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USAGE OF AN EMPIRICAL EQUATION FOR DETERMINATION OF MEAN SEDIMENT DIAMETER IN BEDS OF SMALL MOUNTAIN RIVERS

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Abstract

Knowledge of properties of materials deposited in beds of small reservoirs is important, as it can be used for a range of analytic works, concerning river rehabilitation and river management and other similar undertakings. Usually the one property – the d_{50} value can be obtained using in-situ measurements using sieves but in most cases of preliminary, large scale research may not be feasible. In this paper the Osuch empirical formula for determination of standard sediment grain sizes of d_{50} is presented. Besides the original formula an improved method of assessing of the slope value for that formula is proposed, which may greatly improve the usefulness of the original, unmodified method. The calculation results are then compared with the in-situ measurements done on many samples taken from the Trzebuńka dam reservoir. The dam was recently partially removed and partially rebuilt, so there was an unique and easy access to wide strata of different layers of sediments, accumulated across many years of dam operation in the exposed bed of partially emptied reservoir. Additionally, the Ratomski formula for riverbed slope determination near dams was used as a reference. The mentioned methods taken together can be used for preliminary analysis before significant works are to be done. The results are quite encouraging and can be a starting point for further method refinement.

Keywords: mean sediment diameter, empirical formula, check dam

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INTRODUCTION

Transformation of hydrological and geomorphological conditions of a river channel has been investigated by many researchers. The former process seem to be understood much better than the latter – see (Magilligan and Nislow 2005) or many similar works, but some papers can be found, for example (Marren *et al.* 2014). Especially interesting is the paper (Brandt 2000), but in any case, it is difficult to find a formula or a method useful for actual river engineering practice.

The expected value of mean grain particle diameter is an important parameter for many studies concerning various aspects of river restoration and other works, including flood protection for mountain rivers. The ability to get that value, even without much precision, can greatly simplify many preliminary studies, although any further steps must include detailed in-situ measurements, including sieve analysis. However, if an easy-to-do method could be proposed, not requiring too much of additional parameters, it would be a powerful engineering analytic tool, even if of limited or preliminary use.

One of the quite often used formulas is the Osuch empirical equation (Osuch 1964), formulated in the 1964 for the Polish Carpatian Mountain rivers, like Soła, Raba, Skawa, Dunajec and mountain streams like Poniczanka, Trzebuńka, Stradomka. Impact of environment conditions are accommodated by coefficients given in Table 2.

The formula is as follows:

$$d_{50} = K \cdot I^{a} \cdot A^{b} \cdot q^{\gamma} \tag{1}$$

where:

K – constant coefficient, depending on the applicability range of the formula (Table 2)

I – value of riverbed slope used for calculations (‰)

A – watershed area (km^2)

q – specific river run-off ($l/s/km^2$), calculated as river flow value of Q_{50} divided by A (the possible ranges of values for parameters α, β, γ are given in Table 2 – further in this paper).

However, the veracity of the results of the formula are disputed. It has been widely used for some engineering purposes in the southern Poland for a time, but nevertheless sometimes (as with any empirical formula) the results were far from accurate (to say it mildly), for unknown reasons.

It was determined that improving the method should consist of two steps: first to improve the original formula, and second to test it, using very detailed sediment data obtained from the reservoir of recently demolished dam on Trzebuńka river, tributary of Raba River of southern Poland. Presentation of this is the main purpose of the paper.

TRZEBUŃKA RIVER DAM

The Trzebuńka river dam was built in 1935 to create a head for small hydroelectric power plant. In the eighties of XX century the plant was removed, the section of the river was rebuilt and stabilized, the dam itself was heightened by approximately 1m (Figure 1). Its main purpose was also changed into sediment accumulation and means of stopping of riverbed erosion upstream. The height of the structure was approximately 4m, with stone slabs (partially) as cladding. After ten years however, the reservoir had been completely filled with deposits.

Figure 1. Heightened part of the dam, as seen while emptying of the reservoir

The dam has never been renovated and its state badly deteriorated, downstream river bank erosion started and riverbed rock base appeared as well. Additionally, it was considered to be seriously detrimental for migration of fish. In 2012 the lower part of Trzebuńka river was included in the area of "Tarliska Górnej Raby" Project (Ab Ovo 2011), the dam was proposed to be removed or seriously rebuilt. It was finally decided that a cascade of small basins (twelve of them) would be created in place of the removed main body of the dam (Figure 3). The above mentioned dam re construction/removal is the first such an undertaking in Poland. There are, however, many similar cases in other countries, quite well described in the literature, especially the changes occurring in the river bed (Ashley *et al.* 2006, Ferrer-Boix *et al.* 2014, Evans *et al* 2007, Wildman and MacBroom 2005).

During removal and construction works many soil and deposit samples were taken. The deposits had been accumulating in the reservoir for a long time, across different hydraulic and hydrological conditions. Therefore it was a unique opportunity to get the data about the deposits and its accumulation processes across a wide spectra of time and conditions.

Apart from deposit research, some geomorphological and geodetic measurements were also undertaken.

The first observation refered to the coarse material, which probably came from the original riverbed, and then was covered by some fine deposits eroded from the catchment area.

TRZEBUŃKA RIVER

The Trzebuńka is a left tributary of Raba river (Figure 2). Its length is 11.12 km, the springs are at 570 m a.s.l, and the mouth is at the Stróża village at 303 m a.s.l. The area of the Trzebuńka river catchment is 33 km^2.The catchment area is used mostly for agriculture. Forests take a significant part of the area, more then average for this part of the country. There are small settlements, the biggest – Trzebunia village lies in the middle of the valley. The Trzebuńka river begins as a set of small streams coming from the mountains Babica and Pieskowa. The upper part of the valley is of the v-shape, typical for a mountain river, the lower part is relatively flat, with a width of a few meters up to 300 m at the mouth.

The lower wider part is of a floodplain type, made of gravel and pebbles, in places with some thin (up to approx. 0.5 m) intrusions of layers of clay. For areas above the floodplains it is similar, but the clay layers (sedimented soil) are much thicker and can reach up to approx. 2m. Valley slopes near the surface are of weathered rocks (clay with pebbles), sandstone and occasionally conglomerates.

The quaternary base of the valley consists of the four types of flysch rocks: shale with some thin sandstone inclusions, mixed shale, Ciężkowice sandstones (wide layers of sandstone and conglomerates with shale inclusions) and layers of sandstones with some marl rocks.

The riverbed is made of flysch rocks and sediments (deposits), consisting of sandstone and conglomerate pebbles. The main source of coarse sediments is mostly side erosion of the riverbed in the flat part of the valley.

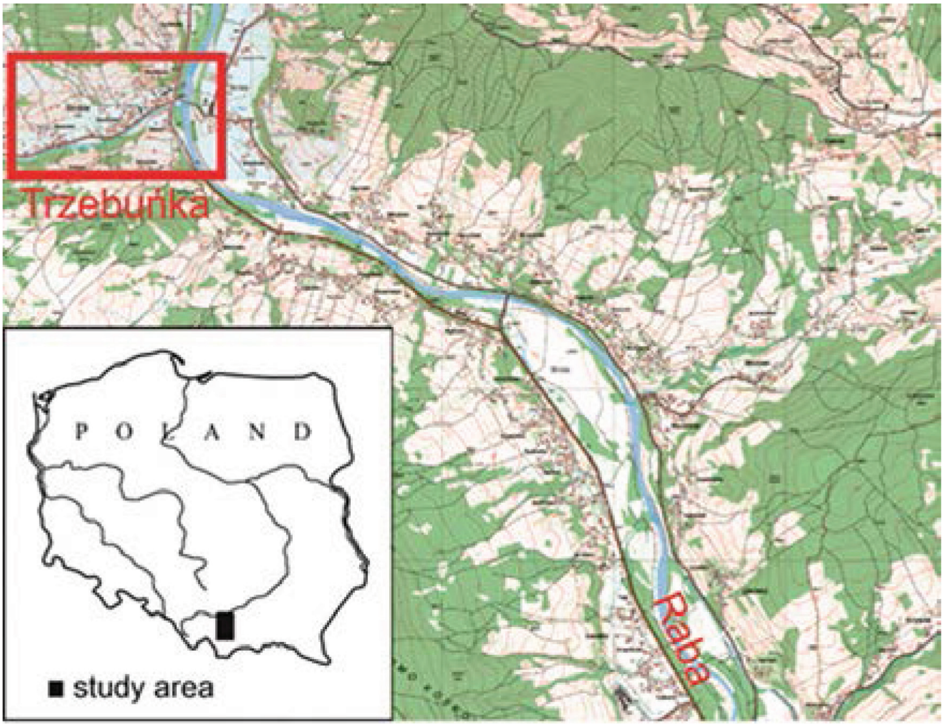

Figure 2. Study area

RESEARCH METHODS

During the construction works sediment samples were taken while consecutive layers of deposits were removed. The samples were taken in three places: very near of the main body of the dam, then to the left and to the right, about 20 meters from the first place. The next step was to analyse the samples, using a standard method for granulometric measurements of the Polish standard of PKN-CEN ISO/TS 17892-4. Grain size was determined, as well as the characteristic diameters of deposits, including the $d_{50\%}$ values. The entire sample set is a representation of the entire deposited strata, coming from the bed itself as well as the catchment area. For each of the layers the individual value of d_{50} was determined, and then it was compared with the calculated value obtained using the Osuch equation (Osuch 1964).

THE RESULTS

The samples were taken during emptying of the reservoir, after partial removal of the dam (Table 1). The entire cross-section of sediments was uncovered (see Figure 4 below), the five main zones were visible. With the fine materials some organic particles were present.

Figure 3. From the top clockwise: The dam seen from downstream – year 2012 and 2015; view upstream; reservoir after dam and deposit removal; cascade of basins in place of the main dam body; old dam remains, reservoir before the work commenced

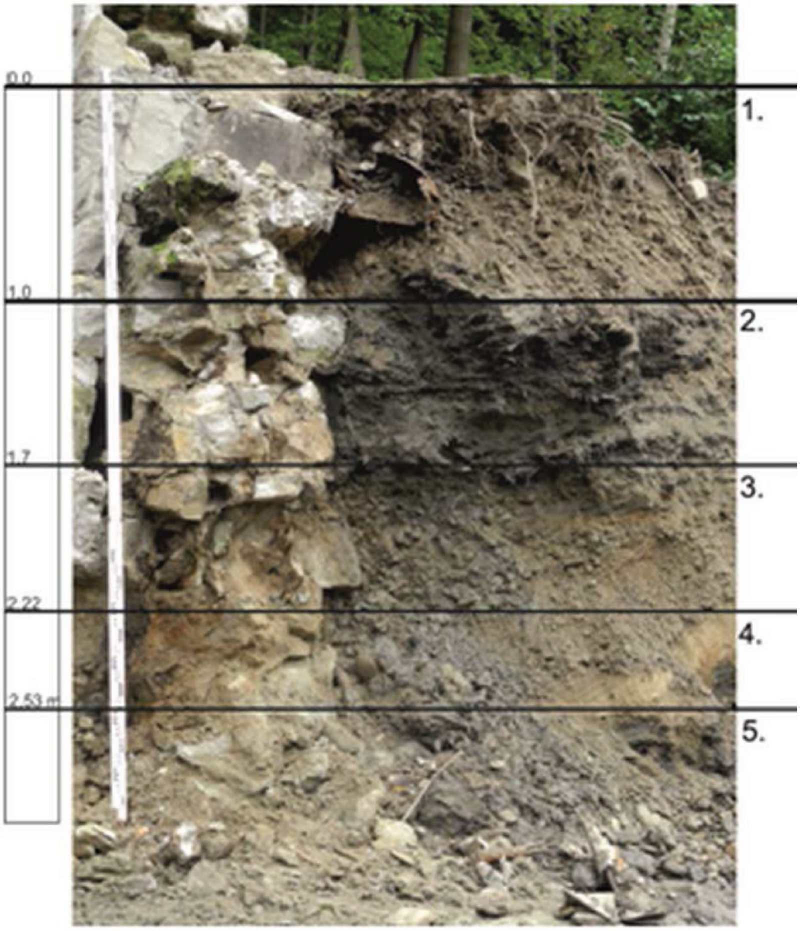

Figure 4. Place near the dam, after its removal and partial excavation of deposits

For the top layer there is a clear lack of paving stones which was removed just before of construction works. It was, however, taken from adjacent, undisturbed location.

After suitable preparation the samples were analysed using the set of standard sieves. The result of that are grain size curves which can be used for deposit description, see Figure 5 below.

There is a clear division of groups of curves into three parts: coarse, fine and organic sediments. The samples were taken from the both sides of the reservoir. On the right side (looking down the river) mostly the coarse sediment was found (Figure 6). The riverbed layout may indicate that it had been the side of the former main stream with maximum water velocities, which washed out the fine parts. Probably this is the cause that almost no fine sediments were found there.

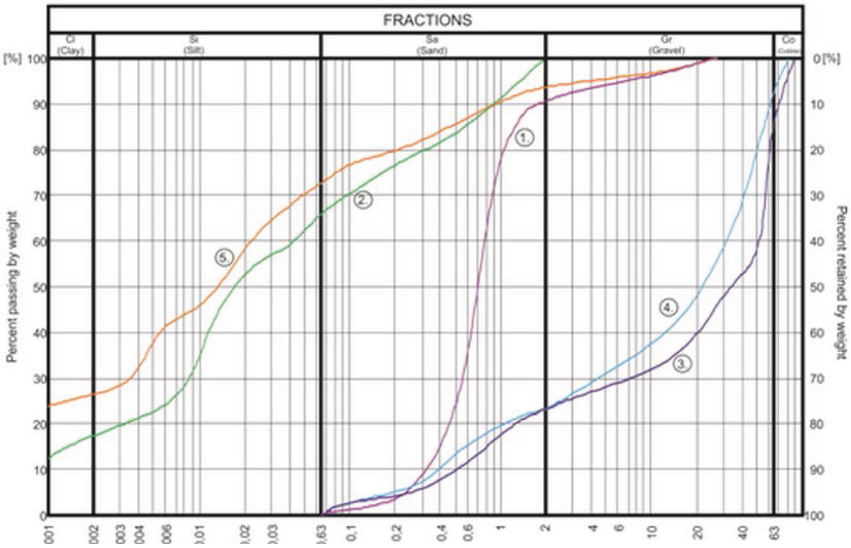

Figure 5. Grain size distribution curves for samples taken near the dam, for layers labelled as in fig. 4

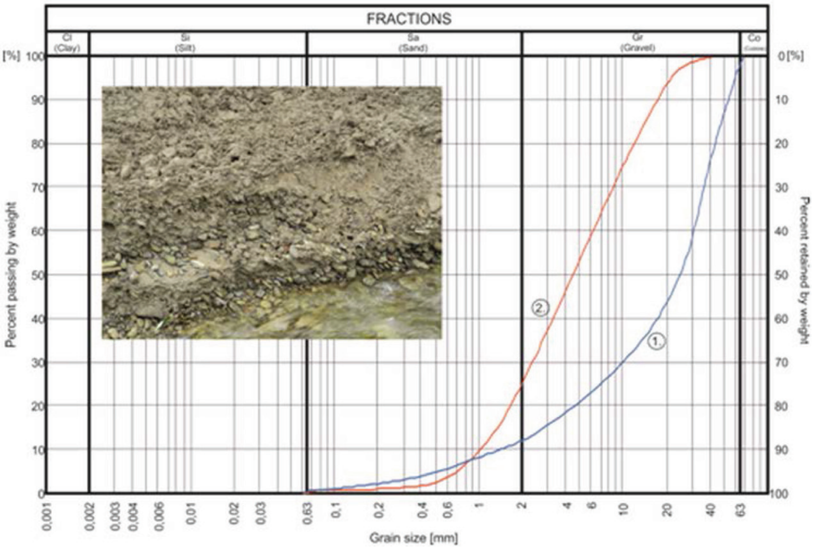

Figure 6. Right bank of the river, partially exposed deposits; grain size distribution curves for the two selected layers

The left side was more diverse, there were six different deposit layers. It is similar to the first sample site (by the dam) as there is a clear distinction into coarse and very fine deposits. Between the two some organic material is clearly visible (see below Figure 7).

Figure 7. Left size of the reservoir, exposed deposited layers

Again, the samples were analysed to obtain the grain distribution curves (Figure 8).

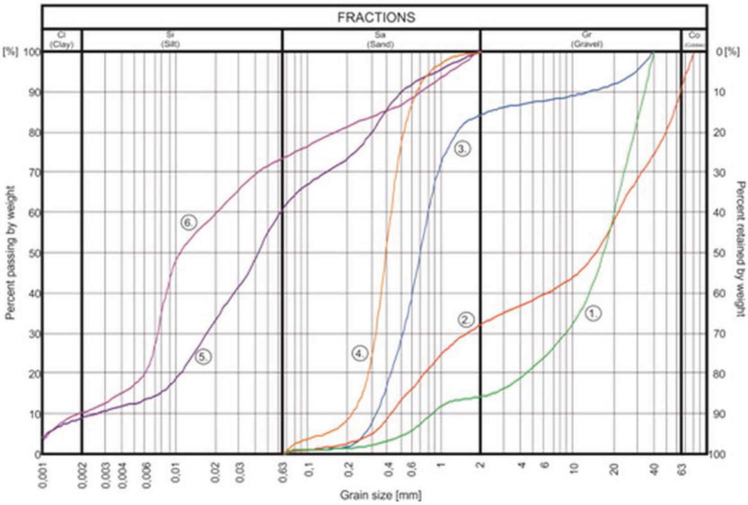

Figure 8. Grain distribution curves for deposit samples taken from the left side of the reservoir

The sediment was transported in a steady way, the main part was moved during flood events. Although the reservoir was of relatively small volume, the dam structure was able to stop almost entire part of dragged debris, the floating debris was partly moved over into the lower part of the river. During major flood events the finer parts were actually behaving like floating debris. The fine deposit layer was being formed while the water started to recede, after the coarse material had already become immobile, then the fine started to come down as well.

Table 1. Characteristic grain diameters for the sampled layers, with excluded points (marked as deleted)

Type of sediment	Characteristic diameter d	Layer location
Coarse Sand	~~0,66mm~~	Near dam
Aggeagate – gravel	17 mm, 27 mm	Near dam
Gravel	4,3 mm, 25 mm (cladding)	Reservoir – right side
Aggragate – medium	~~0,37 mm, 0,38 mm~~	Reservoir – left side
Gravel	13 mm, 16 mm	Reservoir – left side
Mean diameter of mixed up deposit	**17,05 mm**	

DETERMINATION OF THE D$_{50}$ DIAMETER USING OSUCH EMPIRICAL FORMULA

The Osuch formula was given in (1), the range of values for the parameters are presented in Table 2.

Table 2. The range of values for Osuch formula for d50 diameter determination

Scope of geomorfological parameters	Constant coefficients for formula			
	K	a	b	γ
Riverbed slope: $I \geq 0,8$ ‰ Catchement area: $A > 10$ km^2 Specific surface runoff: $q > 100$ l/s/km^2	0,69	0,809	0,357	0,136
Riverbed slope: $I < 0,8$ ‰ Catchement area: $500 < A < 20000$ km^2 Specific surface runoff: $80 < q < 300$ l/s/km^2	$0,206 \cdot 10^{-6}$	3,3	0,845	1,865

RIVERBED SLOPE

The mean grain size of deposited material is gradually changing down the river, it is usually sufficient to know the mean value of aggregated slope. For mountain river it is usually enough to use topographic maps with elevation contour lines with map scale of 1:10 000. The longitudinal profile of Trzebuńka river is shown on Figure 9, with three distinct (aggregated) slope values. The averaged slope above the dam is i=1.4 %. The section length is 6.89 km and according to Osuch it is too long, so additionally the part of the slope inside the reservoir was taken into account. There are, however, two different slope values: first from the map – before the dam was built (empty reservoir) and the second – after long time, with completely filled up reservoir. Therefore, there are two sets of calculations:

- Before dam construction – empty reservoir
- Reservoir completely filled with deposited debris

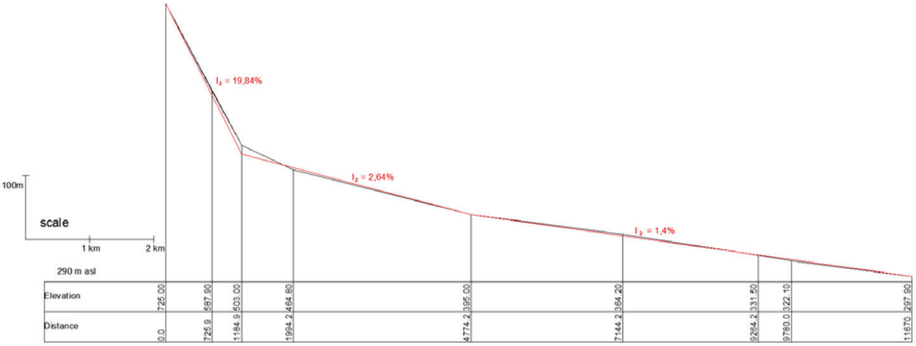

Figure 9. Longitudinal profile of Trzebuńka riverbed, up to its mouth into Raba river (right end)

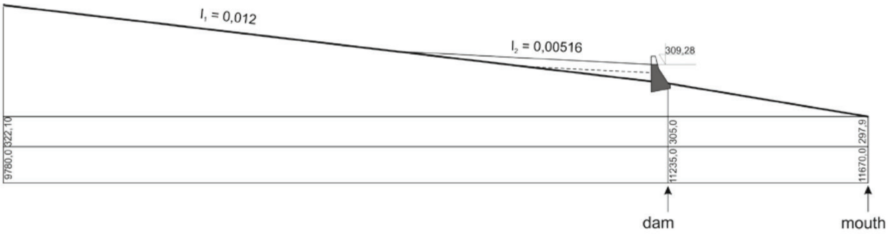

Figure 10. Trzebuńka river longitudinal profile, lower part

It was decided to take into calculations the slope values for up to 1.5 km of length immediately upstream of the dam (Figure 10), for up to 10% rise in slope values (but more than approx. 800 m). This gave us distance of 1435 m with slope value of 0.011916 (dimensionless). The next (upper) part was of radically more slope of 0.014 (>10% change, see Table 3). This is the proposal to change to the slope value parameter determination, as a modification for standard Osuch formula recommendations.

Therefore, the parameter values for Osuch formula are as follows:
$A = 32.61\ \text{km}^2$
$Q_{50\%} = 15.48\ \text{m}^3/\text{s} \rightarrow q = 474.701\ \text{l/s/km}^2$

So the formula is (taking into account the values of Table 2):

$$d_{50} = 0,69 \cdot I^{0,809} \cdot A^{0,357} \cdot q^{0,136} \tag{2}$$

The calculations results are presented below in Table 3:

Table 3. Results of d_{50} calculations using Osuch formula, different slope approximations, in-situ d_{50} values

A = 32.61 km² q = 474.701 l/s/km²	**Lower section (too long)**	**Empty reservoir bottom – 305.0 m.a.s.l**	**Filled up reservoir crest – 309,28 m.a.s.l**	**averaged slope (mean of empty & filled up reservoir)**	**Slope calculated using Ratomski empirical formula**	**Sample grain analysis**
I [-] I [‰]	0.014 14.00	0.012 12.00	0.0089 8.93	0.01045 10.45	0.00516 5.16	Min d_{50} = 4.3 mm
d_{50} [mm]	46.80	41.32	32.53	36.94	20.87	Max d_{50} = 27 mm
						Average d_{50} = 17.05 mm

COMMENTS

The d_{50} diameter was determined from the samples of each layer in the three excavation sites. The very fine part was not taken into account as it was assumed that it was sediment coming from the catchment area, not the riverbed itself. The results of the sample analysis are shown in Table 1, while the comparison with the value obtained from the Osuch formula is presented in Table 3.

There are differences in data obtained from soil samples concerning an order magnitude for d_{50} diameter. In the case of values computed for different (but actual) slope values, they also differ, but not so much.

The lowest value is obtained for completely filled-up situation (Table 3) of 32.53 mm, the biggest value is of 46.80 mm as for the entire lower section of the river (excluded from analysis as too long, too far away from actual dam). The other calculated values are in the middle. The interesting point is that the minimal diameter for actually measured values is not even close to any calculated values. This may mean that using the Osuch formula is not appropriate for modeling such small grains of deposits. On the other hand, the value of Max d_{50} (27 mm) is quite near to the calculated value for the filled-up reservoir slope (32.53 mm), the value is surprisingly close (about 17% of difference). It is especially interesting as the Osuch formula is an entirely empirical one. For the values of an average slope the results are more distant however.

To compare the possible results of the calculated slope, another empirical formula (the Ratomski formula) was included into Table 3 . This is a rarely used formula for assessing the slopes of deposits accumulated in small reservoirs in southern Poland (Ratomski 1991). Its construction is simple: $I_c=I_0 \cdot 0.43$, where I_c is the calculated slope of riverbed near the dam after it has been completely filled-up and I_0 is the original slope (empty reservoir). The most interesting point is that the final $d_{50\%}$ calculations using this value give the best results, closely matching the average value of d_{50}, with about 22% of difference (Table 3). There is, however, a methodology issue of stacking together two empirical formulas. As for now we are not in a position to recommend such a method, but the work is in progress.

The slope value is indeed a dominating factor for calculations. It is very important to clarify not-to-clear original recommendations for determination of its value as for “average slope”.

For the long slope of 1.4%, the calculated value of d_{50} is very much bigger than the actual one obtained from the samples. Even the layer of bigger stones, called paving layer, was of a smaller characteristic diameter. For lower slope values the results get better. It can be explained that while taking samples, the grain sizes of the entire depth of the filled-up reservoir were assessed – as it had been gradually deposited over years. Therefore, it was a unique opportunity to peek into the history of sediment accumulation.

CONCLUSION

The slight modification of slope value parameter determination method led to quite good and encouraging results for practical usage of Osuch equation, although only for larger d_{50} values. If it is to be validated by further analysis and field research (as it is planned to be done) it may become a really important engineering and analytic tool for geomorphological studies of river evolution, a kind of breakthrough in this field.

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