Application of 1-D sediment transport model to the forecast of the erosion downstream from a dam (Dobczyce)

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English summary

Dam construction influences the form of a channel upstream and downstream from a hydraulic structure. Erosion is the main process downstream from each structure. The objective of this paper is to present computational method to define the degradation process in the case of cutting off the sediment transport by a dam. Two one-dimensional sediment transport and riverbed evolution models Rubarbe and Model SSDD (Sediment Sorting Downstream from a Dam) were used. These models were applied to a 6 km reach of the Raba River in Poland downstream from the Dobczyce Dam.
The difference between the models consists in water flow equations: in Rubarbe the full Saint Venant equations are used while the SSDD model is based on simplified flow equation. However the most important difference between the two models is, in SSDD, the modelling of sediment sorting during the erosion process. Therefore the calculation results differ significantly. The results of SSDD were compared with the field measurements of sediment diameter changes and the concordance was satisfactory.

Résumé français : *Un modèle de transport de sédiments unidimensionnel et son application à l'érosion à l'aval d'un barrage (Dobczyce).*

La construction d'un barrage influence la forme du chenal à l'amont et à l'aval de l'ouvrage. A l'aval, l'érosion est le processus majeur. L'objectif de cette communication est de présenter une méthode de calcul du processus d'érosion dans le cas d'une interception des sédiments par un barrage. Deux modèles unidimensionnels de transport de sédiments et d'évolution du lit RubarBE et SSDD sont utilisés. Ces modèles sont appliqués à un bief de 6 kilomètres de la Raba à l'aval du barrage Dobczyce.
Une différence entre les deux modèles réside dans les équations du fluide: équations de Saint Venant complètes pour RubarBE et simplifiées pour SSDD. Cependant la différence la plus importante entre les deux modèles est l'utilisation dans SSDD du tri granulométrique pendant le processus d'érosion. De ce fait, les résultats obtenus diffèrent fortement. Les résultats de SSDD comparés aux mesures de terrain en terme de granulométrie sont jugés satisfaisants.

Streszczenie polskie: *Zastosowanie programu 1-D Transportu Rumowiska do przewidywania erozji poniżej zapory (Dobczyce)*

Budowla hydrotechniczna przegradzająca rzekę wpływa na morfologię koryta tej rzeki zarówno powyżej jak i poniżej swojego położenia. Głównym procesem poniżej każdej zapory jest erozja miejscowa i erozja na długości. Tematem pracy jest przedstawienie metody obliczeniowej, która może określić i zdefiniować ten niszczący proces w warunkach całkowitego odcięcia dopływu rumowiska z górnego stanowiska budowli. W pracy zastosowano dwa różne, jednowymiarowe modele opisujące zmiany zachodzące w korycie rzeki, Rubarbe i model SSDD (**S**ediment **S**orting **D**ownstream from a **D**am). Modele te zostały zastosowane dla 6 km odcinka rzeki Raby poniżej zapory w Dobczycach.
Podstawowa różnica pomiędzy modelami polega na tym, że Rubarbe opisuje przepływ wody za pomocą pełnych równań St. Venanta, natomiast SSDD wykorzystuje ich uproszczoną formę. W modelu SSDD przyjęto również inną interpretacje samego procesu erozji poprzez wprowadzenie sortowania rumowiska i może być to powód znacznych różnic w otrzymanych wynikach. Wyniki SSDD wykazują zgodność z wynikami pomiarów poziomu dna i średnicy rumowiska.

1. Erosion downstream from a dam

Dam construction influences the form of a channel upstream and downstream from a hydraulic structure. The erosion downstream from a dam is composed of two phenomena - local scour and riverbed degradation along important length of a river reach. The latter is a long-duration and long-distance phenomenon. This paper presents one case of riverbed erosion, the degradation downstream from the Dobczyce Dam on the Raba River.

The Raba River is a mountainous tributary of the Wisła River in Poland. The river is located about 30 km to the south of Kraków (Fig. 1). The river in the cross-section located close to the dam is characterized by the following parameters:

- catchments area: 768 km^2
- $Q_{1\%}$= 1260 m^3/s
- $Q_{0,3\%}$= 1560 m^3/s
- $Q_{0,1\%}$= 1900 m^3/s
- $Q_{0,05\%}$= 2700 m^3/s

In 1974-87 years the Dobczyce Dam was constructed at km 60 of the river. Maximum dam height is 30.6 m. The main purpose of the construction was water supply for Kraków. The dam cuts off upstream bed load transport completely.

Figure 1: Location of Dobczyce Dam.

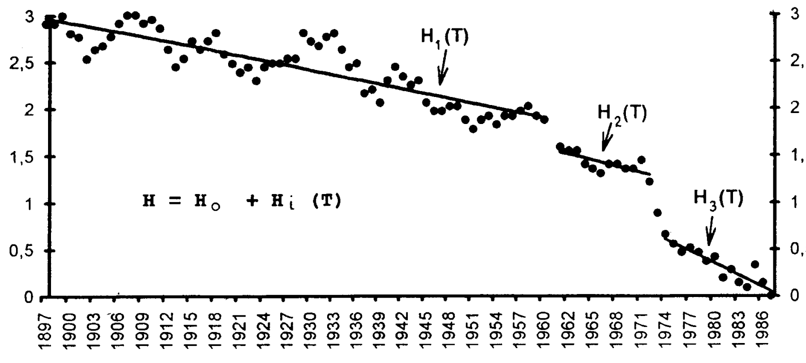

Figure 2: Variations of the Raba riverbed levels in the 20th century (in m).

Slow degradation of the Raba riverbed was observed during the last 100 years. Figure 2 presents evolution of the riverbed during the previous century. The rate of erosion during the first 60 years was about 1,7 cm per year. The river bed changes were intensified by human activities: deforestation, which reduces retention ability of the catchment area, changes in agriculture and the urbanization. The next reason for riverbed degradation is hydraulic engineering activities, for example

river training (Ratomski and Witowska, 1993). Raba river was trained during 1855 – 1976 years.
The most important factor of rapid riverbed deepening was also floods. The peak floods of exceptional magnitude in 1960 and 1972 as well as engineering structures accelerated erosion process. After 1972, trends of degradation was increasing. In this period of time, the Dobczyce dam started to influence the channel downstream.

2. SSDD model

The objective of the current paper is describing the erosion process downstream from the dam. The Authors used two one-dimensional models. Rubarbe is a model developed in Cemagref and is described in a companion paper (Paquier, 2003). Second model, is SSDD (***S****ediment* ***S****orting* ***D****ownstream of a* ***D****am*). This model was developed in the Institute of Water Management and Engineering in Kraków. The main purpose of this model was to describe the degradations process caused by cutting off the sediment transport by a dam. It is very important that SSDD model joins the degradation process by the sediment sorting phenomena.
Process of erosion can be expressed by four basic equations.
The first two ones describe the fluid flow and they are kinematics wave flow equations, composed by:

Continuity equation:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q_b$$

Dynamic equation (Chezy formula):

$$Q = A \cdot \frac{1}{n} \cdot R^{2/3} \cdot I^{1/2}$$

where:
Q – discharge [m^3/s],
A – area of flow [m^2],
x – distance between cross-section [m],
t – time [s],
q_b – lateral water flow [m^3/s],
I – water-surface slope [-],
R – hydraulics radius [m],
n – roughness coefficient [m].

The difference between the models used is the difference in water flow equations: in Rubarbe the full Saint Venant equations are used while the SSDD model is based on simplified flow equation.
The next two equations describe the sediment movement and they are as follows:
Sediment transport continuity equation:

$$\frac{\partial z}{\partial t} + \frac{1}{\gamma_r \cdot b_i} \cdot \frac{\partial G_r}{\partial x} = 0$$

Sediment transport formula:

$$\gamma \frac{Q_s}{Q}\left(\frac{k_s}{k_r}\right)^{3/2} hJ = 0.047\gamma_s d + 0.25\left(\frac{\gamma}{g}\right)^{1/3} q_s^{2/3}$$

where:
q'_s – sediment flow[$N{\cdot}s^{-1}m^{-1}$];
k_s, k_r – velocity coefficient in Manning, Strickler formulae [-];
Q – water discharge [m^3/s],
Q_s - water discharge due to beginning of sediment movement [m^3/s],
γ_r – specific weight of sediment, γ_r=2650 [$kg{\cdot}m^{-3}$].

In Rubarbe and in the SSDD model, the Meyer-Peter-Müller sediment transport formula was used. SSDD model uses also variation of the Meyer–Peter–Müller one adapted for Carpathian mountain rivers. This formula contains coefficients taking into account sediment mixture and the blocking effect.

$$g_{wi} = \left(\frac{\rho \cdot g \cdot h_i \cdot I - f_i \cdot g \cdot \Delta\rho_s \cdot d_i}{0{,}25 \cdot \rho^{0{,}33}}\right)^{1{,}5} \cdot \Delta p_i \cdot b_i \cdot \frac{\rho}{\Delta\rho_s}$$

where:
b_i – active width [m],
d_i – sediment diameter [m],
f_i – shear stress for i – index diameter [-]
γ – water density [kgm^{-3}],
γ_s – sediment density [kgm^{-3}],
Δp_i – percentage of a diameter [%].

These equations are solved separately for every time step with appropriate initial and boundary conditions and for the following assumptions:

- the sediment transport cut-off caused by a dam,
- steady flow in the considered time step,
- no tributaries along the considered river reach.

Presented computation method consists of following steps:

- solution of the water flow equations,
- sediment transport calculations for given cross-sections and slopes between them,
- establishing the new grain distribution curves based on sediment transport,
- establishing the new channel dimensions and a new slope.

3. Verification of SSDD model

The main purpose of this model was to establish the changes in sediment size and sediment sorting in riverbed downstream from a dam (Lenar-Matyas, 2001), (Lenar-Matyas and Lapuszek, 2000).

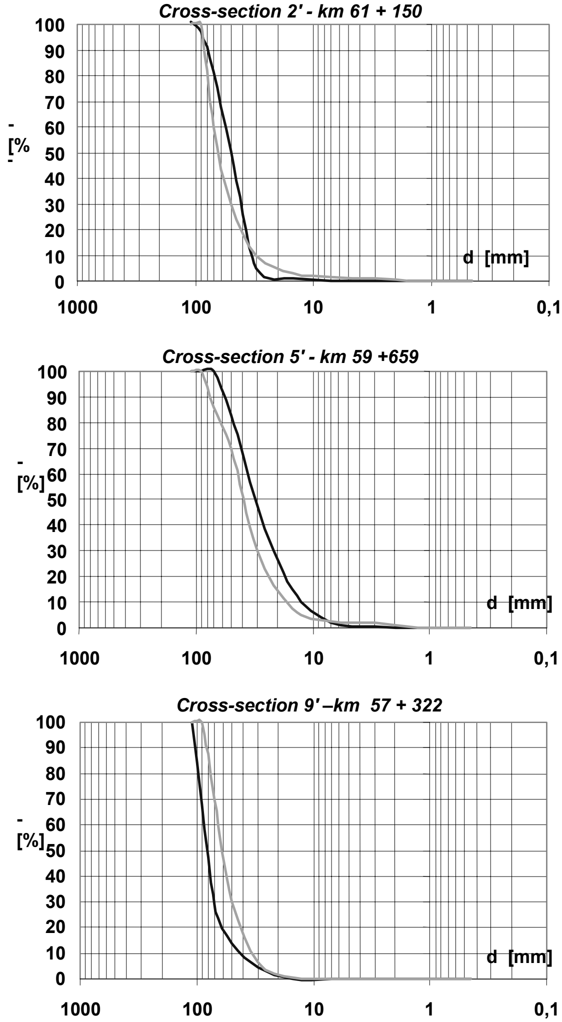

Figure 3: Sediment grain distribution obtained by field measurements and by calculation.

First, SSDD model was used to describe this process in the Raba River. The calculations were carried out for the 6 km of the river reach, where there are no tributaries. The natural 10-river cross-sections downstream from the Dobczyce Dam were used. The riverbed in every cross-section was divided into 3 to 5 bands. The calculations were done for the natural sequences of flows from 1987 to 1999 years. Maximum flow in this time period was 300 m^3/s. The results of the calculation were compared with sediment grain distribution obtained by field measurements.

These measurements are done in 2nd, 5th and 9th cross-sections. In these sections, the real main diameters of sediment were compared as well as the calculated appropriate coefficients (table 1):

- sorting coefficient: $\boldsymbol{u} = \dfrac{\boldsymbol{d_{60}}}{\boldsymbol{d_{10}}}$

- $\boldsymbol{C_d} = \dfrac{\boldsymbol{d_{90}} \cdot \boldsymbol{d_{10}}}{\boldsymbol{d_{50}^2}}$

		Bed load sample	Calculated bed load
Cross-section 2'	d_{10}	30	32
	d_{50}	62	50
	d_{60}	70	60
	d_{90}	85	80
	u	2,33	1,88
	C_d	0,66	1,02
Cross-section 5'	d_{10}	18	14
	d_{50}	40	30
	d_{60}	44	38
	d_{90}	75	58
	u	2,44	2,71
	C_d	0,84	0,90
Cross-section 9'	d_{10}	35	40
	d_{50}	60	80
	d_{60}	65	85
	d_{90}	80	100
	u	1,86	2,13
	C_d	0,78	0,63

Table 1: Comparison of main diameters (mm) between bed load samples and calculated bed load.

Erosion process that reduces slope gradually, causes reduction of sediment transport and, the reappearance of armour coat. In this moment sediment nominal diameter does not increase and erosion is considerably reduced.
Field measurements and computation of sediment grading curve SSDD model show a suitable agreement, particularly if sorting coefficient is considered.

4. Study case

The same 6 km reach of the Raba river, without tributaries, was used for comparison of numerical models. The calculations were done for the constant liquid discharge 100 m^3/s. The initial condition for sediment transport was $Q_s = 0$ kg/s. The total time of simulation was 50 days. These conditions were taken only for testing models, because they cannot appear in reality.

The mean diameter of this reach is varied. Rubarbe takes different sediment size and roughness along the reach (Table 2). In SSDD model, these parameters change along the reach and also in time. It is the main difference between the two models that influences the results of the calculations.

	d_{50} (m)	K
km 62,000 ÷ km 60,272	0,0255	35,7
km 60,272 ÷ km 58,790	0,0318	33,2
km 58,790 ÷ km 56,360	0,0729	23

Table 2: Sediment size and Strickler coefficient in Raba River.

A second difference is the way of computing slope. In SSDD model, the initial slope is the measured slope of free water surface for Q = 100 m^3/s. In every time step, new bottom slope is calculated on the bases of the computed riverbed deformation. It means that, after erosion or deposition process defined in each cross-section, a new rating curve is computed. On the base of the new curves, a new slope between the cross-sections is established.

5. Results of models

Results of both model computations are presented on Figure 4.

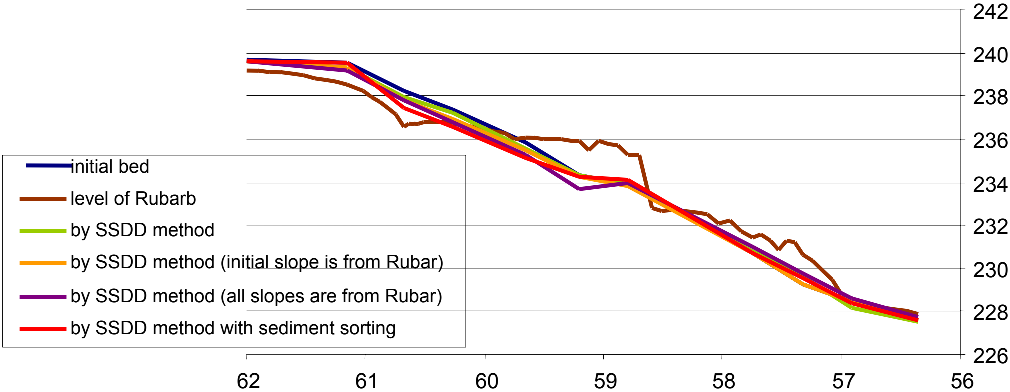

Figure 4: Rubarbe model and SSDD model computations - Water elevations (in m) along river distance (in km) .

In the diagram, are shown initial bed, results from Rubarbe and four results from SSDD. The first result obtained by SSDD was based on water slope calculated by

SSDD method. Change in the bed elevation was not high. In next calculation, only initial water slope from Rubarbe was taken. Change in bed level was not big too. Third calculation is the case taking into account the slopes of water surface calculated by Rubarbe at every time step. In this case, results obtained were somewhat different but not comparable with Rubarbe's results. The final computation was done with sediment sorting. Last result was different too.
The verification of the computation results is very difficult because, in such a simplified case, there was no field measurements of riverbed level after the erosion process. However, the very different results obtained by Rubarbe seem linked to the simultaneous use of interpolated cross sections and sudden change in sediment diameter.

6. Conclusion

The models represent two different approaches to a detailed comparison.
The main differences areas follows:
- Erosion distribution in a cross-section
- Number of cross-sections is different; in other words, in Rubarbe, cross-sections were added by interpolating geometry resulting in change of the geometry of the whole reach.

Besides these computations for comparison carried out for unrealistic inflow hydrograph (for simplicity reasons), the results obtained by SSDD model, for more realistic data corresponds to observed trends.
Developments to reach a crossed validation of the two models requires:
- Changes in SSDD model in the treatment of slope
- The same cross-section treatment, which means same number of cross sections and same method for changing the shape,
- Introduction of sediment sorting to Rubarbe,
- Computation for natural hydrograph,
- Field measurements of river bed level.

7. References

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