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APPRAISE OF CONSEQUENCES OF EROSIVE PROCESSES OCCURRING IN THE SKAWA RIVER SECTOR

Erosive processes have been evaluated in a sector of the Skawa river characterized by high pliability to erosion (proportion between the bend radius and the river channel width equals on the average 6.5). Within two years, channel erosion caused by 6 freshets was investigated with flows *Q* within the range of probability of waters from 20% to 50%. Bank and bottom erosion as well as transportation of the bed material and material from falls of bank slopes were found to occur. Intensity of this transportation was calculated based on Bagnold's equation. The calculated value of transported bed load was comparable with that obtained from direct measurements. The effects of transportation were also reflected by changes of the grain size distributions after passage of a freshet wave. Bank erosion was the dominating process that changed the river channel shape. It was found that in the examined sector the retreat of the bank slope proceeded at the rate of 1.20 m/year.

1. INTRODUCTION

Erosion in mountain rivers is a process proceeding permanently; direction of its activity and intensity depends on such factors as water flow, gradient of the river channel, regime of water flow, bed load and frequency of its migration. Erosion of the river bed begins when transportation of bottom material prevails over the amount of material obtained from the upper parts of the river, and bank erosion is manifested by shifting of banks and channel migration.

River dynamics is the problem of interest of hydrotechnicians and geomorphologists [1–5]. Many authors investigated channel processes against the background of hydraulic processes prevailing in water flows [6–8]. A considerable amount of papers describe effects of freshets and their influence on erosive phenomena, bottom material

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transportation and its accumulation [9–12]. In frequently expressed opinion, transport of bottom material is a factor regulating relations between all channel processes. For example: increase in the amount of transported material causes increase in bank erosion, whereas, when transportation intensity decreases bottom erosion or bed load accumulation may increase [13–16]. It results from the analysis of a number of investigations that erosion and geometry of the river channel are closely related: intensity of bank erosion is a function of the relation of the channel width and radius of its curvature. Occurrence of erosive processes leads also to disturbance of hydrodynamic stability of the flow even if they occur only in some sectors. Local lack of hydrodynamic balance causes a consequent destabilization of the channel in adjacent sectors. Erosion investigated in the sector of the River Skawa located in the upper part of its course is an example illustrating this type of river activity.

2. CHARACTERISTICS OF THE STUDIED SKAWA RIVER SECTOR

The Skawa river, 91 km long with the watershed area A of 1187 km^2 is one of the biggest right-bank mountain tributaries of the Wisła river. It takes its sources in the sandstones and Magurian slates in the transitional area (region) between Babia Góra Range and Sieniawa Gate. The springs rise from the north-west slope of the main Łysa Góra massifs 700 m above sea level. The Skawa Valley and its tributaries are narrow deeply indented with lots of gorges of big drop. There are considerable denivelations between the ridges and beds of the valleys often reaching up to 600 m. The investigated sector (Fig. 1) is localized near the Wadowice water gauge section.

Fig. 1. Part of a studied sector of the Skawa river

In field research, the geological structure of the bed within the investigated stretch was estimated based on the exposed ground visible in the bottom and on the scarps.

Up to the depth of 3.0–4.5 m it is built of gravel containing thick pebbles, the overlaying layer consists of alluvial river deposits represented by 2.0–3.0 m thick sand clay and gravel clay formations covered with 0.20–0.30 m soil layer.

3. FRESHETS

The probable and daily water discharges for the investigated Skawa river sector were obtained from observations carried out by the Institute of Meteorology and Water Management (IMGW), the Wadowice gauging station which is situated in the immediate vicinity of the investigated stretch. Six floods were observed in the researched period from 2004 to 2005 (Fig. 2). Water discharge *Q* ranged from 62.5 $m^3 \cdot s^{-1}$ (November 24,

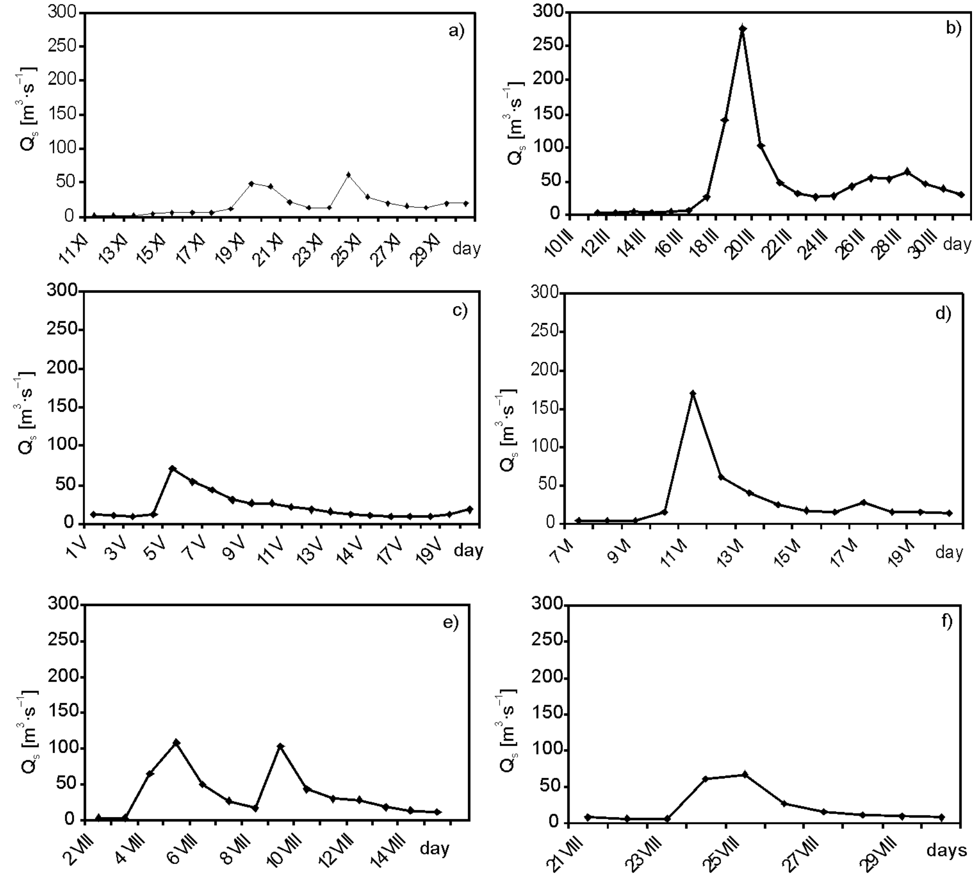

Fig. 2. Water discharges for the Wadowice gauging station:
a) freshet of 11–30.09.2004, b) freshet of 11–31.03.2005, c) freshet of 01–20.05.2005,
d) freshet of 07–20.06.2005, e) freshet of 01–15.08.2005, f) freshet of 21–31.08.2005

2004) which corresponds to the discharge of probable occurrence lower than $Q_{50\%}$ to $Q = 276$ m^3·s^{-1} (March 19, 2005) which corresponds to a discharge of probable occurrence between $Q_{20\%}$ and $Q_{50\%}$. The latter water discharge approximated a medium high stage. In Table 1, mean characteristic water discharge values and probable discharge values for the Wadowice gauging station are presented.

Table 1

Mean characteristic water discharge in the river Skawa sector
and probable discharge for the Wadowice gauging station

Catchment area [km^2]	Medium-low stage [m^3·s^{-1}]	Annual average [m^3·s^{-1}]	Medium-high stage [m^3·s^{-1}]
838	3.04	8.50	250
Water flow with percentage probability of appearance [m^3·s^{-1}]			
1%	20%		50%
1043	385		190

4. CHARACTERISTICS OF CROSS-SECTIONS AND AN ATTEMPT TO ESTIMATE THE INTENSITY OF LATERAL AND DEEP-SEATED EROSION

In August 2004, four cross-sections, schematically presented in Fig. 3, were measured in the analyzed Skawa river sectors. The I–I Section was situated at 21 + 400 km of the water course (measured from its mouth) and was the lowest measured cross-section. The other sections were localized at a distance of l = 120 m above the base section. Special measurements were taken on the right river bank whose height h_p approaches 4.0 m (metal sounds were set into scarps to read the thickness of the eroded material). All the surveyed sections had the scarp slope close to the natural slope gradient and an almost vertical part of the scarp up to 2.50 m heig. The shape of all the sections was trapezium like with the maximum depression in the central part of the channel or shifted towards the eroded bank. The proportion between the bend radius and the channel width r/b for this stretch was 6.5 which indicates high susceptibility to erosion [11].

The sections were the point of reference for the measurements taken in the years to follow. Survey and field research conducted after floods in November 2004 as well as in May and August 2005 did not demonstrate measurable changes in the topography of the river bed as the observed discharges were not able to move the bed material. Shear stress was decidedly lower than the critical stress which, when exceeded, sets bed rubble in motion. Thus, it can be stated morphologically inactive. As regards the banks, the changes observed were minimal and the metal sounds showed the maximum change Δb_p = 0.03 m. The changes did not concern all surveyed height of the scarp but occurred locally at various heights above water level which seems to indicate that they were caused by other reasons independent of the flowing water. Most probably they resulted from a combination of various factors such as destructive effect of rain drops, eolic erosion, and animal activity, swelling and shrinking of ground causing pebbles to come off from scarps. The disconnected material accumulated at the foot of the vertical bank.

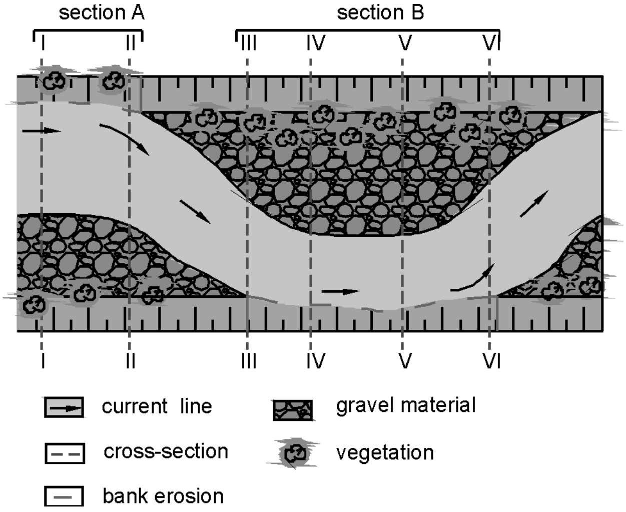

Fig. 3. Outline of the measuring sector

The spring flood was most active morphologically and caused lateral bank migration. The displacement b_p ranged from 0.13 m to 0.15 m. The highest displacement was noticed in section II–II (Fig. 4b) $\Delta b_p > 1.5$ m in the bed and ca.0.8 m at the level of approximately 1 m.

The smallest changes were found in the closing section of the investigated stretch IV–IV (Fig. 4d) and Δb_p did not exceed 0.1 m. Nevertheless it should be mentioned that the changes observed in this section did not occur in the entire bank but only in its part up to ca. 1.2 m. The lateral erosion was accompanied by bed erosion, the changes were observed in bed ordinate and reached $\Delta h_d = 0.2$ m at the maximum. In section III–III (Fig. 4c) the bed erosion was more intensive as (close to the measure point) it formed an erosion trough about 8 m long, 2 m wide and the mean depth of 0.4 m. It was cut out along a wooden obstruction, namely a tree trunk ca. 2 m away from the bank. In cross-sections from I–I (Fig. 4a) to III–III, a superstructure of gravel bar was observed at the opposite cambered bank, $\Delta h_1 = 0.1$ m at the maximum.

Variability of material fractions in the crosswise profile was its characteristic feature. The thickest material was found close to the current and as moving towards the opposite direction of the eroded bank it was becoming smaller and smaller. In IV–IV section, the upper part of the bar was locally washed away (over the area of 15 m long, up to 20 m wide an up to 0.08 m thick layer was carried away).

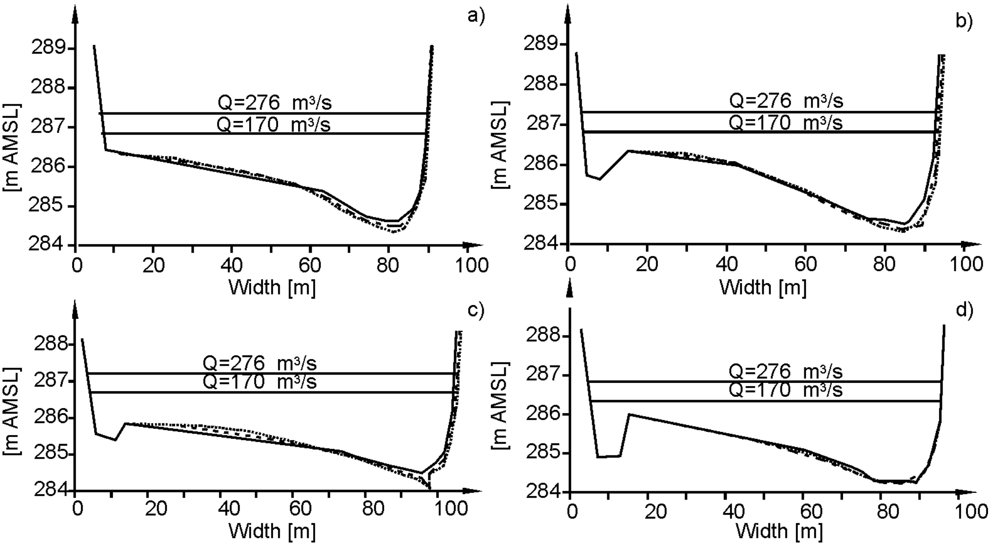

Fig. 4. Cross-sections measured on the Skawa river: a) sector A, cross-section I–I, b) sector A, cross-section II–II, c) sector B, cross-section III–III, d) sector B, cross-section IV–IV; solid lines – measured in August 2004, dashed lines – in March 2005, dotted lines – in June 2005

The estimated volume V_1 of the material eroded from the investigated sector was 366 m^3, and that deposited within the point bar V_2 =155 m^3. The shear stress and the individual stream power were calculated for the conditions in the channel during a freshet. The values were τ =56.6 N·m^{-2}, ω =22.44 kg·m^{-1}·s^{-1}, respectively. The value of the shear stress was 1.9-fold higher than the limit value (τ_{cr} = 39.43 N·m^{-2}) which is necessary to set the bed material in motion. The above calculations indicate that both the bed material and that torn off from the scarps were transported throughout the researched river stretch. The existing stream power was sufficient to set in motion even the biggest grains found when sampling grain size composition. The second flood which caused some changes in the topography of the river bed and in the shape of the river banks was observed on 11.06.2005 and the water discharge Q recorded on that day was 170 m^3·s^{-1}. Shear stress and stream power were τ = 41.15 N·m^{-2}, ω = 11.24 kg·m^{-1}·s^{-1}, respectively. The calculated values indicate that the stress in the river bed and the stream power were high enough to transport bed rubble, but smaller than those observed in May. The transportation ability of the channel was lower than that found during spring flood.

The layer of the material detached from the bank did not exceed Δb_p = 0.8 m and was recorded in III–III section. Within the cross-sections I–I and III–III, further lowering of the bed grade line by 0.10 m was obsetved at the maximum. In the closing section IV–IV, the mean increase of the bed layer was 0.15 m at the area of the right bank while below this section an additional layer was found on the existing meander point bar. No significant changes were found in this section as regards the shape of the bank scarp ($\Delta b_p < 0.02$ m), a further washing away of the gravel point bar was noted ranging from 0.04 m to 0.07 m. The estimated volume V_1' of the material detached from the bank scarp and eroded from the channel bed was 121 m^3, while the volume V_2' of the material deposited on the point bar approximated 77 m^3.

5. GRAIN SIZE COMPOSITION OF THE BED MATERIAL

The grain size composition of the rubble was determined for the II-II section in each survey which helped to demonstrate how the bed material changed after the flood. Table 2 shows the selected diameters of grains and the characteristics of the grain size distribution such as domination coefficient $C_d = (d_{95} \cdot d_{10})/d_{50}^2$, standard deviation $\delta = (d_{84}/d_{16})^{0.5}$ separation degree $\mu = d_{60}/d_{10}$ and heterogranulation index $\varepsilon = d_{90}/d_5$.

Table 2

Selected diameters of grains and the characteristics of the grain size distribution

Date	d_m [m]	d_{10} [m]	d_{16} [m]	d_{50} [m]	d_{60} [m]	d_{84} [m]	d_{90} [m]	μ	ε	δ	Cd
August 2004	0.057	0.020	0.025	0.053	0.072	0.102	0.110	3.6	23	2.3	0.82
March 2005	0.054	0.013	0.020	0.052	0.060	0.090	0.100	4.6	22	2.6	0.53
June 2005	0.047	0.019	0.019	0.045	0.052	0.072	0.080	5.2	20	2.7	0.49

An analysis of grain size distribution shows changes in grain size composition depending on the varying hydrodynamic conditions during flood. One can notice a reduction of the mean diameter by $\Delta d = 0.01$ m in June 2005 compared with the initial grain-size composition. Concurrently a significant increase of small fractions percentage was observed at simultaneous decreasing by $\Delta p_i = 17\%$ of percentage of bigger sizes fractions $d > 0.08$ m in a sample of material.

6. INTENSITY OF BED LOAD TRANSPORT

Having at disposal geometrical data and well defined hydraulic conditions in the stretch under research one can calculate the intensity of bed load transport being the effect of flood. In order to estimate the intensity of this transport i_b we used the following formula according to Bagnold [17]:

$$i_b = \left(\omega - \omega_0\right)^{3/2} h^{-2/3} d^{-1/2}$$

To eliminate the diversity in size the author suggested the following unidimension form of the equation

$$\frac{i_b}{\left(i_b\right)_*} = \left(\frac{\omega - \omega_0}{\left(\omega - \omega_0\right)_*}\right)^{3/2} \left(\frac{h}{h_*}\right)^{-2/3} \left(\frac{d}{d_*}\right)^{-1/2}$$

The values with an index are arbitrarily chosen basing on the results available from field and laboratory research and are as follows:

$$\left(i_b\right)_* = 0.1\,\mathrm{kg} \cdot \mathrm{m}^{-1} \cdot \mathrm{s}^{-1}, \qquad \left(\omega - \omega_0\right)_* = 0.5\,\mathrm{kg} \cdot \mathrm{m}^{-1} \cdot \mathrm{s}^{-1},$$

$$h_* = 0.1\,\mathrm{m}, \qquad d_* = 1.1 \cdot 10^{-3}\,\mathrm{m}$$

Calculations were made for the II-II cross-section taking into consideration all rubble fractions. By multiplying the intensity of bed load transport by the duration of the given filling and the width of the transport belt we obtained the total weight of the transported material which was converted into volume. The result obtained and the hydrodynamic data are plotted in Table 3.

Table 3

Weight and volume of the transported material

Date	$i_{b\,\max}$ [$\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$]	G [kN]	V [$\mathrm{m^3}$]	V′ [$\mathrm{m^3}$]
March 2005	0.34	6039.1	232	211
June 2005	0.12	1496.5	57	44

The results calculated according to Bagnold's equation were correspondent with those obtained in field research. The volume of the transported bed material acquired using the equation and that obtained in direct survey are comparable.

7. RECAPITULATION OF RESULTS AND CONCLUSIONS

The applied method of survey enabled estimation of morphological changes in the river channel caused by flood.

The present study proved that processes such as destructive action of rain drops, eolic erosion, activity of animals, heaving and shrinking of ground in rainy and dry weather are of secondary importance compared with the action of flood.

Within the researched sector, a dominating process which changed the shape of the channel was bank erosion, whose intensity depends on the volume of water discharge and its duration. Nevertheless, no linear correlation was found between the volume of the discharged water and the intensity of the occurring processes.

Irrespective of bank erosion, a significant manifestation of flood activity is bed material transport in the channel which, no matter how intensive, causes changes in grain size distribution after the flood.

The mean rate of bank scarp withdrawal was 1.20 m per year in the researched stretch.

SYMBOLS

b – width of channel, m
b_p – width of erosion belt on a right bank, m
$d_{10\%,\ 50\%}$ – the size of sediment which respectively percent of the sample is finer
d_i – diameter of a grain fraction i
G – weight, kN
h_p – height of a right scarp, m
p_i – percentage of fraction i
r – radius of meander, m
i_b – intensity of bed load transport, $\mathrm{kg\cdot m^{-1}\cdot s^{-1}}$
R_h – hydraulic radius, m
Q – discharge, $\mathrm{m^3\cdot s^{-1}}$
$Q_{50\%}$ – water flow with 50% probability of appearance, $\mathrm{m^3\cdot s^{-1}}$
$Q_{20\%}$ – water flow with 20% probability of appearance, $\mathrm{m^3\cdot s^{-1}}$
V – volume, $\mathrm{m^3}$
V' – difference between bulk of dead load accumulated and bed material eroded along the studied sector, $\mathrm{m^3}$
$\bar{v}$ – mean cross-sectional velocity of water, $\mathrm{m^3\cdot s^{-1}}$
C – Chezy coefficient
I – water surface slope
Δb_p – thickness of the eroded bank layer, m
Δb_d – difference of river bed elevation, m
Δb_1 – difference of bar elevation, m
τ – shear stress, $\mathrm{N\cdot m^{-2}}$
τ_{cr} – critical shear stress, $\mathrm{N\cdot m^{-2}}$
ω – stream power, $\mathrm{N\cdot m^{-1}\cdot s^{-1}}$

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