



Twentieth-century development of floodplain forests in Polish Carpathian valleys: The by-product of transformation of river channels?



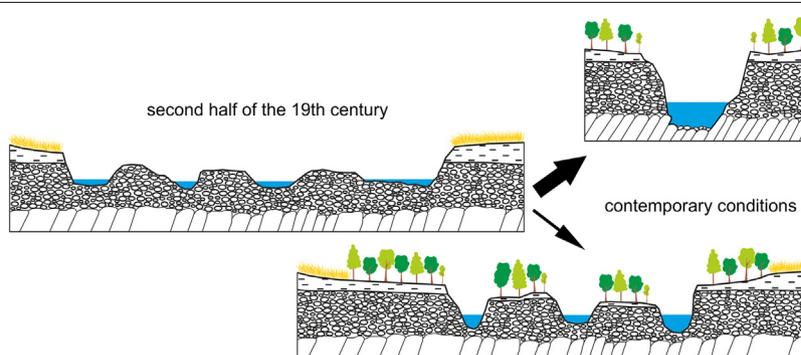
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HIGHLIGHTS

- We examined changes in the extent of floodplain forest and their relation to channel changes of Polish Carpathian rivers.
- Corridors of four rivers presented on historical maps and aerial photos from the last 130 years were analysed.
- Forest developed on lateral parts of the former, wide channels narrowed in the course of river channelization.
- In the 20th century islands developed in unmanaged river reaches and were eliminated from channelized reaches.
- Floodplain forests exert a beneficial influence on the river ecosystems but are also a source of flood hazard.

GRAPHICAL ABSTRACT



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ABSTRACT

Changes in forest extent in the corridors of four rivers of the Polish Carpathians over the last 130 years and their relation to changes in planform river geometry were investigated through the analysis of 1:25000-scale maps from the 1870s and aerial images from the mid-20th century and 2009. Average proportions of river and its geomorphic units as well as floodplain and its land cover features in the total width/area of the analysed river corridors were determined and compared between the three dates. All the analysed rivers narrowed significantly over the study period. This increased considerably the proportion of floodplains in the area of the river corridors, while lateral parts of the former, wide channels became a place of forest development. In the Koszarawa and Raba valleys, forest developed also on parts of the former floodplains following a decline in agricultural and pastoral use of lands with shallow, poor soils. The proportion of forest in the total area of the river corridors increased from 0–7.5% in the 1870s to 28.5–46.5% in 2009, and the forest expansion was mainly driven by the timing and scale of channelization works that reclaimed parts of the former channels from the rivers. A reduction in flow and sediment dynamics of Carpathian rivers over the 20th century enabled development of islands in their active zones. However, channelization works eliminated islands from most river reaches and thus islands persisted only in scarce unmanaged reaches. The expansion of floodplain forests in Carpathian valleys improves functioning of the river ecosystems but the resultant increased delivery of large wood to river channels may generate flood hazard. Optimal river management should avoid removal of riparian trees to maximize the environmental benefits but enable undisturbed transfer of driftwood through bridge cross-sections to minimize the flood hazard resulting from floodplain forest development.

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1. Introduction

Valley floors of major rivers of the Polish Carpathians are typified by moderately cool or moderately warm climate (Mirek, 2013). Under natural conditions of the Holocene, they were overgrown with forest (Ralska-Jasiewiczowa, 1972; Obidowicz et al., 2013). Major rivers draining the Polish part of the Western Carpathians formed then island-braided channels in their mountain reaches and single-thread channels in foothill reaches (Wyżga et al., 2016b). In the 19th century riparian areas of major mountain rivers in Europe were typified by an open landscape or were overgrown with pioneer vegetation communities (Kondolf et al., 2002; Comiti, 2012; Rinaldi et al., 2013) and the lack or only scarce occurrence of riparian forest was also characteristic of major valleys of the Polish Carpathians (Baumgart-Kotarba, 1980; Wyżga et al., 2012, 2016b). At that time, multi-thread river morphology was common in European mountain areas (Gurnell et al., 2009; Rinaldi et al., 2013), including the Polish Carpathians (Wyżga, 1993; Wyżga et al., 2012, 2016b; Hajdukiewicz et al., 2019). In the 20th century, especially in its second half, the proportion of forest in the riparian areas increased considerably, both in the Polish Carpathians (Wyżga, 2007; Wyżga et al., 2012; Hajdukiewicz and Wyżga, 2019) and other European mountain regions (Kondolf et al., 2002, 2007; Liébault and Piégay, 2002; Rinaldi et al., 2013). The 20th century also saw a widespread simplification of channel pattern and a reduction in width of European mountain rivers (Liébault and Piégay, 2002; Comiti, 2012; Rinaldi et al., 2013; Hajdukiewicz et al., 2019) that led to a remarkable decline in the occurrence of multi-thread morphology of these rivers (Gurnell et al., 2009; Wyżga et al., 2016b). However, particular mountain regions in Europe or individual rivers in these regions differed in the causes of the channel adjustments (Gurnell et al., 2009; Rinaldi et al., 2013), which might have encompassed a decrease in sediment fluxes following catchment reforestation (Kondolf et al., 2002; Liébault and Piégay, 2002), river impoundment by a dam reservoir (Petts and Gurnell, 2005), in-channel gravel mining (Rinaldi et al., 2005) or river channelization (Zawiejska and Wyżga, 2010).

Multi-thread rivers are typified by significant lateral channel mobility and its reduction might have stimulated forest development in the riparian areas. Such a reduction in lateral channel mobility may result from artificial bank reinforcement in the course of river channelization. The development of woody vegetation on river banks also increases their resistance to erosion (Hubble et al., 2010), diminishing the intensity of lateral channel migration also in unmanaged river reaches (Gran and Paola, 2001; Ielpi and Lapôtre, 2020), which facilitates further expansion of riparian forest in these reaches. In the 20th century, channel adjustments encompassing channel narrowing and a reduction in river braiding affected riparian vegetation dynamics in numerous river valleys (Aucelli et al., 2011; Cadol et al., 2011; Kui et al., 2017; Janssen et al., 2020). Abandonment of the agricultural and pastoral use of floodplain areas with poor soils was another factor that must have stimulated forest expansion in river valleys during the 20th century (Kolecka et al., 2017). According to the forest transition theory, gradual economic and demographic changes lead to agricultural specialization and reforestation of marginal lands (Meyfroidt and Lambin, 2011; Rudel et al., 2019). A considerable increase in forest cover that occurred in the Polish Carpathians over the 20th century (Kozak et al., 2007) largely reflected the operation of this factor (Munteanu et al., 2014); however, different factors might have influenced the timing and intensity of forest encroachment on hillslopes and valley floors. The conditions, distribution and dynamics of large-scale changes in forest cover in the Polish Carpathians are already well recognized (Kozak et al., 2007; Munteanu et al., 2014) but detailed causes and precise timing of forest development on the valley floors in the region have not been identified so far.

River islands are discrete areas of vegetation within rivers, surrounded by either low-flow channels or exposed sediment surfaces. In mountain rivers, they originate as a result of the encroachment and development of woody vegetation on bars separating interconnected

low-flow channels (Rinaldi et al., 2013). Common in mountain braided rivers under natural conditions in the Holocene (Gurnell and Petts, 2002), islands are now scarce in the rivers of European mountains, including the Polish Carpathians. Scarcity of islands in contemporary rivers limits opportunities for observation and understanding of the processes responsible for their disappearance and those leading to their development. Engineering works resulting in the transformation of natural, multi-thread channels into single-thread ones have been the obvious reason for the elimination of islands from many mountain rivers, and nowadays islands are mostly reported from the rivers that have avoided major disturbances from human activity (Tockner et al., 2003). However, islands were also scarce in unmanaged, bar-braided rivers of the 19th century, which were intensely supplied with sediment from largely deforested hillslopes. In contrast, they increasingly developed over the 20th century following a reduction in agricultural and pastoral activities in mountain catchments (Kondolf et al., 2002; Wyżga et al., 2012, 2016b). Results of flume experiments (Gran and Paola, 2001; Bertoldi et al., 2015; Mao et al., 2020) and field observations (Gurnell and Petts, 2006) indicated that initial establishment of vegetation on river banks and channel bars induces feedbacks that promote island development and may lead to a change in the style and intensity of river braiding.

The presence of floodplain forest and islands in a river valley significantly influences the course of physical and biological processes in the rivers and their floodplain areas. Forest communities on river banks increase the biodiversity of not only riparian ecosystem (Naiman and Decamps, 1997) but also aquatic and terrestrial ecosystems within the active zone of rivers (Gurnell et al., 2005). High environmental values of the river corridors with forest communities developed along river banks and within mountain rivers are highlighted by establishment of several Natura 2000 areas in forested river valleys (Perzanowska and Grzegorzczak, 2009) which still 100 years ago were devoid of forest (Kondolf et al., 2007). However, the development of floodplain forest might have been also a source of flood hazard caused by trees and shrubs fallen to river channels, that can be displaced by floodwaters and accumulate at vulnerable sites (Ruiz-Villanueva et al., 2014, 2017). Identification of a region-specific trajectory of forest development on the valley floors of Polish Carpathian rivers is thus important for improved management and/or restoration of the rivers, which should simultaneously fulfill the requirements of amelioration of ecological river state, indicated in the Water Framework Directive (European Commission, 2000), and of reducing flood hazard, indicated in the Floods Directive (European Commission, 2007) of the European Union.

Based on the analysis of four rivers draining the Polish Carpathians, this study aims to: (i) present changes in planform geometry of the rivers since the 1870s; (ii) determine the course and causes of the 20th-century expansion of floodplain forest in the valleys of Polish Carpathian rivers; (iii) explain a dichotomous fate of islands in the rivers during the 20th century; and (iv) discuss the effects of floodplain forest development on riverine ecosystems and its implications for river management.

2. Study area

The 20th-century expansion of floodplain forest is illustrated with changes in four rivers draining different parts of the Polish Carpathians: the middle course of the Czarny Dunajec River, the lower course of the Koszarawa, the upper course of the Biała and the middle course of the Raba (Fig. 1). Table 1 presents hydrological characteristics of the rivers in delimited study reaches and physiographic characteristics of their catchments.

The Czarny Dunajec drains the Inner Carpathians. It originates at an elevation of ~1500 m a.s.l. in the high-mountain Tatra massif (with the highest point in the catchment at 2176 m a.s.l.), and then flows on the length of 38 km in the Tatra Mountains foreland (Fig. 1). Average annual precipitation totals range from 1200 to 1700 mm in the high-mountain

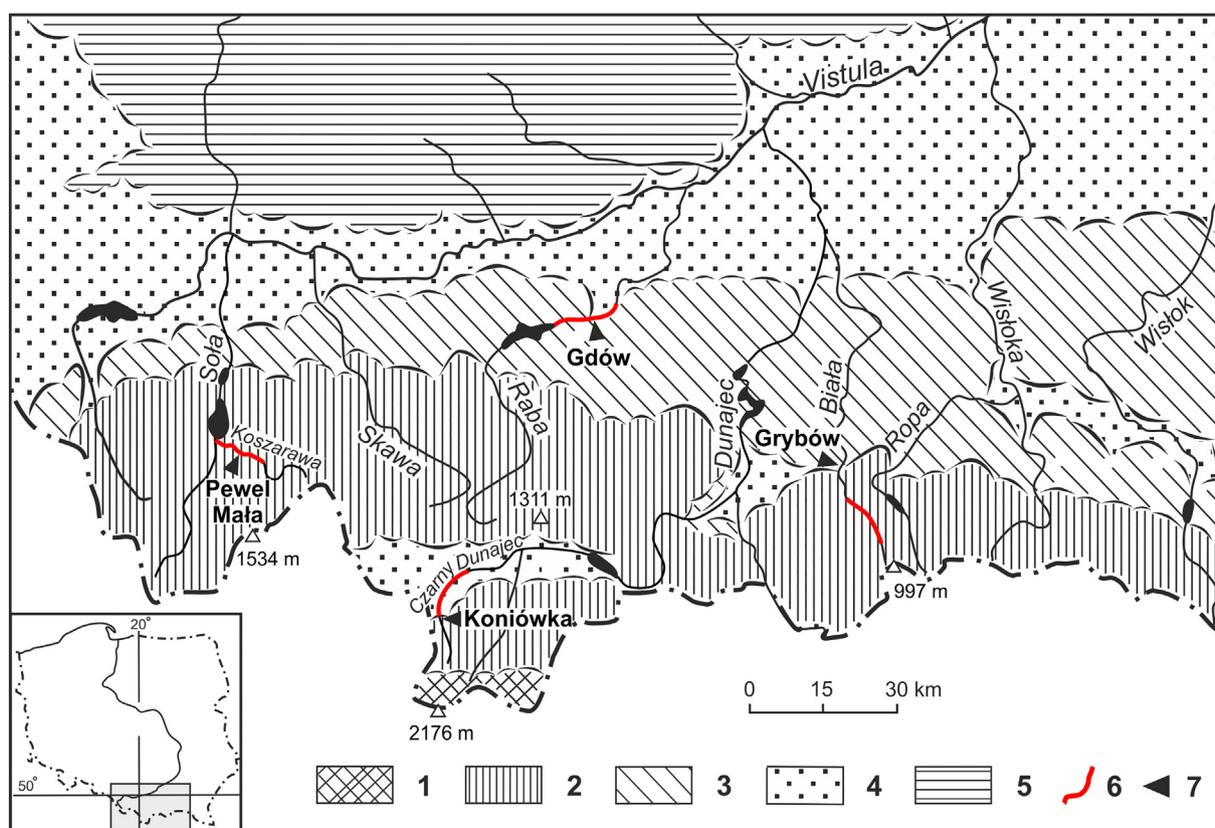


Fig. 1. Location of the studied reaches of the Czarny Dunajec, Koszarawa, Biała and Raba rivers shown on the background of physiogeographic regions of southern Poland. The study reach of the Czarny Dunajec consists of an upper part channelized in the second half of the 20th century and a lower part that has remained unmanaged. 1 – high mountains; 2 – mountains of intermediate and low height; 3 – foothills; 4 – intramontane and foreland basins; 5 – uplands; 6 – analysed river reaches; 7 – water-gauge stations.

part of the catchment and from 800 to 900 mm in its foreland part (Niedźwiedź and Obrębska-Starkłowa, 1991). A 12.1-km-long study reach (Table 1) was delimited within the Orawa–Nowy Targ Basin (Fig. 1) where the river flows through a non-cohesive alluvial plain formed from quartzitic, granitic and sandstone material. Despite the high precipitation in the Tatras, the Czarny Dunajec is typified by relatively low flashiness of flood flows as indicated by the lowest coefficient of runoff irregularity (ratio of the highest and the lowest flow on record; Table 1) calculated for the Koniówka water-gauge station located at the beginning of the study reach (Fig. 1). This reflects relatively high water storativity related to deep karstic water circulation and effective infiltration of water into thick slope mantles and washed glacial till in the high-mountain massif (Kundzewicz et al., 2014). However, relatively steep channel slope (Table 1) and the non-cohesive nature of the alluvial plain cause that the river forms a multi-thread channel in unmanaged sections.

The three other rivers under analysis drain the Outer Western Carpathians underlain by flysch and their bed material is composed of sandstone gravels with a subordinate proportion of shale clasts. The Koszarawa is located in the western part of the region, with maximum elevation in its catchment at 1534 m a.s.l. (Fig. 1). This part of the mountains captures relatively high precipitation from oceanic air masses arriving from W and NW directions, and thus average annual precipitation totals in the catchment range from 900 to >1300 mm (Niedźwiedź and Obrębska-Starkłowa, 1991). The Koszarawa originates at an elevation of ~1000 m a.s.l. At the Pewel Mała gauging station (Fig. 1), the coefficient of runoff irregularity is 1400 (Table 1), indicating moderate flashiness of the runoff from the catchment. Such a hydrological regime, relatively steep channel gradient (Table 1) and the delivery of coarse material to the river (Owczarek, 2007) underlie the formation of a multi-thread or wandering channel pattern in unmanaged river reaches. Forest development in the river corridor was investigated in a

Table 1
Hydrological characteristics of the study rivers and physiographic characteristics of their catchments.

River/catchment parameter	Czarny Dunajec River	Koszarawa River	Biała River	Raba River
Average for the lowest annual discharge ($\text{m}^3 \text{s}^{-1}$)	0.94	0.70	0.6	2.3
Mean annual discharge ($\text{m}^3 \text{s}^{-1}$)	4.4	4.4	2.8	12.1
Average for the highest annual discharge ($\text{m}^3 \text{s}^{-1}$)	54	64	22	318
Coefficient of runoff irregularity	453	1400	7500	2000
Maximum catchment elevation (m a.s.l.)	2175	1534	997	1311
Distance of the upper end of the study reach from the river source (km)	25.3	20.2	8.1	71.3
Length of the study reach (km)	12.1	10.6	9.1	16.6
Elevation of the upper and lower end of the study reach (m a.s.l.)	725–616	421–344	457–376	239–206
Channel gradient in the study reach ^a (m m^{-1})	0.009	0.007	0.009	0.002
Catchment area at the upper end of the study reach (km^2)	135.5	139.6	17.2	768.4
Absolute and relative increase in catchment area along the study reach (km^2 ; %)	24 18%	118 85%	73,426%	318 41%

^a Values of channel gradient refer to channel sinuosity and elevation difference along the study reaches in 2009.

10.6-km-long reach (Table 1) located in the lower course of the Koszarawa (Fig. 1).

The Biła River drains the eastern part of the Outer Western Carpathians and the upper part of its catchment has low-mountain relief with the highest point at an elevation of 997 m a.s.l. (Fig. 1). Here, average annual precipitation totals vary between 800 and 950 mm (Niedźwiedź and Obrębska-Starkłowa, 1991). At the Grybów gauging station characterizing the runoff from the upper part of the catchment (Fig. 1), the coefficient of runoff irregularity amounts to 7500 (Table 1), reflecting a lack of major aquifers in this area. The high flashiness of runoff and the delivery of coarse sandstone material to the river are reflected in the formation of a multi-thread channel pattern in the upper course of the Biła (Wyżga et al., 2016b). A 9.1-km-long study reach was delimited relatively close to the river source (Fig. 1), which explains the largest relative increase in catchment area on its length among the four study reaches (Table 1). Importantly, in the mid-20th century a majority of native inhabitants of the eastern part of the Polish Carpathians were resettled to other areas and their lands on the valley floors, including the study reach of the Biła, were nationalized (Lach and Wyżga, 2002).

A 16.6-km-long study reach of the Raba (Table 1) is located in the middle, foothill course of the river (Fig. 1). The river originates at an elevation of 780 m a.s.l. and the highest point in its catchment is located at 1311 m a.s.l. Average annual precipitation totals in the mountain part of the catchment range from 900 to >1200 mm and those in the foothill part vary between 750 and 900 mm (Niedźwiedź and Obrębska-Starkłowa, 1991). At the Gdów gauging station located in the middle of the study reach (Fig. 1), the coefficient of runoff irregularity equals 2000 (Table 1); the relatively high flashiness of runoff reflects low water storativity of the flysch bedrock and the high precipitation captured from oceanic air masses on predominantly NW facing slopes (Wyżga, 1991). Such a hydrological regime is reflected in the river's name which derives from the Celtic language and means *furiosus* (Rzebiak, 1985). During the two last centuries the river in the study reach experienced remarkable changes in channel pattern in response to alterations in the intensity of agricultural and pastoral activities on hillslopes in the catchment: from a single-thread to a multi-thread channel in the 19th century and back to a single-thread morphology in the 20th century (Wyżga, 1993; Wyżga et al., 2016b).

In freely developing reaches of Polish Carpathian rivers, forest succession on the banks starts with pioneer willow thickets with *Salix eleagnos*, *S. purpurea*, *S. fragilis* and *S. alba* and continues through older willow (mostly *S. alba* and *S. fragilis*) and poplar (*Populus nigra*) stands on low, frequently flooded banks to the stands of alder forest (with *Alnus incana* in upper river reaches and *A. glutinosa* in lower reaches) on higher, rarely inundated floodplain surfaces. In channelized reaches, river floodplains are overgrown with mature willow or alder forest.

3. Study methods

The following cartographic and photogrammetric materials were used in the analysis: map of the Third Military Survey of the Austro-Hungary (*Spezialkarte der österreichisch-ungarischen Monarchie*) at a scale of 1:25000 from the 1870s, orthophotos produced from the oldest available aerial photographs taken at around the mid-20th century at scales varying between 1:10000 and 1:24000 (Czarny Dunajec – 1954, Raba – 1955, Koszarawa – 1958, Biła – 1967) and orthophotos from 2009 at a scale of 1:10000 available at the State Geodetic Survey of Poland (Fig. 2). The aerial photographs used to produce the orthophotos were taken during vegetation season at base-flow conditions in all analysed rivers. The Austrian map was scanned and georeferenced in the PL-1992 coordinate system using control points. The Root Mean Square (RMS) error reflecting the geometric accuracy of orthorectification of particular sheets of this map varied between 5 and 10 m. The RMS error of the orthorectification of the archival aerial photos ranged from 0.5 to 1.3 m, whereas the RMS error for the orthophotos from 2009 was

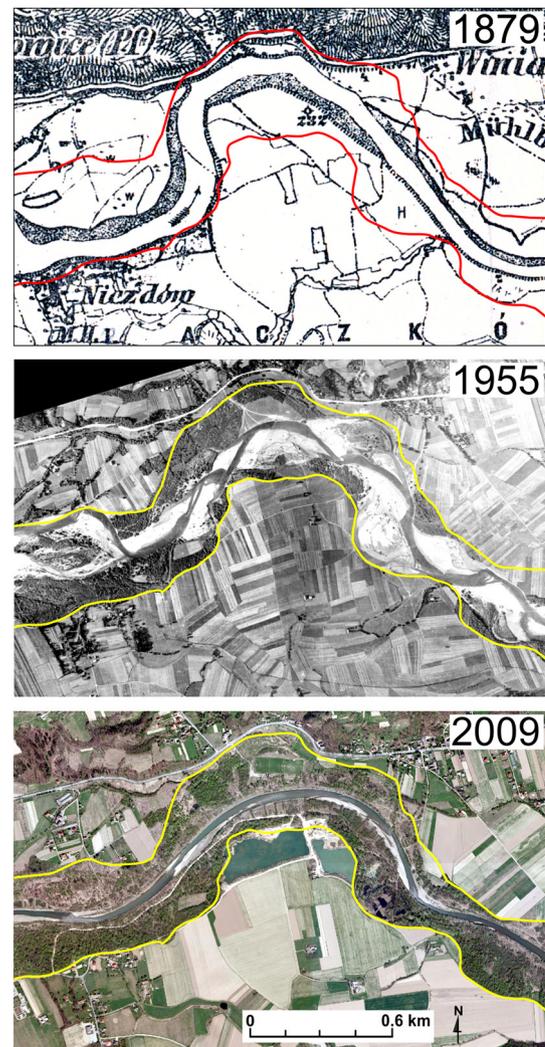


Fig. 2. Cartographic presentation of the Raba River on a 1:25000 military map of Austro-Hungary from 1879, an aerial photo at a scale of 1:10000 taken in 1955, and an 1:10000 orthophoto from 2009. Red and yellow lines indicate boundaries of the river floodplain. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

0.75 m. The pixel size of the orthophotos generated from the aerial photos from the mid-20th century equalled 0.5 m, while that of the orthophotos from 2009 was 0.25 m.

These source materials were analysed with GIS methods to determine temporal changes in the proportion of forest and other land cover categories within the corridors of the four rivers. The analysis focused on changes in the relative rather than the absolute area of given land cover categories to allow for comparison between the rivers considered. The boundaries of floodplain and active river zone were delimited on the historical map and the orthophotos (Fig. 2) and digitized using the ArcGIS software. The floodplain boundaries on the valley floors were delimited based on the analysis of digital elevation models and interpretation of the historical map and orthophotos in terms of the extent of erosional action of flood flows. Additionally, a field inspection helped determine external boundaries of the river floodplains, and the position of the boundaries was held constant over the study period. The following land cover subcategories (geomorphic units) were subsequently distinguished and digitized within the active zone of the study rivers: low-flow channels, channel bars and islands (Fig. 3). In turn, the floodplain areas were subdivided into floodplain forest, unfenced area (collectively for meadows and pasture, arable land and wasteland) and built-up area (Fig. 3). Apart from these categories/subcategories,

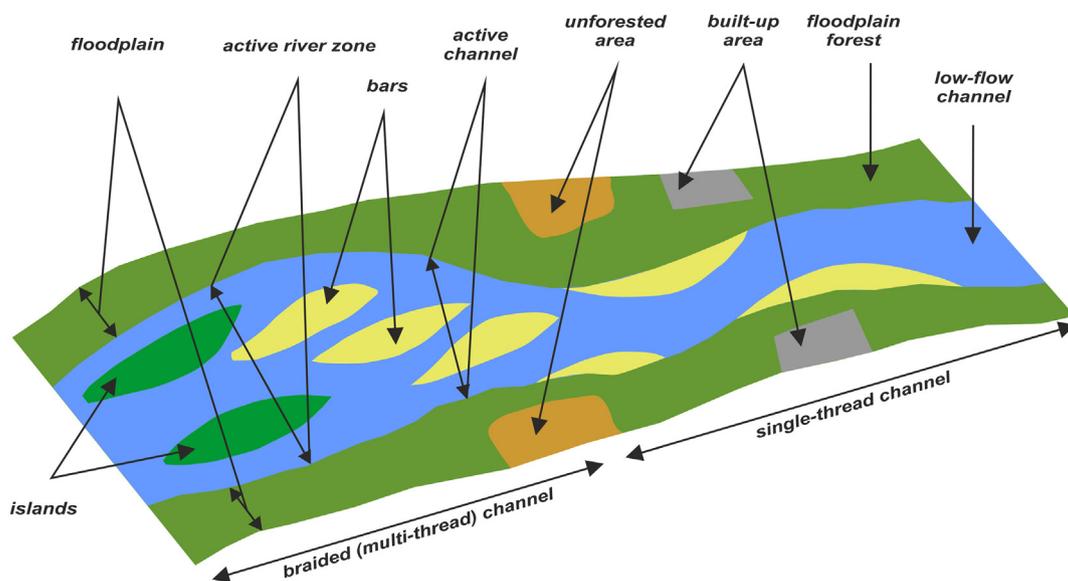


Fig. 3. General features of planform morphology and floodplain land cover of the analysed mountain rivers.

floodplain forest and islands were aggregated into a separate category encompassing forested areas within the river corridors. Fig. 3 illustrates nomenclature used to describe the elements of planform morphology and floodplain land cover of the analysed mountain rivers.

A delimited study reach of each analysed river was divided into 100-m-long segments, and polygons delineating the extent of given land cover categories were divided between successive river segments. This resulted in 121 consecutive segments of the Czarny Dunajec, 106 segments of the Koszarawa and 91 segments of the Biała. In the Raba, changes in river length reflecting alterations in channel sinuosity caused that the study reach from the 1870 was divided into 175 segments, that from the mid-20th century into 195 segments and that from 2009 into 166 segments. For each segment, widths of river and its corridor, total area of river corridor, and areas of river, floodplain, low-flow channels, bars, islands, floodplain forest, unforested floodplain area, built-up area, as well as a combined area of floodplain forest and islands were determined. Then, the percentage of individual land cover categories in the total width/area of the river corridor in each segment was calculated and mean proportions of these categories at particular analysed dates were obtained for the study reaches of the four rivers. As rivers form a single, continuous feature along their corridors, in the following analysis the proportion of river width in the average width of river corridor is described to better visualize the degree of river narrowing through time, whereas for other land categories we refer to changes in their proportion in the corridor area.

Because of non-normal distribution of some data samples, the non-parametric Friedman test was applied to verify the statistical significance of differences in the proportion of each land cover category in the total width/area of river corridor among all the analysed dates. In turn, significance of the differences between pairs of the analysed dates was verified with a Fischer's least significant difference *post hoc* test. Differences between samples were considered statistically significant if p -value was <0.05 .

4. Results

4.1. Changes in river planform

The analysed Polish Carpathian rivers experienced significant narrowing between the second half of the 19th century and the first decade of the present century (Friedman test, $p < 0.00001$), but they differed in the timing and the degree of the narrowing (Table 2, Fig. 4).

In the Czarny Dunajec draining the Inner Carpathians, river width decreased during that time by three-fourths and the degree of the river narrowing was similar in both periods analysed (Table 2, Fig. 4). In the 1870s the river covered 42.7% of the width of its corridor on average, occupying from 12.5% to 84.2% of the corridor width in individual channel segments. By the mid-20th century river width significantly decreased to 23.9% of the corridor width on average (Fischer's LSD test, $p < 0.0001$), varying between 3.1% and 60.7% among individual channel segments. In the first period under analysis (i.e. between the 1870s and the mid-20th century), this tendency towards river narrowing was a predominant channel change along the whole study reach (Fig. 5). The river narrowing was associated with a slight reduction in the average number of low-flow channels from 2.3 in the 1870s to 2.1 in the mid-20th century, but the river maintained its multi-thread channel pattern. In this period, the average proportion of low-flow channels and channel bars in the corridor area decreased significantly by about half—that of low-flow channels from 11.8% to 4.4% (Fischer's LSD test, $p < 0.0001$; Fig. S1 in the Supplementary data) and that of channel bars from 27.9% to 13.4% ($p < 0.0001$; Fig. S2). However, the average proportion of islands in the corridor area increased significantly from 2.4% to 4.8% ($p < 0.0001$; Fig. S3), which reflected more than a threefold increase in the proportion of islands in the river area.

Between the mid-20th century and 2009 (i.e. in the second period analysed), mean river width in the study reach of the Czarny Dunajec decreased significantly from 23.9% to 10.6% of the corridor width (Fischer's LSD test, $p < 0.0001$), at the end of this period ranging from 2.7% to 34.8% in individual channel segments (Table 2, Fig. 4). This reflected significant decreases in the average proportion of channel bars in the corridor area from 13.4% to 3.2% ($p < 0.0001$; Fig. S2) and that of islands from 4.8% to 1.5% ($p < 0.0001$; Fig. S3), whereas the proportion of low-flow channels increased from 4.4% to 5.9% ($p < 0.0001$; Fig. S1). However, this average pattern of channel changes conceals the dichotomous evolution of the upper and lower parts of the study reach (consisting of eighty and forty-one 100-m-long river segments, respectively) over the last six decades. In the upper part, the river was heavily channelized, with the resultant reduction of the average number of low-flow channels to 1.3 and narrowing of the river to 7% of the corridor width (Fig. 5-left panels). The average proportion of low-flow channels in the corridor area changed to 5.6%, while that of channel bars was dramatically reduced to 1.4% and islands were completely eliminated (Fig. 5-left panels). In the lower part of the reach, the river remained unmanaged, maintaining a multi-thread channel pattern

Table 2

Changes in mean proportion of land cover categories and subcategories in the total area of river corridor in 100-m segments of the analysed reaches of the Koszarawa, Czarny Dunajec, Biała and Raba rivers between the 1870s and 2009, and statistical significance of the differences between the analysed dates indicated by a Friedman test.

Land cover category	Land cover subcategory	Mean value in			Significance of Friedman test
		1870s	Mid-20th century	2009	
Czarny Dunajec River	River	42.7	22.6	10.6	$p < 0.00001$
	Low-flow channels	11.8	4.4	5.9	$p < 0.00001$
	Channel bars	28.5	13.4	3.2	$p < 0.00001$
	Islands	2.4	4.8	1.5	$p < 0.00001$
Floodplain		57.3	77.4	89.4	$p < 0.00001$
	Riparian forest	0.0	12.1	28.5	$p < 0.00001$
	Unforested area ^a	55.4	62.7	50.4	$p < 0.00001$
Riparian forest and islands	Built-up area	1.9	2.6	10.5	$p < 0.00001$
		3.0	16.9	30.0	$p < 0.00001$
Koszarawa River	River	28.1	28.8	18.2	$p < 0.00001$
	Low-flow channels	21.8	12.7	10.7	$p = 0.003$
	Channel bars	5.9	14.1	5.8	$p < 0.00001$
	Islands	0.4	2.0	1.7	$p < 0.00001$
Floodplain		71.9	71.2	81.8	$p < 0.00001$
	Riparian forest	7.5	28.8	46.5	$p < 0.00001$
	Unforested area ^a	64.0	39.2	28.6	$p < 0.00001$
	Built-up area	0.4	3.4	6.7	$p < 0.00001$
Riparian forest and islands		7.9	30.8	48.2	$p < 0.00001$
Biała River	River	57.8	19.9	16.3	$p < 0.00001$
	Low-flow channels	20.4	5.2	6.1	$p < 0.00001$
	Channel bars	37.4	14.1	9.2	$p < 0.00001$
	Islands	0.0	0.6	1.0	$p < 0.00001$
Floodplain		42.2	80.1	83.7	$p < 0.00001$
	Riparian forest	2.4	27.6	45.3	$p < 0.00001$
	Unforested area ^a	36.8	51.4	36.0	$p = 0.0001$
	Built-up area	3.0	1.1	2.4	$p = 0.0003$
Riparian forest and islands		2.4	28.2	46.3	$p < 0.00001$
Raba River	River	52.2	38.5	11.2	$p < 0.00001$
	Low-flow channels	29.2	14.3	8.7	$p < 0.00001$
	Channel bars	23.0	21.7	2.5	$p < 0.00001$
	Islands	0.0	2.5	0.0	$p < 0.00001$
Floodplain		47.8	61.5	88.8	$p < 0.00001$
	Riparian forest	5.5	34.1	45.9	$p < 0.00001$
	Unforested area ^a	41.9	26.9	40.1	$p < 0.00001$
	Built-up area	0.4	0.5	2.8	$p < 0.00001$
Riparian forest and islands		5.5	36.6	45.9	$p < 0.00001$

^a The category of unforested area encompasses meadows and pasture, arable land and wasteland.

with an average of 3.3 low-flow channels in 2009. Here, in 2009 the river width amounted to 17.6% of the corridor width (Fig. 5-right panels). The average proportion of low-flow channels in the corridor area amounted to 6.5% and those of channel bars and islands to 6.5% and 4.6%, respectively. Notably, the proportion of islands in the river area increased to 26% and the ratio of island area to gravel area in the river equalled 0.35, indicating the development of an island-braided channel pattern in this subreach (Fig. 5).

The Koszarawa River draining the western part of the flysch Polish Carpathians narrowed between the second half of the 19th century and the first decade of the present century by one-third (Friedman test, $p < 0.00001$), but the change took place in the second part of this period (Table 2, Fig. 4). In the 1870s the average proportion of river width in the corridor width equalled 28.1% and changed only slightly to 28.8% by the mid-20th century, whereas the range of the variation in this parameter among individual river segments changed from 6.5%–66.5% to 3.0%–74.1% between these dates (Fig. 4). Despite the lack of change in mean river width, the average number of low-flow channels increased from 1.4 in the 1870s to 1.75 in the mid-20th century. The average proportion of low-flow channels in the corridor area significantly decreased from 21.8% to 12.7% between these dates (Fischer's LSD test, $p < 0.0001$; Fig. S1). However, the average proportion of channel bars increased significantly from 5.9% to 14.1%

($p < 0.0001$; Fig. S2), whereas that of islands experienced no significant change (Fig. S3).

In the last six decades, mean width of the Koszarawa decreased by one-third to 18.2% of the corridor width ($p < 0.0001$) and the range of width variation diminished to 6.1%–47.5% (Fig. 4). At the same time, the average number of low-flow channels decreased to 1.4. The average proportion of channel bars in the corridor area decreased from 14.1% to 5.8% ($p < 0.0001$; Fig. S2), whereas no significant change in the proportion of low-flow channels was recorded (Fig. S1). The proportion of islands in the corridor area changed marginally (Fig. S3), but with the simultaneous reduction in river width, their proportion in the river area increased to 9.3%.

The Biała River draining the eastern part of the flysch Western Carpathians narrowed over the last 130 years by nearly three-fourths (Friedman test, $p < 0.00001$), but most of the change took place in the first study period (Table 2, Fig. 4). Between the 1870s and the mid-20th century, the average proportion of river width in the corridor width decreased from 57.8% to 19.9% (Fischer's LSD test, $p < 0.0001$) and the range of width variation changed from 21.4%–100% to 4.3%–43.3% (Fig. 4). During this period the average number of low-flow channels in the river was reduced from 2.1 to 1.5. These changes were associated with significant decreases in the proportion of low-flow channels in the corridor area from 20.4% to 5.2% ($p < 0.0001$; Fig. S1)

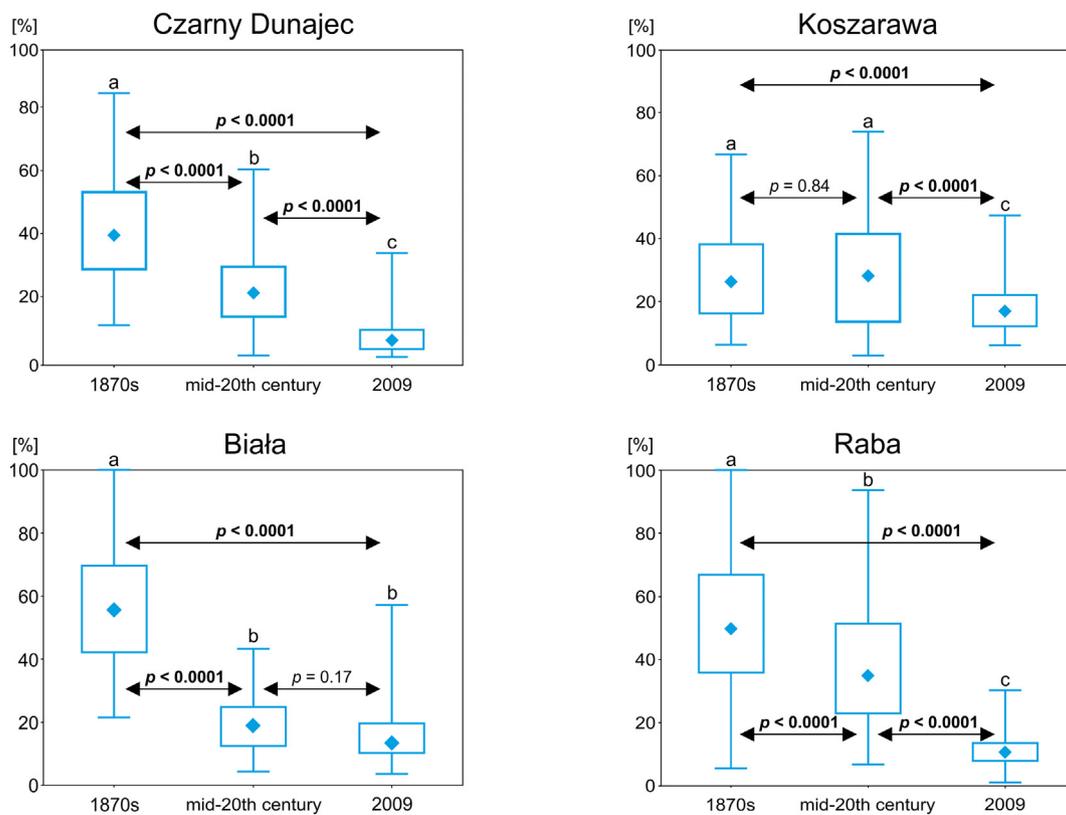


Fig. 4. Changes in the proportion of the active zone of the four analysed Carpathian rivers in the total width of their corridors between the 1870s and 2009. Boxplots show median (diamonds), quartiles (boxes) and extreme values (whiskers) for analysed 100-m-long segments of each river. Different letters denote statistically different samples indicated by a Fischer's LSD *post hoc* test and significance of the differences between the analysed dates is indicated. Statistically significant differences are indicated in bold.

and that of channel bars from 37% to 14.1% ($p < 0.0001$; Fig. S2), whereas the proportion of islands did not change significantly (Fig. S3).

Between the mid-20th century and 2009, the average proportion of river width in the corridor width decreased from 19.9% to 16.3% (Table 2), but this change was not statistically significant (Fig. 4). Importantly, during this period the range of width variation increased to 3.4%–57.0% and the average number of low-flow channels in the river rose to 1.8. These changes were associated with a significant reduction in the proportion of channel bars in the corridor area from 14.1% to 9.2% (Fischer's LSD test, $p < 0.01$; Fig. S2), whereas no significant changes in the proportion of low-flow channels (Fig. S1) and islands (Fig. S3) in the corridor area were recorded. However, it should be emphasized that the proportion of islands in the river area changed over the last 130 years from 0 in the 1870s to 6.1% in 2009.

The Raba River in its reach within the Carpathian Foothills narrowed over the last 130 years by more than three-fourths (Friedman test, $p < 0.00001$), with a greater part of the narrowing having occurred in the second period under analysis (Table 2, Fig. 4). From the 1870s to the mid-20th century the average proportion of river width in the corridor width decreased from 52.2% to 38.5% (Fischer's LSD test, $p < 0.0001$), whereas the range of width variation changed little from 5.9%–100% to 7.0%–94.2% (Fig. 4). In the 1870s the river flowed in either straight or multi-thread channel with an average number of 1.45 low-flow channels and a sinuosity index of 1.10 in the study reach. In the mid-20th century the average number of low-flow channels was the same as in the 1870s, but the river flowed in a sinuous channel with a sinuosity index of 1.29. The change in channel pattern was reflected in a significant reduction of the proportion of low-channels in the corridor area from 29.2% to 14.3% between the analysed dates ($p < 0.0001$; Fig. S1), whereas the proportion of channel bars changed little (Fig. S2) and the proportion of islands significantly increased from 0% to 2.5% ($p < 0.0001$; Fig. S3).

In the last six decades mean width of the Raba decreased markedly to 11.2% of the corridor width ($p < 0.0001$) and the range of width variation shrank to 1.2%–30.5% (Fig. 4). The proportion of channel bars in the corridor area was dramatically reduced to 2.5% ($p < 0.0001$; Figs. 2, S2), islands were completely eliminated ($p < 0.0001$; Fig. S3), whereas the proportion of low-flow channels decreased moderately, though significantly ($p < 0.0001$) to 8.7% of the corridor area (Fig. S1). At the same time, the river sinuosity was reduced to 1.03 and channel pattern was changed to a straight one.

4.2. Land cover changes in floodplain areas

Changes in the proportion of floodplain area in the corridor area of the analysed rivers were opposite to those in the proportion of the rivers. The river floodplains significantly widened between the second half of the 19th century and the first decade of the present century (Friedman test, $p < 0.00001$), whereas the timing and the degree of the widening differed among the rivers (Table 2, Fig. S4). In the Czarny Dunajec, the proportion of floodplain area increased from 57.3% in the 1870s to 76.1% in the mid-20th century and 89.4% in 2009 (Table 2), and the changes were statistically significant in both periods (Fischer's LSD test, $p < 0.0001$) (Fig. S4). In the first period, the area of floodplain forest increased from 0 to 12.1% of the corridor area ($p < 0.0001$; Fig. S5), whereas unforested area increased less—from 55.4% to 64.1% ($p < 0.0001$; Fig. S6)—and no significant change in the proportion of built-up area was recorded (Fig. S7). In the second period, the area of floodplain forest increased even more spectacularly to 28.5% of the corridor area ($p < 0.0001$; Fig. S5), built-up areas expanded from 2.6% to 10.5% ($p < 0.0001$; Fig. S7), while the proportion of unforested area decreased markedly to 50.4% ($p < 0.0001$; Fig. S6). However, the timing of forest expansion differed between the upper and lower parts of the study reach. In the upper part, the proportion of the corridor area overgrown with floodplain forest increased to 7.5% by the mid-20th century

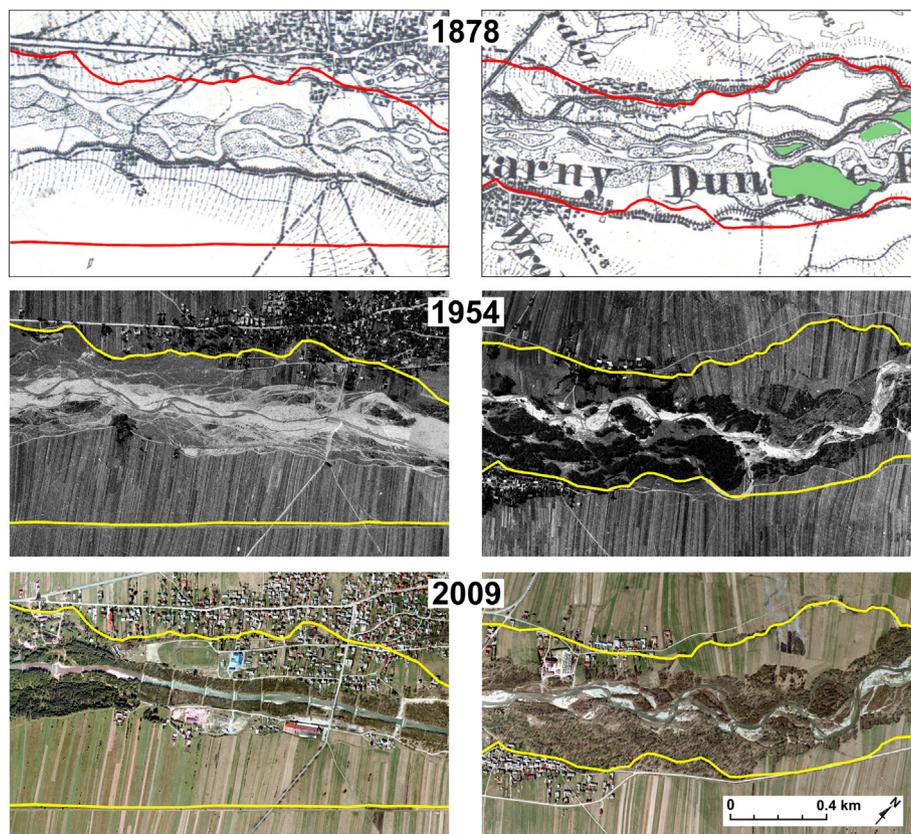


Fig. 5. Changes in river planform and in the occurrence of forest in the river corridor in the upper (left panels) and lower (right panels) parts of the study reach of the Czarny Dunajec between the 1870s and 2009. Red and yellow lines indicate boundaries of the river floodplain. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and to 27% by 2009 (Fig. 5-left panels). In the lower part, 21% of the corridor area was covered with forest already in the mid-20th century and the forest proportion increased to 30% by 2009 (Fig. 5-right panels).

In the valley of the Koszarawa, the floodplain area did not change significantly during the first period considered (Table 2, Fig. S4). Despite this, the extent of all the analysed land cover categories changed during this period: the proportion of unforested area in the corridor area decreased from 64.0% to 39.2% (Fischer's LSD test, $p < 0.0001$; Fig. S6), whereas the proportion of floodplain forest increased from 7.5% to 28.8% ($p < 0.0001$; Fig. S5) and that of built-up area from 0.4% to 3.4% ($p < 0.0001$; Fig. S7). In the second period, the proportion of floodplain area increased from 71.2% to 81.8% ($p < 0.0001$) (Table 2, Fig. S4). Floodplain forest expanded then to 46.5% ($p < 0.0001$; Fig. S5) and built-up area to 6.7% of the corridor area ($p < 0.0001$; Fig. S7), whereas unforested area continued the decreasing tendency, shrinking to 28.6% by 2009 ($p < 0.0001$; Fig. S6).

In the Biała valley, the proportion of floodplain in the corridor area almost doubled between the 1870s and the mid-20th century (Table 2), increasing from 42.2% to 80.1% (Fischer's LSD test, $p < 0.0001$; Fig. S4). In that period floodplain forest expanded markedly—its proportion in the corridor area changed from 2.4% to 27.6% ($p < 0.0001$; Fig. S5)—and the proportion of unforested area increased from 36.8% to 51.4% ($p < 0.0001$; Fig. S6). However, built-up area shrank from 3.0% to 1.1% ($p < 0.0001$; Fig. S7). Between the mid-20th century and 2009, no significant change in floodplain area occurred (Fig. S4). However, the area of floodplain forest increased considerably to 45.3% ($p < 0.0001$; Fig. S5) at the expense of unforested area that shrank to 36.0% of the corridor area ($p < 0.0001$; Fig. S6). At the same time, the proportion of built-up area did not change significantly (Fig. S7).

In the river corridor of the Raba, the floodplain increased in area in both study periods (Table 2). In the first period, its proportion in the corridor area changed from 47.8% to 61.5% ($p < 0.0001$; Fig. S4). However,

the proportion of floodplain forest increased to a greater extent from 5.5% to 34.1% ($p < 0.0001$; Fig. S5), partly at the expense of unforested area that shrank from 41.9% to 26.9% ($p < 0.0001$; Fig. S6), whereas the proportion of built-up area did not change significantly (Fig. S7). In the second period, the floodplain area increased even more spectacularly to 88.8% of the corridor area ($p < 0.0001$; Fig. S4), and the change was associated with increases in the extent of all the analysed categories of land cover—the proportion of floodplain forest grew to 45.9% ($p < 0.0001$; Fig. S5), that of unforested area to 40.1% ($p < 0.0001$; Fig. S6) and that of built-up area to 2.8% ($p = 0.03$; Fig. S7).

4.3. Changes in the extent of forested area in the river corridors

All analysed rivers experienced significant changes in the extent of forested area (i.e. the aggregated area of floodplain forest and islands) in their corridors over the last 130 years (Friedman test, $p < 0.00001$; Table 2), and these changes were statistically significant in each of the two periods considered (Fig. 6). In the corridor of the Czarny Dunajec, forested area increased from 3% in the 1870s to 30% in 2009 and the scale of the increase was similar in both analysed periods (Table 2). In the upper part of the study reach that was channelized in the last six decades, the proportion of forested area changed from 0 in the 1870s to 27.5% in 2009 and a majority of the increase took place after the mid-20th century (Fig. 5-left panels). In the lower part of the study reach that remained unmanaged over the last 130 years, the extent of forested area changed from 6.1% in the 1870s to 33% in 2009, but three-fourths of the increase were achieved by the mid-20th century (Fig. 5-right panels). In the three remaining rivers, forested area increased from 2.4%–7.9% of the corridor area in the 1870s to 45.9%–48.2% in 2009, and until the mid-20th century more than half of the increase occurred in the Koszarawa and the Biała, while three-fourths in the Raba (Table 2; Fig. 6).

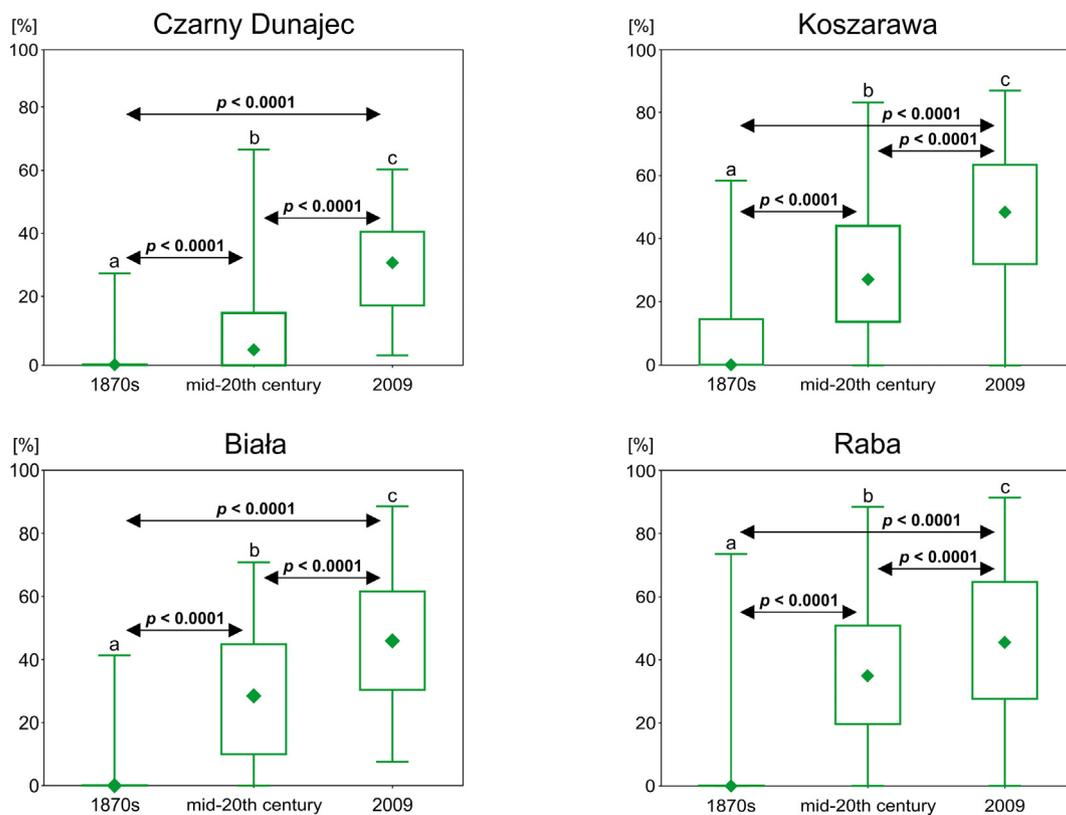


Fig. 6. Changes in the proportion of the aggregated area of floodplain forest and islands in the total corridor area of the four analysed Carpathian rivers between the 1870s and 2009. Boxplots show median (diamonds), quartiles (boxes) and extreme values (whiskers) for analysed 100-m-long segments of each river. Different letters denote statistically different samples indicated by a Fischer's LSD *post hoc* test and significance of the differences between the analysed dates is indicated. Statistically significant differences are indicated in bold.

5. Discussion

5.1. Causes of changes in planform geometry of Polish Carpathian rivers

In the second half of the 19th century, Polish Carpathian rivers flowed in wide, predominantly multi-thread channels. Such channel geometry reflected rapid water runoff and high sediment yield generated by largely deforested mountain catchments that were subjected to intense cultivation and grazing (Wyżga, 1993; Wyżga et al., 2012, 2016b). High rates of turnover of active river zones prevented development of islands in the rivers (Wyżga et al., 2012).

In the 20th century channel narrowing and incision coupled with the transformation of multi-thread channels into single-thread ones were common evolutionary tendencies of mountain rivers in Europe (Surian and Rinaldi, 2003; Gurnell et al., 2009; Rinaldi et al., 2013), and such changes typified also rivers of the Polish Carpathians (Wyżga, 1993; Wyżga et al., 2016b; Hajdukiewicz et al., 2019). By 2009 channel width of the rivers analysed in this study decreased to 21%–65% of the value from the 1870s. This narrowing of the rivers was mainly caused by the regulation of their channels. In the foothill reach of the Raba and in the Biała River, intense channelization works were initiated in the 1900s and within two decades resulted in the replacement of the wide, multi-thread channel by a considerably narrower, single-thread channel with reinforced banks (Wyżga, 1993, 2001; Szuba, 2012). During a pause in channelization works in the 1940s–1950s, the Raba destroyed the reinforcements of its banks and formed a natural channel which was, however, narrower than the pre-regulation channel. This re-established natural channel was sinuous and typified by markedly smaller low-flow channel width than the pre-regulation channel, which reflected a river metamorphosis induced by a reduction in catchment sediment supply over the first half of the 20th century (Wyżga, 2001; Wyżga et al., 2016b) and reinforced by

forest establishment on the river banks (cf. Tal and Paola, 2010). It was a renewed channelization of the river undertaken in the second half of the century that caused straightening and a dramatic narrowing of the channel (Wyżga, 2001; Wyżga et al., 2016b) leading to the nearly complete disappearance of gravel bars from the river. In 1986 impoundment of the Raba immediately upstream of the study reach interrupted the continuity of sediment transport in the river, contributing to the channel narrowing in the second period considered. In contrast, the narrowing of the Biała channel caused by its regulation in the first decades of the 20th century appeared persistent despite a relatively steep channel slope and thus high stream power of flood flows in the analysed reach. This probably reflected a small thickness of the alluvium on the valley floor and incision of the narrowed river into bedrock, which increased its lateral stability. In the second half of the century, the river width decreased only slightly. At that time a reduction in catchment sediment supply resulting from an increase in forest cover in the mountain part of the catchment (cf. Lach and Wyżga, 2002) and in-channel gravel mining increasing sediment deficit in the river (Wyżga et al., 2010) might have contributed to the continuation of the narrowing tendency of its channel.

Until the mid-20th century channelization works in the study reach of the Czarny Dunajec were limited to local, small-scale interventions (e.g. near bridges). The narrowing of the river channel in the first analysed period mainly reflected a reduction in flow and sediment dynamics in the river caused by environmental changes in the catchment (Zawiejska and Wyżga, 2010; Wyżga et al., 2012). They encompassed a change in precipitation regime, evidenced by a decrease in the intensity of hydrometeorological phenomena in the high-mountain Tatra massif with the decline of the Little Ice Age at around the 1890s (Kotarba, 2004), and an increase in forest cover in the catchment (Wyżga et al., 2012). In the second half of the century, channelization works caused remarkable narrowing of the river in the upper part of the study reach

(Zawiejska and Wyżga, 2010; Hajdukiewicz and Wyżga, 2019), whereas the relatively small narrowing of the river's active zone in the lower part of the study reach most likely reflected a reduction in the river dynamics induced by land use changes in the catchment (Wyżga et al., 2012) and by sediment deficit caused by large-scale, in-channel gravel mining carried out in the 1950s–1960s (Wyżga et al., 2010; Zawiejska et al., 2015).

The Koszarawa, like many other mountain tributaries to main Carpathian rivers, was subjected to channelization only in the second half of the 20th century. The works were continued to the beginning of the present century, and they were responsible for the river narrowing recorded in the second analysed period. The largest width of this river recorded in the mid-20th century and the increase in the number of low-flow channels and the area of gravel bars between the 1870s and the mid-20th century most likely reflected the occurrence of a very large flood a few months before the aerial photo from 1958 was taken, as such floods are known to heavily influence the width and braiding patterns in gravel-bed rivers (Belletti et al., 2015).

5.2. Causes and course of the 20th-century expansion of floodplain forest

A rapid population growth that occurred in southern Poland in the 19th century, coupled with a lack of income sources other than agriculture, caused that in the second half of the century every suitable land was either cultivated or grazed—in the Carpathians, valley floors were particularly useful for these activities. At the same time, fast turnover of active river zones by migrating shallow low-flow channels (Adamczyk, 1981) resulted in recurrent erosion of woody vegetation on river banks. Consequently, valleys of Polish Carpathian rivers lacked floodplain forest and were typified by the occurrence of wide active channels bounded by agricultural land (Baumgart-Kotarba, 1980; Wyżga et al., 2012, 2016b). At that time such a situation occurred also in other mountain regions of Europe (Kondolf et al., 2002, 2007; Piégay, 2003; Rinaldi et al., 2013).

In the valleys of the Czarny Dunajec, Biała and Raba rivers, the increase in the area of floodplain forest between the 1870s and 2009 was almost the same as that in the floodplain area in the river corridors (Fig. 7). Here, the floodplain forest developed on lateral, higher parts of the former, wide channels that were reclaimed as a result of the river channelization and incision. In the Czarny Dunajec and Biała valleys, the floodplain area increased until the mid-20th century considerably more than the area of floodplain forest (Fig. 7). In these parts of the

Polish Carpathians, agricultural and pastoral activities long remained a principal source of income of the inhabitants, and thus a considerable proportion of the areas reclaimed from these rivers was grazed or even cultivated. In the mid-20th century, arable lands, meadows and pasture covered ca. 75% of the floodplain area in the study reach of the Czarny Dunajec River (Hajdukiewicz and Wyżga, 2019). However, the areas reclaimed from the rivers had very shallow, poor soils and the emergence of new sources of income (work in industry, services and tourism) during the second half of the century (Kukulak, 1994) caused that these areas have been increasingly abandoned and left for forest growth. In the Czarny Dunajec valley, the areas of floodplain and floodplain forest increased during the second half of the century considerably more in the upper, channelized part of the study reach than in its lower, unmanaged part, which highlights the role of the river channelization in the expansion of floodplain forest.

In the Raba valley, the increase in the area of floodplain forest until the mid-20th century was twice larger than that in floodplain area (Fig. 7), which was caused by two factors. First, the study reach of the Raba is situated close to urban areas and this relatively early enabled local inhabitants to gain income outside agriculture and to abandon lands with the poorest soils, including those reclaimed from the river as a result of its channelization in the first decades of the 20th century. Second, the growth of bends of the sinuous channel formed by the river at the mid-century caused erosion of agricultural lands situated outside the wide, pre-regulation channel, whereas a proportion of the areas reclaimed from the 19th-century river and subsequently overgrown with floodplain forest remained untouched. As a result of renewed river channelization in the second half of the 20th century, a considerable proportion of the area of the sinuous channel was reclaimed, with most of the reclaimed area being left for forest development.

In the Koszarawa valley, floodplain area did not increase until the mid-20th century but floodplain forest developed at the expense of arable fields and meadows, whereas in the second half of the century the increase in the area of floodplain forest was greater than that in floodplain area (Fig. 7, Table 2). Similar to other catchments in the western part of the flysch Polish Carpathians, the catchment of the Koszarawa is predominantly underlain by resistant sandstones (Wyżga et al., 2016b). As a result, the Koszarawa is a bedload river (cf. Schumm, 1968) which deposits a relatively thin cover of fine-grained sediments on its floodplain, and thus the floodplain areas are typified by poor soils. The study reach of this river is situated close to a town and the

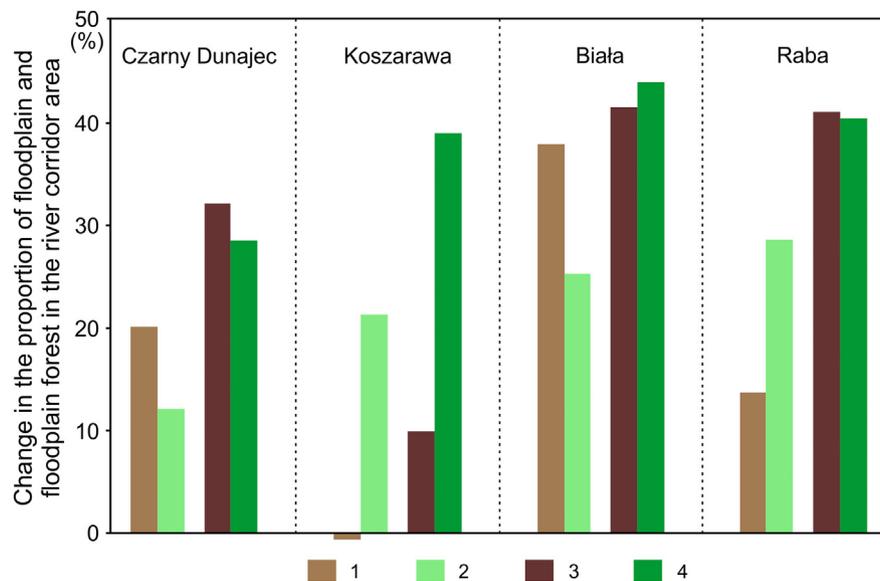


Fig. 7. Changes in the average proportion of floodplain (1,3) and floodplain forest (2,4) in the total area of the corridor of the Czarny Dunajec, Koszarawa, Biała and Raba rivers between the 1870s and the mid-20th century (1–2) and between the 1870s and 2009 (3–4). Note that almost all the analysed changes represented increases, except from a slight decrease in the proportion of floodplain of the Koszarawa River between the 1870s and the mid-20th century.

emergence of non-agricultural sources of income in the 20th century enabled local inhabitants to abandon lands with poor soils occurring on the pre-channelization floodplain and to left them for forest development. In the second half of the century, lands reclaimed from the river as a result of its channelization were also left for forest development.

5.3. Occurrence of islands in Polish Carpathian rivers

Multi-thread rivers of the Polish Carpathians from the late 19th century were typified by bar-braided morphology (Fig. 8a) (Wyżga et al., 2012, 2016b). This indicates that rivers of that time turned over their beds faster than trees established on gravel bars were able to grow to a mature, scour-resistant state (cf. Paola, 2001; Hicks et al., 2008). In the first half of the 20th century, forest development on the floodplains of all studied Polish Carpathian rivers was accompanied by the appearance or increased occurrence of islands in the active zones (Table 2). In the second half of the century, most multi-thread reaches of Polish Carpathian rivers were channelized, which caused the elimination of islands and has led to incision of the narrowed rivers, in some sections associated with transformation of alluvial channel beds to bedrock or bedrock–alluvial beds (Fig. 8b) (Zawiejska and Wyżga, 2010; Wyżga et al., 2012, 2016b; Hajdukiewicz and Wyżga, 2019; Hajdukiewicz et al., 2019). In the reaches that avoided channelization, such as the lower part of the study reach of the Czarny Dunajec, the proportion of islands in the active river zone increased resulting in the formation of an island-braided channel pattern (Fig. 8c) (Wyżga et al., 2012, 2016b).

An external factor enabling the increasing development of islands over the 20th century was a reduction in flow and sediment dynamics of the rivers (Zawiejska and Wyżga, 2010; Wyżga et al., 2012) driven by a decline in agricultural and pastoral activities on hillslopes and the associated increase in forest cover in the catchments (Kozak et al., 2007; Wyżga et al., 2012; Munteanu et al., 2014) but also a change in precipitation pattern after the end of the Little Ice Age (Zawiejska and Wyżga, 2010). A significance of this factor is highlighted by the development of numerous islands where abandonment of a channelization scheme leads to channel widening and passive river restoration

(Mikuś et al., 2019; Gorczyca et al., 2020). However, island establishment on gravel bars and forest development on river banks must have induced important feedbacks stimulating the development of island-braided channel pattern. Vegetative regeneration of trees and shrubs eroded along river or island margins and deposited on gravel bars enabled establishment of pioneer islands and further growth of older islands (Mikuś et al., 2013; cf. also Gurnell et al., 2001; Moggridge and Gurnell, 2009). Island vegetation generates considerable resistance to flow (Järvelä, 2004) and thus reduces flow velocity and bed shear stress above vegetated surfaces (Vargas-Luna et al., 2015). Consequently, the vegetation acted as an ecosystem engineer (Gurnell and Petts, 2006), stimulating rapid accretion of fine sediments (Mikuś et al., 2013) that reduced the potential for trees uprooting by flood flows and thus enhanced island stability. Another effect of low flow velocities above islands must have been increased concentration of flood flows in low-flow channels leading to the formation of deeper, more stable channels between islands (Fig. 8c). Flume experiments with varied vegetation density in a river confirmed that vegetation itself can significantly modify the style and intensity of braiding without a change in external controls (Gran and Paola, 2001; Bertoldi et al., 2015; Mao et al., 2020).

5.4. Implications of floodplain forest development for riverine ecosystems and river management

While the 20th-century forest expansion in the riparian areas of Polish Carpathian rivers must have exerted numerous impacts on socio-economic functions of, and ecosystem services provided by, these areas (cf. Dufour et al., 2019; Riis et al., 2020), below we focus on impacts of the change in land cover on the functioning of riverine ecosystems and their implications for river management. Differences in the type of riparian vegetation influence the structure of aquatic habitats and trophic subsidies between terrestrial and aquatic realms (Capon and Pettit, 2018). Trees and shrubs overgrowing river banks supply the river ecosystem with leaf litter (Hoover et al., 2011) which provides food for benthic invertebrates and can be a major source of carbon for aquatic biota in oligotrophic mountain watercourses

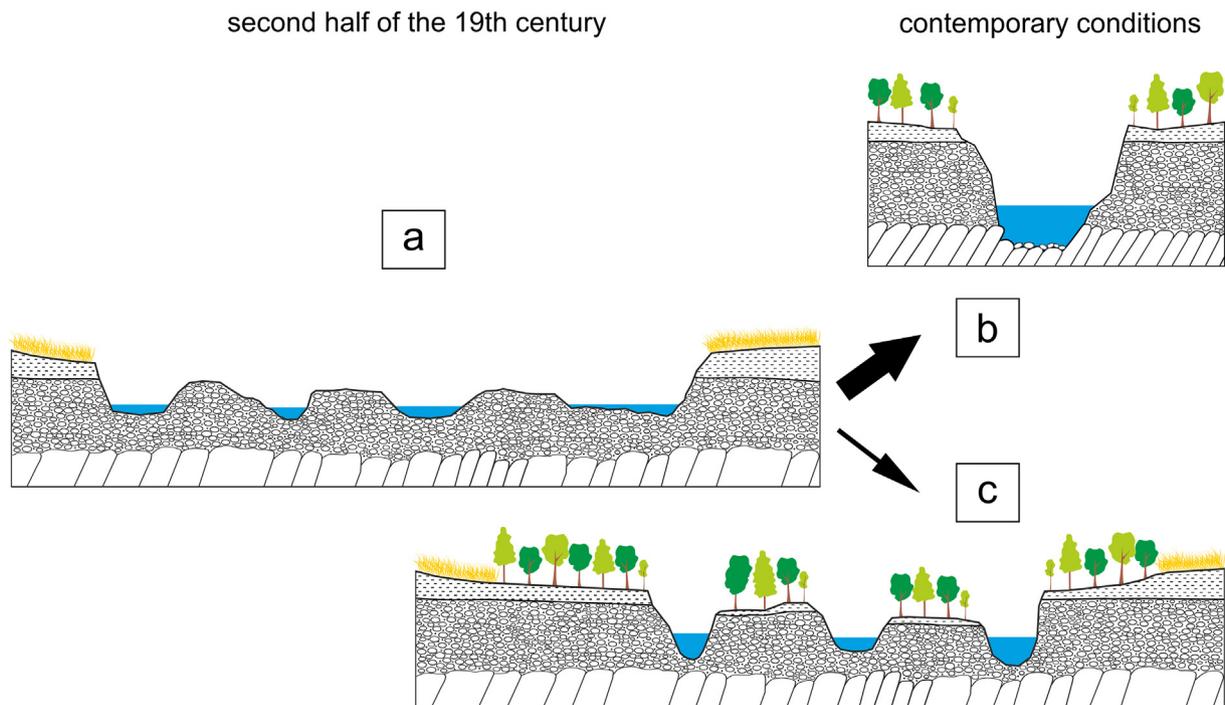


Fig. 8. Conceptual model of the evolution of multi-thread rivers of the Polish Carpathians since the second half of the 19th century. a – 19th century rivers with wide gravel-bed channels typified by bar-braided morphology and lacking riparian forest; b – narrow and deep channels, in some reaches incised to bedrock, formed as a result of channelization; c – channels with island-braided morphology in unmanaged reaches. Contemporary rivers are bounded by floodplain forest.

(Vannote et al., 1980). If terrestrial invertebrates resting or feeding on bankside trees fall on water surface, they can be eaten by fish (Paetzold et al., 2007). Shading provided by trees growing along river margins prevents excessive water warming harmful for coldwater fish; in summer it results in slower changes of water temperature in comparison to rivers lacking the water shading by riparian trees (Simmons et al., 2015). Dense tree canopies reduce the evaporation from water surface (Riis et al., 2020), which is especially important for fish communities during extremely low water stages. Forested floodplains have high hydraulic roughness and thus they tend to slow down flow velocity in floodplain areas, which increases floodwater levels at the site but reduces downstream-recorded peak flows (Thomas and Nisbet, 2007).

The most apparent effect of forest development on the valley floors is the delivery of considerable quantities of large wood to the channels—currently most European rivers store and generate more wood than they did still in the first half of the 20th century (Piégay, 2003). Large wood stored in river channels increases morphological and hydraulic diversity of habitats and in-channel retention of organic matter, provides substrate and a food source for many benthic invertebrates and the shelter from predators for many aquatic organisms (Gurnell et al., 1995; Wyżga et al., 2003). Re-sprouting of the living wood of willows, poplars and alders deposited on gravel bars is the most common process leading to island inception in multi-thread sections of Polish Carpathian rivers (Mikuś et al., 2013, 2019). A major proportion of wood recruitment to the rivers takes place as a result of bank retreat during floods (Wyżga and Zawiejska, 2005, 2010), and subsequent displacement of the wood by floodwaters may lead to its accumulation in critical sites such as bridge cross-sections, where it creates flood hazard to nearby areas of the valley floors (Hajdukiewicz et al., 2016; Ruiz-Villanueva et al., 2017). In larger rivers of the Polish Carpathians, wood can be transported long distances (up to 10 km or more during a flood event) in channelized and incised, single-thread reaches (Mikuś et al., 2016; Wyżga et al., 2017) but is preferentially deposited in wide, multi-thread reaches (Wyżga and Zawiejska, 2010; Wyżga et al., 2017) where vegetative regeneration of living wood pieces substantially reduces wood remobilization by subsequent floods (Mikuś et al., 2016). A long-practiced approach of river managers to reducing wood-related flood hazard through clearing of riparian forests in the vicinity of vulnerable sites such as bridges or urban reaches is thus not only environmentally detrimental but also ineffective. Instead, the hazard should be reduced by replacing bridges supported by piers, prone to wood clogging, with bridges lacking pier(s) in the channel—which would enable undisturbed wood transfer during floods (Wyżga et al., 2016a)—and by preservation or restoration of multi-thread river reaches to allow them to operate as natural wood traps (Wyżga and Zawiejska, 2010; Mikuś et al., 2016).

6. Conclusions

All the analysed rivers of the Polish Carpathians narrowed significantly between the 1870s and 2009, although they differed in the timing and scale of the narrowing. The river narrowing considerably increased the proportion of floodplains in the total area of the river corridors and lateral, higher parts of the former, wide channels reclaimed from the rivers as a result of their channelization and incision became a place of forest development; in the Koszarawa and Raba valleys, forest developed also on parts of the former floodplains following a decline in agricultural and pastoral use of lands with shallow, poor soils. As a result, the proportion of floodplain forest in the corridors of the study rivers increased from 0–7.5% in the 1870s to 28.5–46.5% in 2009. While the increase in forest cover in Carpathian catchments during the 20th century mainly depended on changes in socioeconomic and sociodemographic factors (Munteanu et al., 2014), the expansion of forest on the valley floors of Polish Carpathian rivers primarily reflected the timing and scale of channelization works. A reduction in flow and sediment dynamics

of Carpathian rivers over the 20th century enabled development of islands in their active zones and led to the change from bar-braided to island-braided channel pattern. However, channelization works eliminated islands from most reaches of Polish Carpathian rivers and thus islands persisted only in scarce unmanaged reaches. The expansion of floodplain forests in Carpathian valleys beneficially influences the functioning of river ecosystems but the resultant increased delivery of large wood to river channels may be a cause of flood hazard. Changes in river management practices are thus needed that would allow maximizing the environmental benefits and minimizing the flood hazard resulting from floodplain forest development.

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.

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Appendix A. Supplementary data

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