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Changes of fluvial processes caused by the restoration of an incised mountain stream

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ABSTRACT

The construction of a high check dam on mountain Krzczonówka Stream, Polish Carpathians, in the mid-20th century caused numerous detrimental changes to the downstream reach. In 2014 the check dam was lowered to make the structure passable for river biota. Before that, several block ramps were constructed in the deeply incised downstream reach to facilitate entrapment of the sediment expected to be released from the lowered check dam. When the check-dam lowering was underway, a flood flushed out from the dam reservoir a considerable amount of sediment that was efficiently trapped by the block ramps. To determine to what extent the environmental problems caused by the long-term sediment starvation of the stream were mitigated by the restoration works, one-dimensional hydraulic modelling of flood flows was performed for pre- (2013) and post-flood conditions (2015) in ten study cross-sections. Moreover, hydromorphological quality of the stream was determined before the onset of restoration activities (2012) and after their completion (2015). The flood of 2014 deposited about 15,650 m^3 of bed material in the downstream reach, which re-established an alluvial channel bed and increased bed elevation by 0.50 m on average. Bed aggradation reduced flow capacity of the channel and increased water stages attained at given flood discharges. This significantly decreased bed shear stress and entrainable grain size of bed material. The proportion of the total flow conveyed over the floodplain and retention potential of the floodplain increased, although these effects were largely dependent on the amount of bed aggradation in the study cross-sections. The hydromorphological quality of the stream improved in 4 out of the 5 evaluated cross-sections, with 3 cross-sections being upgraded from moderate to good quality class. The study demonstrated effectiveness of block ramps in mitigating problems in the physical functioning of an incised mountain stream.

1. Introduction

Since the late nineteenth century, numerous check dams were constructed in headwater streams draining European mountains to reduce sediment flux in the channels receiving substantial amounts of material from largely deforested hillslopes (Rinaldi et al., 2013; Piton et al., 2016). In the Polish Carpathians, many closed check dams were built in the Raba River catchment (Fig. 1), where hillslopes were subjected to intense agricultural use (Wyżga, 1993). Apart from the disruption of longitudinal connectivity of the streams for riverine biota, check dams constructed in mountain streams created discontinuities in bedload flux, drastically reducing the sediment supply to downstream reaches (Rinaldi et al., 2013). The construction of the check dams coincided with widespread changes in catchment and channel management, including hillslopes reafforestation (Kondolf et al., 2002; Lach and Wyżga, 2002; Boix-Fayos et al., 2008) and channel regulation (Wyżga, 2001). These changes reduced sediment delivery to headwater channels, hence exacerbating the sediment deficit in their reaches downstream of the check dams. Consequently, a number of adverse effects on the operation of physical processes in the streams and their recipients were recorded.

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Channel incision and changes in bed substrate were direct and the most obvious effects of the sediment deficit in mountain watercourses. Rapid incision of mountain channels during the twentieth century in response to alterations in sediment fluxes was reported from many areas, including France (Liébault and Piégay, 2001), Italy (Surian and Rinaldi, 2004), Spain (Gómez-Villar and Martínez-Castroviejo, 1991), Czech Republic (Škarpich et al., 2013) and Poland (Wyżga, 2008). Incision was usually associated with coarsening of bed material and development of channel pavement (e.g. Wyżga, 1993; Liébault and Piégay, 2001), but where an incising channel cut through the whole thickness of alluvium, the gravelly channel bed was transformed into a bedrock bed (Hajdukiewicz et al., 2019).

Incision increases cross-sectional area of the channel and thus also its flow capacity and this effect is especially pronounced in mountain streams that had relatively small initial channel capacities (Wyżga et al., 2016c). Consequently, deeply incised mountain watercourses were found to have low potential for floodwater retention in floodplain areas (Wyżga, 1999; Czech et al., 2016).

Unit stream power—the rate of flow energy expenditure per unit river area—and bed shear stress indicating the force exerted by flow on unit bed area characterize the potential of flood flows for geomorphic work and sediment transport (Chang, 1988). Unit stream power is calculated as the product of water density, gravitational acceleration, water discharge and water-surface slope divided by flow width. In turn, mean cross-sectional shear stress is calculated with Du Boys' formula as the product of water density, gravitational acceleration, mean water depth (or hydraulic radius) and water-surface slope. As river incision increases concentration of flood flows in the deepened channel, narrow, incised reaches of mountain watercourses may be typified by a few times larger values of these parameters at given flood discharges than neighbouring, vertically stable reaches with a shallow and wide channel (Radecki-Pawlik et al., 2016). High values of these parameters increase channel sensitivity to erosion (Bizzi and Lerner, 2015) and the likelihood of catastrophic channel change during large floods (Krapesch et al., 2011; Yochum et al., 2017), and thus they are important drivers of erosional hazard during floods.

River continuity for biota and sediment transport is one of key elements of the hydromorphological quality of watercourses (European Commission, 2000). Closed check dams (apart from dams and weirs) disrupt this continuity (Belletti et al., 2020), hence degrading hydromorphological integrity of the watercourses. They may also deteriorate hydromorphological conditions in downstream reaches through their impacts on channel geometry (incision), bed substrate, the complexity of erosional and depositional channel forms, the presence of in-channel

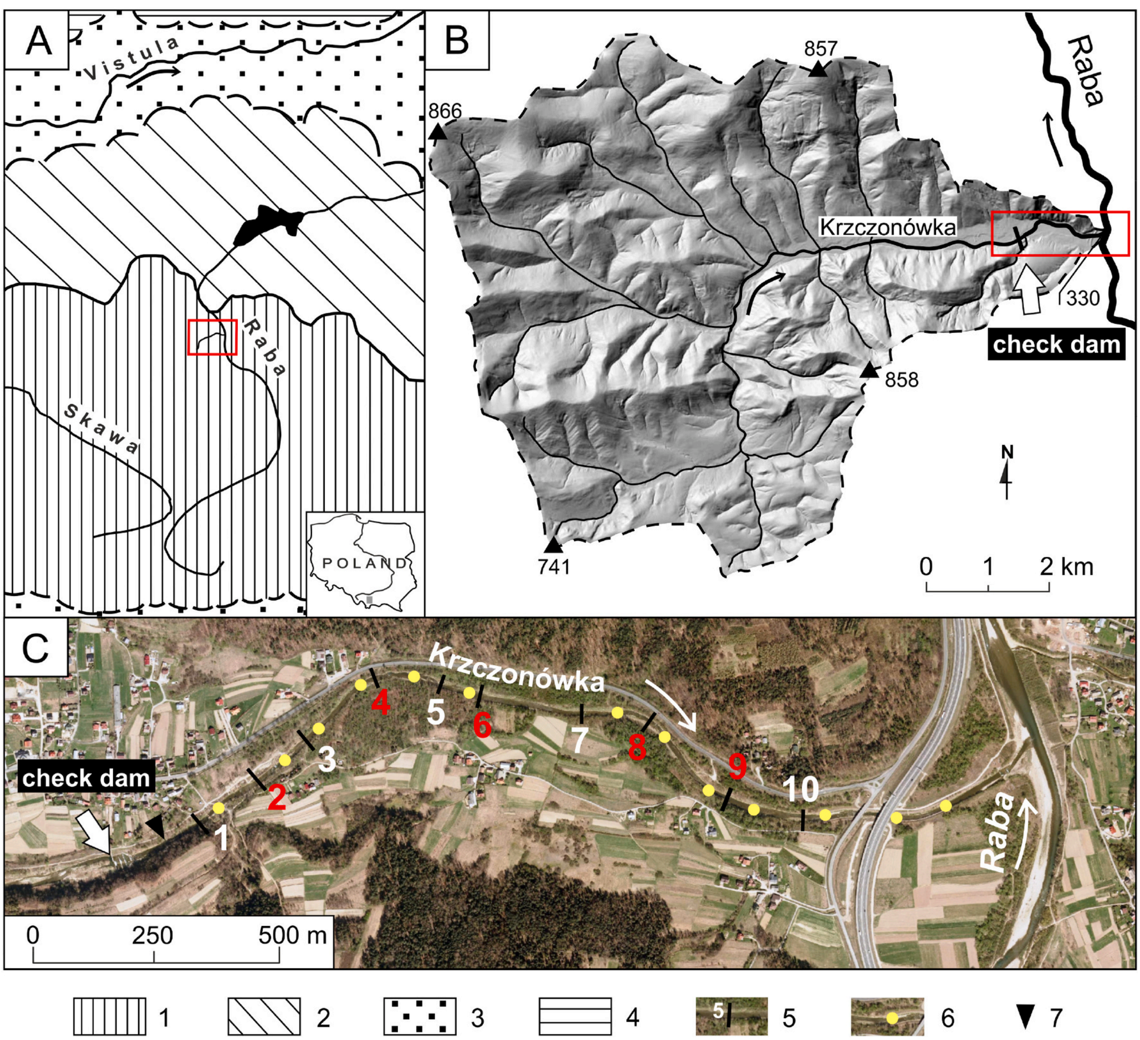

Fig. 1. (A) Location of Krzczonówka Stream in relation to physiographic regions of southern Poland. (B) Krzczonówka Stream catchment. (C) Orthophoto from 2009 showing the studied stream reach and the location of surveyed cross-sections and block ramps formed in 2013. 1 – mountains of intermediate and low height; 2 – foothills; 3 – intramontane and submontane basins; 4 – uplands; 5 – surveyed stream cross-sections; 6 – block ramps; 7 – water-gauge station. Red numbers denote the cross-sections for which the assessment of hydromorphological stream quality was performed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

wood, bank height and riparian vegetation structure (Conesa-García and García-Lorenzo, 2009; Galia et al., 2018; Zema et al., 2018).

The abovementioned adverse effects of check dams, especially if combined with those of the catchment-wide reduction of sediment delivery to channels, underlined the demand for the removal of some of the structures to enable abundant bed material supply to downstream reaches from the artificial storage of coarse sediment in the dam reservoirs (e.g. Landon et al., 1998). Over the last few decades, an increasing number of dams were removed worldwide, predominantly in the USA (O'Connor et al., 2015; Foley et al., 2017; Sneddon et al., 2017), with most of them being relatively small structures less than 5 m in height (Hart et al., 2002). Dams are often removed when they become old and the reservoirs fill with sediment. Dam removals also provide an opportunity to improve physical and ecological functioning of the watercourses and thus, they have become an important tool of river restoration (Hart et al., 2002; Magilligan et al., 2016a; Sneddon et al., 2017). However, understanding of changes in fluvial forms and processes caused by a dam removal is still incomplete, because only a small proportion of the removals were monitored (Hart et al., 2002). Stream response may vary with dam function and size and the mode of its decommissioning, the volume, calibre and cohesion of the sediment trapped by the dam, downstream channel dimensions and geometry, and the magnitude of and the time to bed mobilizing events (Pizzuto, 2002; Magilligan et al., 2016b).

In the last three decades, various types of eco-friendly, transversal hydraulic structures were constructed in stream channels to mitigate or prevent channel incision (Pagliara et al., 2016). Shields et al. (1995) described the construction of a series of small stone weirs in an incised lowland stream, that locally impounded base flow and increased pool habitat availability and overall physical heterogeneity of the channel. Boulder check dams mimicking step-pool morphology were used to dissipate flow energy and stabilize the bed in steep mountain streams (Lenzi, 2002; Kostadinov and Dragović, 2010). In streams that prior to channelization and/or incision were typified by a pool-and-riffle channel pattern, various types of fish-passable, transversal structures mimicking riffles were constructed from rocky material, either superimposed on or mixed with river gravels, in order to control bed erosion, improve aquatic habitats and form backwatering pools. The terms *rock riffles* (Newbury et al., 2011; Newbury, 2013) and *block ramps* (Tamagni et al., 2010) were used in the literature to describe them, but as the structures are artificially installed in channels, in this study we call them block ramps to avoid confusion with natural river features.

Most check dams constructed in Polish Carpathian streams were filled with sediment already a few decades ago (Ratomski, 1991) and have remained in that state, whereas the downstream reaches are currently deeply incised. This situation calls for restoration measures that would not only release the sediment trapped by the check dams to downstream reaches, but would also effectively retain it in the incised channels with high transport capacity. It can be achieved with a novel approach combining a decommissioning of old check dams with installation of block ramps in the downstream reach. This study presents changes in fluvial processes caused by the restoration measures implemented in Krzczonówka Stream, which encompassed a lowering of a high check dam and construction of several block ramps in the downstream reach to trap the sediment released from the dam reservoir in the incised channel (Wyżga et al., 2021). The response of the stream to the check-dam lowering was driven by a moderate flood and thus was particularly rapid. The study aims to determine the influence of the restoration measures coupled with passage of the moderate flood on:

- morphology and bed substrate of the incised reach;
- hydraulic parameters of flood flows and maximum entrainable grain size of bed material;
- the potential of the stream floodplain for floodwater retention;
- hydromorphological quality of the stream reach downstream from the lowered check dam.

2. Material and methods

2.1. Geographical setting

Krzczonówka Stream is a left-bank tributary of the Raba River in the Polish part of the Western Carpathians (Fig. 1). It has a length of ca. 17 km and drains a catchment 92.9 km^2 in area. The catchment has low-mountain relief, with the highest point located at an elevation of 867 m a.s.l. and the stream mouth to the Raba River at 330 m a.s.l. (Fig. 1B). It is underlain by flysch complexes of the Magura Nappe composed of sandstones and shales with a subordinate occurrence of marls and conglomerates.

Annual precipitation totals in the catchment amount to ca. 800 mm on average (Niedźwiedź and Obrębska-Starklowa, 1991). Low retention potential of the flysch bedrock results in a great variability of stream discharge; based on 45 years of record (1971–2015) at the Krzczonów gauging station, the coefficient of flow irregularity (ratio of the highest and the lowest discharge on record) is 1820. At this station located 1.9 km from the stream mouth (Fig. 1C) and characterizing runoff from 96.5% of the catchment area, mean annual discharge amounts to 1.52 m^3 s^{-1} and the average for the highest annual discharges equals 12 m^3 s^{-1}. Larger floods typically occur between May and August and are caused by a few days-long rainfall with the average intensity of 8–10 mm h^{-1} and the total sum of precipitation exceeding 200–250 mm (Wyżga et al., 2016a).

The study was conducted in the 2-km-long, lowest reach of the stream located downstream of a 3.7-m-high, closed check dam (Fig. 1C). The check dam was built in the years 1935–1951 and its construction caused long-term sediment starvation of the downstream reach. A map of the Third Military Survey of Austro–Hungary indicates that in the late nineteenth century the stream in the lowest reach flowed in a wide, multi-thread channel. In the early 1960s the channel was still wide, but single-thread (Lenar-Matyas et al., 2015). Channelization works comprising training of the stream with numerous groynes and lining of concave banks with gabions and rip-rap started in the late 1950s and since then they have caused up to a threefold narrowing of the active channel (Lenar-Matyas et al., 2015). Both sediment starvation and channelization of the stream induced up to 2 m of channel incision and transformation of the alluvial bed into a bedrock–alluvial or bedrock bed. As a result, in 2012 the channel was relatively deep (Fig. 2A) and bedrock exposures occurred on ca. 50% of the reach length, especially close to the check dam (Fig. 3A).

2.2. Stream restoration activities and the flood of 2014

In 2012 a decision was made about a lowering of the check dam on Krzczonówka Stream to make it passable for fish. Complete removal of the check dam was not possible as it might have threatened the stability of a terrace with settlements on the right bank of the stream upstream of the dam. To trap the sediment flushed out from the dam reservoir in the deeply incised channel, construction of block ramps in the stream was planned before the check-dam lowering. The ramps were intended to constitute positive channel forms mimicking riffles, that would reduce excessive flow capacity of the incised channel, while remaining relatively stable. The Hey and Thorne regime equations (Thorne et al., 1997) were used to calculate the grain size of material for the ramps and their geometric parameters (minimum bankfull width, average and maximum bankfull depth at the ramp crest, and average spacing between ramps) that would ensure persistence of the ramps at different rates of bedload supply from upstream. The sediments stored upstream from the check dam had median grain size of 46 mm and the calculations indicated that the ramps should be made with the material ca. 3–4 times coarser than these sediments (Jeleński and Wyżga, 2016).

The block ramps were constructed in March 2013 (Fig. 2B) of rock rubble from a nearby quarry with a topping of coarse gravel compacted by a road roller. They were spaced about 120 m apart and located at

Fig. 2. (A) View of the Krzczonówka channel shortly before the installation of block ramps. (B) Works to install a block ramp in Krzczonówka Stream in March 2013. (C) View of the block ramp during low flow in May 2013. Visible considerably steeper water slope on the ramp than upstream of it and parabolic cross-section of the ramp causing concentration of flow in the middle of the channel.

thalweg inflection points, like natural riffles. Only in the middle part of the reach, the lack of access for heavy machinery prevented installation of ramps, and here the distance between the neighbouring ramps was 325 m (Fig. 1C). The ramps on their downstream side had a slope a few times steeper than the average channel slope. Moreover, they were concave in cross-section in order to concentrate flow in the middle of the channel (Fig. 2C).

Fig. 3. View of Krzczonówka Stream in the vicinity of cross-section 2 in 2012, before installation of block ramps (A), and after the passage of the flood of 2014 (B). Visible change from bedrock to alluvial boundary conditions as a result of gravel deposition in the channel.

The works to lower the check dam were conducted between April and October 2014. They resulted in the lowering of the crest of the structure and its total height by 1.7 m. The rebuilt structure has a height of 2 m and consists of three weirs with a trapezoidal notch ca. 0.4 m deep cut in the central part of weir crest to facilitate fish migration through the structure. In May 2014, when the works on the dam were in progress, a flood occurred flushing out a considerable amount of gravel filling the dam reservoir and depositing it downstream from the dam. Considerable aggradation of the channel bed at the gauge cross-section during the flood radically changed the hitherto existing rating curve for the Krzczonów gauging station, and this prevented a reliable record of the peak discharge of the flood. The peak discharge at the station was thus estimated on the basis of maximum unit runoff recorded during the flood at the nearby Stróża station on the Raba River (1.02 $m^3\ s^{-1}\ km^{-2}$) and at the Lubień station on Lubieńka Stream, the neighbouring tributary to the Raba (1.1 $m^3\ s^{-1}\ km^{-2}$). Based on these coefficients, the peak discharge on Krzczonówka Stream was calculated at 92 and 99 $m^3\ s^{-1}$, which was subsequently averaged to 95.5 $m^3\ s^{-1}$, the flow of a 7-year recurrence interval.

2.3. *Study methods*

2.3.1. *Field measurements*

In 2012, at the beginning of the restoration project, 10 study cross-sections were delimited in the stream reach downstream from the check dam (Fig. 1C). They were located to run across pools at the half-distance between the planned block ramps, and they remained in the same position throughout the restoration project, even though the actual location of some block ramps was modified because of necessary access for heavy machinery. Channel morphology and bed material in the cross-sections were surveyed after the installation of block ramps in the stream but with still unchanged check dam (2013) and during (2014) and after the check-dam lowering (2015). The geometry of the cross-sections was surveyed with an optical level at base-flow conditions (Fig. S1A in the Supplementary material). The grain size of bed material was sampled at 0.5 m intervals across the channel (Fig. S1B). It was determined through the transect sampling of surface bed material (Wolman, 1954), with 15 particles measured at each sampling point. Median (D_{50}) grain size of each sample was established from the distribution of the *b* axis diameters of measured particles, and average D_{50} grain size of the bed material was then calculated from the median values of grain-size distribution at all sampling points in a cross-section. Water depth and depth-averaged flow velocity at base-flow conditions were measured using an electromagnetic current meter at 0.5 m intervals across the channel (Fig. S1C); the values of low-flow discharge calculated on the basis of these measurements were then used in calibration of Manning's roughness coefficients for the channel bed in successive cross-sections. Finally, the floodwater slope in the cross-sections was approximated by base-flow water slope measured between upstream and downstream pools.

2.3.2. Hydraulic modelling of flood flows

The one-dimensional, steady-flow HEC-RAS model (USACE, 2010) was used to simulate hydraulic conditions in the study cross-sections. The modelling was performed for flood discharges of the following recurrence intervals and the associated probabilities of exceedance (in parentheses): 2 years (50%), 5 years (20%), 10 years (10%), 20 years (5%), 25 years (4%), 33 years (3%) and 50 years (2%). The discharges were determined on the basis of a series of annual maximum discharges from the years 1971–2015 at the Krzczonów gauging station located just upstream of cross-section 1 (Fig. 1C). They were considered to be the same at all study cross-sections along the 1.5-km-long stream reach. This was justified by a small increase in catchment area along the reach and making comparisons between conditions typifying the same cross-sections in different years rather than between different cross-sections.

The modelling input data comprised channel slope, channel and floodplain geometry in the study cross-sections, and channel bed and floodplain roughness. Manning's roughness coefficient for the channel bed was calculated with the empirical equation of Strickler (1923) from the median (D_{50}) grain size of surface bed material averaged for all samples in a cross-section. Accuracy of the roughness values for the channel bed was then verified by comparing observed and modelled water elevation in the study cross-sections for a low discharge recorded during hydraulic measurements in 2013 and 2015. It indicated that modelled values fitted the observed ones well, with a mean error in the water elevation in 2013 amounting to 5.5 cm (median = 3 cm) and that in 2015 to 3.5 cm (median = 3 cm) (Fig. S2). Manning's roughness coefficients for the channel bank and floodplain parts of the stream cross-sections with different types of vegetation cover/land use were assigned in line with the criteria of Chow (1959) (Table S1 in the Supplementary material). Considerable bed aggradation in the Krzczonów gauge cross-section during the 2014 flood and the resultant loss of reliability of the rating curve for the gauging station precluded calibration of the model for flood discharges. However, we should emphasize that with the same roughness coefficients assigned for channel banks and floodplain in 2013 and 2015 and with the confirmed accuracy of the roughness values for the channel bed, the model should correctly reproduce differences in water elevation at given flood discharges between these years, although absolute values of water elevations in each year may not be accurate.

In each cross-section, bank edges were indicated at the place of a first sudden change in the cross-section profile, above which the surface was covered by permanent vegetation (Radecki-Pawlik, 2002). It allowed the model to partition a total flood flow into the flows conveyed in the channel and floodplain zones of the cross-section and to compute given hydraulic parameters not only for the total cross-section but also for its channel and floodplain parts.

2.3.3. Evaluation of changes in the conveyance and the retention of floodwater in the floodplain area

With the distribution of flood flows between the channel and the floodplain indicated by the HEC-RAS model, it was possible to determine the role of floodplain in the conveyance and the retention of floodwater at given flood discharges. This was done using the analysis which compares the proportion of flow area in the floodplain zone with the proportion of discharge conveyed over the floodplain (cf. Wyżga, 1999; Czech et al., 2016). This approach is based on the assumption that the cross-sectional area of flow in a floodplain zone can be partitioned into two conceptual components: one in which water would flow with the same mean velocity as in the channel zone, and another in which water would remain motionless, hence being temporarily retained on the floodplain (Bhowmik and Demissie, 1982). The first component would take the same proportion of the total flow area as is the proportion of the total flow conveyed over the floodplain. The remaining part of the cross-sectional flow area in the floodplain zone refers to the second component and determines the retention potential of the floodplain in the analysed cross-section. Results of the hydraulic modelling performed for the stream conditions existing in 2013 and 2015 were compared to determine changes in the conveyance and the retention of floodwater in the floodplain area caused by bed material entrapment by block ramps and the resultant bed aggradation during the flood of May 2014.

2.3.4. Data analysis

The volume of bed material retained downstream from the check dam during the flood of 2014 was assessed on the basis of flood-caused changes in mean bed elevation and channel width in successive study cross-sections and distances between the cross-sections. A Wilcoxon signed-rank test was used to examine differences in average values of the hydraulic parameters and the retention potential typifying the study cross-sections in 2013—after the installation of block ramps in the stream—and in 2015, after the end of restoration activities. This test for dependent statistical samples was used because analysed characteristics typifying the stream in 2015 were dependent on their initial state existing prior to the check dam lowering and aggradation of the channel bed by released sediment. Differences were considered statistically significant if p-value <0.05.

2.3.5. Assessment of changes in hydromorphological stream quality

Hydromorphological quality of the stream was assessed in 2012, before the onset of restoration activities, and in 2015, after all restoration activities in the stream had been completed. As the relatively close spacing of the study cross-sections precluded considerable differences in hydromorphological quality between successive cross-sections, the assessment was performed only for half of them (Fig. 1C). This was done using the River Hydromorphological Quality method that was previously demonstrated to be useful in river restoration planning and evaluation (Hajdukiewicz et al., 2017). The method consists in scoring of 10 groups of features of the channel, river banks, riparian zone and floodplain according to their specification in the European Standard EN-14614 (CEN, 2004).

The assessment, performed simultaneously by five specialists in fluvial geomorphology, hydrobiology and river engineering, was preceded by field inspection and presentation of the information on the assessed stream and scoring procedure. First, diagrams of the evaluated cross-sections and stream appearance on orthophoto and ground photos were presented. Second, for each assessed feature, near-natural and extremely modified conditions were indicated, whereas the whole spectrum of conditions between these extreme states was reserved for expert evaluation. Identification of near-natural conditions was based on the assumption that hydromorphological reference conditions represent the state of the watercourse that exists or would exist under contemporary environmental conditions in the catchment but without human modifications to the channel, riparian areas and floodplain of the stream (Wyżga et al., 2012). For instance, natural channel geometry would be represented by island-braided channel morphology (cf. Mikuś et al., 2019) and would deviate from bar-braided morphology typical of the nineteenth century, with the change reflecting a reduction in flow and sediment dynamics of Polish Carpathian watercourses during the twentieth century (Wyżga et al., 2016b). Third, before the assessment for 2015, changes of the stream recorded during the restoration project were also discussed.

Each assessed category was scored on the scale from 1 (for near-natural conditions) to 5 (for extremely modified conditions). The scale was partitioned into five equal-width classes of hydromorphological quality (high, good, moderate, poor and bad) defined in the Water Framework Directive (European Commission, 2000; CEN, 2004). The aggregated score, averaged from the scores of the five experts, allowed each of the evaluated cross-sections to be assigned to a particular class of hydromorphological quality.

3. Results

3.1. Sedimentary and morphological effects of bed material entrapment by block ramps

The flood of May 2014 flushed out a considerable amount of gravelly material hitherto stored behind the check dam. Block ramps installed in the incised reach of the stream facilitated sediment entrapment and, consequently, ca. 15,650 m^3 of the material were retained downstream from the check dam and the sediment wave reached ~1.9 km from the dam. This gives an average value of sediment retention of 8.3 m^3 per 1 m of channel length. The sediment deposition caused burying of bedrock exposures on the channel bed (Fig. 3), hence re-establishing the occurrence of an alluvial bed in the whole stream reach downstream from the check dam. It also buried block ramps on a distance of 1.2 km from the check dam.

On average, sediment deposition increased mean elevation of the channel bed in 10 study cross-sections by 0.50 m and that of low-flow water surface by 0.39 m, but the increases were not evenly distributed along the study reach (Fig. 4). Bed aggradation and the resultant increase in the elevation of low-flow water surface were relatively large close to the check dam, attaining maximum values of around 1 m in cross-section 3, and decreased downstream to 0.2 and 0.12 m, respectively, in cross-section 10 (Fig. 4). As a result of this downstream decrease in the scale of bed aggradation, mean channel slope in the study reach increased from 0.0073 m m^{-1} in 2013 to 0.0076 m m^{-1} in 2015, i.e. by 4%. Importantly, the lack of block ramps on a relatively large distance in the middle part of the study reach prevented sediment retention and bed aggradation—in cross-section 6 located 300 m upstream of a block ramp, between 2013 and 2015 mean elevation of the channel bed increased only by 0.18 m and that of low-flow water surface by 0.05 m (Fig. 4).

The delivery by the 2014 flood of bed material previously stored in the dam reservoir and its subsequent reworking by lower flows resulted in marked changes of bed-material grain size in the study reach. In 2013 median grain size of the bed material in the study cross-sections amounted to 50.1 mm on average, varying between 38 and 66 mm in individual cross-sections. The survey performed two months after the flood of May 2014 indicated fining of the bed material, with the average value of median grain size in the study cross-sections amounting to 44.1 mm and D_{50} values in individual cross-sections ranging from 29 to 53 mm. However, the survey in 2015 showed that the average value of median grain size in the study reach amounted to 53.4 mm, with D_{50} values in individual cross-sections varying between 41 and 66 mm.

The flood of May 2014 increased bankfull channel width in the study cross-sections by 7.4% (i.e. 1.4 m) on average, with the increase in

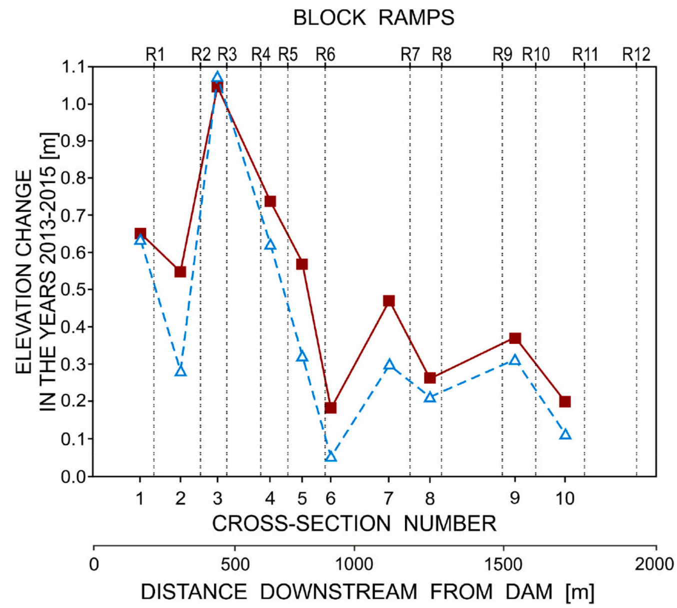

Fig. 4. Changes in mean elevation of channel bed (solid squares and solid line) and in the elevation of low-flow water surface (empty triangles and dashed line) in 10 study cross-sections of Krzczonówka Stream between 2013 and 2015. The location of block ramps along the stream reach downstream from the lowered check dam is also shown.

individual cross-sections varying between 0 and 4 m (Table S2). This small channel widening reflected reinforcement of one channel bank with rip-rap in some cross-sections and the occurrence of bedrock exposures along channel margins in the others but also the relatively low magnitude of the flood. On average, maximum channel depth decreased by 31.4%, i.e. by 0.44 m (Table S2). As the relative decrease in channel depth was considerably larger than the relative increase in channel width, a combined effect of these changes in cross-sectional morphology of the stream was a reduction in flow capacity of its channel.

3.2. Changes in hydraulic parameters of flood flows and maximum entrainable grain size of bed material

Hydraulic modelling indicated that the reduction in flow capacity of the stream channel due to the sediment entrapment by block ramps exerted a marked influence on hydraulic parameters characterizing geometry of flood flows (Fig. 5A). The reduction increased the proportion of flood flows conveyed in the floodplain zone of the stream, which decreased mean water depth and increased the lateral extent of inundation at given flood discharges. The reduction in mean water depth increased from 10% at a 2-year flood to 17% at the flood of 10-year frequency and then decreased to about 10% at higher flood flows. The change in mean water depth was statistically significant for flood magnitudes up to a 25-year discharge (Fig. 5A). In turn, the increase in flow width ranged from 12.7% at the 2-year discharge to 52.6% at a 20-year flood and then its scale diminished to 6% at the flood of 50-year frequency. A statistically significant increase in flow width was recorded for flood magnitudes up to a 33-year discharge (Fig. 5A).

The described changes in geometry of flood flows were associated with marked changes in the values of parameters characterizing flow hydrodynamics (Fig. 5B). Unit stream power calculated for total cross-section decreased markedly between 2013 and 2015, and the reduction ranged from 59.1% at the 2-year flood to 66.1% at the discharge of 10-year frequency, and then its scale diminished with increasing flood magnitude to 39.6% at the 50-year flood. The reduction in unit stream power was statistically significant for flood magnitudes up to the 33-year discharge (Fig. 5B). In turn, the reduction in bed shear stress

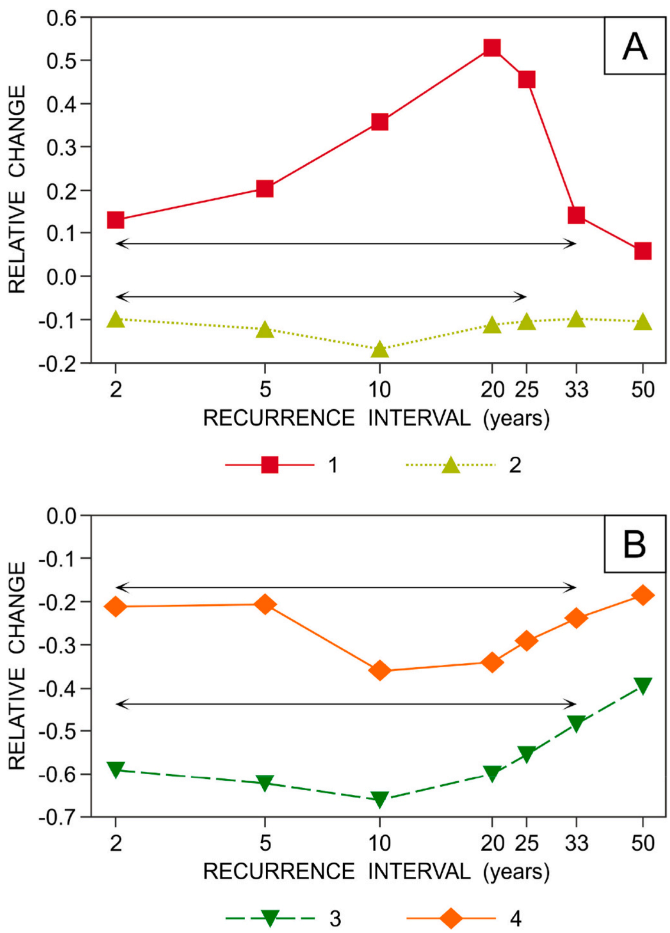

Fig. 5. Relative change in average values of hydraulic parameters characterizing geometry (A) and hydrodynamics (B) of flood flows of given recurrence intervals between 2013 and 2015. 1 – flow width; 2 – mean water depth; 3 – unit stream power; 4 – bed shear stress. Arrows indicate the extent of flood frequencies, for which the analysed changes in the hydraulic parameters were statistically significant.

calculated for total cross-section equalled ca. 21% at 2- and 5-year discharges, attained the maximum value of 36.1% at the 10-year flood, and with a further increase in flood magnitude its scale diminished to 18.6% at the flood of 50-year frequency. Similar to changes in unit stream power, a statistically significant reduction in bed shear stress was also recorded for flood magnitudes up to the 33-year discharge (Fig. 5B).

Below we analyse in greater detail changes in unit stream power and bed shear stress calculated for the portion of flood flows conveyed in the channel zone of the stream, as they are more relevant for bed material mobility and the stability of bank-protection structures than changes in total cross-section. Average data for the 10 study cross-sections indicate that in 2013, before the bed aggradation, unit stream power in the channel zone increased rapidly with increasing flood magnitude, attaining the maximum value of 832.1 W m^{-2} at the discharge of 20-year frequency, and subsequently slowly decreased with a further increase in flood discharges (Table 1). In 2015, after the bed aggradation induced by block ramps, unit stream power in the channel zone increased at a slower rate than in 2013 up to the flow of 10-year frequency, then remained at a similar level up to the flow of a 25-year recurrence interval and finally increased again with a further increase in flood magnitude, attaining the maximum value of 608 W m^{-2} at the flow of 33-year frequency (Table 1). The reduction in the parameter value ranged from 16.4% at a 50-year flood to 35.8% at the flow of 20-year frequency, and the reduction was statistically significant for flood magnitudes up to the 33-year discharge (Table 1).

Table 1
Average values of unit stream power in the channel zone of the study cross-sections of Krzczonówka Stream at flood discharges of given recurrence interval before (2013) and after (2015) the aggradation of channel bed by the sediment released from the lowered check dam. Results of the Wilcoxon test for the significance of difference of the parameter between 2013 and 2015 are also indicated. *p* values <0.05 are indicated in bold.

Recurrence interval	Discharge (m^3 s^{-1})	Unit stream power in channel zone (W m^{-2})		Relative change	Significance of change
		2013	2015		
2 years	37.0	290.1	226.0	- 22.1%	**$p = 0.007$**
5 years	81.2	549.1	450.9	- 17.9%	**$p = 0.02$**
10 years	113.2	744.0	555.8	- 25.3%	**$p = 0.01$**
20 years	144.0	832.1	534.3	- 35.8%	**$p = 0.01$**
25 years	154.0	829.4	563.3	- 32.1%	**$p = 0.01$**
33 years	171.5	791.6	608.0	- 23.2%	**$p = 0.03$**
50 years	185.0	724.1	605.5	- 16.4%	$p = 0.07$

In 2013 bed shear stress in the channel zone increased rapidly with increasing flood magnitude, reaching the maximum value of 206.3 N m^{-2} at the discharge of 20-year frequency, and then slowly decreased with a further increase in flood magnitude (Table 2). In 2015 the parameter increased at a slower rate than previously up to the flow of a 10-year recurrence interval, then slightly decreased as flood flow increased up to the 20-year discharge and finally increased again with a further increase in flood magnitude, reaching the maximum of 154.6 N m^{-2} at the 33-year flood (Table 2). After bed aggradation took place, the highest value of the parameter was lower by one-fourth than the previous maximum recorded in the incised channel. The degree of the parameter reduction at a given flood magnitude ranged from 14.4% at the 50-year flood to 30.5% at the discharge of 20-year frequency, with a statistically significant change recorded for flood magnitudes up to the 33-year discharge (Table 2).

Average values of bed shear stress calculated for the flows conveyed in the channel zone of each cross-section were used to determine stream competence, i.e. the maximum size of bed material particles entrained by discharges of given frequency before and after the aggradation of the channel bed (cf. Gordon et al., 1992). In 2015 entrainable grain size was significantly lower than in 2013 for flood magnitudes up to the 33-year discharge and the pattern of the differences followed the differences in bed shear stress. We illustrate the effect of stream changes on entrainable grain size for 2-year and 20-year floods. While in 2013 the 2-year discharge could mobilize particles with the diameter varying between 77 and 204 mm in particular study cross-sections (115 mm on average), in 2015 it could entrain grains with the maximum diameter ranging from 70 to 175 mm in these cross-sections (mean = 94 mm); on average, entrainable grain size decreased by 18% (Fig. 6A). In 2013 the 20-year flood had a competence ranging from 125 to 396 mm in particular cross-

Table 2
Average values of bed shear stress in the channel zone of the study cross-sections of Krzczonówka Stream at flood discharges of given recurrence interval before (2013) and after (2015) the aggradation of channel bed by the sediment released from the lowered check dam. Results of the Wilcoxon test for the significance of difference of the parameter between 2013 and 2015 are also indicated. *p* values <0.05 are indicated in bold.

Recurrence interval	Discharge (m^3 s^{-1})	Bed shear stress in channel zone (N m^{-2})		Relative change	Significance of change
		2013	2015		
2 years	37.0	103.9	85.2	- 18.0%	**$p = 0.005$**
5 years	81.2	158.4	135.4	- 14.5%	**$p = 0.04$**
10 years	113.2	194.5	152.2	- 21.7%	**$p = 0.009$**
20 years	144.0	206.3	143.4	- 30.5%	**$p = 0.009$**
25 years	154.0	204.5	148.0	- 27.6%	**$p = 0.009$**
33 years	171.5	193.6	154.6	- 20.1%	**$p = 0.02$**
50 years	185.0	178.7	153.0	- 14.4%	$p = 0.06$

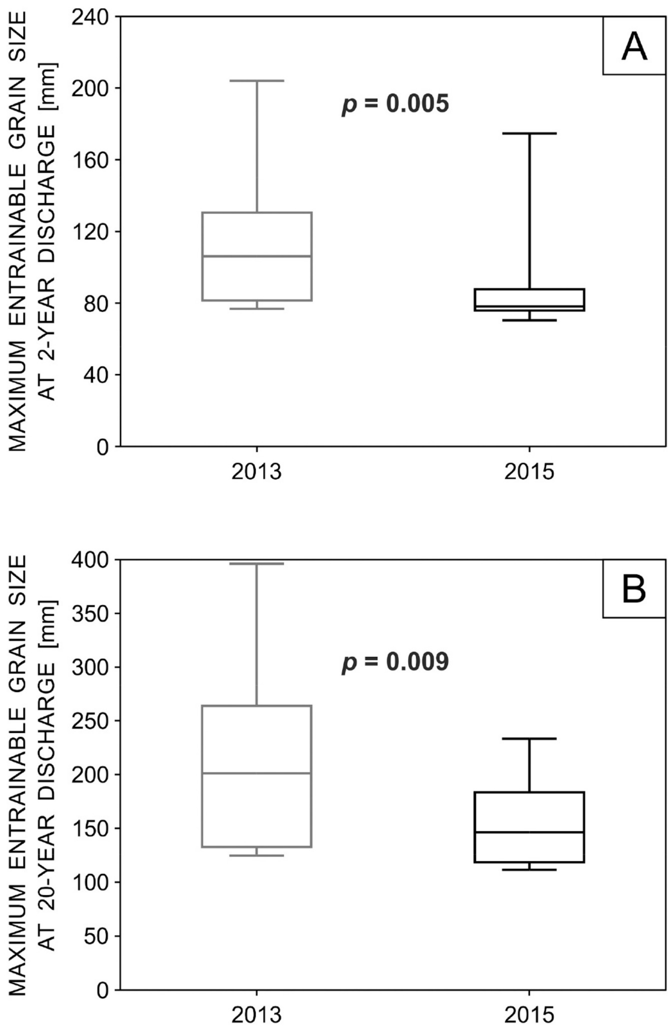

Fig. 6. Maximum size of bed material particles mobilized by 2-year (A) and 20-year flood discharges (B) in 10 study cross-sections of Krzczonówka Stream before (2013) and after (2015) the aggradation of channel bed by the sediment released from the lowered check dam. Boxplots show median (centre line), the first and the third quartiles (bottom and top of boxes) and extreme values (whiskers). Results of the Wilcoxon test for the significance of difference of the parameter between 2013 and 2015 are also indicated.

sections, whereas in 2015 stream competence varied between 111 and 233 mm, and this was reflected in the reduction of the average value of entrainable grain size for the 10 study cross-sections from 228 to 158 mm—a change by 31% (Fig. 6B).

3.3. Changes of floodwater retention in the floodplain zone

Based on average data for the 10 study cross-sections, the bed aggradation-caused increase in the proportion of total flood flow conveyed in the floodplain zone equalled 0.5% (change from 0.1% to 0.6%) at a 2-year flood, attained the greatest value of 5.9% (change from 4.0% to 9.9%) at the flood of 20-year frequency, and then diminished to 2.9% (change from 10.3% to 13.2%) at a 50-year discharge. However, the associated increase in the proportion of flow area in the floodplain zone was only slightly larger and this was reflected in a relatively minor increase of the retention potential of the study cross-sections. On average, the increase of the retention potential ranged from 0.7% (i.e. from 17.6% to 18.3%) at the 50-year flood to 3.8% (from 6.6% to 10.4%) at the flood of 10-year frequency, but the change was not statistically significant (with p values varying between 0.05 and 0.51) for any flood magnitude.

Notwithstanding the lack of significance of the average change in the retention potential of the stream floodplain in the 10 study cross-sections, it is interesting to compare changes in the retention potential between cross-section 3, where the channel bed aggraded between 2013 and 2015 by 1.05 m, and cross-section 9 with the increase in bed elevation amounting to 0.37 m only (Fig. 7). In cross-section 3, before the restoration activities a very small proportion of the total flow was conveyed in the floodplain zone and noticeable floodplain inundation started at the 20-year flood (Fig. 7, Table 3). After the bed aggradation induced by the restoration activities, noticeable flow in the floodplain zone was already recorded at the flood of 5-year frequency (Fig. 7), and at higher flood magnitudes a proportion of the total flow conveyed over the floodplain increased by more than 10%. However, the proportion of flow area in the floodplain zone increased about twice more and this was reflected in a remarkable increase in the retention potential of the floodplain in this cross-section (Table 3). Moreover, prior to the restoration activities water started to be retained on the floodplain at the flow of 10-year frequency, while after the activities the onset of floodwater retention occurred already at the 2-year flood (Table 3).

In cross-section 9, before the restoration activities the channel was shallower than in cross-section 3 (Fig. 7). As a result, flood flows conveyed in this cross-section were typified by greater proportions of discharge and flow area in the floodplain zone, and for most flood magnitudes considered the retention potential was here greater than in cross-section 3 (Table 3). However, a larger distance of this cross-section from the lowered check dam was reflected in a considerably smaller increase in bed elevation and the resultant smaller increases in water stages associated with given flood discharges than in cross-section 3 (Fig. 7). Consequently, the retention potential of the floodplain in this cross-section increased little or not at all and was lower than in cross-section 3 (Table 3).

3.4. Changes in hydromorphological stream quality

The assessment performed in 2012, at the beginning of the restoration project, indicated that only one of the five evaluated cross-sections of Krzczonówka Stream represented good hydromorphological quality, whereas the remaining four cross-sections were classified as representing moderate quality (Fig. 8, Table S3). One of the assessed categories—in-river vegetation and organic debris—was considered to be in poor condition (Fig. 9) manifested in the lack of wooded islands and very scarce deposits of large wood in the incised channel. Average scores for six assessment categories indicated a moderate degree of modification of stream hydromorphology in these categories (Fig. 9). The evaluated cross-sections highly varied in longitudinal stream continuity (Fig. 9, Table S3) according to their distance to the check dam. A considerable disturbance to this continuity in the cross-sections located close to the check dam was reflected in their worst overall score (Fig. 8, Table S3).

The assessment performed in 2015, after the completion of all restoration activities in the stream, indicated improvement in the hydromorphological quality of four out of the five cross-sections. This improvement allowed three cross-sections to be upgraded from Class 3 to Class 2 of hydromorphological quality (Fig. 8, Table S4). The largest improvement—by 1 quality class on average—took place with respect to bed substrate (Fig. 9), reflecting the transformation of bedrock or bedrock–alluvial channel bed into a gravelly bed. Somewhat lesser but clearly apparent improvement was indicated with regard to the presence of erosional and depositional channel forms and longitudinal stream continuity; in both these categories, the largest improvement occurred in the cross-sections located close to the check dam, which reduced the variation in scores given to evaluated cross-sections (Fig. 9). Moreover, the presence of scarce wood deposits in the channel resulted in better evaluation of in-river vegetation and organic debris, which allowed for upgrading the stream in this assessment category from Class 4 to Class 3 (Fig. 9).

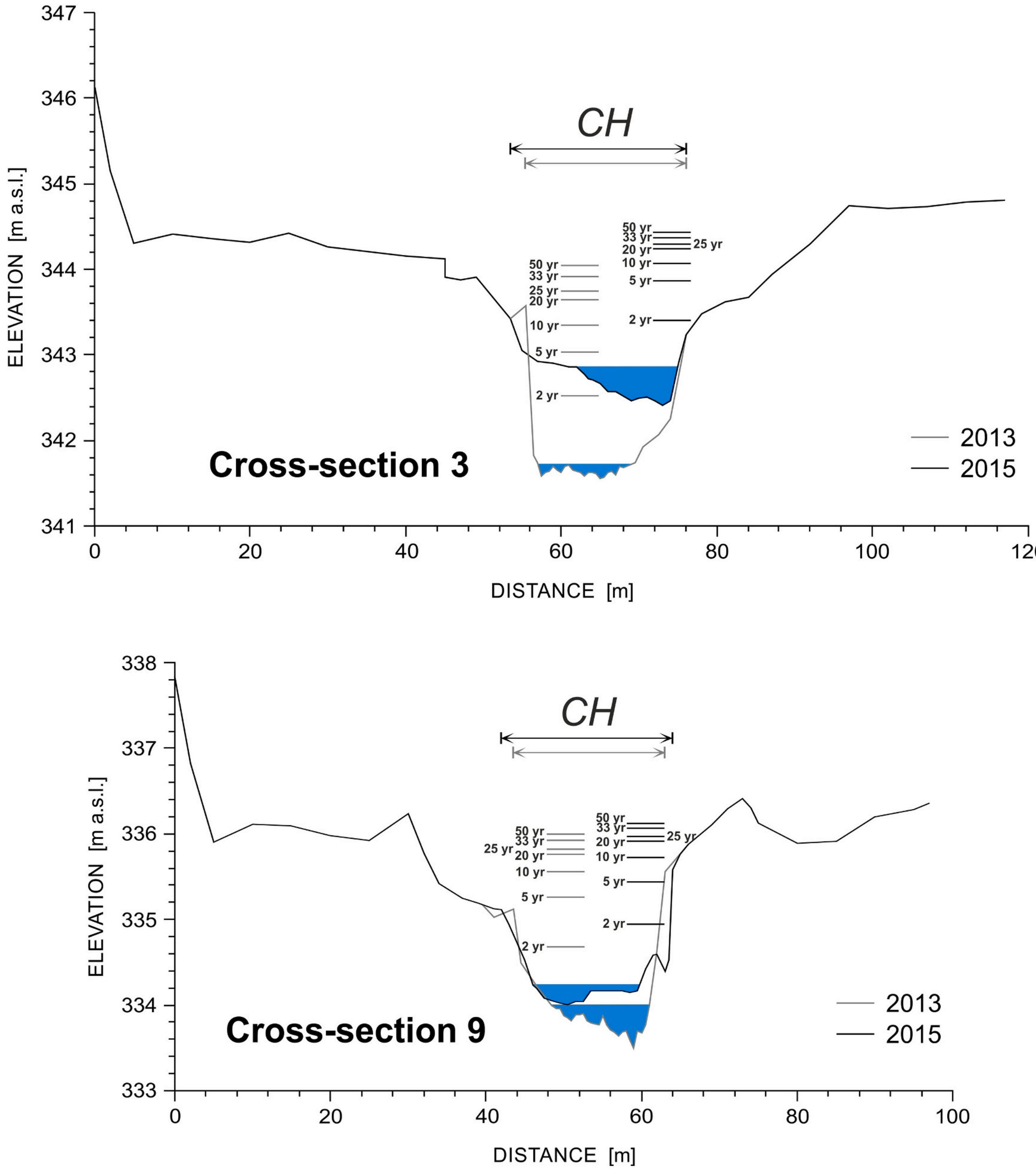

Fig. 7. Morphology of the Krzczonówka Stream channel in cross-sections 3 and 9 and the elevation of water stages associated with flood discharges of given recurrence intervals in 2013—before the installation of block ramps—and in 2015, after entrapment by the block ramps of the bed material flushed out from the lowered check dam. The cross-sections are located 470 m and 1530 m downstream from the check dam. Arrows indicate the extent of the stream channel.

4. Discussion

This study has demonstrated changes in fluvial form and processes in Krzczonówka Stream induced by the lowering of a closed check dam and the construction of block ramps in the incised downstream reach. The release of impounded gravels after dam removal typically occurs during high flows necessary to mobilize coarse-grained sediments (Pizzuto, 2002); in Krzczonówka Stream a moderate flood flushed out such sediments from the dam reservoir when the technical works aimed to modify the check dam and to lower its crest were in progress. The erosion of impounded sediments and their deposition in the downstream reach were thus event-driven, in contrast to the process-driven, more gradual course of these processes following the removal of dams with finer sediments stored in their reservoirs (cf. Pizzuto, 2002). Bulk deposition of the sediments flushed out from the reservoir of the lowered check dam caused marked fining of the bed material, but subsequent outwashing of finer grains from the channel bed resulted in renewed coarsening of the surface layer over several months after the flood. As such differing tendencies of grain-size alterations were also observed after check-dam removal on a mountain river in Taiwan (Wang and Kuo, 2016), they seem to be a characteristic feature of the response of bed material in a gravel-bed channel to this type of restoration activities.

The thickness of deposited sediments was relatively large close to the dam and diminished downstream as observed also in other studies (Wang et al., 2014; Magilligan et al., 2016b). However, the sediment deposition and the resultant bed aggradation were clearly stimulated by block ramps that had been installed in the incised channel lacking a well developed pool-and-riffle pattern. As the ramps locally elevated bed surface by a few tens of centimetres, they impounded flows, hence forming pools on their upstream side (Fig. 2C; cf. Newbury, 2013). The ramps reduced cross-sectional area of the channel and thus a proportion of flood flow had to be conveyed over the floodplain, although this effect

Table 3
Percentage of flow conveyed in the floodplain zone, percentage of flow area in the floodplain zone, and retention potential of the floodplain in cross-sections 3 and 9 of Krzczonówka Stream before (2013) and after (2015) the aggradation of channel bed by the sediment released from the lowered check dam. The bed aggradation equalled 1.05 m in cross-section 3 and 0.37 m cross-section 9.

Recurrence interval	Discharge (m^3 s^{-1})	Cross-section 3						Cross-section 9					
		Percent of flow in floodplain zone		Percent of flow area in floodplain zone		Retention potential (%)		Percent of flow in floodplain zone		Percent of flow area in floodplain zone		Retention potential (%)	
		2013	2015	2013	2015	2013	2015	2013	2015	2013	2015	2013	2015
2 years	37.0	0.0	0.2	0.0	0.8	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0
5 years	81.2	0.0	4.8	0.0	11.9	0.0	7.1	0.7	2.1	3.2	6.1	2.5	4.0
10 years	113.2	0.2	9.3	1.5	19.5	1.3	10.2	4.1	5.8	10.2	11.8	6.1	6.0
20 years	144.0	0.8	13.0	5.7	25.8	4.9	12.8	7.0	8.3	14.7	15.6	7.7	7.3
25 years	154.0	1.4	14.1	8.3	28.1	6.9	14.0	7.9	9.1	16.0	17.8	8.1	8.7
33 years	171.5	2.7	15.8	13.1	32.2	10.4	16.4	9.4	10.7	18.4	22.5	9.0	11.8
50 years	185.0	3.8	17.0	16.8	35.7	13.0	18.7	10.6	11.9	21.4	26.5	10.8	14.6

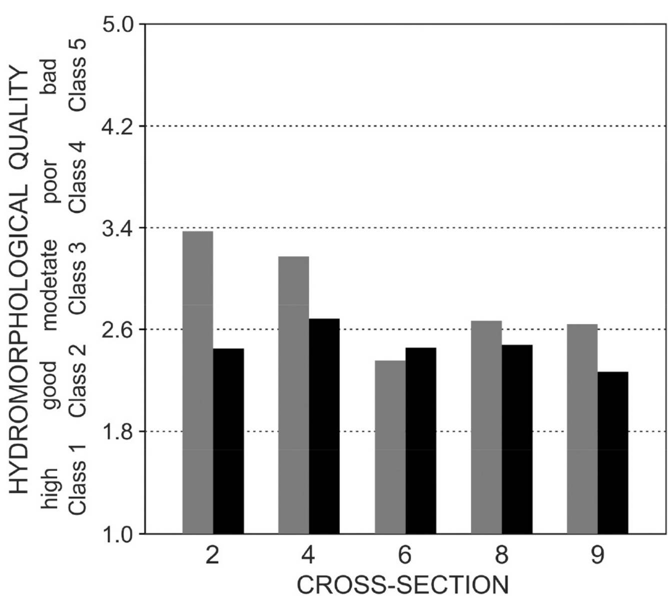

Fig. 8. Scores of hydromorphological quality of Krzczonówka Stream in the evaluated cross-sections given during the assessments in 2012, before the commencement of restoration activities (grey), and in 2015, after completing the activities (black).

was relatively low during the 7-year flood of May 2014. Moreover, the ramps must have considerably increased resistance to flow in the incised channel as they were typified by relatively high grain roughness and they augmented channel-form roughness by forcing flow meandering in the vertical dimension (Keller and Melhorn, 1978). All these factors facilitated deposition of the sediments flushed out from the dam reservoir in pools between the block ramps (similar to the deposition of reservoir-released sediments in pools between natural riffles; Wohl and Cenderelli, 2000), and the amount of delivered sediment was sufficient to bury the ramps as far as 1.2 km from the dam. However, little bed aggradation was recorded in the middle part of the downstream reach, where the relatively large distance between successive ramps caused that the deeply incised channel was occupied by a moderately steep run (cf. Jowett, 1993), not impounded by the downstream ramp.

One-dimensional modelling was used to analyse changes in hydraulic conditions caused by the bed aggradation with the sediment released from the lowered check dam. Because the lowermost reach of Krzczonówka Stream is deeply incised and has low channel sinuosity (sinuosity index, SI = 1.04), a vast proportion of the total volume of flood flows is conveyed in the channel zone. Under such conditions, the retardation of flood flows on the floodplain is low (Wyżga, 1996) and it is justified to analyse the flows using a one-dimensional approach (Bates et al., 2014).

Hydraulic modelling indicated that prior to restoration activities the level of the lower bank edge in the study cross-sections could be attained, on average, by the flow of 5.5-year frequency, at which the average value of unit stream power was 565 W m^{-2}. Under natural conditions, such high values of unit stream power at bankfull flow typify disequilibrium floodplains which are periodically subjected to catastrophic erosion during extreme floods (Nanson and Croke, 1992). In managed channels, such values of unit stream power indicate credible to high potential for geomorphic change, including the erosion of channel banks and adjacent infrastructures (Yochum et al., 2017). Bank-protection structures and bedrock margins of the incised channel maintained the lateral stability of Krzczonówka Stream in its lowermost reach, but the loss of this stability during a large flood might result in considerable damage to bank revetments and valley infrastructure, as it was recorded in artificially narrowed, incised reaches of another Polish Carpathian river (Hajdukiewicz et al., 2016).

The high flow capacity of the incised channel was reflected in high shear forces exerted on the channel boundary and in high competence of the stream, with a 2-year flood entraining cobbles and a 20-year flood able to mobilize cobbles and small boulders. This high competence of flood flows has resulted in outwashing of gravelly alluvium and exposing bedrock on about half of the length of the lowermost stream reach. As indicated by its considerable longitudinal extent, the channel-bed transformation did not reflect local bed scour by the water falling from the check dam (cf. Lenzi et al., 2003; Conesa-García and García-Lorenzo, 2009) but rather a combination of the long-term sediment starvation of the stream and its high transport capacity.

The entrapment of the dam-released sediments by block ramps and the resultant bed aggradation reduced the capacity of the Krzczonówka channel to the flow of 3.2-year frequency on average. Although this flow capacity was still substantially greater than the modal capacity of rivers at equilibrium conditions (equal to the flow of 1.5-year frequency; Williams, 1978), the reduction exerted a remarkable influence on the parameters characterizing the stream hydrodynamics at flood flows. As a result of the reduction in bankfull discharge and an increase in channel width, the average value of unit stream power at bankfull conditions decreased by two-fifths to 330 W m^{-2}. Such unit stream power still exceeded the upper limit of values typical of equilibrium braided rivers (300 W m^{-2}; Nanson and Croke, 1992), but the degree of exceedance was relatively low. At given flood discharges, unit stream power in the channel zone was lower by up to one-third than before the restoration activities, and a similar scale of reduction was calculated for bed shear stress in the channel zone. Values of bed shear stress decreased because a combined effect of bed aggradation and increase in channel width on mean water depth in the channel zone greatly exceeded that resulting from small steepening of channel slope in the study reach. The largest reduction in both parameters was recorded for a 20-year flood, in

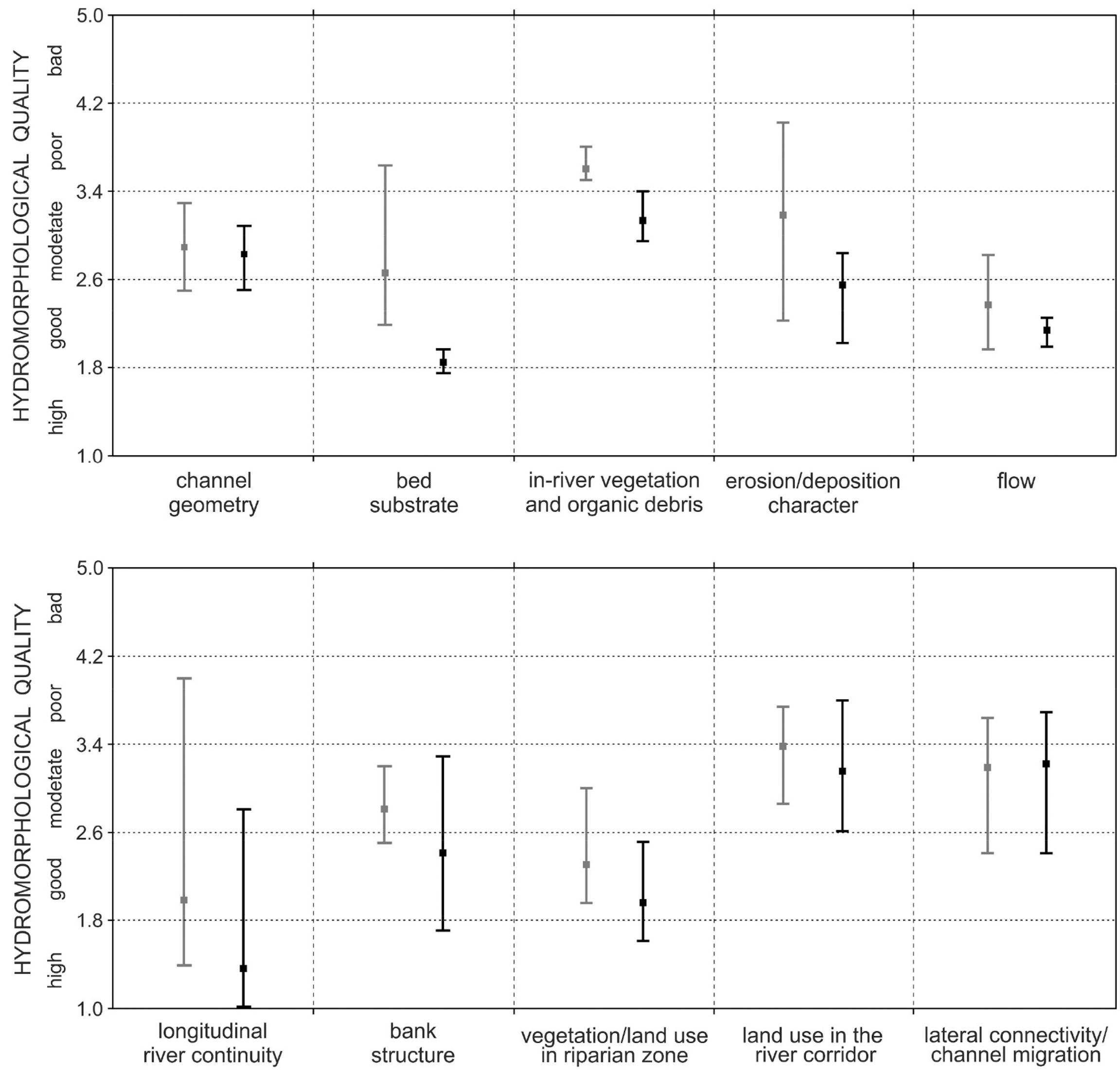

Fig. 9. Range and mean value of the average scores in particular assessment categories of hydromorphological quality given to evaluated cross-sections of Krzczonówka Stream in 2012, before the commencement of restoration activities (grey), and in 2015, after completing the activities (black).

association with the largest increases in flow width and the proportion of flood flow conveyed in the floodplain zone. The reduction in shear forces was reflected in reduced stream competence—currently, even high flood flows are not able to mobilize boulders. Summarizing, the changes in flow hydraulics resulting from aggradation of the channel bed indicate a considerable reduction in the erosional threat to bank revetments and valley infrastructure and in the potential of flood flows for flushing out of gravelly material from the lowermost stream reach.

In deeply incised mountain rivers, a very small proportion of flood flows is conveyed over the floodplain and the potential for floodwater retention in the floodplain area is very low (Wyżga, 1999; Czech et al., 2016). Such a situation typified also the lowermost reach of Krzczonówka Stream before the restoration activities. After the sediment release from the dam reservoir, the contribution of the stream floodplain to the conveyance and the retention of floodwater increased markedly where the channel bed aggraded substantially, but did not change noticeably in the cross-sections with a minor change in bed level. Consequently, no significant change in the potential for floodwater retention was found for the whole set of the study cross-sections. The amount of material released from the lowered check dam was apparently too small to result in a complete recovery of the stream from channel incision caused by the long-term sediment starvation. The situation may improve in the future, provided a sufficient delivery of bed material from the upstream reaches and its entrapment by the block ramps more distant from the lowered check dam.

Before the restoration activities, the hydromorphological quality of Krzczonówka Stream was evaluated as moderate, which reflected considerable human impacts on the condition of its habitats. The high check dam disrupted longitudinal connectivity of the stream for riverine biota, particularly in the cross-sections located close to the structure. The existence of water-saturated sediments underlying bed surface is crucial for benthic invertebrates and spawning of lithophilic fish (Brunke and Gonser, 1997), whereas the transformation of the gravelly channel bed into a bedrock one eliminated vertical connectivity of the stream ecosystem on a considerable proportion of reach length. The spatial complexity of habitats is one of key controls on hydromorphological quality (Elosegi et al., 2010); in Krzczonówka training works and stream incision considerably reduced the diversity of erosional and depositional channel features. Wooded islands cannot develop in narrow, incised channels (Mikuś et al., 2019) and check dams prevent downstream transfer of large wood (Galia et al., 2018)—consequently, in-river vegetation and organic debris constituted the worst evaluated category of the hydromorphological stream quality.

The implemented restoration measures and the entrapment in the incised channel of the sediments released from the reservoir of the lowered check dam improved the hydromorphological integrity of Krzczonówka, and currently most of the study reach of the stream represents Class 2 of hydromorphological quality, hence fulfilling the requirement of the Water Framework Directive (European Commission, 2000). The better average quality scores of the evaluated cross-sections mainly reflected the re-establishment of alluvial bed substrate, increased presence of erosional and depositional channel forms and the restoration of longitudinal connectivity of the stream ecosystem.

5. Conclusions

Restoration measures applied in the mountain Krzczonówka Stream appeared useful in mitigating problems in its physical functioning caused by the stream partitioning by a high check dam, long-term sediment starvation and the resultant channel incision:

- As a result of the lowering of the high check dam, the construction of block ramps downstream from the dam and the passage of the flood of 2014, an alluvial channel bed was re-established still during the restoration project. The channel bed aggraded on most of the stream length downstream from the dam.
- Bed aggradation reduced flow capacity of the channel and the reduction caused the lowering of unit stream power and bed shear stress at given flood discharges. These changes in the parameters characterizing stream hydrodynamics will be reflected in reduced bed material mobility and lower potential for damage to bank reinforcements during subsequent floods.
- Increased proportion of flood flows conveyed over the floodplain resulted in greater floodwater retention in the floodplain zone of the stream, although the effect was not statistically significant in the set of 10 study cross-sections. The effect may be enhanced during subsequent floods as bed material delivered from the upstream reaches of Krzczonówka will be trapped by the block ramps more distant from the check dam.
- As a result of changes in bed substrate, the occurrence of erosional and depositional channel forms and longitudinal connectivity of the stream, its hydromorphological quality improved in 4 out of the 5 evaluated cross-sections downstream from the lowered check dam.

The study has demonstrated effectiveness of block ramps in the entrapment of bed material in an incised mountain stream. This restoration measure may be particularly useful for the reduction of excessive flow capacity of a stream, where no forest occurs in the riparian area or the channel is wider than the height of riparian trees, which precludes such a reduction resulting from spontaneous formation of wood dams or from construction and placement of such dams (Wyżga et al., 2018). A crucial factor for the effectiveness of the restoration measure in reducing flow capacity of incised channels is availability of the bed material that can be trapped by block ramps. In Krzczonówka, such material was delivered from the reservoir of the lowered check dam, resulting in rapid bed aggradation. In other settings, bed aggradation induced by block ramps installed in an incised channel may be slower, reflecting the rate of delivery of the bed material calibre sediments produced by bed and bank erosion in the upstream reach.

Glossary

Check dam Transversal hydraulic structure built to control stormwater runoff, stabilize channel bed and reduce the flux of coarse sediment in a stream by storing it in the dam reservoir.

Block ramp Low-head transversal hydraulic structure lacking a vertical step that is passable for fish and other riverine biota, while enabling dissipation of the energy of flowing water.

Fluvial processes Processes causing the physical interaction of flowing water with channels and floodplains of streams and rivers. They encompass hydrological, hydraulic, morphological and sedimentary processes occurring in watercourses.

Bankfull flow The flow filling a channel to the top of the banks.

Credit author statement

None.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoleng.2021.106286.

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