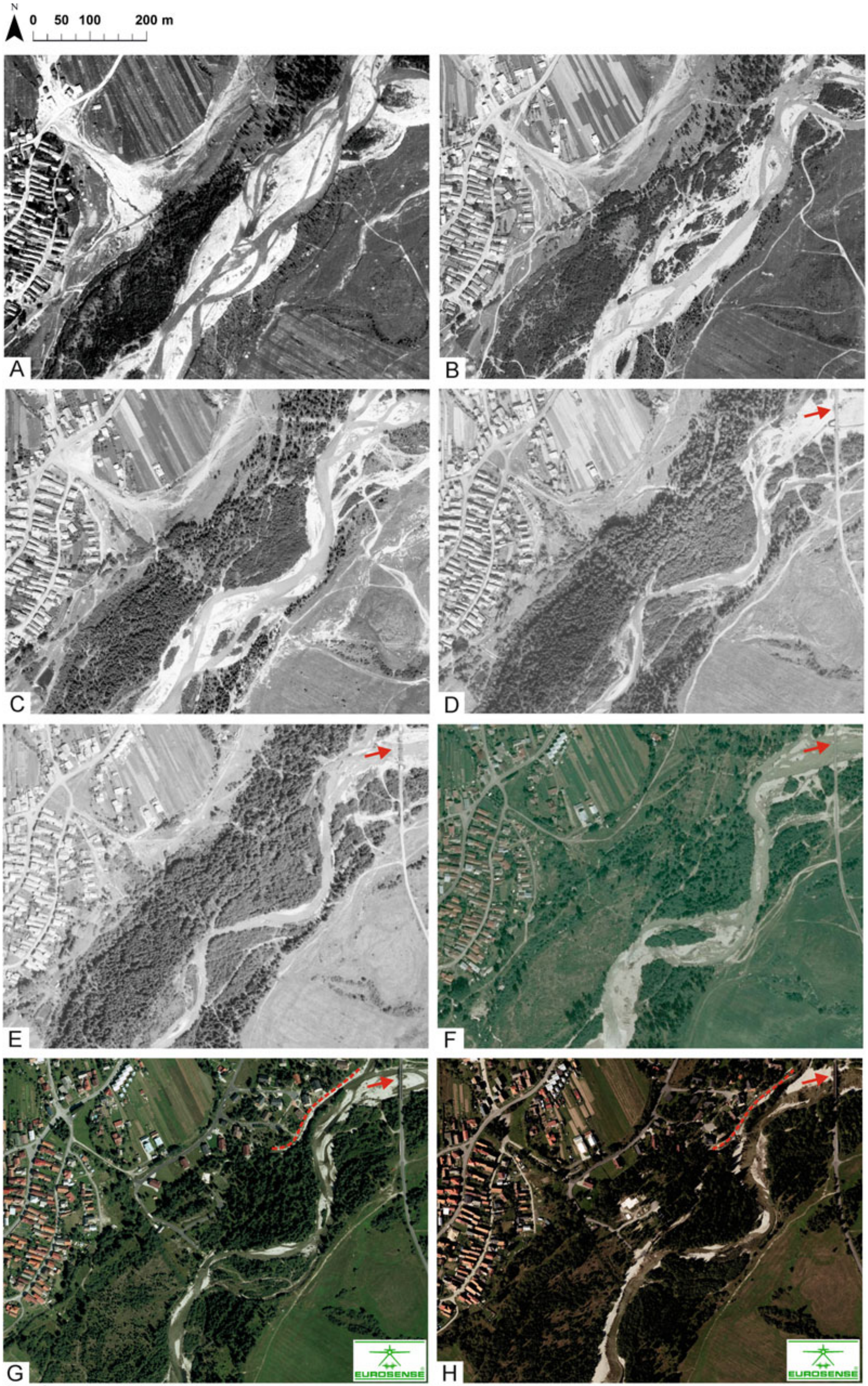

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Fig. 15.7 The decreasing trend of the braidplain area from 1949 to 2018 (A: 1949; B: 1961; C: 1973; D: 1986; E: 1992; F: 2003; G: 2012; H: 2018) represented on the river reach near the Pribylina settlement. The aspect of the infrastructure development (the bridge construction in the upper left corner of the image indicated with a red arrow from D to H) in interaction with riverbank strengthening (red dashed line in G and H) due to expansion of the built-up area, stabilized this river reach in the lateral direction. *Source* BW aerial images Topographic Institute in Banská Bystrica; coloured orthophoto ©EUROSENSE, s.r.o.

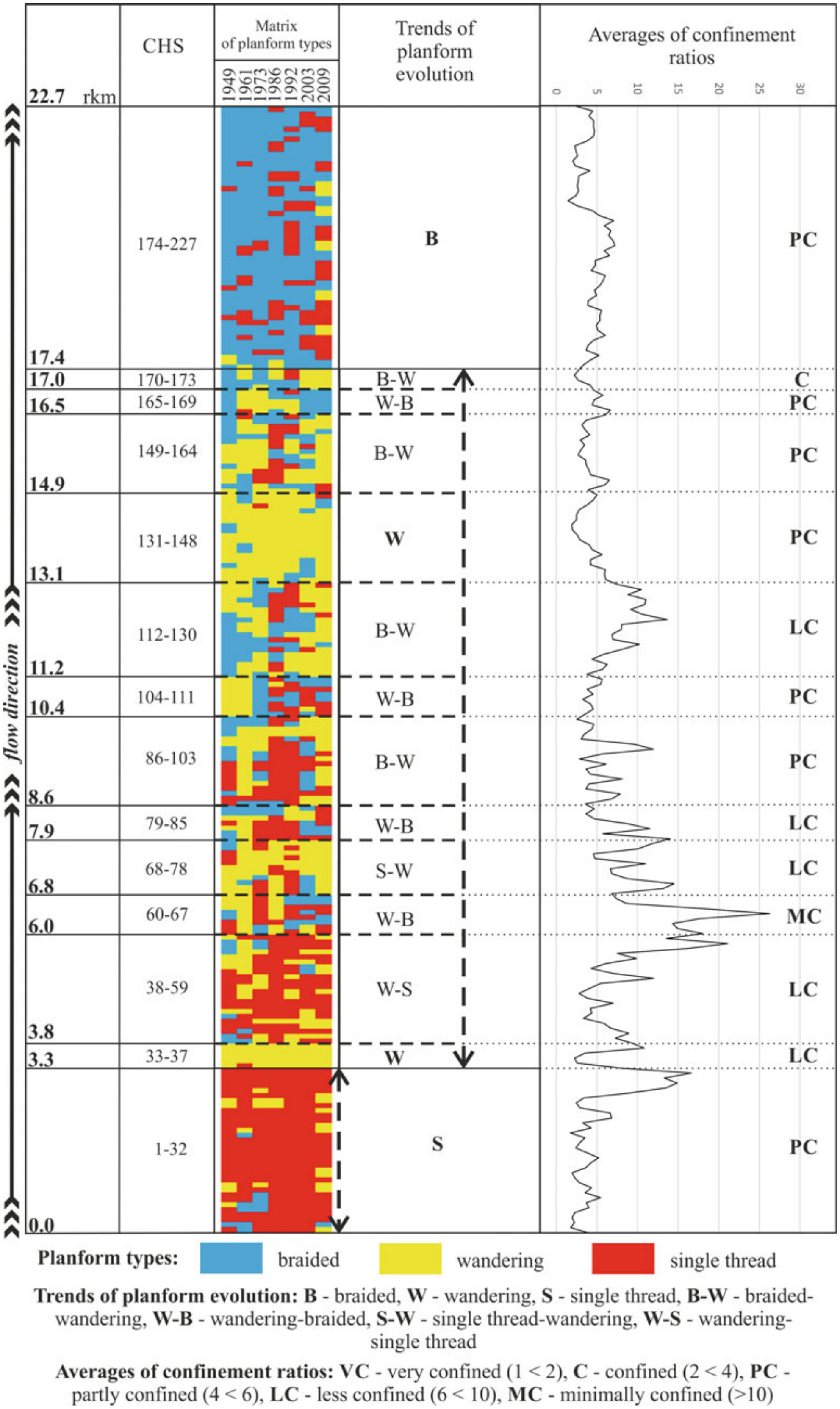

Fig. 15.8 Spatio-temporal matrix of channel planform types, evolutionary trends and averages of valley confinement ratios of the Belá River in study period 1949–2009 (Kidová et al. 2017). The matrix presents the planform type arrangement within the frame of the whole river length in one-time horizon as well as the channel planform within the frame of one channel segment (CHS) in each time horizon. Diversity of planform evolutionary trends allows one to classify CHS into seven categories. Their relation to the valley setting is illustrated by averages of the confinement ratio. Published with permission of Acta Scientiarum Polonorum

Table 15.1 Type and numerical code of vegetation patches on individual in-channel landforms in ArcGIS environment

Morphological type	Number code	Vegetation type	Characteristics	Number code	Final type/code
Island	10	xxx	>90% tree vegetation	0	10
Lateral bar (island attached)	20	No vegetation	Vegetation cover < 10%	1	21
		Sparse vegetation	Herb and shrub vegetation < 50%	2	22
		Dense vegetation	Herb and shrub vegetation > 50%	3	23
Lateral bar (bank attached)	30	No vegetation	Vegetation cover < 10%	1	31
		Sparse vegetation	Herb and shrub vegetation < 50%	2	32
		Dense vegetation	Herb and shrub vegetation > 50%	3	33
Mid-channel bar (low flow channel)	40	No vegetation	Vegetation cover < 10%	1	41
		Sparse vegetation	Herb and shrub vegetation < 50%	2	42
		Dense vegetation	Herb and shrub vegetation > 50%	3	43
Low-flow channel	99	xxx	xxx	99	99

changes in their size. A classification key was designed to identify the vegetation structure (Table 15.1).

The areal representation of vegetation types on the Belá River for individual categories of in-channel landforms is quite diverse and varies from year to year. Island-attached lateral bars have the smallest proportion of areas (bars) without vegetation (with vegetation cover up to 10%) during the whole study period. However, this is not surprising, given the natural vegetation succession from islands to their close surroundings. A similar trend is observed for bank-attached lateral bars, where the formation of new bars without a vegetation cover is characteristic for river reaches with the single-thread planform with a sinuous channel. On the opposite side of such river bends (upstream river reaches) point bar formation occurred, but from the point of whole river length, they represent only a small part of this type of bars. The dominant bank-attached lateral bars (code 30) originated mainly due to avulsion processes. This bar type is less influenced by flow discharge changes, compared with the mid-channel bars. This is evidenced by their prevailing total area with a vegetation cover above 50% (code 33), which dominates throughout the whole study period. The most exposed in-channel landforms within the river active zone are mid-channel bars (code 40), whose stabilization by vegetation in multi-thread river systems rarely has a long-term character.

In the case of the Belá River, the area of mid-channel bars without vegetation (code 41) is significantly represented mainly in the period 1949–1973, which was characterized by several extreme floods (in 1948, 1958, 1960s, 1973). After 1973, another large flood (7 years RI) was recorded only in 1997, i.e. 24 years later. During this period, stabilization of the mid-channel bars with vegetation up to 50% (code 42) was registered. In 1992, the mid-channel bar area with vegetation above 50% prevailed. After a flood event with lower magnitude (2–5 years RI in 2001), the mid-channel bars were flooded and remodelled, whereas most of the developed vegetation cover was destroyed (situation in 2003). The area of the mid-channel bars with all three types of vegetation was equalized. During this period, morphologically most significant changes as the channel incision into bedrock and narrowing of the river active zone occurred. These changes resulted in a decrease in the area of mid-channel bars with all types of vegetation cover. On the other hand, the significant prevailing of the island and bank attached lateral bars with vegetation cover above 50% in 2009 was registered.

Both the area and the number of bars with individual types of vegetation cover were analyzed. The number of island-attached lateral bars (21) and mid-channel bars (41) without vegetation (with vegetation up to 10%) prevailed (among the individual types of vegetation cover for 21, 22, 23 and for 41, 42, 43, respectively) during the whole study period 1949–2009. As in other monitored morphometric parameters, the number of bars without vegetation decreased due to stable flow discharges in 1986–1992. A more balanced number of individual types of vegetation cover are observed on the bank-attached lateral bars (code 31, 32, and 33). As expected, the number of bars with vegetation cover above 50% increased during the study

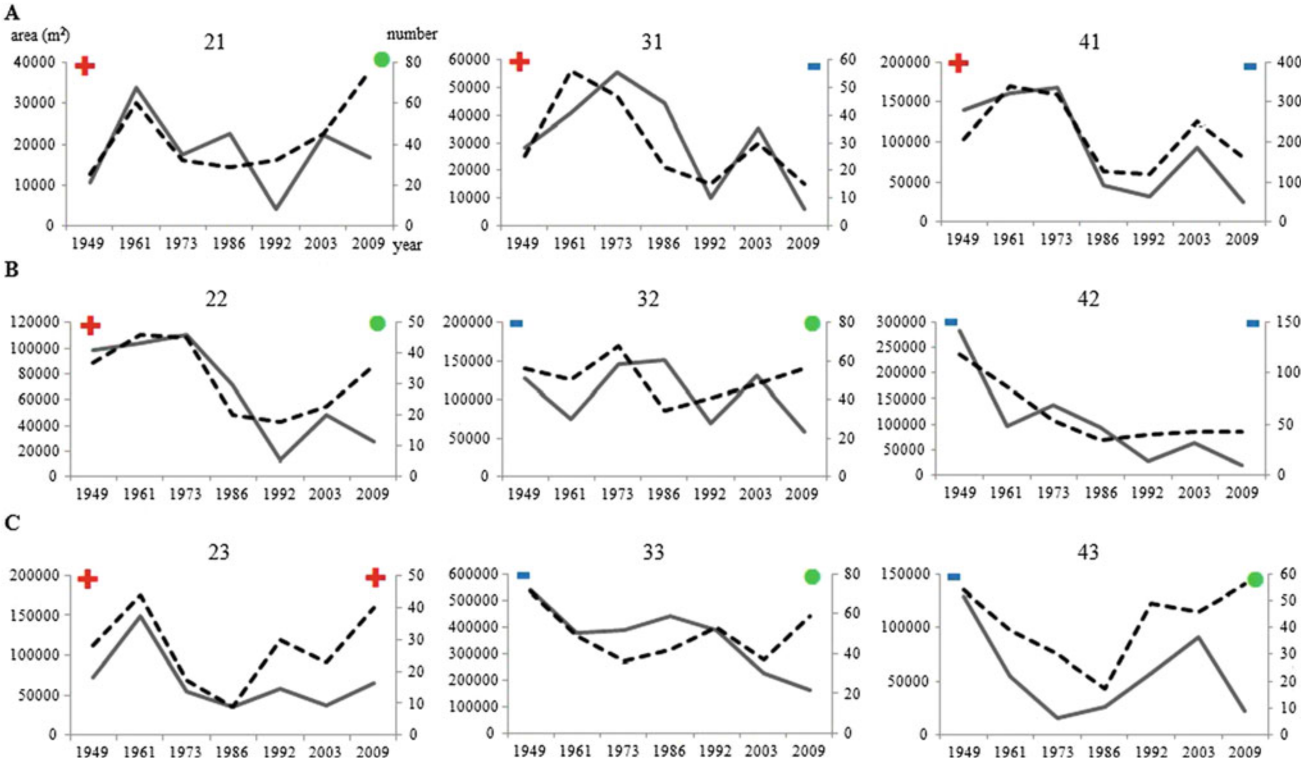

Fig. 15.9 The interdependence of area (full line, m^2) and number (dashed line) of individual categories of three monitored in-channel landforms: island-attached lateral bar (20); bank-attached lateral bar (30); mid-channel bar (40) with vegetation cover <10% (01, A), with herb and shrub vegetation <50% (02, B), with herb and shrub vegetation >50% (03, C) in the study period 1949–2009. Indicated symbols (+, –, •) refer to trends in the first and last period of observation

period. On the contrary, the dominant number of mid-channel bars without vegetation (code 41) shows the presence of ongoing braiding processes.

However, the question remains, which conditions favour changes in the river bed morphology, whether a smaller number of bars with a larger area or a larger number of bars with smaller area within the river active zone? We try to find the answer in the graphs of the interdependence between the number and area of the three types of vegetation cover on the individual in-channel landforms (Fig. 15.9). In the mutual variability of these two parameters (the area and the number), it is possible to find a certain similarity in the progress of individual curves. The same beginning in 1949, which have a rising (+) (codes 21, 31, 41, 22, 23) or a decreasing (−) character (codes 32, 42, 33, 44), we registered for the curves of the number and area. As a result of flood events in the 1950s and 1960s, the arrangement of in-channel landforms has changed, which is reflected in their number as well as in the size of their areas. The curves for all forms with individual types of vegetation are sinusoids. The exception is the mid-channel bar with vegetation up to 50%, whose dependence curves have a decreasing trend over the whole study period. Vegetation on island-attached lateral bars in the period 1961–1973 decreases uniformly for 21, 23 and increases for 22. The mutual deviation of the direction of the curves occurs in 1986–1992. The vegetation cover of the longitudinal benches near the islands increases and their area is shrinking. A similar variability in this period was observed for the vegetation cover on island-attached lateral bars and mid-channel bars. The trend of the number and area curves is towards equilibrium in 2003 for almost all the categories. Smaller flood events (2–5 years RI in 2001 and 2008) probably influenced the morphology of the Belá River in a much more specific way than the larger floods in the past, resulting in the ending of the dependency curves in 2009. The curves are representing decreasing for both area and number (code 31, 41, 42), mutual ascending (code 23) or increasing numbers and decreasing area (code 21, 22, 32, 33, 43) what reflects the fact that these landforms occur more often in the channel but have a smaller area (•). Each vegetated bar area is differently transformed by the internal dynamics of the river, developing and responding to changing hydrological and climatic conditions in the river basin in a different way.

The downward trend of vegetated areas up to 10% and 50% on mid-channel bars and the expansion of small areas with vegetation cover above 50% in terms of the stabilizing function of vegetation in the active river zone have a

Table 15.2 Identification of the driving forces influencing the Belá River as a non-linear river system

Force	Form	Process/Influence
Human disturbances	Flood protection dikes and bank stabilization	Active river zone reduction, channel narrowing
	Stony grade control structure	Groundwater depth changing, loss of the channel morphological segmentation, change of discharge profile, and sediment connectivity
	Gravel mining	Bed erosion processes acceleration, channel incision to bedrock, abort dynamic structure of fluvial landforms, channel narrowing and straightening, island area increasing, loss ability for further lateral bank erosion
	Small hydropower plant	Channel fragmentation, disrupting of the flow continuity, and hydrodynamic uniformity
	Forest landcover change	Erosion base descending, sediment input reduction from source zone and tributaries
Environmental conditions	Physical-geographical	Slope, valley confinement
	Tectonic	Holocene, Würm
	Litologic	Sandstone, claystone, conglomerate
	Hydrologic-climatic	Maximum annual discharge
Inner dynamics of the river	Discharge	Average daily discharge
	Sediments	Sediment size and source, sediment base thickness, fluvial landforms formation
	Vegetation structure	Flow and velocity of sedimentation rates, in-channel landform stabilization

negative impact on the Belá River. The predominant areas with vegetation above 50% indicate degradation of the braided planform and the development of the wandering one. Generally, a change in the vegetation cover on bars primary reflects the internal response of the river system to changes caused by erosion-accretion processes (such as channel incision into bedrock). However, the variability in vegetation cover changes and its stabilization function on the Belá River in the longer term regulate the dynamics of channel transformation.

15.5 Notes on River Management

The findings of the bio-morphological development of the braided-wandering Belá River over the last 60 years, as well as changes in environmental conditions and human disturbances, clarify the driving forces (Table 15.2) that influence the inner dynamics of morphological changes and even help to predict the evolutionary trend. The results have clearly shown a decreasing trend in the area of the river active zone as well as in the magnitude of floods with a maximum of 5–10 years recurrence interval. It also points to the long-term degradation of the river system in the form of simplifying the braided-wandering planform to the wandering-meandering one, increasing island area, narrowing due to channel incision and vegetation succession, as well as channel straightening. Although it is possible to characterize the Belá River as being in a threshold state of metastable equilibrium, it can be expected that the system will continue to be simplified.

Preservation of the natural characteristics of riverbed morphology is closely related to the preservation of its ecological importance and function. Thus, one of the most important input variables in optimizing river management is accepting Water Framework Directive (2000/60/CE) and preventing further irreversible interventions in the river active zone. The understanding of this dynamic non-linear river system, where the lateral/ vertical erosion, bar (re)formation and avulsions are part of autoregulation mechanism of the river, requires a specific attention in decision sphere. Preference given to nature-based solutions and integrated management approach in line with Natura 2000 management recommendation is desired.

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