Acta Sci. Pol.
Formatio Circumiectus 17 (1) 2018, 79–93
ENVIRONMENTAL PROCESSES

www.formatiocircumiectus.actapol.net/pl/ ISSN 1644-0765 DOI: http://dx.doi.org/10.15576/ASP.FC/2018.17.1.79

ORIGINAL PAPER Accepted: 1.03.2018

VARIABILITY OF THE RIVER BED SYSTEM AND MORPHOLOGY IN THE REGION OF THE BLOCK RAMP IMPACT (THE CASE OF THE PORĘBIANKA RIVER)

Karol Plesiński✉

Department of Hydraulic Engineering and Geotechnics, Faculty of Environmental Engineering and Land Surveying, University of Agriculture in Krakow, al. Mickiewicza 24/28, 30-059 Kraków

ABSTRACT

The paper presents the influence of block ramp on system and morphological riverbed. One of twenty-five block ramp structures, located in the Porębianka River and situated in the central part of the cascade, was chosen for testing. In the observed section of the river, high morphological variability of the riverbed was observed in the years 2010–2011, caused by freshets. Additionally, in one period, the morphological changes were also caused by river training work, consisting in repairing block ramps of increased roughness, which were destroyed during the freshets, as well as damaging involvement with the riverbed. Despite the anthropogenic impact on the river channel, the research has shown that the morphology of the riverbed is returning to its natural structures, which are characteristic of the braided rivers. This confirms the thesis that the block ramps of increased roughness cause differentiation in river morphology, and restoration of the braided character of the channel. Therefore, we can conclude that river defends itself against damaging human activity. In addition, the paper describes the beginning of the movement of the debris, for the grain of boulder located in the Porębianka River, in the hydrodynamic conditions persisting during field measurement series. These conditions were based on Shields' diagram and the graph showing the relationship of threshold shear stress for the given grain diameter of boulders.

Keywords: riverbed morphology, block ramp of increased roughness, diversification, beginning of sediment transport, Porębianka river

INTRODUCTION

The Water Framework Directive (Directive 2000/60/EC – Dyrektywa 2000/60/WE) introduced in European countries and in Poland forces the European Union Member States for use not merely technical approach to the problem of river engineering. Natural and aesthetic values of the streams, rivers and river valleys are more and more frequently noticed and taken into account, also at the time of creating plans for maintenance of the river channel (Hernik 2010). In connection with the above, new hydro-technical constructions, requiring monitoring, have begun to be introduced for some time now. In this aspect, structures that meet many technical and natural requirements are crushed-stone block ramps with increased roughness. The operation of these structures consists in creating the degree of roughness that is high enough for the energy of flowing water to be dispersed on the bottom plate or just below; whereas the values of hydrodynamic parameters were comparable at both stations. These structures are often laid in such a way, which causes the concentration of the stream flow in the middle part of the object, and that in turn makes

✉e-mail: k.plesinski@ur.krakow.pl

it possible to maintain the minimum filling necessary for migrating aquatic organisms even during low flows. At the same time, they affect the bottom material of the watercourse, protecting the bottom against erosion of the river bed, reduce the gradient of the watercourse. Their impact on the riverbed is also reflected in the renewal of the tendency towards the braiding of the riverbed, by recreating gravel bars in the channel, which are necessary forms supporting the creation of favourable habitats for the existence of bottom macro-invertebrates and spawning fish. In addition, they create better biological conditions in the stream through greater oxygenation of water, and are well suited to the landscape (Radecki-Pawlik and Skalski 2008, Skalski et al. 2012, 2016, Plesiński et al. 2014, 2015, Radecki-Pawlik 2014, Kałuża et al. 2015, Bylak et al. 2017, Radecki-Pawlik et al. 2017).

These objects can successfully replace traditional concrete barrages, without the need to build expensive and often technically misplaced fish passes. In addition, the barrage as an object crossing the bed transversely is an element artificially disturbing the natural course of the watercourse (changing the system of the river into a one-channel system), constituting a barrier for migrations of many species of aquatic organisms (Plesiński et al. 2013, 2014, Radecki-Pawlik 2013, Pagliara et al. 2017, Plesiński and Radecki-Pawlik 2017, Radecki-Pawlik and Plesiński 2017).

The purpose of the present work is to assess the operation of the block ramp of increased roughness on the system and morphology of the bottom of the riverbed in the region of its impact. The research was conducted in the area of one of the block ramps, which is located within a cascade of 25 such objects on the Porębianka River. In the work, the author put forward the following research hypothesis: Riverbed in the area of the block ramp with increased roughness has certain self-defence abilities against the negative impact of a human activity, which will be manifested by the river's re-braiding.

DESCRIPTION OF THE STUDIED OBJECT

The catchment of the Porębianka River is located in the Western Beskidy Mountains, on the northern slopes of the Gorce mountain range (Kondracki 2000). The highest point of the catchment is the mount of Kudłoń (1276 m a.s.l.), whereas the lowest point is the mouth of the Porębianka River where it joins the Mszanka River in Mszana Dolna (400 m a.s.l.). Administratively, the catchment is located in the Małopolska region, in the Limanowa district.

The Porębianka River is a 15.4 km long watercourse. Sources of the stream are located on the slopes of the Obidowiec Mountain (1000 m a.s.l.). The stream initially flows as Porąbka River, taking several tributaries. In Poręba Wielka, the river is joined with the Koninka stream (6.5 km long), together forming the Porębianka River. Then, in Niedźwiedź, the Konina stream flows into Porębianka, which is its longest tributary (10.7 km). Next, the river flows through the town of Podobin, in which there is a barrage correction made of block ramps with increased roughness. The river flows into the Mszanka River in Mszana Dolna. It is a fourth order watercourse according to traditional classification.

The catchment of the Porąbianka River, with an area of 71.8 km^2, is limited from the west by the hills of Potaczkowa, Krzyżowa and Jaworzyna Ponicka, and from the east, by the peaks of Witów, Pieronek and Kiełbaśna. The southern boundary of the catchment runs along the ridge of Obidowiec to Stare Wierchy, and along the ridge of Mostownica and Kudłoń. These ridges are two of the seven ridges descending from Turbacz, which is the highest peak of the Gorce Mountains.

The catchment of the Porębianka River is an uncontrolled catchment, however in the years 1982–1991 there used to be a water gauge located in Niedźwiedź, 5.2 km from the estuary. The water levels and flows at the IMGW water level station were then under observation. The water levels and flows observed in 1982–1991 indicate that Porębianka is a typical mountain stream, characterized by high variability of water levels. The average water levels exhibit the lowest values in February and October, and the highest values in April and May, which is caused by spring thaws. The amplitude of water levels in the observed period was 151 cm (WWW = 350 cm, NNW = 199 cm). The observed flows were as follows: $NNQ = 0.23\ m^3 \cdot s^{-1}$, $SNQ = 0.59\ m^3 \cdot s^{-1}$, $SSQ = 1.34\ m^3 \cdot s^{-1}$, $SWQ = 5.63\ m^3 \cdot s^{-1}$ and $WWQ = 63.5\ m^3 \cdot s^{-1}$.

The high variability of water levels is caused by a rapid reaction of the catchment to precipitation. The maximum flows are 200–300 times higher than the minimum flows (Krzemień 1984). This is due to the rapid surface runoff of water on the poorly permeable flysch substrate, as well as to partial deforestation of the catchment. The largest freshets occur during summer precipitation, while the freshets caused by spring thaws are smaller albeit long-lasting (Komędera 1993).

Due to the lack of sufficient and up-to-date hydrological data, characteristic and maximum annual flows were calculated with a certain probability of exceedance at the place of measurements. The average annual *SSQ* flow was calculated using the Punzet and Krzanowski equations: $SSQ = 1.27\ \mathrm{m^3 \cdot s^{-1}}$ according to Punzet formula, and $SSQ = 1.29\ \mathrm{m^3 \cdot s^{-1}}$ according to Krzanowski formula, corresponding to the values determined on the basis of water gauge observations.

METHODOLOGY

Field measurements were made in the Porębianka riverbed at the lower and upper station of the block ramp with increased roughness. They consisted in geodetic, hydrodynamic, and granulometric measurements.

Geodetic measurements were carried out in the river channel. They made it possible to determine the dynamics, scope and size of changes in the system of the bottom and its morphology. They were carried out most often after the passage of freshets, and with the observed change in the morphology of the bottom of the watercourse. These measurements were made using the TOPCON GTS-226 total station theodolite.

Hydrodynamic measurements of the flowing water were carried out using the OTT Nautilus 2000 hydrographic mill. This device makes it possible to measure the water velocity in the range of $0.001\ \mathrm{m \cdot s^{-1}}$ to $10\ \mathrm{m \cdot s^{-1}}$. By using this device, several measurement perpendiculars were determined in the area, in which the instantaneous velocities just above the V-shaped bottom were measured ($\mathrm{m \cdot s^{-1}}$) as well as the filling level of h (m). The arrangement of the measurement perpendiculars for the measuring series 4a is shown in Figure 1.

The value of dynamic velocity and shear stress was determined using two methods. The first one is based on the use of knowledge of the velocity profile distribution in the river, expressed in the equation of Von Karman-Prandtl (Bergeron and Abrahams 1992):

$$V = \left(\frac{V_*}{\kappa}\right) \ln\left(\frac{z}{z_0}\right) \tag{1}$$

where:

V_* – dynamic velocity, $\mathrm{m \cdot s^{-1}}$,
κ – Von Karman's constant, –,
z – vertical measurement height, m,
z_0 – filling level of the channel, m.

Dynamic velocity is obtained as a result of plotting the regression line between the instantaneous velocity values and the logarithmic value of the measurement distance from the bottom. If the plotted line takes the shape of a straight line, then we can calculate the dy-

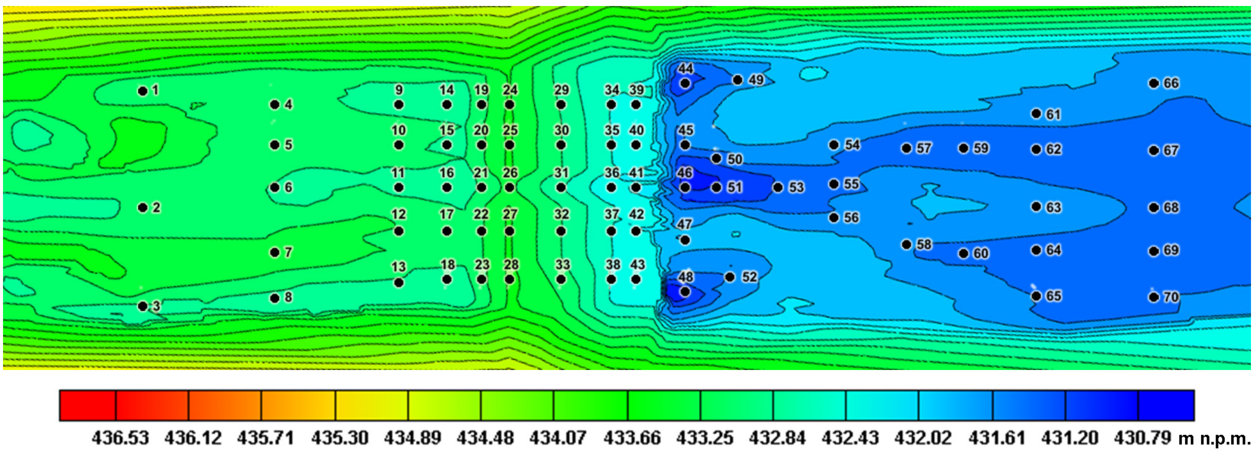

Fig. 1. Hydrodynamic measurement points for series 4a

namic velocity from the coefficient of its slope in relation to the abscissa axis (Godon et al. 2007):

$$V_{*,1} = \frac{a}{5,75} \ [\mathrm{m \cdot s^{-1}}] \tag{2}$$

where:

a – slope coefficient of the line taking the form of the equation (where: *x* – is the height above the bottom, on which the velocity measurement was made; *b* – free term of the equation).

The calculated value of the dynamic velocity was used to determine the forces acting on the bottom of the watercourse and shear stress, according to the formula by Godon et al. (2007):

$$\tau_1 = \rho \cdot (V_{*,1})^2 \ [\mathrm{N \cdot m^{-2}}] \tag{3}$$

where:

ρ – density of water, $\mathrm{kg \cdot m^{-3}}$.

The second method used to calculate shear stress is based on the classic formula by Graf (2001):

$$\tau_2 = \gamma \cdot h \cdot I \ [\mathrm{N \cdot m^{-2}}] \tag{4}$$

where:

γ – volumetric weight of water, $\mathrm{N \cdot m^{-3}}$,
h – filling level of the channel, m,
I – gradient of the riverbed, –.

Knowing the shear stress, one can determine the dynamic speed and the Reynolds number (Graf 2001):

$$V_{*,2} = \sqrt{\frac{\tau_2}{\rho}} \ [\mathrm{m \cdot s^{-1}}] \tag{5}$$

$$\mathrm{Re}_* = \frac{V_{*,2} \cdot d}{\nu} \ [-] \tag{6}$$

where:

d – diameter of the bottom sediment grain, m,
ν – kinematic coefficient of water viscosity, –.

Dimensionless critical shear stress was determined from the following formula (Radecki-Pawlik 2014):

$$\theta = \frac{\tau_2}{(\rho_s - \rho) g d} \ [-] \tag{7}$$

where:

ρ_s – bottom sediment density, $\mathrm{kg \cdot m^{-3}}$,
g – gravitational acceleration, $\mathrm{m \cdot s^{-2}}$.

From the bottom of the riverbed, bottom sediment was taken using the Wolman method (1954). It is used in river channels, which have gravel and stony material in the bottom ($d \geq 2$ mm). The method consists in a random collection of a minimum of 100 pebbles along a straight line, which is defined by the centre of the gravel bar, or across the channel of the watercourse. Then the measurement of the length d_1, the width d_2 and the height d_3 of the collected boulders is taken, whose values are used in order to determine the diameter of the given boulder, namely:

$$d_i = (d_1 \cdot d_2 \cdot d_3)^{1/3} \ [\mathrm{mm}], [\mathrm{m}] \tag{8}$$

where:

d_1, d_2, d_3 – boulder grain axes: longest, medium and shortest.

For all the previously collected boulders, a reliable average diameter and mean diameter were determined:

$$d_m = \sum d_i \cdot p_i \cdot \left(\sum p_i\right)^{-1} \ [\mathrm{mm}], [\mathrm{m}] \tag{9}$$

where:

d_i – average value of the diameter from the particular considered interval, m
p_i – percentage content of grains of the accepted range in the entire sample,%.

$$d_{śr} = \frac{d_{20} + d_{50} + d_{80}}{3} \ [\mathrm{mm}], [\mathrm{m}] \tag{10}$$

where:

d_{20}, d_{50}, d_{80} – characteristic lengths (hydraulic diameters), m

Next, on the basis of the measured values of hydrodynamic parameters, the possibility of transporting bed load in the given measurement perpendiculars has been determined, at the observed flow. To this end, we have used the Shields chart (see: Fig. 2a) (Shields 1936) and a graph of dependencies between shear stresses and grain diameters of rubble (see: Fig. 2b) (Radecki-Pawlik 2014). The Shields chart (1936) is generally known in the literature of the subject. From the value of shear stress, we determine dimensionless critical shear stress, that is the so-called Shields parameter; and from the grain diameter, we calculate the Reynolds grain number. The correlation of the two parameters made it possible to show in which measuring divisions the movement of the bottom material with a given grain diameter takes place. The second graph also relies on the relationship of shear stresses to the grain diameter, with the difference that here, the shear stress values are defined from the bottom velocity profile. This graph is based on the measurements by Kellerhals, Lane, Fahenstock, Scott and Gravlee, Wolman and Eiler, and Baker, who experimentally determined the force needed to move the grain of a given size (Shields 1936, Radecki-Pawlik 2014).

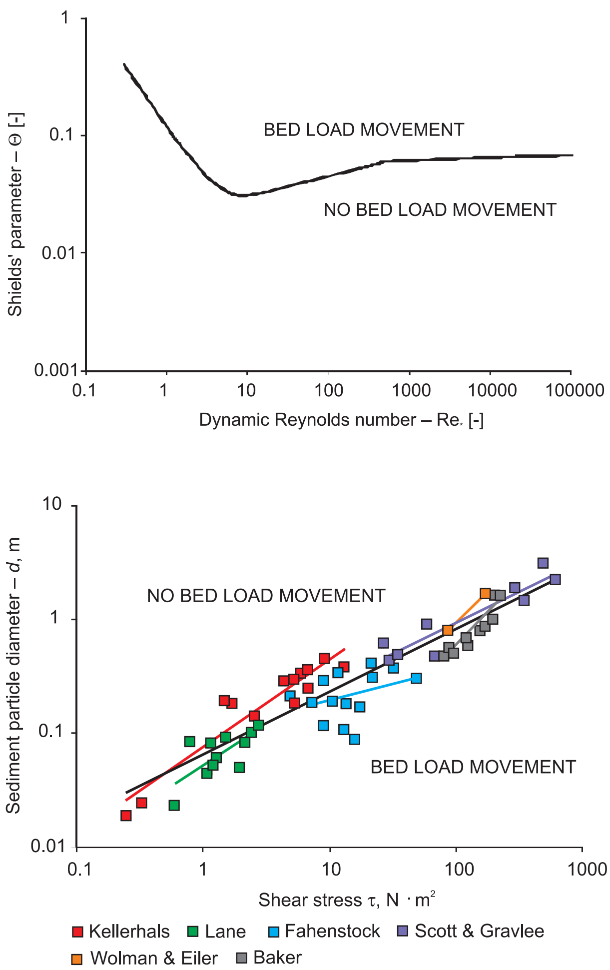

Fig. 2. Shields' diagram (Shields 1936) (a) and the graph showing the beginning of bed load transport movement depending on shear stress (b) (Radecki-Pawlik 2014)

RESEARCH RESULTS ALONG WITH DISCUSSION

In the channel of the Porębianka River, field measurements consisting of seven series of tests were carried out, lasting for the period of 2010–2011 (see: Fig. 3).

The first measurement series (1a) was carried out in April 2010, during the flow of $Q = 2.25 \text{ m}^3 \cdot \text{s}^{-1}$ (see: Fig. 3). At that time geodesic measurements of the riverbed were carried out, as well as hydrodynamic measurements and bottom sediment sampling from the river bottom.

In May and at the beginning of June 2010, there was a freshet with the flow culmination of $Q = 55 \text{ m}^3 \cdot \text{s}^{-1}$, which corresponded to the probability of exceedance once every five years ($p = 21\%$). This was a compound phase, which caused a flood in the lower sections of river valleys, on the Vistula River and its Carpathian tributaries. As a result of its operation, the morphology of the river channel changed. Towards the end of June 2010, a complex of measurements was performed (series 2a) consisting of geodetic measurements, hydrodynamic measurements, and bottom sediment measurements. Field measurements were taken at the flow of $Q = 2.40 \text{ m}^3 \cdot \text{s}^{-1}$. In October 2010, hydrodynamic parameters were measured (series 2b, $Q = 1.25 \text{ m}^3 \cdot \text{s}^{-1}$). Field studies during series 2a and 2b were carried out with the same layout and morphology of the bottom of the watercourse.

In November and December 2010, maintenance and repair works were carried out in the riverbed and in its close vicinity. The repair works consisted in renovating the sloping apron of some block ramps with increased roughness, which were damaged by the May freshet. One of the results of these works was to filling the pools existing in the channel, whereas and the gravel bars were taken out. As a result, the bottom of the watercourse was changed, hence in April 2011 a new series of measurements (3a) was conducted. At the flow of $Q = 1.15 \text{ m}^3 \cdot \text{s}^{-1}$, geodetic, hydrodynamic, and granulometric measurements were made. Then, the hydrodynamic parameters (series 3b) were again measured with the same morphology of the watercourse as before (3a series) but with a higher flow, amounting to $Q = 3.80 \text{ m}^3 \cdot \text{s}^{-1}$.

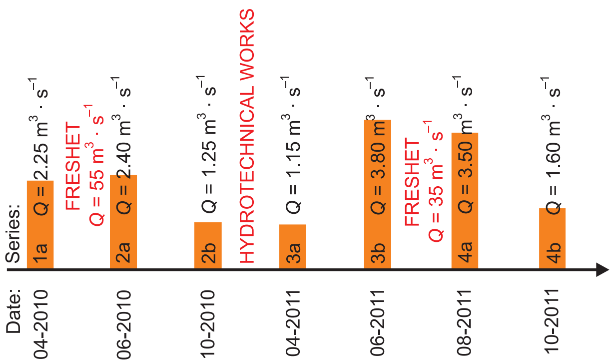

Fig. 3. Measurement series

At the turn of July and August 2011, a freshet with culmination peak was observed, amounting to $Q = 35$ m$^3 \cdot$ s^{-1}, corresponding to the probability of exceedance equal to $p = 35\%$. As a result of the freshet's passage, the bottom of the watercourse channel has changed. The next series of field tests was carried out in August (series 4a) and in October 2011 (series 4b) with a flow of $Q = 3.50$ m$^3 \cdot$ s^{-1} and $Q = 1.60$ m$^3 \cdot$ s^{-1}, respectively. At that time (series 4a and 4b) a whole series of field measurements (geodesy, 2 × hydrodynamics and granulometry) were made. During the series 1a, 17 geodetic cross-sections were made, due to which the bottom system was examined (see: Fig. 4):

- Above the block ramp with increased roughness:

The main current of flowing water ran through the right side of the channel, approaching the embankment at a distance of 1.5 m. Additionally, there was also a stream running through the centre of the channel, with a wider water table, but usually of a smaller depth and velocity than in the main current. At a distance of 45 m from the block ramp, and within one-third's distance from the right bank, there was a mid-channel gravel bar (H), which braided the described section of the river. It also reduced the cross-section of the flowing water in the right braid, which was the cause of the stream's acceleration, deepening of the bottom, and creating the main current. On the other, left side of the channel, at a distance of 45–30 m from the block ramp, a side gravel bar (G) of a small width was deposited, which did not significantly affect the diversity of the flow regime. At one-third of the channel's width from the left bank, and at a distance of 22–30 m from the block ramp, another gravel bar (F) was also noticed. In its shadow, there is a flattering and de-levelling of the riverbed. The main current, flowing through the right braid, connects with the stream flowing through the middle braid.

- Below the block ramp with increased roughness:

The main current of the flowing water ran through the centre of the channel. In both left and right sides of the riverbed, gravel bars formed in the channel, which were located at 5–10 m from the block ramp, at one-fourth of the channel's width on both sides (gravel bars A_1 and B_1). Further two gravel bars were located at a distance of 15–22 m (gravel bars A_2 and B_2). In the central part of the channel, at a distance of 30–45 m, a mid-channel gravel bar (C) was observed, the presence of which caused separation of the flowing stream of water into two branches. During the series 2a and 2b, geodetic measurements were repeated. Several cross-sections were made, which were located in the

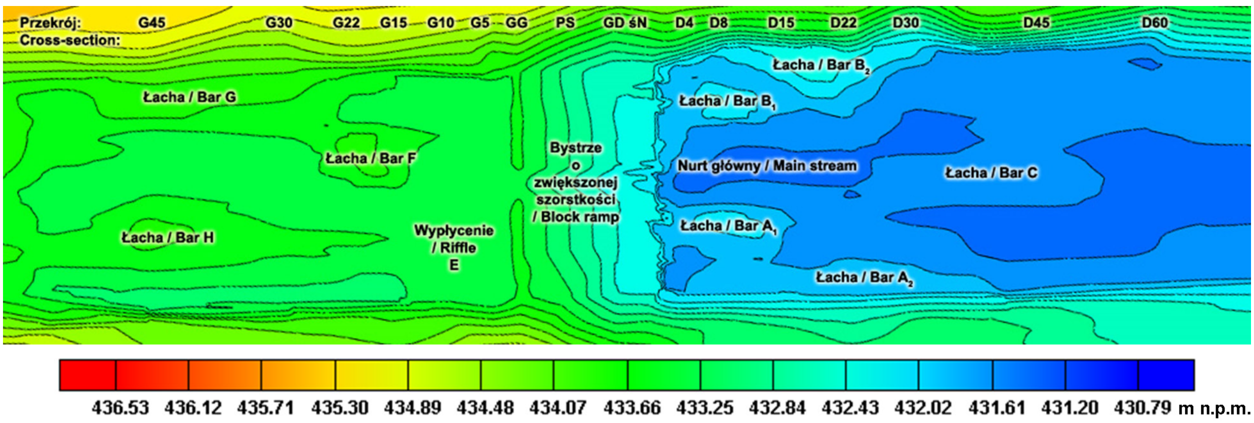

Fig. 4. Riverbed morphology observed during the measurement series 1a

same places as during the previous series. The measurements were aimed at demonstrating changes in the morphology of the watercourse, which occurred during the passage of the freshet wave (see: Fig. 6):

- Above the block ramp with increased roughness:

The middle part of the sloping apron of the block ramp with increased roughness, located above the section of the channel under investigation, was washed out and damaged during the freshet. The boulders that the structure consisted of were moved a few meters down the river. Most of them were deposited at the end of the stilling basin or just below it (see: Fig. 5). As a result, the stream was split into two streams, and behind the oversize grains, a large-sized mid-channel gravel bar (I) was formed. As a result of increasing the flow of water in the central braid, the side gravel bar (G) was partially washed out, leaving only its partial form. Its length has decreased from approximately 15 m in 1a series to approximately 6 m. From 22 m above the analysed structure onwards, there is a flattening and levelling of the bottom of the watercourse, observed during series 1a.

- Below the block ramp with increased roughness:

Two large channel gravel bars (A and B) formed on either side of the channel. Gravel bar A, located on the right side of the channel at a distance of 10–60 m below the block ramp, entered the flood plain with its width. Its formation can be explained by the phenomenon of formation of river shafts, which are created during freshets. In the location where the main channel passes into the flood plain, the velocity of the flowing water drops significantly, which leaves bed load transported so far accumulating in the area. On the left side of the channel, gravel bar B has formed, which was narrower than gravel bar A, but just as long.

Between the gravel bars, one channel was formed, in which the flowing water had more power than during the 1a series. Undoubtedly, contributing to the formation of this channel was the pool that focused the stream on the block ramp, because during the freshet wave, the additional accumulation of flow in this place caused a very large increase in forces acting on the river bed below this pool, and therefore, the elimination of boulders. The distribution of the velocity of flowing water during the passage of the freshet wave can be understood in detail by observing the system and the morphology of the riverbed. In its central part, as a result of the stream concentration on the block ramp, the water velocity was very high, which led to bottom erosion and channelling of the flow. On the other hand,

Fig. 5. Sloping apron of the block ramp, damaged as a results of the freshet wave

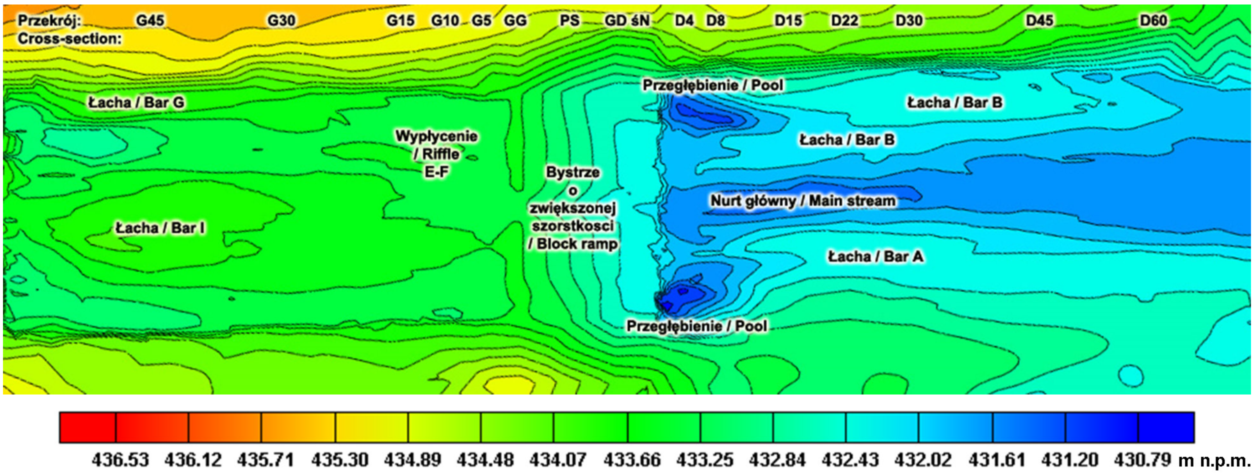

Fig. 6. Riverbed morphology observed during the 2a–2b measurement series

the velocities on the sides were low enough to allow accumulation of the bed load transported.

In addition, pools with the depths of 0.6 m (left) and 0.9 m (right) have been created on the sides of the channel just below the structure, so-called potholes or evorsion hollows. Their formation was caused by the decrease in the amount of water flowing out of the basin (especially during the freshets).

The occurrence of these pools is disadvantageous to the stability of the structure. During freshets and the continuous elimination of boulders from the evorsion hollows, the larger rocks building the stilling basin are falling down.

Series 3a and 3b measurements were conducted in the first half of 2011. Earlier, during the winter, hydro-technical works had been performed, consisting in the repair of some block ramps with increased roughness, which were destroyed during the passage of the freshet wave. In addition, maintenance works were carried out in the riverbed, consisting of clearing the gravel bars, and backfilling the bools in the bottom of the watercourse. As a result of these works, there has been a change in the morphology and arrangement of the bottom of the watercourse (see: Fig. 7):

- Above the block ramp with increased roughness:

The channel of the watercourse was almost evenly levelled. All existing gravel bars were completely cleared. Only in the right part a slight pool was observed, which was associated with the higher speed of water in this place, and which was the remnant of the

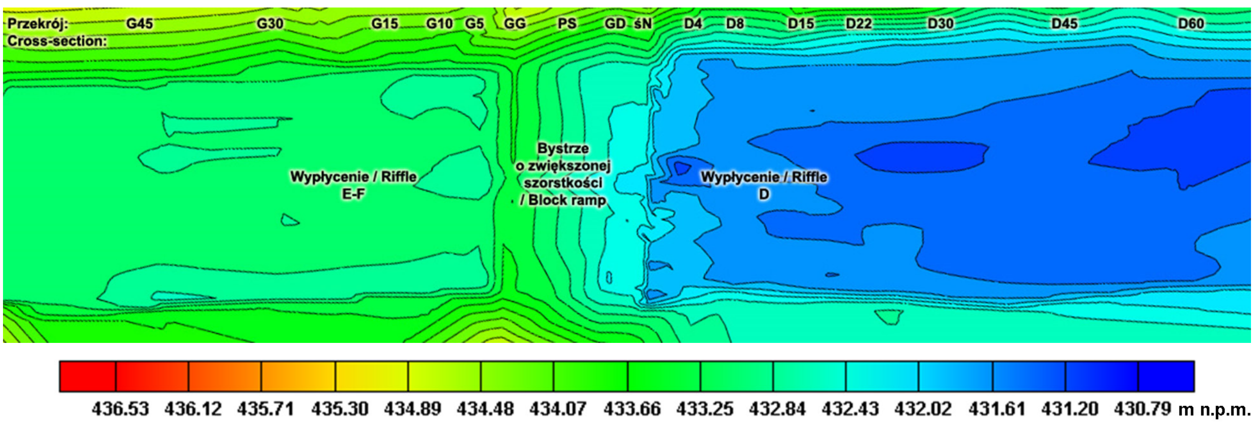

Fig. 7. Riverbed morphology observed during the 3a–3b measurement series

previous braid. Maintenance works carried out before the described measurement series were unprofessional, because the ordinate of the bottom of the watercourse was reduced by an average of 0.40 m on the entire section above the examined block ramp.

- Below the block ramp with increased roughness:

The channel below the structure has also been levelled. Side gravel bars have been cleared. A part of the main channel located in the central part was covered with bed load material. Also the pools located on the left and right side of the channel, just below the structure, have been filled up. Field measurements carried out during series 4a and 4b were made after the passage of the freshet wave, culminating in a flow of $Q = 35\ m^3 \cdot s^{-1}$. As a result, both the system and morphology of the bottom have changed (see: Fig. 8):

- Above the block ramp with increased roughness:

Two gravel bars were created in the channel. One of them (gravel bar G) was located at one-fourth of the width of the channel from the left bank, and 40–50 m from the structure. The other (gravel bar E), was also located at one-fourth of the width of the riverbed, but from the right bank, at a distance of 10–60 m above the structure. At a distance of up to 10 m from the block ramp, a flattening was observed, which was also seen during the previous measurement series.

- Below the block ramp with increased roughness:

At a short distance below the block ramp, in the lateral parts of the riverbed, pools were formed again – evorsion hollows, whose depth, however, was smaller than during the measurement series 2a–2b. In the middle part of the channel, as a result of a stream flowing out of a high speed from the pool, and concentrating the water on the block ramp, below the structure, bottom erosion was created, whose initial stage could be observed already during the measurements of series 3a–3b. During the freshet wave, in the side parts of the channel, at a distance of 10–30 m below the object, rubble was deposited, thus recreating the side gravel bars (A, B) also observed in series 2a–2b. Only the volume of the accumulated sediment was smaller than in the previous case, however, the freshet wave also had a lower culmination flow ($Q = 35\ m^3 \cdot s^{-1}$) than the previous freshet ($Q = 55\ m^3 \cdot s^{-1}$). At the distance of 30 m, the mid-channel gravel bar (C) began to recreate, which occurred during measurements in the 1a series. The deposition of boulders in this location can be explained by the fact that the power of water flowing on the block ramp and immediately below the structure was lower than during the previous fresher, which made the energy of flowing water more dispersed and displaced already at a distance of 25 m from the structure. At the flow of $Q = 55\ m^3 \cdot s^{-1}$, at this point the energy and velocity of water was still too large for the deposition of bed load material to be seen, which we were able observe during the series 4a–4b.

From the observations made, it can be clearly stated that despite the maintenance works carried out in the river channel, which destroyed the braiding of the riverbed (the pool was filled, and boulders were removed from the gravel bars), the riverbed returned to its earlier bottom system and morphology.

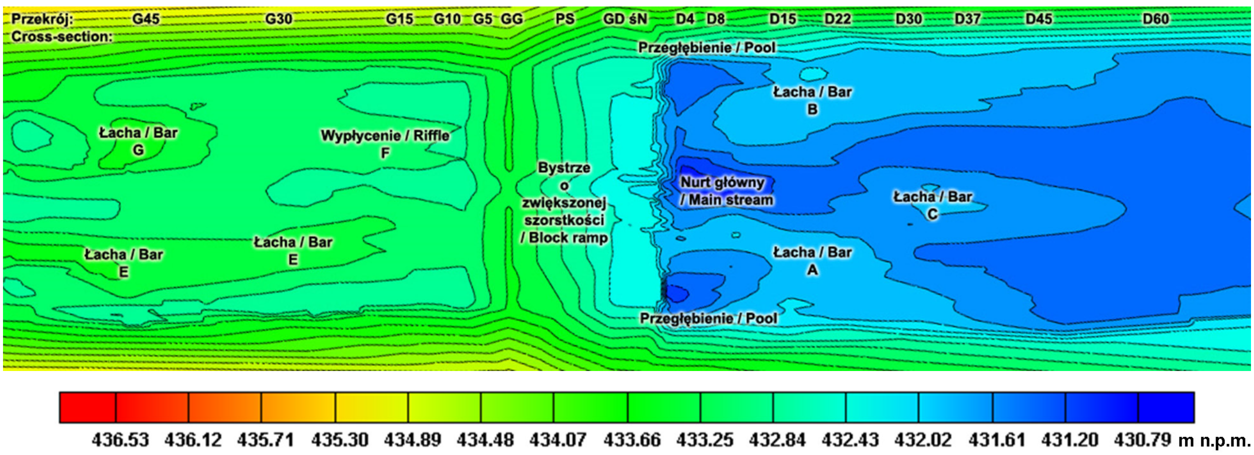

Fig. 8. Riverbed morphology observed during the 4a–4b measurement series

On the basis of hydrodynamic and ganulometric measurements, the possibility of bed load transport was analysed, using two diagrams based on the values of shear stress parameters (that is, a graph illustrating the correlation between shear stress and grain diameter (Radecki-Pawlik 2014), and the Shields chart (1936).

The series 3b and 4a were compared with each other, and it turned out that they shared by a similar flow rate of $Q = 3.80\ m^3 \cdot s^{-1}$ and $3.50\ m^3 \cdot s^{-1}$, respectively. These were flows well above the average annual flow and the highest flow, of all flows for which field measurements were made.

When analysing the measurement series 3b and referring to the graph showing the ratio of sheer stress at which the grain size is activated (Radecki-Pawlik 2014) (see: Fig. 9), it was noticed that the transport of the entire bed load occurring in the river bottom should occur in a pool which concentrated the stream current through the sloping apron, and in the middle part of the basin. Transport of small and medium bed load material was noted in the middle part of the riverbed, below the block ramp (at 4 m and 8 m from the object), where the stream of water flowed out of the structure at a considerable speed. However, it already had less transport capacity, which may indicate that there is no possibility of transporting thick fractions of the bed load. Transient conditions, where it was impossible to explicitly confirm the current conditions of bed load transport, prevailed above all on the upper part of the structure, where the stream of water entering the ramp significantly increased in velocity. Similar conditions prevailed also in the lower station, at a distance of 15–22 m from the structure, where the stream of water stabilized, and the impact of the block ramp began to decrease.

In the riverbed, in the region of the impact of the block ramp with increased roughness, a significant variation in the morphology of the watercourse channel was found, which promotes the formation of many different habitats for macro-invertebrate fauna living

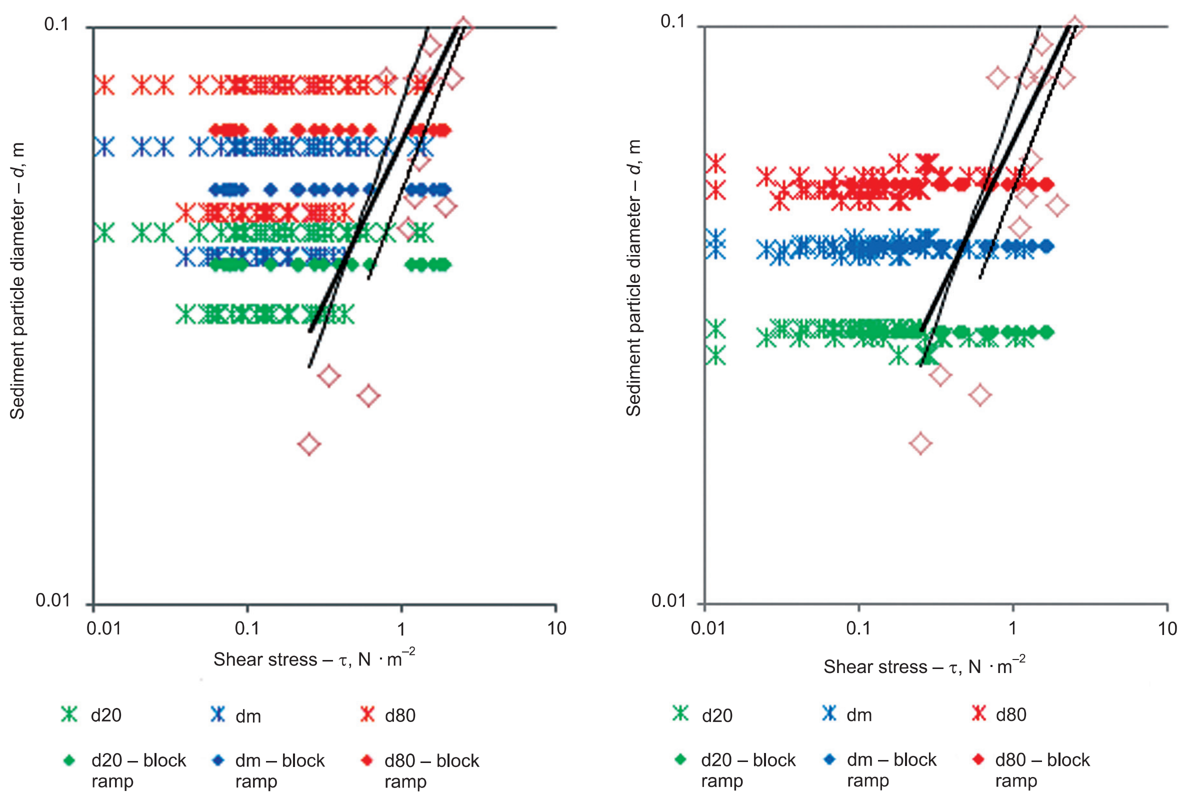

Fig. 9. Graph showing the threshold shear stress for the bed-load transport at 3b (left) and 4a (right) measurement series (Radecki-Pawlik 2014)

in the aquatic environment (Kłonowska-Olejnik et al. 2006, Zasępa et al. 2006a, 2006b, Wyżga et al. 2008). The morphology of the channel is variable not only in space, but also in time. The riverbed in the region of the analysed hydro-technical structure has a tendency to reconstruct itself and revert to its original layout. This can be confirmed on the basis of the restoration of the system and the morphology of the channel to the condition from before the maintenance works that had negative impact on the channel. Aligning and levelling of the riverbed during the maintenance works resulted in decreasing the dynamics and the differentiation of hydrodynamic and morphological parameters in the riverbed. This affects the deterioration of habitats for macro-invertebrate fauna, causes faster runoff of freshet waters, creation of higher unit power of the flowing stream, and activates the movement of boulder grains of larger diameter at lower flow, and thus faster formation of bottom erosion (Wyżga 2008, Wyżga et al. 2009). Therefore, boulders should not be removed from gravel bars in the channel of the watercourse, and neither should pools or evorsion hollows be filled. The natural system of the bottom of the riverbed, consisting of the sequence of successive riffles and trims, together with the bottom forms, must be preserved, so that the river may be in a state of hydrodynamic equilibrium. Furthermore, hollows formed just below the structure may pose a potential danger to the stability of the entire structure, while on the other hand they can provide a hiding place and a resting place for fish before they make their way through the block ramp, which Ślizowski also confirms in his research (2002).

In turn, when analysing individual correlations on the Shields' diagram (1936) (see: Fig. 10), we can conclude that the bed load transport occurred only on the sloping apron of the block ramp with increased roughness. On the other hand, in the upper and the lower station, even very close to the structure, no favourable conditions for the transport of bed load were noticed. During series 4a, the situation was similar. From both diagrams used in the analysis (see: Fig. 9, 10), it follows that sediment transport should take place on the sloping apron of the block ramp with increased roughness. The use of a graph showing the relationship between shear stress and the diameter of the sediment, showed that also below the structure there was a bed load transport for a distance of 15–22 m. In turn, according to the Shields diagram, in the series 4a, bed load transport below the structure was observed, which was new compared to the 3b series. The occurrence of this phenomenon can be explained by the formation of two side channel gravel bars after flooding, which accumulated the flow of the stream in the bottleneck, and this led to the activation and transport of boulders.

In addition, according to the Shields diagram, sediment transport should also occur in the pools, that is, in evorsion hollows created below the structure. This was inconsistent with the reality, because in the pools, the water was standing and no dragging of the bottom material was observed. Discrepancies resulting from the application of both methods spring from the fact that the Shields diagram uses the shear stresses calculated via the classical method, which in turn depend on the gradient of the riverbed and its filling. This contributes to increasing the shear stress values in places where the riverbed has a large drop (sloping apron of the block ramp with increased roughness) or high filling (evorsion hollows). The high value of the parameter obtained by this method favours inaccurate determination of places susceptible to dragging of the bed load bottom material of a given diameter.

Some deviations from the actual conditions were also noticed during laboratory experiments that were carried out in the hydraulic channel of the Department of Hydraulic Engineering and Geotechnics of the University of Agriculture in Krakow by Michalik and Książek (2000). The beginning of movement of individual stones in the bed load was then investigated. Studies have shown that the movement of boulders is activated with a lower value of Shields critical stress, and the ratio of Θ and Re_* for the analysed grains is placed under the threshold curve in the no-movement zone. This may suggest that the line separating the zone of the sediment movement from the zone its absence refers to the conditions of a homogeneous bottom, with densely packed boulder grains.

CONCLUSIONS

The following conclusions can be drawn on the basis of the research presented herein:

1. In the area of the impact of block ramps with increased roughness, there was a significant variation in the morphological conditions of the watercourse.

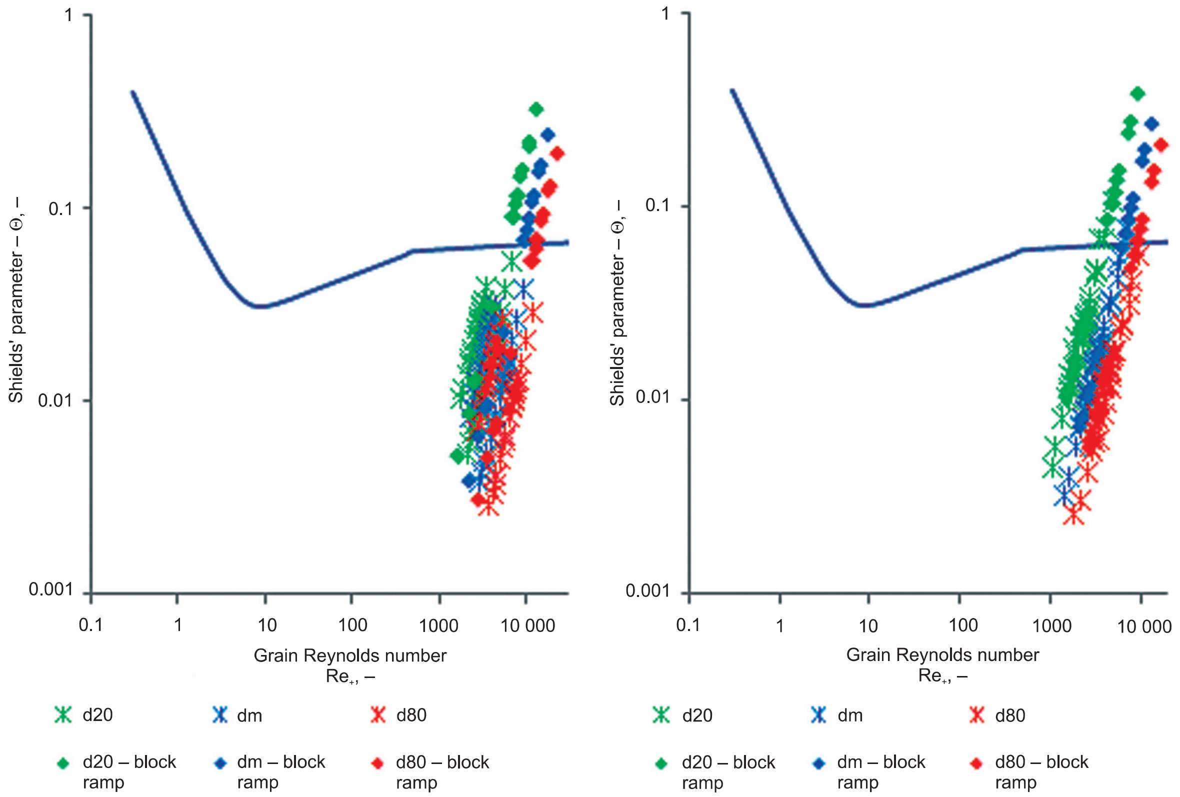

Fig. 10. Shields' diagram for bed-load transport at measurement points of the 3b (left) and the 4a (right) series (Shields 1936)

2. The evorsion hollows forming below the block ramp, on the one hand, constitute a potential danger to the stability of the structure, because the boulders forming the stilling basin of the structure are washed and turned over. This constitutes a loss, which, with larger sizes, can reduce the efficiency of energy dissipation of the flowing water, and in the worst-case scenario, lead to failure and damage to the entire structure. On the other hand, fish swimming upstream can rest in these hollows in order to gain physical strength to overcome the obstacle. Therefore, in the engineering aspect, it is more beneficial to cover these hollows, while for the water fauna, it is more beneficial to leave them.
3. Maintenance works carried out in the Porębianka River channel after the measurement series 2b (October 2010), and before the measurement series 3a (April 2011) were unjustified, because the bottom of the channel was levelled, further lowering its grade line by 0.40 metres in the upper station. Then the hollows within the river channel were filled, and gravel bars were removed. Moreover, the effect of engineering works was very unstable, because after the passage of the next freshet wave (from July/August 2011 with the flow of $Q = 35\ \mathrm{m^3 \cdot s^{-1}}$), the channel system restored itself, returning to the state from before maintenance works (i.e. to the system existing during measurement series 2b). This may indicate the ability of the morphological layout of the river bed to restore itself to the state from before its destruction.
4. The stream of water flowing at a significant velocity out of the hollow that concentrates the flow of liquid on the block ramp with increased roughness, causes erosion of the bottom in the middle part of the river bed during freshets. In addition, the lower velocity of flowing water in the side parts of the channel causes deposition of the carried bed load material, creating lateral gravel bars. In this way, a channel is created with a narrowed cross-section, and the stream of liquid flows un-

der strongly turbulent conditions, which makes it possible to transport the boulders at relatively low flows.

5. With the help of diagrams depicting boundary parameters of the bed load movement, it is possible to determine if conditions prevailing in the given location of the riverbed favour sediment transport. According to these conditions, it was found that the bed load movement should occur on the sloping apron of block ramp with increased roughness, and in the stilling basin, but only if there is a supply of sediment to these places. Often with medium-high flows, the sediment transport was observed just below the structure in a place where the stream of water concentrated on the block ramp left it at considerable speed.

REFERENCES

Bergeron, N.E., Abrahams, A.D. (1992). Estimating shear velocity and roughness length from velocity profiles. Water Resources Research, 28(8), 2155–2158

Bylak, A., Kukuła, K., Plesiński, K., Radecki-Pawlik, A. (2017). Effect of a baffled chute on stream habitat conditions and biological communities. Ecological Engineering, 106, 263–272

Dyrektywa 2000/60/WE Parlamentu Europejskiego i Rady z dnia 23 października 2000 r. ustanawiająca ramy wspólnotowego działania w dziedzinie polityki wodnej.

Gordon, N.D., McMahon, T.A., Finlayson, B.L., Gippel, C.J., Nathan, R.J. (2007). Stream Hydrology. An introduction for ecologists. John Wiley & Sons, London

Graf, W.H. (2001). Fluvial Hydraulics. Flow and transport processes in channels of simple geometry. John Wiley & Sons. Chichester

Hernik, J. (2010). Why do we protect cultural landscapes? [W:] A. Radecki-Pawlik, J. Hernik. Cultural Landscapes of River Valleys. Wydawnictwo UR, Kraków, 11–13.

Kałuża, T., Radecki-Pawlik, A., Plesiński, K., Walczak, N., Szoszkiewicz, K. (2015). Changes in local channel morphology and its hydraulic and hydrodynamic consequences following the introduction of plant basket hydraulic structures (PBHS) – the Flinta River example. [W:] R.F. Carvalho, S. Pagliara (red.) IWLHS – The International Workshop on Hydraulic Structures: Data Validation. IAHR, University of Coimbra, Marine and Environmental Sciences Centre, Coimbra, 137–148

Kłonowska-Olejnik, M., Radecki-Pawlik, A., Skalski, T. (2006). Wybrane metody biologiczne w ocenie stanu ekosystemu uregulowanego cieku górskiego (potok Młynne, Gorce). XX Zjazd Hydrobiologów Polskich, 5–8.09.2006, Uniwersytet Mikołaja Kopernika, Toruń.

Komędera, M. (1993). Zmiany systemu korytowego Mszanki. Praca magisterska UJ. Maszynopis.

Kondracki, J. (2000). Geografia regionalna Polski. PWN, Warszawa

Krzemeń, K. (1984). Współczesne zmiany modelowania koryt potoków górskich w Gorcach. Zesz. Nauk. UJ, Prace Geograficzne, 59, 83–96.

Michalik, A., Książek, L. (2000). Drag force on individual particles on turbulent flow conditions. [W:] J. Sobota (eds.). 10th International Conference on Transport and sedimentation of solid particles, 4–7.09.2000, Wrocław, cz. 1.

Pagliara, S., Radecki-Pawlik, A., Palermo, M., Plesiński, K. (2017). Block ramps in curved rivers: morphology analysis and prototype data support of design criteria for mild bed slopes. River Research and Applications, 33(3), 427–437

Plesiński, K., Jadach, A., Laszek, W., Radecki-Pawlik, A. (2014). Zmiany warunków hydrodynamicznych w rejonie bystrza o zwiększonej szorstkości na rzece Rabie w Karpatach. Nauka Przyr. Technol., 8(4), #57, 1–16.

Plesiński, K., Radecki-Pawlik, A. (2017). Block Ramps: Field Example. [W:] A. Radecki-Pawlik, S. Pagliara, J. Hradecky (red.). Open Channel Hydraulics, River Hydraulic Structures and Fluvial Geomorphology: For Engineers, Geomorphologists and Physical Geographers. CRC Press, Taylor & Francis Group, Boca Raton – London – New York, 82–97

Plesiński K., Radecki-Pawlik A., Michalik P. (2017). Prognozowanie zmian korytotwórczych w uregulowanym korycie rzeki Czarny Dunajec z wykorzystaniem modelu jednowymiarowego. Przegląd Naukowy – Inżynieria i Kształtowanie Środowiska, issue 77, vol. 26, 346–360

Plesiński, K., Radecki-Pawlik, A., Wyżga, B. (2013). Analysis of chosen hydraulic parameters of a rapid hydraulic structure (RHS) in the Porębianka River in the Gorce Mountains, Polish Carpathians. [W:] D.B. Bung, S. Pagliara (red.). IWLHS – The International Workshop on Hydraulic Design of Low-Head Structures. Bundesanstalt fur Wasserbau, Aahen, 121–128

Plesiński, K., Radecki-Pawlik, A., Wyżga, B. (2015). Sediment Transport Processes Related to the Operation of a Rapid Hydraulic Structure (Boulder Ramp) in a Mountain Stream Channel: A Polish Carpathian Example. [W:] P. Heininger, J. Cullmann (red.). Sediment Metters. Springer, Koblenz, 39–58.

Radecki-Pawlik, A. (2013). On using artificial rapid hydraulic structures (RHS) within mountain stream channels – some exploitation and hydraulic problems. [W:] Experimental and Computational Solutions of Hydraulic Problems. Red. P. Rowiński. GeoPlanet: Earth and Planetary Sciences, Monograph. Springer, 101–115.

Radecki-Pawlik, A. (2014). Hydromorfologia rzek i potoków górskich. Działy wybrane. Wydawnictwo UR, Kraków.

Radecki-Pawlik, A., Plesiński K. (2017). Boulder ramps: selected hydraulic, environmental and designing problems. The case of Polish Carpathian streams. Wydawnictwo UR, Kraków, ss.102.

Radecki-Pawlik, A., Skalski, T. (2008). Bankfull discharge determination using the new invertebrate bankfull assessment method. J. Water and Land Development, 12, 145–154

Radecki-Pawlik, B., Radecki-Pawlik, A., Plesiński K., Kukuła, K., Bylak, A. (2017). Wybrane problemy eksploatacyjne bystrzy o zwiększonej szorstkości (stopni -ramp) w aspekcie ich projektowania i funkcjonalności biologicznej. Acta Sci. Pol., Formatio Circumiectus, 16(1), 127–147

Shields, A. (1936). Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung. Mitteilung der Preussischen Versuchsanstalt fur Wasserbau und Schiffbau, 26, Berlin.

Skalski, T., Kędzior, R., Radecki-Pawlik, A. (2012). Riverine ground beetles as indicators of inundation frequency of mountain stream: a case study of the Ochotnica Stream, Southern Poland. Baltic J. Coleopterol., 12(2), 117–126.

Skalski, T., Kędzior, R., Wyżga, B., Radecki-Pawlik, A., Plesiński, K., Zawiejska, J. (2016). Impact of incision of gravel-bed rivers on ground beetle assemblages. River Res. Applic. Wiley Online Library (wileyonlinelibrary.com).

Ślizowski, R. (2002). Wpływ bystrzy o zwiększonej szorstkości na migrację ryb w potokach górskich. Zesz. Nauk. AR w Krakowie, 393, Inżenieria Środowiska, 23, 331––336

Wolman, M.G. (1954). A method of sampling coarse river-bed material. Transactions, American Geophysical Union, 35(6), 951–956

Wyżga, B. (2008). Wcinanie się rzek polskich Karpat w czasie trwania XX wieku. Prace Komisji Paleogeografii Czwartorzędu PAU, 5, 35–39

Wyżga, B., Bojarski, A., Jeleński, J., Zalewski, J. (2008). Zagrożenia dla zrównoważonego stanu środowiska cieków karpackich i proponowane działania zaradcze. [W:] B. Wyżga (red.). Stan środowiska rzek południowej Polski i możliwości jego poprawy – wybrane aspekty. PAN, Kraków

Wyżga, B., Kaczka, R., Łajczak, A., Obidowicz, A., Radecki-Pawlik, A., Zawiejska, J. (2009). Współczesne przekształcenia rzek i torfowisk na Podhalu oraz ich ochrona. [W:] A. Uchman, J. Chowaniec (red.). Budowa geologiczna Tatr i Podhala ze szczególnym uwzględnieniem zjawisk geotermalnych na Podhalu. LXXIX Zjazd Naukowy Polskiego Towarzystwa Geologicznego, 27––30.09.2009, Bukowina Tatrzańska.

Zasępa, P., Kłonowska-Olejnik, M., Radecki-Pawlik, A. (2006a). Wpływ wybranych zmian abiotycznych w rejonie łachy żwirowej potoku górskiego na mikrosiedliska makrobezkręgowców dennych. Infrastr. Ekol. Ter. Wiej., 4(2), 221–232.

Zasępa, P., Radecki-Pawlik, A., Kłonowska-Olejnik, M., Przybyła, K. (2006b). Zróżnicowanie mikrosiedlisk makrobezkręgowców dennych w obrębie łachy bocznej potoku górskiego. Infrastr. Ekol. Ter. Wiej., 2(2), 5–16.

ZMIENNOŚĆ UKŁADU I MORFOLOGII DNA RZECZNEGO W REJONIE ODDZIAŁYWANIA NARZUTOWEGO BYSTRZA O ZWIĘKSZONEJ SZORSTKOŚCI (PRZYKŁAD Z RZEKI PORĘBIANKI)

ABSTRAKT

W pracy przedstawiono wpływ bystrza o zwiększonej szorstkości na układ i morfologię koryta rzecznego. Do badań wybrano jedno z dwudziestu pięciu bystrzy znajdujących się w korycie rzeki Porębianki, usytuowane w środku kaskady. Na obserwowanym odcinku stwierdzono dużą zmienność morfologiczną koryta, która była spowodowana przechodzącymi na przestrzeni lat 2010–2011 falami wezbraniowymi. Dodatkowo, w pewnym okresie zmiany w układzie i morfologii koryta zaszły w skutek działania prac utrzymaniowych. Działania te polegały na naprawie uszkodzonych podczas wezbrania bystrzy o zwiększonej szorstkości, ale także i na niekorzystnej ingerencji w dno koryta rzecznego. Pomimo antropogenicznego wpływu na koryto, z przeprowadzonych badań wynika, że morfologia analizowanego koryta rzecznego powraca do swoich naturalnych struktur, które są charakterystyczne dla rzek roztokowych. Potwierdza to tezę, że bystrza o zwiększonej szorstkości powodują zróżnicowanie morfologii koryta rzecznego i odtworzenie jego roztokowego charakteru, a tym samym możemy stwierdzić, że rzeka ma tendencję do pewnego bronienia się przed szkodliwą działalnością człowieka. Ponadto w pracy określono początek ruchu rumowiska dla ziaren otoczaków znajdujących się w korycie Porębianki podczas hydrodynamicznych warunków zastanych przy pomiarach terenowych. Warunki te określono na podstawie wykresu Shieldsa i wykresu obrazującym graniczne naprężenie styczne dla danych średnic ziaren otoczaków.

Słowa kluczowe: morfologia koryta rzecznego, bystrze o zwiększonej szorstkości, zróżnicowanie, początek ruchu rumowiska, rzeka Porębianka