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COMPARISON OF DIFFERENT METHODS OF MODELING THE PHENOMENA OF SEDIMENT TRANSPORT IN RIVERBEDS

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ABSTRACT. The study of the phenomena associated with sediment transport is important to determine if erosion or deposition will occur in a riverbed, the extent of this processes, as well as the time and distance over which it will occur. For a better understanding of these phenomena, it is necessary to identify and study all the factors and parameters that determine the mechanisms of solid transport processes in the riverbeds. Over time, several researchers have developed different formulas for calculating solid loads, models that were later integrated into various hydroinformatics tools. The use of these tools allows comparing the results obtained by applying various calculation models. This paper compares the results of sediment transport modeling in riverbeds using some of these calculation formulas: Engelund-Fredsøe; Van Rijn; Meyer-Peter & Müller; Sato, Kikkawa & Ashida, respectively Ashida, Takahashi and Mizuyama. The modeling is done on a river sector, using the advanced hydroinformatic tool MIKE11 by DHI. Comparing the results obtained by modeling, using various models, with the data obtained from the measurements make it possible to choose the best model for the studied water course.

Keywords: modeling, sediment transport, riverbed, Romania.

1. INTRODUCTION

Sediment transport in riverbeds is the movement of solid particles due to a combination of gravity with the movement of the water. Sediment transport occurs in natural river or in man-made channel systems, where the particles are non-cohesive (sand, gravel, boulders, etc.), or cohesive (mud or clay).

Sediment transport in rivers is essentially a two-phase flow problem in which the fluid phase is water, and the solid phase is sediment particle. The processes of erosion, transport, and deposition of sediment are natural processes and have been occurring throughout the geologic time. (Imran, 2008)

The study of the phenomena associated with sediment transport is important to determine if erosion or deposition will occur in a riverbed, the extent of this erosion or deposition, as well as the time and distance over which it will occur.

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For a better understanding of these phenomena, the origin of the sediments must also be studied, if they come from the riverbed or following surface erosion on the slopes and reach the water through surface runoff. (Griffiths and Topping, 2017)

Sediment transport is involved in solving several environmental, geotechnical and geological problems. Sediment movement is important for aquatic ecosystems, especially for fish and other organisms in rivers. The most important negative effects of sediment transport are the worsening of river water quality through turbidity and chemical elements contained in the alluvial particles, respectively the clogging of hydrotechnical works (reservoirs, waterways). (Government of Canada, 2016)

Knowledge of sediment transport can be used to properly plan the life of a reservoir. Flow in canals, sills and around bridge piers can cause erosion of the riverbed, damaging the surrounding environment and damaging the foundations of structures.

The sediment transport occurs through three mechanisms although the particle size of the transported material is very different. The three mechanisms are rolling or traction, in which the particle moves along a sedimentary bed but is too heavy to be lifted from it; saltation; and suspension, in which particles remain permanently above the bed, sustained there by the turbulent flow of the water (Costa, 2016).

There are three modes of sediment transport in a water course (Fig. 1).

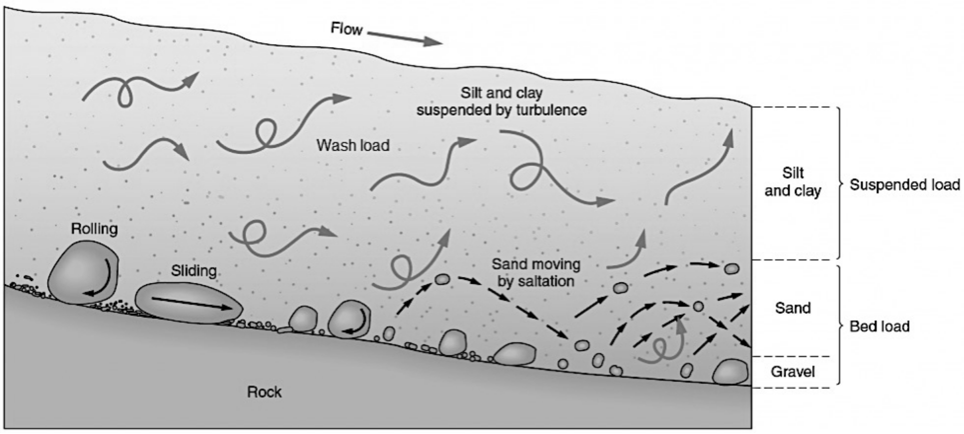

Fig. 1. ***Modes of sediment transport in a water course (source https://worldrivers.net/2020/03/31/sediment-transport/)***

The bed load is the part of the total load that is more or less in contact with the bed during the transport. It primarily includes grains that roll, slide or bounce along the bed.

The suspended load is the part of the total load that is moving in suspension without continuous contact with the bed as a result of agitation of fluid turbulence.

The first two modes of transport, which together are called total load transport has effects on the bed morphology. The third mode of transport, wash load is not important as it consists of very fine particles transported in water and not represented in the bed. (Kunte, 2003)

The phenomena of sediment transport in riverbeds were modelled on Bega River sector (City of Timisoara to Romanian - Serbian border, Bega River is transboundary water course), in order to Bega River sustainable development (Fig. 2).

Fig. 2. ***Area plan of Bega River and studied sector***

2. DATA AND METHODS

2.1. MIKE11 advanced hydroinformatic tool

The MIKE11advanced hydroinformatics tool was used to model the solid transport in the water course. This is part of the DHI software products, is a professional engineering software package for the simulation of flows, water quality and sediment transport in estuaries, rivers, irrigation systems, channels, and other water bodies. MIKE11 is a user-friendly, fully dynamic, one-dimensional modelling tool for the detailed analysis, design, management and operation of both simple and complex river and channel systems. The used modules for modelling are Hydrodinamic module and Non-cohesive Sediment Transport module (NST) module (DHI, 2014)

The MIKE11 hydrodynamic module (HD) uses an implicit, finite difference scheme for the computation of unsteady flows in rivers and estuaries.

The MIKE11 HD module solves the vertically integrated equations for the conservation of continuity and momentum, i.e., the Saint-Venant equations. The basic forms of the equations used in MIKE 11 are show in equations 1 and 2.

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

$$\frac{\delta Q}{\delta t}+gA\frac{\delta h}{\delta x}+\frac{\delta\left(\alpha\frac{Q^2}{A}\right)}{\delta x}+\frac{g|Q|Q}{C^2AR}=0 \tag{2}$$

where: *Q* is discharge, *x* is longitudinal channel distance, *A* is cross-sectional area, *q* is lateral inflow, *t* is time, *h* is flow depth, *C* is the Chezy coefficient and *R* is the hydraulic radius.

The non-cohesive sediment transport module (NST) can be run in two modes: explicit and morphological. In the explicit mode output is required from the hydrodynamic module (HD): discharge and water levels (cross-sectional area and hydraulic radius), both in time and space. The explicit mode is useful where significant morphological changes are unlikely to occur. There is no feedback from the sediment transport calculations to the HD module.

In the morphological mode sediment transport is calculated in tandem with the HD module. The feedback from the sediment transport calculations to the HD is achieved through solution of the sediment continuity equation and through the updating of the bed resistance and the following sediment transport. This model requires more computation time than the explicit model but is more representative of the dynamic alluvial processes. (DHI, 2014)

The NST module have different models for the calculation of sediment transport rate and alluvial roughness. All these models can be run using a single representative grain size or using a number of grain sizes representing grain size fractions in graded material as an add-on module.

Five transport models will be use to model the transport of sediments in the riverbeds (calculation of the suspended load and bed load): Engelund-Fredsøe; Van Rijn (these options are available in both modes; explicit and morphological); Meyer-Peter & Müller; Sato, Kikkawa & Ashida, respectively Ashida, Takahashi and Mizuyama model. Next, the first two models are briefly presented, because they allow the calculation of both a suspended load and bed load. (DHI, 2014)

2.2. Engelund-Fredsøe sediment transport model

The sediment transport model presented by Engelund & Fredsøe (1976) gives a more detailed description of sediment transport and its relation to the flow resistance. The bed load function is given by the equation 3:

$$\Phi_b=5\left[1+\left(\frac{\frac{\pi}{6}\beta}{\theta`-\theta_c}\right)^4\right]\left(\sqrt{\theta`}-0.7\sqrt{\theta_c}\right) \text{ and } \phi_b=\frac{q_b}{\sqrt{(s-1)gd^3}} \tag{3}$$

where: Φ_b is the bed load function, β is the dynamic friction coefficient, and is close to 1, θ' is the dimensionless skin friction, θ_c is the critical dimensionless bed shear stress (or Shields' parameter), q_b is the bed load transport rate, *s* is the specific gravity of the bed material, *d* is the mean grain size of the bed material and *g* is the acceleration of gravity.

The suspended load q_s is found as the integral of the current velocity u and the concentration of suspended sediment c (equation 4):

$$q_s = \int_a^D cudy \tag{4}$$

where: a is the thickness of the bed layer which can be approximated by $2d$, where d is the grain diameter, and D is the flow depth. (Engelund and Fredsøe, 1976)

2.3. Van Rijn sediment transport model

In the van Rijn transport model the sediment load is divided into bed load and suspended load according to the relative magnitudes of the bed shear velocity and the particle fall velocity. When the bed shear velocity exceeds the fall velocity then sediment is transported as both suspended and bed load.

Bed load is considered to be transported by rolling and saltation and the rate is described as a function of saltation height. In this model the bed load transport rate q_b is computed from the product of particle velocity, u_{bs}, saltation height, δ_b, and the bed load concentration, c_b (equation 5):

$$q_b = u_{bs} \cdot \delta_b \cdot c_b \tag{5}$$

Expressions for the particle velocity and saltation height were obtained by numerically solving the equations of motion applied to a solitary particle.

The suspended load rate q_s is determined from the depth-integration of the product of the local concentration c and flow velocity u (equation 6).

$$q_s = \int_a^D cudy \tag{6}$$

where: a is the reference level, and D is the flow depth. (DHI, 2014)

The reference concentration is determined from the bed load transport. The reference concentration is defined for a reference level a below which all sediment is considered to be transported as bed load.

The reference level a is approximated by: $0.5H$ (H is the known bed form height); k, the equivalent sand roughness when the bed form dimensions are unknown; or a minimum value of $0{,}01D$, D is water depth. The reference concentration is defined from equation 7:

$$q_b = c_b \cdot u_{bs} \cdot \delta_b = c_a \cdot u_a \cdot a \tag{7}$$

where: c_b is the bed concentration, u_{bs} is the velocity of bed load particles, δ_b is the saltation height, u_a is the effective particle velocity at reference level a, c_a is the reference concentration. (Rijn, 1984)

2.4. Study case

The data required for hydrodynamic modelling are: longitudinal profile of studied river sector (Fig. 2); 13 cross-sections (where was performed over time bathymetric measurements by Banat Water Basin Administration) (Fig. 3); time series: discharge hydrograph – average monthly discharge for 2005 in cross-section upstream of Timisoara – duration of simulation 1 year; boundary conditions: Q-H curve in cross-section situated downstream, on the state border (Fig. 4); ST parameters- non-cohesive sediments, average diameters of sediments $d_{average} = 0,001$ m. (ANAR)
The simulation hypotheses are:
- Time step: fixed time steps, 5 minutes
- Simulation period: 1/6/2005 1:00:00 PM – 12/5/2005 1:00:00 PM (1 year).

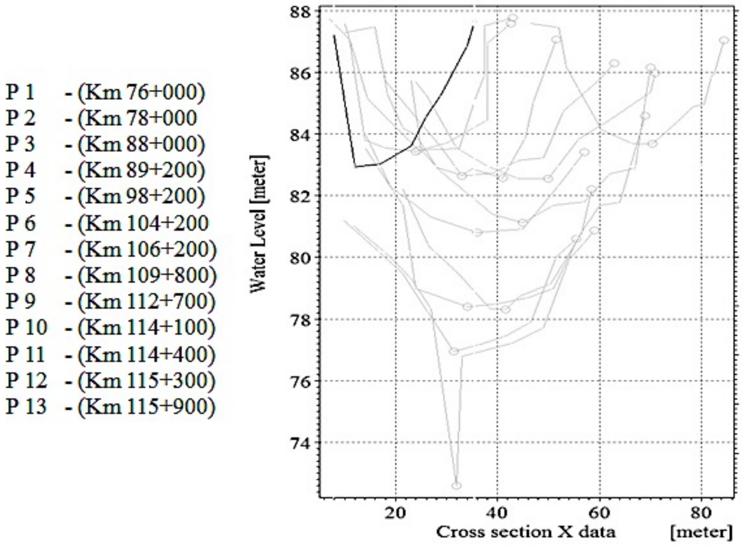

Fig. 3. ***Cross-sections between upstream Timisoara and RO-SRB border***

3. RESULTS AND DISCUSSION

Five transport models will be used to calculate the transport of sediments in the riverbeds (calculation of the suspended load and bed load): Engelund-Fredsøe; Van Rijn; Meyer-Peter & Müller; Sato, Kikkawa & Ashida, respectively Ashida, Takahashi and Mizuyama. The results can be seen in the following figures, where the maximum of the suspended load and bed load in the considered cross-sections were represented (Fig. 5, 6, 7, 8, 9, 10 and 11). For comparison, the obtained values are also given in Table 1, where you can see the values calculated in each cross-section, with the used models.

From the analysis of the results, the following aspects can be observed:
all graphs have approximately the same shape, the maximum being reached both in the case of the bed load and in the case of the suspended load in section 11, with the

exception of the Engelund-Fredsøe model, where we have two peaks of the same value, only for bed load.

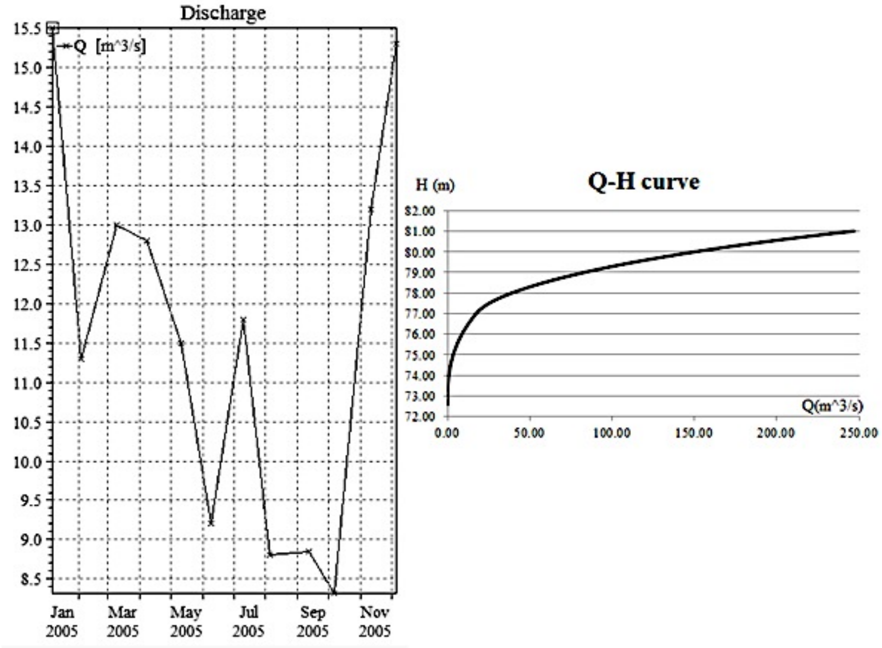

Fig. 4. ***Discharge and Q-H curve on studied sector***

The appearance of the maximum values in this section can be explained by the variation of the slope of the water bottom, having a counter slope in this area, due to the existence upstream of the Timisoara water plant, which captures the water from Bega;

Table 1. Bed load and suspended load maximum value

Nr.	Cross section	Bed load maximum value (m^3/s)					Suspended load maximum value (m^3/s)	
		Engelund-Fredsøe	Van Rijn	Meyer-Peter & Müller	Sato, Kikkawa & Ashida	Ashida, Takahashi and Mizuyama	Engelund-Fredsøe	Van Rijn
1	BEGA 76000	0.000	0.000	0.000	0.000	0.001	0.000	0.001
2	BEGA 78000	0.000	0.001	0.000	0.001	0.004	0.000	0.002
3	BEGA 88000	0.003	0.003	0.001	0.001	0.008	0.002	0.001
4	BEGA 89200	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	BEGA 98200	0.007	0.008	0.002	0.003	0.019	0.006	0.002
6	BEGA 104200	0.004	0.004	0.001	0.002	0.011	0.003	0.001
7	BEGA 106200	0.000	0.001	0.000	0.001	0.004	0.000	0.002
8	BEGA 109800	0.011	0.448	0.036	0.038	0.313	0.117	0.067
9	BEGA 112700	0.022	0.596	0.055	0.059	0.480	0.192	0.096
10	BEGA 114100	0.018	5.142	0.187	0.197	1.679	0.475	0.554
11	***BEGA 114400***	***0.022***	***8.190***	***0.263***	***0.277***	***2.368***	***0.680***	***0.825***
12	BEGA 115300	0.015	0.398	0.037	0.040	0.328	0.122	0.064
13	BEGA 115900	0.008	0.036	0.006	0.007	0.055	0.019	0.012

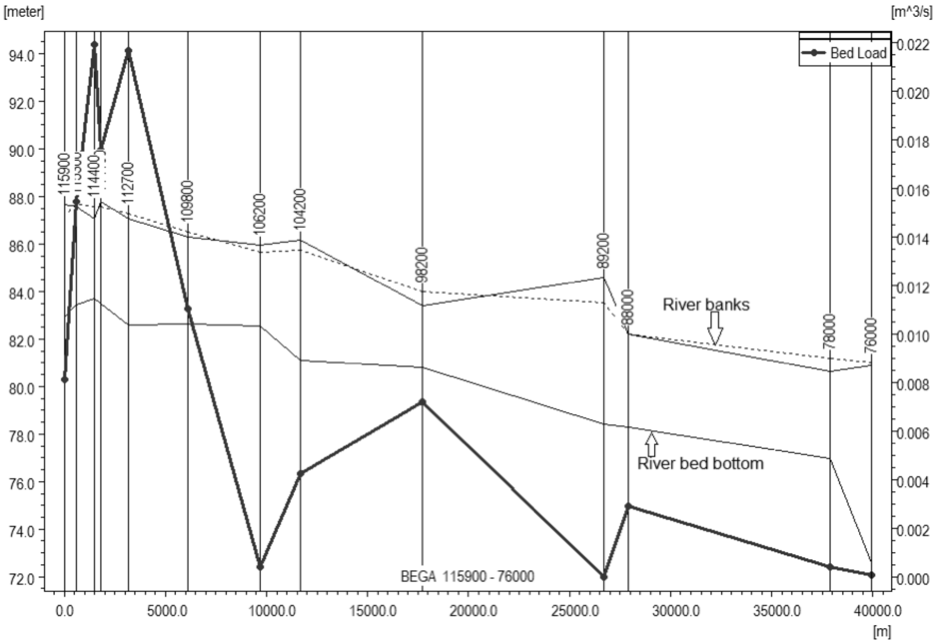

Fig. 5. ***Variation of maximum values of bed load, with Engelund-Fredsøe model, along longitudinal profile of the Bega River***

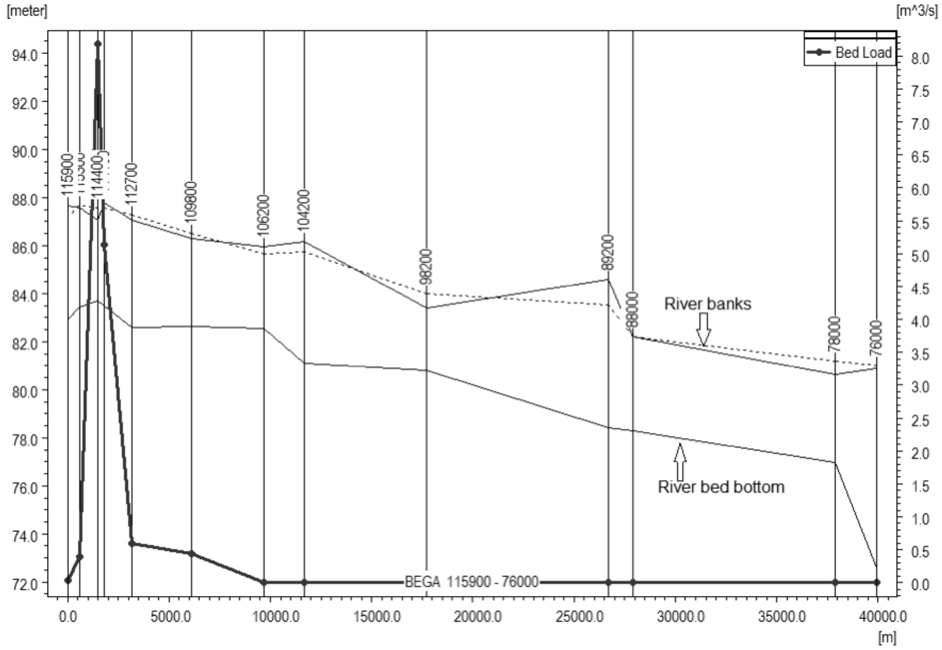

Fig. 6. ***Variation of maximum values of bed load, with Van Rijn model, along longitudinal profile of the Bega River***

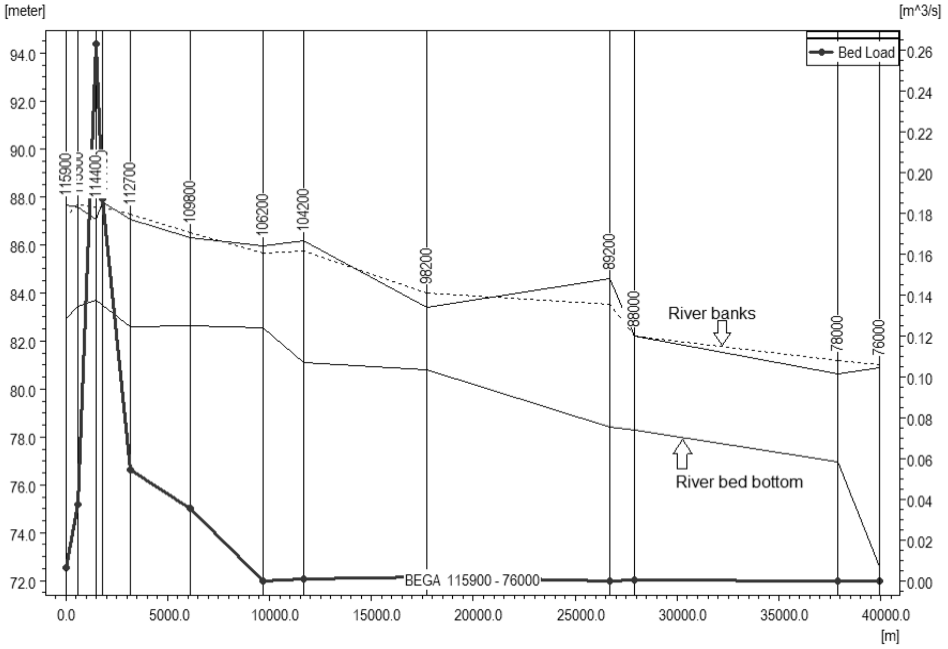

Fig. 7. ***Variation of maximum values of bed load, with Meyer-Peter & Müller model, along longitudinal profile of the Bega River***

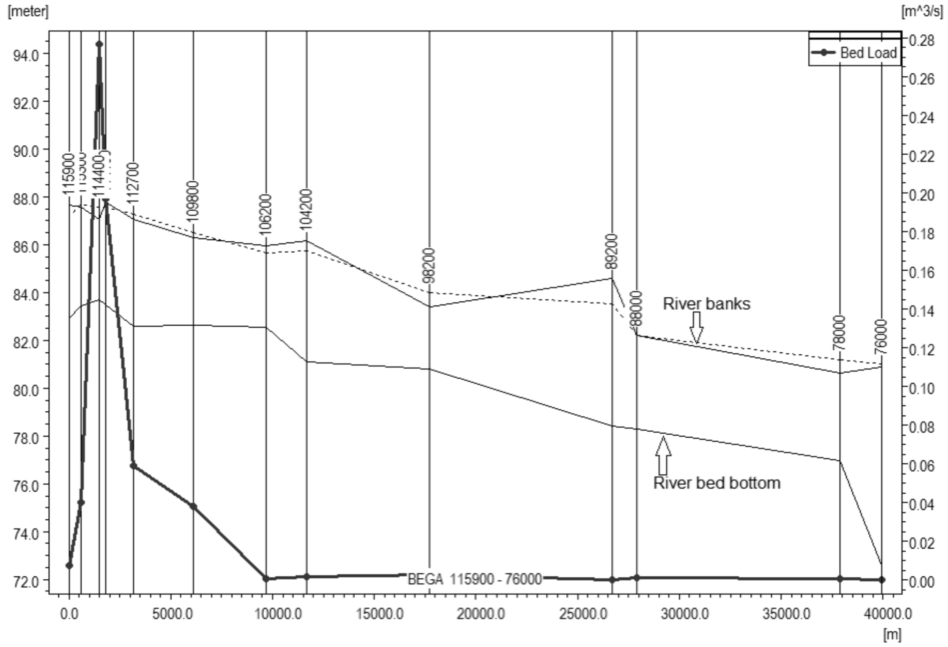

Fig. 8. ***Variation of maximum values of bed load, with Sato, Kikkawa & Ashida model, along longitudinal profile of the Bega River***

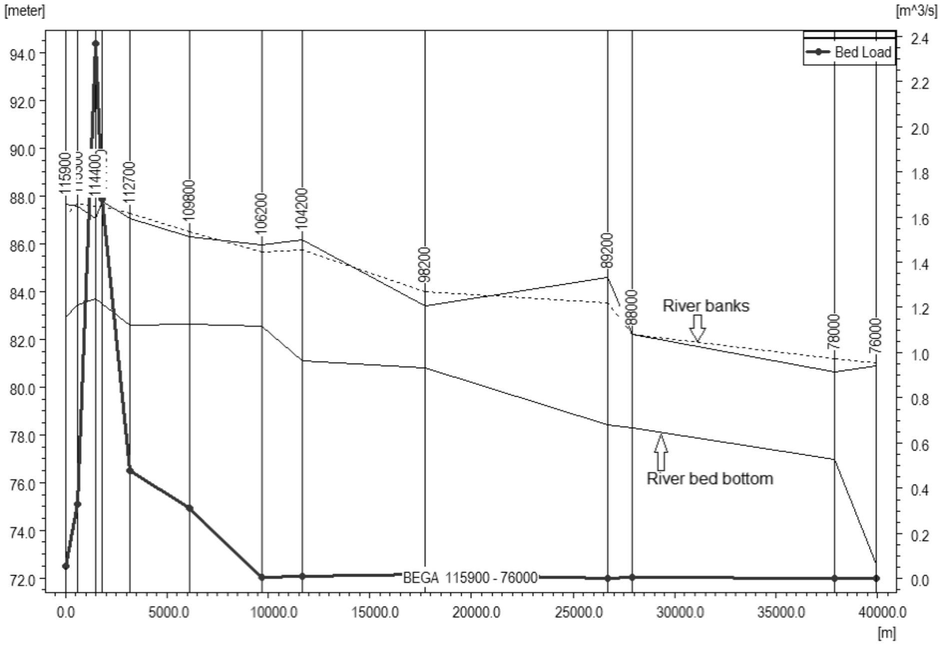

Fig. 9. ***Variation of maximum values of bed load, with Ashida, Takahashi and Mizuyama model, along longitudinal profile of the Bega River***

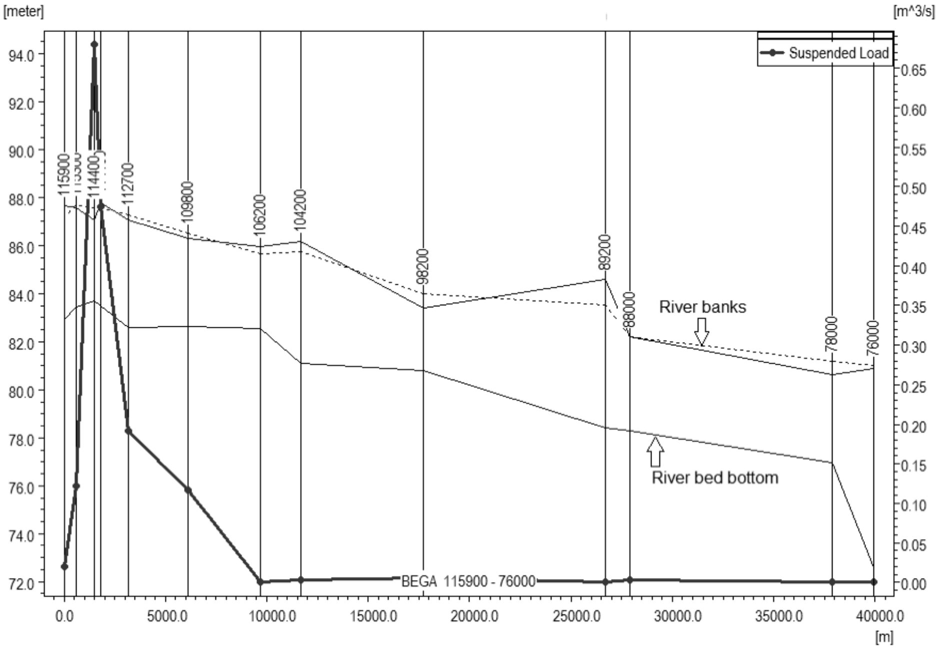

Fig. 10. ***Variation of maximum values of suspended load, with Engelund-Fredsøe model, along longitudinal profile of the Bega River***

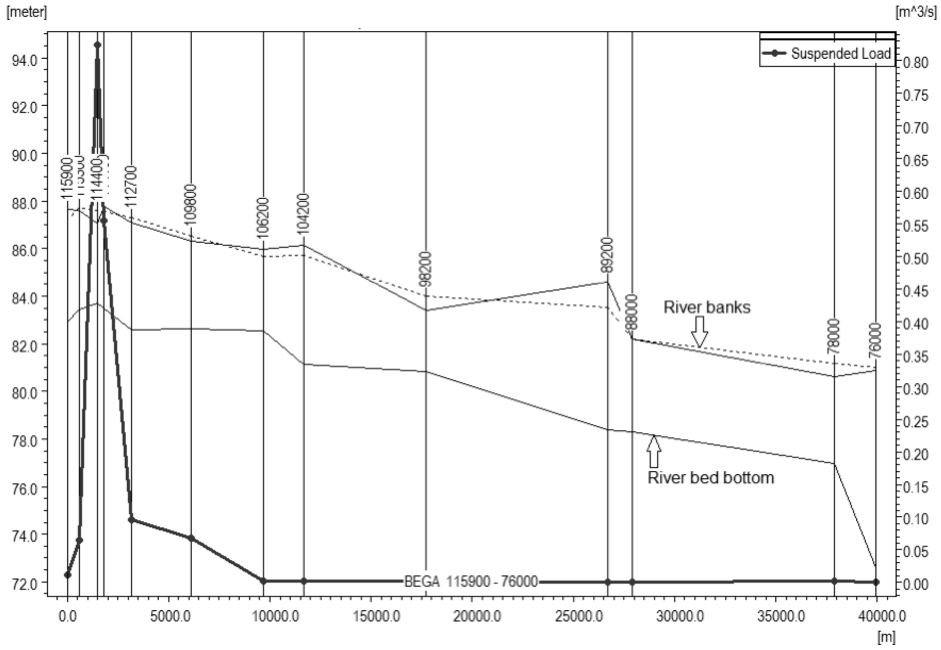

Fig. 11. ***Variation of maximum values of suspended load, with Van Rijn model, along longitudinal profile of the Bega River***

- in case of suspended load, both used models give values of the same order of magnitude, with a difference of approximately 21 %;
- in case of bed load, the 5 used models give maximum values located in a much wider range, from 0.022 to 8.190, appropriate values being given by Meyer-Peter & Müller and Sato, Kikkawa & Ashida sediment transport model.

The big differences can be explained by the complexity of the solid transport phenomenon, by the multitude of parameters involved in the calculations, by the simplifying assumptions made, respectively by the way of numerical mathematical calculation.

In case of calibration of models for suspended load and bed load calculation, separate computation of suspended load and bed load is advantageous. In the future, the development of this kind of models is necessary.

The selection of sediment transport model for a particular case study depends on the nature of the water course under study and on experience in sediment transport modelling of specialists which involved in respective projects.

In the absence of any such knowledge and experience, trial simulations should be carried out with each model to see which gives better results, appropriate with measurements.

After selection of most appropriate transport model further adjustments can be made to the predicted transport rates during the calibration procedure by the use of the two factors Factor 1 and Factor 2.

These are specified in ST parameter editor →Calibration Factors and are used to apply a linear correction factor to the predicted suspended and bed load transport rates, respectively (or to the total load, Factor 1 only) (DHI, 2014)

4. CONCLUSIONS

The study of the phenomenon of sediment transport in water courses is important in the design, execution and exploitation phases of various works and hydrotechnical arrangements. The quantity and mode of transport of sediments determine many aspects of the exploitation of hydrotechnical works: in the case of water treatment plants, the sizing of decanters, de-sand filters and strainer sizing in the case of reservoirs, the clogging processes determine the period in which the reservoirs can satisfy the users' requirements; in the case of navigable channels, knowing the areas of erosion and deposition of alluvium determines the provision of the necessary depth for ships.

An important step to achieve management plans of water resources and management of sediment loads is water quality and quantity evolution forecast in watercourses. This requires the creation of models and, respectively, the development of advanced hydroinformatics tools to solve these models.

The advanced hydroinformatic modeling tools for water quality, quantity and sediment transport provides satisfactory results with regard to the status of water bodies both in normal periods, flooding and dry periods, and in case of accidental events.

The detailed results obtained from modeling and forecast increase general understanding of the evolution of water characteristics in water bodies and support authorities to act (in time and space), in case of accidental events, according to the plans of action in emergency situations, based on risk management plans of watercourses.

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