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 AKJournals

The impact of hydropeaking on sediment transport

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ABSTRACT

Variable renewable energy sources, e.g. solar and wind power, require flexible management of energy sources to stabilize the power grid. Immediate changes in power generation and power usage is compensated for by the operation of hydropower plants. This subsequently leads to frequent flow fluctuations – hydropeaking downstream of the hydropower plant. This study examines the short-term impacts of hydropeaking of hydropower plants on the sediment transport using numerical morphodynamic model. The model is calibrated to field measurements and subjected to various hydropeaking scenarios on daily to sub-daily scale. Based on this study, the effect of hydropeaking of hydropower plant 23.42 km upstream of the studied river section would have negligible effect on the bedload transport in the studied cross section.

KEYWORDS

hydropeaking, hydropower plant, sediment transport, numerical model

1. INTRODUCTION

Hydropower plays an important role in the European energy market, being a flexible energy source, and it is gaining importance in many developing countries. The Intergovernmental Panel on Climate Change (IPCC) expects the share of low carbon energy to increase more than threefold [1, 2] under the strict Representative Concentration Pathway (RCP) 2.6 scenario to mitigate CO₂ concentration in the atmosphere. In addition, the European Union aims to increase the use of renewable energy sources to 20% of total consumption by 2020 [3].

The dynamic development of the energy market (the emergence of renewable energy sources, in particular hard to predict sources e.g. solar and wind power plants) requires more flexible management of energy sources in order to keep the power grid stable. Immediate changes in electric power generation and consumption will most likely continue to be compensated for by the operation of hydropower plants and their importance will increase in this respect [4, 5].

Hydropower at the time of operation causes frequent flow fluctuations – hydropeaking [6], whose effects on flow and sediment regime changes have direct or indirect impacts on river morphology, river ecosystems and the restructuring of natural habitats [7, 8]. There is a general assumption that hydropeaking occurs on rivers with high pressure hydropower, so most of the studies to date have focused on rivers affected by large reservoir water works [9], while studies on hydropower plants with smaller retention capacity are rather exceptional and addressed in a local context [10]. Several studies have quantified the medium to long-term change in flow and sediment regimens based on data with daily and greater time intervals [11–14]. Fewer studies have worked with shorter than daily intervals to capture flow peaks [6, 15, 16]. However, they prefer to deal with the ecological effects of hydropeaking.

The subject of this work is the study of the short-term impact of the hydropower plant operation on the sediment flow regime downstream. The work is focused on the examination

of the hydromorphology of the Slovak-Hungarian Danube River section from 1,810 to 1,792 km (Sap – Klížska Nemá). The section well represents the typical problems associated with disturbing the alluvial flow by a hydropower plant where the continuity of the sediment movement by the built dam is interrupted [17, 18].

Medium- to long-term morphological changes of the river section of interest caused by the construction of the Gabčíkovo Waterworks are well documented in [11, 12]. During the first 10 years since the Gabčíkovo Waterworks was put into operation in 1992, the most dynamic changes occurred in the section Sap – Medveďov and later downstream of Medveďov. The riverbed of the Danube deepened by about 4–5 m during that period and from 1,798 to 1,780 km developed several meters high deposits [11].

The current course of the Danube riverbed indicates a continuing decrease in slope in the upper, more dynamic section (Sap – Gönyü) [11]. This trend may have an adverse effect on groundwater levels and is already adversely affecting navigational conditions. The North-Transdanubian Water Directorate in Hungary performs regular measurements of the amount of transported sediments in the cross section of the Medveďov Bridge (1,806 km). From 1998 to 2015, it performed 66 measurements at various flow rates. The analysis of the amount of transported sediments showed a decrease of 94% of the transport of sediments. Based on these findings, there is a presumption that the riverbed morphology has stabilized in the section Gabčíkovo – Medveďov [12]. Decreasing trend of sediment transport in the area of interest was also recorded by Holubová [11] independent of the Török study [12]. Milder morphological changes are expected, for instance slow bank erosion, particularly during flood events, accompanied by a slight riverbed aggradation [12]. The primary source of the change of the riverbed morphology aside from natural flooding will be the transformed discharge from Gabčíkovo Waterworks.

The hydropower plant Gabčíkovo, as a part of the Gabčíkovo – Nagymaros waterworks, was designed as peaking power plant to compensate for the sudden demands in the power grid. Yet since its launch in 1992, it has been operating as a run-off-river hydropower plant. The

hydropower plant is capable to transform flow rates of up to $5,040 \text{ m}^3 \text{ s}^{-1}$ on sub-daily to hourly sale.

Aim of this paper is the study of the short-term impacts of the transformed discharge from a hydropower plant, with the capacity of hydropeaking, on the sediment transport downstream. More precisely, this study focuses on the amount of transported bedload by variously fluctuating flow rate.

2. MATERIAL AND METHODS

The basis for modeling sediment transport is the hydrodynamic model of interest area created by Mike 21 FM (Flow Model) code [19]. It is a system of numerical modeling for simulating water surface elevations, flow of rivers, bays and coastal areas. By design it simulates unsteady 2D flow in a single layer (vertically homogeneous). Mike 21 FM code has been used and verified in a large number of studies. The mathematical formulation of the model is not the subject of the work – it is described in detail in the scientific documentation of the model [19].

The modeled section has a total length of ca. 18 km and consists of ~82,000 elements. It is a part of larger, properly calibrated pure hydrodynamic numerical model specifically developed for River Information Services [20]. Map of hydraulic roughness is the result of the calibration process (Fig. 1). Sediment transport models can be sensitive to hydraulic roughness, yet bed roughness does not make a good calibration parameter. Therefore, it was determined independently during hydraulic calibration prior to any sediment transport simulation.

The computational network of the model consists of a combination of structured curvilinear and unstructured triangular networks. The topography of the channel and tributaries is discretized by a structured curvilinear grid and the floodplain by an unstructured triangular grid (Fig. 2). The characteristic terrain features were discretized to a reasonable degree of accuracy, whilst favoring the computational speed over resolution. The element size in river channel varies from 6×10 to 10×25 m depending on the

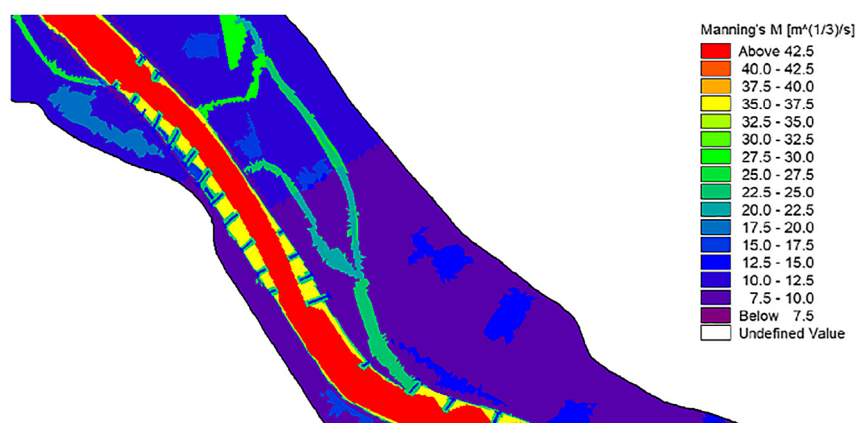


Fig. 1. Detail of bed roughness map of the river section of interest

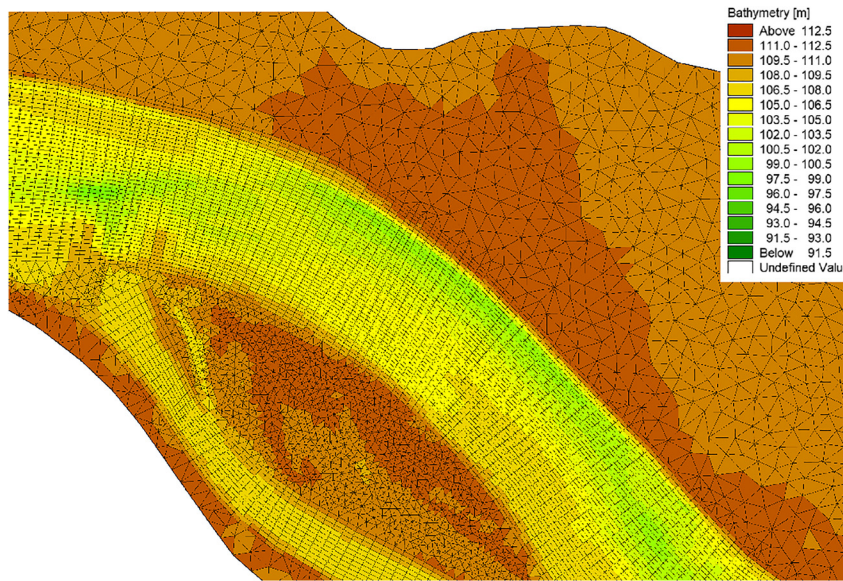


Fig. 2. Detail of computational grid of the river section of interest

spatial terrain segmentation. To ensure computational stability, the quality criteria of the computation grid, during the creation of the numerical model were respected [19].

Grain size distribution of the riverbed material is the essential input data for a morphological model. An extensive program of bed material sampling was performed in 2014. Bed material samples were taken in a total of 56 locations along the Danube River channel. They were subsequently processed by the sieving method in the hydraulic laboratory of the Water Research Institute in Slovakia. Sampling was carried out from the boat using a cylindrical sampler. In the studied section 1,810 km – 1,792, the bottom material is very well sorted. It consists mainly of fine to coarse gravel with a predominantly uniform median grain size ranging from 7.8 to 14.4 mm [21]. Similar range of median grain size in studied river section was obtained by method proposed in [22].

The sediment transport in this study is solved using a 2D model Mike 21 Sand Transport (ST) code [22], which calculates the transport of non-cohesive materials. Mike 21 ST code is equipped with several sediment transport formulas (Engelund and Hansen [23], Van Rijn [24], Engelund and Fredsøe [25], Meyer-Peter-Müller [26]). Each of them suited for different type of alluvial river. The considered model uses the classic Peter-Meyer-Müller relationship, which is well suited for studied river section [11]. This relationship is derived for river systems with dominating bed load over suspended sediment and slopes from 0.0004 to 0.02 [26]. Meyer-Peter-Müller established a relationship of dimensionless sediment transport Φ to the dimensionless shear stress applied to the bottom material by:

$$\Phi_{bl} = 8(\theta' - \theta_c)^{1.5}, \quad (1)$$

expressed as intensity of sediment transport:

$$S_{bl} = 8(\theta' - \theta_c)^{1.5} \sqrt{(s - 1)gd_{50}^3}, \quad (2)$$

where θ' is the roughness-dependent part of Shields parameter [-]; θ_c is the critical Shields parameter [-]; Φ_{bl} is the dimensionless sediment transport [-]; S_{bl} is the sediment transport [m^2/s]; s is the specific weight [-]; g is the gravitational constant [m/s^2]; d_{50} is the median grain size [mm].

The uncertainty of the numerical models can be minimized if measured data are available for calibration and verification. Calibration is the adjustment of calibration parameters in a model to produce results similar to the measured values. Subsequent verification of the model consists of comparing the results of the calibrated model with the data to be verified. It is therefore optimal to dispose of two sets of data. In that case, good quality results are achieved. Even if reliable verification data is not available, numerical models can provide useful qualitative data. For example, they can be used to assess the morphological effects of different scenarios, where the amplitude of change and/or trend is critical. Results gathered from unverified models are sufficient for many practical problems of river engineering [27].

Sediment data for calibration are usually rare, requiring modelers to make assumptions and evaluate the sensitivity and uncertainty of these assumptions throughout the modeling process [28]. In case of scarcity or absence of sediment data, alternative means of sediment data acquisition, e.g. optical granulometry can be utilized [29]. The studied section of Danube River benefits from several studies [11, 12] and [30, 31]. Bedload measurements were undertaken throughout single river cross section at 1,795.58 km for discharges ranging from 972–4,745 $\text{m}^3 \text{s}^{-1}$ (in six verticals during a total of 71 campaigns). Samples were collected using a basket-type bedload sampler with a mesh

size of 3 mm and a trapping efficiency of 0.7. Each bedload value represents an average of 10 repeated measurements in order to minimize the error due to temporal fluctuation in bed load rate [31]. Bedload data originating from this study provide extensive foundation for proper calibration of a morphodynamic model of studied river section.

Calibration parameters were selected by assessing relative sensitivity and uncertainty of each model input. Hydraulic roughness as mentioned earlier belongs to the category of high sensitivity, but low uncertainty. Proper calibration parameters should be high in uncertainty and at the same time the model should be highly sensitive to them. Median grain size and dimensionless riverbed material porosity fulfill these requirements. The plausible range of median grain size was 7.8–14.4 mm [21]. Plausible dimensionless porosity ranges from coarse sand to medium gravel or 0.39 to 0.32 respectively. Optimal results were achieved with median grain size 8 mm and porosity of 0.34. Comparison of measured bedload and simulated bedload of calibrated model is depicted in Fig. 3.

It has to be noted that the simulated bedload near the right bank is significantly lower than the measured bedload. This can be attributed to the point bar formation on the right side of the river channel, which developed sometime between years 2002 and 2013 and subsequent shift of flow paths. There can be identified ca. 2 m riverbed elevation difference near right riverbank in Fig. 3. The majority of the discharge is concentrated in the zone of highest flow depth in this cross section (station 50 m–150 m). For this reason, the measurement values from station 50 m–150 m are considered as more decisive during the calibration process.

In order to study the short-term impact of transformed flow rates on sediment transport downstream of hydropower plant, the calibrated model was subjected to various

hydropeaking scenarios. The regulatory aspect of the hydropower plant was represented by the change in flow rate over time for both, increase and decrease of flow rate at the hydropower plant outlet. In other words, the studied parameter was the steepness of both ascending and descending arm of each hydropeaking fluctuation of the hydrogram expressed in $\text{m}^3 \text{s}^{-1} \text{h}^{-1}$.

In order to isolate the parameter, all scenarios were calculated with equal cumulative inflow volume of 300 million m^3 during constant time frame of 44.0 h. A total of six scenarios were evaluated ranging from 200–1,200 $\text{m}^3 \text{s}^{-1} \text{h}^{-1}$ in 200 $\text{m}^3 \text{s}^{-1} \text{h}^{-1}$ increments. Scenario 1 limits the change in flow rate to 200 $\text{m}^3 \text{s}^{-1} \text{h}^{-1}$ and represents the normal operation of the hydropower plant. Subsequent scenarios represent gradually intensifying hydropeaking. Scenarios are summarized in Table 1. Flowrates of corresponding scenarios are depicted in Figs. 4–9.

Additionally, the minimum flow rate of each scenario was defined at 1,250 $\text{m}^3 \text{s}^{-1}$ and maximum at 2,750 $\text{m}^3 \text{s}^{-1}$. This range was carefully chosen not to exceed the range of the measured calibration data (1,000–3,000 $\text{m}^3 \text{s}^{-1}$) and thus minimizing the error of the experiment. Scenario 1 represents one hydropeaking event. All other scenarios dispose of

Table 1. Summary of experimental scenarios and their parameters

Scenario	Change in flow rate over time ($\text{m}^3 \text{s}^{-1} \text{h}^{-1}$)	Cumulative volume (mL m^3)	Duration (h)
1	200	300	44
2	400	300	44
3	600	300	44
4	800	300	44
5	1,000	300	44
6	1,200	300	44

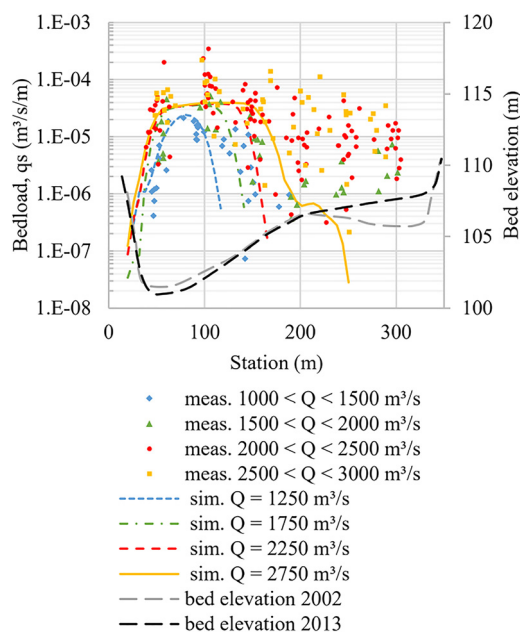


Fig. 3. Comparison of measured bedload and simulated bedload for various flow conditions

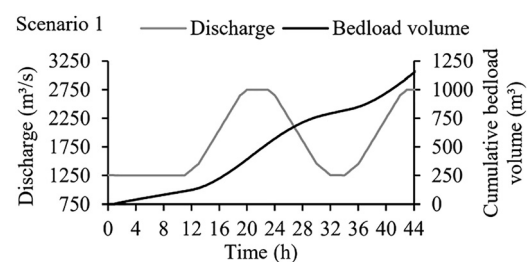


Fig. 4. Hydrogram of scenario 1 and cumulative bedload volume

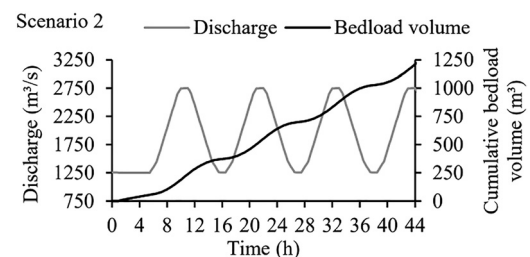


Fig. 5. Hydrogram of scenario 2 and cumulative bedload volume

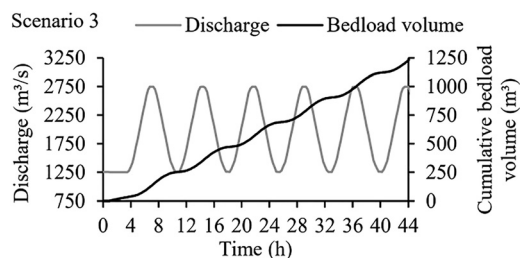


Fig. 6. Hydrogram of scenario 3 and cumulative bedload volume

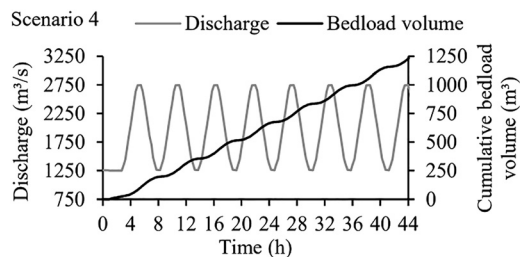


Fig. 7. Hydrogram of scenario 4 and cumulative bedload volume

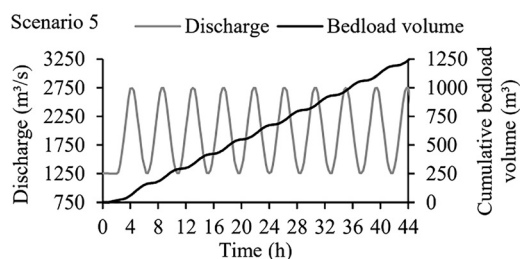


Fig. 8. Hydrogram of scenario 5 and cumulative bedload volume

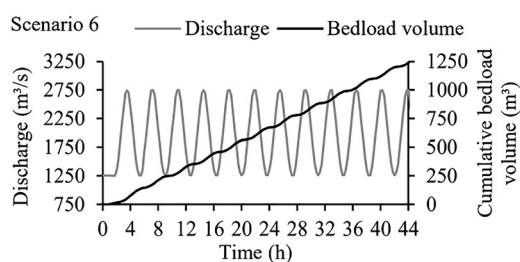


Fig. 9. Hydrogram of scenario 6 and cumulative bedload volume

multiple hydropеaking events in order to fulfill the condition of constant cumulative volume in given time frame.

3. RESULTS AND DISCUSSION

The evaluation of the experiment was executed in following fashion: In order to minimize the error, the bedload transport was computed for the same cross section as it was calibrated (1,795.58 km). A cumulative bedload volume was calculated

Table 2. Calculated cumulative volume evaluated for each scenario and percentual deviation from average

Scenario	1	2	3	4	5	6
Volume (m ³)	1,189	1,172	1,175	1,131	1,135	1,127
Deviation from average	3%	1%	2%	-2%	-2%	-2%

along the cross section for each computational scenario (Figs 4–9). The maximum percentual deviation from average cumulative bedload volume amounts to 3%, which is well within the margin of error and therefore negligible (Table 2). This might be attributed to the considerable distance of 23.42 km from the source of the discharge fluctuations.

4. CONCLUSION

In order to study the short-term impact of transformed flow rates on sediment transport downstream of hydropower plant, a numerical model was created and calibrated according to field measurements. Using numerical modeling System Mike 21 ST code, it was possible to calibrate the model to a reasonable degree of accuracy. Subsequently the calibrated morphodynamic model was subjected to six hydropеaking scenarios. All scenarios were design be bound by operational bounds of the considered hydropower plant Gabčíkovo. The regulatory aspect of the hydropower plant was represented by the change in flow rate over time for both, increase and decrease of flow rate at the hydropower plant outlet. In the evaluation phase, the total volume of bedload calculated for river cross section at 1,795.58 km was compared for each scenario. The differences of transported volumes for calculated hydropеaking scenarios were well within the margin of error of ca. 3% from the average value and therefore considered negligible. Based on this study, the effect of hydropеaking of hydropower plant 23.42 km upstream of the studied river section would have negligible effect on the bedload transport.

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