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Using 1D and 2D computer models when predicting hydrodynamic and morphological parameters of a boulder block ramp: Poniczanka stream, Carpathians

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Abstract: When modelling flow and/or sediment transport in streams and rivers, one must frequently use the computer software of differing levels of complexity. The level of sophistication, accuracy, and quality of results are the parameters by which models can be classified as being 1D, 2D, or 3D; it seems certain that in the future, there will also be 4D and 5D models. However, the results obtained from very sophisticated models are frequently questionable, and designers in the field of hydraulic structures must have considerable experience distinguishing important information from irrelevant information. Thus, this paper aims to investigate the effect of the selected boulder block ramp hydraulic structure at Poniczanka stream on the bed-load transport. We evaluated sediment transport using the CCHE2D numerical model. We analysed several scenarios depending on the river bed type (erodible, non-erodible, rocky) and examined the rock blocks used for hydraulic structure construction. The obtained results were compared with the Hjulström and the Shields graph, which are a classic approach for identifying fluvial processes in river channels. In addition to these two methods, numerical modelling using the 1D HEC-RAS (Hydrologic Engineering Center's River Analysis System) modelling were conducted, which included the determination of horizontal and vertical changes to the river bed morphology of the examined section of river reach as well as providing the basic hydrodynamics parameters which, from the practical point of view, designers involved in the process of designing ramps could use.

Keywords: boulder blocks ramps, low head hydraulic structures, field measurements, hydraulics, river bed morphology, HEC-RAS model, CCHE2D model

INTRODUCTION

In recent years, member states across Europe have been implementing the Water Framework Directive 2000/60/WE (so called WFD) of the European Union. There has been a prolonged debate among designers, river managers, fishers, and biologists on applying all hydraulic structures and engineering methods intended to preserve river beds in the best possible condition. Simultaneously maintaining a river morphology close to nature while preventing river bed erosion (through sediment transport management) and providing flood protection. Along many sections of the Carpathian rivers, river bed systems are still obliged to comply with technical river regulations that are not always appropriate [Curtean-Bănăduc *et al.* 2007; Zalewski *et al.* 2021]. It is, therefore, necessary to recognise which mountain river training structures can be accommodated in a mountain river fluvial system and positively affect the biological life of both macrobenthos and fish [Bylak *et al.* 2017; Kukuła 2003; 2006]. Thus, field studies and works were undertaken to examine the boulder block ramps within the mountain channels and later use these investigations' results for modelling ramps. The numerical and physical modelling in laboratories (e.g. Pagliara *et al.* [2017])

improves their construction in terms of their hydraulics and their impact on the river environment. No one would question that water flow is a very complex problem needing theoretical understanding and much practical knowledge. Physical analyses of this phenomenon provide a quantitative description of water flow, allowing the creation of mathematical models that have an important practical application. Over recent years, the practical implementation of numerical software programs has rapidly improved; therefore, the results obtained through them can be applied to practical solutions [Gąsiorowski *et al.* 2015; Szymkiewicz 2012; 2015]. However, one has to be very careful and experienced when using models. The similarity between a river and its model can only be partially verified. In this sense, only some modelling results might be used for design recommendations [Plesiński *et al.* 2015; 2018b; 2022]. Ultimately, the engineer who decides if the model works correctly and if the results are reliable. Mistakes that are made might later lead to errors in design that could cause catastrophic structural failure.

In the present paper, numerical modelling of a Boulder Block Ramp (BBR), which belongs to the low head hydraulic structures group, was performed using the CCHE2D and the HEC-RAS (Hydrologic Engineering Center's River Analysis System) models.

To introduce boulder ramps, one has to bear in mind that the stabilisation of mountain stream channels, characterised by steep longitudinal slopes, considerable changeability of the water stage, flash floods, and massive bed-load transport, can be obtained through the construction of stages of falls or weirs to create a given critical slope of the stream bed. Such measures unfavourably influence the natural environment. In this context, the best solution to the problem of river-channel protection from the impact of flash flows caused by the reduction of the longitudinal slope of the river seems to be the application of boulder ramps [Knauss 1980; Oertel 2013; Pagliara *et al.* 2017; Pagliara, Palermo 2013; Radecki-Pawlik 2013; Tamagni *et al.* 2014; Weitbrecht *et al.* 2016].

These structures enable the migration of fish and benthic macroinvertebrates (benthos), lead to water oxidation, and blend into the landscape [Bylak *et al.* 2017; Plesiński *et al.* 2018a]. The pools which form, the presence of which is caused by the hydrodynamics of the flow, should be preserved in the sections between the rapid hydraulic structures. Stones of different sizes should be placed in the river bed to create shelter for fish and other living organisms [Radecki-Pawlik *et al.* 2018]. Such shelters should also be located along river banks. The proposed solutions meet the ecological requirements of blending into the landscape and requirements connected with the stabilisation of the stream channel.

The proper selection of stone sizes and their positioning on the rapid hydraulic structure (RHS) significantly influences the efficiency of the rapid and its integration with the natural environment. The dimensions of stones in the slope plate of the rapid in relation to the computational velocity and the rapid slope are presented in Table 1 [Knauss 1980]. Flow velocity over the RHS can be measured for a better understanding of the hydraulics of structures and to improve their construction with regard to meeting the environmental requirements given by the EU Water Framework Directive.

Special attention is given to sediment transport in the paper. Sediment transport in rivers and streams has been extensively studied since the 1950s, resulting in various models that have thus far been used for load prediction. The major sources of sediment in natural rivers and streams are overland flow, stream-channel erosion, bank cutting, and small erosion channels made in unconsolidated soil [Engelund, Hansen 1967]. Estimates of transport rates in gravel-bed rivers have either been developed using formulae or obtained from sampling exercises, the former being considerably more uncertain and the latter more accurate [Wilcock *et al.* 2001]. In this paper, we focused on sediment transport modelling under the influence of boulder block ramps (BBR). One particular ramp was chosen for the investigations and examined in detail.

Table 1. Dimensions of stones on the boulder block ramp

Water velocity v (m·s^{-1}) for BBR inclination			Stone dimension (m)
1:8	1:10	1:15	
2.50	2.70	3.70	0.6
4.60	4.90	5.80	0.8
7.00	7.60	8.90	1.2

Source: Knauss [1980].

The examined structure is situated in Poniczanka stream in the Polish Carpathians. We performed numerical modelling of the stream channel within the area of influence of this BBR hydraulic structure. The modelling analyses different variants depending on the type of sloping apron of the BBR (erodible, non-erodible, and rocky). The primary purpose of these simulations was to demonstrate the effect of the analysed BBR on bed-load transport and morphology changes of the river bed. To confirm the reliability of the used model, we compared the obtained results with the Hjulström and Shields graph [Hjulström 1935; Shields 1936], which is a classic approach to identifying fluvial processes in river channels. Field data was collected and field measurements were conducted to perform such an analysis. Finally, based on the obtained numerical modelling results and the classical Hjulström and Shields approach, we did a comparative analysis to evaluate the consistency of the CCHE2D model with the Hjulström and Shields graph.

The additional purpose of this paper was to present the hydrodynamic parameters of the BBR in Poniczanka stream and provide readers with information on the hydraulics of the ramp obtained with 1D HEC-RAS model. HEC-RAS is a one-dimensional model designed to aid hydraulic engineers in the channel-flow analysis and floodplain determination. The model's results can be immediately understood by designers and river managers, hence our decision to use this model here to show basic hydraulics. In HEC-RAS, the primary procedure is to compute water surface profiles assuming a steady, gradually varied flow scenario called the direct step method. Because HEC-RAS authors proposed a very clear method using a basic hydraulics equation, the problems which might occur could be checked and easily verified.

MATIERIALS AND METHODS

FIELD STUDY AREA

The Poniczanka is a stream located in the Polish Carpathians. The Poniczanka is a tributary of the Raba River, a tributary of the Vistula River. The Poniczanka catchment is located on the northwestern slope of the Gorce Mountains and covers an area of approximately 33.1 km^2 (Fig. 1).

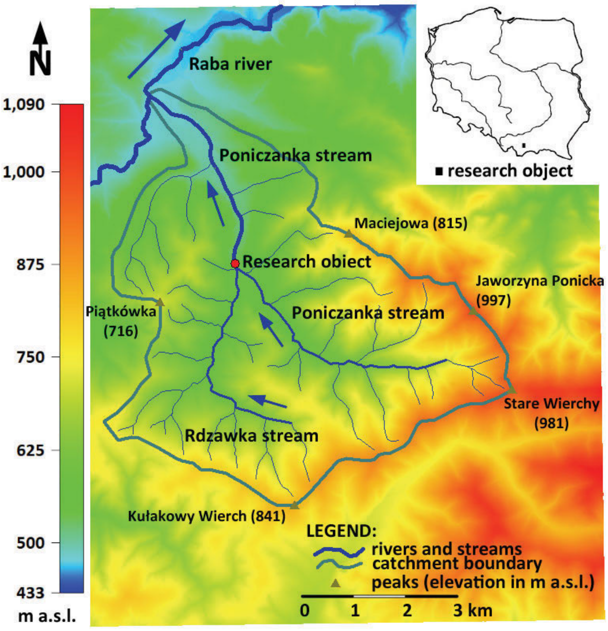


Fig. 1. The Poniczanka catchment and the researched boulder block ramp position; source: own elaboration

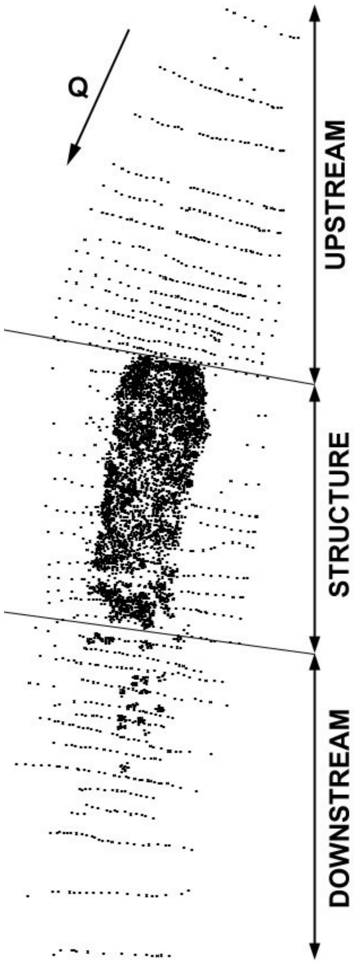


Fig. 2. Survey measurement points along the research reach and BBR; source: own elaboration

The sources of the river are at an altitude of 986 m a.s.l., and the lowest point of the catchment is at 485 m a.s.l. The examined boulder block ramp hydraulic structure (Fig. 2) is located on Poniczanka stream, 3.5 km upstream from the mouth of the Raba River. This BBR is an example of a cascade ramp; the width of the notches is around 10 m. The distance between the upstream and downstream curtain walls is 24 m. The block ramp is made of blocks with a diameter of approximately 1.2 m (Photo 1) (measured as axis 'b' in terms of sediment measurement requirements). Upstream and downstream of the BBR, a one-thread channel was formed by non-engineered river banks.

Photo 1. Boulder block ramp on Poniczanka stream views: a) towards upstream, b) towards downstream (phot.: *K. Plesiński*)

STUDY METHODS

Field measurements

The measurements were performed to deliver data for precise modelling with CCH2D and HEC-RAS, and use with the Hjulström and Shields graph. Detailed survey measurements were conducted using the Topcon GTS-226 level and the Topcon Total Station GTS-105N along a 100 m river reach. The BBR was very densely packed with boulders at approximately 50 m upstream and 40 m downstream from the block ramp (Fig. 2).

Measurements were performed in May 2014, both before and just after a flood (Q = 33.5 m^3·s^{-1}), to show changes in the

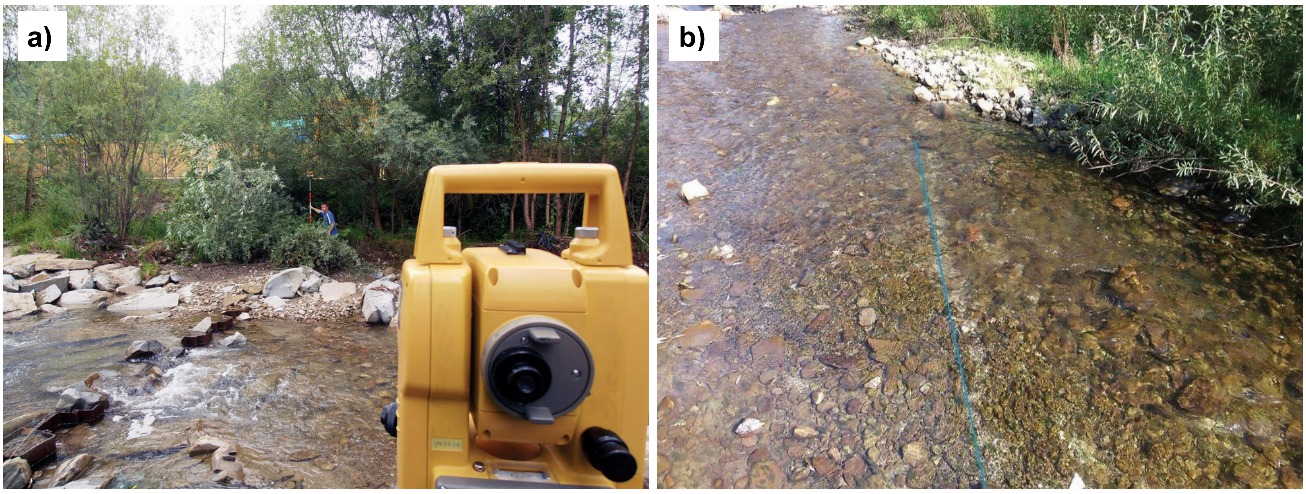


Photo 2. Measurements along Poniczanka stream: a) survey of the BBR, b) bed sediment collection (phot.: *K. Plesiński*)

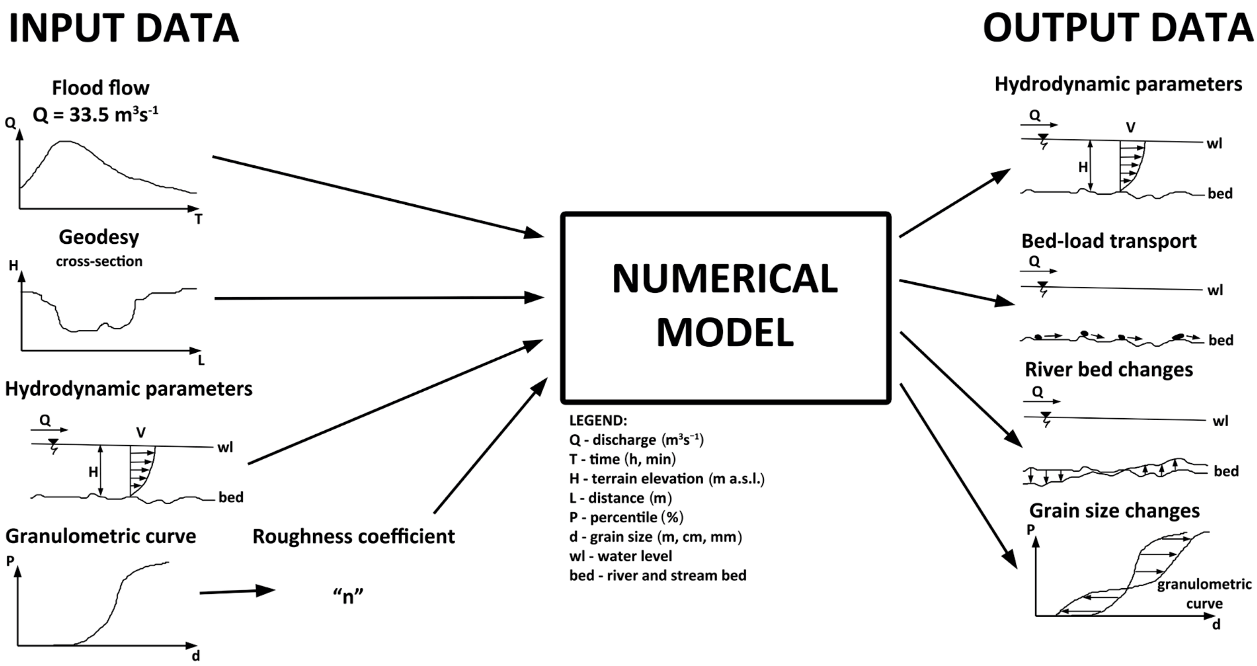


Fig. 3. A schematic diagram of the input data and output data at the models; source: own elaboration

morphology of the bed after the flood. For the minimum annual flow for this stream, $Q = 0.01\ m^3 \cdot s^{-1}$, the annual average flow $Q = 0.56\ m^3 \cdot s^{-1}$, and the maximum annual flow $Q = 38.10\ m^3 \cdot s^{-1}$ for the Rabka gauge station on Poniczanka stream for the rating curve relating to the previous 20 years. Measurement points were concentrated across the stream section with the boulder block ramp hydraulic structure to obtain its detailed geometric shape (Fig. 2, Photo 2a).

In the next stage of the process, coarse and fine sediment were sampled. The grain size of coarse gravel material was performed by the Wolman method [Wolman 1954], which involved measuring the "*b*" axis of 400 particles along a transect (Photo 2b). For fine sediment grains, an aerodynamic analysis was done.

The survey and the sediment sampling were both performed before and after the May 2014 flood. Concerning particle size distribution d_{mean} of the bed-load, the median diameter was calculated based on the 20th, 50th, and 80th percentile (d_{20}, d_{50}, and d_{80}, respectively) from Folk and Ward [1957] and Helley [1969]:

$$d_{\text{mean}} = \frac{(d_{20} + d_{50} + d_{80})}{3} \tag{1}$$

By obtaining field results, it was possible to perform numerical analyses. This was performed using the CCHE2D and the HEC-RAS program for the same value as that which occurred during the May 2014 flood). A schematic diagram (Fig. 3) of both models' input data and output data is shown below.

1D HEC-RAS model

The model was developed to simulate one-dimensional steady flow, unsteady flow, and sediment transport/mobile bed computations in rivers [Brunner 2010; 2016]. Although the model is one-dimensional, it can describe complex river cross-sections and their variation along the river. The sediment transport capability of the model was tested to simulate its effect on the river bed and banks based on the hydrodynamics computed by HEC-RAS 5.0.7 (Hydrologic Engineering Center's River Analysis System).

The HEC-RAS is a one-dimensional river analysis model that can make calculations for steady flow, unsteady flow, sediment transport, and water temperature modelling [Brunner 2010]. The model can perform calculations for both prismatic and natural channels. It is free software developed by the US Army Corps of Engineers to aid water engineers and planners. The river analysis components within HEC-RAS include steady flow water surface profile computations, unsteady flow simulations, sediment transport simulations, and water quality analyses. A common factor for all four simulation routines is that they all adopt the same geometric representation of the river system.

Additionally, the model contains some hydraulic design features that can be used once the water surface profiles have been computed [Brunner 2010]. In HEC-RAS, the water surface profile is calculated using an iterative procedure known as the standard step method from one cross-section to the other through the energy equation. Values for flows are needed for each cross-section to calculate the water surface profiles. These should be specified from upstream to downstream for each reach. For a given river system, at least one flow value should be entered for each reach. When a flow value is entered for a steady flow, it stays constant until another value is encountered within the same reach [Brunner 2010].

The basic computational procedure of HEC-RAS for steady flow is based on the solution of the one-dimensional energy equation [Brunner 2010; 2016]. Energy losses are evaluated by friction and contraction/expansion coefficients. The momentum equation may be used in situations where the water surface profile rapidly varies.

The basic computational procedure is based on an iterative solution to Equation (2):

$$H = Z + Y + \frac{av^2}{2g} \tag{2}$$

where: H = the total energy (m), which at any given location along the stream is the sum of potential energy $Z + Y$ and kinetic energy $\frac{av^2}{2g}$ (m), a = Saint-Venant coefficient (–), g = gravitational acceleration (m·s^{-2}). The change in energy between two cross-sections is called head loss.

2D CCHE2D model

The CCHE2D is an integrated software package developed at the National Center for Computational Hydroscience and Engineering, of the Mississippi University. It is a general numerical model for two-dimensional simulation and analyses of free surface flows and the associated processes [Jia, Wang 2009; Wu 2004; Wu, Wang 2005]. The equations used in the CCHE2D software are: Equation (3) – the continuity equation and Equation (4) – the momentum equation.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{3}$$

$$\frac{\partial}{\partial t}\left(\frac{Q}{A}\right) + \frac{\partial}{\partial x}\left(\frac{\beta Q^2}{2A^2}\right) + g\frac{\partial h}{\partial x} + g(S_f - S_0) = 0 \tag{4}$$

where: x and t = the place (m) and time (s) axes, A = the flow area (m^2), Q = the flow discharge (m^3·s^{-1}), q = the unit discharge (m^2·s^{-1}), h = the flow depth (m), β = the correction of the momentum factor (–), S_0 = the slope of the river bed (–), and S_f = the frictional slope (–).

In the dynamic wave method, a complete momentum equation is used. The complete momentum equation and the continuity equation can only be solved by numerical methods. The momentum equation for the wave spreading model in Equation (5). The equation for non-uniform sediment transport in Equation (6):

$$\frac{\partial h}{\partial x} + S_f - S_0 = 0 \tag{5}$$

$$\frac{\partial (AC_{tk})}{\partial t} + \frac{\partial Q_{tk}}{\partial x} + \frac{1}{L_s}(Q_{tk} - Q_{t*k}) = q_{lk} \tag{6}$$

where: C_{tk} = sediment density for the size of k units (kg·m^{-3}), Q_{tk} = the rate of actual carried alluvia for the size of k units, L_s = the length of the distance that sediment is inconstantly carried (m), and q_{lk} = the side discharge or output sediments in the width unit (m) [Kamanbedast *et al.* 2013].

A model mesh was created in the CCHE2D program using previously conducted survey measurements; therefore, it accurately maps the terrain. It is also used to visualise the results of the analysis. Greater mesh and smaller mesh node distances provide a higher level of accuracy in the results but require a longer simulation time. Here, the mesh was designed to be 113 m long and 24–30 m wide (I = 150, J = 400, which gives 60,000 nodes). For modelling purposes, three variants of BBR were analysed as far as the river bed is concerned: the first variant assumed an erodible block ramp (variant 1); the second, a non-erodible BBR (variant 2); and rocky BBR – plain rock bed (variant 3). Depending on the type of variant, different degrees of roughness were determined. In variants 1 and 2, the roughness coefficient was n = 0.047, calculated using the Strickler formula [Yen 1991], assuming that the diameter (d_m) of the boulders along the BBR was an average of 1 m. In variant 3, the roughness coefficient was supposed to be n = 0.015, and this value was read from the hydraulic tables provided by Chow [1959]. Based on field measurements and grain size distribution, seven grading classes have been assumed, summarised in Table 2 and Figure 4, and further applied in numerical modelling.

Table 2. Grain size distribution and adopted seven grading classes using measurement data

Specification		Grading class						
		1	2	3	4	5	6	7
Diameter (m)		0.023	0.028	0.038	0.049	0.062	0.070	1.000
Percentage share of grain size in each class	area 1	7.5	8.5	24.0	27.5	19.5	13.0	0
	area 2	10.0	15.0	27.0	23.0	13.0	12.0	0
	area 3	16.0	12.0	20.0	27.0	16.0	9.0	0
	area 4	13.0	12.0	35.0	21.0	19.0	0	0
	area 5	0	0	0	0	0	0	100

Source: own study.

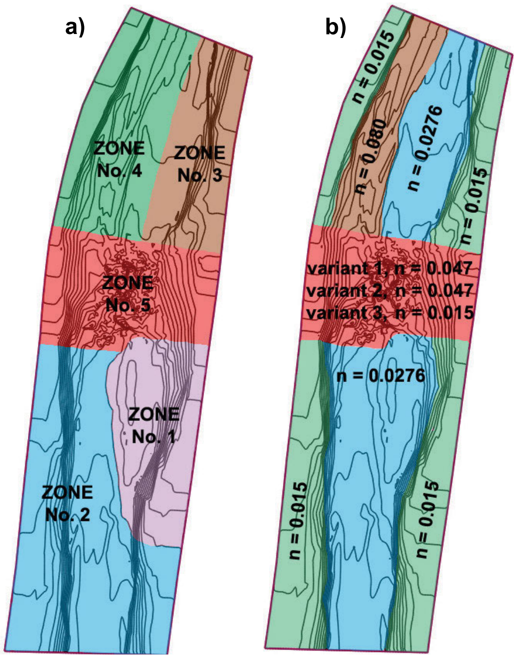


Fig. 4. River bed zones defined in the model: a) grain areas, b) roughness coefficients *n*; source: own study

RESULTS AND DISCUSSION

CLASSICAL APPROACH

When discussing sediment transport, one needs to know the difference between the competence and the capacity of a river. The competence is the maximum particle size of load a river is able to carry, whereas capacity is the total volume of material a river can transport. The Hjulström curve [Hjulström 1935] shows the relationship between river velocity and competence; it shows the velocities at which sediment will normally be eroded, transported, and deposited. The critical erosion velocity curve shows the minimum velocity needed for the river to erode (pick up) and transport material of different sizes (e.g., bed-load or suspension). A greater velocity is required to erode material compared to just transporting it. The mean settling velocity curve shows the velocities at which different-sized particles are deposited. In his field study, Helley [1969] found a very strong agreement with Hjulström's discoveries for large particles referring to coarse gravel.

Critical values of the parameters of disturbance of the stability of particles of the river bed material are also determined according to the Shields criterion (1936). The graph shows the relationship of $Q = f$ (Re*). Sediment transport can start in laminar and turbulent motion, with the lowest shear stress values in the transient motion. It is not possible to describe the Shields curve with a single mathematical relationship; therefore, several researchers described the curve with a series of formulas valid for selected ranges of Reynolds number (Re*) [Dąbkowski 1992; Hämmerling *et al.* 2014].

Thus, it was decided to use the classical and reasonable Hjulström and Shields concept [Graf 1984; Hjulström 1935; Shields 1936] to verify all the data obtained by numerical modelling. To compare the results, twenty-one different points were selected in the analysed sections (Fig. 5), which differ in terms of morphology and roughness [Buffington 1995]. The flow velocity (v), the change in river bed elevation (ΔH), and the d_{50} sediment diameter were then read from CCH2D at these points (Tab. 3).

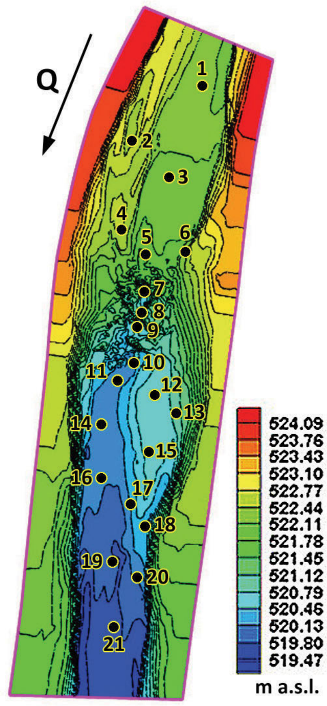


Fig. 5. Points of analysis created in the CCH2D model; source: own study

Table 3. Characteristics of flood wave transition for variant 1 based on numerical modelling

Point	Parameter							
	v (m·s^{-1})	ΔH	d_{10}	d_{25}	d_{50}	d_{75}	d_{90}	d_{mean}
		m						
1	3.53	–0.023	0.021	0.025	0.041	0.050	0.060	0.033
2	0.38	0.014	0.022	0.028	0.035	0.044	0.054	0.041
3	3.00	0.187	0.021	0.025	0.041	0.050	0.060	0.043
4	1.73	–0.106	0.022	0.028	0.035	0.044	0.054	0.043
5	2.86	0.148	0.022	0.028	0.035	0.044	0.054	0.044
6	2.87	–0.406	0.021	0.025	0.041	0.050	0.060	0.043

cont. Tab. 3

Point	Parameter							
	v (m·s^{-1})	ΔH	d_{10}	d_{25}	d_{50}	d_{75}	d_{90}	d_{mean}
		m						
7	2.72	0.347	–	–	–	–	–	0.053
8	2.54	0.024	–	–	–	–	–	0.0883
9	1.48	0.919	–	–	–	–	–	0.068
10	0.61	0.814	0.024	0.027	0.035	0.048	0.065	0.049
11	2.25	0.575	0.024	0.027	0.035	0.048	0.065	0.053
12	3.14	–0.157	0.026	0.032	0.040	0.053	0.065	0.046
13	3.32	0.065	0.026	0.032	0.040	0.053	0.065	0.045
14	2.15	0.012	0.024	0.027	0.035	0.048	0.065	0.047
15	3.75	–0.010	0.026	0.032	0.040	0.053	0.065	0.045
16	2.18	–0.072	0.024	0.027	0.035	0.048	0.065	0.044
17	2.31	0.312	0.026	0.032	0.040	0.053	0.065	0.046
18	2.60	–0.344	0.026	0.032	0.040	0.053	0.065	0.045
19	3.03	–0.096	0.024	0.027	0.035	0.048	0.065	0.045
20	2.61	0.259	0.024	0.027	0.035	0.048	0.065	0.046
21	2.97	0.095	0.024	0.027	0.035	0.048	0.065	0.044

Explanations: v = flow velocity, ΔH = change in river bed elevation, d_{10}, d_{25}, d_{50}, d_{75}, d_{90} = sediment diameters for the 10th, 25th, 50th, 75th, and 90th percentiles, respectively, d_{mean} = mean sediment diameter.
Source: own study.

2D MODELLING WITH CCHE2D

Firstly, the grain size characteristic diameters for the 10th, 25th, 50th, 75th, and 90th percentiles were determined for twenty-one selected points (Fig. 5). Based on the Hjulström and the Shields graph, the points were checked for erosion and transport, and sedimentation of the material for the three variants of the BBR was considered. Next, it was identified whether the results obtained were consistent with those obtained from numerical modelling. The compliance test was based on results obtained from the Hjulström and the Shields graph for results from numerical modelling, and based on field observations (survey data from before and after the flood of May 2014 – changes in river morphology are shown in Fig. 6). In cases where the river bed change (ΔH) after the simulation is negative, there is river bed erosion; otherwise, there is sedimentation. In this scenario, the results from CCHE2D were compared with those obtained

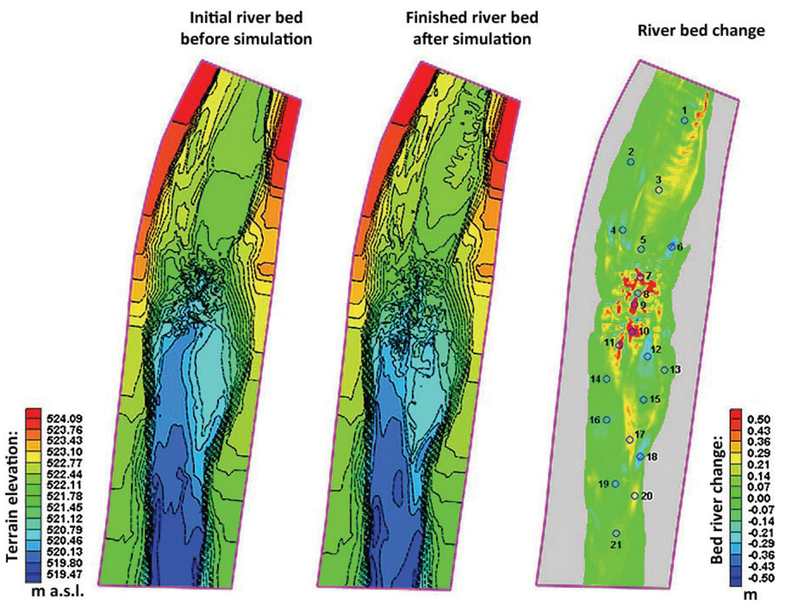


Fig. 6. Initial river bed, finished river bed after simulation and morphological changes as well as twenty-one analysed points marked for BBR variant 1 acc. to CCH2D model; the left scale presents altitude in metres above sea level; the right scale presents differences in altitude in metres; source: own study

from the Hjulström and the Shields graph. If at least three of the five analysed characteristic gravel diameters were the same, it was considered that the CCHE2D model is consistent with the Hjulström and the Shields graph. A similar analysis was conducted based on field observations (survey field data) in which changes in the river bed morphology of the stream bed were compared with the changes obtained from numerical simulation.

In the paper, the detailed results of the study are presented only for the first variant with the erodible sloping apron of the BBR (Tabs. 3, 4); the test procedure in the remaining two is identical. However, all the results are presented in Table 4 for the three variants of BBRs tested in our analysis. Based on the figure for river bed changes, erosion occurred at points 1, 4, 6, 8, 12, 15, 16, 18, and 19, while sedimentation occurred in the remaining points (Fig. 6).

Table 4. Consistency of numerical results with the Hjulström graph

Point	Parameter						Consistency of CCH2D model with Hjulström graph
	d_{10}	d_{25}	d_{50}	d_{75}	d_{90}	ΔH	
1	E	E	E	E	E	–	yes
2	S	S	S	S	S	+	yes
3	E	E	E	E	E	+	no
4	T	T	T	T	S	–	no
5	E	E	E	E	E	+	no
6	E	E	E	E	E	–	yes
7	–	–	–	–	–	+	–
8	–	–	–	–	–	+	–
9	–	–	–	–	–	+	–
10	S	S	S	S	S	+	yes
11	E	E	T	T	T	+	no
12	E	E	E	E	E	–	yes
13	E	E	E	E	E	+	no
14	E	E	T	T	T	+	no
15	E	E	E	E	E	–	yes
16	E	E	T	T	T	–	no
17	E	E	T	T	T	+	no
18	E	E	E	T	T	–	yes
19	E	E	E	E	E	–	yes
20	E	E	E	E	T	+	no
21	E	E	E	E	E	+	no

Explanations: E = erosion, T = transport, S = sedimentation: determination of the stream carving activity based on the Hjulström graph for the characteristic diameters d_{10}, d_{25}, d_{50}, d_{75} and d_{90} in the analysed points; d_{10}, d_{25}, d_{50}, d_{75} and d_{90} = as in Tab. 3, ΔH = change in bottom ("–" erosion, "+" sedimentation).
Source: own study.

Table 3 shows the results of numerical modelling during the flood wave transition for variant 1. The results include the flow velocity (v), between 0.38 and 3.75 m·s^{-1}, and the river bed level (ΔH) change, varying from –0.406 m to 0.919 m. In eight cases, erosion was observed (negative results), while in thirteen cases, sedimentation was observed (positive results) – Table 3.

The distribution of the grain size upstream from the BBR is: from 0.021 up to 0.022 m for diameter d_{10}; between 0.025 and 0.028 m for d_{25}; between 0.035 and 0.041 m for d_{50}; between 0.044 and 0.050 m for d_{75}; between 0.054 and 0.060 m for d_{90}; between 0.033 and 0.044 m for d_{mean}. Downstream from the BBR, the distribution of the grain size is as follows: between 0.021 and 0.026 m for diameter d_{10}; between 0.027 and 0.032 m for d_{25}; between 0.035 and 0.041 m for d_{50}; between 0.048 and 0.053 m for d_{75}; between 0.054 and 0.065 m for d_{90}; between 0.044 and 0.053 m for d_{mean}.

The Hjulström graph (Fig. 7) indicates whether erosion, transport, or sedimentation of the material occurred. Looking at this graph, it is possible to see the grain size fraction eroded under the flood condition, which caused the morphological changes of cross-sections of Poniczanka presented in Figure 8 that were measured in the field just after the examined flood. Having the results obtained from the Hjulström graph, it was then possible to compare them with numerical modelling results (Tab. 3). In eight cases, similar results were observed, while inconsistencies were found in ten cases. This yielded a 44% agreement between the CCHE2D model and Hjulström's classic graph. Based on this analysis, it could be stated that erosion occurred at points 1, 6, 12, and 15. For points 2 and 10, sedimentation was observed. However, sediment transport was observed in the remaining points.

Based on changes in the river morphology of the analysed cross-sections, a change in the river bed level could be observed (Fig. 8). One can notice five cross-sections upstream from the tested BBR and seven downstream from it. The cross-sections

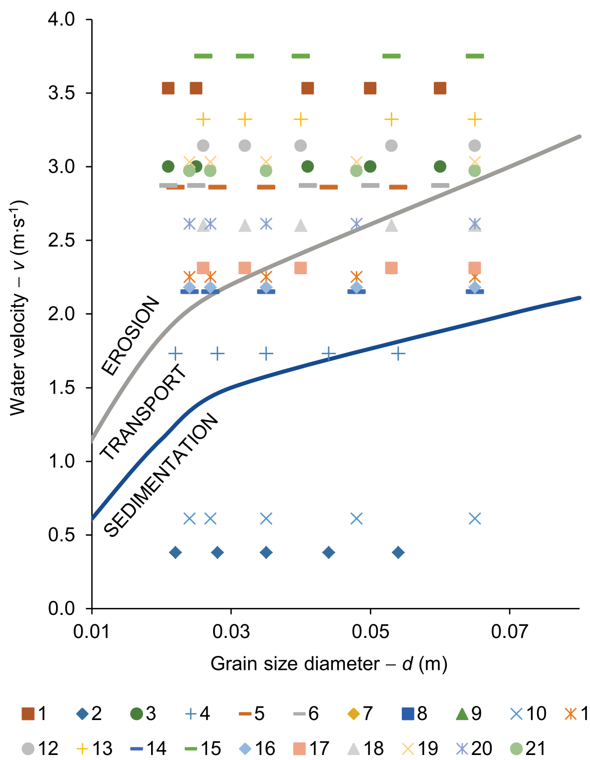


Fig. 7. Hjulström graph with the analysed points for the BBR with erodible river bed calculated in the CCHE2D model; source: own study

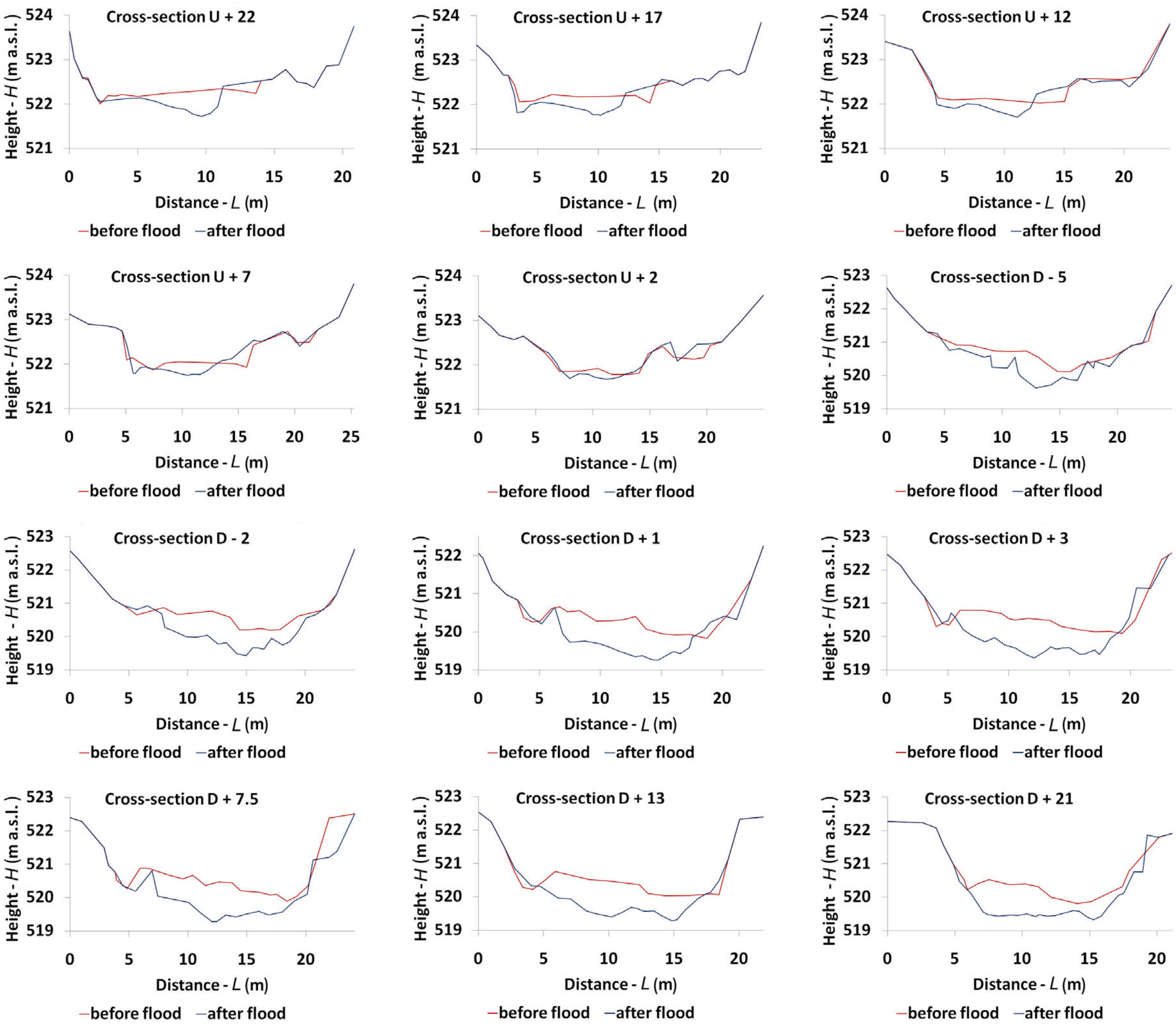


Fig. 8. Changes to the river bed before and after the May 2014 flood in selected cross sections; source: own study

were performed at distances of 22, 17, 12, 7, and 2 m upstream from the BBR and at distances of 1, 2, 3, 5, 7.5, 13, and 21 m downstream from it.

Erosion of the river bed of up to 0.5 m could be observed in all cross-sections upstream of the BBR. The largest incision can be seen in the cross-sections furthest upstream from the BBR, with a tendency to decrease the incision to 0.15 m in the cross-section closest to the BBR. While in all the analysed sections at the lower station downstream of the BBR, the river bed incision reaches 1 m.

Table 5 presents the analysis of the consistency of numerical modelling results with the Hjulström and the Shields graph in the context to field observations for three different variants. The first column compares the consistency of the CCHE2D model with the Hjulström graph for the erodible block ramp (variant 1), then for the non-erodible block ramp (variant 2) and third for the rocky plain river bed (variant 3). The highest consistency was noted for variant 1 (44%), while for variant 2 it was 39%, and it was the lowest for variant 3 (33%). Columns 5, 6, and 7 illustrate the CCHE2D model consistency with the Shields graph for individual variants. The highest consistency was achieved at 61% for variants 1, while 56% for variant 2 and 3.

1D MODELLING WITH HEC-RAS

Our available data set from Poniczanka stream was compiled and analysed for an improved understanding of the river system and in support of subsequent numerical modelling. The 1D HEC-RAS model requires the use of data of particular value, including river bathymetry, flow data, water levels, and sediment characteristics. These data were described in detail in this paper in different chapters. To look at sediment data in the Poniczanaka boulder ramp area, we first employed the HEC-RAS model, which was seen as suitable for performing this study.

In the HEC-RAS, boundary conditions are required to form initial water surface profiles at the extremes of the river system (upstream and downstream). The basic computational procedure of HEC-RAS for steady flow is based on the solution of the one-dimensional energy equation [USACE 2016a, b]. Energy losses are evaluated by friction and contraction/expansion. The momentum equation may be used when the water-surface profile rapidly varies. We decided to calculate changes in hydrodynamic parameters for the Poniczanka ramp based on the initial and boundary conditions which we observed in the field and could apply directly to the model.

Table 5. Analysis of the consistency of numerical modelling results in the CCHE2D model with Hjulström and Shields graph in the context of field observations

Section	Point	Consistency of the CCHE2D model with Hjulström graph for the			Consistency of the CCHE2D model with Shields curve for the		
		erodible BBR (variant 1)	non-erodible BBR (variant 2)	rocky BBR (variant 3)	erodible BBR (variant 1)	non-erodible BBR (variant 2)	rocky BBR (variant 3)
Upstream	1	yes	no	no	yes	no	no
	2	yes	yes	yes	yes	yes	yes
	3	no	no	no	no	no	no
	4	no	no	no	yes	yes	yes
	5	no	no	no	no	no	no
	6	yes	yes	yes	yes	no	no
Downstream	10	yes	yes	yes	yes	yes	yes
	11	no	no	no	no	yes	no
	12	yes	yes	yes	yes	yes	yes
	13	no	no	no	no	yes	no
	14	no	no	no	no	no	no
	15	yes	yes	no	no	yes	no
	16	no	no	no	yes	no	yes
	17	no	no	no	no	no	yes
	18	yes	yes	yes	no	no	yes
	19	yes	yes	yes	no	no	yes
	20	no	no	no	no	yes	no
	21	no	no	no	no	no	no
Consistency (%)		44	39	33	61	56	56

Source: own study.

One has to bear in mind that there is a lot of uncertainty in sediment modelling in the HEC-RAS due to uncertainty in the data for the bed change calculation and the empirical nature of applied functions, which are highly sensitive to physical variables [Brunner 2010]. The HEC-RAS model uses hydrodynamic simplifications for the mobile bed transport by implying a quasi-unsteady flow assumption rather than an unsteady flow, which would take a longer computation time. The quasi-unsteady flow technique applies a series of discrete steady flow profiles which remain constant for the given time intervals.

Various transport functions exist in the HEC-RAS model where a special module is installed to perform sediment transport calculations and a formula for the calculation could be chosen by the user. The formula is usually corresponding with characteristic of the river or the stream and the most common parameter for selecting a transport function is the grain size distribution from a grain size curve for the sediment. This is because the transport functions have been developed for a range of grain size applications. Such grain-size curves were done using sieve analysis method for Poniczanka stream in the research reach. In the HEC-RAS model, there are seven different transport functions to choose from a list, but for the purpose of this study, we have chosen Meyer-Peter and Müller [1948] equation (MPM). MPM equation is the most popular in Poland but also it is a formula which fits the best for Polish Carpathian alluvial mountain streams which cats through Carpathian flysch. Numerous studies have been performed in Polish Carpathian rivers [Bartnik 1992; Michalik 1990], and the MPM equation has been verified using radioisotope methods [Michalik 1990; Radecki-Pawlik 2014] and the values obtained from the MPM equation were in line with field study observations.

To run HEC-RAS for the Poniczanka BBR, we ran the modelling for the flood with a discharge Q = 33.5 $m^3 \cdot s^{-1}$. Under this discharge entrainment and transport of sediment particles for Poniczanka stream could be noticed since threshold shear stresses for sediment motion are high enough for sediment movement. Based on Table 6, it can also be seen that the consistency of the HEC-RAS model with the Hjulström and the Shields plot. The consistency of numerical modelling results with the Hjulström and the Shields graph and in the context of field observations was observed at 68 and 79% appropriately.

Below, we present the graphs showing the modelling results. In Figure 9, we present changes to the river bed taken from HEC-RAS and CCHE2D for comparison of the obtained results.

Figure 10 presents the results of the comparison of the Hjulström graph with the results obtained with HEC-RAS, as this was due to it being prepared similarly for CCHE2D. Finally, Figure 11 presents the results obtained with the 1D model and the 2D model in the Shields classical graph.

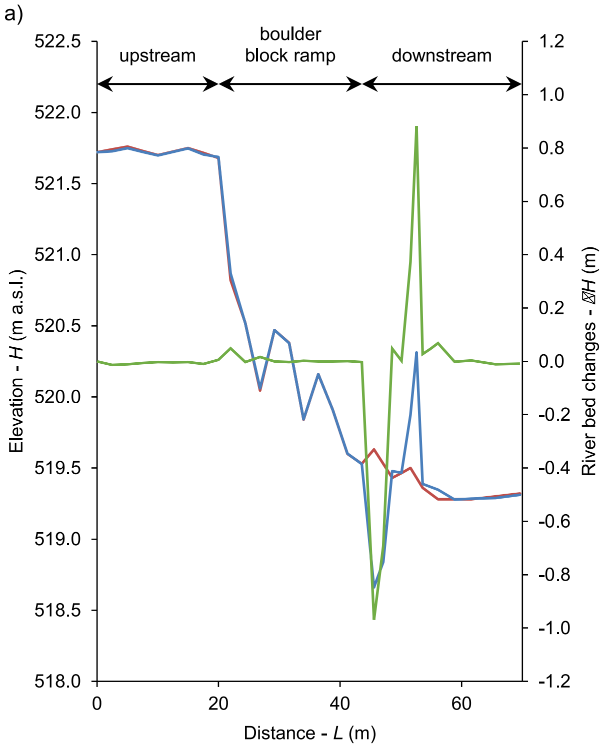
As may be seen from the results of simulation with HEC-RAS, the consistency of the model output data with the Hjulström graph is very high at the level of 68% and additionally 79% with

Table 6. Analysis of the consistency of numerical modelling results in the HEC-RAS model with Hjulström and Shields graph in the context of field observations

Section	Point	Consistency of the HEC-RAS model with	
		Hjulström graph	Shields curve
Upstream	1	yes	yes
	2	no	yes
	3	no	yes
	4	yes	yes
	5	yes	yes
	6	yes	yes
Down-stream	10	yes	yes
	11	yes	yes
	12	no	no
	13	no	no
	14	no	no
	15	no	no
	16	yes	yes
	17	yes	yes
	18	yes	yes
	19	yes	yes
	20	yes	yes
	21	yes	yes
	22	yes	yes
	23	yes	yes
Consistency (%)		68	79

Source: own study.

a)



b)

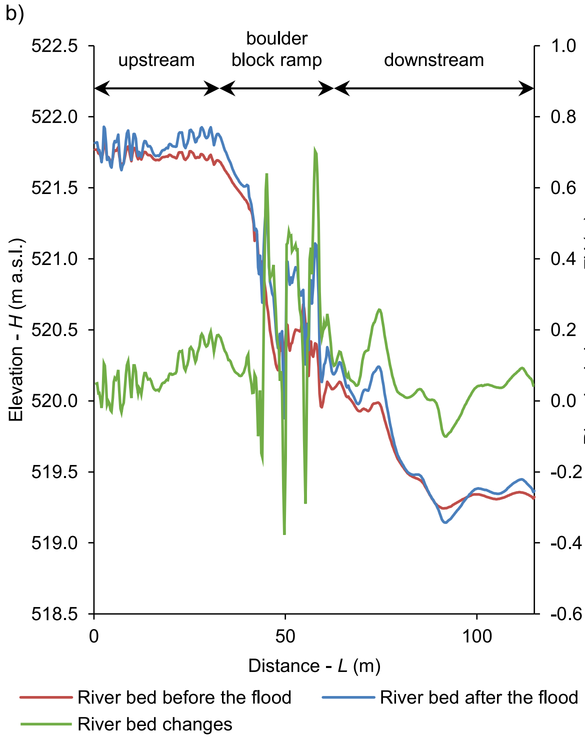


Fig. 9. Graphic visualisation of results of changes to the river bed before and after flood on the Poniczanka BBR and within its vicinity for: a) the HEC-RAS model, b) the CCHE2D model; source: own study

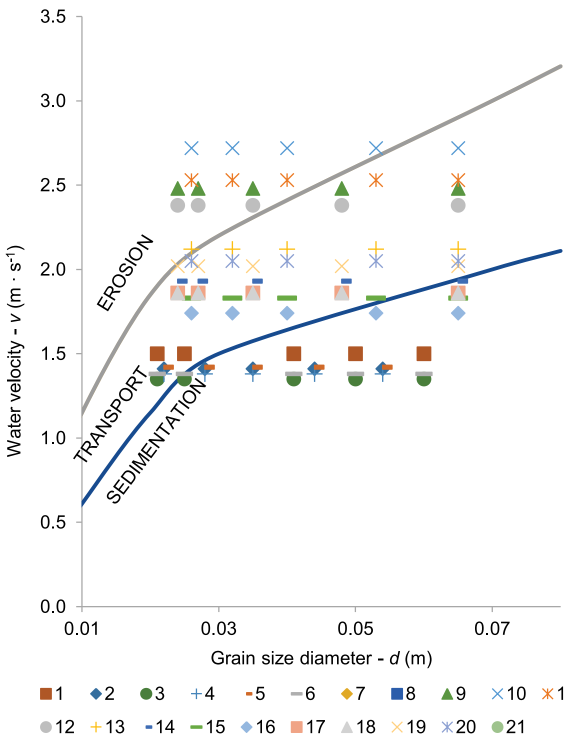


Fig. 10. Hjulström graph with the analysed points for the BBR calculated in the HEC-RAS model; source: own study

the Shields curve. Simple hydraulics – often criticised by many, but in fact, is not so simple – used in the 1D HEC-RAS model in addition to the MPM sediment transport equation. In this case is the most appropriate choice for the Polish Carpathians [MICHALIK 1990; RADECKI-PAWLIK 2014] gives a good approximation of the

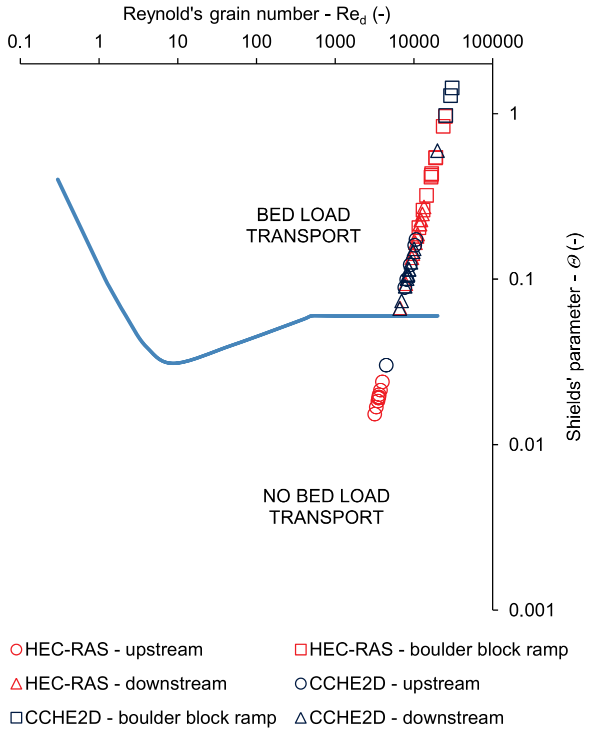


Fig. 11. Shields graphs with the analysed points for the BBR and river channel calculated in the 1D HEC-RAS and the 2D CCHE2D model; source: own study

results of erosion transport and sedimentation in comparison to the classical Hjulström concept. This is contrary to previously presented 2D CCHE2D model results which could only yield a maximum of 56% consistency. This raises the question of why this occurs. Our field observations, which have been performed over the last 30 years on streams in the Carpathians, show significant incision of streams and rivers due to there being a lack of sediment which might be transported [Hajdukiewicz *et al.* 2018; Wyżga *et al.* 2016; 2018; Zawiejska *et al.* 2015]. This is interesting, especially in small catchments where sediment is mined from river channels (illegally as well as legally) [Mikuś *et al.* 2013; Radecki-Pawlik *et al.* 2015; Wyżga *et al.* 2016]. It appears as though in such conditions, the simple prediction of erosion, transport, and deposition (in our case, the Hjulström concept) works better than any sophisticated modelling. This is also confirmed by the works of Michalik [1990] in which many methods of sediment transport calculation for flysch in the gravel beds of Polish Carpathian rivers were tested in a radioisotope experiment for the Raba and Dunajec rivers, where the well know MPM sediment equation is the most effective. Returning to our modelling, 1D HEC-RAS presents an opportunity to apply MPM and at the same time, does not require any mesh to be constructed where many errors might occur when working with 2D models. Many simplifications in HEC-RAS are in line with the clear Hjulström concept and Shields postulates. Furthermore, any 2D and especially 3D modelling demands a huge effort to stabilise a model due to boundary conditions and verifications performed on field data. In 1D HEC-RAS, we basically have roughness and a slope responsible for obtained results [Czech *et al.* 2016; Kałuża *et al.* 2018; Kundzewicz *et al.* 2017]. These two factors are very sensitive but also very easy to verify. For 2D models, we are not always sure if we have an appropriate mesh size or a long enough time for calculations. It is very often not a fault of the model but rather a limitation of computer power since we cannot wait for the results for days or even, in the case of 3D modelling, for weeks [Plesiński *et al.* 2018b; 2022]. Thus, the main point of our research presented here is that for engineering activities such as designing simple hydraulic structures and/or predicting some river bed changes, it is worth using classical approaches. The classical approach in our case pointed here in Hjulström graph is helpful because we are saving a lot of energy, time, and money. If one has time and has to follow such requirements, in our opinion that it is appropriate to start from a 1D model and then continue with 2D or 3D; this is mostly dependent on time and the skills of the designer because one has to bear in mind that learning 2D or 3D models often takes a considerable amount of time [Szymkiewicz 2000; 2012]. Thus, for river managers and people who design low-head hydraulic structures or deal with riverbank erosion, we would definitely recommend simple solutions, which in fact, are not so simple what they seem to look like, because they need experience and knowledge of rivers, especially in the regional context [Kałuża *et al.* 2018; Plesiński *et al.* 2018b; 2022; Radecki-Pawlik *et al.* 2015; Wyżga *et al.* 2016; 2018].

CONCLUSIONS

The above-presented comparison between the 1D HEC-RAS and 2D CCHE2D numerical models and the classical Hjulström's and Shields' methods results concerning changes to the morphology of a river channel and along a sloping apron of a boulder block ramp (BBR) hydraulic structure leads to the following conclusions.

1. The 2D CCH2D numerical analyses enabled the identification of the flow velocity for individual variants. For variants 1 (erodible) and 2 (non-erodible), the same values were recorded; for variant 3 (rocky), the obtained values were significantly higher. This indicates a change in the type of river bed and a decrease in the coefficient of roughness n, resulting in a faster flow of water.
2. In the case of the BBR, analysed cross-sections of the stream channel were surveyed in the field before and after the flood in May 2014. The main observation was an erosion of the river bed following the flood. The largest incision values of the river bed were found furthest upstream from the BBR, so the dissipation of kinetic energy on the apron slop of the BBR was insufficient, and therefore the downstream bed was scoured. Below the structure, there is no additional protection against scouring the river bed (eg. energy dissipation basin).
3. The results of the CCHE2D model show little agreement with the results of sediment transport obtained in the Hjulström's and Shields' diagrams. Despite the correct calibration of the tested cross-sections, small deviations were obtained, amounting to 44, 39 and 33% for Hjulström's diagram and amounting to 61, 56 and 56% for Shields' diagram. This may suggest a low efficiency of simulated bed load transport by the CCHE2D model for BBR. Probably, the CCHE2D model should not be used to simulate bed-load transport in the BBR region (and perhaps other hydraulic structures).
4. The 1D HEC-RAS model gives a good approximation of erosion, transport, and sedimentation values compared with the Hjulström concept results, which gave a very high consistency

level of 68%. The HEC-RAS modelling results are at the highest level of consistency, 79% with Shields curve results.
5. Predicting the phenomena of erosion, transport, and sedimentation of bed material and calculating bed-load transport rates in a gravel-bed channel using a single numerical model, gives results that may be inconsistent with field observations and with predictions obtained employing the classic Hjulström approach based on extensive empirical evidence. This is reflected in all analysed variants. The lowest consistency when comparing the CCHE2D model with both the Hjulström and the field observations was for variant 3 (rocky). Furthermore, 1D HEC-RAS modelling results are consistent with the Hjulström approach. This indicates that both models should be used for designing purposes when possible. It is also recommended to use the classic approach based on the Hjulström graph for forecasting river bed changes and, if possible, parallel field observations for confirmation.
6. The final conclusion that one might draw is that it is worth comparing any modelling results with classic tests and field observations to obtain the best results for designing BBRs and other similar hydraulic structures. This definitely reduced or even prevented errors in designing hydraulic structures that could cause structural failure and stopped errors in designing. However, personal experience of the designer and modelling hydraulics structures are keys to success with regard to avoiding structural failures and improving structural safety and understanding the regional conditions concerning hydrology, geology, and geomorphology.

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