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Numerical 2D Simulation of Morphological Phenomena of a Block Ramp in Poniczanka stream: Polish Carpathians

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Abstract: *The description of flow in streams is a very complex problem. Physical analyses of this phenomenon provide a quantitative description of water flow, allowing the creation of mathematical models that have an important practical meaning. The rapid development of numerical software programs has improved their practical implementations; therefore, the results of analyses and solutions of flow problems in both open channels and pipes obtained through numerical modelling could be applied in practical solutions. Numerical models are often practical in studies covering a wide range of analysed parameters. However, it must be understood that the similarity between a real river and its model could only be partially verified. The main purpose of this paper is to investigate the effect of the selected boulder block ramp hydraulic structure on Poniczanka stream on sediment transport using the CCHE2D numerical model, assuming several situations, depending on the type of riverbed (erodible, non-erodible, rocky) and the kind of rock blocks used for hydraulic structure construction. The obtained results were compared with the Hjulström graph, which is a classic approach for the identification of fluvial processes in river channels (erosion, sedimentation, transport). In addition to these two methods, field observations were carried out which included the determination of horizontal and vertical changes to the riverbed morphology of the examined section river reach.*

Keywords: *Boulder blocks ramps, low head hydraulic structures, field measurements, hydraulics, riverbed morphology.*

1. Introduction – Research Objective of the Paper

Analysis and description of the water flow in the stream channel, especially in places where one would deal with hydraulic structures, is a very complex problem needing not only theoretical but also a lot of 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 meaning. The rapid development of numerical software programs has improved their practical implementation; therefore, the results obtained through them can be applied in practical solutions (Szymkiewicz, 2000, 2012). However, one has to be very careful and experienced when using models. Bruk (1988) states that the similarity between river and its model could only be partially verified. In that sense only some results of modelling might be used for design recommendations (also Plesiński et al., 2015). Ultimately, an engineer is the person 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 was performed, using the CCHE2D model, of a boulder block ramp (BBR) which belongs to the group of low head hydraulic structures (Bung and Pagliara, 2013; Pagliara et al., 2017; Oertel 2013; Pagliara and Palermo 2013, Radecki-Pawlik, 2013). The examined structure is situated in Poniczanka stream in the Polish Carpathians. Numerical modelling of a stream channel within the area of this BBR hydraulic structure's influence was also performed. The modelling analyses were carried out for different variants depending on the type of sloping apron of the BBR (erodible, non-erodible, and rocky). The main purpose of these simulations was to demonstrate the effect of the analysed BBR on bed load transport and on morphology changes of the riverbed. In order to confirm the reliability of the model used, the obtained results were compared with the Hjulström graph (Hjulström, 1935), which is a classic approach to the identification of fluvial processes in river channels (erosion, sedimentation, transport). To do such an analysis, field data were collected as well field measurements were completed. Finally, based on the obtained numerical modelling results and the classical Hjulström approach, a comparative analysis was performed to evaluate the consistence of the CCHE2D model with Hjulström graph.

2. Field Study Area

Poniczanka stream is a stream located in the Polish Carpathians. Poniczanka is a tributary of the Raba River which is a tributary of the Vistula. Poniczanka catchment is located on the north-western slope of the Gorce Mountains and covers an area of approximately 33.1 km^2. The sources of the river are at an altitude of 986 m above sea, whereas the lowest point of the catchment is at 485 m. The examined boulder block ramp hydraulic structure (Fig. 1) is located on Poniczanka stream, 3.5 km upstream from the mouth of the Raba River. This BBR belongs to the group of cascade ramps of which 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 (Fig. 1) (measured as axis "b" in terms of sediment measurement requirements). Upstream and downstream of the BBR, there is a one thread channel formed with non-engineered river banks.

Figure 1. Boulder block ramp on Poniczanka stream: upstream view and a focus view of a ramp

3. Methodology

The first part of the methodology concerns field measurements. The measurements were carried out to deliver data for precise modelling with CCH2D as well as for using them with Hjulström graph. Detailed survey measurements were carried out using the Topcon GTS-226 level and the Topcon Total Station GTS-105N along a 100 m river reach including the BBR, which were very dense at approximately 50 meters upstream and 40 meters downstream from the block ramp (Figs. 2 and 3). Measurements were performed before and just after a flood which occurred in May 2014 Q = 33.5 m^{3}s^{-1} (for a minimum annual flow for this stream Q = 0.01 m^{3}s^{-1}, annual average flow Q = 0.56 m^{3}s^{-1} and maximum annual flow Q = 38.10 m^{3}s^{-1} for the Rabka gauge station on Poniczanka stream for the rating curve relating to the previous 20 years) to show changes in the morphology of the bed after the flood. Measurement points were concentrated across the stream section with the boulder block ramp hydraulic structure to obtain its detailed geometric shape (Figs. 2 and 3).

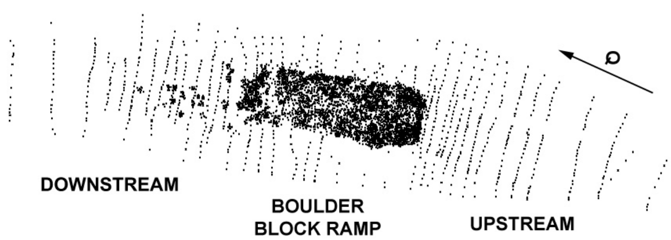

Figure 2. Survey measurement points along the research reach and BBR

Next, coarse and fine sediment were sampled. Determining the grain size of coarse gravel material was performed by means of the Wolman method (Wolman 1954) which involved measuring the '*b*' axis of 400 particles along a transect (Fig. 3). For fine sediment, sieve and aerodynamic analysis was done.

Both the survey and the sediment sampling were performed before and after the May 2014 flood. The medium value of the particle size distribution d_{mean} of the bed load, which is the value of the particle diameter at 50% in the cumulative distribution, was calculated on the basis of the 20th, 50th, and 80th percentile from (Folk and Ward, 1957; Helley, 1969):

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

By obtaining field results, it was possible to carry on numerical analyses. This was performed using the CCHE2D program; the algorithm of which is based on the finite element method (Jia, 2009; Wu, 2001; Wu and Wang, 2005) and the finite volume method (Wu, 2004) for the Q = 33.5 m^3s^{-1} (the same value as that which occurred during the May 2014 flood).

The equations which are used in the CCHE2D software are: Eq. (1) – the continuity equation and Eq. (2) – the momentum equation.

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

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

Figure 3. Survey along Poniczanka: survey of the ramp and Wolman method application

In these equations, x and t represents the place and time axles. A is the flow area, Q is the flow discharge, h is the flow depth, S_0 is the slope of the riverbed, b is the correction of the momentum factor, g is the gravitational acceleration, q is the unit discharge, and S_f represents the frictional slope. In the dynamic wave method, complete momentum equation is used. The complete momentum equation together with the continuity equation can only be solved by numerical methods. The momentum equation for the wave spreading model is Eq. (3). The equation for non-uniform sediment transport is Eq. (4).

$$\frac{\partial h}{\partial x} + S_f - S_0 = 0 \tag{3}$$

$$\frac{\partial (AC_{tk})}{\partial t} + \frac{\partial Q_{tk}}{\partial x} + \frac{1}{L_s}\left(Q_{tk} - Q_{t*k}\right) = q_{lk} \tag{4}$$

Where C_{tk} is sediment density for the size of k units, Q_{tk} is the rate of actual carried alluvia for the size of k units, Q_{t*k} is the capacity for carrying sediment, L_s is the length of the distance that sediment is carried inconstantly, and q_{lk} is the side discharge or output sediments in the width unit (Kamanbedast et al., 2013).

A model mesh was created in the CCHE2D program using previously conducted survey measurements; therefore, it is a faithful mapping of the terrain. It is also used to visualise the results of the analysis. Greater mesh accuracy and smaller mesh nodes distance give 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 have been analysed as far as the riverbed 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 the variants, different degrees of roughness was 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 BBR was an average of 1 m. In variant 3, the roughness coefficient was assumed to be n = 0.015, and this value was read from the hydraulic tables given by Chow (1959). Based on field measurements and grain size distribution, seven grading classes are assumed, which are summarised in Table 1 and are later used in numerical modelling – these are presented in Fig. 4.

Table 1. Margins to use in this paper

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
Area 1	7.5%	8.5%	24%	27.5%	19.5%	13%	0%
Area 2	10%	15%	27%	23%	13%	12%	0%
Area 3	16%	12%	20%	27%	16%	9%	0%
Area 4	13%	12%	35%	21%	19%	0%	0%
Area 5	0%	0%	0%	0%	0%	0%	100%

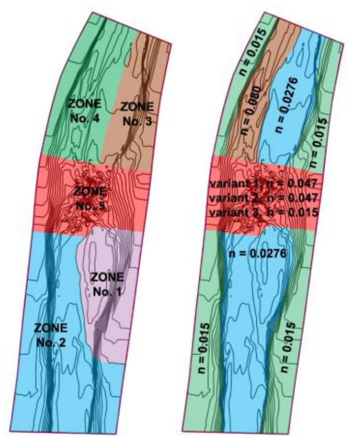

Figure 4. Grain areas (left side) and roughness coefficients "n" (right side) defined in the model

4. Results and Discussion

In this part of the paper, a comparison of the data obtained from numerical modelling using the CCH2D model with the classic Hjulström graph (Hjulström, 1935) is presented. When discussing sediment transport, you need to know the difference between the competence and capacity of a river. The competence is the maximum size of load a river is able to carry whereas capacity is the total volume of material a river can transport. The competence of a river is the maximum particle size that a river can transport at a particular point. The Hjulström curve shows the relationship between river velocity and competence; it shows the velocities at which sediment will normally be eroded, transported, or 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., as bedload or in 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. Helley (1969) found a very strong agreement with Hjulström discoveries for large particles in his field study referring to coarse gravel. Thus, it was decided to use the classical and reasonable Hjulström concept (Graf, 1984) to verify all the data obtained by modelling. To compare the results, twenty-one points were selected at different points of the analysed section (Fig. 5), which differ in terms of morphology and roughness (Buffington, 1995). The flow velocity (v), the change in riverbed level (ΔH) and the d_{50} sediment diameter were then read from CCH2D at these points (Table 2).

Firstly, for twenty-one selected points, the grain size characteristic diameters for 10, 25, 50, 75, 90 percentiles were determined. Based on the Hjulström graph, the points were checked for erosion, transport, or sedimentation of the material for the 3 variants of the BBR were considered. Next, it was observed whether the results obtained were consistent with the results obtained from numerical modelling. The compliance test was based on the results obtained from the Hjulström graph, results from numerical modelling, and on the basis of field observations (survey data done before and after the flood of May 2014 – changes of river morphology are shown in Fig. 6). In cases where the riverbed change (ΔH) after the simulation is negative, there is riverbed erosion. Otherwise, there is sedimentation. With this assumption, the results from CCH2D were compared with the results obtained from the Hjulström 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 graph. A similar analysis was conducted based on field observations (survey field data), where changes in the riverbed 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 (Tables 2 and 3), as the test procedure in the remaining two is identical. However, later in Table 4, all the results are presented for the three variants of BBRs tested in our analysis. On the basis of the figure of riverbed changes, erosion occurred at points 1, 4, 6, 8, 12, 15, 16, 18, 19, while sedimentation occurred in the remaining points (Fig. 6).

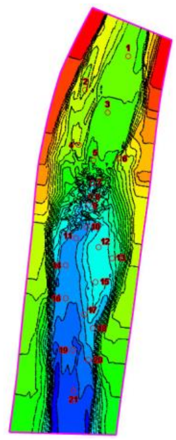

Figure 5. Graph created in the CCH2D model with marked analysis points

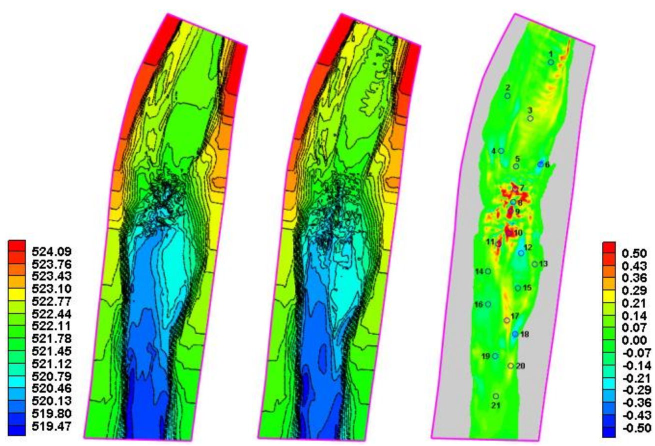

Figure 6. Graphs created in CCH2D model with initial riverbed, riverbed after simulation and morphological changes as well as twenty–one analysed points marked for BBR variant 1. The left scale presents altitude in meters above sea level; the right scale presents differences in altitude in meters.

Table 4 shows the results of numerical modelling during the flood wave transition for variant 1. The results include the flow velocity (v), which is between which is between 0.38 $m/s^{-1} < v <$ 3.75 m/s^{-1} and the change of the riverbed level (ΔH), from 0.406 m to 0.919 m. In eight cases, we noticed erosion was noticed (negative results), while in thirteen cases, sedimentation was noticed (positive results) (Table 3).

The distribution of the grain size upstream from the BBR for diameter d_{10} is from 0.021 m up to 0.022 m; for $d_{25,}$ between 0.025 m and 0.028 m; for $d_{50,}$ between 0.035 m and 0.041 m; for $d_{75,}$ between 0.044 m and 0.060 m; for $d_{90,}$ between 0.054 m and 0.060 m, and the d_{mean} is between 0.033 m and 0.0444 m. For downstream from the BBR, the distribution of the grain size is as follows: for diameter $d_{10,}$ it is between 0.024 m and 0.022 m; for $d_{25,}$ between 0.027 m and 0.032 m; for $d_{50,}$ between 0.035 m and 0.044 m; for $d_{75,}$ between 0.048 m and 0.053 m; for $d_{90,}$ between 0.054 and 0.065 m, and, finally, the d_{mean} is between 0.044 m and 0.053 m.

Table 2. Results of numerical modelling during the flood wave transition for variant 1 – symbol description in the text

Point	***V*** ms^{-1}	***ΔH*** m	***d*$_{10}$** m	***d*$_{25}$** m	***d*$_{50}$** m	***d*$_{75}$** m	***d*$_{90}$** m	***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	0.05	0.060	0.043
7	2.72	0.347	–	–	–	–	–	0.053
8	2.54	0.024	–	–	–	–	–	0.883
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	–0.01	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	2.6	–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

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

Based on changes in the river morphology of the analysed cross sections, a change riverbed 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 were performed at distances of 22, 17, 12, 7, 2 meters upstream from the BBR and at distances of 1, 2, 3, 5, 7.5, 13, 21 meters downstream from it.

Table 3. Consistence of numerical results with the Hjulström graph

Point	d_{10}	d_{25}	d_{50}	d_{75}	d_{90}	ΔH	Consistence of CCH2D model with Hjulström graph
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

Where:
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; ΔH – change in bottom (– erosion, + sedimentation)

Now it could be observed that erosion of the riverbed is up to 0.5 m in all cross sections upstream of the BBR. The largest incision can be seen in 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 riverbed incision reaches 1 m.

Table 4 presents the analysis of the consistence of numerical modelling results with the Hjulström graph and field observations for three different variants. The first column compares the consistence of the CCHE2D model with the Hjulström graph for the erodible block ramp (variant 1), then for a non-erodible block ramp (variant 2) and the rocky plain riverbed (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 4, 5, and 6 illustrate the CCHE2D model consistence with field observations for individual variants. The highest consistency was achieved at 44% for variant 1 and 2, while it was 39% for variant 3. Based on Table 6, it can also be seen that the consistence of the CCHE2D model with the Hjulström plot and field observations was observed for only five sites (1, 2, 6, 12, 18, and 19). For eight points, there was no consistency in any analyses (item 3, 4, 5, 11, 13, 17, 20, 21).

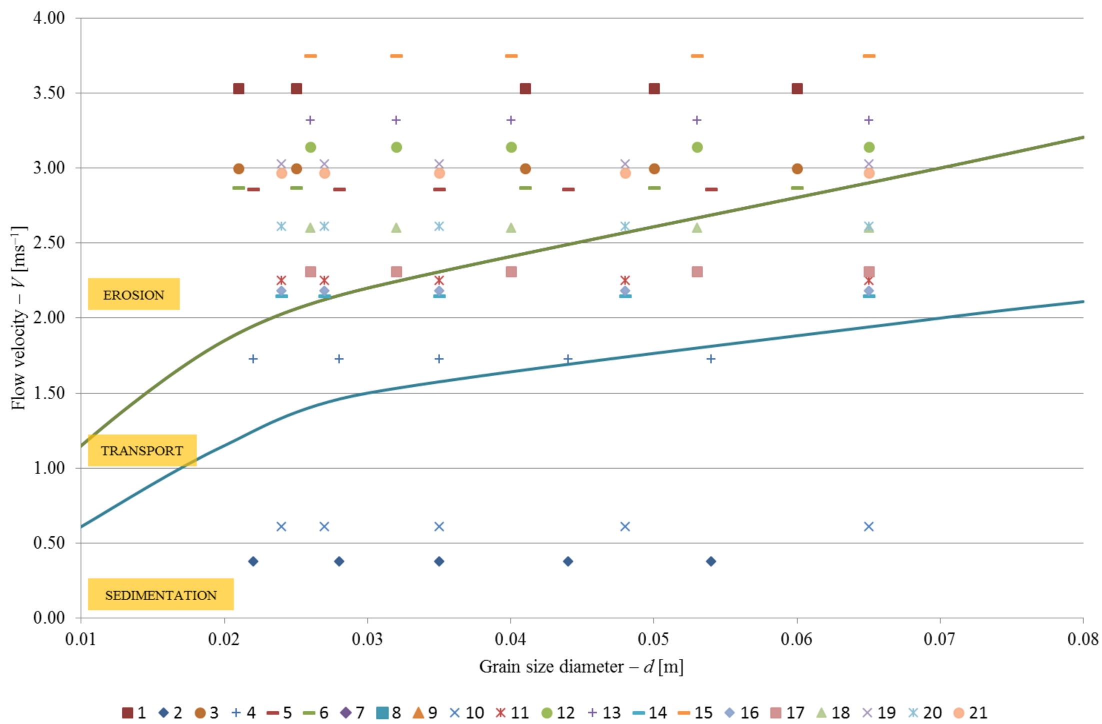

Figure 7. Hjulström graph with the analysed points for the BBR with erodible riverbed

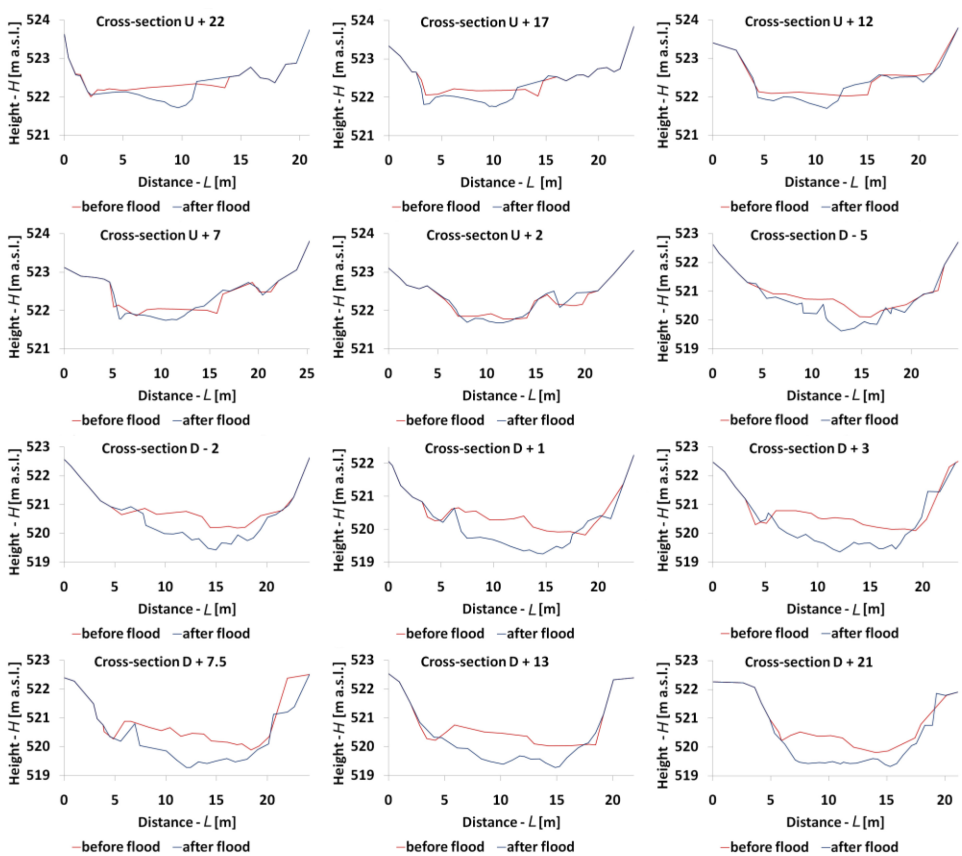

Figure 8. Changes of the riverbed before and after the May 2014 flood in selected cross sections

Table 4. Analysis of the consistence of numerical modelling results with Hjulström graph and field observations

Point	Consistence of the CCHE2D model with Hjulström graph for the erodible BBR (variant 1)	Consistence of the CCHE2D model with Hjulström graph for the non-erodible BBR (variant 2)	Consistence of the CCHE2D model with Hjulström graph for the rocky BBR (variant 3)	Consistence of the CCHE2D model with field observations for the erodible BBR (variant 1)	Consistence of the CCHE2D model with field observations for the non-erodible BBR (variant 2)	Consistence of the CCHE2D model with field observations for the rocky BBR (variant 3)
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	NO	NO	NO
5	NO	NO	NO	NO	NO	NO
6	YES	YES	YES	YES	YES	YES
7	–	–	–	–	–	–
8	–	–	–	–	–	–
9	–	–	–	–	–	–
10	YES	YES	YES	NO	NO	NO
11	NO	NO	NO	NO	NO	NO
12	YES	YES	YES	YES	YES	YES
13	NO	NO	NO	NO	NO	NO
14	NO	NO	NO	NO	YES	YES
15	YES	YES	NO	YES	YES	NO
16	NO	NO	NO	YES	YES	YES
17	NO	NO	NO	NO	NO	NO
18	YES	YES	YES	YES	YES	YES
19	YES	YES	YES	YES	YES	YES
20	NO	NO	NO	NO	NO	NO
21	NO	NO	NO	NO	NO	NO
Consistency	**44%**	**39%**	**33%**	**44%**	**44%**	**39%**

5. Conclusions

The above presented comparison between CCHE2D numerical model and classical Hjulström method results, which was done in term of the changes in 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 CCHE2D numerical model was used to calculate erosion, transport, and sedimentation phenomena in three variants of BBRs (boulder block ramps): erodible, non-erodible, and rocky. The obtained results showed that based only the obtained riverbed level change (ΔH), it is not possible to distinguish the kind of phenomena.
2. Numerical analyses allowed determining flow velocity for individual variants. For variants 1 (erodible) and 2 (non-erodible) the same values were recorded, while for variant 3 (rocky) the values obtained were much

higher. This indicates a change in the type of riverbed, and a decrease in the coefficient of roughness 'n' which results in a faster flow of water.

3. The obtained particle size distribution results after numerical modelling, irrespective of the tested variant of the riverbed, indicate that the larger grain diameters are in the lower cross section – this may be related to the reduction of the flow velocity and erosion of coarse fractions from the sloping apron of BBR.
4. The CCHE2D model results are not consistent with the results of the sediment transport obtained with the Hjulström graph. Despite correct calibration of the tested cross-sections, slight variances were achieved (variant 1 is 44%, 2 is 39% and 3 is 33%). This may imply a low efficiency of the simulated transport of bed load by the CCHE2D model for BBR. Similar studies conducted by Plesiński et al. (2015) on Porebianka stream also found that the effectiveness of the simulation of morphological changes within the region of BBR was low.
5. Cross sections of the stream channel were surveyed in the field before and after the flood in May 2014. Mainly, erosion of the riverbed after flooding can be observed. The largest values of incision of the riverbed were found furthest upstream from the BBR, which indicates the efficiency of the construction of such structures.
6. Granulometry measurements allow the observation of smaller grain sizes for the main stream, downstream of the BBR. This confirms the results of the numerical calculations and suggests a reduction in flow velocity upstream of the BBR. By comparing the results of the granulation of the riverbed material before and after flood, it is possible to observe a coarsening effect in the individual points, which proves the beneficial effect of the BBR
7. Predicting the phenomena of erosion, transport, and sedimentation of bed material and calculating bed-load transport rates in a gravel-bed channel by means of a single numerical model, especially a 2-dimensional model such as CCHE2D, gives results that may be inconsistent with field observations and with predictions obtained by means of the classical Hjulström approach based on extensive empirical evidence. This is reflected in all analysed variants. The least consistency when comparing the CCHE2D model with both the Hjulström and the field observations was for variant 3 (rocky). Thus, it is concluded that the model used does not work for all variants, especially variant 3; therefore, it is recommended to use the classical approach based on the Hjulström graph for forecasting riverbed changes and, if possible, parallel field observations for the purposes of confirmation.
8. One general conclusion which one might draw is that it is worth comparing any modelling results with classic tests and field observations in order to obtain the best results for designing BBRs and other similar hydraulic structures. It definitely reduce or even stop errors in designing that could cause structure failure as well as stop against designing features which are not in line with hydraulic structures.

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