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CAUSES AND MECHANISMS OF THE DISAPPEARANCE OF BRAIDED CHANNEL PATTERNS (THE EXAMPLE OF THE BIAŁKA RIVER, WESTERN CARPATHIANS)

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Abstract

The channels of multi-threaded (braided) rivers occur commonly in areas that fulfill certain conditions such as substantial influx of bed material and gradients large enough to create significant energy of flowing water. Natural conditions favoring the formation of multithreaded channels are present in the Carpathians in Poland in Podhale – a large basin located in the piedmont area of the high-mountain Tatra massif. The area had experienced glaciation in the Pleistocene. Yet the 20th century – and especially its second half – was a period of rapid and irreversible elimination of braided channels across the region. The Białka is considered to be the last braided river in the Carpathians in Poland. Many parameters like: structure (morphologic reach sequence), degree of braiding (BI index, W/D) and also a number of hydrodynamic ones (unit stream power, critical stress, shear stress, others) were investigated in order to assess a current stage of development of the Białka river channel. The Białka river channel appears to be a complex system with a differentiated structure. Its channel system is a mosaic of different types described by the following sequence: straight-sinuous-braided. It represents an intermediate type that is somewhere between a single- and a multi-threaded channel. Future evolution of the Białka river channel appears to include further degradation and transformation into a poorer channel ecosystem.

Key words

multi-threaded river channel • wandering channel • hydromorphologic analysis • human impact • Białka River • Polish Carpathians

Introduction and purpose

Braided channels evolve thanks to the large gradients of valleys, which increase the lateral supply of material, as well as the balanced energy of flowing water associated with relatively high river channel gradients. Other important factors in braided channel formation include high dynamics in stream discharge, small amount of cohesive or fine-grained material in the structure of the alluvial plain, presence of coarse-grained channel bed material, and one other important factor – an ample supply of debris moving towards the channel (Leopold & Wolman, 1957; Schumm, 1960; Knighton, 1998).

According to Schumm (1985), the presence of excess sediment is a precondition for the occurrence of braided river channels that are assumed to be braided along their entire length.

The inclusion of other factors associated with channel evolution and functioning such as variable rates of debris supply, variable diameter of channel material, variable gradient, variable stream power, and variable environmental conditions in the form of vegetation in the channel contributed to the expansion of the classification to include more channel system types (Church, 1992, 2002). This new classification differentiates multi-threaded channels with respect to non-inundated channel landforms. The surfaces of bars located between channel braids were identified as a bar-braided channel pattern. In addition, channel braids separated by islands were identified as an island-braided channel pattern. An intermediate type was also identified – a channel type between a single-threaded channel and a braided channel, designated a gravel-bed wandering river (Neill, 1973; Church, 1983; Ferguson & Werrity, 1983; Deslonges & Church, 1989; Rinaldi et al., 2016; Wu et al., 2018).

The complexity of braided river channel systems was investigated by Brice (1964, 1975) who created the *channel pattern classification* largely based on channel planar geometry and channel landforms, which made it possible to identify various degrees of braiding. Other approaches use parameters based on the number and/or length of cross bar channels per reach of river relative to reach length – the length of the midline of the widest channel (Bridge, 1993). The evaluation of the location and size of bars and islands makes it possible to show the stage of braided channel development (Germanowski & Schumm, 1993).

Multi-threaded river channels with high energy are characterized by a specific hydrologic regime with frequent and substantial changes in discharge and water level. The consequence of this is variability in stream power across a broad range, and high stream energy leads to periodic increases in the power of erosion together with increase of sediment load (Leopold & Wolman, 1957; Schumm, 1960; Vázquez-Tarrío et al., 2019). Both the strength of erosion and the quantity of gravel are responsible for the maintenance of the pattern of a braided river channel or alternatively its degradation or even complete decline.

Existing knowledge on the link between morphology and stream power as well as other key parameters characterizing bed material transport in braided river channels is not very extensive when it is compared with existing knowledge on other types of rivers and an array of experimental studies (Egozi & Ashmore, 2008; Crosato & Mosselman, 2009; Egozi & Ashmore, 2009; Ziliani et al., 2013; Książek et al., 2020). While it is known that braided river channels are overloaded with sediments, the determination of boundary conditions for the transport of bed material, necessary for the evolution of braided channels, is quite difficult (Thorne, 1997). Braided channels are found in the case of rivers characterized by significant coarseness significant roughness coefficient and strongly affected by the degree of sorting, imbrication, and the hidden grain effect. The shape of gravel-bed material is also quite important (Mueller & Pitlick, 2014). One rather significant difficulty in this type of research is the measurement of key parameters in a rapidly changing multi-channel river environment (Bristow & Best, 1993; Ettema & Armstrong, 2019).

It appears that multi-threaded river channels, both braided and wandering are the most susceptible to changes associated with human impact (Surian & Rinaldi, 2003; Piégay et al., 2006; Surian, 2006). The degradation of these types of channels in the Polish Carpathians is a good example and a warning of problems associated with decline in such valuable river ecosystems (Wyżga, 1993; Zawiejska & Krzemień, 2004; Wyżga, 2007; Gorczyca & Krzemień, 2010). The morphologic parameters' change of Białka channel were discussed by Gorczyca et al. (2018).

Present-day variances in the morphology of the braided channel of the Białka River are the result of long-term evolution across the piedmont of the Tatra Mountains, which may be best described as lateral migration following every major flood event. The present-day river channel of the Białka is the least affected by human impact major river in the Podhale area. It remains as proof of the presence of conditions favorable to the formation of braided channels in the Tatra piedmont area (Baumgart-Kotarba, 1983a; Gorczyca et al., 2011; Radecki-Pawlik, 2011; Wyżga, 2013, Fig. 1). The two remaining braided river channels in the region – the Biały Dunajec and the

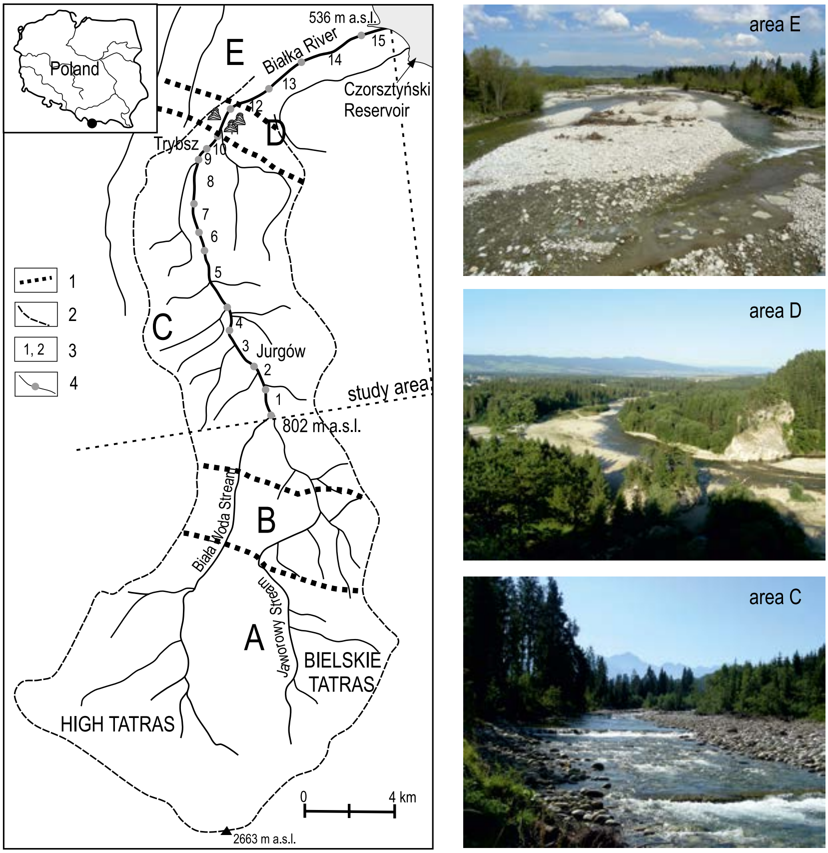

Figure 1. Location of elementary morphologic channel reaches; 1 – boundaries of physical geographic regions; A – Tatra Mountains (High Tatras, Bielskie Tatras), B – Sub-Tatra Basin, C – Gubałowskie Foothills, D – Skalicowy Belt (Kramica Hill, Obłazowa Hill), E – Orawsko-Nowotarska Basin, 2 – catchment boundary, 3 – numeration of morphodynamic reaches, 4 – boundaries of channel reaches

Czarny Dunajec – have already been regulated and degraded to a substantial degree (Krzemień, 2003; Korpak, 2007; Zawiejska et al., 2015). It is highly likely that human impact in the 20th century helped in the narrowing and straightening of their channels even in the case of unregulated reaches.

Human impact also triggered significant changes in the hydromorphologic conditions of braided rivers in other mountainous areas in Europe. Limitation of the supply of gravel material, extraction of river sediments as well as straightening and narrowing of the channels led to the disappearance of braiding in many rivers (Garcia-Ruiz et al., 1997; Kondolf, 1997; Surian & Rinaldi, 2003; Rinaldi et al., 2005; Wohl, 2006; Rączkowska et al., 2012). Rivers more strongly affected by human impact responded more quickly to these changes, especially rivers in catchments more strongly affected by major changes in land use (Lach & Wyżga, 2002; Rinaldi et al., 2005).

Geomorphologic studies continue to examine the causes and mechanisms of the decline of braided river channels in mountainous areas and in their foreland (Surian & Rinaldi, 2003). In many cases, studies emphasize the significance of maintaining a natural river regime, mainly a natural flood regime, as well as the role of the debris supply in the process of maintaining a braided channel (Liébault et al., 2013; Belletti et al., 2015; Surian et al., 2015). The present study is part of the discussion on the decline and maintenance of braided river channels.

The purpose of the study is to show the causes and mechanisms of the decline of a braided river channel on the example of the Białka River in southern Poland. In order to accomplish this goal it is necessary to identify both braided channel patterns as well as hydrodynamic parameters that illustrate natural processes shaping the Białka channel. Only a combination of morphology and channel pattern analysis and river energy data will make it possible to identify channel sections affected by braiding decline and understand its causes.

Study area

Material carried by proglacial and pronival rivers accumulated across the piedmont area of the glaciated Tatras in Poland in the Pleistocene. Alluvial fans were built up by these rivers in the Sub-Tatra Basin and this material then made its way via narrow valleys to the wide Orawsko-Nowotarska Basin. Braided river channels evolved under such conditions in the thick gravel layers of the Tatra piedmont. The Białka was one such braided river channel to emerge in this part of the Carpathians (Fig. 1).

The Białka river catchment covers an area of 232 km^2. More than 60% of its area is that of the High Tatras and the Bielskie Tatras – a high mountain area (Fig. 1). This part of the catchment is not part of the study area discussed in this paper. The study area covered in this paper is a 23 km stretch of the river between its confluence with Jaworowy Stream and its mouth at the Czorsztyński Reservoir. This part of the catchment is formed of flysch as well as a small number of limestone and dolomite outcrops in the Skalicowy Belt. The valley of the Białka is filled with Quaternary formations consisting of thick layers of gravel with sand and silt inserts. The gorge reach between Kramica Hill and Obłazowa Hill is best described as a formation built of rocky Jura limestone of the Czorsztyn series (Birkenmajer, 1979, 2007) (Fig. 1). The upstream gradient is 7.2%, while the middle stream and downstream gradient is less than 2%. Mean discharge at the Trybsz water gauge is 5 m^3·s^{-1}, while spring and summer flood events produce discharge between 200 and 300 m^3·s^{-1}.

The Białka catchment has an elongated shape, which divides into two sections in the upstream area. The Biała Woda Stream and Jaworowy Stream occupy 35% and 29% of the total area of the catchment, respectively. In the downstream area of the catchment, which is the study area in this paper, the Białka River is not joined by any larger tributary – one which could effectively alter flood hydrographs (Fig. 1).

The Białka River is characterized by a snow and rain hydrologic regime that remains under the control of conditions in the high mountain part of the catchment. The river has two water gauging sites operated by Poland's State Hydrologic and Meteorological Service (Łysa Polana and Trybsz). Observation data from the last two decades (1994-2014) indicate that larger than average flood events occur in May due to the rapid melting of snow in the higher Tatra part of the catchment. A second period characterized by smaller floods consists of the summer months of June and July when heavy rainfall and continuous rainfall yield large amounts of water in the catchment.

The mean discharge maximum for the Białka River occurs in July. In 1934 the river experienced its largest measured discharge at 433 $m^3 \cdot s^{-1}$ (Baumgart-Kotarba, 1983a), while its mean discharge for the period 1994-2014 stands at 7.5 $m^3 \cdot s^{-1}$. Minimum water levels for the period 1995-2010 for the Trybsz gauging site indicate channel deepening (Fig. 2), with the total increase in depth at 51 cm or 3.4 cm per year. The deepening process has halted over the last four years.

Methods

Field work

Field work in the form of channel and floodplain surveys was performed in the month of August of 2009 and in September of 2010. Limited geomorphological mapping and field measurements were continued in the years 2012-2018. A questionnaire was used in the survey process along with field instructions produced by the Department of Geomorphology at the Institute of Geography and Spatial Management at Jagiellonian University (Kamykowska et al., 1999). The course followed by the river channel as well as the set of landforms identified in the channel based on orthophotos and digital terrain model (DTM from Airborne LiDAR; 4 point m^{-2}, created in 2010-2013) were used to divide the Białka River channel into basic hydromorphologic reaches. The river channel was examined utilizing morphometric and morphologic parameters (48 qualitative and 57 quantitative pieces of data from Kamykowska et al., 1999). The log used to collect data covers the following four groups of data: (1) initial information, (2) channel parameters, (3) hydrodynamic parameters, and (4) hydrometeorologic parameters of the studied period of time. The parameters included channel features such as location, geology, morphometry, cross-section, longitudinal profile, banks and river-bottom features, sediments and man-made features (river training and gravel mining) as well as hydrodynamic data and hydrometeorologic data for the research period and overall catchments characteristics. Quantitative information were used to calculate indices characterizing the studied channel river.

In the measurement process a total of 23 km of the Białka River were surveyed and

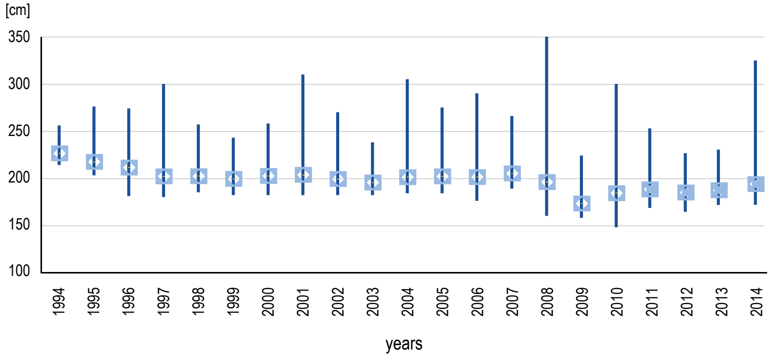

Figure 2. Minimum, mean, and maximum water levels in the years 1995 – 2014 measured at the Trybsz gauging site

15 reaches with an uniform structure and different from the neighbouring reaches of river were identified. The field surveys were supplemented with morphometric measurements of the channel and its various landforms using an orthophotomap made in 2009, 2013, 2017 (Head Office of Geodesy and Cartography_ https://www.gov.pl/web/gugik-en) using QGIS software. A typology of each studied reach of river was produced using the reach boundary method based on all channel characteristics, channel landforms, and gravel characteristics (Kaszowski & Krzemień, 1999; Fig. 3). Finally, four types of Białka channels have been distinguished. The fractions of channel gravel was identified for 26 gauging sites in 2011 (Witek, 2011). The procedure used was the Wolman (1954) pebble count method (sampling 100 pebbles in a grid pattern). The samples were obtained from the surface of channel bars and the level of bankfull discharge.

Indexes of braiding

The parameters of the river channel and channels forms measured during field studies and determined by GIS analyses were used to calculate the braiding indexes. Braiding index values were calculated based on a detailed analysis of the distribution and morphometry of channel landforms in each of the 15 studied reaches of the Białka River:

braiding index (*BI*) (Brice, 1964) is defined as follows:

$$BI = 2(\Sigma Li)/Lr$$

where:

$\Sigma\ Li$ – is the total length of bars and/or islands in the reach, and

Lr – is the length of the reach measured midway between banks.

A total braiding index of 1.50 was selected by Brice to differentiate braided from non-braided reaches of river (Yeasmin & Islam, 2011). Braiding index values were calculated using a modified version that incorporates the number of channel landforms. The Brice (1964) method was used to identify three types of the index of braiding: (1) total (all mid-river landforms), (2) stabilized (islands only), (3) transient (midriver bars only). These indices of braiding allowed to determine the development stages of the river channel.

Moreover, the river channel was characterized with use of the following indices:

- degree of braiding (Brice, 1975) – percentage of the length of the reach with a multithreaded system relative to the length of the entire studied reach of river,
- character of braiding (Brice, 1975) and pattern of development of braided channel – equilibrium (A), aggrading (B), and degrading (C) gravel bed channels (Germanowski & Schumm, 1993),
- *W/D* ratio – width to depth ratio of river channel (Selby, 1985) (Fig. 4).

Hydrodynamic parameters

A hydraulic model based on MIKE 11 software (by DHI) was created in order to determine the hydraulic characteristics of the Białka river channel. This is a one-dimensional model that solves Saint Venant equations in fully dynamic form and uses a numerical AbbotIonescu solution scheme. The hydraulic model's boundary conditions consisted of the Białka Łysa Polana water gauge (initial discharge) and the Czorsztynski Reservoir (downstream boundary condition).

Boundary conditions were determined based on increases in the catchment area and were defined as tributaries concentrated at the mouth of lower order watercourses as well as distributed tributaries representing broad area runoff from a differential catchment. The horizontal structure of the river network was determined using a digital elevation model, while channel geometry was introduced in the form of geodetic cross sections. A total of 70 cross sections located 400 to 500 meters apart were identified for the analyzed stretch of river using GPS-RTK. Channel cross sections measured in the field were supplemented later with data on the terrace section generated using a digital elevation

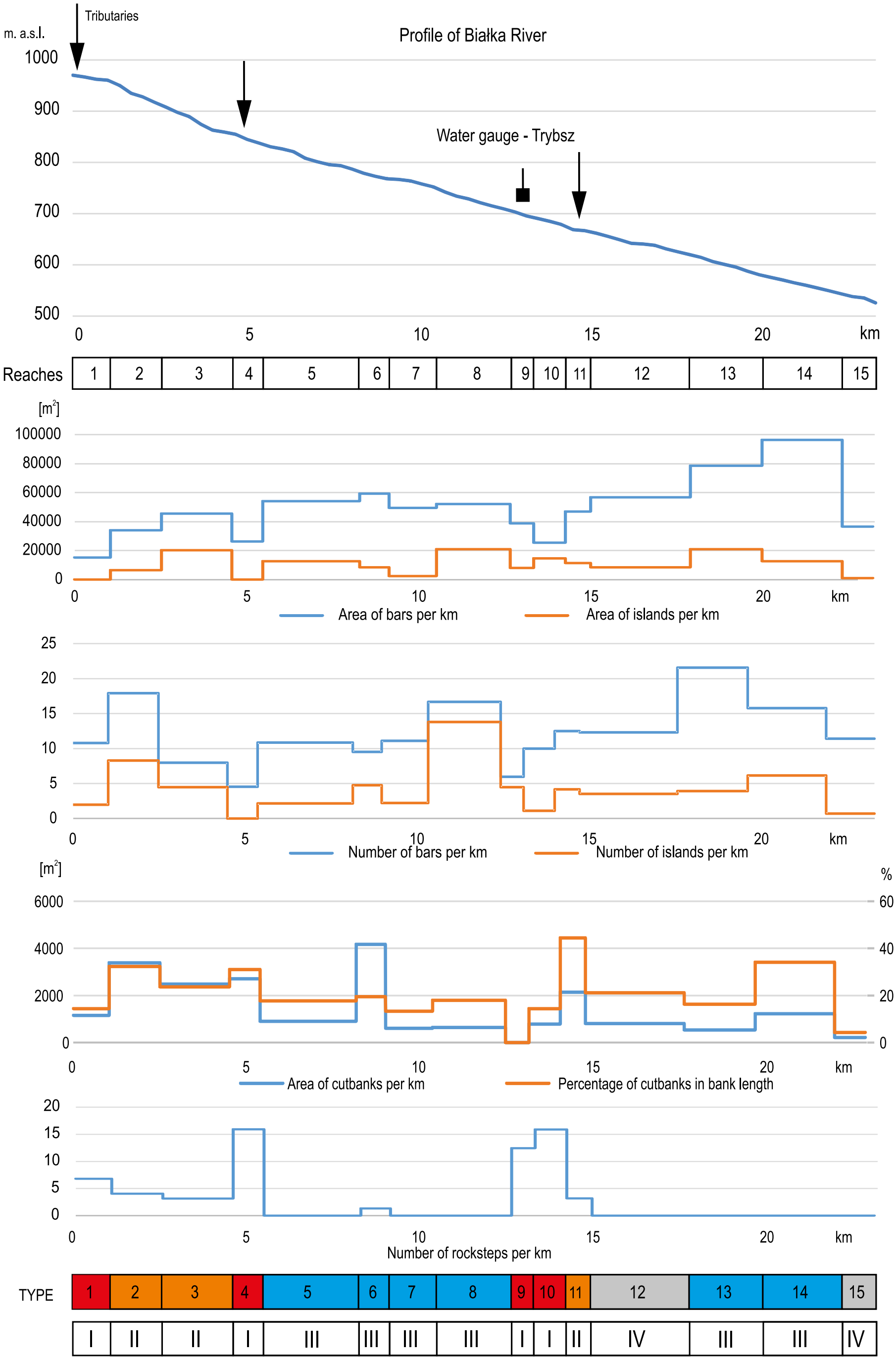

Figure 3. Characteristics of the Białka river channel and channel types: Type I – incision channel, Type II – incision and deposition channel, Type III – channel that is characterized by deposition and bank erosion, Type IV – channel affected by human impact

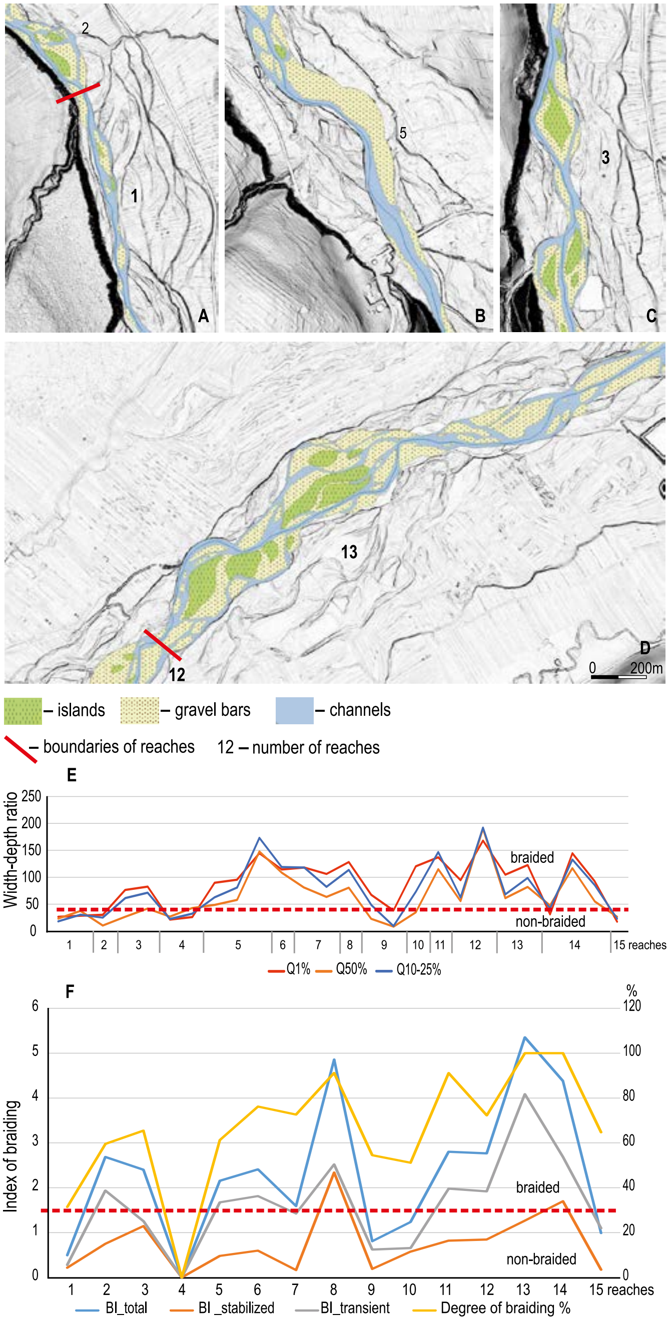

Figure 4. Channel schemes, examples of various river channel types; A – degraded single-threaded channel, B, C – wandering channel, D – braided channel; Indexes of braiding; E – W/D index for water Q1%, Q50% and Q10 to 25%; F – index of braiding according to Brice (1964, 1975)

model. Bridge structures found crossing the river were also surveyed geodetically and were entered into the model as a pair of culvert and wire structures.

Bed roughness coefficients were determined based on an orthophotomap. The model was calibrated using historical hydrologic data (*discharge versus water depth* and *range of inundation*) based on the flood of 2010. It was then evaluated using data from the independent gauging station Trybsz at Białka River. A calculation time step of 20 seconds was used for the simulation for the period from May 1, 2010 to May 30, 2010. Simulations were performed for discharge (probability of exceedance: 50%, 25%, 10%, 1% – the data was obtained from the IMWG (Institute of Meteorology and Water Management, Poland), which provided basic parameters such as discharge Q ($m^3 \cdot s^{-1}$) and elevation above sea level H as well as additional parameters such as mean velocity at cross section v ($m^3 \cdot s^{-1}$), the slope of water table I S (-), and width of wet channel w (m).

Hydrodynamic parameters were calculated including unit stream power, shear stress, and discharge capable of transporting bed material. Critical stresses were calculated with the use of Mayer-Peter and Müller formula. The bed material characteristics was made by in situ measurements. Data for shear forces calculation was obtained from the Mike 11 model.

Unit stream power was the first parameter calculated describing the level of energy available to erosion and transport processes operating in a river channel (Bagnold, 1966; Rhoads, 1987). It is the amount of energy dissipated per one square meter (on the length of 1 meter and averaged on the channel width) for a given discharge value; it is expressed in $W \cdot m^{-2}$

$$\omega = \frac{\rho g Q S}{\mathrm{w}} \qquad (1)$$

where:
ρ – is the density of water,
g – is the acceleration due to gravity,
Q – is the mean annual flood discharge,
S – is the channel slope, and
w – is the bankfull channel width.

Stream power is a useful variable for comparing channel energy between rivers (Magilligan, 1992; Darley, 1996; Nanson & Knighton, 1996; Fonstad, 2003; Ferguson, 2005).

The intensity of fluvial processes was described here with critical stresses on multifraction bed material (Bartnik, 1992; Michalik 1990; Shields, 1936; Wang, 1977; Strużyński et al., 2013a; Przyborowski et al., 2022) and compared to the change in unit stream power (Knighton, 1998; Bojarski et al., 2005).

Given Lane's Theory, which states that the predominance of erosion and accumulation is reflected by the ratio of the parameters of flowing water to sediment supply and sediment characterization (Rosgen, 1996), this paper describes balanced fluvial processes in terms of water discharge reflected by bedload incipient motion. Due to the variable energy of flowing water in sustainable sections, the processes of creating armored bottom and bed material mixing during massive transportation should alternate. Bed armouring has been identified using Armour program (Bartnik & Strużyński, 1999). This software calculates changes of granulometric composition of bed cover basing on the Gessler's method (Simons & Sentürk, 1977). While bed material can be divided into fractions every of them varies with critical stresses. This method lets calculate the probability of grain movement for every fraction. Basing on changing probability of different fraction not to be moved, the Armour program calculates the change of granulometric distribution of bed cover during the changing discharge. Results obtained from the program were used by authors to find the discharge specific for armouring, maximum armour and then, destruction of bed cover (transportation of all fractions).

In most cases intense fluvial processes start in natural rivers within this range of bankful flow and armouring under low or average flow conditions (Pickup & Warner, 1976; Strużyński et al., 2013b). Progressive erosion can be interlaced with bed armoring. High erosion can finally lead to bed incision and even lowering of the channel to the bedrock (Strużyński et al., 2013b). An armored bed indicates, in most cases, an imbalance in the hydrodynamics of river channels, especially braiding channels. The methodology for estimating armored coatings for gravel-bed rivers studied in this paper is based by Bartnik and Strużyński (1999) on the Wang formula (1977) as well as takes into consideration the stochastic nature of bedload transport patterns proposed by Gessler (Simons & Sentürk, 1977). We analyzed two fractions, d_{50} and d_{90} because they reflect different phenomenon appearing in the river channel. Large share of this fraction in the bed volume content indicate high motion of bed cover and the transport of mixed bed cover. This can be found in reaches characterized by high rates of bed movement. The size of d_{50} within stable reaches becomes much smaller than biggest ones. Predominance of armoring process can be found in reaches afflicted with the low rates of debris alimentation or relatively low energy of the water stream. The classification of movement for "rough" bed flow conditions is done herein with the use of a bed stabilizing fraction ($d_{90\%}$) (Bray, 2002). Destroying armored bed starts from taking fraction d_{90} into motion (Bartnik, 1992). The simplified methodology of channel hydro- and morphodynamics evaluation is based on the method proposed by Strużyński (2013).

The procedure for all cross sections consists of the following steps:

- evaluation of channel capacity (Fig. 5A),
- determination of maximum stress (Fig. 5B),
- estimation of bed armoring for grain size data (Fig. 5C),
- determination of critical stress for the bed stabilizing fraction d_{90} (Fig. 5C),
- classification of bedload mobility in separated reaches (Fig. 5D).

The procedure above defines 6 classes of bedload mobility (Tab. 1). Calculated stress and stream power change for individual cross sections and reaches are presented using graphs (Fig. 5b – unit stream power, 5c – shear stress). On figure 5c water level resulted with the incipient motion of bed material fractions d_{50} and d_{90} has been drawn. Bed stability analysis results are discussed in the context of influence on channel morphology (Fig. 6).

Table 1. Stability of channel bed cover in a river with a coarse bed

Value	Description	Discharge from p%	Discharge to p%
0	virtually immobile	> 1	-
1	very rarely moved	1	5
2	rarely moved	5	10
3	quite mobile	10	25
4	mobile	25	50
5	highly mobile	< 50	-

Discharge p% – the maximum annual peak discharge with given occurrence frequency

Results

Białka channel patterns and morphology

The Białka river channel is characterized by significant physical diversity. A total of 15 structurally uniform reaches have been identified along the length of the Białka (Figs. 2, 3). Each of 15 identified river channel reaches was classified into one of four channel types characterized by predominant processes: Type 1 – Incision channel, Type II – Incision and deposition channel, Type III – Channel that is characterized by deposition and bank erosion, Type IV – Channel affected by human impact (Fig. 3).

Type I is characterized by a predominance of channel incision. This channel type applies to channel reaches 1 and 4 as well as 9 to 10. Reaches 1, 4, 9, and 10 are single-threaded reaches with few accumulation landforms. The river channel was incised as deep as 2.5 m over most of the length of these reaches. Channels of this type are also characterized by a large surface of bedrock r with multiple rock steps – most of these are low – up to 0.5 m. Some steps reach 1.5 m.

Type II applies to channel reaches 2, 3, and 11. Type II includes much more accumulation landforms than Type I, including a very

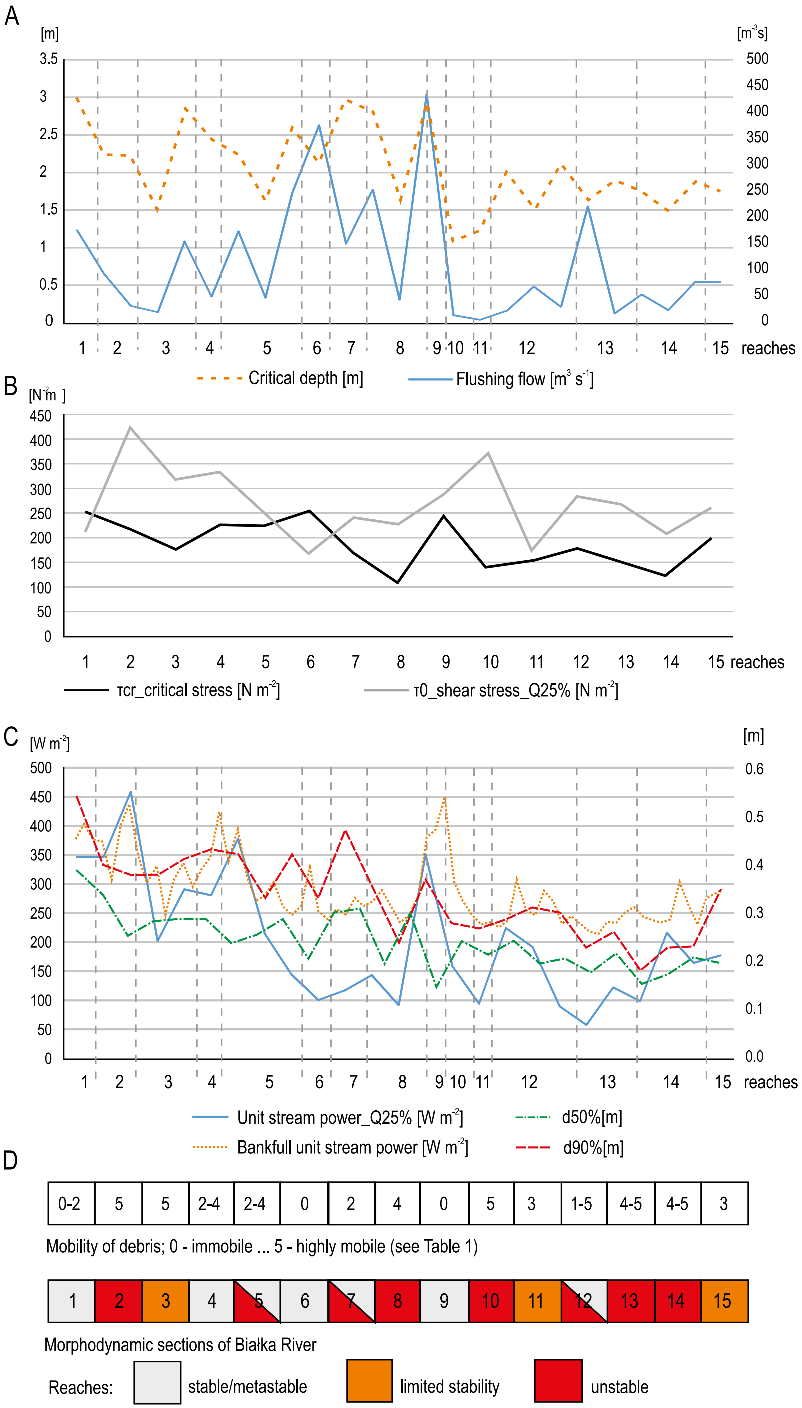

Figure 5. Stable reaches, somewhat stable reaches, and unstable reaches identified on the basis of hydraulic parameters, bedload mobility, and fraction of bed material (A, B, C, D)

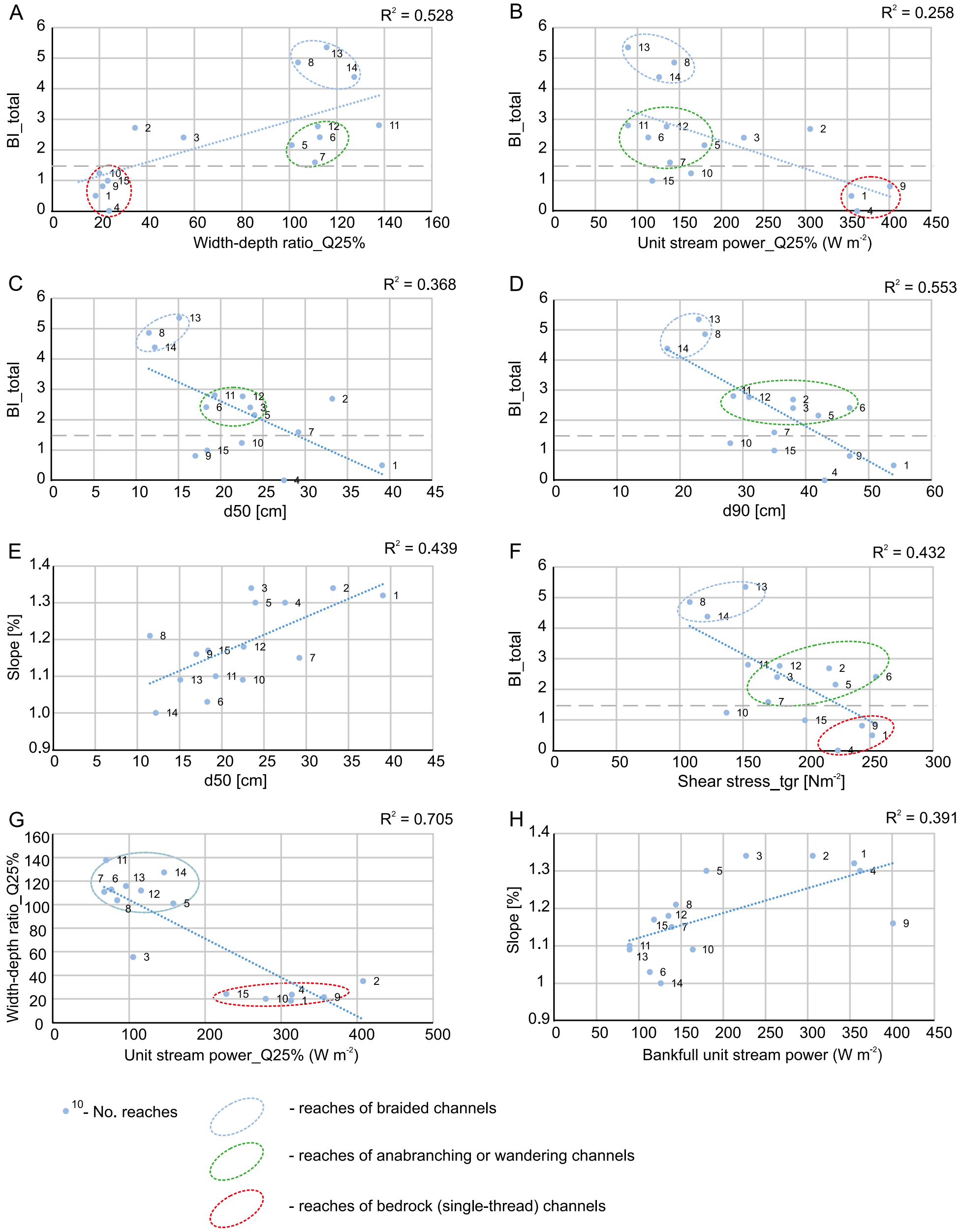

Figure 6. Relationships between hydrodynamic and morphologic parameters and braiding indexes characterizing the Białka river channel

large number of lateral bars and some mid-river bars as well. Type II includes a maximum two threads. Substantial erosion in the river channel is confirmed by local rock outcrops and rock steps (Fig. 3). Present-day channel erosion associated with both Type 1 and Type 2 is marked by the relief of the alluvial plain with its dry hanging channel bends and isolated channel bends. This shows the braided past of the studied stretch of the Białka River.

Type III applies to channel reaches 5 to 8 as well as 13 and 14. These multi-threaded and locally sinuous channels cut into a wide valley floor built of gravel. These areas are, for the most part, characterized by deposition and redeposition of transported material as well as by riverbank erosion. The key feature of the river channel in this case is numerous lateral bars, mid-river bars, islands, and minor channels, which indicate substantial channel migration. Reaches 13 to 15 of the Białka River are well-developed braided reaches featuring a channel migration pathway as wide as 220 m. Riverbank erosion and accumulation can freely occur along this stretch of river. The maximum width of the channel migration zone is 350 m (Fig. 4). Investigations performed by Nowak (2022) within reaches numbered in this paper as 14 and 15 confirm the high mobility of the bed load while maintaining the vertical arrangement of this watercourse.

Type IV applies to channel reaches 12 and 15, both of which have been regulated to a substantial degree. Reach 12 features a channel that cuts into alluvial material and possesses two or three secondary threads depending on location. However, the main channel of this reach has an artificially increased gradient and is deeper than the remaining secondary threads. Reach 15 is the mouth reach of the Białka River and terminates at the Czorsztyński Reservoir. This reach is often dredged and has been reduced to a single channel.

The Białka river channel is characterized by a uniform gradient for the most part along the entire study length. Only the upstream part of the river channel features more variable characteristics and uneven longitudinal

Table 2. Characteristics of the studied river channel reaches

Reach no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Slope [%]	1.32	1.34	1.34	1.3	1.3-1.6	1.03	1.15	1.21	1.16	1.09	1.1	1.18	1.09	1.0	1.17
BI (Brice 1964)	0.5	2.7	2.4	0.0	2.2	2.4	1.6	4.9	0.8	1.2	2.8	2.8	5.4	4.4	1.0
Active threads	1	1-2	1-2	1	1-3	1	1	2-3	1	1	1-2	1-2	2-3	2-4	1
Maximum no. of threads	1	3	2	1	3	2	2	3	1	1	2	4	3	4	1
Degree of braiding / share of multithreaded channel (Brice 1975)	31.5	59.5	65.4	0.0	61.2	76.2	72.6	91.2	54.5	51.1	91.1	72.3	100	100	64.7
Evolution stage of braided river (Germanowski and Schumm 1993)*	-	C	C	-	B/C	C	C	B/C	-	C	C	C/B	B/C	B/C	C
Reach type (Krzemień 2012)**	I	II	II	I	III	III	III	III	I	I	IV	III	III	III	IV
River types (channel morphologies) (Rinaldi et al., 2016) ***	St	St/ Wa	Wa	St	Ab/ Wa	Wa	Wa/ Sb	IB/ Ab	St	Wa/ Sb	Wa/ IB	Wa/ IB	IB	IB	Wa (a)

* A – equilibrium; B – aggrading and C – degrading;

** Type: I – incision channel, Type II – incision and deposition channel, Type III – channel that is characterized by deposition and bank erosion, Type IV – channel affected by human impact;

*** Channel morphologies: St – Single-thread - Straight; Sb – Sinuous with alternate bars; B – Braided; IB – Island-Braided; Ab – Anabranching (high energy); Wa – Wandering; a – anthropopressure profile. Uneven profile usually follow incision patterns and the outcrops and rock thresholds produced by erosion. Reaches cut into alluvial material and covered with granitoid pebbles are characterized by a regular longitudinal profile. The largest channel gradient occurs along the first five reaches of river in the Tatra piedmont area. The river channel gradient decreases starting with reach 6 and the decrease continues as far as reach 8 (Fig. 3, Tab. 2).

The cross section of a stretch with incision as the primary natural process usually consists of a single channel whose cross section resembles a trapezoid or rectangle (reaches 1, 4, 9). Two or four small threads, best described as elliptical in shape, can be found in the cross section of deposition type stretches of river affected by riverbank erosion (reaches 8, 12-14). In the case where one of the threads possesses a channel that cuts deeper into bedrock, its cross section will tend to resemble a trapezoid (reaches 2, 3, 5; Fig. 3)

Braiding indexes

The distribution of bars and islands in the Białka river channel varies substantially depending on location. Type I reaches are dominated by lateral bars. Types II, III, and IV are characterized by accumulation and deposition processes and a large number of all types of accumulation landforms such as lateral bars, mid-river bars and islands. Differences are manifested in most cases in the total surface area of bars and islands and in their number (Fig. 3). Type III reaches feature a large number of bars and islands, which also happen to be quite large in terms of surface area.

The Brice (1975) braiding index (*BI*) was calculated for: (1) all mid-river landforms (total *BI*), (2) only for mid-river bars (transient *BI*), and (3) only for islands (stabilized *BI*). The assumed minimum *BI* value of 1.5 (Yeasmin & Islam 2011) divides the Białka river channel into braided stretches (reaches 2, 3, 5-8, 11-14) and non-braided stretches (reaches 1, 4, 9, 10, 15). Stabilized *BI* values are highest for reaches 3, 8, 13, and 14 (Fig. 4, Tab. 2). The pattern of these reaches may be considered to be the most stable of the studied braided reaches of river.

The distribution of *BI*-transient values closely resembles that of *BI*-total and illustrates the significant role of mid-river bars in the morphology and functioning of the Białka channel. Braiding index values are high (Brice, 1975) and most reaches of river fit into two intervals: 35% to 65% and over 65%. The greatest degree of braiding was calculated for reaches 6 to 8 and 11 to 14 (Fig. 4). These reaches possess a multi-threaded channel that functions both at low and medium discharge. In the case of the other reaches, a broad multi-threaded channel does not necessarily imply water flow via all secondary threads at all times.

The *W/D* index compares channel bank width to channel depth (Carson, 1984). The index is designed to differentiate braided channel reaches and non-braided channel reaches – a value of 40 is used as a boundary value. Index values calculated for *Q1%* and *Q50%* as well as bank width in the range from *Q10%* to *Q25%* classify reaches 1, 4, 9, 10, and 15 as nonbraided. The highest *W/D* values were calculated for reaches 5, 6, 7, 8, 11, 12, and 14 (Fig. 4).

The largest undercut of riverbanks surfaces are found upstream and this is determined by the characteristics of local bedrock. The incisions in the Flysch bedrock tend to be substantial – 5 to 6 meters high – and can reach a height of 20 meters. Downstream reaches of the river are characterized by very small, but very frequently occurring, undercut of riverbanks surfaces, especially within a large fan formed of river sediment. While the number of bank incisions is large, their height is rather small, one or two meters, not exceeding 3 meters. If the surface area of incisions is excluded from the analysis, then the length of riverbank incisions is comparable for upstream and downstream reaches of river – between 20% and 30% of riverbank length affected by bank erosion (Fig. 3).

Channel bed material

The quantity of supplied material follows a decreasing pattern in the downstream direction in the Białka river channel, while the mean diameter of smaller gravel d_{50} varies less than does the larger fraction d_{90} along the entire studied length of the river. This difference is especially noticeable for the upstream section and the middle section of the river, where bed material size is much larger than that for the downstream section. In reaches 1 to 4, the largest bed material varies little in size, ranging from 55 to 62 cm. In reaches 5 to 9, the largest pebbles range from 40 to 55 cm in size. Maximum bed material size starts to decrease somewhat starting with reach 10 (35 to 41 cm).

Channel hydrodynamics

The Białka River is characterized by substantial differences in channel patterns and morphology (width, depth, number of threads) and bed material from one channel reach to another, which results in very different functional conditions in the river channel. The boundary parameters can be both, the shear stress and stream power. Bed stability had been assessed by the use of shear stress for grain size d_{90} which stabilizes the bed surface/cover. The hydraulic parameters were compared with the stream power calculated for the chosen section.

Unit stream power is a parameter that identifies equilibrium conditions or the lack thereof in a river such as the Białka. There are few sites on this river where this parameter did attain low values between 35 and 100 W m^{-2}. Values in this range were noted only for reaches 8 and 11 to 15 (Fig. 5). All of these reaches are characterized by equilibrium at a low level of debris supply. In most cases, measured unit stream power values ranged from 100 to 300 W m^{-2}. These reaches of river are characterized by very large stream energy and equilibrium can only be maintained in the presence of a steady supply of debris from riverbanks and local tributaries. Values higher than 300 W m^{-2} were noted for reaches 1, 2, 4, and 9 (Fig. 5). The effects of strong continuous incision make these four reaches of river unstable.

Rates of water flow resulting in armor scouring and bedload transport tend to vary strongly along the length of the Białka river channel. The largest variation in bed cover scouring discharge (the highest peaks) ranging between 0.2 to 2.5 and even 3.0 m reflects the highest noted bankfull discharge values, and the largest variances were observed in the middle section of the Białka river channel (reaches 6, 7, 9; Fig. 5). The discharge values were significantly lower in the multi-threaded downstream section of the river (reaches 11, 12, 14, 15; Fig. 5). Lower than average values were also noted for reaches characterized by intense bed erosion (reaches 2, 3, 4; Fig. 5).

The middle section of the Białka river channel appears to be the most stable. In this section of river, the discharge needed to trigger the movement of bed material ranges between a high value of 200 m^3·s^{-1} and an even higher value of 400 m^3·s^{-1} (Fig. 5). Very large fluctuations in free capacity can be observed from one reach to another and even within the same reach in the Białka river channel. Stable and unstable reaches intertwine along the entire length of the studied stretch of river. Only the downstream stretch from reach 12 to 15 was characterized by similar discharge values, which suggests a relatively unstable river channel. There was one exception in this particular stretch of river – that of the area located close to a bridge (reach 12).

Six classes of bed material stability were identified ranging from immobile to highly mobile. At most measurement sites, the bed material cover is characterized by average or very high mobility (Fig. 5). The correlation between bed stability described by critical discharge and bed stability index is 0.86. Both parameters indicate that most reaches lose stability with average flows.

The stability of channel reaches along the entire studied length of the Białka River was determined based on an analysis of channel hydrodynamics in the form of unit stream power and shear stress compared to critical stress (*t0* i *tcr*) for *Q25%*, bed material fraction (d_{90}), and the mobility index for channel material (Fig. 5). Reaches 1, 4, 6, and 9 featuring large fractions (d_{90} over 40 cm) in a relatively immobile state, along with large unit stream power values as well as growing shear stress are considered stable reaches of river channel. These four reaches cut deep into the bedrock and feature significant bar imbrication. Reaches 5, 7, and 12 can be described as reaches with a complex structure and functioning. Hydrodynamic parameters do vary significantly from site to site (Fig. 5). In these cases, stream power is average, with increasing shear stress, and the amount of bed material is small and it is only mobile to an average extent. The remaining reaches are unstable or stable to a limited extent. These types of reaches possess a mobile gravel load, finer fractions, and the energy needed to facilitate the transport and deposition of bed material.

Discussion

Planform and morphology of river channel

Differences in the pattern and morphology of the Białka river channel in its longitudinal profile and its division into morphologic reaches are largely associated with differences in channel hydraulic parameters (Fig. 5). It is frequently the case that key parameters such as unit stream power, bankfull discharge, discharge, grain size that tears away river channel armor, unit stream power and shear stress vary much more than the channel pattern itself would suggest (Figs. 3, 5). This indicates that channel morphology is not homogeneous and it changes across short distances within the morphologic reaches identified in the field during the study period. Another reason of such a not perfect fit is the transported load supply changes within a river profile as well as changes in natural geologic pattern (influencing depth/width ratio of the channel).

The Białka river channel follows an alternating pattern of stable bedrock reaches and unstable alluvial reaches (Figs. 3, 5). The unit stream power of most channel reaches is quite high, which leads to incision in the presence of a reduced supply of debris.

Boundary values such as a *BI* of 1.5 (Brice 1975), *W/D* of 50 (Carson, 1984), as well as unit stream power over 35 W m^{-2} (Carson 1984) or 50 to 300 W m^{-2} (Nanson & Croke, 1992; Rinaldi et al., 2016) can be used to identify braided reaches and non-braided reaches of river. Nearly half the studied reaches were found to meet the criteria for braiding (Figs. 4, 6). Certain reaches can be described as "strongly braided" (island braiding and anabranching) and others as transitionally braided (wandering type) (Figs. 3, 4, 5, 6). Braided reaches are those characterized by deposition as well as riverbank erosion. Incision is present in the latter case at some locations. Another distinct group of reaches can be described as not already braidedand currently subject to erosion as well as characterized by very large unit stream power and large pieces of bed material (Fig. 5). This includes straight channels with riffle pools.

External factors affecting channel degradation

The causes of the degradation of the Białka channel and the disappearance of braiding can be a reduction of the supply of debris or the lack thereof. The present-day Białka River "inherited" its supply of channel bed material from its era of braided development under the fluvioglacial conditions present across the piedmont of the glaciated Tatras at the time (Baumgart-Kotarba, 1983a). According to Baumgart-Kotarba (1983a), the only debris supplied from the Tatras today is sandy material and fine gravel, while larger pieces of debris are being held behind by moraine boulders in the Tatra Mts.

Currently, material for transportation is supplied by bank erosion along the alluvial plain and incisions in flysch rock as well as via tributaries. The shortage of bed material in the Białka River as well as increasing human impact in the form of changing land use constitute favorable conditions for incision at the expense of bank erosion. Over the last few centuries a leading source of clastic material supplied to the Białka channel has been arable land, which constituted about 65% of all agricultural land in the 20th century in the study area (Górz, 1994; Bryła et al., 2021). The share of arable land began to decline in the 1990s when Poland began its political and economic transition. By 2005 the share of arable land had declined to 29% of all agricultural land, being replaced by meadows and pastures (71% of all farmland) (www.BDL.stat.gov.pl). This then led to a decline in the supply of debris to the Białka River and to other Carpathian rivers (Wyżga et al., 2013). Nanson and Knighton (1996) analyzed a similar pattern for the Bella Coola River in western Canada. Over the last century, multiple reaches of this river have changed from unstable reaches characterized by anabranching and large islands filled with vegetation to more stable single-threaded sinuous channels. The cause of this slow change was found to be a reduced supply of debris making its way to the Bella Coola river channel.

Another reason for the disappearance of a braided channel may be human impact. The Białka River has not been regulated extensively compared with other rivers in the Carpathian Mountains in Poland (Zawiejska & Krzemień, 2004; Korpak, 2007; Wyżga, 2008; Gurnell et al., 2009; Gorczyca & Krzemień, 2010). Structures built within the mouth reach of the river in the 1960s were later destroyed by several floods (Baumgart-Kotarba, 1983a, b). While this is the most braided reach of the river today, it retains a much narrower zone of channel migration than it did prior to regulation in the 1960s (Baumgart-Kotarba, 1983a, b; Gorczyca & Krzemień, 2010; Hajdukiewicz et al., 2019). Another key problem has been that of channel bed material extraction. Additionaly, large pieces of bed material (20-30 cm of diameter) are extracted for construction and decorative purposes. Gravel and boulders extraction distorts bed material transport at flood stages (Korpak et al., 2009; Gorczyca & Krzemień, 2010; Hajdukiewicz & Wyżga, 2013).

In recent decades, many fluvial studies have emphasized the role of land vegetation in the formation and transformation of river channels (Hey & Thorne, 1986; Hickin, 1984; Hupp & Osterkamp, 1996; Abernethy & Rutherfurd, 1998). Vegetation impacts the hydraulics of flow as well as aggradation, bank stability, and the emergence of multiple channels (Thorne, 1990; Hupp & Osterkamp, 1996; Bendix & Hupp, 2000; Gurnell et al., 2001). Research by Gran and Paola (2001) as well as Tal and Paola (2007) suggests that vegetation plays a fundamental role in the conversion of multi-threaded river channels into single-threaded river channels.

Research by Baumgart-Kotarba (1983a) discusses major changes in the braided Białka river channel and channel migration pathway due to the encroachment of vegetation on bars. The onset of widespread vegetation growth on bars and their gradual stabilization are usually noted two or three years following a major flood event. Baumgart-Kotarba (1983a,b) asserts that willow (*Salix incana*) and alder (*Alnus incana*) trees encroach upon bars situated outside of the reach of maximum annual discharge – following 5 to 7 years without a flood event. Smaller bars combine into larger bars and become stabilized by vegetation – subsequently to become islands – which is the next major step in the conversion of river channel migration pathways into alluvial plains.

Baumgart-Kotarba (1983a) indicates that an alluvial plain evolves due to lateral shifts associated with the migration of river channels. The question is whether this functional model is still representative of the Białka River today. Perhaps incision has created incisions in a permanent sense that make the main channel immobile and side channels dry up to the point where floods are no longer able to shift channels sideways and fragment channel bars.

Large landforms can be observed in the Białka river channel today due to the merger of bars and islands. Inactive channels can be easily observed across combined bars. Some of the inactive channels are hung (about 2 m above the main channel's floor) and dry and remain only in fragmentary form. The next stage of the degradation process involves the conversion of these large mid-river landforms into lateral landforms as well as the "attachment" of islands to the alluvial plain (Figs. 4, 7). When this process is combined with the large energy of a high mountain river and high unit stream power values as well as local human impact, the linkage of channel landforms becomes also accompanied by incision. The largest river channel cuts deep into the channel floor and it becomes the permanent channel in a given channel system, which ultimately leads to the loss of multi-threading.

A good example of gradual change from an anabranching system with two main spurs and a large island to a narrow multi-threaded channel is reach 8, which is characterized by a high index of braiding value. When this river channel was observed on maps from the 1980s (Baumgart-Kotarba, 1983a) and compared with the present-day channel, it is quite easy to observe a gradual process of degradation in the braided channel along with the growth of the alluvial plain at the expense of the channel migration zone. In addition, large incisions made by the main channel in relation to the size of the alluvial plain make sideways channel migration impossible (Fig. 7).

Stages of development of river channel

The Białka river channel appears to be a complex system. Parameters and indexes that describe it as well as the relationship between *BI* and bed material fractions (d_{50} and d_{90}) and river channel gradient, shear stress, and unit stream power make it possible to identify three distinct groups of channel reaches (Fig. 6). The first braiding group includes only three reaches characterized by the highest values of *BI* and *W/D* and relatively low values of unit stream power. Reaches in Group One feature fine bed material, no imbrication, and are characterized by low stability leading to frequent motion of bed material. Group Two includes the largest number of reaches and consists of wandering and anabranching reaches, which have evolved from a degraded braided channel or gradual plant overgrowth (Figs. 5, 6). A lower *BI* value results from bar imbrication, more stable bed material, mergers of bars and islands, and conversion of mid-river bars into lateral bars. This helps the main thread become a permanent channel at the expense of secondary threads and in conjunction with stronger incision. Group Three consists of reaches with a rocky floor affected by erosion. These reaches of river channel are stable and cut deep into the channel floor and follow a set course with little probability of planar development (Figs. 5, 6).

A conceptual model of braided river development (Fig. 7) is used to show several stages of development in the braided Białka river channel with only a limited debris supply. The first stage is that of a braided river that receives large quantities of bed material. The river at this stage is wide and its channel is shallow. It also features numerous mid-river landforms. This initial development stage is characterized by unit stream power values of 50 to 150 W m^{-2} and mobile bed cover along with a diverse granulometry of material covering the surface of river channel landforms.

The second stage is a braided channel degradation stage (Germanowski & Schumm, 1993). This is a transitional stage from a shallow and wide braided channel to a channel with limited lateral erosion and accelerated incision. Channel deepening leads to the formation of a wandering river channel with a confined primary channel, large bars and islands, islands that merge with the floodplain, and vegetation that substantially stabilizes channel landforms (Reinfelds & Nanson, 1993; Gran & Paola, 2001, Zanoni et al., 2008; Bollati et al., 2014; Rinaldi et al., 2016). Hydraulic parameter values increase locally and bed material becomes less mobile. The island braided channel transforms into an anabranching channel as well as a wandering channel at some locations.

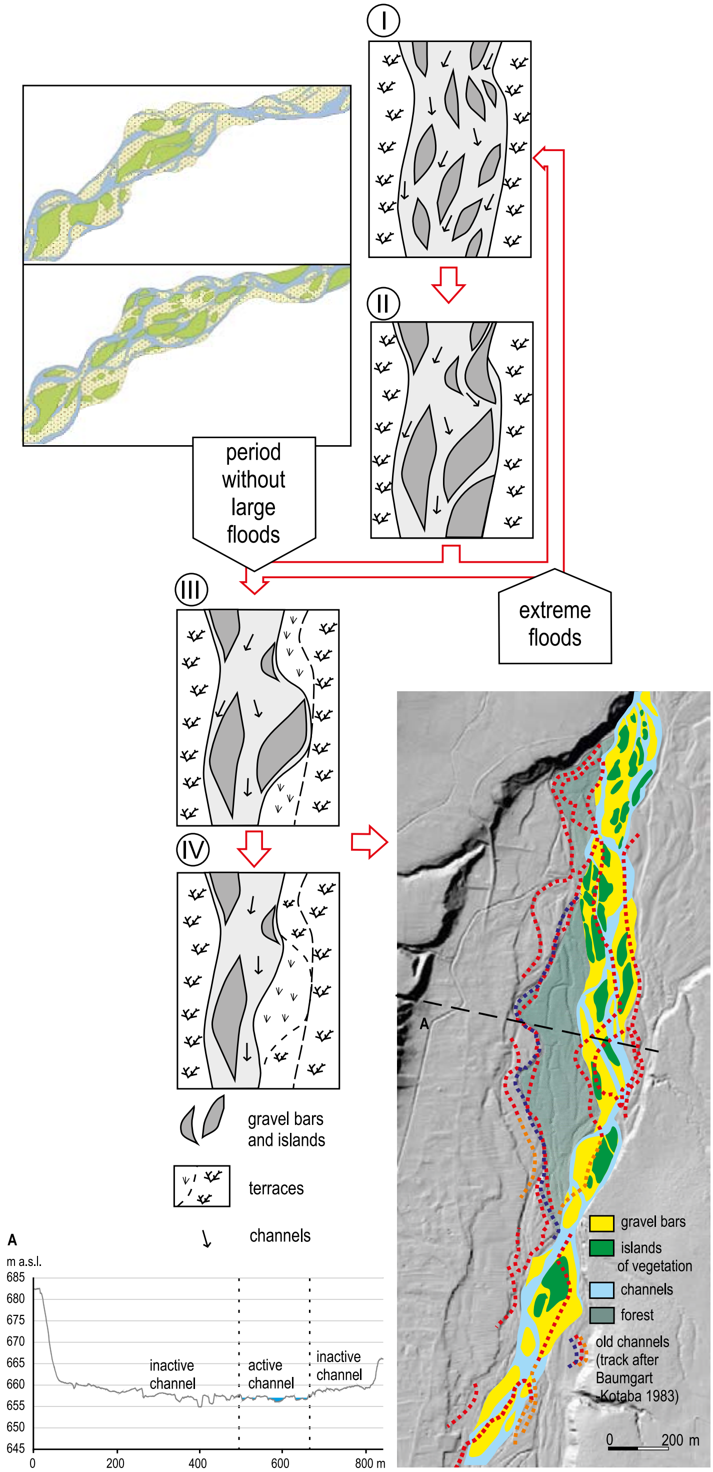

Figure 7. Conceptual model of braided river development experiencing degradation on the example of the Białka river channel; Degradation of the braided reaches of the Białka River (reach 8, river channel from the 1980s, based on Baumgart-Kotarba, 1983a,b)

Two similar braided channel degradation stages occur in a classification scheme of channel adjustments for Italian rivers by Surian and Rinaldi (2003). In this situation, further channel development may occur via two different pathways (Fig. 7). Flood-free periods tend to reinforce this trend. According to Baumgart-Kotarba (1983a, b), it only takes about 7 years without a flood on the Białka River for bars to become fixed with vegetation and for the main current to dominate smaller currents.

However, a major flood event can prompt a river channel to revert from Stage Two to Stage One. The importance of floods, especially large floods occurring every 10 years, in braided channel reconstruction is indicated by Belletti et al. (2015). On the other hand, Surian et al. (2015) notes that even small floods on the Tagliamento River, occurring every 1 to 2.5 years, may damage vegetation and refresh braided river morphology. This may imply different patterns of braided river development in different climates and local conditions in general.

Unfortunately, once a certain stage of braided channel degradation is reached, it is not possible to reactivate braiding patterns following flood events. This is the third stage of the conceptual model (Fig. 7).

Development in Stage Three can go in the direction of further incision in the main channel, drying up of side channels, cutting down into the solid rock, and bars and islands merge with the alluvial plain. River channels at Stage Three cannot really revert to Stage One or even Stage Two under current environmental conditions in the study area.

Stage Four represents the final stage of degradation – the formation of a confined single-thread with deep floor incisions and hanging lateral bars. Debris material fixed in place by vegetation and hanging high above the lateral bar channel experiences few if any instances of transport. Its rocky floor and minor floor obstacles are able to help facilitate rapid water flow in this last stage of river channel degradation (Fig. 7).

The Białka and other rivers in the Polish Carpathians do not represent an isolated case (Hajdukiewicz et al., 2019). Studies on braided rivers in the Alps in southeastern France show that 56% of braided river length is now degraded, and maximum channel incision reaches 8 meters (Liébault et al., 2013).

Today the Białka River does not have a multi-threaded, braided channel in its entire length, but only a few reaches that may be described as braided according to parameters proposed by Brice (1975), Carson (1984) or Rinaldi et al. (2016). The location and size of bars and islands was used to classify most of the studied multi-threaded reaches of the Białka as Stage Three reaches – *degrading gravel bed channels* (Germanowski & Schumm, 1993). The Białka River channel includes straight, sinuous, and braided reaches identified in terms of structural aspects (Nanson & Knighton, 1996). The multi-threaded reaches of the Białka river channel possess a complex internal morphology based on which some can be classified as anabranching channels with high energy or "transitional" channels gradually transforming into wandering channels (Van den Berg, 1995; Burge, 2005; Rinaldi et al., 2016; Wu et al., 2018).

At the same time, the entire studied river channel system consists of alternating types that can be arranged into the following sequence – straight, sinuous, and braided – and can be described as a wandering channel. An increasing number of river channels are being classified as wandering, which constitutes an "intermediate" classification between multi-threaded and single-threaded (Ferguson & Werrity, 1983; Burge, 2005; Wooldridge & Hickin, 2005; Rice et al., 2009; Rinaldi et al., 2016). It can be reviewed using a channel type scheme created by Burg (2005) where channel types are analyzed in relation to unit stream power and *W/D* (Fig. 8). Channel reach parameters identified for the Białka river channel fit quite well into categories proposed by Van den Berg (1995), Nanson and Knighton (1996) as well as Rinaldi et al. (2016). Four types of the Białka river channel, designated by the authors, perfectly reflect the relationship of the unit stream power and width to depth ratio of river channel. The Białka River possesses characteristics of a braided river, a wandering river and confined single-thread. Its further evolution will likely include further degradation of its few remaining braided reaches and a gradual conversion into a less diverse single-threaded channel ecosystem. Taking in the account current development trend of the Białka river channel, we can expect rhat wandering reaches may be characterized by Unit stream power and W/D parameters typical for confined single-thread channels in the future (Fig. 8).

The pattern of the Białka channel varies substantially from section to section, but the braiding indices (BI or W/D) classifies most sections of the Białka channel as braided.

Processes currently impacting the braided channel of the Białka are characterized by hydrodynamic parameters. The variation range of these parameters is very large, which implies highly variable discharge and bed material transport conditions that change from one section to another and even within a single section with a uniform morphology.

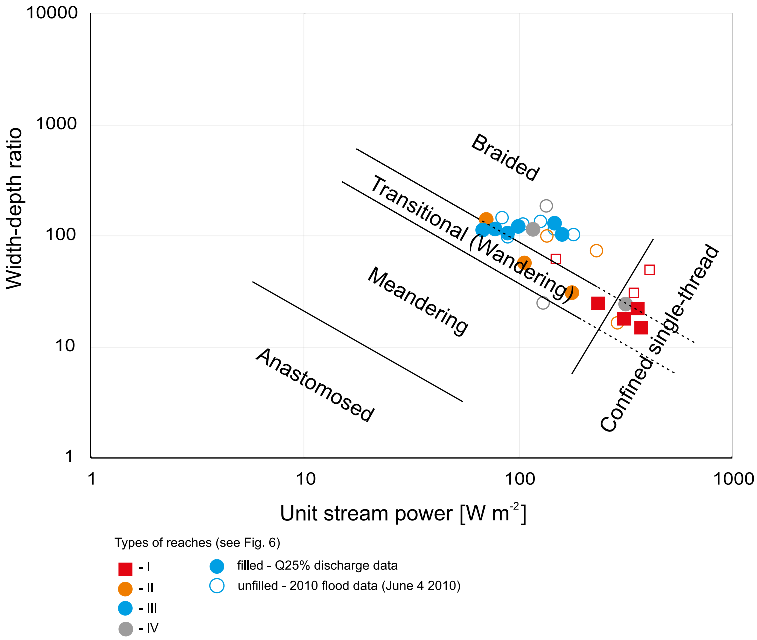

Figure 8. Relationship between *W/D* and unit stream power for the Białka River versus the channel classification by Van den Berg (1995); Nanson and Knighton (1996)

Conclusions

The present-day braided channel pattern of the Białka serves as a record of its past evolution in the foreland of mountains glaciated in the Pleistocene.

Current environmental conditions and human impact in the Białka River channel do not favor the maintenance of existing braided sections.

Discharge and bed material transport conditions and their corresponding parameter value ranges are noted for both braided and non-braided rivers. Many sections of the Białka are classified as transitional – wandering thanks to unit stream power values of 100 to 450 W m^{-2} and critical stress from 100 to 250 N m^{-2}.

The decline of the braided channel pattern of the Białka is occurring at an uneven rate along the length of the river. Research has shown that the decline in the braiding pattern takes place via increased incision and hanging side channels. This leads to the linkage of midchannel bars and islands with lateral bars and the expansion of the alluvial plain at the expense of the riverbed. The outcome of this process is permanent flow via the deepest channel leading to the formation of single-channel river.

Two of the main reasons why the Białka's braided channel is disappearing are limited gravel influx to the river channel and local deficits in the sediment load. These are due to human impact in the channel and land use changes in the catchment. The Białka channel is regulated in some sections – made either more narrow or dredged by crosscutting islands and bars. The decreasing share of arable land in favor of pastures has reduced the amount of debris supplied to the river channel. Decades of illegal gravel extraction may have also contributed to the declining sediment load in the river channel. The magnitude of the illegal extraction is difficult to estimate.

The present-day Białka channel system usually consists of a sequence of several types of channel ranging from a straight channel to sinuous to wandering to braided. We predict that differences in the morphology of the studied channel between its various channel types will increase over time. In accordance with the conceptual model proposed in the paper, channel development will occur in two basic ways. The first path of development will affect braided channels. The degree of braiding will increase in periods with a high frequency of flooding and will decrease during long periods without flooding. The second path of development will affect confined and transitional type of channel. Increasing incision will lead to the isolation of side channels and permanent flow via a single channel resulting in a total decline of the river's braided channel.

Relationship between the unit stream power and the W/D ratio can be seen as a universal indicator for separating types of channels and determining the development tendency of the river channel.

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Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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