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STUDIES OF BED FORMS IN THE WISŁOKA RIVER AND WATER RESERVOIR AT KREMPNA

Summary

Attempt was undertaken at determination of the kind of river bed forms occurring on the bottom of the Wisłoka River and in the water reservoir at Krempna. The paper aims at examination of the conditions of bed forms and determination of their kinds according to classification criteria. Conditions of formation of bottom forms were defined according to the criteria given by Simons and Richardson [after Dąbkowski *et al.* 1982], Robert [after Radecki-Pawlik 2006], Zanke [1982], Hjulsröm [after Sundborg 1967], Ashley [1990] and van Rijn [1984]. In the course of studies three measurements of velocity in appointed cross-sections were performed during the period July-September 2005.

During measurements samples of bottom sediments were collected and their granulometric compositions determined. Great differentiation in the granulometric composition was found in particular parts of the point bars giving evidence of the process of process of washing out small fractions from the interstitial spaces in the proximal part of the point bars. The examined bars were qualified according to the criteria by Ashley to the type of lateral and point bars of lens-like shapes in longitudinal profile.

Bed deposit samples from the reservoir at Krempna were collected. The bed deposits of the reservoir are constituted of fine mineral material. Variability of granulation in deposits layers was stated. According to the Zanke's nomogram in two examined reservoir cross-sections no movement of bed material exist and according to the Simons and Richardson's diagram in the examined cross-sections the bed should be flat. However, in the inflow cross-sections II at the higher flow and bed-shear stress over 1 $N \cdot m^{-2}$ ripples may occur. This is confirmed by underwater photos taken in the Krempna reservoir. They permitted to define the morphological structure of the bed. In the reservoir, the occurrence of bed forms was not found.

Key words: bed forms, bars, sediment, bed-load, river, small water reservoir

INTRODUCTION

Morphological structure of river bed is conditioned mainly by the flow that forms the river bed and by the kind of mineral material and its way of dislocating as well as by the deposits in the river bed. Formation of bottom or river bed forms is one of the effects of bed-load movement. Bed forms formed in the bed built of fine grained sediment are of significant influence on the hydraulic conditions of the river bed. They arise with the initiated sediment movement. Their shape and dimensions are not unchangeable and change with velocity and depth changes in the stream channel. When velocity and filling are unchangeable the shape and dimensions of bed forms depend then on sediment granulation. These affect stronger water flow and sediment transport at full river channel flow, influencing also the value of the coefficient of roughness, hence, resistance of movement [Radecki-Pawlik 2006]. The process of bars formation was also the subject of a number of publications and detailed description was given by Radecki-Pawlik [2002]. The material building bars in mountain streams is, as a rule, coarse grained with considerable content of gravel fraction. Bed-shear stresses are a decisive factor in formation of bars and in causing their dislocation. Exceeding the critical values for particular fractions in the freshet conditions causes movement of sediment.

It is assumed that the flow resistance over a flat bed at the absence of sediment movement is higher and decreases with an increase in transport intensity. Bed forms influence flow resistance and their dimensions depend on flow conditions. It is of a significant meaning in hydraulic calculations of open channel. In the case of high flows, the value of the coefficient of roughness decreases. Adoption of constant value of the coefficient of roughness for a stream channel, irrespectively of the height of filling, is a great simplification [Dąbkowski *et al.* 1982]. According to the most frequently quoted criterion of division and formation of bed forms given by Simons and Richardson [Dąbkowski *et al.* 1982] phases of particular forms can be distinguished starting from a flat bed, ripples, dunes, transitory forms, anti-dunes to chute and pools [Radecki-Pawlik 2002]. With regard to the value of the Froude number, conditions of formation of particular bed forms are distinguished. Investigations and observations carried out in an alluvial bed showed the classifications of movement according to the Froude number Fr into quiet when $Fr < 1$ and rapid when $Fr > 1$ is too general and does not reflect the phenomena occurring in the stream [Dąbkowski *et al.* 1982]. The fact of what hydraulic conditions prevail in a given sector of stream is conditioned also by local flow parameters, viscosity of fluid, properties of the bed material and river bed dimensions. Simon and Richardson [Dąbkowski *et al.* 1982] distinguished two areas of movement: the lower and upper one and a transitory zone in dependence on the bed form, grain size of the sediment, intensity of sediment movement, flow resistance, and the way of energy distribution of particular filaments of water flow. The lower area is characterized by low values of bed-shear stress and ripples, or folds occurring on the bottom, whereas the top area corresponds with high values of bed-shear stress with bed forms. On the other hand, Yalin [1979] finds the kind of bed forms dependent on the relation of bed-shear stress to critical bed-shear stress and parameters considering the height of the from and flow rate.

A proper appraisal of bed forms is of great importance in calculation of not only the flow quantity but also in the estimation of the amount of sediment transported by rivers and streams. The effect of bed forms and of their dislocation sediment concentration was investigated by Ikeda [1983]. Robert [after Radecki-Pawlik 2006] presented, in forms of diagram, ranges of grain diameter and bed-shear stress corresponding with the determined bed forms. Dependence of the kind of bed forms was presented, among others, by Zanke [1982], Hjulsröm [after Sundborg 1967], Ashley [1990]. Another classification criterion was presented by van Rijn [1984] differentiating bed forms in dependence on the parameter of the stage parameter and diameter d_{50}.

The majority of results on bed forms and their influence on the conditions of water and sediment flow was the effect of laboratory studies. In natural conditions bed forms undergo considerable changes in consequence of differentiation of flow, mineral material in the channel bed due to the spatial bed forms arrangement, and channel bed structure. Recognition of bed roughness, type and arrangement of bed forms is of great importance in calculations of flow velocity and sediment transportation.

The first aim of the paper is the determination of bed-shear stress in a mountain river bed caused by the analysed flows and determination of critical bed-shear stress and the corresponding flow initiating movement of the bed sediment. Another aim of the paper is the examination of conditions of bed form formation in a water reservoir and determination of their kind according to the classification criteria given by Simons and Richardson [after Dąbkowski *et al.* 1982], Robert [after Radecki-Pawlik 2006], Zanke [1982], Hjulsröm [after Sundborg 1967], Ashley [1990] and van Rijn [1984].

With this aims in view, the investigations were carried in the river bed of the Wisłoka river upstream of the small water reservoir at Krempna. These included the determination of the granulometric structure of the bed material of the river bed and the topography of river bed forms with morphological analysis, as well as examination of the bed shape of the water reservoir.

CHARACTERISTIC OF THE INVESTIGATION AREA

The Wisłoka River belongs to the catchment of the upper Vistula River. The total length of the Wisłoka River is 163.6 km, and its catchment area is 4110.2 km^2. Its length from the springs to the reservoir at the locality of Krempna is 18.6 km, and drains a partial catchment area of 165.3 km^2.

The area of the catchment is of mountainous or submountainous relief. Hills are separated by valleys whose bottom are about 400 m a.s.l. This influences greatly the formation of flood wave and amount of sediment brought into the Wisłoka River. The catchment area, with regard to its mountainous character, is to a great extent covered with forests. Territories occupied by forest constitute about 80% of the catchment area. A great part of the forest belong to the Magura Landscape Park of, whose area is in 95.7% covered with forests.

The reservoir at Krempna, of recreational character, was built in the years 1970-1972. It is located in the upper course of the Wisłoka River at the km 145.023. A 145 m long earth dam with concrete four-span weir and movable gates constitutes the damming element. The initial capacity of reservoir at Krempna was increased in year 1987 in consequence of desilting and rebuilding. The storage capacity of the reservoir equals 119.1 thousand m^3, and headwater elevation is 375 m a.s.l. The reservoir surface area is 3.2 ha and length of the reservoir is 400 m.

INVESTIGATION METHOD

Investigations of river bed forms in the River Wisłoka were performed in 4 measurement cross-sections at the km 146.123 (cross-section VI), km 145.873 (cross-section V), km 145.673 (cross-sections IV) and km 145.623 (cross-section III), i.e. respectively 600 m, 350 m, 250 m and 200 m upstream of the inflow into the reservoir at Krempna and in the reservoir in the inflow (cross-section II) and close to the dam (cross-section I). The locations of the cross-sections are presented in Figure 1.

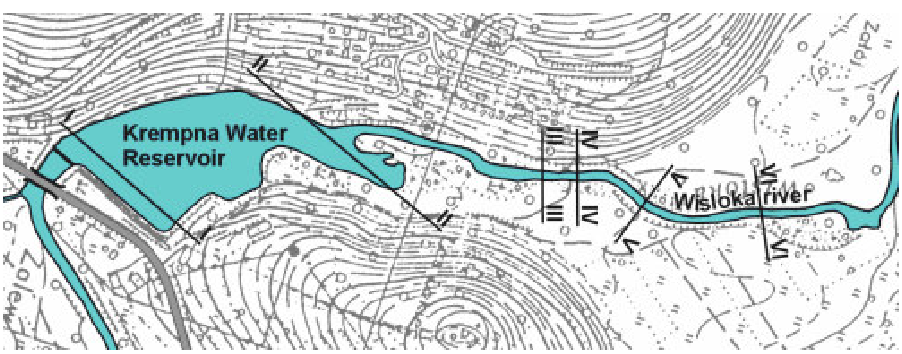

Figure 1. Location of measuring cross-sections

Investigations of river bed forms were carried out in September 2005. During investigations the flow in the River Wisłoka was 0.9 $m^{-3} \cdot s^{-1}$ at maximal water level in the river bed equaling 0.45 m. Investigations of bed forms close to the dam and the backwater cross-section of the reservoir at Krempna were carried in July-September 2005. Measurements of flow velocity were made according to the method included in the PIHM instruction and "Measurement procedure…" IMGW [2002]. Measurements were performed in appointed hydrometric verticals by use of an induction hydrometric current meter of the Nautilus C 2000 OTT Hydrometrie type.

In order to examine the morphology of the reservoir bed, underwater photos of the cross-section of the reservoir bed were taken. The photos were taken at the flow of 0.9 $m^{-3} \cdot s^{-1}$. These photos permitted to define the changes of bed shape and to find the occurrence of bed forms in the reservoir. The height of bed change of height or bed forms was established by use of a matrix with a graduated network of squares. It enables, after making use of underwater photos, to define the height of changes of bed shape. The modulus of the network of the matrix is 1.0 cm. After cutting of the matrix into the bed a part of bed sediments was removed from the photographed side so as to expose the bed profile. After the loosen silt had settled and water clarity was achieved, photos of the bed were taken.

Bed sediments samples were also collected from the river bed and from the reservoir bed in order to determine the granulometric composition by use of the Cassagrande's method in the form modified by Prószyński [PN-R-04032. 1998]. The mean diameter and d_{50} were defined and bed-shear stress and transport stage parameter were calculated.

RESULTS

The dimensions of the river bed bars in the Wisłoka River present in cross-sections: III, IV, V and VI were determined. The dimensions, i.e., maximal length, width and height are 27 m × 8 m × 0.95 m for the bar in cross-section III, 4.41 m × 9 m × 0.70 m for the bar in cross-section IV, 66 m × 6 m × 0.65 m for the bar in cross-section V and 85 m × 13 m × 0.8 m for the bar in cross-section VI respectively. The investigated point bars were classified according to the Ashley's criterion [1990] to the type of lateral and point bars of lens-like shapes in longitudinal profile. Sediment samples for granulomertic examinations were taken in distal, proximal and middle parts of the bars in section III and for the bed in water current. The granulometric curves were presented in Figure 2.

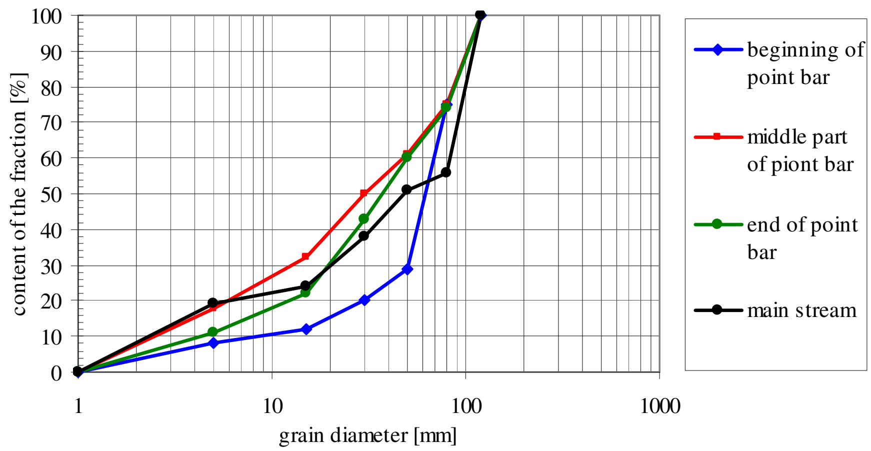

Figure 2. Curves of bed load graining taken from the Wisłoka River in the beginning, middle and end parts of point bars and in the main stream of river

Great differences were found in the granulometric composition in particular parts of the bars (Figure 2). The average value of the grain diameter d_{50} in the proximal part of the point bar was about 6.3 cm, and 3.0 cm in the distal part. This may give evidence of washing out of small fractions from the interstitial spaces of the proximal part of point bar. However, the mean value of the diameter d_{50} of the sediment collected from bed in the water current is 3,4 cm.

During three hydrometric measurements in the Wisłoka River the flows were 0.90 $m^{-3} \cdot s^{-1}$, 3.12 $m^{-3} \cdot s^{-1}$ and 7.56 $m^{-3} \cdot s^{-1}$. The calculated mean velocity of the river water ranged from 0.23 $m \cdot s^{-1}$ to 0.49 $m \cdot s^{-1}$, and the calculated bed-shear stress were 9.32-19.85 $N \cdot m^{-2}$. The results are presented in Table 1.

Table 1. Results of calculations of flow velocity, dynamic velocity and bed stress in the Wisłoka River

Date of measurement	Water flow Q [$m^3 \cdot s^{-1}$]	Depth in river h [m]	Mean velocity V [$m \cdot s^{-1}$]	Overall bed shear velocity V_* [$m \cdot s^{-1}$]	Bed-shear stress τ [$N \cdot m^{-2}$]
06.09.2005	0.90	0.45	0.23	0.097	9.32
12.08.2005	3.12	0.63	0.37	0.122	14.99
18.08.2005	7.56	0.89	0.49	0.141	19.85

Critical bed-shear stresses calculated from the mean diameter according to Shields [van Rijn 1984] are 55-58 $N \cdot m^{-2}$. When these values are exceeded, the movement of sediment takes place in the proximal and distal part of the bars and in the current bed. After exceeding the depth of 1.36 m, the critical bed-shear stress will be exceeded and the movement of sediment grain of diameter d_{50} will occur in distal parts of point bars, whose mean diameter d_{50} is 3.0 cm. In the proximal parts of the point bars the sediment consists of coarse grains of mean diameter 6.3 cm. When 1,49 m is exceeded, the movement of the sediment building proximal part of the point bars will occur.

During measurements of velocities in the reservoir the bed sediment was also sampled in cross-sections I and II. Silt samples were taken from the upper, i.e., surface layer, and the lower one, i.e., 0.4 m under bed surface.

Bottom sediments of reservoir are constituted of fine grained mineral material. Variability of granulation in deposited layers was also stated. The top layer is formed of a fine material, this being confirmed by determined mean diameter (d_m) and diameters d_{50} of bed sediment. These are: d_m=0,299 mm and d_{50}=0,074 mm at the inflow cross-section lower layer, d_m=0,268 mm and d_{50}=0,033 mm at the inflow cross-section upper layer, d_m=0,054 mm and d_{50}=0,015 mm at the outflow cross-section lower layer, and d_m=0,026 mm and d_{50}=0,014 mm at the outflow cross-section upper layer. In Figure 3 the granulometric curves of bed sediments of the reservoir at Krempna are presented.

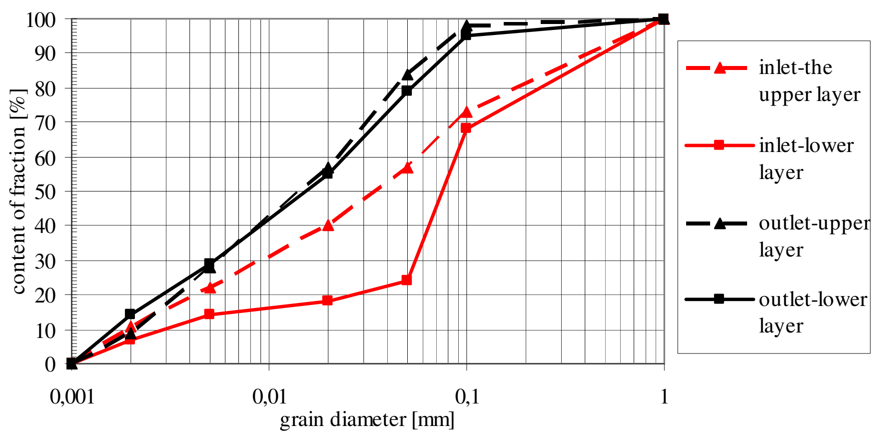

Figure 3. Curves of bed load graining taken from reservoir at Krempna in inlet cross-sections (cross-section II) and in outlet cross-sections (cross-section I)

Different hydraulic conditions prevail in the water reservoir. Mean velocities are seriously reduced; in cross-section II at the flow rate of 0.90 $m^{-3}\cdot s^{-1}$ they are on average 14 times lower than those in the river cross-sections, whereas, at the flow rate of 7,56 $m^{-3}\cdot s^{-1}$ they are over 47 times lower than those in the river cross-sections. Cross-section I located closer to the dam is characterized by a considerably larger area. Here the mean velocities are over 21-71 times lower than in the river cross-sections. Table 2 shows the results of calculations of mean velocities, bed-shear stress and transport stage parameter in reservoir in examined cross-sections.

Table 2. Results of calculations of flow velocity, bed-shear stress and transport stage parameter in reservoir cross-section I and II

Date of measurement	Cross-section	Maximal depth h [m	Mean depth h [m]	Mean velocity in cross-section [$m \cdot s^{-1}$]	Bed-shear stress [$N \cdot m^{-2}$]	Transport stage parameter [-]
06.09.2005	I	0.92	0.41	0.003	0.045	-0.999
12.08.2005		0.96	0.43	0.011	0.148	-0.994
18.08.2005		1.02	0.45	0.023	0.315	-0.973
06.09.2005	II	2.68	1.37	0.011	0.147	-0.925
12.08.2005		2.70	1.41	0.036	0.490	-0.171
18.08.2005		2.71	1.43	0.076	1.040	2.733

According to the Zanke's nomogram, in the two examined sections of the reservoir there is no movement of the bed material, and according to the Simons and Richardson's diagram, considering the mean diameter d_m = 0.026 mm (cross-sections I) and d_m = 0.268 mm (cross-sections II), the bed should be flat in the studied cross-sections. However, in the inflow cross-sections II at the higher flow and bed-shear stress over 1 $N \cdot m^{-2}$ ripples may occur. This is confirmed by the underwater photos taken in the reservoir Krempna. They permitted to define the morphological structure of bed. In the reservoir, the occurrence of bed forms was not found. The bed of the Krempna reservoir close to the dam part in cross-section I (figure 4) does not show any bed shape changes and no bed forms were stated, whereas, in the inflow part of the reservoir in cross-section II, the bed formed of fine fraction sediment demonstrates slight height differentiation

(fig. 5). Analysing the underwater photos, it was found that change of bed level does not exceed 1,0-1,5 cm.

As it follows from analysis of the data referring the Hjulsröm's diagram flow velocity correspond with the conditions of sediment transport in the studied reservoir cross-sections with the exception of the inflow cross-section at the flow of 0,9 $m^{-3} \cdot s^{-1}$ conducive conditions to sedimentation of the transported sediment will occur. Application of the Ashley's and van Rijn's nomograms proved impossible since the values of mean velocities and transport stage parameters are beyond the range of values in the diagrams. Only in the inflow cross-section at the flow of 7,56 $m^{-3} \cdot s^{-1}$ according to van Rijn's diagram there exists a possibility of ripples formation. The transport stage parameter established for this flow is 2,73.

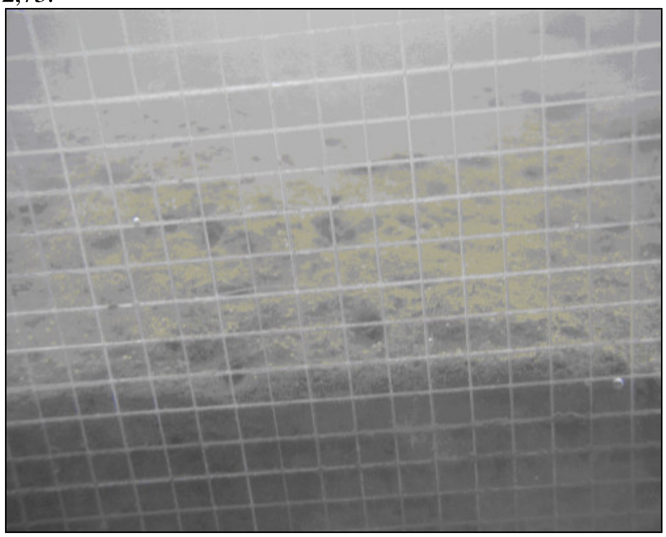

Figure 4. The surface of the bottom of the Krempna reservoir in the cross-section nearby the dam (cross-section I)

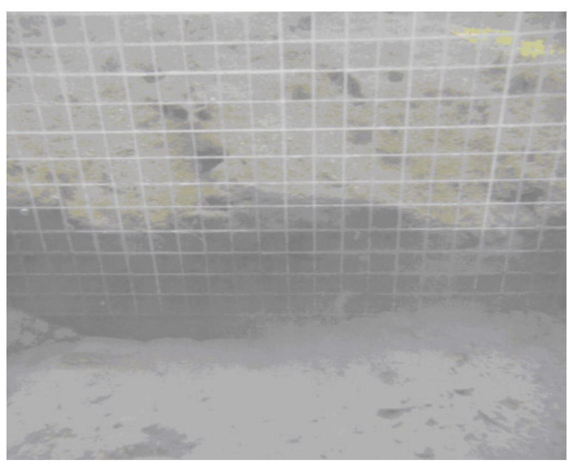

Figure 5. The profile of the bottom of the Krempna reservoir made in the inlet cross-section (cross-section II)

CONCLUSIONS

The bed of the Wisłoka River is built of coarse grained mineral material. Occurrence of river bed forms was stated. These were qualified according to Ashley to the type of lateral and point bars of lens-like shapes in longitudinal profile. Great differentiation of granulometric composition was founded in the proximal and distal parts of point bars. This gives the evidence that the fine fractions were washed out from the interstitial spaces of the proximal part of point bars. Movement of sediment grains of diameter d_{50} in the river occurs after exceeding the depth of 1,36 m. With regard to the bigger grains forming, the proximal parts of bars grains of a diameter d_{50} will be included to sediment movement after exceeding the depth of 1,49 m.

Differentiation of the granulometric composition was found in the surface layers of sediment in the reservoir. Nearer to the dam, the bed is built of fine grained mineral material of mean diameter 0,033 mm. Different hydraulic conditions prevailing there account for the distribution of material in the reservoir. Deceasing mean velocity of water flow in particular cross-sections causes decrease in suspended and bed-load transport efficiency, bed-shear stress changing *so ipso* the conditions of sediment transport and of bed form formation. In the reservoir no typical bed forms are formed; it was only established that in the inflow part of the reservoir the bed shows slight differentiation of height, not exceeding, however, 1,0-1,5 cm. Absence of conducive conditions of formation of bed forms was confirmed by analysis of measurement data and applied Zank's, Simons and Richardson's, and Hjulsröm's nomograms. With regard to the obtained values of mean velocities and transport stage parameter application of Ashley's and van Rijn's nomograms in qualification of bed forms in the reservoir proved to be not applicable. There exists a possibility of ripple formation in the inflow cross-section only. According to the van Rijn's diagram the formation of bed forms in the inflow part of the reservoir is possible at higher flows exceeding the value of 7,56 $m^{-3} \cdot s^{-1}$.

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