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Analysis of historical changes in planform geometry of a mountain river to inform design of erodible river corridor

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ABSTRACT

The analysis of changes in planform geometry of the Biała River during the last 130 years is used to diagnose hydromorphological river degradation and thus to verify the need of river restoration through establishing an erodible river corridor. Outcomes from the analysis are then used for delimiting the erodible corridor and predicting the potential for future river widening in the corridor. The study analyses presentations of the active river zone and the structure of river geomorphic units on topographic maps from 1878, 1935 and 1962, aerial photos from 1967, 1977 and 1987, and orthophotos from 1998 and 2009. As a result of river channelization followed by channel incision, during the study period the width of the Biała was reduced to 16%–57% of its width in 1878. The river narrowing was associated with a reduction in the proportion of channel bars in the total river width and nearly complete elimination of islands. All these changes demonstrated the degradation of hydromorphological integrity of the river and the need for its restoration by allowing free channel development in an erodible corridor. The belt of the river migration during the last 130 years identified on the basis of overlays of the river position from all dates was ~5 times wider than the contemporary river. This justified delimiting the erodible river corridor on a substantially larger area of the valley floor than the area of the river in 2009. In 2009 the river was narrower than the largest river width recorded between 1878 and 1998 along nearly the whole length of the study river sections. This indicates that the concentration of flood flows in the narrow channel, increasing their unit stream power, is a factor increasing the potential for future bank retreat and channel widening in the erodible corridor of the river.

1. Introduction

Analyses of changes in planform channel geometry enable recognition of the relative influence of natural and human factors on river narrowing processes (Liébault and Piégay, 2002; Comiti et al., 2011; Wyżga et al., 2016b) and of the impact of these changes on river habitat conditions (Harrison et al., 2011; Rinaldi et al., 2013; Hajdukiewicz et al., 2019), riparian vegetation (Allred and Schmidt, 1999; Cadol et al., 2011) and riverine communities (Oscoz et al., 2005; Lau et al., 2006; Wyżga et al., 2014; Oglęcki et al., 2021).

A significant decrease in channel width during the last century, accompanied by the elimination of braided channel pattern as a result of human impacts was characteristic of Carpathian rivers (Zawiejska and Wyżga, 2010; Kidová et al., 2016; Hajdukiewicz et al., 2019) as well as rivers in other mountain and piedmont regions of Europe (Liébault and Piégay, 2002; Surian and Rinaldi, 2003; Gurnell et al., 2009). Such changes have numerous negative consequences for the hydromorphological integrity of rivers (Elosegi et al., 2010). Channel narrowing and the simplification of flow pattern in a river reduce the heterogeneity of aquatic habitats. Thus, a variety of habitats with different combinations of water depth, flow velocity and bed-material grain size is replaced with commonly occurring habitats with relatively deep, fast-flowing water and coarse bed substrate (Muhar et al., 2008; Wyżga et al., 2009, 2011; Hohensinner et al., 2018). High flow velocity and bed shear stress typifying narrow channel sections (Czech et al., 2016) and a scarcity of flow refugia for aquatic biota in such sections (Negishi et al., 2002) cause that during floods benthic invertebrates and juvenile fish can be readily flushed out to downstream sections. High shear forces exerted by flood flows on the channel bed facilitate the entrainment and downstream transfer of bed material; over time, it leads to channel incision and transformation of the alluvial channel bed into a bedrock bed (Hajdukiewicz and Wyżga, 2019; Hajdukiewicz et al., 2019) and the resultant loss of habitat for benthic invertebrates and spawning grounds for lithophilic fish. Narrow channels

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of mountain rivers create unfavourable conditions for in-channel retention of large wood (Wyżga and Zawiejska, 2010) and development of wooded islands (Mikuś et al., 2019), the occurrence of which enhances the diversity of aquatic and terrestrial communities in mountain rivers (Gurnell et al., 2005; Mikuś et al., 2013). Recognition of those and other adverse effects of human impacts on the habitat integrity of rivers (Muhar and Jungwirth, 1998) and the condition of riverine communities (Allan and Castillo, 2007) has inspired activities aimed to improve the degraded river attributes, which are collectively called river restoration (Wohl et al., 2015). In the European Union, restoration activities have been reinforced by the requirement of the Water Framework Directive to re-establish good ecological status of surface waters (European Commission, 2000), mandatory to all member states.

One of the measures used in river restoration is the establishment of an erodible river corridor: a part of valley floor, in which free channel migration and development is allowed (Rapp and Abbe, 2003; Piégay et al., 2005; Kondolf, 2012; Wyżga and Zawiejska, 2012). The concept of the erodible river corridor has been applied in various rivers of the world (Rohde et al., 2005; Nieznański et al., 2008; Zerfu et al., 2015). Restoring the possibility of free channel migration enables channel widening in artificially narrowed stretches, also through the destruction of existing bank reinforcements by the river. Free channel development in an erodible corridor is assumed to restore habitat integrity, hence allowing for an improvement of the ecological river state (Rohde et al., 2005). The erodible corridor establishment is a highly sustainable strategy of ecological restoration allowing the river to “heal itself” through the functioning of channel migration zone (Kondolf, 2012), but it is particularly useful in the reaches where a future impact of channel migration on private property and valley infrastructure will be minimal (Piégay et al., 1997; Bojarski et al., 2005). Establishing an erodible corridor is also crucial for planning of development along rivers as it requires predicting the extent of the area that is at risk of erosion during channel migration (Zerfu et al., 2015).

Piégay et al. (2005) indicated that delimiting the lateral extent of an erodible river corridor can be based on identification of the belt of historical river migration or numerical modelling of future channel migration. Numerical models have mostly been used for simulating the evolution of meandering rivers (Howard, 1992; Darby et al., 2002; Coulthard and Van de Wiel, 2012); they are rather suitable for short-term predictions of river channel migration and require the selection of appropriate parameters to obtain reliable predictions (Zerfu et al., 2015). In turn, overlays of historical channel positions indicate a migration belt of the river, i.e. the area of a valley floor that was turned over by the migrating river between given dates. If such dates refer to relatively short periods, the identified river migration belt allows for establishing the amount of bank retreat in these periods, which facilitates prediction of the rate of future channel migration (e.g., Klaasen et al., 1993; Kondolf, 2011). For longer periods, during which a river could have repeatedly reworked a given area, the identified river migration belt indicates an area, where the river’s lateral mobility is relatively unconstrained, e.g. because of the occurrence of low banks with a lacking or thin cover of cohesive, overbank sediments. So identified river migration belt is thus useful for delimiting an erodible river corridor.

In the valleys of mountain and foothill rivers, a considerable proportion of flood damage results from the erosion of river banks and rapid lateral shift or widening of channels during flood events (e.g. Hajdukiewicz et al., 2016), although this type of flood hazard is neglected in the maps of flood hazard and risk and the plans of flood risk management required by the EU Floods Directive (Wyżga et al., 2016a). Studies of channel widening caused by high-magnitude floods indicated that the scale of the widening depends on unit stream power of the flood calculated on the basis of pre-flood channel width (Krapesch et al., 2011; Comiti et al., 2016; Scorpio et al., 2018). The risk of abrupt channel widening should thus be included in river corridor planning (Comiti et al., 2016), with anti-erosional revetments constructed on the boundaries of erodible river corridors, where these boundaries run close to a current channel position (Bojarski et al., 2005; Jeleński and Wyżga, 2016) and/or where the river is typified by high unit stream power reflecting the constriction of flood flows in an artificially narrowed channel. Establishing the degree of narrowing of a contemporary river in relation to its largest historical width may thus provide a useful indicator characterizing the river potential for future widening (especially an abrupt one) in an erodible corridor.

The Biała is one of Polish Carpathian rivers that were severely affected by in-channel human interventions during the last century, with a number of detrimental effects revealed in the river and on the valley floor. Channelization of the river resulted in the impoverishment of aquatic communities, which was particularly pronounced where the regulated channel incised deeply (Wyżga et al., 2013, 2014). Flood flows conveyed in channelized sections of the river were typified by high values of unit stream power and bed shear stress (Czech et al., 2016), which facilitated erosional damage to bank reinforcements and valley infrastructure, and was the reason for increased economic losses during floods in these sections (Hajdukiewicz et al., 2016). River channelization and incision considerably increased flow capacity of the channel (Czech et al., 2016) and the resultant reduction in floodwater retention in the floodplain area must have aggravated flood hazard in downstream valley sections (Wyżga et al., 2018). Forest cover in the mountain part of the catchment substantially increased in the second half of the last century (Kozak et al., 2007; Munteanu et al., 2014) and the resultant reduction in catchment sediment supply to the river might have significantly contributed to adverse changes of the river. To restore the Biała, at the end of the 2000s water authorities proposed the establishment of an erodible corridor in two sections of the river located in its mountain and foothill course. In these sections, a large proportion of the land is state-owned and channel migration is rather unlikely to affect private land and infrastructure (Wyżga et al., 2021). However, an important question was whether the observed changes of the river represent its hydromorphological degradation induced by in-channel human interventions or rather reflect an adjustment of river hydromorphology to altered environmental conditions in the catchment.

In this study, we analyse changes in planform geometry of the Biała and the river position on the valley floor that occurred between 1878 and 2009, i.e. in the period for which reliable presentation of this relatively small river on historical maps and archival photogrammetric materials was available. The study aims at: (i) recognition of changes in river width and the structure of geomorphic units of the river to verify its hydromorphological degradation and the need of establishing an erodible river corridor; (ii) identification of the belt of historical river migration, useful for delimiting the erodible river corridor, and (iii) establishing the degree of narrowing of the contemporary river in relation to its historical width, characterizing the river potential for future widening in the erodible corridor.

2. Study area

The gravel-bed Biała River drains the flysch Outer Western Carpathians in southern Poland (Fig. 1). The river is 102 km long and its catchment has an area of 983 km^2. The Biała originates at an elevation of ca. 730 m a.s.l. in the Beskid Niski Mountains and the highest point of its catchment is located at 997 m a.s.l. In its mountain course, the river is supplied with non-cohesive, coarse to medium-sized sandstone material. Here, the river is typified by very high variability of discharges (with the ratio of the highest and the lowest flows recorded at the Grybów water-gauge station amounting to 7500) conditioned by the occurrence of only shallow, slope aquifers in the mountain part of the catchment. The non-cohesive nature of the material supplied to the river and the high flow variability cause that in unmanaged reaches the Biała tends to form a wide, multi-thread channel. In its foothill course, the river runs across alternating sandstone and shale bedrock complexes that deliver both cobble–pebble material and large amounts of fines to its channel.

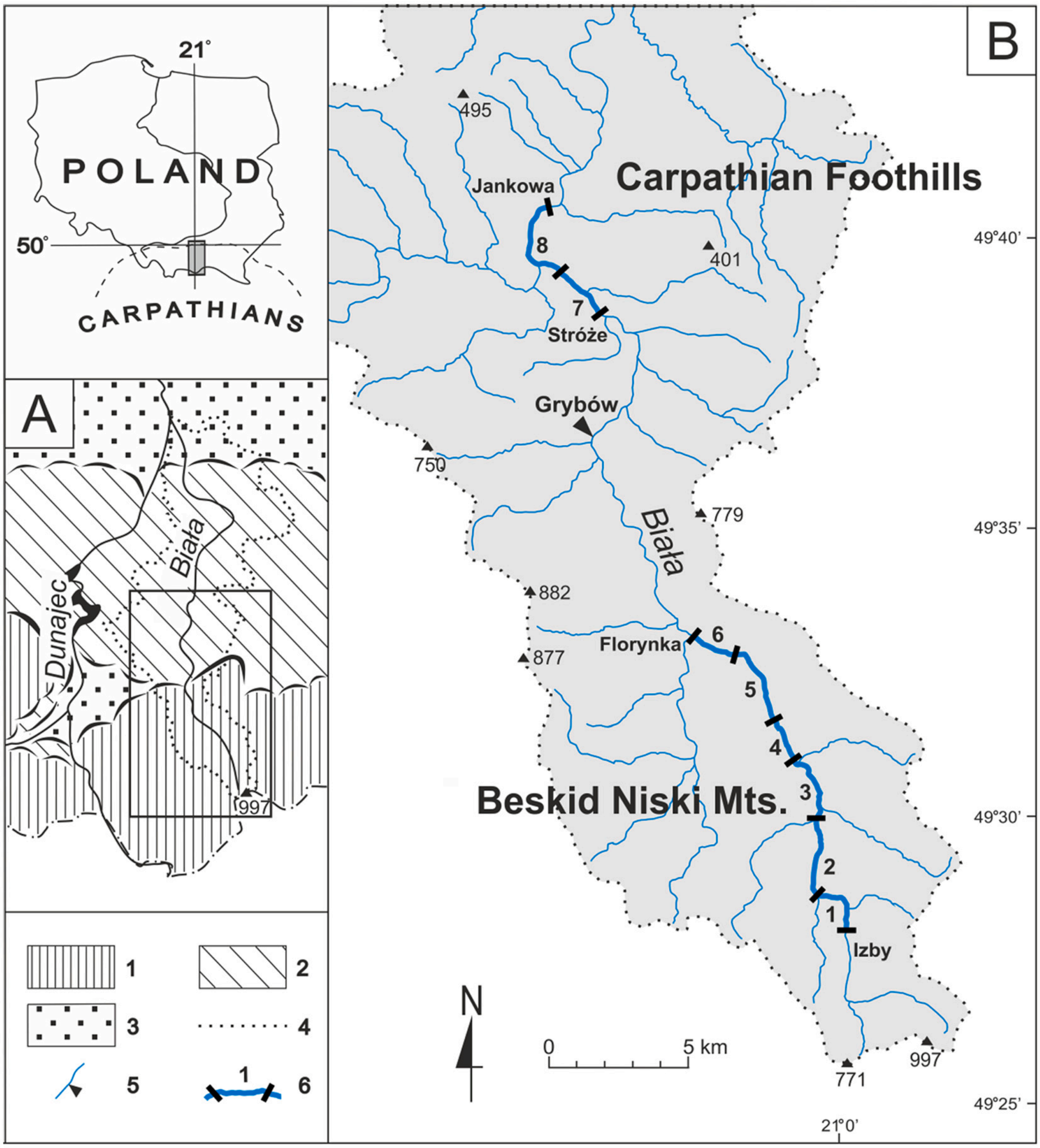

Fig. 1. (A) Location of the Biała River in relation to physiogeographic regions of southern Poland. (B) Drainage network of the upper and middle parts of the Biała catchment and detailed setting of the studied river reaches. Reaches 1–6 are located in the upper section of the planned erodible corridor and reaches 7–8 in the lower section. 1 – mountains of intermediate and low height; 2 – foothills; 3 – intramontane and submontane basins; 4 – boundary of the Biała catchment; 5 – flow-gauging station; 6 – study reaches.

Consequently, in unmanaged reaches the river tends to form a sinuous channel but maintains a gravel bed.

Annual precipitation totals in the catchment range from 650 to 700 mm in its lowermost parts to 950 mm in its highest parts (Niedźwiedź and Obrębska-Starklowa, 1991). The river hydrological regime is typified by the occurrence of frequent, small to moderate floods caused by snowmelt and rare, large floods resulting from prolonged frontal rains during summer.

The study was conducted in two sections of the Biała, which were proposed for establishing an erodible river corridor. The upper section, 14.5 km long, is located in the mountain river course between altitudes of 523 and 378 m. The lower one has the length of 5.9 km and is located in the foothill river course between altitudes of 292 and 272 m (Fig. 1).

3. Materials and methods

Analysis of changes in planform geometry of the Biała River since the 1870s and between particular periods in the twentieth century was performed with use of a topographic map of the Third Military Survey of Austro–Hungary (*Spezialkarte der österreichisch–ungarischen Monarchie*) from 1878 (scale 1:75000), Polish topographic maps from 1935 (scale 1:100000) and 1962 (scale 1:25000), aerial photos taken at 1967, 1977 and 1987 (scale 1:15000–1:25000), and orthophotos from 1998 and 2009 at a scale of 1:10000. The topographic maps were scanned and georeferenced in the PL–1992 coordinate system using control points with the geometric accuracy of orthorectification (RMS error) ranging between 3.5 and 15 m. The pixel size of the Austro-Hungarian map from the 1878 was 6.3 m, while that of the maps from 1935 and 1962 equalled 1.7 m. The aerial photos were transformed to orthophotos with an RMS error of 0.5–0.7 m. The pixel size of the orthophotos generated from the aerial photos from 1967, 1977 and 1987 ranged between 0.5 and 0.75 m and that of the orthophotos from 1998 and 2009 was 0.25 m.

Planform geometry of the river channel was determined for eight river reaches, with six of them located in the mountain section of the planned erodible corridor and two in the foothill section. These reaches were delimited between bridges or river confluences with tributaries because of their fixed position during the whole study period. (Fig. 1.) On the cartographic/photogrammetric materials from each date except 1935 and 1962, boundaries of active river zone and river geomorphic units (low-flow channels, channel bars and islands) were digitized using ArcGIS (Fig. 2). Establishing the extent of active river zone as well as bars and islands on the maps from 1935 and 1962 was not possible—the map from 1935 depicted only the course of low-flow channel, whereas on the map from 1962 it was accompanied by larger bars only. As a result, for these dates only the low-flow channel was digitized and its width was established. River course in each study reach was divided into 100-m-long segments and the width of active river zone (i.e. river width) and the widths of river geomorphic units in each segment were determined. Mean values of these parameters were subsequently calculated separately for eight river reaches. Additionally, channel length in each river reach was also determined for all investigated dates.

The belt of the river migration during the last 130 years in the

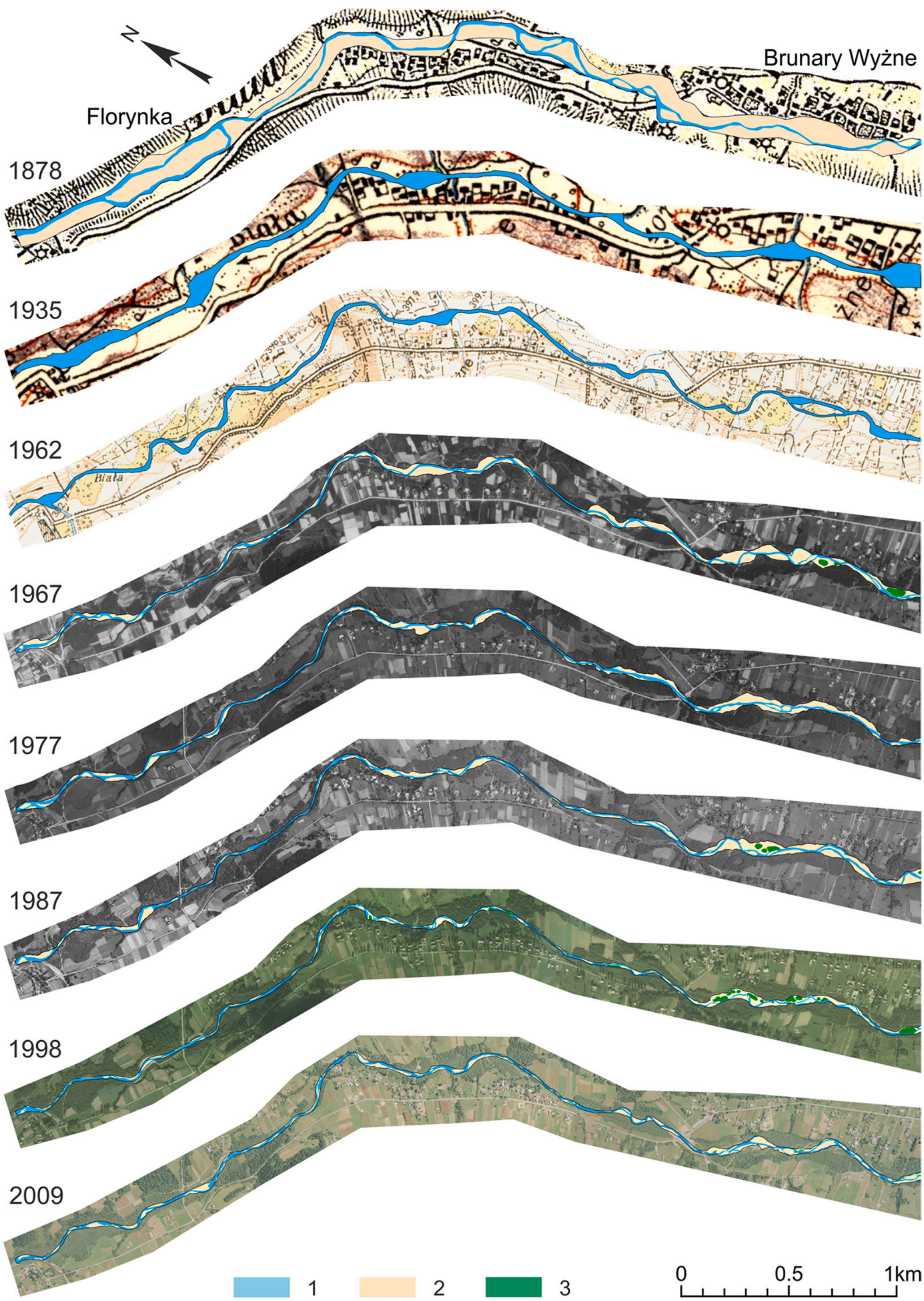

Fig. 2. Low-flow channel (1935, 1962) or active zone (other dates) of the Biała River in the lower part of the mountain section of the planned erodible river corridor digitized on the archival maps and ortophotos from the years: 1878–2009. Elements of active river zone: 1 – low-flow channel; 2 – channel bars; 3 – islands.

reaches of planned erodible river corridor was determined on the basis of overlays of the extent of active river zone at all analysed dates, which indicated extreme positions of the left and right river bank in the period 1878–2009 (Fig. 3). For each river reach, a polygon of the extreme extent was digitized and minimum and maximum widths of the belt of river migration were measured, whereas mean belt width was determined by dividing the area of the polygon by the river length from 2009.

The increase in unit stream power of a river resulting from artificial constriction of its channel determines the river potential for future widening. To assess this potential along the planned erodible corridor of the Biała without the calculation of exact values of unit stream power for long river sections with a considerable downstream increase in catchment area and thus flood discharges, we compared a contemporary width of the river with its largest width recorded over the last 130 years. The degree of the river narrowing in relation to historical river width, N, was established for successive 25-m-long river segments and its values were classified into four categories: $N < 1$ (no narrowing), $1 < N < 2$ (up to twofold narrowing), $2 < N < 4$ (two- to fourfold narrowing), and $N > 4$ (narrowing greater than fourfold).

4. Results

4.1. River planform changes

The analysis of historical changes in planform geometry of the Biała indicated that during the last 130 years the river experienced not only considerable narrowing but also marked changes in the structure of geomorphic units. In the upper section of the planned erodible corridor, mean river width diminished between 1878 and 2009 from 86 m to 27 m, whereas in the lower section the change in mean river width was even more spectacular: from 111 m to 27 m. In the upper section of the erodible corridor, smaller changes in river width in relation to the second half of the 19th century occurred in reaches 1–4, where the river narrowed from 1.75 to 3.5 times. A greater scale of river narrowing, ranging from 5.1 to 6.3 times, was recorded in reaches 5–6, where most of the narrowing occurred before 1967 (Fig. 4, Table 1). In reaches 7–8 from the lower section of the planned erodible corridor, the river narrowed from 3.8 to 4.5 times and the change also took place before 1967 (Fig. 4, Table 1). In the years 1967–2009 changes in the width of all analysed river reaches were relatively small compared to the river narrowing recorded until 1967. After 1967 a progressive decrease in river width took place only in reaches 4 and 7 (Fig. 4, Table 1). In 2009 the largest river width among the analysed reaches typified reach 3 (Fig. 4, Table 1).

The width of the low-flow channel(s) in all study reaches decreased markedly until 1967 (until 1977 in reaches 1–2 with lacking data for 1967) and then remained more or less constant or slightly increased to 2009 (Fig. 5). As a result, in 2009 the low-flow channel width of the Biała ranged from 21% (in reach 8) to 60% (in reach 4) of that from 1878 (Fig. 5). At the end of the study period, the river's low-flow channel was narrowest in reach 1, which reflected the smallest catchment area and river confinement by a valley side in this reach. Throughout the study period the largest low-flow channel width was recorded in reaches 7–8 (Fig. 5) as here the river drains a considerably larger catchment area than in its mountain section. Over the study period the width of the low-flow channel(s) of the Biała decreased less than the river width. As a result, the average proportion of low-flow channel in the total river width increased in the upper section of the planned erodible corridor from 29% (range in reaches 1–6: 17%–57%) in 2009 to 36.9% (range: 24%–57%) in 2009, whereas in the lower section it increased from 67% (range in reaches 7–8: 51%–82%) to 70% (range: 66%–74%) between these dates (Table 1).

The reduction in river width over the study period predominantly reflected a decreased width of channel bars in the river. In the second half of the 19th century, extensive channel bars occurred in the river (Fig. 6). At that time their proportion in the total river width in reaches 1–6 ranged from 43% to 83%, amounting to 71% on average, whereas in reaches 7–8 bars represented 18%–49% of the river width, with the average of 33% (Table 1). Until 1967 the width of channel bars was substantially reduced, particularly in reaches 5 and 6, where it decreased approximately 4 times (Fig. 6). After 1967 relatively minor changes in the width of channel bars occurred in reaches 1–3 from the upper section of the planned erodible corridor and in reach 8 from the lower section, and in 2009 the width of channel bars in these reaches amounted to 33%–75% of that from 1878. However, in reaches 4–6 from the upper section and in reach 7 from the lower section, bar narrowing continued and in 2009 the width of channel bars equalled only 11%–21% of the value from 1878 (Fig. 6). By 2009 the proportion of channel bars in the total river width decreased in the upper section to 58% on average, with the variation between 43% and 62% among reaches 1–6, whereas in the lower section it decreased less—to 30% on average—and ranged from 26% to 34% in reaches 7–8 (Table 1).

In the second half of the 19th century islands did not occur in the river. Between 1878 and the second half of the 20th century islands developed especially in reaches 2–4, where their largest proportion was recorded in 1977 and 1998 (Fig. 7, Table 1). In 1977 islands occupied 13% of the active river zone in reach 2 and 24% in reach 3, whereas in 1998 their maximum proportion—20%—was recorded in reach 4 (Table 1). In reaches 5–8, islands were occasionally recorded only in 1998 (Fig. 7, Table 1).

The length of the Biała channel increased between 1878 and 2009 in all study reaches, but the scale of the increase was very small, ranging from 1.1% to 6.2% in individual reaches (Table 2). Initially, in some reaches slight channel shortening took place until 1935 (or 1962 in

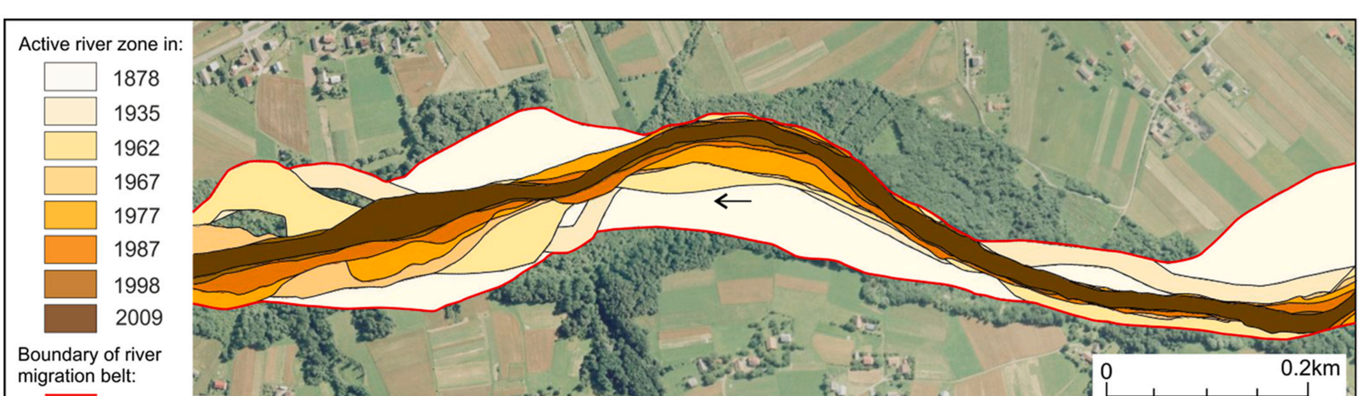

Fig. 3. Extent of the active zone of the Biała River digitized on the archival maps and orthophotos from the period 1878–2009 and the belt of river migration in this period shown for a fragment of the mountain section of the planned erodible corridor.

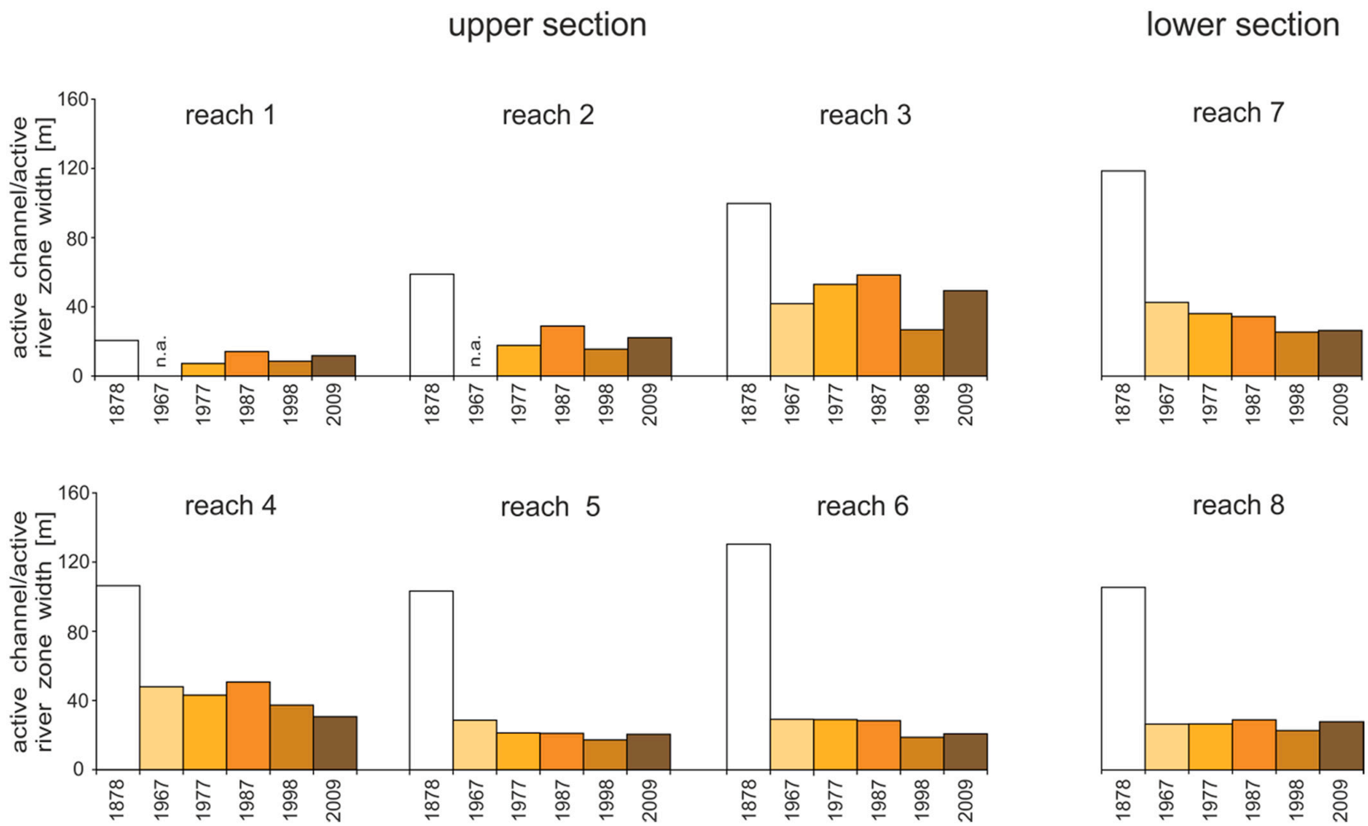

Fig. 4. Changes in mean width of the active channel/active river zone of the Biała River in reaches 1–6 of the upper section of the planned erodible river corridor and reaches 7–8 of the lower section between 1878 and 2009. n.a. – not available.

Table 1
Changes in width of the Biała River and in proportions of particular elements of its active channel/active river zone in reaches 1–6 of the upper section of the planned erodible river corridor and reaches 7–8 of the lower section between 1878 and 2009.

Year	Morphometric parameter	Upper section						Lower section	
		Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Reach 6	Reach 7	Reach 8
1878	River width (m)	20.6	59.1	99.9	106.3	103.1	130.3	118.7	105.5
	Relative width of low-flow channel (%)	56.8%	31.3%	29.2%	16.8%	29.0%	31.6%	50.7%	81.7%
	Relative width of channel bars (%)	43.2%	68.7%	70.8%	83.2%	71.0%	68.4%	49.3%	18.3%
	Relative width of islands (%)	0%	0%	0%	0%	0%	0%	0%	0%
1967	River width (m)	–	–	41.9	47.9	28.7	29.0	42.5	26.3
	Relative width of low-flow channel (%)	–	–	21.7%	19.6%	31.8%	35.6%	42.1%	48.5%
	Relative width of channel bars (%)	–	–	72.5%	72.9%	68.2%	64.4%	57.9%	51.5%
	Relative width of islands (%)	–	–	5.8%	7.5%	0%	0%	0%	0%
1977	River width (m)	7.3	17.7	52.9	43.0	24.0	28.8	40.4	26.2
	Relative width of low-flow channel (%)	99.6%	30.0%	19.3%	21.3%	36.5%	38.1%	49.0%	62.7%
	Relative width of channel bars (%)	0.4%	56.7%	56.5%	78.7%	63.5%	61.9%	51.0%	37.3%
	Relative width of islands (%)	0%	13.3%	24.2%	0%	0%	0%	0%	0%
1987	River width (m)	14.3	29.1	58.3	50.8	20.9	28.2	34.6	28.6
	Relative width of low-flow channel (%)	32.2%	24.0%	16.0%	18.9%	37.3%	41.4%	63.3%	73.8%
	Relative width of channel bars (%)	62.2%	74.0%	79.4%	77.4%	62.7%	58.6%	36.7%	26.2%
	Relative width of islands (%)	5.6%	2.0%	4.6%	3.7%	0%	0%	0%	0%
1998	River width (m)	8.6	15.6	27.1	37.2	17.1	18.5	25.5	22.4
	Relative width of low-flow channel (%)	73.8%	39.6%	30.8%	25.2%	56.5%	60.1%	72.1%	81.2%
	Relative width of channel bars (%)	26.2%	55.6%	61.0%	54.9%	41.4%	39.9%	27.7%	18.4%
	Relative width of islands (%)	0%	4.8%	8.2%	19.9%	2.1%	0%	0.2%	0.4%
2009	River width (m)	11.7	22.3	49.4	30.5	20.3	20.7	26.4	27.6
	Relative width of low-flow channel (%)	42.8%	37.8%	24.3%	35.7%	52.0%	57.3%	73.7%	66.3%
	Relative width of channel bars (%)	57.2%	60.9%	62.0%	61.7%	48.0%	42.7%	26.3%	33.7%
	Relative width of islands (%)	0%	1.3%	13.7%	2.6%	0%	0%	0%	0%

reach 1), but subsequently channel length increased by a few per cent, attaining maximum values at different dates between 1962 and 1998 in particular reaches (Table 2). Between 1998 and 2009 some channel shortening occurred in four reaches from the upper section of the planned erodible corridor and the shortening was most pronounced in reach 1 (Table 2).

4.2. Belt of historical river migration

In the upper section of the planned erodible river corridor, the belt of

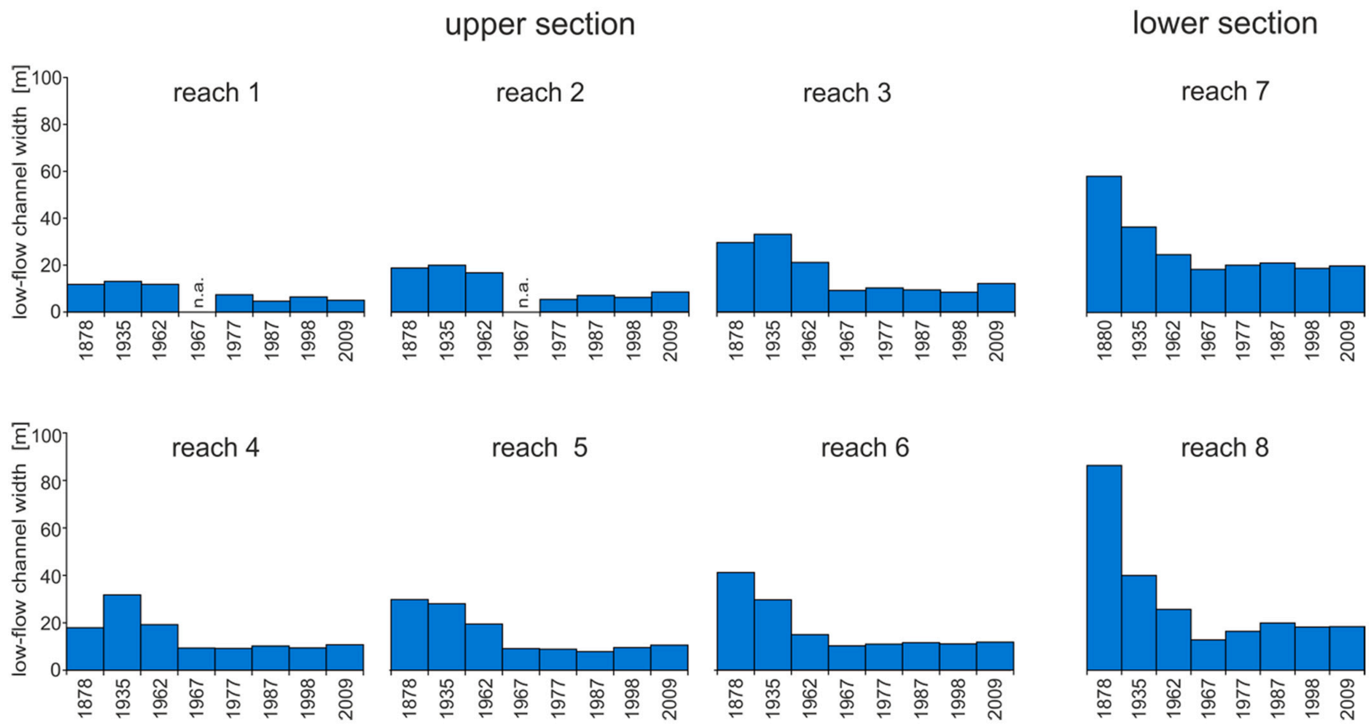

Fig. 5. Changes in mean width of the low-flow channel(s) of the Biała River in reaches 1–6 of the upper section of the planned erodible river corridor and reaches 7–8 of the lower section between 1878 and 2009. n.a. – not available.

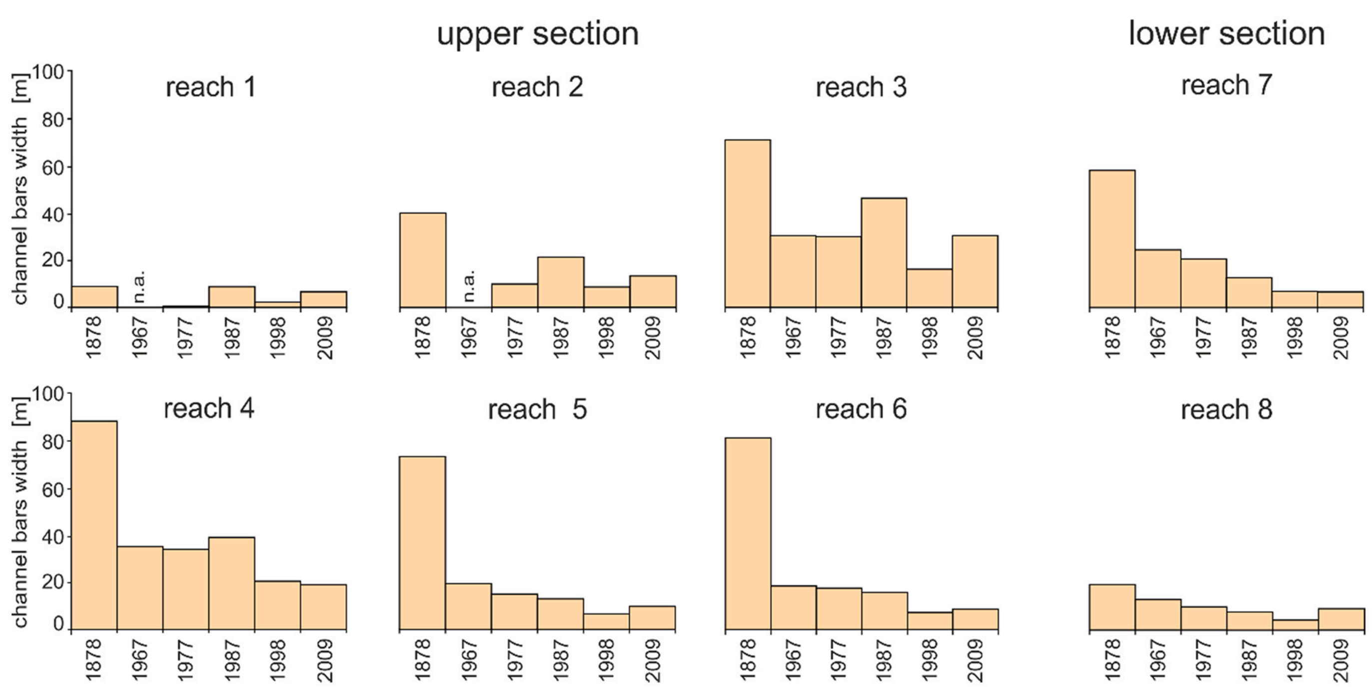

Fig. 6. Changes in mean width of channel bars of the Biała River in reaches 1–6 of the upper section of the planned erodible river corridor and reaches 7–8 of the lower section between 1878 and 2009. n.a. – not available.

the river migration in the years 1878–2009 had a mean width of 132 m, varying between 32 and 261 m (Fig. 8). On average, it was 4.9 times wider than the mean width of the contemporary river (26.9 m). In the upper part of the section, mean width of the river migration belt progressively increased from 75 m in reach 1 to 163 m in reach 3, but with the higher rate of the increase in mean width of the contemporary river from 12 m to 49 m between these reaches, the ratio of belt width to contemporary river width decreased downstream from 6.4 in reach 1 to 3.3 in reach 3 (Fig. 8). In the lower part of the section, mean width of the river migration belt in individual study reaches varied between 135 m and 164 m, but the reduction in mean width of the contemporary river to 21 m in reach 6 caused that the ratio of the belt width to contemporary river width progressively increased downstream, attaining 7.1 in this reach (Fig. 8).

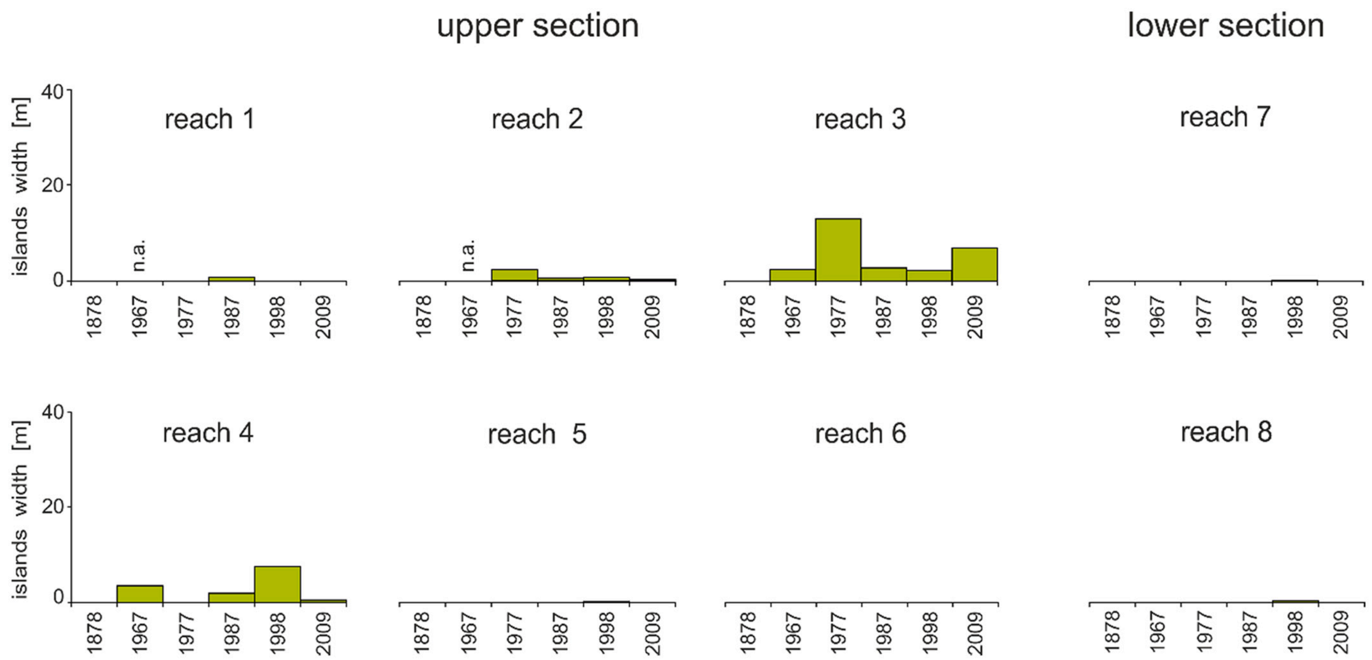

Fig. 7. Changes in mean width of islands of the Biała River in reaches 1–6 of the upper section of the planned erodible river corridor and reaches 7–8 of the lower section between 1878 and 2009. n.a. – not available.

Table 2
Length of the Biała channel presented on the map from 1878 and the percentage change of channel length between 1878 and the dates of successive analysed cartographic and photogrammetric materials shown for reaches 1–6 of the upper section of the planned erodible river corridor and reaches 7–8 of the lower section.

Reach number	Length in 1978 [km]	Percentage change of reach length until the year						
		1935	1962	1967	1977	1987	1998	2009
Upper section								
1	1.56	0%	−1.3%	–	–	3.2%	9.7%	1.3%
2	3.09	−2.9%	−0.7%	–	4.6%	1.3%	7.8%	4.6%
3	2.75	0.7%	5.9%	6,6%	10.3%	6.6%	6.6%	2.6%
4	1.86	−1.6%	5,4%	3,3%	3.3%	3.2%	3.3%	3.3%
5	3.57	0.8%	5,1%	2.0%	2.0%	2.0%	4.8%	4.8%
6	1.15	0%	7.9%	6.1%	7.0%	3.5%	6.1%	3.5%
1–6	13.98	−0.5%	3.5%	–	–	3.2%	6.3%	3.6%
Lower section								
7	2.55	2.1%	4.5%	2.7%	2.7%	6.2%	6.2%	6.2%
8	3.16	−3.3%	3.3%	0.8%	1.1%	−1.4%	−0.3%	1.1%
7–8	5.71	−0.9%	3.8%	1.7%	1.8%	2.0%	2.6%	3.4%

In the lower section of the erodible corridor, the river migration belt was 142 m wide on average (with downstream width variation between 68 m and 224 m), exceeding mean river width (27.1 m) 5.3 times (Fig. 8). This reflected very similar widths of the river migration belt (142 m and 141 m) and the contemporary river (26 m and 28 m) in reaches 7 and 8 (Fig. 8).

The smallest width of the river migration belt in individual reaches typically occurred in the vicinity of bridges, the location of which remained similar over the study period. The largest width exceeded the width of the contemporary river from 5.3 (in reach 3) to 13.5 times (in reach 1); in five reaches, it exceeded 200 m (Fig. 8).

4.3. Degree of the river narrowing

A comparison of the width of the Biała from 2009 with its largest width in the period 1878–2009 indicated a considerable narrowing of the contemporary river. In the upper section of the planned erodible corridor, only 10.3% of channel segments of the contemporary river were wider than previously, whereas the river narrowed up to two-fold in 31.4% of segments, between two- and four-fold in 38.9% of segments and more than four-fold in 19.4% of segments (Fig. 9). In the lower section, the contemporary river was wider than its historical counterpart only in 3.9% of channel segments, while it was up to twice narrower in 30.9% of segments, between two and four times narrower in 44.2% of segments and more than four times narrower in 21% of segments (Fig. 9). Therefore, currently almost all channel segments along the planned erodible corridor are narrower than they were a century or a few decades ago, with the modal proportion of the segments being from two to four times narrower.

5. Discussion

5.1. Changes in planform geometry of the Biała as an evidence of hydromorphological river degradation

In the second half of the 19th century the Biała flowed in a wide, multi-thread or sinuous channel with a large proportion of channel bars. During that time the occurrence of a wide channel with multi-thread

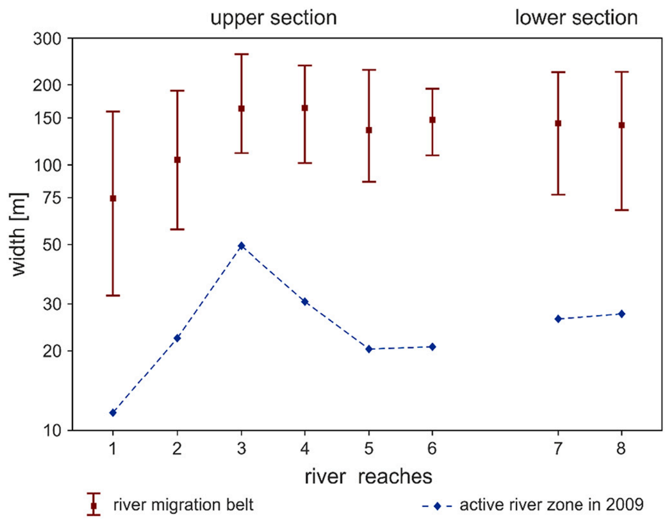

Fig. 8. Width of the belt of migration of the Biała River in the years 1878–2009 and mean width of the active river zone in 2009 shown for 8 study reaches from the sections of planned erodible corridor. Whiskers indicate the maximum and minimum widths of the river migration belt and squares show its mean width. A logarithmic scale is used for the vertical axis of the diagram.

morphology was typical of the majority of mountain and piedmont rivers in Europe (Petts et al., 1989; Gurnell et al., 2009; Rinaldi et al., 2013), including rivers of the Polish Carpathians (Wyżga, 1993; Wyżga et al., 2016b; Witkowski, 2021; Hajdukiewicz and Wyżga, 2022). Such channel geometry reflected rapid water run-off and intense delivery of sediment from largely deforested hillslopes (Kondolf et al., 2002; Wyżga et al., 2012; Rinaldi et al., 2013). Rapidly migrating channels turned over the river bed faster than trees and shrubs colonizing channel bars were able to reach a mature, scour-resistant state (cf. Hicks et al., 2008), hence preventing island development in the river (Wyżga et al., 2016b; Hajdukiewicz and Wyżga, 2022).

Between 1878 and 2009 the width of the Biała decreased three-fold, on average, in the upper study section and four-fold in the lower section, and most of the narrowing took place before 1967. Channelization of the river was the principal reason for its narrowing. In the lower study section (reaches 7–8) and in the lower part of the upper section (reaches 5–6), the river was channelized in the first decades of the 20th century (Szuba, 2012), and subsequently its bed has degraded by up to 2.5 m with the resultant channel incision into flysch bedrock (Wyżga et al., 2013), which must have considerably increased lateral stability of the narrow channel. In reaches 1–4 from the upper study section, channelization works were more scattered along the river and less concentrated in time over the 20th century, whereas their main phase took place in the 1950s–1960s. Bed degradation following channelization works in these reaches was lower, between 0.5 and 1 m (Wyżga et al., 2013), but at some locations the river dissected the whole thickness of gravelly alluvium and exposed flysch bedrock on the channel bed.

Depopulation of the mountain part of the catchment in the mid-20th century resulted in a considerable increase in forest cover of the area during the second half of the 20th century (Kozak et al., 2007), which must have reduced catchment sediment supply to the river (cf. Lach and Wyżga, 2002). The resultant deficit of the sediment available for fluvial transport was exacerbated by in-channel gravel mining, and at some locations, particularly in reach 1, gravel mining was so intense that it appeared a principal reason for the sediment deficit in the river, resulting in rapid channel incision (Wyżga et al., 2010) and river shortening recorded between 1998 and 2009 (Table 2).

With free channel development, rivers respond to a reduction in sediment load by changing a bar-braided morphology to an island-braided morphology (e.g. Wyżga et al., 2012; Hajdukiewicz and Wyżga, 2022) or by replacing a wide and straight channel with a narrow and sinuous one (Schumm, 1969; Wyżga et al., 2016c), as both these changes increase channel resistance to flow and thus adjust river's transport capacity to the reduced sediment load. If such changes occurred in the Biała, they would simply constitute a change in hydromorphological conditions without their degradation. During the 20th century, islands started to develop in the upper study section (cf. also Hajdukiewicz and Wyżga, 2022) but subsequently channelization works caused their elimination from most river reaches, and currently a significant proportion of islands is found only in reach 3 with the largest river width (Fig. 7, Table 1). Channel length in both study reaches increased between 1878 and 2009 only by about 3% on average (Table 2) and the resultant reduction of channel gradient had a negligible effect on unit stream power of flood flows, particularly in comparison to that resulting from the substantial channel narrowing. With the lack or insufficiency of compensating mechanisms, concentration of flood flows in the narrow, regulated channel coupled with the reduced availability of sediment for fluvial transport leads to channel incision (Wyżga, 2001; Wyżga et al., 2016c) and, indeed, such a channel adjustment took place in the Biała during the 20th century.

The substantial narrowing of the river over the study period was associated with a reduction in the proportion of channel bars in the total river width. A reduced occurrence of channel bars in a river is a typical

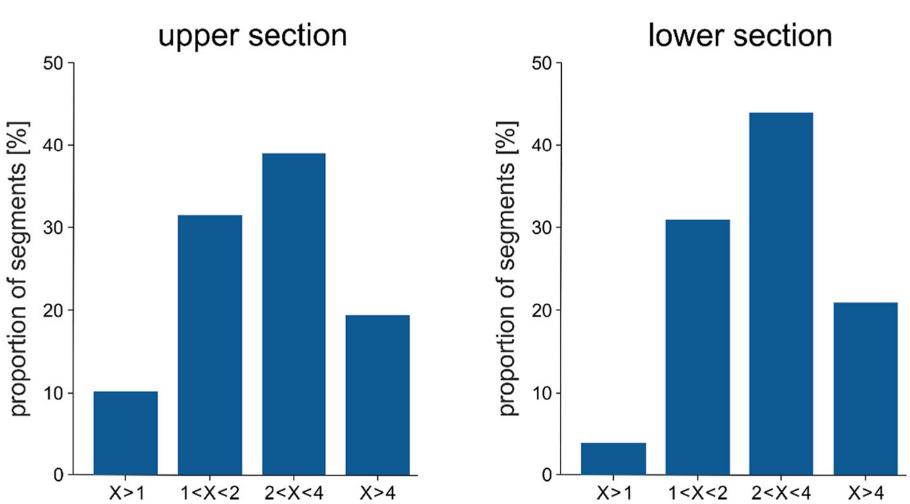

Fig. 9. Proportion of the 25-m-long segments of the Biała River from the upper and lower sections of the planned erodible river corridor with different degrees of change of the contemporary river width in comparison with the largest river width in a given segment from the years 1878–2009.

consequence of channel regulation (e.g. Hajdukiewicz and Wyżga, 2019, 2022) which tends to reclaim from the river its lateral, emergent parts, while leaving the areas permanently covered with water in low-flow channels. However, such a change degrades hydromorphological conditions as it eliminates exposed riverine sediments which provide habitats for riparian animals such as ground beetles (Sadler and Bates, 2007) and flow refugia for aquatic biota during floods (Brunke and Gonser, 1997), and reduces the availability of shallow-depth, slow-velocity zones in low-flow channels, which are used as nursery areas by juvenile fish (Sukhodolov et al., 2009).

The analysis of historical changes in planform geometry of the Biała provided direct information about the alterations of a small number of hydromorphological river attributes. However, the assessment of contemporary hydromorphological quality of this river in 10 pairs of neighbouring channelized and unmanaged cross-sections identified hydromorphological features which were particularly degraded as a result of river channelization and the resultant channel incision. In the channelized cross-sections, channel geometry, the presence of erosional and depositional channel forms, bank structure, and channel mobility and lateral connectivity of the river with its floodplain were evaluated 2.5 classes worse, and vegetation/land use in the riparian zone nearly 2 classes worse (on a 5-class scale) than in the unmanaged cross-sections (Hajdukiewicz et al., 2017). Channelization alters not only planform river geometry but also cross-sectional one, reducing the heterogeneity of habitats of aquatic biota, with detrimental effects on fish and benthic invertebrate communities (e.g. Wyżga et al., 2009, 2011). A reduced abundance of erosional and depositional channel forms resulting from the simplification of flow pattern in a river decreases the availability of specific habitats, such as deep pools used by fish for overwintering, as low-flow refugia and resting places (Sukhodolov et al., 2009). Riverbank protection works simplify bank geometry, removing fish habitats such as shoals and bank niches (Florsheim et al., 2008; Hajdukiewicz and Wyżga, 2019), whereas habitats of the terrestrial invertebrates (e.g. ground beetles) and vertebrates (bank swallow, common otter, beaver) residing in burrows formed in alluvial banks (Mikuś, 2020) are eliminated as a result of lining of river banks with gabions or riprap. A shifting mosaic of aquatic and terrestrial habitats in river corridors (Stanford et al., 2005) is sustained by free channel migration (Rinaldi et al., 2013), whereas stabilization of river banks with engineering structures leads to the loss of this mosaic and the progressive maturation of forest communities along river banks (Škarpich et al., 2016). Restricting channel mobility prevents the delivery of sediments and large wood to the river from eroded channel banks (Florsheim et al., 2008). Lateral hydrological connectivity is crucial in a river ecosystem for the periodic exchange of nutrients and organisms between the river and its floodplain (Thoms, 2003; Kondolf et al., 2006), but such connectivity is reduced or disrupted as a result of river channelization and the resultant channel incision (Hohensinner et al., 2004; Wyżga et al., 2016c; Kidová et al., 2021). Finally, bulldozing riparian areas in the course of channel regulation results in the formation of gravelly surfaces along river margins, which long remain unvegetated or overgrown with ruderal vegetation (Hajdukiewicz and Wyżga, 2019).

The above discussion indicated that the channelization of the Biała, the effects of which on planform river geometry were documented in this study, must have resulted in thorough degradation of the hydromorphological river quality. As the main degrading agent was related to restricting channel mobility and constricting the river in a narrow, regulated channel, re-establishment of the river's ability to form its channel freely within an erodible river corridor can be viewed as a proper restoration measure.

5.2. The belt of historical river migration as a criterion of delimiting the erodible river corridor

The extent of the belt of historical river migration on the valley floor—apart from extent of the river floodplain and the location of buildings and infrastructure requiring protection from erosion—was an important criterion of delimiting an erodible corridor in two sections of the Biała (Wyżga et al., 2021). In this study focused on the utility of data about past river activity, we analysed the belt of river migration during the last 130 years, for which cartographic and photogrammetric materials provide reliable data about river location.

A rapid increase in the width of the river migration belt from reach 1 to reach 3 reflected not only a downstream increase in river discharges but also a change from river confinement by a valley side in reaches 1 and 2 to mostly unconfined river development in reach 3 (Hajdukiewicz et al., 2016). In reaches 3 and 4, the unconfined river development coupled with a relatively scarce occurrence of bank reinforcements resulted in the largest width of both the river migration belt and the active zone of the contemporary river. Although the valley floor in reaches 5–6 from the lower part of the mountain section is wider than in reaches 3–4, these reaches were typified by somewhat smaller average and maximum widths of the river migration belt. The river in these reaches was channelized already in the first decades of the 20th century (Szuba, 2012), which must have limited river migration on the valley floor since that time. In turn, considerable narrowing of the river caused by its channelization and subsequent deep channel incision (Wyżga et al., 2013) was reflected in a substantially greater ratio of the migration belt width to contemporary river width. In the first decades of the 20th century, the Biała was also channelized in the lower investigated section (Szuba, 2012), although a tendency of the river to meander in its foothill course facilitated destruction of bank reinforcements and subsequent river migration on the valley floor until a renewed channel regulation. Nevertheless, as a result of channel regulation and subsequent river incision, the width of the river migration belt in reaches 7–8 does not exceed that typifying reaches 3 and 4 despite substantially greater river discharges in the foothill course of the river.

In both investigated river sections, the belt of the river migration during the last 130 years was considerably wider than the contemporary river (Fig. 8). This allowed for delimiting an erodible river corridor on a substantially larger area of the valley floor than the area of the river from 2009. The upper section of the erodible corridor delimited on the basis of the three criteria had an extent similar to that of the belt of historical river migration (except the vicinity of bridges disrupting continuity of unmanaged reaches along the corridor), with mean width of 112 m, ~4.1 times larger than the width of the contemporary river. The lower section of the erodible river corridor was wider than the belt of the river migration during the last 130 years and its boundaries were predominantly delimited on the basis of the extent of the river floodplain (Wyżga et al., 2021). This apparently reflected a slower rate of floodplain reworking by the migrating river in its foothill reach than in the mountain reach. The lower section of the erodible corridor had mean width of 194 m, 7.4 times larger than the mean river width.

5.3. Degree of the river narrowing as an indicator of future bank retreat in the erodible corridor

The intensity of future bank retreat along an erodible river corridor may reflect a few factors: (i) erodibility of bank materials; (ii) the angle of flow with respect to river bank; (iii) degree of channel incision modifying the height of river banks and thus the amount of material that has to be removed from retreating banks; and (iv) increase in unit stream power of flood flows resulting from channel narrowing in the past (Wyżga et al., 2021). Analysis of cartographic and photogrammetric materials from the historical period provided data about the last factor only, but these data seem easiest to generalize for long river stretches.

The analysis of changes in the width of the Biała during the last 130 years indicated that the contemporary river is narrower than its historical counterpart along nearly the whole length of the investigated sections, more than twice narrower along three-fifths of the upper section of the erodible corridor and two-thirds of the lower section, and more than four times narrower along one-fifths of both river sections.

These values indicate that the concentration of flood flows in the narrow channel increasing their stream power is a factor that must have considerably increased the river potential for future bank erosion and channel widening in the erodible corridor. Indeed, the passage of an 80-year flood in June 2010 caused that the Biała channel widened by half in unmanaged cross-sections and by one-third in channelized cross-sections, with the difference reflecting lower erodibility of artificially reinforced river banks in channelized reaches (Hajdukiewicz et al., 2016).

6. Conclusions

This study has analysed changes in planform geometry of the Biała River in the Polish Carpathians during the last 130 years to diagnose its hydromorphological degradation, to delimit an erodible river corridor and to predict the river potential for future widening in the corridor. As a result of channelization works which started in the first decades of the 20th century, the river width was reduced 1.75–3.5 times in the mountain study section and 3.8–4.5 times in the foothill section. The proportion of channel bars in the total river width decreased in favour of low-flow channel(s), whereas islands which started to form in the river in the 20th century were eliminated with continued channelization works. The river incised by up to 2.5 m in response to the increase in its transport capacity resulting from channelization and the reduction in sediment supply to its channel caused by land use changes in the catchment. All these channel changes have led to the degradation of hydromorphological river integrity. As these changes negatively affected riverine communities and the ecological river state (Wyżga et al., 2013) and increased flood hazard in the river valley (Hajdukiewicz et al., 2016), their documentation was an important argument for establishing an erodible river corridor intended to enable a river recovery in the study reaches.

Overlays of the river position on successive cartographic and photogrammetric materials indicated the belt of the river migration during the last 130 years. It was ~5 times wider than the contemporary river and its extent was applied as one of the criteria used for delimiting the erodible corridor of the Biała. Moreover, the analysis of changes in planform river geometry enabled us to determine the degree of narrowing of the contemporary river in relation to the pre-channelization river width in successive segments of the study reaches. The analysis demonstrated that the historical river width exceeded the contemporary river width along nearly the whole length of the study reaches, with the river being more than twice wider along 2/3–3/4 of their length. As the degree of river narrowing can be considered a proxy for the increase in unit stream power of flood flows in relation to its undisturbed levels, it indicates the intensity of a future tendency towards bank retreat and river widening in given channel segments.

Glossary

Erodible river corridor – A part of valley floor, in which free channel migration and development is allowed.

Hydromorphology – Physical habitat conditions for riverine biota determined by the hydrological regime and morphological pattern of the watercourse.

Active river zone – Currently active area of the river, encompassing low-flow channels, channel bars and islands.

River migration belt – A part of valley floor, in which river tended to recurrently migrate in a defined period of the past.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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