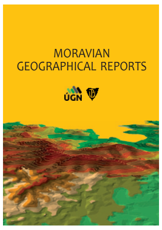

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Using the Relative Elevation Models to delimit the floodplain level development: The case of the braided-wandering Belá River, Slovakia

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Abstract

The Belá River is a specific submountain river running through the Liptov Basin in the Slovak Carpathians. Its transformation from a braided to a braided-wandering system and degradation including incision of the river system has been observed since the middle of the 20th century. These processes have created a complex system of floodplains with development stages. For their identification, the Relative Elevation Model normalizing absolute floodplain elevation to the river channel changes has been established. Three models have been prepared, from the channel bottom and water level elevation gauge by GPS, and the water level elevation by LiDAR. Based on the resulting models, the floodplain was identified and delineated to an active or potentially active floodplain, to an inaccessible floodplain spread behind artificial structures, and to a perched floodplain beyond the reach of the river. Spatial statistics, including "Hot spot analysis" and "Cluster and outlier analysis" have been used to identify recent river floodplain formation from 1949 to 2018, caused by simplification and incision of the Belá River. The unique aspect and contribution of the research lies in implementing and comparing the Relative Elevation Models and linking them to floodplain age.

Keywords: *Floodplain, floodplain delimitation, floodplain development, Relative Elevation Model, braided-wandering river, Belá River*

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1. Introduction

The Belá River is a typical example of a braided-wandering river, with a high gradient and huge and irregular sediment input. During the last decades, the river has been affected by transformation and degradation of the river pattern. The process has been unevenly accompanied by narrowing, shifting and incision of the braidplain due to decreasing discharge, reducing extreme floods and land cover changes. As a result of the processes, floodplain levels have been formed, with different relative heights to the river channel. However, their distribution and position along the river are not proportional. The novelty of the publication lies in the generation of Relative Elevation Models (REMs) based on the various input data, and combined with aerial photographs, this method has the potential to capture the trend and enable prediction of the river floodplain development. Therefore, the objectives of the study are:

i. To generate the Relative Elevation Models;
ii. To compare and evaluate the models and the used method;
iii. To identify and highlight the levels and development stages of the river floodplain; and
iv. To evaluate a process-oriented model of the river floodplain development.

The determination of various floodplain stages and definition of a process model of the floodplain development will primarily depend on the quality and interpretation of the REMs.

2. Theoretical background

The river floodplains, stretching along the watercourses as products of fluvial activity, represent a unique and unmistakable feature of the landscape. They are distinctive not only by their ecological but also by geomorphological characteristics, they provide records of previous river behaviour and changes. A river floodplain is a relatively flat area developed from alluvium, extending from the river banks and periodically inundated (Huggett, 2011). Nevertheless, definitions can vary based on different approaches or principles of delimitation (Rhoads, 2020). As well as definitions, a research of river floodplains has been focused and applied in diverse directions, based on floodplain delineation (Lóczy et al., 2012), level development (Kiss et al., 2017), management (Olson et al., 2014; Croke et al., 2016; Jakubínský et al., 2021), restoration (Eder et al., 2022), or ecology (Gray & Harding, 2007; Hauer et al., 2016).

Generally, the floodplain is formed and reworked by different river processes, mostly migration and accretion (Brierley & Fryirs, 2005), described by evolution models (Bollati et

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al., 2014). The formation of a river floodplain along the braided rivers creates mosaics of multi-aged floodplain units by the migration and accretion of the braidplain, easily determined by aerial photographs (Haschenburger & Cowie, 2009). Beechie et al. (2006), used vegetation for floodplain age assessment, where the age classes of a floodplain varied from 5 to 25 years, with a mean 8-year erosion return period. The floodplain along the Waimakariri River in New Zealand has a 250-year return period based on the dendro-chronology, field observations and time-lapse of aerial photographs (Reinfelds & Nanson, 1993). Determining the age of the river floodplain based on the former position of the river (Greco et al., 2007; Whited et al., 2007) is a more reliable method for the determination of the floodplain stage (Haschenburger & Cowie, 2009). Specifying the position of the channel (Ziliani & Surian, 2012) should enable a prediction of possible future channel movements and thus better prevent any negative consequences of these shifts (Marti & Bezzola, 2006).

The lateral shifting and channel migration are variable in time and space, resulting in uneven input, accumulation, and erosion of material from the river channel and river floodplain. Therefore, the river floodplain has an asymmetrical character, with longitudinal and lateral differentiation, creating perched floodplains (Lehotský et al., 2015). The contrast is even more distinguishable along braided rivers (Lehotský et al., 2018). A height differentiation of the river floodplain can be affected by climate change or by land use changes (Kadlec et al., 2009) affecting the hydrology (Zaprowski et al., 2005). The climate changes strongly and irregularly affected the discharges of the water streams across the Europe (Blöschl et al., 2019). The braided rivers are susceptible to discharge changes (Hajdukiewicz et al., 2018; Nardi & Rinaldi, 2015), or human impact (Gurnell et al., 2009) which strongly affect mountain streams (Wohl, 2006). Therefore, the last century led to the transformation and degradation of the mountain streams (Armaş et al., 2013; Rădoane et al., 2013; Dufour et al., 2015; Krzemień et al., 2015; Nardi & Rinaldi, 2015; Wyżga et al., 2016). Channel incision can affect the level of the groundwater table (Greco et al., 2008), and the connection between the channel and the river floodplain (Lehotský et al., 2018).

A river development process led by incision can generate floodplain level formation and can possibly be described by cross-section profiles (Kiss et al., 2017). LiDAR (Light Detection and Ranging) and its different height classification intervals enable the identification of forms in the vicinity of the waterstream (Moretto et al., 2012). The Relative Elevation Model (REM) provides a different view of the floodplain for the floodplain delimitation, identification or other analyses. The height above river (HAR) model (Jones, 2006) was used to identify side channels on a floodplain by digitizing lines across the floodplain with an elevation of a water surface. The water surface was subsequently subtracted from a standard Detail Terrain Model (DTM). Dilts et al. (2010) pointed out a problem in how to generate the cross-section properly, to uniformly capture the river floodplain. They used ArcGIS Spatial Analyst to implement the Kernel Density and Cost-distance function, to calculate inundation areas and a bathtub model. The Kernel Density was modified by Olson et al. (2014) and compared with an IDW method and Cross-section method. Greco et al. (2008) used a channel water surface during the dry season base flow and subtracted it from topographic maps, using the IDW method.

The cross-section method yields valuable results but requires the largest effort level. Similarly, Slaughter and Hubert (2014) visualized features on a floodplain, by adjusting the elevation of the river to the initial elevation level, removing downstream changes in elevation related to the channel gradient. Besides, Coe (2016) modified previous methods and simplified them. Dilts (2015) provides an automatic ArcGIS toolbox, useful for quick HAR model generation. The Toolbox quickly and easily identifies changes in elevation on the floodplain across the river channel but with lower resolution output. According to Greco et al. (2008), the relative elevation model has huge potential for studying rivers and floodplains in combination with other attributes of the river. The proper method for such visualization could be challenging. However, the above mentioned studies presented models generated from water levels, and no study generated such a model from the river bottom or compared the models.

3. Data and methods

3.1 Study area

The Belá River (see Fig. 1) has a notable place among the Slovak rivers because of its specific dynamic of braided-wandering channel planform. It arises in a submontane area of the High Tatra Mountains and after 23.6 km flows into the Váh River. The catchment area is 244 km^2, with average temperature from 4 to 8 °C and average annual precipitation from 550 to 1,200 mm. Historically, the braided river system gradually changed and transformed into a braided-wandering river system during the second half of the 20th century (Kidová & Lehotský, 2012). The most significant factors of morphological changes are land cover changes and discharges (Fig. 2) (Kidová et al., 2016a), which degraded the multi-temporal river system as a consequence of sediment volume decreasing from the floodplain and upper part of the river (Lehotský et al., 2018). Two gauging stations are localized at Podbánske (922.72 m a. s. l.) and Liptovský Hrádok (359.3 m a. s. l.) with an average annual discharge of 3.5 m^3.s^{-1} and 6.8 m^3.s^{-1}, respectively (Kidová & Lehotský, 2013). The extreme flood events are represented by discharges higher than 60 m^3.s^{-1} (Kidová et al., 2016b). The largest flood events appeared on 18.07.1934 (179 m^3.s^{-1}) and 29.06.1958 (180 m^3.s^{-1}), but extreme floods and discharges gradually decreased (Kidová & Lehotský, 2012) which affected channel pattern changes (Kidová et al., 2016a, 2016b). The Belá River is affected by no dam regulation.

Land cover changes, human impact (Kidová et al., 2016b) and gravel mining (Radecki-Pawlik et al., 2019) strongly affected the channel transformation process. Channel engineering of the river channel and its surroundings was constructed to protect settlements against flood events and to stabilize the river channel (Kidová et al., 2021). However, it caused an incision of the channel, increased the local erosion base and accelerated landslides (Kidová et al., 2016a). The heaviest anthropogenic impact affected the lower part of the river, decreasing upstream (Kidová et al., 2016b). The first systematic flood control management appeared from 1925 to 1948 and it led to reducing the floodplain area (Kidová, 2010). In 2000, a small hydropower plant was built which heavily affected local part of the river channel and resulted in hungry water eroding the riverbed upstream (Kidová & Lehotský, 2013). Furthermore, land cover changes brought the sediment volume variation which led to the incision of the river (Kidová & Lehotský, 2012) as a result of forest cover area transformation (Kidová et al., 2016a). The incision caused by the processes described above has disconnected the river channel and the floodplain (Lehotský et al., 2018).

3.2 Data

Three types of data were used in the paper, including (1) the orthophoto mosaic, (2) the LiDAR data, and (3) the terrain survey data. The orthophoto mosaic was provided by the Geodesy, Cartography and Cadastre Authority of the Slovak Republic (ÚGKK SR), capturing the area of the Belá River in 1949, 1961, 1973, 1986, 1992, 2003, 2006, 2009, 2012, 2015 and 2018. The point cloud was collected from 2018 to 2019 by ÚGKK SR, with

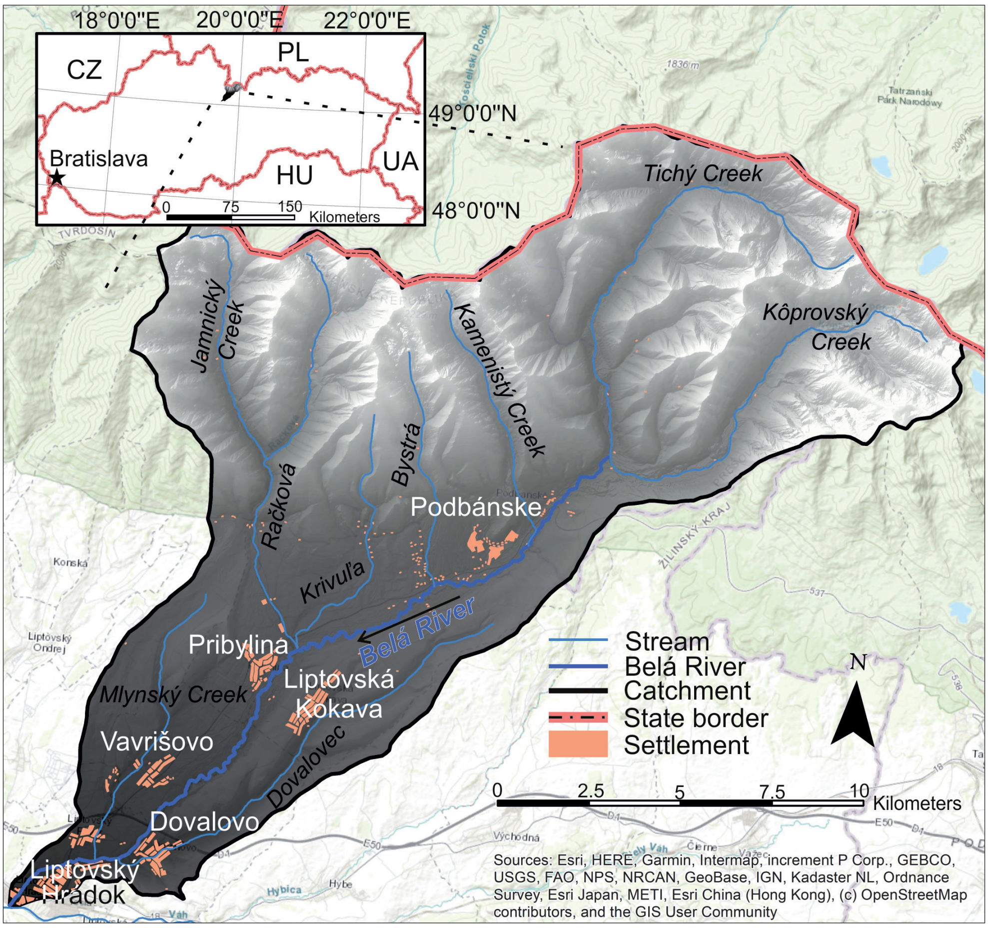

Fig. 1: The location of the Belá River study area in the northern part of Slovakia, represents an unmistakable component of the piedmont Carpathian region. The Bela River is strongly influenced by numerous right-side tributaries, dominating over the left-side tributaries. Simultaneously, with a significant anthropogenic intervention in the lower part of the catchment, they significantly disturb the gradient of the stream. The left side of the river is confined by terraces, strongly limited in its lateral movement.
Source: Authors' elaboration

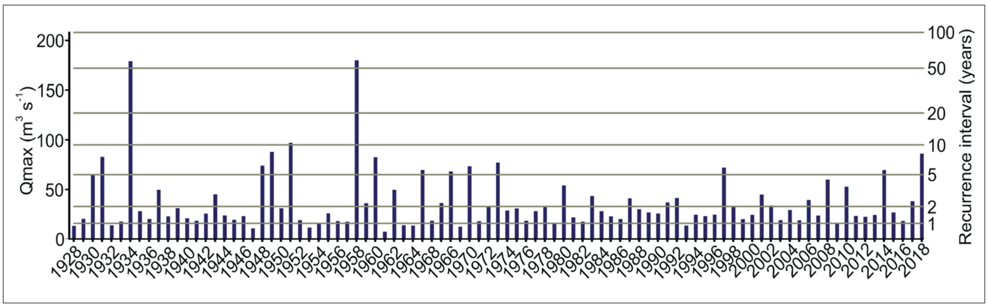

Fig. 2: The maximum annual discharges at the Podbánske gauging station. The extreme flood events are decreasing, affecting the river behaviour, and subsequently the river floodplain development.
Source: Authors' elaboration based on data from Slovak hydrometeorological institute (SHMÚ)

a horizontal accuracy of 3 to 4 cm and a vertical accuracy of 7 to 17 cm. The upper locality has the designation 26_Tatry and the lower 25_Ružomberok. Altogether 34 footprints of point clouds were used (Tab. 1). The terrain data were collected in 2017 and 2018 by GPS Leica Zeno with aerial GG03s with RTK corrections 2–11 cm. The terrain data consisted of 358 points of water level and 364 points of channel bottom in the longitudinal profile. For analyses, we pick 44 points, approximately every 500 m along the floodplain centreline.

3.3 REM formation

Firstly, from the LiDAR point cloud data, the DTM with 1 m resolution was generated, necessary to identify and delineate the river channel and river floodplain edges. The floodplain was perceived as an alluvial landform spread from the banks of the river to the edge of the adjacent terraces, in terms of the genetic floodplain by Nanson and Croke (1992). The floodplain boundary was determined as a slope and elevation change between the considered floodplain and the lower edge of the terrace based on the DTM. The changes in elevation between the terrace and the floodplain often reached more than 30 m. On the other hand, elevation differences between the perched floodplain and the active floodplain were generally less than 2–2.5 m, and they are harder to distinguish (Fig. 4). Moreover, it is still possible to identify remnants of fluvial activity on the perched floodplain from the DTM or from the orthophoto mosaics (1949, 1961, 1973). A geological map of Slovakia (Geologická mapa Slovenska, 2023) can distinguish floodplain fluvial sediments from terraces and orthophoto mosaic (ÚGKK SR) supports the identification of floodplain edges in indistinct locations.

Locality	Number of footprints	Date of footprinting	Time of flying (round on the hours)	Podbánske ($m^3.s^{-1}$)	Liptovský Hrádok ($m^3.s^{-1}$)
26_Tatry	10	10.06.2018	06:00–08:00	5,317–5,370	8,806–8,806
	4	12.09.2018	10:00–12:00	2,384–2,385	3,354–3,458
25_Ružomberok	2	19.11.2019	11:00–12:00	5,827–5,847	8,799–9,305
	17	24.11.2019	10:00–14:00	4,317–4,354	7,243–7,522
	11	25.11.2019	09:00–16:00	4,075–4,140	7,243–7,522

Tab. 1: The LiDAR footprints were used to create the DTM, overlaying the riverbed of the Belá River. The table contains the code designation of the area, the number of footprints in the given area, the date and time of recording, and the variation of discharges (in $m^3.s^{-1}$) during the given periods at the Podbánske and Liptovský Hrádok gauging stations
Source: Authors' conceptualization based on data from the Geodesy, Cartography and Cadastre Authority of the Slovak Republic

Secondly, the floodplain was divided into 500 m wide cross-sections based on a Fluvial Corridor Toolbox (Roux et al., 2015), perpendicularly on a streamline (Fig. 3). Afterwards, each cross-section was attributed with the water level elevation (lowest point from gravel on a channel bar) derived from the LiDAR/DTM, along with the water level and bottom elevation measured by GPS in the field. The values were separately interpolated to the whole floodplain area by the "Topo to raster" interpolation as contours, with 1 m resolution and with other default settings. Afterwards, the raster was subtracted from the original floodplain DTM in ArcGIS 10.5. "Topo to raster" interpolation was chosen based on the most accurate results at floodplain margins and at greater distance from the channel, compared to other interpolation methods, including Dilts (2015) automatic toolbox. Normalized rasters of the Relative Elevation Model (REM) represent the results of the model.

3.4 Delineation of floodplain

The floodplain was delineated based on the REM into three groups, including: (1) an inaccessible floodplain (floodplain with no inundation caused by artificial structures such as dikes or roads), (2) a perched floodplain (an inaccessible floodplain with no inundation caused by incision of the river), and (3) an active or potentially active floodplain. First, the inaccessible floodplain was delineated. The dikes and roads were easily identified by the orthophotos and the REMs, protruding above the surroundings. The floodplain from those structures to the edge of the terraces was understood as the inaccessible floodplain. The remaining floodplain was divided into the perched and active floodplain. Identification of, and distinguishing between, active and perched floodplain using only DTMs or Hillshade were unclear and problematic (Fig. 4). However, using the REM it is possible to identify the perched floodplain quickly and accurately. The changes in the elevation of the river floodplain relative to the channel could be several meters, recognizable in the cross-section profile. The perched floodplain was considered a higher continuous part of the genetic floodplain, mostly boldly separated by high or sharp edges. The rest of the floodplain was considered an active or potentially active floodplain.

3.5 Spatial statistics

The age of the floodplain was determined by the overlapping position of channels based on the method of Greco et al. (2007). The river channel was delineated by the definition of Lehotský et al. (2015), as including gravel bars, but without river islands. The river islands presented potentially stable parts of the braidplain and floodplain. Accumulation of alluvium between two following years, minus erosion of subsequent years, represents the age of the floodplain. The study is represented by aerial photographs from 1949, 1961, 1973, 1986, 1992, 2003, 2006, 2009, 2012, 2015 and 2018. The volume of deposited fluvial material does not have uniform distribution over time, moreover, channel incision and river training affect the river channel and its surroundings. These processes could result in floodplain levels formation. The identification of the changes was based on spatial statistics of the floodplain mosaic. The null hypothesis for the pattern analysis was, that there is no spatial pattern of floodplain formation in the study area.

Using the "Zonal Statistic as Table" tool in the "Spatial Statistic" ArcGIS, the MEAN value from the REM was calculated for each polygon representing a particular river floodplain age. The distribution of polygons with their relative height can vary, be dispersed or clustered. The Global Moran's I by the "Spatial Autocorrelation (Moran's I)" represents how features (polygons) differ in the study area (Mitchell & Grifin, 2021). The next step was to find the hot spots and cold spots of the spatial distribution of polygons with relative elevation height mean values by a "Hot Spot Analysis (Getis-Ord Gi*)". The Gi* statistic reveals, if there is or is not a concentration of high or low values. The result was compared to the "Cluster and Outlier Analysis (Anselin Local Morans I)", to find clusters of high and low values. Eventually, areas with concentrations of high and low values were analyzed. The polygons with the high values (hot spots) represented the parts of the newly formed floodplain created by the incision of the river and the low values represented the floodplain formed due to simplification, narrowing and side channel abandonment. A process-oriented model of river floodplain development was the outcome of this analysis.

4. Results

4.1 The REM settings

The elevation of the floodplain along the 23.6 km long Belá River on the DTM rises from 626.49 m a. s. l. to 985.08 m a. s. l., but the values do not reflect the relative elevation to the water stream. The Relative Elevation Models (REMs), a normalized

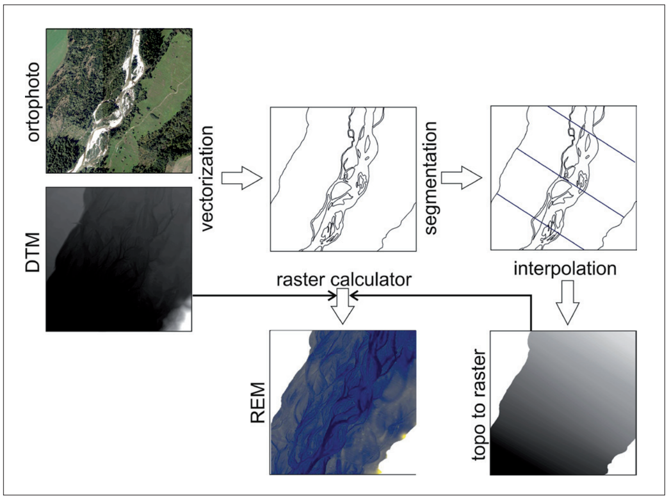

Fig. 3: The method of the Relative Elevation Model generation. The floodplain and channel position (in 2018) were delimited based on the orthophotos and DTM. The cross-sections were created every 500 m perpendicularly on a floodplain centreline. The value for every cross-section was subtracted and subsequently interpolated as a water level raster, and then the raster was subtracted from the original DTM. The process was accomplished for DTM and GPS water level and river bottom. The result of the processes were the REMs
Source: Authors' conceptualization

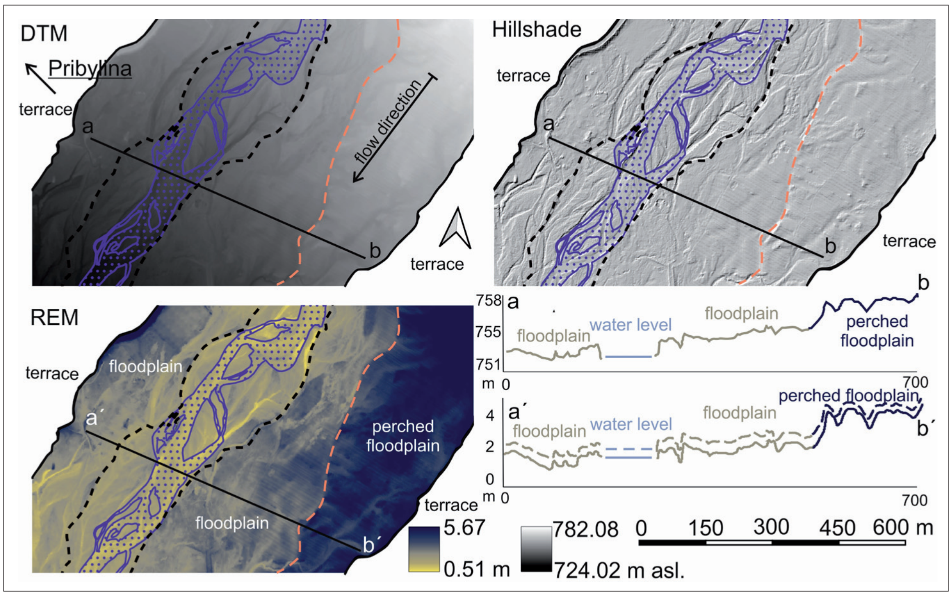

Fig. 4: A floodplain visualization near the Pribylina settlement by the DTM, its Hillshade and the REM. The area with blue dots symbolizes the river channel position in 2018, black dot lines are a historical extension of braidplain. The active floodplain and perched floodplain were identified, and distinguishable on REM. The cross-section a-b represents the profile of the floodplain generated from DTM. The cross-section a'–b' represents two REMs profiles. A solid line represents a profile normalized to the channel bed, and a discontinuous line represents a profile normalized to the water level
Source: Authors' conceptualization

DTM to the water stream, decreased the range of the values (see Tab. 2). For the research, three REMs were generated utilizing: the DTM water level (REMwater^{DTM}), the water level measured by GPS (REMwater^{GPS}), and the channel bottom measured by GPS (REMbottom^{GPS}). The difference in mean value between REMwater^{DTM} and REMwater^{GPS} was 0.02 m, and their minimum and maximum differences fluctuated by 0.02 m. The range of the values was almost identical (Fig. 5) which confirms their similarity. The mean difference between two REMs generated from GPS (REMwater^{GPS} and REMbottom^{GPS}) was 0.51 m, corresponding to a mean water level in the river channel represented 0.48 m. Thus,

	DTM	REMwater^{DTM}	REMwater^{GPS}	REMbottom^{GPS}
Min.	626.49	– 2.18	– 2.20	– 1.83
Max.	985.08	16.04	16.02	16.52
Mean	759.62	2.16	2.14	2.65
Range	358.59	18.22	18.22	18.35
Std.	91.11	1.44	1.44	1.44

Tab. 2: The basic characteristics of the river floodplain are represented by DTM and three REMs
Source: Authors' conceptualization

REMwater^{DTM} and REMwater^{GPS} show high similarity, and the difference between REMwater^{GPS} and REMbottom^{GPS} represents the difference in water level and channel bottom elevation.

The distribution of river floodplain values on the DTM (Fig. 5) primarily follows the width of the river floodplain, which widens distinctively twice at the mouth of the Váh River in the lower part (pixel values from 620 to 700), twice in the vicinity of the Podbánske settlement (pixel value from 710 to 850 m), and narrows considerably in the upper part in the surroundings of the Pribylina settlement. On the other hand, the REM represents the distribution of values indicating the average height of the floodplain along the river stream, comparing the stream bottom or the water stream level. Floodplain elevation normalized to channel, redistributed the elevation values, and decreased the mean value of floodplain elevation.

4.2 Floodplain delimitation

The floodplain along the Belá River has a total area of 9.364 km^2 with irregular width (from 60 m to 1,000 m) and an elevation range of 358.59 m a. s. l. However, a significant part of the floodplain is situated behind the dikes or road embankments, creating an

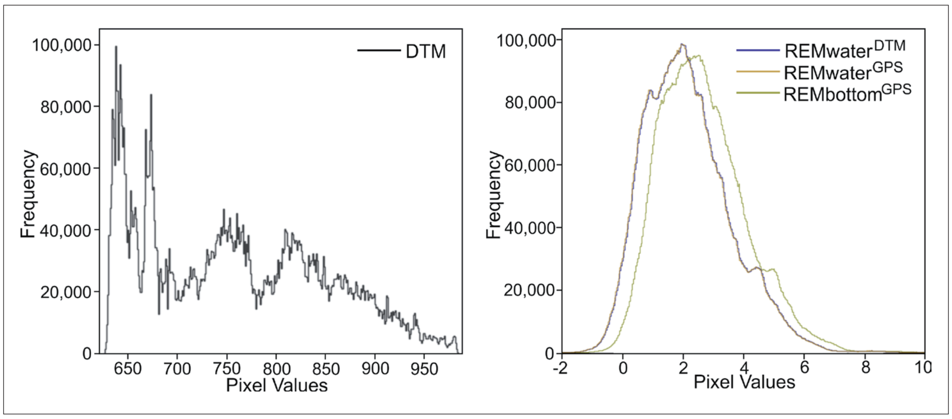

Fig. 5: The distribution of elevation values of the Belá River floodplain expressed by the DTM (left) and three REMs (right). The value distribution of REMwater^{DTM} and REMwater^{GPS} are nearly identical
Source: Authors' elaboration

isolated floodplain. The inaccessible floodplain represents 31.6% (2.961 km^2) of the entire topographical floodplain. The largest part of the inaccessible floodplain is situated along the lower part of the river along the Liptovský Hrádok, in the places with dikes construction, and in the higher part, where the roads intersect the floodplain (Fig. 6). The relative height of the inaccessible river floodplain ranges from 0 to 6 meters (Fig. 7).

The perched floodplain was especially detached, representing 2.767 km^2, or 29.5% of the topographic floodplain. They represent the continuous surfaces of the river floodplain, considerably higher than the river channel and surrounding floodplain, mostly with sharp edges. There were no critical height differences, but most of the perched floodplain was higher than 2.5 m above the channel bottom. The histograms represent the values from 1.5 m to 7.0 m above the water level. The perched floodplain was located irregularly along the river, with a higher portion between the Podbánske and Pribylina, and around the small hydraulic power station near Dovalovo. In some places, three levels of the river floodplains (Fig. 8) along the Belá River were identified, with limited or no active floodplain. The first location was identified in the Tichý and Kôprovský creek confluence, and the other location was located around the small hydraulic power plant near Vavrišovo (Fig. 1).

The active river floodplain represents 3.635 km^2, 38.8% of the topographic floodplain (including island area 0.374 km^2). The height of the active floodplain was considerably lower, from – 1.0 m to 2.5 m. The active floodplain or potentially active floodplain was extended mainly from Podbánské downstream to the small hydroelectric power station near Vavrišovo. The largest extent was situated in the vicinity of the Pribylina. The width of the river floodplain increased along the whole Belá River, with the most extensive around Liptovský Hrádok (Fig. 5 and Fig. 6). However, the width of the active floodplain was reduced in this part by the dike constructions in the middle of the 20th century.

4.3 Spatial Statistic

Altogether, 2,177 polygons of the newly formed floodplain were generated, by the overlapping of river channel position of aerial images from 1949 to 2018, representing 1.252 km^2. In total, the most extensive floodplain was formed from 1949 to 1986 (Fig. 9). However, the periods were not equally long, and the increase per year fluctuated. The mean formation of floodplain per year was 31,228 m^2. The increase in floodplain that occurred between 2003–2006 almost the doubled mean formation of floodplain per year. The mean relative elevation value of the formed floodplain was decreasing gradually. While the floodplain

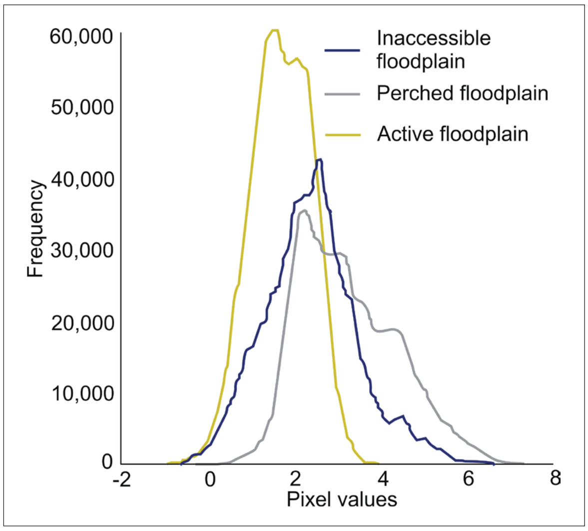

Fig. 7: Three floodplain pixel values distribution based on REMwater^{GPS}
Source: Authors' elaboration

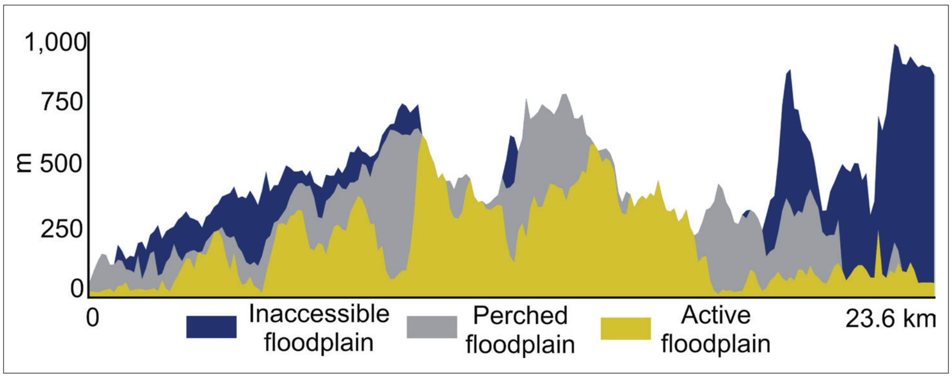

Fig. 6: The floodplain width variation measured every 100 m
Source: Authors' elaboration

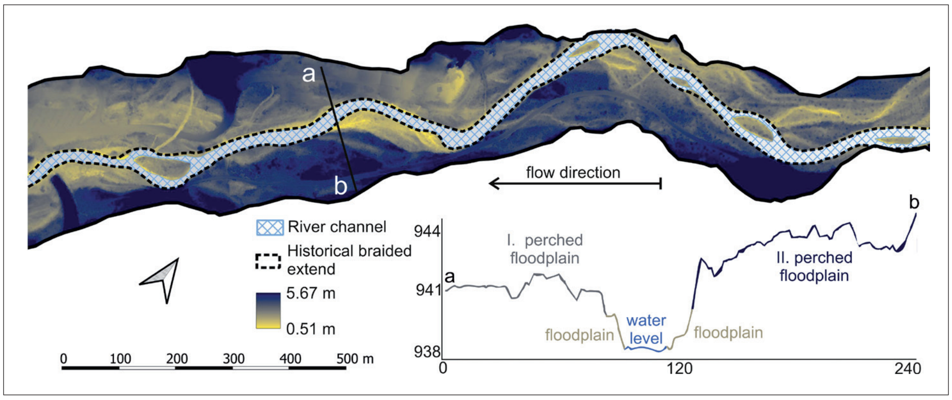

Fig. 8: The highest part of the Belá River floodplain is not fully developed, but there are still remnants of the former position of the channel and perched floodplain formation, marked as I. and II. perched floodplain
Source: Authors' conceptualization

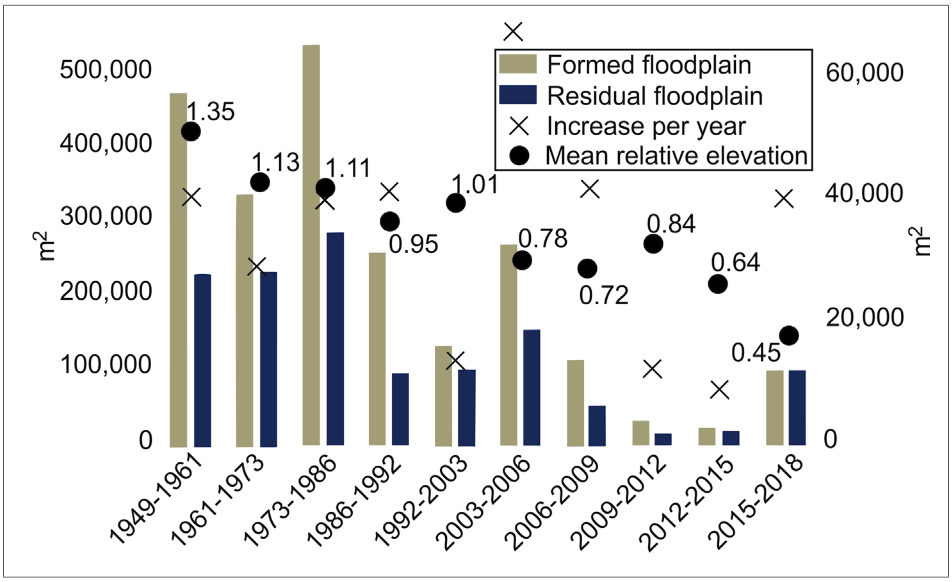

Fig. 9: The graph visualizes the increase of floodplain formation based on aerial photography and a present remnant of the formed floodplain (scale on the left), the increase of floodplain formation per year (scale on the right) and the present relative elevation of the floodplain derived from REMwater^{GPS}
Source: Authors' calculations and elaboration

formed between 1949 to 1961 has a relative height of 1.35 m, the floodplain formed from 2015 to 2018 has a relative height of 0.45m. The older parts of the river floodplain were situated higher compared to a recently formed floodplain, indicating the gradual incision of the water stream.

The spatial statistics was used for identification of the processes of the recent floodplain formation, for the three REMs. Based on the 'Spatial Autocorrelation (Morans I)', large values in z-score and extremely low p-values were received, indicating statistically significant hot spots and statistically significant cold spots of the floodplain formation from 1949 to 2018. Based on that, the null hypothesis was rejected in each case (Tab. 3) of the statistic, and also Moran's Index pointed to a clustered pattern of polygons in each case. The processes in the river have a trend of developing a new floodplain either by incision of the river channel or by simplifying the original braided river pattern.

The river floodplain was formed irregularly along the Belá River, while two processes predominated, incision and simplification. The locations of the processes were identified by hot spot analysis, complemented by cluster analyses and visualized for a better spatial interpretation (Fig. 10). None of the mentioned processes prevailed, but they occurred evenly along the stream. In the upper part of the river, near the confluence of Tichý Creek and Kôprovský Creek, the river floodplain was perched, narrow, and poorly formed. Most of the river floodplain was relatively high concerning the river channel. Moreover, the active and newly formed river floodplain were made up of isolated floodplain pockets, accompanied by incision. There was no space for the channel shifting and the new floodplain was created sporadically by the sediment accumulation.

More significant river floodplain formation occurred between the Podbánske and Pribylina settlements. The incision of the river channel was caused by the abandonment of the side channels, which became part of the floodplain. The greater shifting of the river channel was limited mainly by its confinement by the left-hand terrace which cut bluffs, and the perched floodplain along both sides of the Belá River in the higher part of the river. In the section with cut bluffs of the terrace, the active floodplain has the same width as a topographic floodplain.

In the vicinity of Pribylina, the river floodplain was significantly developed as a result of river training. The lateral, right-side channels were artificially cut off from the rest of the braidplain and thus became part of the river floodplain. However, these may become active again in the event of high-water levels or erosion of the artificial gravel embankment. The hot spot analysis shows these abandoned channels as cold spots, but the cluster analysis identified higher elevation portions of the river floodplain on the opposite side with no river training.

These portions of the floodplain were statistically less significant, but the trend of higher values continues and culminates approximately one kilometer downstream, below the village of Pribylina. Between Pribylina and Vavrišovo, a river floodplain developed mainly by simplification of the braidplain, confirmed by cold spots and low values of the clusters (Fig. 10). In this part of the stream, the active floodplain extended to the entire width of the topographic floodplain, and the Belá River is potentially able to migrate in the whole width.

A significant change occurred near the village of Vavrišovo, where the small hydroelectric power plant was built. As a result, the river channel was significantly simplified and simultaneously incised. The original part of the river floodplain was several meters above the current watercourse and the river floodplain was completely cut off from the watercourse. The incision reached more than 5 meters and several stages of development of the river floodplain can be identified. These stages thus became a perched floodplain, active 70 years ago. The perched floodplain

REM type	Moran's Index	z-score	p-value	Pattern	Null hypothesis
REMwater^{DTM}	0.507134	170.652381	< 0.00000	clustered	rejected
REMwater^{GPS}	0.466663	154.835203	< 0.00000	clustered	rejected
REMbottom^{GPS}	0.447573	148.506958	< 0.00000	clustered	rejected

Tab. 3: The result of the "Spatial Autocorrelation (Moran's I)" analysis for three REMs
Source: Authors' calculations

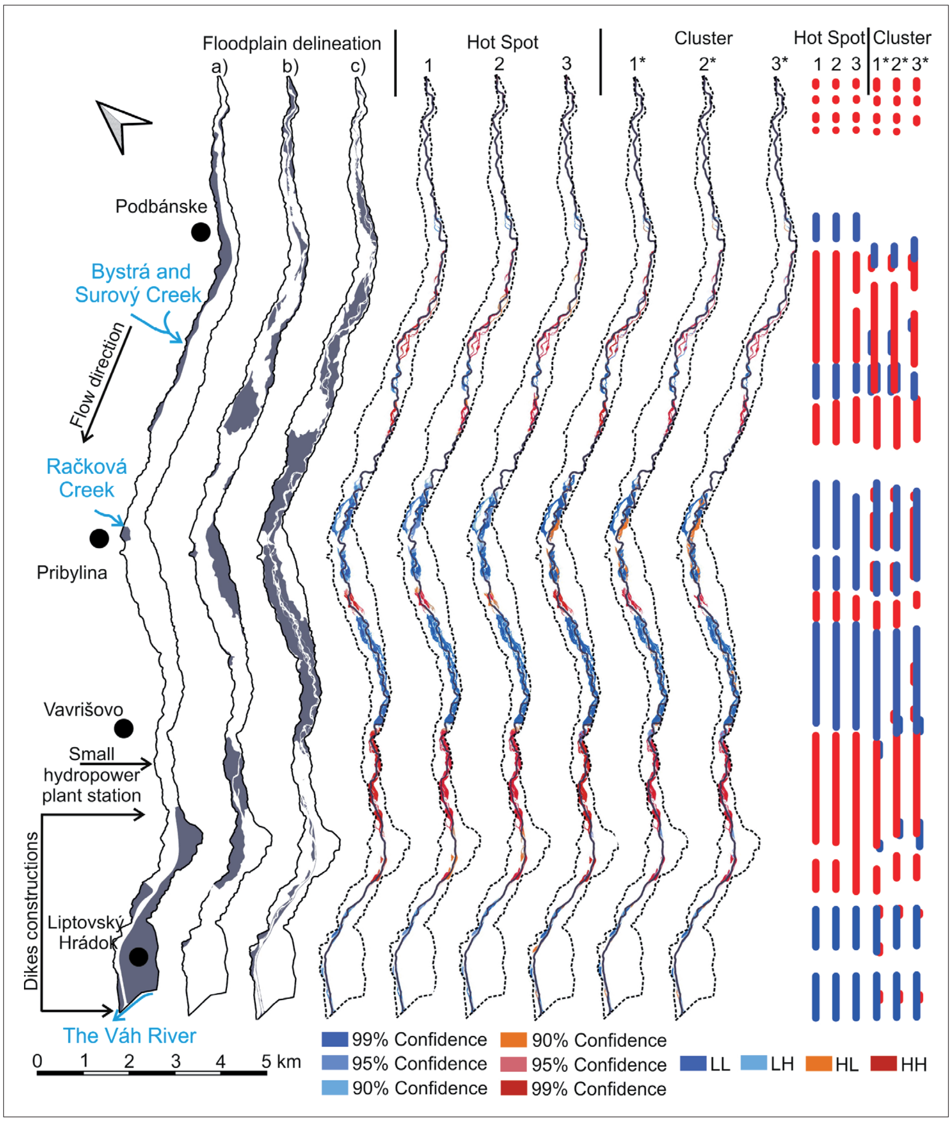

Fig. 10: On the left side, maps represent three types of floodplain delineation based on REMs models: a) inaccessible floodplain, b) perched floodplain, and c) active floodplain. For every REM the "hot spot analysis" and the "cluster and outlier analysis" were run for new floodplain formation from 1949 to 2018. Altogether, three REMs were used, REMwater^{DTM} (1), REMwater^{GPS} (2), and REMbottom^{GPS} (3). On the left, the results of analyses are visualized by maps. The cold spot Confidence is visualized in blue colour and hot spot confidence in red colouration. The cluster of low values (LL) and low values surrounded primarily by high values (LH) have blue colouration, and high values (HH) and high values surrounded primarily by low values (HL) have red colouration. The cross sections on the right represent 150 m long sections of the floodplain and river channel typical for each part of the river floodplain
Source: Authors' elaboration

stretched from the Vavrišovo to the Liptovský Hrádok, where in the middle of the last century the watercourse was significantly modified by the construction of dikes. In this lower part of the stream, the floodplain was situated only as a floodplain pocket or is completely lacking, and the river channel occupied the entire space between the dikes. The formation of the new river floodplain was insignificant and only in small patches, which shows cold spots in the spatial statistics. Paradoxically, the part of the stream with the widest topographic floodplain lacks an active floodplain completely.

5. Discussion

5.1 The REM generation

The river floodplain along the Belá River was formed into an active and perched river floodplain by discharge changes and anthropogenic interventions. The complex topography of the floodplain, its significant changes in gradient and height prevented floodplain level identification from DTM (Fig. 4) or orthophoto images. Therefore, three REMs were created that adjust and normalized the river floodplain elevation according to changes in the river channel elevation.

The REMs indicated a noticeable similarity in value distribution (Fig. 5). The distribution of the values was not uniform, and the histograms demonstrate the sharp redistribution changes, for example around 5 m above the channel (Fig. 5). Despite this, there were found no connection between these value distributions and the further floodplain level delineation. Previously, the models were used in basic floodplain visualization (Coe, 2016), in the identification of side channels (Jones, 2006) and riparian vegetation (Dilts et al., 2010; Slaughter & Hubert, 2014), or in the delineation of migration zone of a river (Olson, 2014). However, there was no research focused on floodplain delimitation or floodplain process-oriented model of floodplain development.

The quality and success of the model depended on the type of input data. While Jones (2006) used an actual water level derived from the LiDAR point cloud, Dilts et al. (2010) used an inundation level, and Greco et al.(2008) used a dry season base-flow channel water surface. There was no recommendation or required type of input. The water level naturally fluctuates, and the bottom is formed by riffles and pools. The bank-full condition seems to be the most appropriate for the identification and analysis of fluvial features above the river channel. However, determination of the bank-full condition for a lowland stream is easier as opposed to a braided stream, where high gradient and sinuosity of the channel could be a problem for the model (Coe, 2016). The incision of the Belá River, a large accumulation of material on the banks, and the dynamic nature of the water stream disenables acquiring the required data. Therefore, three types of data were used and compared, including channel bottom elevation.

The research focusing on model building from the bottom of the channel has been lacking. Greco et al. (2008) used the channel bathymetry as information for average summer low-flow value, but not as a reference elevation. In the research, water level data and bottom elevation data were collected by GPS. Their comparison did not show significant differences in the patterns and distributions of values. Anyway, the result depends not only on the quality of the data but also on the experience of the data collector. Additionally, if the REMwater^{DTM} and REMwater^{GPS} are compared, only small differences are distinguishable. Yet, it is possible to collect data by GPS in one terrain survey with no huge water level fluctuation, while accessible LiDAR data can often be collected in the span of a few days with different water levels.

The water level values have been interpolated from points (Olsen et al., 2014) and cross-sections (Jones, 2006). Dilts et al. (2010) pointed out that the method of the parallel cross-sections and perpendicular cross-sections on the river channel (Fig. 11a and 11b) distribute values irregularly. The point interpolation was inappropriate for the high sinuous Belá River, where the lower parts of the sinuous channel could disproportionately affect the lower or higher portion of the floodplain. Besides, the interpolation accuracy decreased with increasing distance from the Belá River, and the REM values should be the most accurate close to the main river channel (Greco et al, 2008). The modified cross-section method was used in this study as the most appropriate method with the best results. The cross sections were placed perpendicularly on the centre line of the floodplain (Fig. 11c) every 500 m, along the centre line of the floodplain. This ensured that even the furthest points on the floodplain reach the same relative height accuracy as the nearer locations perpendicular to the river channel, in comparison to other methods. Additionally, a very dense distribution of cross-sections created too sharp and disturbing a transition of REM (Fig. 12). High stream gradients and step-pool morphology indicate more frequent knickzones occurrence (Hayakawa & Oguchi, 2006), which could affect the final model.

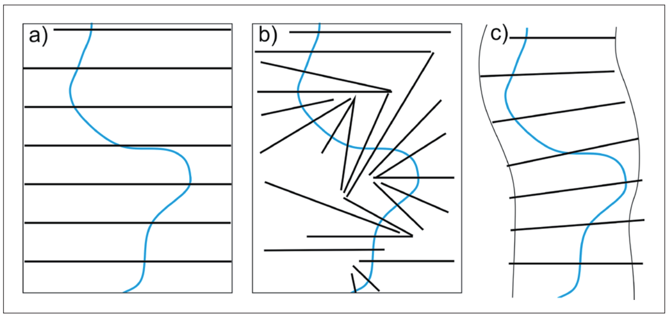

Fig. 11: The methods of cross-section settings. The a) represent parallel cross sections, which do not respect the sinuous of the river, b) represent cross sections perpendicularly on the river channel, which leave large gaps and the interpolation could inappropriately affect the different parts of the floodplain. Compromise is the method c), where the cross-section lines are leading perpendicularly on the floodplain centre line
Source: Authors' conceptualization based on Dilts et al. (2010)

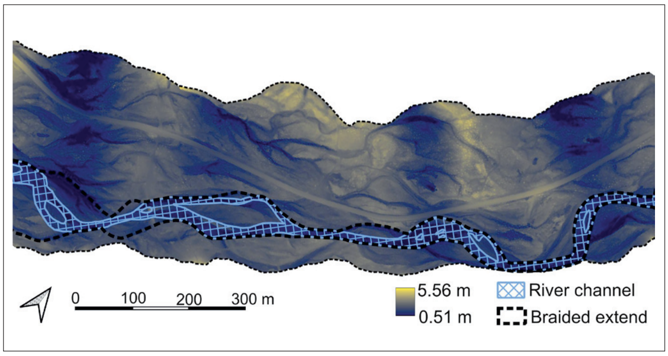

Fig. 12: The REM model was generated from the water level by a 100 m cross-section. Too dense cross sections created irregular model due to channel gradient changes. A similar problem appears with DTM detrended for channel gradient
Source: Authors' conceptualization

5.2 Floodplain delineation

The extension and identification of a river floodplain could differ depending on the determination of the principles of its delimitation (Křížek et al., 2006). Different approaches on how to delimit floodplains were presented by Lóczy et al. (2012), together with the identification of four subdivisions of the river floodplain based on slope, floodplain width, sinusoid, valley confinement and maximum relief. The floodplain along the Belá River was delimited by the edges of the terraces. The different transitions in the river stream affected the character of the floodplain (Jain et al., 2008). During the development and formation of the floodplain along the Belá River, levels of floodplain were created, separated by different heights and in some places formed to a perched floodplain identified based on the REMs.

A high and low floodplain was identified by Kiss et al. (2017) by cross sections, but REMs provided a proper method of identification of perched floodplain on an extensive spatial scale. However, there was no exact elevation value that separates the floodplain levels. They were identified due to sharp edges and higher continuous surfaces on REM (Fig. 4), significantly separated from the river channel. Eder et al. (2022), identify former floodplain, active and potential floodplain along the Danube River based on the inundated areas and historical data. On the other hand, the REM allows the possibility of identifying multiple levels of floodplains, their edges and also forms located around the watercourse, such as ledges, dikes or other artificial structures.

Additionally, the REM could have broad utilization in design tools for planting plans in riparian restoration projects or for predicting the presence of plant communities (Greco et al, 2008). Figure 13 shows the relative elevation of settlements and buildings concerning the REMs. The settlements Liptovský Hrádok or Pribylina spread on the floodplain relatively low to the river, protected by dikes and the recreational facilities spread relatively high to the river. On the other hand, the marginalized Roma community, situated only tens of meters away from the braidplain of the Belá River is situated on a relatively low floodplain unprotected by dikes (Fig. 13). This could be an example of using the REM in environmental justice or flood hazard analysis. Besides that, the REM could be valuable information for estimating and predicting flood inundation patterns or surrogate water table model (Greco et al., 2008), or it is possible to look for a correlation between the height of the floodplain and vegetation quality due to incision of the channel.

5.3 The floodplain formation

The river floodplain widened and narrowed unevenly downstream. In the uppermost part at the confluence of Tichý and Kôprovský Creeks, the topographic floodplain was the narrowest

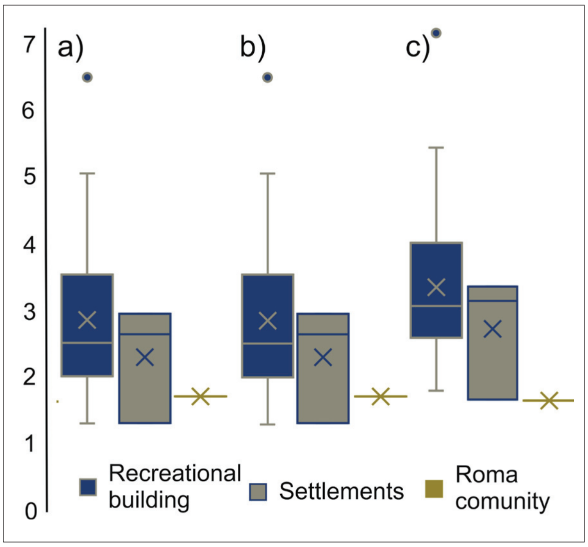

Fig. 13: The box plot presents the distribution of mean values of relative height to the water level for three types of settlements. The mean values were generated from: a) REMwater^{DTM}; b) REMwater^{GPS}; c) REMbottom^{GPS}. The recreational buildings are scattered at the floodplain without dike constructions. The settlements (Liptovský Hrádok and Pribylina) are situated behind the dikes. The marginalized Roma settlement is located close to the river without flood protection
Source: Authors' conceptualization

with an almost absent active floodplain. The channel had a single-thread character (Lehotský et al., 2018) and with floodplain pockets resemble a canyon character, which had specific conditions for the development of the floodplain (Tranmer et al., 2015). There was a significant change in the height of the river floodplain, where two floodplain levels were identified, the upper exceeding 3 m (Fig. 8). Spatial statistics shows the formation of floodplain in the area in patches, with high relative elevation.

The higher part of the floodplain could be considered a low terrace because of the missing interaction with the channel, with many recreational facilities exhibited in this section. It seems, that the higher parts of the river floodplain are more stable. Haschenburger and Cowie (2009) term stable parts of floodplain along the braided river as a mature floodplain and suggest that by dating it is possible to shed light on when conditions change which led to the formation of stable parts of the floodplain.

Gradually, from Podbásnke to Vavrišovo, an expansion of the topographic river floodplain appeared. The expansion of the floodplain in the foothills area was observed similarly by Lóczy et al. (2012). The active floodplain along the Belá River was significantly narrowed by the road embankment between Podbánske and Pribylina, and by the perched floodplain along both sides of the channel almost in the whole river reach. A noticeably extended perched floodplains and contraction of active floodplain was formed by the channel incision after the Surový and Bystrá Creeks flow to the Belá River. The incision since 1949 is highlighted by spatial statistics (Fig. 10).

The side tributaries could have a strong influence on the river reaches, and disturb them (Nardi & Rinaldi, 2015). The difference in the amount of precipitation and the amount of sediment input in a sub-basin can strongly influence the local formation of the floodplain. For example, a decreasing discharge has been observed since mid-20th century with no flood situation exceeding a 10-year recurrence interval since 1958 to 2018 (Fig. 2). Catastrophic flood events have also been absent since 1958. Furthermore, the right-sided channel of Belá River before Račková Creek confluence, was narrowed and shifted closer to the main channel between 1949 and 1961, probably as a result of the lack of flood events. More importantly, the relative height of the channel decreased in average only slightly from 0.29 m to – 0.3 m. In 1973 the channel was inactive. This leads us to the idea, that the river floodplain could be formed by gradual incision of the main channel, and simultaneously by narrowing and simplification of the braidplain. Abandoning of side channels caused by vast incision which reached from 3 to 5 m has been observed on the Prahova River (Armaş et al., 2013). On the Belá River, such vast incision could be mitigated by local cut-bluffs sediment input.

The river channel before Pribylina is confined to the left-hand terrace, causing multiple cut-bluffs. Only in one cut-bluff 10,102.9 m^3 of mass was transferred to the river (Rusnák et al., 2020). It can be assumed that the amount of sediment supplied to the channel during the cut-bluffs could mitigate the incision of the stream. Along and downstream of the cut-bluffs, the simplification of the river channel and the formation of a river floodplain was observed, without channel incision. Moreover, from the vicinity of cut-bluffs downstream, the perched floodplain was replaced by the active floodplain across its entire topographic floodplain width. The amount of material that entered the river probably affected the floodplain formation and prevented extensive cutting of the channel.

According to Lehotský et al. (2018), the whole Belá River showed a simplification process due to sediment transport interruption. The narrowing and simplification of the channel with no or very limited incision, resulted in the formation of an extensive river floodplain between Pribilina and Vavrišovo (Fig. 10). According to Majerčáková et al. (2007), decreasing discharges together with a lack of extreme flood events and a change in the sediment supply (Kidová et al., 2016a) negatively affected the channel pattern from braided to single-thread channel (Kidová et al., 2016b). Dufour et al. (2015) claimed that the narrowing and transformation from the bar-braided river pattern to a single-thread system that occurred on the Magra River was a result of local factors rather than long-term. Nevertheless, the transformation of the Belá River seems to be rather a regional problem (Wyżga et al., 2016) than a local one.

Generally, braided rivers are formed by the pulse character of flood events (Bertoldi et al., 2010) and are sensitive to floods (Nardi & Rinaldi, 2015). If the pulses are missing, the channel pattern is simplified (Kidová et al., 2016a). This can affect riparian plant species since many species depend on the reshaping of the braidplain (Tockner et al, 2000). The missing flows and extreme flood events (Fig. 2) led to the narrowing and simplification of the braided river pattern of the Belá River (Kidová, 2016a) and consequently to a new river floodplain formation. However, the incision of the riverbed was observed only locally. The reduced peak range created a larger and relatively stable area in the Ngaruroro River in New Zealand, where degradation of the braided river pattern did not necessarily lead to significant channel incision (Haschenburger & Cowie, 2009). The increase of floodplain formation was observed also in the Polish Carpathians accompanied by expansion of the riparian forests (Hajdukiewicz & Wyżga, 2022). The trend of degradation and simplification of river channel patterns of mountain and submountain streams is a far-reaching issue, not a regional problem.

However, floodplain formation can be disrupted by strong anthropogenic impact. The river floodplain around the Vavrišovo had a canyon character stronger than the upper most part of the river but with a lower gradient. The canyon character was a result of the construction of a small hydroelectric power plant. The stream was significantly incised and the lateral connectivity between the channel and the floodplain was interrupted (Kidová & Lehotský, 2013). Rusnák et al. (2018) detected the advancing incision in the locality by UAV by identification of three bar levels. Additionally, the incision supported sliding activation upstream (Rusnák et al. 2020).

The active floodplain in the locality of the small hydroelectric power plant was absent totally, surrounded by the perched floodplain, with relative elevation reaching up to 5 m from the channel bottom. The spatial statistics supported the previous observations and research and displayed the extent of the perched floodplain in the area. Besides, the perched floodplain represents the former active braidplain in the mid-20th century. Haschenburger and Cowie (2009) suggested that aggradation and also degradation may promote floodplain formation. However, the degradation of the Belá River due to anthropogenic impact is so extensive that it promotes direct perched floodplain formation. On the other hand, the process of incision of the river channel can trigger its widening, by exceeding a critical height for mass failure of channel banks (Bollati et al., 2014).

Downstream the topographical floodplain reaches a width up to 1 km, largely replaced by isolated inaccessible floodplain behind the dike constructions. The dike constrictions interrupt the connectivity between the channel and the floodplain (Kidová, 2010), accompanied by gravel mining as an additional human impact affecting the channel (Radecki-Pawlik et al., 2019). The channel bed was reinforced by a stabilization threshold to prevent additional incision in the river reach (Kidová, 2010). In the locations where the dikes were not constructed, the perched floodplain was formed. Due to the limitation of the active width of the river, floodplain development becomes less likely (Haschenburger & Cowie, 2009). The effect of the anthropogenic impact was an obvious interruption of the lateral connection of the channel with the rest of the floodplain. Furthermore, the active river floodplain between the dikes further from the small hydroelectric plant exhibits a gradual decrease of hot spot and their replacement by cold spots within the spatial statistics.

The impact of the small hydropower plant decreased gradually downstream demonstrating its negative impact and the disruption of the lateral connectivity of the Belá River (Lehotský et al., 2018) since its construction (Kidová et al., 2016a). In the Polish Carpathians rivers, the channel width decreased to 21–65% of the value from the 1870s since 2009 (Hajdukiewicz & Wyżga, 2022) due to anthropogenic impact. Using the example of the Belá River, the changes in discharges and sediment supply changes have prompted a simplification of the river pattern, but not necessarily the incision of the channel into the bedrock, primarily induced by anthropogenic interventions in the stream. Nowadays it is possible to demonstrate the different impacts of climate change and anthropogenic impact. However, according to Majerčáková et al. (2007), if the catchment has too many local anthropogenic impacts in the future, the parsing of total impact into anthropogenic impact and climate change impact will be essentially impossible.

The floodplain along the Belá was developed predominantly by narrowing and incision of the main channel. It is evident that incision is quite active near the tributaries or the anthropogenic impact section, while simplification is the main process along the whole water stream. In the presented research, the perched floodplain has been identified from REMs and in the vicinity of the small hydropower plant station, after the confluence of the Kôprovský and Tichý Creeks and after the confluence of the right-sided tributaries with the Belá River, while the active floodplain followed. The ongoing processes have been confirmed by spatial statistics.

While Bollati et al. (2014) claimed that there was no reliable determination of whether incision and narrowing started simultaneously or if one of the two processes supported the other, this research suggests that the simplification was accompanied by incision, advancing contraction of the braidplain and gradual lowering of the riverbed (Fig. 9). These processes were intensified in locations with side tributaries, and by anthropogenic intervention, which strongly and significantly influenced erosion-accumulation processes in the river reaches. Primarily the anthropogenic impact can initiate considerable incision of the riverbed (Ziliani & Surian, 2012).

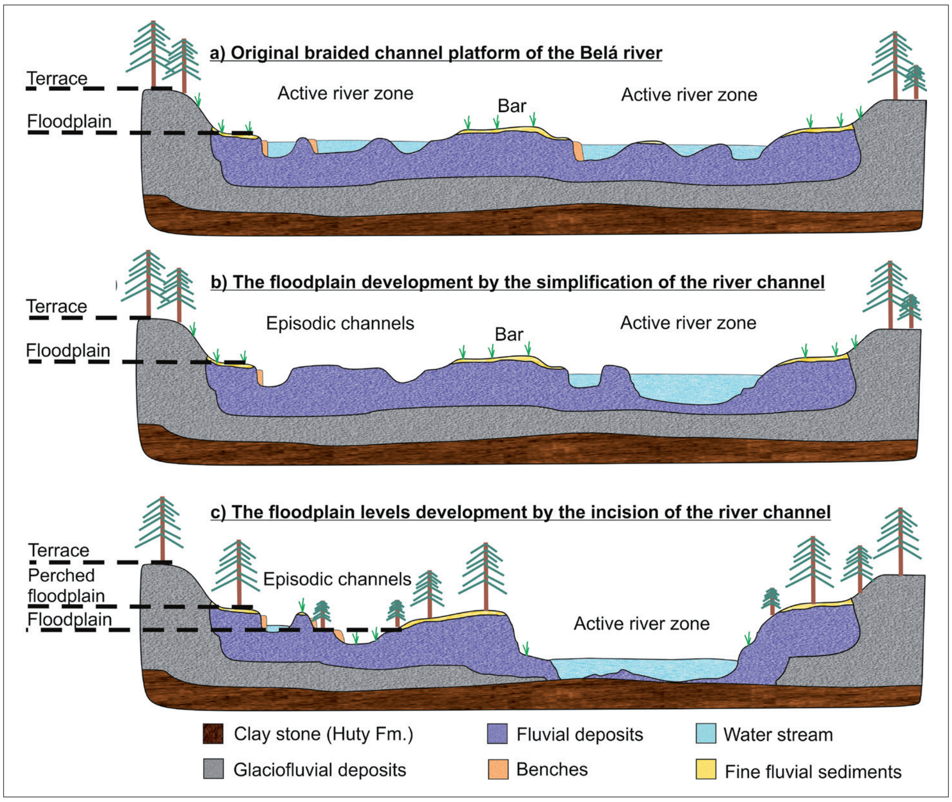

Fig. 14: The sketch represents a basic concept of the process model. The original braidplain is followed by two ongoing processes on the Belá River, responsible for river transformation and floodplain development
Source: Authors' conceptualization

The results lead us to the idea, that the perched floodplain could be considered a result of cyclical channel evolution, which is typically characterized by an initial degradation (phase of initial bed incision), resulting in bank unstability and widening, and finally completed by a stage of aggradation (Bollati et al., 2014). The perched floodplain was identified along the Belá River as a presumable remnant of the completed cycle of channel evolution. Dating of the perched river floodplain could determine when a similar cycle occurred. The recent evolution of the Belá River indicates the predominant initial phase of the cycle in a major part of the river, based on gradual simplification and abandoning of the side channels. It can be presumed, that the contemporary simplification and incision of the river will develop an additional level of the perched floodplain made of the current active floodplain.

6. Conclusions

The submountain Belá River can be understood as a glacial relic, which is more susceptible to climate changes and anthropogenic interventions. Decreasing discharges, lack of extreme flood events, modification of land use in the catchment area and anthropogenic interventions have affected the Belá River over the last 70 years, resulting in the simplification of the river pattern (Kidová et al., 2016b). Moreover, the anthropogenic interventions have intensified the ongoing processes. Using the Relative Elevation Models (REMs), it is possible to identify the active, inaccessible, and perched floodplain with its levels. In combination with floodplain dating and spatial statistics, two basic evolutionary processes in progress have been identified (Fig. 14) affecting the river floodplain development:

a. The original braided channel planform is characterized by numerous active channels, separated by gravel bars. The river floodplain is formed along the edges of the active river zone by shifting and repeated contraction of the braid plain. However, human intervention, discharges decreased and increased forest cover affect the channel planform and initiate the two main processes of river transformation and floodplain formation.

b. The first process which transforms the river and forms the floodplain is the contraction of the braidplain. As a result of simplification and narrowing of the active river zone, the new floodplain develops along the river sides. The gradual formation of one dominant channel, and the river floodplain prevails. During increased discharges and catastrophic floods, the braided pattern can be restored. In addition, the river floodplain still fulfils the function of accumulating and mitigating floods.

c. The second process is the development of single-thread channel with a strong incision that causes an interruption in the lateral connectivity of the river channel with the surrounding floodplain. The river floodplain forms into several levels and creates a perched floodplain. The reformation of a floodplain is absent due to the impossibility of river channel migration. In case of increased flows and catastrophic floods, there is no connection between the river and perched floodplain levels. The river floodplain no longer has the function of accumulation and mitigation of floods, which can lead to increased floods in the lower parts of the Belá River.

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Data availability

The data used in the research were obtained from: ÚGKK SR, including LiDAR data and aerial photos available at: https://www.skgeodesy.sk/sk; geological maps available at: https://www.geology.sk/geoinfoportal/mapovy-portal/geologicke-mapy/; and data from Slovak hydrometeorological institute (SHMÚ).

References:

Armaş, I., Gogoaşe Nistoran, D. E., Osaci-Costache, G., & Braşoveanu, L. (2013). Morpho-dynamic evolution patterns of Subcarpathian Prahova River (Romania). Catena, 100, 83–99. https://doi.org/10.1016/j.catena.2012.07.007

Beechie, T. J., Liermann, M., Pollock, M. M., Baker, S., & Davies, J. (2006). Channel pattern and river-floodplain dynamics in forested mountain river systems. Geomorphology, 78, 124–141. https://doi.org/10.1016/j.geomorph.2006.01.030

Bertoldi, W., Zanoni, L., & Tubino, M. (2010). Assessment of morphological changes induced by flow and flood pulses in a gravel bed braided river: The Tagliamento River (Italy). Geomorphology, 114, 348–360. https://doi.org/10.1016/j.geomorph.2009.07.017

Blöschl, G., Hall, J., Viglione, A., Perdigão, R. A. P., Parajka, J., Merz, B., …, & Živković, N. (2019). Changing climate both increases and decreases European river floods. Nature, 573, 108–111. https://doi.org/10.1038/s41586-019-1495-6

Bollati, I. M., Pellegrini, L., Rinaldi, M., Duci, G., & Pelfini, M. (2014). Reach-scale morphological adjustments and stages of channel evolution: The case of the Trebbia River (northern Italy). Geomorphology, 221, 176–186. https://doi.org/10.1016/j.geomorph.2014.06.007

Brierley, G. J. & Fryirs, K. A. (2005). Geomorphology and River Management: Applications of the River Styles Framework. John Wiley & Sons.

Coe, D. (2016). Floodplain visualization using lidar-derived relative elevation models. Poster presented at the Digital Mapping Techniques Workshop, May 22–25, 2016, Tallahassee, Florida.

Croke, J., Fryirs, K., & Thompson, C. (2016). Defining the floodplain in hydrologically-variable settings: implications for flood risk management. Earth Surface Processes and Landforms, 41(14), 2153–2164. https://doi.org/10.1002/esp.4014

Dilts, T. E. (2015). Riparian Topography Tools for ArcGIS 10.1. University of Nevada Reno. http://www.arcgis.com/home/item.html?id=b13b3b40fa3c43d4a23a1a09c5fe96b9

Dilts, T. E., Yang, J., & Weisberg, P. J. (2010). Mapping Riparian Vegetation with Lidar Data. ESRI 18–21.

Dufour, S., Rinaldi, M., Piégay, H., & Michalon, A. (2015). How do river dynamics and human influences affect the landscape pattern of fluvial corridors? Lessons from the Magra River, Central-Northern Italy. Landscape and Urban Planning, 134, 107–118. https://doi.org/10.1016/j.landurbplan.2014.10.007

Eder, M., Perosa, F., Hohensinner, S., Tritthart, M., Scheuer, S., Gelhaus, M., …, & Habersack, H., (2022). How can we identify Active, former, and potential floodplains? Methods and lessons learned from the Danube River. Water, 14. https://doi.org/10.3390/w14152295

Gray, D., & Harding, J. S. (2007). Braided river ecology: A literature review of physical habitats and aquatic invertebrate communities. Science & Technical Pub., Department of Conservation.

Greco, S. E., Fremier, A. K., Larsen, E. W., & Plant, R. E. (2007). A tool for tracking floodplain age land surface patterns on a large meandering river with applications for ecological planning and restoration design. Landscape and Urban Planning, 81, 354–373. https://doi.org/10.1016/j.landurbplan.2007.01.002

Greco, S. E., Girvetz, E. H., Larsen, E. W., Mann, J. P., Tuil, J. L., & Lowney, C. (2008). Relative elevation topographic surface modelling of a large alluvial river floodplain and applications for the study and management of riparian landscapes. Landscape Research, 33, 461–486. https://doi.org/10.1080/01426390801949149

Gurnell, A., Surian, N., & Zanoni, L. (2009). Multi-thread river channels: a perspective on changing European alpine river systems. Aquatic Sciences, 71, 253–265. https://doi.org/10.1007/s00027-009-9186-2

Hajdukiewicz, H., & Wyżga, B. (2022). Twentieth-century development of floodplain forests in Polish Carpathian valleys: The by-product of transformation of river channels? Science of the Total Environment, 802, 149853. https://doi.org/10.1016/j.scitotenv.2021.149853

Hajdukiewicz, H., Wyżga, B., Amirowicz, A., Oglęcki, P., Radecki-Pawlik, A., Zawiejska, J., & Mikuś, P. (2018). Ecological state of a mountain river before and after a large flood: Implications for river status assessment. Science of the Total Environment, 610, 244–257. https://doi.org/10.1016/j.scitotenv.2017.07.162

Haschenburger, J. K., & Cowie, M. (2009). Floodplain stages in the braided Ngaruroro River, New Zealand. Geomorphology, 103, 466–475. https://doi.org/10.1016/j.geomorph.2008.07.016

Hauer, F. R., Locke, H., Dreitz, V. J., Hebblewhite, M., Lowe, W. H., Muhlfeld, C. C., ..., & Rood, S. B. (2016). Gravel-bed river floodplains are the ecological nexus of glaciated mountain landscapes. Science Advances, 2(6), e1600026. https://doi.org/10.1126/sciadv.1600026

Hayakawa, Y. S., & Oguchi, T. (2006). DEM-based identification of fluvial knickzones and its application to Japanese mountain rivers. Geomorphology, 78, 90–106. https://doi.org/10.1016/j.geomorph.2006.01.018

Huggett, R. J. (2011). Fundamentals of Geomorphology. Routledge. https://doi.org/10.4324/9780203860083

Jain, V., Fryirs, K., & Brierley, G. (2008). Where do floodplains begin? The role of total stream power and longitudinal profile form on floodplain initiation processes. Geological Society of America Bulletin, 120(1–2), 127–141. https://doi.org/10.1130/B26092.1

Jakubínský, J., Prokopova, M., Raška, P., Salvati, L., Bezak, N., Cudlín, O., …, & Lepeška, T. (2021). Managing floodplains using nature-based solutions to support multiple ecosystem functions and services. Wiley Interdisciplinary Reviews: Water, 8(5), e1545. https://doi.org/10.1002/wat2.1545

Jones, J. L. (2006). Side channel mapping and fish habitat suitability analysis using lidar topography and orthophotography. Photogrammetric Engineering and Remote Sensing, 72(11), 1202.

Kadlec, J., Grygar, T., Svétlik, I., Ettler, V., Mihaljevič, M., Diehl, J. F., ..., & Svitavská-Svobodová, H. (2009). Morava River floodplain development during the last millennium, Strážnické Pomoraví, Czech Republic. The Holocene, 19(3), 499–509. https://doi.org/10.1177/0959683608101398

Kidová, A. (2010). Vývoj antropogénneho vplyvu na morfológiu koryta vodného toku – príklad rieky Belej. In: Zborník vedeckých prác doktorandov a mladých vedeckých pracovníkov “Mladí vedci 2010“ (pp. 7).

Kidová, A., & Lehotský, M. (2012). Časovo-priestorová variabilita morfológie divočiaceho a migrujúceho vodného toku Belá. Geografický časopis, 64(4), 311–333.

Kidová, A., & Lehotský, M. (2013). The Belá river fluvial system. Geomorphologica Slovaca et Bohemica, 1, 90–98.

Kidová, A., Lehotský, M., & Rusnák, M. (2016a). Morfologické zmeny a manažment divočiaco-migrujúceho vodného toku Belá. Geomorphologica Slovaca et Bohemica, 16, 1–60.

Kidová, A., Lehotský, M., & Rusnák, M. (2016b). Geomorphic diversity in the braided-wandering Belá River, Slovak Carpathians, as a response to flood variability and environmental changes. Geomorphology, 272, 137–149. https://doi.org/10.1016/j.geomorph.2016.01.002

Kidová, A., Radecki-Pawlik, A., Rusnák, M., & Plesiński, K. (2021). Hydromorphological evaluation of the river training impact on a multi-thread river system (Belá River, Carpathians, Slovakia). Scientific Reports, 11(1), 6289. https://doi.org/10.1038/s41598-021-85805-2

Kiss, T., Nagy, Z., & Balogh, M. (2017). Floodplain level development induced by human activity-case study in the lower Maros/Mures river, Romania and Hungary. Carpathian Journal of Earth and Environmental Sciences, 12(1), 83–93.

Křížek, M., Hartvich, F., Chuman, T., Šefrna, L., Šobr, M., & Zádorová, T. (2006). Floodplain and its delimitation. Geografie – Sbornik české geografické společnosti, 111(3), 260–273. https://doi.org/10.37040/geografie2006111030260

Krzemień, K., Gorczyca, E., Sobucki, M., Liro, M., & Łyp, M. (2015). Effects of environmental changes and human impact on the functioning of mountain river channels, Carpathians, southern Poland. Annals of Warsaw University of Life Sciences-SGGW. Land Reclamation, 47(3), 249–260. https://doi.org/10.1515/sggw-2015-0029

Lehotský, M., Kidová, A., & Rusnák, M. (2015). Slovensko-anglické názvoslovie morfológie vodných tokov. Geomorphol. Geomorphologica Slovaca et Bohemica, 15, 61.

Lehotský, M., Rusnák, M., Kidová, A., & Dudžák, J. (2018). Multitemporal assessment of coarse sediment connectivity along a braided-wandering river. Land Degradation & Development, 29(4), 1249–1261. https://doi.org/10.1002/ldr.2870

Lóczy, D., Pirkhoffer, E., & Gyenizse, P. (2012). Geomorphometric floodplain classification in a hill region of Hungary. Geomorphology, 147–148, 61–72. https://doi.org/10.1016/j.geomorph.2011.06.040

Majerčáková, O., Škoda, P., & Danáčová, Z. (2007). Vývoj vybraných hydrologických a zrážkových charakteristík za obdobia 1961–2000 a 2001–2006 v oblasti Vysokých Tatier. Meteorologický časopis, 10(4), 205–210.

Marti, C., & Bezzola, G. R. (2006). Bed load transport in briaded gravel-bed rivers, In G. Sambrook Smith et al. (Eds): Braided Rivers: Process, Deposits, Ecology and Management (pp. 199–215). Blackwell Publishing.

Mitchell, A., & Griffin, L. S. (2021). Spatial Measurements and Statistics. ESRI Press.

Moretto, J., Rigon, E., Mao, L., Delai, F., Picco, L., & Lenzi, M. A. (2012). Assessing morphological changes in gravel bed rivers using LiDAR data and colour bathymetry. IAHS Public, 356, 419–427.

Nanson, G. C., & Croke, J. C. (1992). A genetic classification of floodplains. Geomorphology, 4(6), 459–486. https://doi.org/10.1016/0169-555X(92)90039-Q

Nardi, L., & Rinaldi, M. (2015). Spatio-temporal patterns of channel changes in response to a major flood event: the case of the Magra River (central–northern Italy). Earth Surface Processes and Landforms, 40(3), 326–339. https://doi.org/10.1002/esp.3636

Olson, P. L., Legg, N. T., Abbe, T. B., Reinhart, M. A., & Radloff, J. K. (2014). A methodology for delineating planning-level channel migration zones (No. 14-06-025). Washington (State). Dept. of Ecology.

Radecki-Pawlik, A., Kidová, A., Lehotsky, M., Rusnák, M., Manson, R., & Radecki-Pawlik, B. (2019). Gravel and boulders mining from mountain stream beds. In E3S Web of Conferences (Vol. 106, p. 01005). EDP Sciences (pp. 1–11). https://doi.org/10.1051/e3sconf/201910601005

Rădoane, M., Obreja, F., Cristea, I., & Mihailă, D. (2013). Changes in the channel-bed level of the eastern Carpathian rivers: Climatic vs. human control over the last 50 years. Geomorphology, 193, 91–111. https://doi.org/10.1016/j.geomorph.2013.04.008

Reinfelds, I., & Nanson, G. (1993). Formation of braided river floodplains, Waimakariri River, New Zealand. Sedimentology, 40(6), 1113–1127. https://doi.org/10.1111/j.1365-3091.1993.tb01382.x

Rhoads, B. L. (2020). River dynamics: geomorphology to support management. Cambridge University Press. https://doi.org/10.15201/hungeobull.69.3.6

Roux, C., Alber, A., Bertrand, M., Vaudor, L., & Piégay, H. (2015). “FluvialCorridor”: A new ArcGIS toolbox package for multiscale riverscape exploration. Geomorphology, 242, 29–37. https://doi.org/10.1016/j.geomorph.2014.04.018

Rusnák, M., Kaňuk, J., Kidová, A., Šašak, J., Lehotský, M., Pöppl, R., & Šupinský, J. (2020). Channel and cut-bluff failure connectivity in a river system: Case study of the braided-wandering Belá River, Western Carpathians, Slovakia. Science of the Total Environment, 733, 139409. https://doi.org/10.1016/j.scitotenv.2020.139409

Rusnák, M., Sládek, J., Kidová, A., & Lehotský, M. (2018). Template for high-resolution river landscape mapping using UAV technology. Measurement, 115, 139–151. https://doi.org/10.1016/j.measurement.2017.10.023

Slaughter, S. L., & Hubert, I. J. (2014). Geomorphic Mapping of the Chehalis River Floodplain, Cosmopolis to Pe Ell, Grays Harbor, Thurston, and Lewis Counties, Washington.

Tockner, K., Malard, F., & Ward, J. V. (2000). An extension of the flood pulse concept. Hydrological processes, 14(16–17), 2861–2883. https://doi.org/10.1002/1099-1085(200011/12)14:16/17<2861::AID-HYP124>3.0.CO;2-F

Tranmer, A. W., Tonina, D., Benjankar, R., Tiedemann, M., & Goodwin, P. (2015). Floodplain persistence and dynamic-equilibrium conditions in a canyon environment. Geomorphology 250, 147–158. https://doi.org/10.1016/j.geomorph.2015.09.001

Whited, D. C., Lorang, M. S., Harner, M. J., Hauer, F. R., Kimball, J. S., & Stanford, J. A. (2007). Climate, hydrologic disturbance, and succession: Drivers of floodplain pattern. Ecology, 88, 940–953. https://doi.org/10.1890/05-1149

Wohl, E. (2006). Human impacts to mountain streams. Geomorphology, 79, 217–248. https://doi.org/10.1016/j.geomorph.2006.06.020

Wyżga, B., Zawiejska, J., & Hajdukiewicz, H. (2016). Multi-thread rivers in the Polish Carpathians: occurrence, decline and possibilities of restoration. Quaternary International, 415, 344–356. https://doi.org/10.1016/j.quaint.2015.05.015

Zaprowski, B. J., Pazzaglia, F. J., & Evenson, E. B. (2005). Climatic influences on profile concavity and river incision. Journal of Geophysical Research: Earth Surface, 110(F3). https://doi.org/10.1029/2004JF000138

Ziliani, L., & Surian, N. (2012). Evolutionary trajectory of channel morphology and controlling factors in a large gravel-bed river. Geomorphology, 173, 104–117. https://doi.org/10.1016/j.geomorph.2012.06.001

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