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Marta Łapuszek

STUDIES ON RIVERBED EROSION ON THE RABA RIVER CLOSE TO THE STRÓŻA GAUGING STATION

Summary

The aim of the paper is to present the studies on the riverbed erosion on the upper course of Raba river, located from km 81.829 to km 77.751, close to the Stróża gauging station located in km 80.600. This part of the river course is completely changed due to the Project concerning the extension of the Zakopianka road located close to the Raba river. The results of simulation of riverbed evolution before and after the Project carried out by two 1D models (RubarBE and Metoda) are analysed and discussed. The results of computation obtained by both models are verified by field observations carried out in 2001 (before the Project), and in 2009 year (after the Project). The trends of erosion and deposition correspond to the field observations for the dates before and after the Project. Another verification is possible to make for the Stróża cross-section, where observations of cross-sectional geometry and water stages have been carried out from 1900 year till now. The statistical model of riverbed erosion developed for Stróża also confirm the trends obtained there by 1D models.

Key words: mountain river, riverbed erosion, 1D model

INTRODUCTION

Erosion in mountain rivers is observed in catchment areas and in riverbeds. The intensity of riverbed erosion is caused by many factors: climatic (temperature, precipitation type, seasonal duration and occurrence), geological (type of soil and their distribution, land configuration), soil properties (grain-size distribution), hydrological (infiltration rate, type of flow), vegetation cover, etc. The products of erosion in the catchment area finally enter the streams and rivers. Sediment transport is one of the main process that should be considered in the rivers. Even if the sediment load is low, exchanges are always occurring between the banks, the bottom and the low as well. Depending on the hydrodynamic conditions in the riverbed, sediment is transported down the river course. The aim of the paper is the simulation and analysis of evolution of the erosion and deposition that occur along the experimental reach of the mountainous Raba river. The studied reach was modified due to the Project. This human activity have huge consequences on the morphology of studied river reach, therefore the analysis of the riverbed morphology on this reach should be known, principally after the Project.

The scope of the paper is limited to computing and analyzing the riverbed changes before and after the Project. In order to predict the variation of longitudinal bed profile along the river reach and the changes in the cross-sectional geometry of the bed due to erosion or deposition of sediment, two one-dimensional sediment transport and riverbed evolution models RubarBE and METODA are used.

DESCRIPTION OF THE EXPERIMENTAL REACH

The Raba river, in southern Poland, is a mountainous tributary of the Vistula river. In this region the topography of catchment is highly varied. The Raba river is characterized by high erosion process with varied intensity along the river course. The experimental reach is located from km 81.829 to km 77.751 of the Raba river course. The river in the studied reach was repeatedly straightened and narrowed during the 20th century. The engineering activity was the most important factor of high-intensity riverbed erosion observed after the Project. In 2003 an extension of the Kraków-Zakopane road located next to the Raba river, called hereafter the Project, was executed. The flood plains and the river channel have been narrowed and some parts of the river course was changed. So examination of the evolution of the river channel after the Project would be interesting. In the pictures below (Fot. 1, Fot. 2) a part of the river channel before the Project execution (1999) and after (2011) is shown.

Photo 1. Raba river channel close to the Stróża gauging station 1999 [Fot. J. Piwowarczyk-Ogórek]

Photo 2. Raba river channel close to Stróża in the gauging station after the Projectexecution (2011) [Fot. M.Łapuszek]

METHODS OF RIVERBED CHANGES ANALYSIS AND VERIFICATION

The studies on riverbed changes were developed by two 1-D models and by a statistic model of riverbed erosion.

The RubarBE and METODA models

The Hydrology and Hydraulics Research Unit of Cemagref has developed a 1-D model RubarBE for predicting variation of longitudinal riverbed profile along rivers and changes in the cross-sectional geometry. The METODA 1-D model has been developed in Institute of Water Engineering and Water Management of Cracow University of Technology.

The models used for the computation have two components: a component to simulate flow and a component to characterise the changes in river morphology due to erosion or deposition of sediment. The models are based on:
- de Saint Venant equations for water [Paquier, 2003]:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q \tag{1}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\beta\frac{Q^2}{A}\right)+gA\frac{\partial z}{\partial x}=-g\frac{Q^2}{K^2AR^{4/3}}+kq\frac{Q}{A} \tag{2}$$

– equation for conservation of sediment mass [Paquier, 2003]:

$$(1-p)\frac{\partial A_S}{\partial t}+\frac{\partial Q_S}{\partial x}=q_S \tag{3}$$

– and sediment transport capacity relation [Meyer-Peter and Müller, 1948]:

$$C_S=\frac{8L_a\sqrt{g}}{(\rho_s-\rho)\sqrt{\rho}}\cdot(\rho JR-0.047D_{50}(\rho_s-\rho))^{3/2} \tag{4}$$

where:

A – cross-sectional flow area (m^2),
A_S – bed-material area (m^2),
C_s – sediment transport capacity (m^3/s),
D_{50} – median diameter of sediment (m),
g – acceleration due to gravity (m/s^2),
J – friction slope,
K – Manning-Strickler coefficient (m$^{1/3}$/s),

L_a – active width (m),
Q – water discharge (m^3/s),
q – lateral water flow per unit of length (m^2/s),
Q_s – sediment discharge (m^3/s),
q_s – lateral sediment flow per unit of length (m^2/s),
R – hydraulic radius (m),
t – time (s),
x – streamwise coordinate (m),
z – water surface elevation (m),
β – the coefficient of quantity of movement,
ρ – density of water (kg/m^3),
ρ_s –density of sediment (kg/m^3).

In both models, sediment is represented only by the mean diameter D_{50}. This parameter do not clearly describe the processes that occur in many channels such as armouring. Therefore, in RubarBE model a complementary parameter was added, the standard deviation σ, that appears convenient to describe grain size distribution in a river for which sediments are homogeneous. The standard deviation is estimated as the square root of the ratio D_{84} to D_{16}. Extra parameters of one compartment are the shear stress, τ_{mm}, for beginning of the movement and, τ_{fm}, the shear stress at the end of the movement. Generally, these two last parameters are set equal and determined from D_{50}.

In the RubarBE model the space lag effects are taken into account by introducing the following equation:

$$\frac{\partial Q_S}{\partial x} = \frac{C_S - Q_S}{D_{char}} \tag{5}$$

in which D_{char} is a distance that characterizes the ability of sediment transport to reach the value of the sediment transport capacity. For bed-load transport in rivers, this value is generally very small (a few meters), what means that it is shorter that the space step and thus can be neglected. In the METODA model it is not taken into account at all. The method for solving the set of equations in the RubarBE model includes several steps. First, de Saint Venant equations are solved by a Godunov-type second order finite difference scheme that makes the calculation of flow possible even if the critical flow appears [Paquier 1995]. Then, the sediment transport capacity is calculated by solving the spatial lag equation inside a cell. Then the sediment continuity (equation 3) is applied to each cell and the computation leads to the change of A_S. On the base on this change the new shape of cross-section is formed. The active layer that corresponds to the sediment that moves during the time step has its thickness determined from the sediment transport capacity, the velocity of the flow and the space step. Deposition and erosion occur when this active layer is either too thick or not enough thick. Like in RubarBE model, the METODA model is based also on the system of the de Saint Venant equations for water, (1), (2), the equation for conservation of sediment mass (3), and the sediment transport capacity relation (4). The difference is that in METODA equations (1) and (2) are simplified by the assumption that the study reach is in dynamic equilibrium at time *t*.

The dynamic equations for flow in METODA are as follows:

– steady flow:

$$S_0 - S_f = 0 \tag{5}$$

– non uniform flow:

$$\frac{\partial}{\partial x}\left(\beta \frac{Q^2}{A}\right) + gA\frac{\partial z}{\partial x} + gAS_f = 0 \tag{6}$$

where the equation (6) in the model is developed as:

$$z_{i+1} + \frac{\alpha_{i+1}}{2g}\left(\frac{Q}{A_{i+1}}\right)^2 = z_i + \frac{\alpha_i}{2g}\left(\frac{Q}{A_i}\right)^2 + h \tag{7}$$

$$h = \Delta x S_f + C\left|\frac{\alpha_i v_i^2}{2g} - \frac{\alpha_{i+1} v_{i+1}^2}{2g}\right| \tag{8}$$

where:

S_0 – slope of riverbed (-),
S_f – slope of the energy line (-),
Δx – distance between cross-sections (m),
C – coefficient of local losses.

Equation for conservation of sediment mass is solved using the explicit finite difference scheme. The computation of riverbed deformation is based on the assumption, that changes of river bed between the studied cross-sections are linear [Piwowarczyk-Ogórek, 2003].

The value of the increment in the time step t_{j+1} is written by the formula:

$$\Delta z_i = \frac{-\Delta T}{\gamma}\left(\frac{q_{S_{i+1}}^j - q_{Si-1}^j}{\Delta x_i} + \frac{q_{S_{i+1}}^j - q_{S_i}^j}{\Delta x_{i+1}}\right) \tag{9}$$

The distance between the studied cross-sections can be varied, therefore, the ordinate of increment in time t, is described by the equation:

$$\Delta z_i = \frac{\Delta z_{i-1,i} \cdot \Delta x_{i-1,i} + \Delta z_{i,i+1} \cdot \Delta x_{i,i+1}}{\Delta x_{i-1,i} + \Delta x_{i,i+1}} \tag{10}$$

The above formula is the base for computing the (j+1)-th ordinate of increment in time.

In the study case of the natural cross-section, the established quantity of q_s in each band of (k-1)-th cross-section is summed up, and afterwards those value is distributed uniformly on each band of k-th cross-section, by the rule:

– sediments incoming, are distributed uniformly in each band, where sediments move,

– established co-ordinates of increment are averaged in each node between adjacent bands.

The co-ordinate in each band is established by the formula [Piwowarczyk--Ogórek, 2003]:

$$z_{k,i}^{j} = z_{k,i}^{j-1} - \frac{\Delta t}{2\gamma \Delta x_i}\left(q_{S_{k,i}}^{j} - q_{S_{k-1,i}}^{j}\right) \tag{11}$$

The maximum value of time step is written by the formula [Ratomski, 1983]:

$$\max|t| = \frac{\gamma}{2}\varepsilon \cdot \Delta x \cdot \min\left(\frac{\left(B_{akt_i} + B_{akt_{i+1}}\right)\left(h_i + h_{i+1}\right)}{G_{i+1} - G_i}\right) \tag{12}$$

with the assumption, that the value of increment in i-th cross-section cannot exceed the established acceptable value ε. If Δt is exceeded, then the time interval is divided into n time intervals Δt.

The system of equations for water and sediment is solved separately for each time step by the finite difference method.

Data requirements for both models are modest, involving only a few parameters. Thus, the models are relatively easy to calibrate and to implement.

The statistical model

The statistical model of riverbed erosion is based on the assumption that minimal annual water stages correspond to the changes of the riverbed level in the gauging station [Łapuszek, 1999; Punzet et al., 1996]. In a particular gauging station the data series for each specified time interval is approximated by linear interpolation. The investigated equation (equation 5) gives the relation between water stage (*H*) and time (*T*) and it also illustrates the main trends of level changes in the gauging station cross-section in a long time period [Łapuszek, 1999]:

$$H_i(T) = aT + b \tag{13}$$

where *T* is the year of observation, *a*, *b* are estimated parameters. The values of the coefficients *a* and *b* of the line of regression are obtained by using the method of least squares. The equation determining the level of the riverbed at any time is expressed as [Łapuszek, 1999]:

$$H_d = H_Z + H_i(T) \tag{14}$$

where H_d – average level of riverbed in a year *T* (metres above the sea level), $H_i(T)$ – approximated equation 13.

In order to confirm the validity of the computation, the functions determining the level of the bed at any time are compared with the quantity of real changes of the channel cross-section measured in different years.

In the text below, the statistical model for the Stróża gauging station (km 80.600 of the river course) is presented.

THE STUDY CASES AND THE RESULTS OF COMPUTATION

In order to examine RubarBE and METODA models, four cases were studied. The results of computation show, that METODA and RubarBE provide similar trends for the studied test cases (Kadi et al, 2003). The parallel use of the two models tends to validate the accuracy of the numerical schemes and of the results.

In the paper two studied cases are performed:

– for flood discharge hydrograph selected from data set of 30 years (1971-1999),

– for discharge $Q = 250$ m^3/s with the duration $t = 12$ hours (the most often flood wave duration observed in the experimental river course), and for 44 prismatic cross-sectional channel geometries for the experimental river course before and after the Project were taken into account by the models. The results of simulations are shown in Figs.1 and 2.

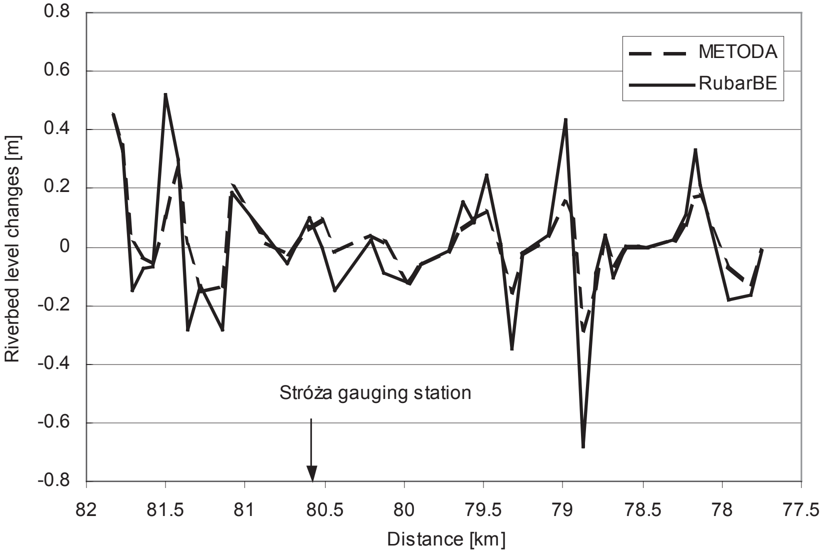

Figure 1. Bottom level changes for 44 cross-sections before the Project ($Q = 250$ m^3/s)

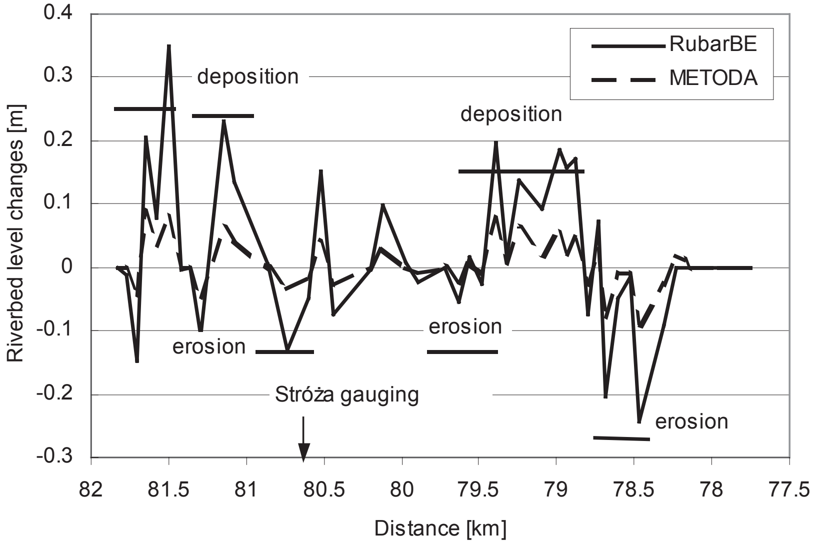

Figure 2. Bottom level changes for 44 cross-sections after river training and for $Q = 250$ m^3/s with erosion and deposition observed in 2009 pointed out

RESULTS ANALYSIS AND VERIFICATION

The first comparison is performed for the computation carried out for discharge Q = 250 m^3/s, with the total simulation time of 12 hours and for 44 cross-sections before the Project (Fig. 1).

The computational results obtained by both models were verified by field observations carried out in 2001, i.e., before the Project. In Table 1 the extended description of the real riverbed evolution observed in 2001 is presented. For simplicity reasons, Table 1 contains verification performed only for the selected 20 cross-sections. The agreement between the results of computation and field observation is that erosion and deposition are located in the same cross-sections.

The very important part of the computation was analysing the impact of the Project on the future riverbed evolution. Sediment transport movement computations were carried out for the new cross-sections obtained after the Project (Fig. 2). First, preliminary verification of obtained results was possible to be made in 2003, just after the Project. However, slight process of erosion and deposition was observed. The river morphology is still developing after the Project, so field observations and measurements should be continued. In Figure 2 the areas of erosion and deposition noticed during the field observation in 2009 are pointed out.

The results of computation and field observation is that erosion and deposition are located in the same cross-sections.

For Stróża gauging station verification was possible to make on the base on the statistical model of riverbed erosion.The 110-year data series for the Stróża gauging station was completed. The relation between low annual water stage (H) and time (T) is given by equation H_i=$f(T)$, (i = 1,2,3) and was determined for each time interval (Fig. 1). The intensity of changes in time is expressed by the slope coefficient of $H(T)$ regression. In Stróża gauging station the process of erosion and deposition is observed, but it is the erosion that played the important role during 110 years of observation. Intensive erosion has been observed after the Project. Using the graph in Fig. 3, it can be calculated that from 2001 till 2010 river bed was depressed by 50 cm. This confirms the tendency computed by both 1-D models for the Stróża gauging station. Changes of channel geometry are also observed (Fig. 4); especially the left bank eroded rapidly. This process is caused by narrowing the left flood plain area and narrowing the main channel as well.

Table 1. Verification of the computation for Q = 250 m^3/s before the Project (2001 year)

Km	Computed riverbed level Δz [m]		Riverbed evolution – field observation
	METODA	RubarBE	
81.501	+ 0.099	+ 0.51	deposition
81.421	+ 0.26	+ 0.3	deposition
81.288	- 0.156	- 0.131	erosion
81.144	- 0.138	- 0.283	erosion
81.080	+ 0.201	+ 0.186	deposition
81.861	+ 0.011	+ 0.036	deposition
80.735	- 0.024	- 0.059	erosion
80.595	+ 0.061	+ 0.101	deposition
80.517	+ 0.095	0.0	deposition
79.977	- 0.122	- 0.122	erosion
79.893	- 0.062	- 0.057	erosion
79.723	- 0.014	- 0.014	erosion
79.091	+ 0.034	+ 0.039	deposition
78.981	+ 0.156	+ 0.431	deposition
78.873	- 0.289	- 0.684	erosion
78.798	- 0.140	- 0.090	erosion
78.309	+ 0.023	+ 0.023	deposition
78.229	+ 0.075	+ 0.11	deposition
78.170	+ 0.172	+ 0.332	deposition
78.89	+ 0.176	+ 0.211	deposition

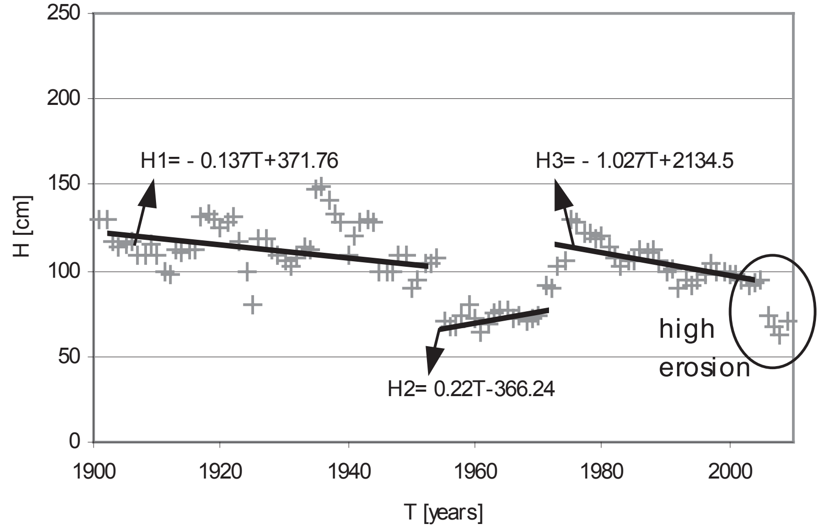

Figure 3. Lowest annual water stages and linear regressions in the Stróża cross-section in 1900-2010

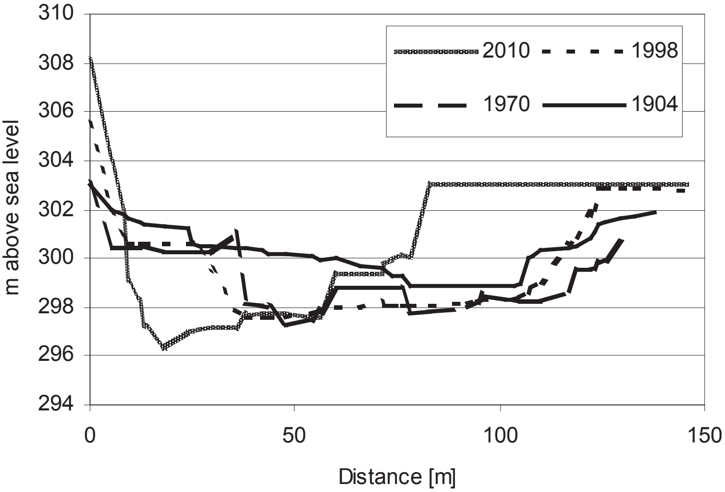

Figure 4. The channel geometry development in 1904-2010 in the Stróża cross-section

CONCLUSIONS

For a mountainous river such as Raba river, it is very important to identify erosion and deposition areas, particularly after the river training. METODA and RubarBE, two 1-D sediment transport models, solving similar equations provide similar trends in the analysed 44 cross-sections of the 4-km studied Raba river reach. These trends of erosion and deposition correspond to field observation. Moreover, computed riverbed erosion in Stróża gauging station corresponds also to the tendency observed in the presented statistical model of erosion.

For the future study, it is important to make new field measurements throughout the whole, experimental reach modified by the Project, just after a flood and also after a longer period of time.

REFERENCES

Kadi K.El., Łapuszek M., Paquier A. 2004. *One dimensional sediment transport model and its application to the mountainous river (Raba),* Selected Problems of Water Engineering, Politechnika Krakowska – Cemagref – Cemagref Editions 2004, BP 44, 92163 Antony, France.

Łapuszek M.1999. *The investigation and forecasting of riverbed erosion in the Carpathian river on the base of Dunajec river,* Doctor's Thesis, Politechnika Krakowska, Kraków 1999 (in Polish).

Meyer-Peter, E. Müller, R. 1948. *Formulas for bed-load transport.* Report on second meeting of IAHR. IAHR, Stockholm: p.39-64.

Paquier, A. 1995. *Modelling and simulation of the wave propagation developed by breaking of the dam..* PhD Thesis, Saint-Etienne: Université Jean Monnet (in French).

Paquier, A. 2003. *What are the problems to be solved by a 1-D river sediment transport model? Example of RubarBE software.* Selected Problems of Water Engineering, Politechnika Krakowska – Cemagref – results of cooperation, Cemagref Editions 2004, BP 44, 92163 Antony, France : p.75-85.

Piwowarczyk-Ogórek J. 2003. *Closed to the nature river cross-section design in the case of the sediment transport equilibrium.* PhD thesis, Cracow University of Technology (in Polish): p.89-90.

Punzet J., Czulak J.1996. *Changes of Carpathian tributaries of Vistula river: Soła, Skawa and Raba in XX Century*. Gospodarka Wodna, nr 6. (in Polish)

Ratomski J. 1983. *The hydraulic method of predicting the bedload sedimentation in the reservoirs.* Cracow University of Technology (in Polish), Zeszyty Naukowe nr 4, Kraków

Dr inż. Marta Łapuszek
Cracow University of Technology
Institute of Water Engineering and Water Management
ul. Warszawska 24, 31-155 Kraków,
tel. 012 628 28 89
mlapuszek@iigw.pl