The influence of a drop-hydraulic structure on the mountain stream channel regime - case study from the Polish Carpathians

Artur RADECKI-PAWLIK[1*]
[1] Department of Hydraulics Engineering and Geotechnics, Agricultural University of Cracow, Poland
30-059 Cracow, Al. Mickiewicza 24-28

*Correspondence to Artur Radecki-Pawlik, Department of Hydraulics Engineering and Geotechnics, Agricultural University of Cracow, Poland. E-mail: rmradeck@cyf-kr.edu.pl.

doi: 10.4316/GEOREVIEW.2013.23.2.158

Article history
Received: April 2013
Received in revised form: July 2013
Accepted: August 2013
Available online: Sept. 2013

ABSTRACT: Basic hydraulic parameters such as shear stress, stream power, unit stream power and water velocities were calculated and measured within the region of a drop hydraulic structure erected on the Kasinczanka stream in the Polish Carpathians. Besides examining the hydrodynamics of the stream the study investigated also the distribution of grain size in the bed-load at the upstream and downstream aprons of the structure. It was revealed that grains deposited at the upstream apron were finer than those deposited at the downstream apron. At the same time, shear stresses and unit stream power values were found to be quite stable upstream of the drop structure, but to change significantly along the stream channel downstream of the structure's energy dissipating pool.

KEY WORDS: drop-hydraulic structure, stream regime, shear stresses, stream power

---

1. Introduction

Only a few field studies in Polish scientific literature have focused on the role that hydraulic structures play in a gravel stream environment, especially in changing a river channel regime, and influencing the distribution of sediment within their region (Błażejewski and Dubil 1989, Błażejewski and Zawadzki 1990, Przedwojski 1993, Ślizowski and Radecki-Pawlik 1996, Radecki-Pawlik and Radzikiewicz 1998, Radecki-Pawlik 1999, 2013, Radecki-Pawlik et al. 2013), although some scientists have tried to examine such conditions in a laboratory flume (Pagliara and Bung 2013).

Drop-hydraulic structures are among the most common hydraulic structures employed when engineering rivers or mountain streams, and thus deserve special attention. After several years of deployment within a stream channel, these structures can influence the hydrodynamics of the stream in their region, and cause changes in the streambed's morphology and granulometry [Peterka 1964, Przedwojski et al. 1995]. Information about velocity, shear stress and stream power distribution within the region of a drop hydraulic structure is potentially of use to designers in determining the length of the lining apron used to protect downstream and upstream parts of the structure against scouring [Ślizowski 1992, Novak et al. 1997, Radecki-Pawlik 2013]. Also, knowledge about the distribution of grain sizes around the hydraulic structure is potentially useful in making bed-load transport calculations within the area, as well as in determining the length of scouring and, finally, calculating the length of rip-rap lining.

This paper reports on the results of an attempt to determine the distribution of some basic hydraulic parameters responsible for forming hydraulic and gravel-bed balance and/or changing a river regime in a small, mountain stream within the region of a drop-hydraulic structure. The research site is situated in the Polish Carpathians. The paper also reports on differences in sediment structure found in the places above which the hydraulic parameters were examined.

2. Study Area

The upper part of the Kasinczanka Stream in the Polish Carpathian Mountains (Figure 1, Phot. 1-3) is flashy and experiences frequent bed-load movement. It is situated in the Carpathian flysh with recognized Palaeogene stratums (beloweskian and magurskian) [Madeyski 1979]. In some parts of the catchment area, limestone and marls have also been identified. The Kasinczanka streambed is mostly alluvial, consisting of sandstone and mudstone bed-load pebbles and cobbles that form a framework, the interstices of which are filled by a matrix of finer sediment.

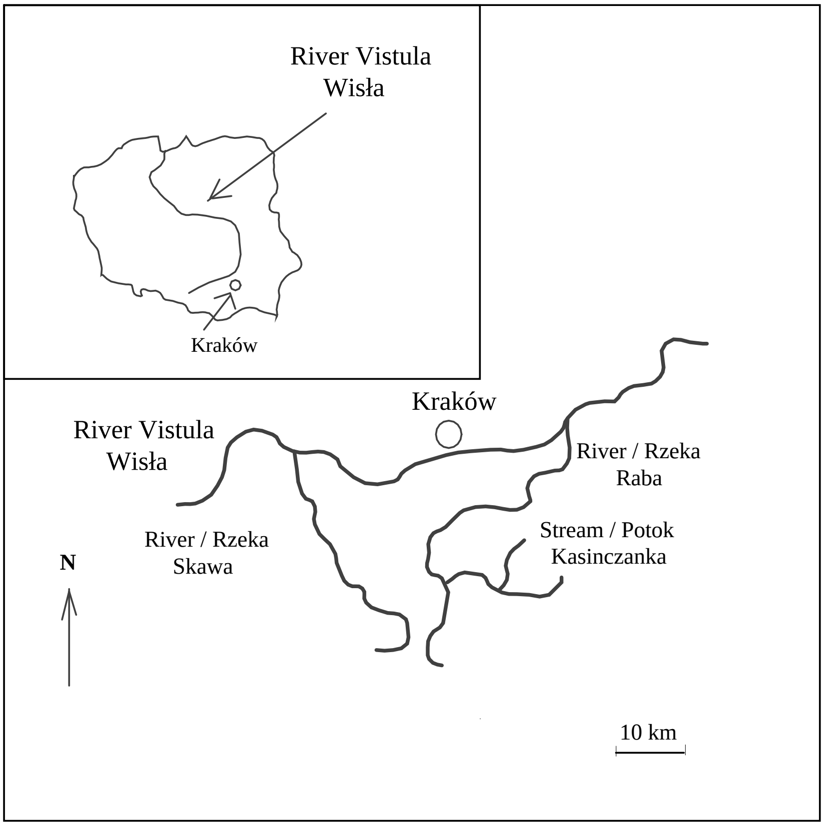

Fig. 1. Location of the research catchment.

Photo 1. Drop hydraulic structure in Kasinczanka stream – general view.

Photo 2. The piano-notch of the Kasinczanka drop hydraulic structure under bankfull.

Photo 3. The piano-notch of the Kasinczanka drop hydraulic structure under low discharge conditions.

Suspended sediment loads are small and contribute insignificantly to channel morphology. Within the study reach, the Kasinczanka cuts through an alluvial bed, built mainly of Quaternary, Holocene river gravels, sands and mudstones. Some basic physical characteristics of the catchment research area are presented in Table 1. In the upper part of the stream, some hydraulic structures have been erected, including a check dam and drop hydraulic structures. The structure that is the focus of this study is the highest of the latter, with a drop of 2.6 meters.

3. Methodology

For the purpose of this investigation, a part of the Kasinczanka Stream was selected with a drop hydraulic structure situated in Weglówka (km. 2 + 637). Field studies included an extensive hydraulic survey of water velocity close to the streambed within research cross-sections of the drop hydraulic structure region in order to calculate shear stress, stream power and unit stream power. A sketch of the research site and research measurement points is showed in Figure 2. Also the longitudinal profile of the river with the drop structure is presented in the Figure 3.

Within the research area, three cross-sections I-I, II-II and III-III were chosen upstream of the notch of the investigated drop-structure, one cross-section (IV-IV) was selected downstream of the drop structure, just below the energy dissipating pool, and two cross-sections (V-V and VI-VI) within a stream channel were chosen.

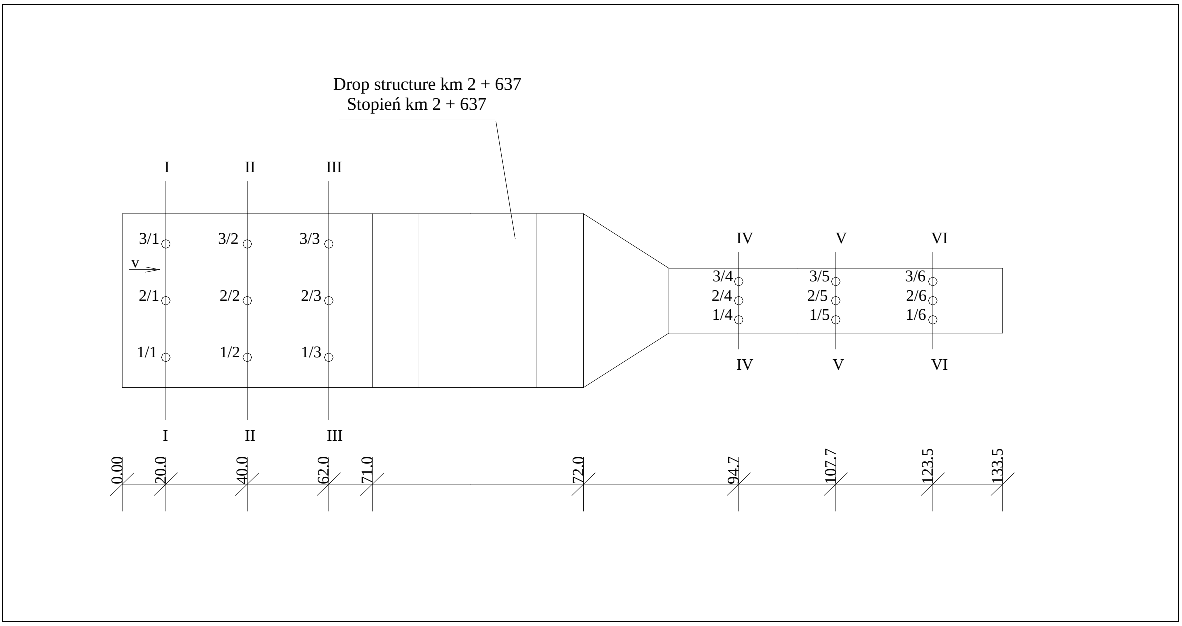

Fig. 2. Sketch of the site with measurement points and cross-sections within the region of the investigated drop-hydraulic structure region.

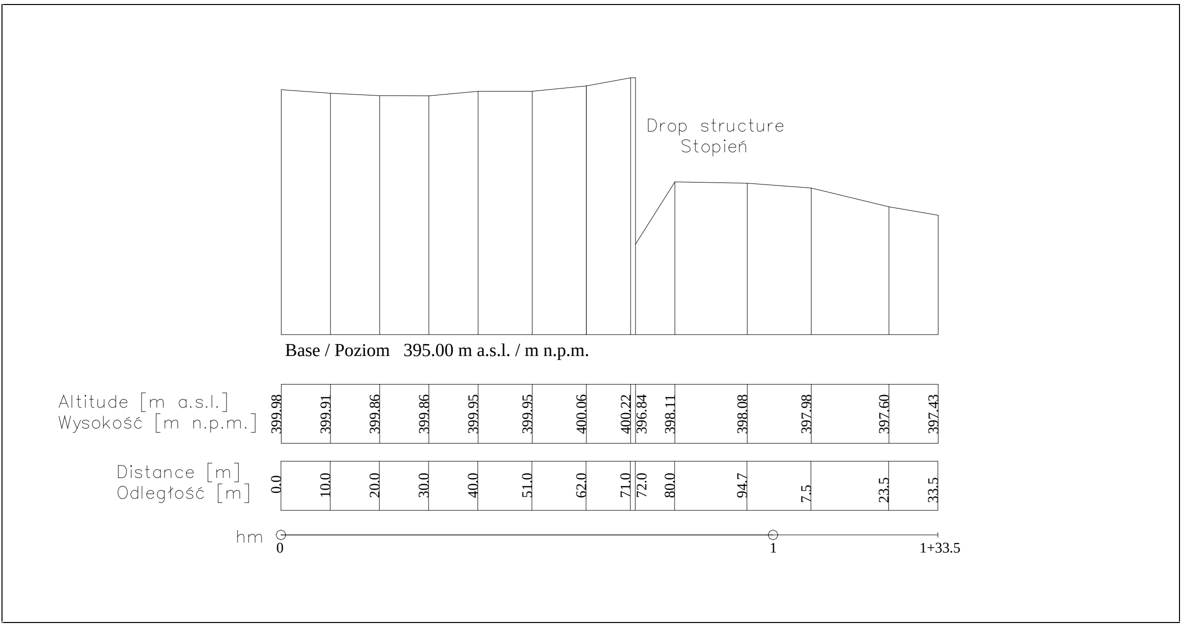

Fig. 3. Longitudinal profile of the investigated region of the drop hydraulic structure.

Water velocity measurements at research points within each cross-section were based on Jarrett's [1990] findings regarding the taking of velocity profiles in mountain stream cross-sections. Gordon et al. [1992] and Bergeron and Abraham's [1992] methods were then applied to the field data, and shear velocity V_* values were calculated from the velocity profiles obtained near-to-river-bed. Finally, the shear stress ² values were calculated from the formula:

$$=$$

$$ {}^{2}=Z={}^{\circ}=v_{*}\overset{0}{=}=[\mathrm{Pa}] \qquad (1) $$

where: ° - water density [kg 〈 m^{-3}], v_* - shear velocity [m 〈 s^{-1}]

The shear velocity value (v_*) was obtained directly from the equation $v = f\ (h)$ [Gordon et al. 1992]:

$$ v_* = \frac{a}{5.75} \qquad (2) $$

where: a – slope coefficient according to the general line equation: $v = ah + b$, in which: h – mean water depth in the stream [m], b – free coefficient.

To determine stream power (t) values, Teisseyre's method [1984] was applied:

$$ \mathrm{t} = ¥\, Q\, E_t\ [\mathrm{N}〈\ \mathrm{m}\ 〈\ \mathrm{s}^{-1}]\ \ [\mathrm{W}] \qquad (3) $$

$$ E_t = \frac{v^2}{2g} + h\ \ [m] \qquad (4) $$

where: ¥ - specific weight [N 〈 m^{-3}], Q - water discharge [m^{3} 〈 s^{-1}], v - mean velocity [m 〈 s^{-1}], g - acceleration [m 〈 s^{2}], h - mean water depth [m] and E_t energy height [m].

Unit stream power (ω) was calculated following Carling [1990]:

$$ \omega = \mathrm{t}\ / A\ [\mathrm{W}\ 〈\ \mathrm{m}^{-2}] \qquad (5) $$

where A is a cross-section area [m^{2}].

For sediment sampling technique was described by Church, McLean and Wolcot [1987] was applied. The samples were collected from the riverbed. Next, a sieving analysis for coarse grains was carried out in the field using round-mesh sieves for hand work [Michalik 1990]. Fine material was carefully collected and analysed in a laboratory. For each surveyed sediment sample, a grain-size curve was plotted. Characteristic grain dimensions were read directly from the grain-size curves. The characteristics of floods and discharges were calculated as follows: Q_{50} using Punzet's formulae for mountainous streams in the Polish Carpathians [Punzet 1972, 1981], mean and minimum annual discharges from Stachy and Krzanowski formulae [Stachy and Herbst 1970, Krzanowski 1976] (Table 1).

Table 1. Physical parameters of the Kasinczanka Stream catchment

Parameter	**Value**
Annual precipitation [mm]	914
Research catchment area [km^{2}]	39.6
Maximum stream altitude [m a.s.l.]	852
Minimum research point altitude [m a.s.l.]	401
Q_{50} [m$^{3}\cdot$ s^{-1}]	15.4
Minimum annual discharge [m$^{3}\cdot$ s^{-1}]	0.143
Mean annual discharge [m$^{3}\cdot$ s^{-1}]	0.630

4. Results

For reasons of clarity the study results are tabulated. Thus, Table 2 shows all hydraulic parameters measured and calculated above research points within the region of the drop hydraulic structure that was the focus of the research (Fig. 2). Measurements were taken under discharge conditions *Q* = 0.73 [m^3 〈 s^{-1}], close to the mean annual flow of *Q* = 0.63 [m^3 〈 s^{-1}] (Tab. 1). This was the most effective way to reflect average discharge conditions in the river. Sediment data are presented in the form of characteristic grain dimensions (Tab. 3).

Table 2. Results of hydraulic measurements and calculations (*h* – mean channel water depth [m])

Point number	**¾ *h* velocity *v* [mĕs^{-1}]**	**Shear velocity *v*$_*$ [mĕs^{-1}]**	**Shear stress 2 [Nĕm^{-2}]**	**Stream power t [W]**	**Unit stream power Jω [Wĕm^{-2}]**
1/1	0.076	0.0023	0.0053	787.7	212.9
2/1	0.097	0.0022	0.0048	1718.7	464.5
3/1	0.073	0.0023	0.0053	966.8	264.3
1/2	0.052	0.0036	0.0129	594.4	174.8
2/2	0.064	0.0022	0.0048	1668.6	490.8
3/2	0.084	0.0021	0.0044	2205.7	648.7
1/3	0.050	0.0022	0.0048	1074.2	249.8
2/3	0.087	0.0022	0.0048	1346.3	313.1
3/3	0.086	0.0028	0.0780	2098.3	487.9
1/4	0.172	0.0119	0.1420	1081.3	675.8
2/4	0.456	0.0098	0.0960	343.7	214.8
3/4	0.595	0.0169	0.2860	504.9	315.6
1/5	0.463	0.039	0.0150	1152.9	1048.1
2/5	0.224	0.0029	0.0084	1518.2	1380.2
3/5	0.058	0.0031	0.0096	644.5	585.9
1/6	0.172	0.0041	0.0170	3229.7	1794.3
2/6	0.222	0.0064	0.0410	1375.5	875.3
3/6	0.157	0.0059	0.0350	1081.3	600.7

Table 3. Characteristic grain sizes [mm] of bed-load samples from measuring

Grain dimension	**Upstream of the apron**			**Downstream of the apron**		
	Cross-section					
	I - I	**II - II**	**III - III**	**IV - IV**	**V - V**	**VI - VI**
d_{95}	115.0	55.0	63.0	193.0	136.8	160.0
d_{90}	100.0	42.1	55.0	175.0	125.0	150.0
d_{84}	85.0	35.0	49.8	158.6	111	138.8
d_{60}	45.0	21.8	28.0	75.0	59.9	98.0
d_{50}	34.0	19.2	22.9	56.6	48.2	68.7
d_{16}	6.0	6.3	7.4	9.8	11.7	15.0
d_{10}	5.0	4.9	5.7	5.9	6.9	7.4

5. Discussion

For the purpose of this discussion, the best way to present the obtained data is in the form of graphs. Thus, Figures 4, 5, 6 and 7 show some of the most important results: the distribution of shear stresses at the upstream and downstream aprons, and the respective distribution of unit stream power values at those aprons. The discussion and conclusions which follow are based on mean annual values, in order to reflect the most common conditions.

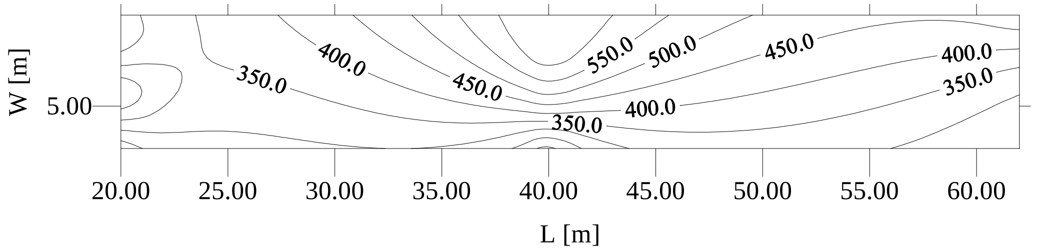

Fig. 4. Distribution of unit stream power values at the upstream apron of the drop hydraulic structure.

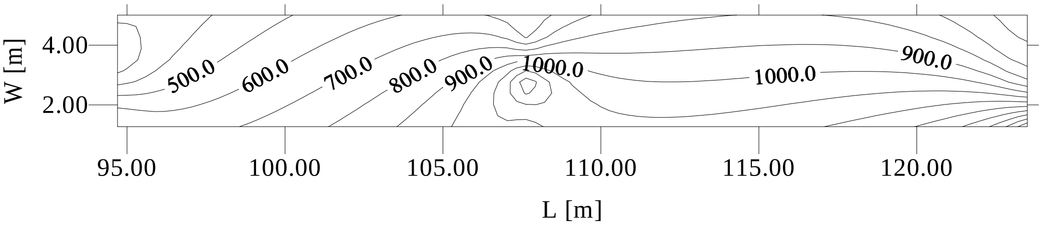

Fig. 5. Distribution of unit stream power values at the downstream apron of the drop hydraulic structure.

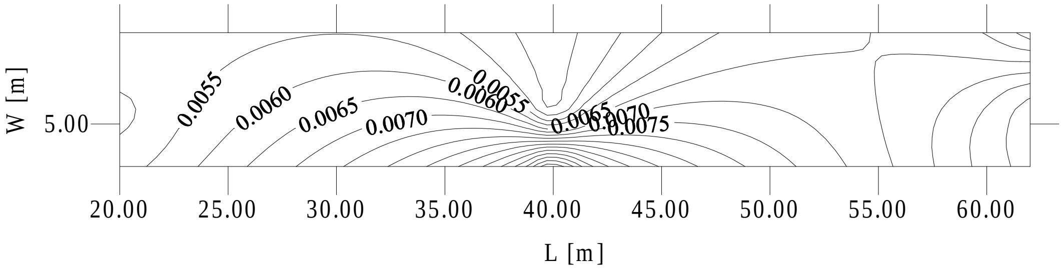

Fig. 6. Distribution of shear stresses at the upstream apron of the drop hydraulic structure.

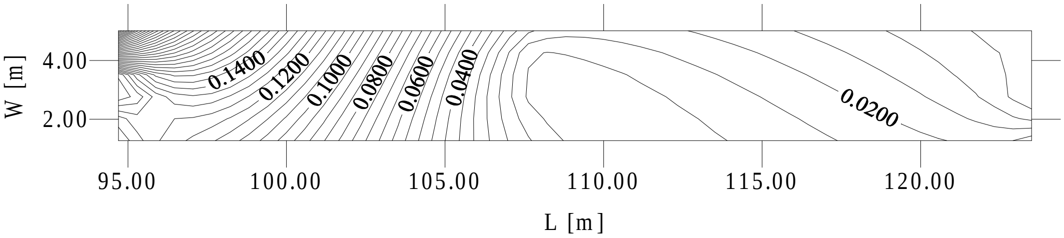

Fig. 7. Distribution of shear stresses at the downstream apron of the drop hydraulic structure.

It was found that sediment grains deposited within the investigated region varied in diameter according to their position up or downstream of the drop hydraulic structure. Generally, for all analyzed cross-sections, characteristic grain dimensions important from the point-of-view of bed load transport movement (d_{50}, d_{84} and d_{95}) varied as follows: at the upstream region of the drop structure (cross-sections I-I, II-II and III-III), d_{50} was respectively 34.0, 19.2 and 22.9 mm (a representative grain size), d_{84} was between 35.3 and 85.0 mm, and finally, d_{95} was between 55.0 to 115.0 mm. In the downstream region of the structure (cross-sections IV-IV, V-V, and VI-VI), the values of d_{50}, d_{84} and d_{95} differed significantly from those obtained in the upstream cross-sections and were the following: d_{50} from 48.2 to 68.7 mm, d_{84} from 111.0 to 158 mm, and d_{95} from 136.8 to 193 mm. Fine grains (d_{10}) were within the same range both upstream and downstream of the drop structure (6.7 mm and 5.2 mm, respectively, all within a range of 6.0 mm).

The above grain-size results indicate that fine grains were deposited upstream and were washed out downstream of the drop structure, while the average values of d_{50}, d_{84} and d_{95} downstream of the structure nearly doubled those found in the upstream region.

At the upstream apron, the velocities of water (at 3/4 water depth – 3/4 *h*) in I-I, II-II and III-III cross sections were between 0.05 and 0.09 m 〈s^{-1}. At the downstream apron (cross-sections IV-IV, V-V and VI-VI), water velocities at the same depth ranged from 0.2 to 0.6 m 〈 s^{-1} and were roughly three times larger than those observed at the upstream apron. The small increase in the velocity value just in front of the notch of the drop structure was insignificant (since that structure is non-depressive in design), meaning that the critical depth was formed above the notch or just inches in front of it.

The shear stresses found in the cross-sections upstream of the drop structure were quite similar, with all values lying between 0.0044 and 0.0078 N 〈 m^{-2}. Only at the right bank in cross-section II-II was one value of shear stress found to be quite unusual, reaching 0.0129 N 〈 m^{-2}. This was possibly caused by a local drop in the cross-section depth in this area, down to 8.25 cm, whereas in all other cross-sections, the depth was consistently between 22.0 and 31.0 cm. At the downstream apron, in cross-section IV-IV, where water comes directly from the dissipating pool of the drop structure into the river channel, the shear stress values ranged from 0.096 and 0.286 N 〈 m^{-2}, a value nearly twice as high as those of shear stresses found in cross-sections V-V and VI-VI (respectively between 0.0096 and 0.015 N 〈 m^{-2}). This sudden change in the shear stress value may be connected with a change of the river channel shape. Between cross-sections IV-IV and V-V, there is a sudden contraction point at which the stream narrows to its natural downstream width.

The value of stream power at the upstream apron was between 594 and 2205 W. At the same time, unit stream power value ranged from 174 and 648 W 〈 m^{-2}, and was highest at the left bank of II-II cross-section. This was related to a slight local change in channel geometry. At the downstream apron, the smallest unit stream power value was in IV-IV cross section (402.1 W 〈 m^{-2}). The value of unit stream power consequently rose in cross-sections V-V and VI-VI to values of 1004.7 and 1090.1 W 〈 m^{-2} respectively. This was connected with increases in water depth from an average of 8.0 cm in cross-section IV-IV, to 21.2 cm in cross-section V-V, and 23.0 cm in cross section VI-VI, resulting in an increase in energy head. Because of that stream power was higher in cross-sections V-V and VI-VI than in cross section IV-IV, just in front of the dissipating pool, despite the fact that the average velocity of water was greater in cross-section IV-IV.

6. Conclusions

1. Any hydraulic structure, and in this case a drop hydraulic structure, definitely influences the hydraulics regime of a stream and affects the sediment bed-load distribution within its region.
2. The characteristic grain size d_{50} - the one most responsible for bed load transport in the equations of Schoklitsch, Parker, Meyer-Peter and Miller, Richard and Simon, Kennedy and others - is at the upstream apron nearly twice as high on average as it is at the downstream apron (25.4 and 57.8 mm respectively). This directly influences the bed-load rate. The other characteristic grain sizes are: at the upstream apron d_{84} = 56.6 mm, d_{95} = 77.7 mm, while at the downstream apron d_{84} = 56.6 mm, d_{95} = 163.3 mm.
3. The grain size d_{10}, representing fine sediment, is in the same range at both aprons, and in this particular example is roughly 6.0 mm (upstream apron: 5.2 mm, downstream apron 6.7 mm).
4. Not taking into account local changes in cross-section geometry, upstream shear stresses are similar in value, averaging of 0.065 N 〈 m^{-2}. This is directly connected with the range of sediment sizes that can be trapped the upstream apron.
5. The average value of water velocity at 3/4 h upstream of the drop structure is roughly three times lower than that at the downstream apron (0.074 and 0.279 m 〈 s^{-1} respectively).
6. The unit stream power values at the upstream apron (367.4 W 〈 m^{-2}) are nearly three times lower than this below the drop structure (832.3 W 〈 m^{-2}). This is connected with changes in water depth and velocity, and the resulting change in energy head line. When leaving the energy dissipating pool of the drop structure, there is a higher shear stress value (in cross-section IV–IV 0.175 N 〈 m^{-2}) than corresponding values found in cross-sections lying in the river channel just downstream of that spot (in cross-section V–V 0.011 N 〈 m^{-2}, and in cross-section VI–VI 0.035 N 〈 m^{-2}). This is connected with a sudden compaction of the channel, in which its contours return to a natural shape.

References

Bartnik W., Strużyński A. 2002. Velocity profile and shear stresses calculation in high volume relative bed roughness flow. [In:] *Proc. of XI Int. Conf. on Transport and Sedimentation of Solid Particles*, Gent, Belgium (September 2002).

Bergeron N. E., Abrahams A. D. 1992. Estimating shear velocity and roughness length from velocity profiles. *Wat. Resour. Res.*, 28 (8), 2155-2158.

Błażejewski R., Dubil A. 1989. Rozmycia miejscowe w sąsiedztwie ostróg rzecznych (Local scouring in the neighborhood of the river groynes). *Gosp. Wod*. 4, 88-92.

Błażejewski R., Zawadzki P. 1990. Rozmycia miejscowe niespoistych gruntów różnoziarnistych poniżej poziomego umocnienia w układzie płaskim (Local scouring of the not-uniform soils below vertical revetments). *Współczesne Problemy Budownictwa Wodnego*, SGGW, Warszawa, 49-66.

Carling P. A. 1990. Particle over-passing on depth-limited gravel bars. *Sedimentology*, 37, 345-355.

Church M.A., McLean J.F., Wolcot J.F. 1987. River bed gravels: Sampling and analysis. *In Sediment Transport in Gravel-Bed Rivers*, Ed. by C.R. Throne et al., John Wiley and Sons, London, 43-87.

Gordon D., McMahon T.A., Ginlayson B.L. 1992. *Stream Hydrology. An Introduction for Ecologists*. Wiley and Sons, London.

Jarrett R. D. 1991. Wading measurements of vertical velocity profiles. *Geomorphology*, 4, 243-247.

Krzanowski S. 1976. Nowa formuła do obliczania średnich rocznych odpływów jednostkowych ze zlewni niekontrolowanych na obszarze karpackiego dorzecza Wisły (The new formulae to calculate unit annual outflows from not controlled catchments within the Carpathian basin of the Vistula River). *Zesz. Nauk. PK, ser. Budownictwo i Inżynieria Sanitarna*, 24, Kraków.

Madeyski M. 1979. *Transport rumowiska unoszonego w wybranych zlewniach podkarpacia* (Suspended transport in chosen Polish Carpathian Catchments). Praca doktorska, AR w Krakowie, maszynopis.

Michalik A. 1990. Badania intensywności transportu rumowiska wleczonego w rzekach karpackich (Investigations of bed-load transport in Carpathian rivers). *Zesz. Nauk. AR w Krakowie seria Rozpr. Hab*., 138.

Novak P., Moffat A.I.B., Nalluri C., Narayann R. 1997. *Hydraulics Structures*. EFN Spon, Chapman and Hall, London.

Pagliara S., Bung D. 2013. *International Workshop on Hydraulic Design of Low-Head Structures*, Editors. FH Aachen University of Applied Sciences, 978-3-939230-04-5, pp. 230.

Peterka A.J. 1964. *Hydraulic design of stilling basins and energy dissipators*, Engineering Monograph No. 25, Washington.

Przedwojski B. 1993. Bed topography and local scour at groynes at river bends. Runoff and sediment yield modelling, *Proc. Int. Symp. SGGW*, Warsaw, 279-284.

Przedwojski B., Błażejewski R., Pilarczyk K.W. 1995. *River training techniques*. Balkema, Rotterdam, Brookfield.

Punzet J. 1972. *Empiryczne wyznaczenie przepływów maksymalnych o określonym prawdopodobieństwie pojawienia się w zlewniach karpackich dopływów Wisły* (Empirical determination of maximum discharges in the Carpathian basin of the Vistula River). PIHM. Warszawa.

Punzet J. 1981. *Empiryczne systemy oceny charakterystycznych przepływów rzek i potoków w karpackiej części dorzecza Wisły* (Empirical stream and river discharge assessment systems in Carpathian basin of the Vistula River). PIHM. Warszawa.

Radecki-Pawlik A. 1999. Badania rozkładu prędkości oraz naprężeń stycznych w strefie oddziaływania bystrza (Investigations of velocity and shear stress distribution within a rapid hydraulic structure region). *Zesz. Nauk. AR w Krakowie*, 19, 71-79.

Radecki-Pawlik A., Radzikiewicz S. 1998. Wpływ budowli regulacyjnej na rozkład naprężeń stycznych oraz skład granulometryczny rumowiska dennego na przykładzie wybranego obiektu hydrotechnicznego (An influence of the hydraulic structure on shear stress and grain size distribution of the mountain stream). *Zesz. Nauk. AR w Krakowie*, 18, 65-74.

Radecki-Pawlik A. 2013. On using artificial rapid hydraulic structures (rhs) within mountain stream channels – some exploitation and hydraulic problems. In: *Experimental and Computational Solutions of Hydraulic Problems*, Rowiński, Paweł (Ed.) Series: GeoPlanet: Earth and Planetary Sciences, Monograph, Springer, p. 425, 2013, pp 101-115.

Radecki-Pawlik A., Plesiński K. & Wyżga B. 2013. Analysis of chosen hydraulic parameters of a rapid hydraulic structure (RHS) in the Porębianka River in the Gorce Mountains, Polish Carpathians. In: *International Workshop on Hydraulic Design of Low-Head Structures*, Pagliara S., Bung D. Editors. FH Aachen University of Applied Sciences.

Stachy J., Herbst M. 1970. *Przestrzenna zmienność przepływów średnich niskich w Polsce* (Spatial distribution of mean-low discharges in Poland). Prace PIHM. z. 100 Wydawnictwo Komunikacji i Łączności, Warszawa.

Ślizowski R., Radecki-Pawlik A. 1996. Badania bystrza o zwiększonej szorstkości na potoku Brennica w miejscowości Brenna (Investigations of a rapid hydraulic structures in Brenna on the Brennica river). *Zesz. Nauk. AR w Krakowie*, ser. Inżynieria Środowiska 16, 71-77.

Ślizowski R. 1992. Badania modelowe wpływu różnych rozwiązań konstrukcyjnych bystrzy o zwiększonej szorstkości na deformację nieumocnionego dna koryta poniżej bystrza (The influence of different kinds of rapid hydaulic structures on the deformation of the bare river bed below the structure). *Rocz. Nauk. Rol.*, PAN, ser. F, tom 83, 1/2, 17-29.

Teisseyre A. K. 1984. The River Bóbr in the Blazkowa study reach (central Sudetes): a study in fluvial process and fluvial sedimentology, *Geologia Sudetica*, vol. XIX, 1, 8-65.