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On sediment transport in the Łososina River in the Polish Carpathians

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Abstract The Łososina River is one of the Polish Carpathian mountain streams that crosses the south of the Beskid Wyspowy Mountains. It is mostly gravel-bed, it is flashy, experiences frequent flooding and often causes trouble for the local communities as far as spring floods are concerned. At the mouth of the Łososina River there is one of the biggest Polish Carpathian artificial lakes—the Żywiecki Water Reservoir (ŻWR). Since the Łososina River transports mostly gravel as the bed load to the ŻWR, in the early seventies it was partly canalized, especially in places where it passes the inhabited areas. The situation of the Łososina River before and after the engineering works is compared. Features such as changes in cross-section geometry, slope, granulometry and bed load transport balance were compared using archives and present-day studies. For the purpose of the study, old engineering projects and reports were used to find out the difference in the Łososina River behaviour.

Key words bed load transport; granulometry; mountain stream; Poland; water reservoir

INTRODUCTION

Economic development of a society is related to the ability to maximize the benefits and minimize the damage caused by rivers. Rivers very often adjust their cross section and their longitudinal profile through the process of downstream sediment transport (Yang, 1996). Generally one can recognize two types of sediments in rivers: bed load and suspended load. In mountain streams where the streambed consists mostly of gravel and coarse sands, bed load is reported to constitute in some extreme cases up to ~70% of total bed load (Selby, 1985). The problems caused by the sediment movement are especially dangerous when water reservoirs for flood protection and for water storage are constructed on such rivers because the sediment trapped in the reservoirs tends to fill them up, reducing their water capacity. To reduce this process (basically reducing the bed-load transport) many engineering works known as river training works are undertaken. This paper examines the sediment budget that was calculated before and after river training works on the Łososina River in the Polish Carpathians. At the mouth of the Łososina River the artificial lake (the Żywiecki Water Reservoir, ŻWR) was built. To undertake the calculations archival materials from river design offices were used with up-to-date measurements.

STUDY AREA

The Łososina River in the Polish part of Carpathian Mountains (Fig. 1) drains the Carpathian flysch. The stream is flashy and experiences frequent bed load movement. Its streambed

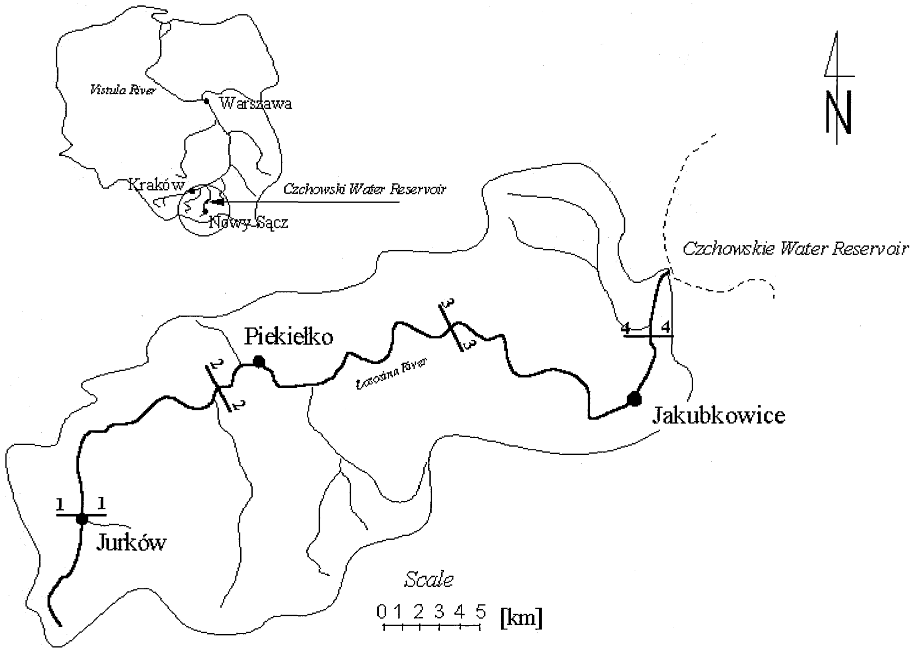

Fig. 1 Catchment study region with the detailed sketch of the research reach.

consists mostly of sandstone and mudstone bed load pebbles and cobbles forming a framework, the interstices of which are filled by a matrix of finer sediment. Suspended sediment load is small but its contributions to channel morphology were taken into consideration during sediment calculations. Many gravel river bed-forms, such as point and middle bars, occur within the investigated reaches of the Łososina River. Most gravel bed-forms can are observed at the riverbanks and within the river channel. After 1975, many river training works were performed along the Łososina channel to prevent bank erosion and to reduce the channel slope. The river cross sections were trained by building drop-hydraulic structures (to reduce slope) and by constructing gabions (stone-baskets along the banks—preventing bank erosion). These works were aimed at reducing the bed load transport along the Łososina and stopping its degradation after the river reservoir Czchów was constructed at the river mouth. The basic hydrological characteristics of the river are presented in the Table 1. All numbers refers to the river channel between cross sections 1-1 and 4-4 (see Fig. 1).

Table 1 Physical characteristics of sites investigated.

Precipitation (mm)	896	Max. stream depth D (m)	2.2
Catchment area (km^2)	410	W/D ratio	21.53
Max. catchment altitude (m a.s.l.)	760	Minimum annual discharge (m^3 s^{-1})	1.26
Min. catchment altitude (m a.s.l.)	241	Mean annual discharge(m^3 s^{-1})	4.78
Channel gradient (average within study area) (–)	0.0106	$Q_{50\%}$ (m^3 s^{-1})	48.63
Stream length L (km)	48.65	$Q_{3\%}$ (m^3 s^{-1})	196.41

METHODS

Sediment load was calculated at four cross sections (Fig. 1). The technique described by Church *et al.* (1987) was applied for sediment sampling. The surface sediment layer was identified as armoured rather than censored (Carling & Reader, 1981; Parker, 1990). Samples were collected from homogeneous bodies of sediment, so as not to combine them with the distinct surface material. The sieving analysis for coarse grains was carried out in the field by hand using round-mesh sieves (Michalik, 1990). Fine material was carefully collected and analysed in the laboratory.

For bed load transport calculations (especially for calculations of transport to the ŻWR) the Meyer-Peter-Muller (Meyer-Peter & Muller, 1948; Michalik, 1990) formula was used:

$$q_i = \left[\frac{\rho_w g h I - f_i g \Delta \rho d_i}{0.25 \rho_w^{\frac{1}{3}}} \right]^{1.5} p_i b \qquad (1)$$

where q_i is unit bed load transport, ρ_w ,and ρ_r are water and sediment density respectively (kg m^{-3}), g is acceleration due to gravity (m s^{-2}), h is water depth (m), I is slope, f_i is Shields shear stress value, $\Delta\rho = \rho_r - \rho_w$ (kg m^{-3}), d_i is sediment size (mm), p_i is percentage of the sediment fraction within the sediment probe, and b is active channel width (m).

Two computer models were used: SPAW_2003v.1.0 (Radecki-Pawlik & Baran, 2000) and SandCalc-1.2 (Wallingford, 1996). A special computer model called Shear_v.1.0 was developed for shear stress calculations (Radecki-Pawlik & Radecki-Pawlik, 2003). The land survey was done following methods described by Przewłocki (2000) and using a TOPCON AT-G7 gheodimeter. Hydrological calculations were made using the Punzet formulae (Punzet, 1972, 1981) using the WODA_2000_v.2.0 computer model (Radecki-Pawlik, 1985). Suspended sediment was measured at the bathymetric station in Jakubowice. Finally, the TransCalc model was used to calculate the sediment budget before and after the river training works on the Łososina River (DWE, 2003). This model calculates the sediment transport under a given threshold discharge (which is the competent flow for the beginning of the movement of bed load) using data such as calculated bed load transport, hydrology (in the case of this paper the discharges for the 12-year recurrence period) and the threshold of beginning of motion derived from the bed load calculations or measurements. Since the software was designed especially for this work a schematic of it is presented in Fig. 2.

All archival materials concerning the slopes of the river and granulometry of its bed before the river training works were provided by Nowy Sącz Municipality Authority, the State Geological Institute in Warsaw and River Water Authority in Krakow and Nowy Sącz.

RESULTS

All basic granulometric parameters calculated for each of the research cross sections and recognized are presented in Table 2. Tables 3 and 4 show the sediment transport data for Łososina before and after river training works. Table 5 presents changes of the unit bed load transport results for the Łososina River after regulation. Figure 3 presents the hydrological events before and after the river training works on the Łososina used in the TransCalc model to calculate the sediment budget along the Łososina.

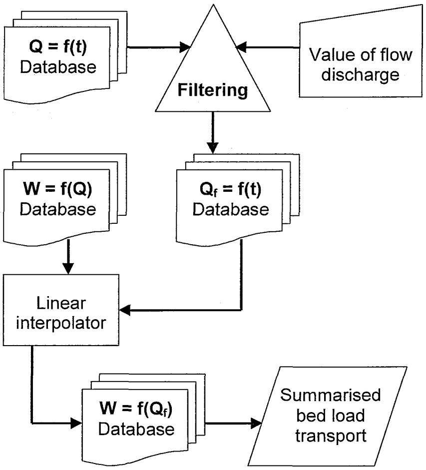

Fig. 2 Schematic of the TransCalc model.

Table 2 Characteristic grain-size diameters before and after the training works.

Sampling cross-section	Before – sediment diameter (mm)				After – sediment diameter (mm)			
	d_{16}	d_{50}	d_{84}	d_{90}	d_{16}	d_{50}	d_{84}	d_{90}
1-1	7	28	83	88	7	30	85	90
2-2	10	30	70	76	6	22	65	70
3-3	12	40	90	95	10	35	88	90
4-4	10	30	58	67	11	22	50	65

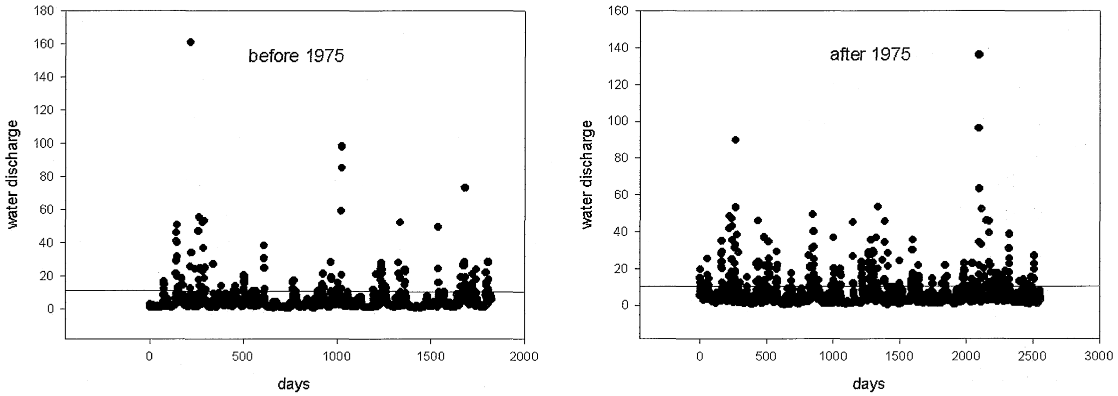

Fig. 3 Hydrology of the Łososina River with the threshold line (the beginning of motion for the sediment) above which the bed-load transport was calculated. The bed load values during those periods were calculated using the TransCalc model.

RECAPITULATION

The following conclusions can be drawn from the analysis of the data:

(a) The most important hydraulic parameter, which determines the value of the decreased shear stresses and bed load transport, is the slope of the river bed which was changed (here: reduced) by the river training works along the Łososina River.

Table 3 Unit bed load transport at the Łososina River—before the training works.

Water depth	Sampling cross-section 1-1 d_{50} = 28 (mm)		Sampling cross-section 2-2 d_{50} = 30 (mm)		Sampling cross-section 3-3 d_{50} = 40 (mm)		Sampling cross-section 4-4 d_{50} = 30 (mm)	
h (m)	Shear stress τ (N m^{-2})	Transport (m^3 s^{-1} mb^{-1})	Shear stress τ (N m^{-2})	Transport (m^3 s^{-1} mb^{-1})	Shear stress τ (N m^{-2})	Transport (m^3 s^{-1} mb^{-1})	Shear stress τ (N m^{-2})	Transport (m^3 s^{-1} mb^{-1})
0.6	No bed load transport							
0.7	21.39	0.00000424	No bed load transport		No bed load transport		No bed load transport	
0.8	23.24	0.0000543						
0.9	28.07	0.0002978						
1.0	29.28	0.000377						
1.1	32.38	0.000606						
1.2	34.67	0.000796						
1.3	43.76	0.001707	25.78	0.0000951				
1.4			28.24	0.0002186	33.47	0.0001043	22.65	0.0000014
1.5			32.28	0.0004829	39.36	0.0004541	27.42	0.0001736
1.6			35.60	0.000747	49.38	0.001345	32.57	0.000505
1.7	Max depth in cross-section 1.3 (m)		41.33	0.001287	52.34	0.001663	38.09	0.00097
1.8			43.98	0.001566	55.38	0.002012	43.98	0.001566
1.9			50.23	0.002295	58.49	0.002393	50.23	0.002295
2.0			53.09	0.00266	61.69	0.002805	53.09	0.00266
2.1			Max. depth in cross-section 2.0 (m)		Max. depth in cross-section 2.0 (m)		Max. depth in cross-section 2.0 (m)	

Table 4 Unit bed load transport at the Łososina River—after the training works.

Water depth	Sampling cross-section 1-1 d_{50} = 30 (mm)		Sampling cross-section 2-2 d_{50} = 22 (mm)		Sampling cross-section 3-3 d_{50} = 35 (mm)		Sampling cross-section 4-4 d_{50} = 22 (mm)	
h (m)	Shear stress τ (N m^{-2})	Transport (m^3 s^{-1} mb^{-1})	Shear stress τ (N m^{-2})	Transport (m^3 s^{-1} mb^{-1})	Shear stress τ (N m^{-2})	Transport (m^3 s^{-1} mb^{-1})	Shear stress τ (N m^{-2})	Transport (m^3 s^{-1} mb^{-1})
0.8	No bed load transport		No bed load transport		No bed load transport		No bed load transport	
0.9	22.85	0.0000039						
1.0	27.78	0.0001931			28.43	0.0000524		
1.1	33.03	0.000539			30.68	0.0001493		
1.2	35.36	0.000727			31.77	0.0002066		
1.3	44.63	0.001637			32.28	0.0002357	17.36	0.0000133
1.4	Max depth in cross-section 1.3 (m)				33.46	0.000307	18.27	0.0000381
1.5					44.77	0.001255	19.21	0.0000714
1.6			17.80	0.0000241	47.54	0.001546	19.95	0.0001022
1.7			24.21	0.0003381	50.38	0.001865	20.94	0.0001485
1.8			26.26	0.00048	53.31	0.002214	21.95	0.0002015
1.9			28.38	0.000645	56.30	0.002591	25.29	0.0004112
2.0			30.57	0.00083	59.38	0.002997	25.72	0.0004418
2.1			32.82	0.001037	Max depth in cross-section 2.0 (m)		Max depth in cross-section 2.0 (m)	
2.2			35.99	0.001353				
2.3			Max depth in cross-section 2.2 (m)					

Table 5 Budget of the unit bed load transport—Łososina River after regulation.

Unit bed load transport (m^3 s^{-1} mb^{-1})							
Depth h (m)	Sampling cross-section 1-1	Depth h (m)	Sampling cross-section 2-2	Depth h (m)	Sampling cross-section 3-3	Depth h (m)	Sampling cross-section 4-4
0.9	0.0002939	1.6	0.0007229	1.5	−0.000800	1.4	−0.0000367
1.0	0.0001839	1.7	0.0009489	1.6	0.000117	1.5	0.0001022
1.1	0.0000670	1.8	0.0010860	1.7	−0.000202	1.6	0.0004028
1.2	0.0000690	1.9	0.0016500	1.8	−0.000202	1.7	0.0008215
1.3	0.0000700	2.0	0.0018300	1.9	−0.000198	1.8	0.0013640
–	–	–	–	2.0	−0.000192	1.9	0.0018838
–	–	–	–	–	–	2.0	0.0022182
Total	0.000683	Total	0.00623	Total	−0.00147	Total	0.006750

(b) The greatest decrease in bed load transport was observed at cross section 4-4. This was the main aim and achievement of the river training works.

(c) The change of the bed load transport along the Łososina River in the research cross sections was as follows: along cross section 1-1 the unit bed load transport was bigger before the river training by about 0.683×10^{-3} m^2 s^{-1} (aggradation after river training works); along cross-section 2-2 the unit bed load transport was also bigger before the river training by about 6.23×10^{-3} m^2 s^{-1} (aggradation after river training works). Along cross-section 3-3 the unit bed load transport is bigger after the river training by about 1.47×10^{-3} m^2 s^{-1} (degradation of the river bed), and finally along cross-section 4-4 the unit bed load transport was bigger before the river training by about $q = 6.75 \times 10^{-3}$ m^2 s^{-1}. Along the whole river the unit bed load transport was larger before the river training by about $q = 6.7 \times 10^{-3}$ m^2 s^{-1}. In other words the river training reduced the bed load transport by that value.

(d) The river training works carried out along the Łososina River changed the bed load transport conditions within the whole river. The bed load transport before the river training works was 7180 t year^{-1} and it became 2279 t year^{-1} after the training works, whereas the suspended load was 70 464 t year^{-1} throughout that whole period. In other words the bed load was reduced from roughly 10% of suspended load down to 3%. It seems the river training works had a great influence on the bed load.

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