

# The quantity and attributes of woody accumulations in the Moravskoslezské Beskydy Mountains streams

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## ABSTRACT

Wood accumulations are important morphological agents forming the character of high-gradient streams in the Moravskoslezské Beskydy Mts. The aim of the research is to define both the extent and character of the impact of wood accumulations on the streams. A total of 126 accumulations have been identified of the total wood volume of 503 m<sup>3</sup> that is unevenly distributed within the studied streambeds. The wood volume in the studied streambeds is particularly dependent on the age and species composition of vegetation, channel morphology, and the geological bedrock resistance to the action of the stream, especially in forced alluvial reaches. The research revealed the deposition of fine-grained material immediately upstream of the wood accumulations, creating gravel bars and capturing fine organic debris. On the other hand, immediately downstream of the accumulations fine-grained fractions are carried away and coarser material is deposited, creating pools and plunge pools, eversion potholes and bank scours. The research further showed a low intensity of the transport of woody material through the streambeds. The accumulations usually occur in the place where the stream has been dammed by a fallen tree member or in structurally predisposed streambed segments. As a result, discontinuities in energy and material flow occur that help to increase the streambed heterogeneity.

## KEYWORDS

large woody debris; high-gradient streams; channel morphology; wood accumulations; grain-size analysis; the Moravskoslezské Beskydy Mts.

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## 1. Introduction and theoretical background

Woody material is a geomorphological and geoeological agent that interacts with streams in a form of dead wood on slopes and in streams or as live riparian trees on stream banks and slopes (Bilby, Naiman 1998). This interaction influences the behaviour of fluvial systems not only within the streams themselves but also on adjacent slopes (Faustini, Jones 2003). The first publications dealing with the mutual relation between streams and woody debris and their impact on the channel morphology appeared in the 1970s studying the mountainous basins in the north-west of the USA (Swanson 1976; Keller, Tally 1979). Local temperate rainforests are drained by gravel-bedstreams that are much studied exactly from the point of the wood-stream interaction, thanks to a large amount of woody material in the channels. A wider interest in these issues started in the 1990s with the spatial diversification of similarly focused researches. From newest studies could be mentioned Gregory et al. (2000), Abbe et al. (2003), Ley Lay et al. (2013) or Wohl (2016). In these days is research divided all around the world, but focus is still on the natural segments of streams and rivers. Natural segments of streams and riparian vegetation represents suitable environment for long time research of interaction between wood and river.

Scientific publications often bring disunity in the terminology and principles of woody material classification (Bilby, Naiman 1998). These discrepancies are related, among others, to the issues of the distinction between large woody debris, fine woody debris and fine organic debris. Therefore, some of the terms this article employs need to be defined.

We distinguish two basic types of woody material, namely *fine organic debris* (FOD) and *woody debris* (WD). Fine organic debris is all woody material interacting with a stream, the diameter of which is less than 3 cm. It includes fine fragmented branches (twigs) or pieces of trees. Its importance consists in capturing fine floating material, particularly leaves, creating specific levels of fined organic material. Woody debris (Gome et al. 2003) is divided into *fine woody debris* (FWD) and *large woody debris* (LWD). The definition of the LWD metrics differs according to individual authors. However, the practice shows that woody material is considered LWD if having the dimensions of 10 × 100 cm (Kaczka 1999; Faustini, Jones 2003). The wood that does not meet these parameters but does not belong to FOD is defined as *fine woody debris* (FWD). A more appropriate term has started to be used lately as an equivalent for woody debris, woody material or LWD, namely *in-stream wood* as it better expresses the affinity between the wood and streams (Cadot, Wohl 2010).

The mechanism by which in-stream wood affects a stream consists in the change of transport parameters of the channel and adjacent bank slopes. The presence

of wood in a stream thus increases the roughness of the channel and the slopes, making it more difficult for any material to move downstream and downslope, and affecting the advance of the flow energy (Bilby, Naiman 1998). Increased roughness means increased capacity to retain transported material, which is supported both by decreased carrying capacity of a stream and simply by the presence of blocking elements (Gippel 1995). Wood in a stream does not always carry with it increased material depositing. On the contrary, it often causes increased removal of material, accelerating erosion processes that lead to a decrease in the stability of adjacent slopes. This mainly happens in the case of a fallen tree consolidating the stream bank or when a fallen member diverts the streamline towards the bank that is less resistant to the water flow than streambed. Owing to the changes in channel hydraulics, woody material influences the passage of sediments through the fluvial continuum, which is reflected by selective erosion and material sorting. Since the kinetic energy is decreased, the stream no longer has the capacity to exceed the level of shear stress necessary to set the sediments in motion (Bilby, Naiman 1998).

The above described physical principles are fundamental for several functions in-stream wood has within fluvial systems. Firstly, the presence of woody material in the channel is a precondition for the formation of wood steps and accumulations (Beschta 1983; Abbe et al. 2003). Wood accumulations may become the leading morphogenetic agent determining the character of high-gradient streams. In this paper is the high-gradient stream defined as reach segment with slope 2° or higher. Furthermore, increasing the channel roughness while decreasing the streamflow, in-stream wood can initiate bedform changes (Montgomery, Buffington 1998). Last but not least, wood assists in the formation of adjacent floodplain morphology (Nakamura, Swanson 1993). Wood can occur individually or in accumulations in the channel (Fig. 1). Dominant share of LWD (apx. 82%) in the study area is concentrated into woody accumulations. For that reason, this paper is focused on wood accumulations entirely. The research comprised and focused from following: i) the mapping of the distribution of wood accumulations and their basic classification; ii) collection and analysis of channel sediments, and iii) morphometric measurement of the accumulations.

Proposed criteria for the classification of wood accumulations combine several methodological approaches (Faustini, Jones 2003; Máčka, Krejčí 2011; Gomi et al. 2003). For the purposes of this work, we distinguish a wood accumulation from wood lying by itself using these criteria: i) the wood must consist of minimally 3 pieces of the dimensions of 10 × 100 cm, touching mutually in at least two points; ii) the wood must mutually interact creating an independent subsystem; iii) at least one piece of the woody material must show fluvial interference (e.g. transport, rotation



**Fig. 1** Accumulation of LWD in the Mazak research area (photo: author, 2015).

of the member axis or member abrasion caused by sediment transport). We measured such wood accumulations and processed them in this study. Individual wood pieces are not included in this paper due to their different way of impact on the fluvial systems.

## 2. Study area

Our research took place in the Moravskoslezské Beskydy Mts. that, being flysch mountains, have a specific position among the other mountain ranges of the Czech Republic. Flysch is prone to morphological changes that are reflected in increased dynamics of the area (Mahel' 1986). We can then identify a wide spectrum of erosion-accumulation landforms that are related to this increased morphological dynamics. Flysch terrain is often subjected to fluvial shaping, which is given by the structural predisposition of flysch to resist stream energy. This can be observed in areas with high-gradient slopes and growing extent of partial sub-basins. Streams on flysch bedrock in Western Carpathians are characterised by a tendency to deepen significantly in their erosion and transport parts than Bohemian Massif bedrock streams

and create alluvial fans at the foot of the slopes. It is typical of streams based in flysch geologic structures that their zones of erosion, accumulation and sediment production are clearly distinguishable. The above mentioned also applies to the localities of Satina, Mazák and Bučací potok brook (Fig. 2), in which the research was conducted. From the point of view of geology, the localities belong to the Godula Formation (Roth 1980) represented by medium rhythmical flysch in which thinly-bedded claystones and siltstones alternate with coarser beds of fine-grained sandstones.

The Satina study area (49°33'26.3"N, 18°26'08.1"E) is found on the north-western slope of the Lysá hora Mt. in the cadastral area of the Malenovice village. The length of the studied stream reach is 2.23 km. The studied area has 146 ha and the altitude ranges from 570 to 1323 m a.s.l. The whole area of interest belongs to the Malenovický kotel Nature Reserve (NR). The Satina stream is a right tributary of the Ostravice River. The Mazák study area (49°31'49.4"N, 18°25'43.0"E) is found 3 km south of the Satina stream, concretely on the north-western slope of the Čupel hill in the cadastral area of the Muchovice village. The area belongs to the Mazácký Grúník NR. The boundaries of the NR

and the study area are identical. The length of the studied reaches is 2.12 km, the total study area has 90 ha and the altitude ranges between 570 and 922 m a.s.l. The area is drained by the Mazák stream, which forms a part of its boundary. The Mazák stream is also a right tributary of the Ostravice River. The subject of the study was not the Mazák stream itself but its four nameless tributaries (referred to as ZT1-4 in the text) that drain the reserve and individually flow into the Mazák stream. The last area of interest is Bučací potok stream (49°51'54.7"N, 18°38'13.2"E) found 6 km south-west of the Satina stream, namely on the northern slope of the Smrk Mt. in the cadastral area of the Ostravice municipality. The study area belongs to the

Bučací potok NR and also in this case the NR and the study area boundaries are identical. The length of the studied reach is 1.01 km, the total study area has 35 ha, and the altitude ranges from 612 to 1047 m a.s.l. where the western branch of the stream springs. The Bučací potok stream is a left tributary of the Ostravice River. Summary attributes of the study reaches are in tables below (Tab. 1; Tab 2).

Due to the absence of the reports on the hydrological regime related to the studied localities, our study had to be based on the data of mean daily discharges obtained from the Ostravice River-Šance Dam profile, which is found 2.3 km (Mazák), 2.7 km (Bučací potok) and 4.9 km (Satina) from the studied localities.

**Tab. 1** Proportion of the channel morphology types (%).

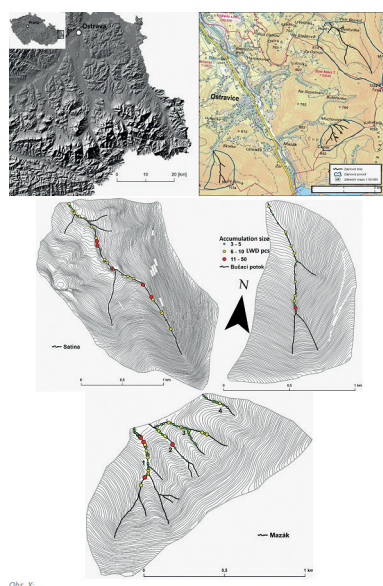
Study area	colluvium	bedrock	cascade	step-pool	plane-bed	pool-rifle
Mazák	9.8	12.1	59.3	18.6	0.2	X
Satina	0.9	9.8	57.6	24.1	6.9	0.7
Bučací p.	10.6	1.9	72.3	15.2	X	X

Data source: author's own measurement

**Tab. 2** Attributes of the study reaches.

Study area	Reach length (m)	Average grad. (°)	Median grad. (°)	Elevation dif. (m)
Mazák	2115	13.1	12.3	511
ZT1	769	13.5	12.9	194
ZT2	489	12.3	11.5	117
ZT3	512	12.1	12.2	111
ZT4	345	14.4	12	92
Satina	2232	7	5.5	304
Bučací p.	1006	15.4	12	254
Σ	5353	11.1	10	1069

Data source: author's own measurement



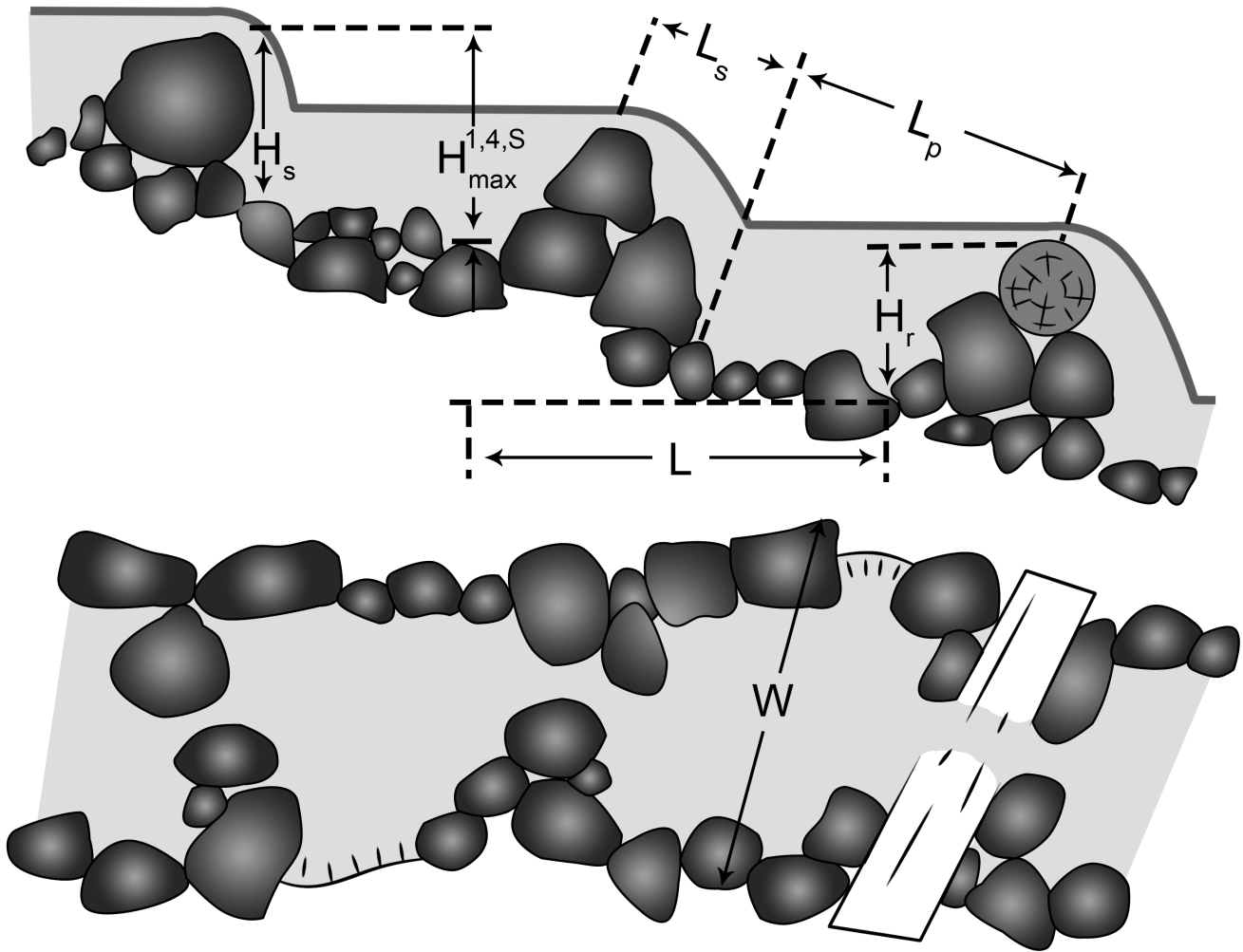
**Fig. 2** Location of the study areas – Mazák (on the left), Bučací potok (in the middle), Satina (on the right).

### 3. Data and methods

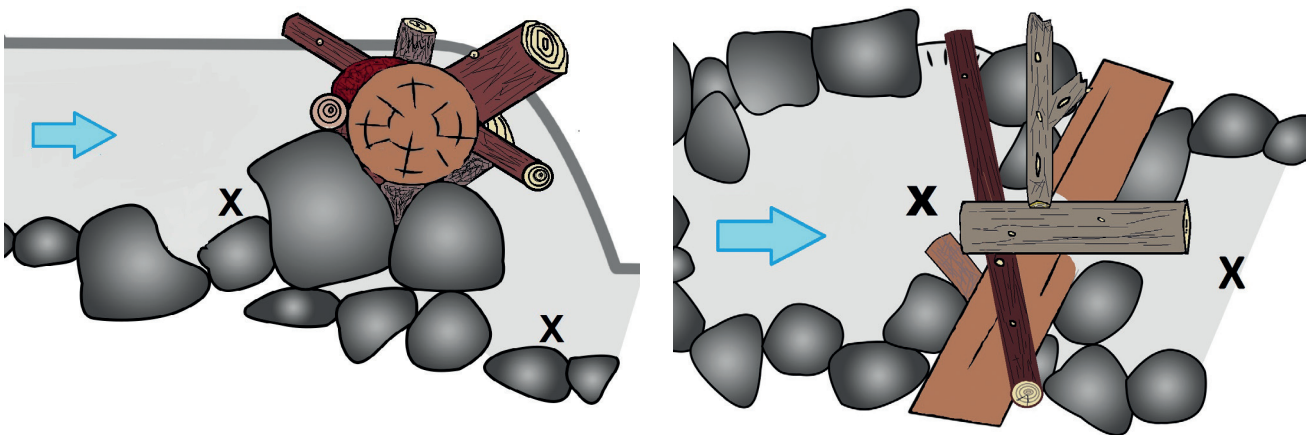
The main intention of the research was to define how and in what intensity in-stream wood accumulations affect the morphometric parameters of high-gradient streams. Field works took place in the years 2015–2016. Basic morphometric parameters measurement represents Fig. 3.

#### 3.1 Analysis of channel sediments

The analysis of channel sediments provides the information on the proportional representation of individual grain-size fractions in channel microforms including potential impact of in-stream wood. Owing to the absence of measurement on the profiles in the study area, the study had to be based on the discharges measured in the Ostravice – Šance Dam profile. The sampling was conducted under a normal hydrological situation corresponding to the discharges of  $Q_{180-190}$  for



**Fig. 3** The principle of measurement in high-gradient streams (adj. Zimmermann, Church 2001).  $L$  – length of formation,  $H_{\max}$  – maximum decline between formations,  $H_s$  – height of formation,  $H_r$  – depth of formation,  $L_s$  – (log) step length,  $L_p$  – pool length,  $W$  – bankfull width.



**Fig. 4:** Pair sampling near wood accumulations.

the Ostravice river in this profile and it took place in the whole spectrum of channel morphologies of high-gradient streams. The samples were taken in places with or without in-stream wood in order to identify potential differences between these two sample groups. The sampling was performed on the surface layer using the method beginning-end of the accumulation (Fig. 4). In order to ensure the highest possible representativeness

of the sampling site, we selected the reaches void of tributaries that might potentially affect the grain-size composition of sediments on the research site. Where possible, reaches potentially affected by in-stream wood were sampled twice, namely immediately upstream and downstream of the wood accumulation, respectively (the so-called pair sampling). The purpose was to detect potential differences between the two samples.

A total of 42 samples were obtained (20 from Mazák, 15 from Satina and 7 from Bučací potok), 27 out of which were taken from the reaches directly affected by in-stream wood. Out of the 27 samples, 16 samples fall within pair sampling, i.e. one sample taken upstream of the accumulation and one sample taken downstream of the accumulation. The remaining 11 samples were only taken upstream but not downstream of the accumulation. Finally, 15 reference samples were taken from reaches void of potential impact of in-stream wood. The samples were taken using a metal sieve with the mesh size of 500  $\mu\text{m}$ ; the loss of fine fraction incurred in sampling and dripping was thus negligible. The range of samples weight was between 319 to 908 grams.

In a laboratory, each sample was thoroughly dried at a temperature of 90 °C, weighed and processed using the Fritsch-system3apro set. First, the samples were wet sieved for 7 minutes at the amplitude of 2 mm and after drying they were dry sieved for 1 minute at the amplitude of 1 mm. The content of individual meshes of the size of 20, 63, 200, 630, 2000, 5000 and 10,000  $\mu\text{m}$  was weighed and processed in the Autosieb programme. Measured values were further processed using the GRADISTAT programme that generated the representation of grain-size fractions with the help of triangle diagrams as follows: (A) clayey particles, silt <0.063 mm; (B) sand 0.063–2 mm; (C) gravel 2 mm (Bunte, Abt 2001). The GRADISTAT programme was also used to calculate sediment sorting, measurement of  $d_{50}$  and  $d_{90}$  parameters and determine the kurtosis according to relevant methodologies (Folk, Ward 1958).

### 3.2 Morphometric measurement of wood accumulations and mapping

The morphometric parameters of in-stream wood are measured where it complies with the conditions presented in the introductory chapter and can thus be considered a wood accumulation. For the purposes of this work, the following parameters are studied (adapted from Gomi 2003; Cadol, Wohl 2010; Máčka, Krejčí 2011): i) the number of wood pieces forming an accumulation; ii) the site of the wood origin; iii) a blocking, stabilising factor; iv) a morphological effect; v) the orientation of the key member; vi) volume estimate; vii) wood proportions. All of these parameters are obtained via field measurement.

*Number of wood pieces forming an accumulation* – It is obtained for each identified accumulation by simple observation or possibly by removing a part of the sediments in order to include buried pieces. In this work, we distinguish accumulations according to the number of pieces as well as cumulative volume of woody material, whereas classifying the wood into each category is based on meeting both criteria: i) small accumulations – 3–5 pcs of LWD; cumulative volume up to 0.5  $\text{m}^3$ ; ii) medium accumulations – 6–10 pcs of LWD; cumulative volume between 0.5 and 3  $\text{m}^3$ ; iii) large

accumulations – 11 pcs and more; cumulative volume exceeding 3  $\text{m}^3$ .

*Site of the wood origin* – It is an attribute that helps to understand the spatial sequence of the formation of individual accumulations. The following types of accumulations are distinguished (Abbe et al. 2003): i) autochthonous, ii) allochthonous, and iii) combined. Autochthonous accumulations originate in a place where by tilting or breaking wood enters the channel where it creates an accumulation together with other pieces of wood. In this case the site of origin can be identified. On the contrary, allochthonous accumulations are only represented by wood that has flown downstream from the upper parts of the stream. In a suitable place this wood stabilises forming an accumulation (Ruiz-Villanueva et al. 2015). The wood shows signs of transport such as bark abrasion and smoothing, and increased heterogeneity of the size of individual wood pieces. The site of origin cannot often be determined unequivocally. In some cases, originally an autochthonous accumulation transforms into a combined type.

*Blocking; stabilising factor* – A blocking or stabilising factor is any obstacle that makes in-stream wood immobile, enabling its accumulating and developing as a wood accumulation. Some blocking factors are given predisposingly, e.g. the outcrops of more resistant sandstone layers, while others (e.g. a fallen member) are distributed randomly. We distinguish the following factors: i) vegetation, ii) boulders, iii) streambed material, iv) a combination of more factors and v) no blocking factor (gravitational stabilisation).

*Morphological effect* – It is a qualitative parameter describing the interaction between woody material and the stream and its morphological displays. The interaction displays are divided into accumulation and erosion displays, whereas both types are distinctively different types of stream channel microforms.

Morphological effect analysis consists in the visual assessment of the surroundings of a given accumulation. For the purpose of this work, we distinguish the following types of morphological effect: i) flow diversion, ii) backwater; iii) step-no pool, iv) step-pool, v) deposits (sediments, fine organic debris and in-stream wood), and vi) no effect. In cases where not one dominating effect can be identified, two types are recorded.

*Key member orientation* – The key member represents the basic structural unit of each accumulation. Metric parameters of the key member are important determinants of the origin and functioning of wood accumulations (Abbe et al. 2003). Each accumulation usually contains only one key member.

The aim of this method is to quantify the directions of the members and determine whether they are random and evenly represented and whether some of them may possibly create better predisposition for the formation of wood accumulations. The orientations relative to channel axis were measured using

a special protractor and the values were evaluated in the Stereonett 2.46 programme, which generates rosette diagrams.

*Volume estimate* – We are able to measure at least a part of the members forming an accumulation, namely the upper layer represented by the members that have formed part of the accumulation the shortest time. The share of these members in the total number of the members within an accumulation decreases with the size and morphological complexity of the accumulation. In cases of larger accumulations where measurement of all pieces was impossible, the accumulation was partly disassembled so that all pieces could correctly be measured.

Formulas for the calculation of the accumulation volume can be expressed as follows (1, 2). The first formula (1) is a simple calculation of the volume of a cylinder representing an alternative for the Huber's formula in cases where bare members are preserved. Distortion of the results due to natural member narrowing is avoided by measuring the radius in the member's half. Similarly, branched trees need to be broken down into 'cylinder' prime elements and summed up again.

$$V_s = \pi r^2 \times h, \quad (1)$$

where  $V_s$  is tree volume,  $r$  is the radius of the base, and  $h$  is tree height.

The other formula (2) calculates the total LWD volume within an accumulation.

$$V_a = V_z + V_{sx}, \quad (2)$$

where  $V_a$  is the total accumulation volume,  $V_z$  is the total volume of measurable members, and  $V_{sx}$  is the total estimated volume of unmeasurable pieces.

The mapping of the distribution of wood accumulations took place on the basis of field research. Wood accumulations that were localised using a laser rangefinder were photographed and marked in working field maps. Measured data and drafts were used to create a set of maps of the study areas containing the topographic information of the position of wood accumulations.

### 3.3. Multidimensional data analysis

Selected morphometric and grain-size parameters were subjected to statistical assessment in the R and NCSS 11 programmes using correlation matrices, linear regression models and methods of multidimensional data analysis (PCA – Principal Component Analysis, DCA – Detrended Correspondence Analysis, RDA – Regularised Discriminant Analysis). The output of the NCSS 11 programme was processed in the Grapher 9 and Corel Draw X3 programmes. The basic question was whether and, where applicable, to what extent woody material participated in the variability of the studied channel parameters and sediment

samples. The data set was divided into two separately assessed parts. The first set contains the data free of possible influence of woody material (reference sampling), while the other set is represented by the data of pair sampling immediately upstream and downstream of a wood accumulation. The main difference between the two ones consists in the determination of controlling and controlled variables and the choice of relevant methods for this type of data division.

In the case of pair sampling, the controlling variable corresponds to woody material or wood accumulation volume. Controlled variables are then the following parameters: gradient (laser measurement), accumulation height, accumulation width (field measurement,  $d_{50}$ ,  $d_{90}$ , sediment sorting, and the distribution of grain-size fractions (gravel, sand, silt and clay) in the samples (from GRADISTAT). Due to data heterogeneity (qualitative – ordinal; quantitative – proportional), there arose a need for standardisation using a range so that in the  $n$ -dimensional space all measured axes had the same length and were thus mutually comparable. Standardised data made it possible to create a correlation matrix of all variables. Since the design of statistical testing allows for the assumption of a controlling variable, the DCA analysis had to be carried out in order to find out whether the gradient length was linear or unimodal. Data prepared in this way can further be assessed using the RDA analysis that provides the information on whether the factor of wood volume correlates with the variability of the studied controlled morphometric parameters. With regard to the differentiation of pair data, this data set can be divided to find out if the potential influence on the variability of morphometric parameters is significant upstream or downstream of a wood accumulation. Furthermore, linear regression models were constructed. In case the histogram showed skewed distribution, apart from the basic linear regression model, a generalised linear regression model was constructed with negative binomial distribution. The results of regression models were tested by means of the ANOVA tool to determine whether the potential influence of the controlling variable on the controlled variable was statistically significant. The last point of the statistical processing was the PCA analysis that looked at general ties and influences across the studied parameters disregarding the control influence of woody material. As for reference sampling, morphometric wood features were not included in the parameter analyses, nor the accumulation height and width were measured, with the exception of the bankfull width at the site of sampling. The other above mentioned parameters were also used in this data set. The procedure of the statistical evaluation is very similar to that of pair sampling, yet no linear regression models are made, nor RDS analyses are performed. The result is therefore a correlation matrix, including a table and a PC graph that can be compared with the results of pair sampling.

### 4. Results

Field research and laboratory data analysis showed that wood accumulations actively influenced the morphology of high-gradient streams changing hydraulic parameters of the channels. There are 126 wood accumulations in the study areas, all of which were included in the scientific research. The accumulations help to retain bed sediments, water and organic material, increasing the heterogeneity of the channel and diversity of adjacent biotopes. The research results include the following items:

#### 4.1 Distribution of wood accumulations

The distribution of in-stream wood is mainly affected by the age of the stand and its species composition. Channel reaches that drain water from the oldest fragments of the Carpathian primary beech-fir forests such as the whole ZT1 reach and the middle and upper Satina reaches contain the highest number of wood pieces and highest accumulation volume. On the contrary, the highest number of accumulations found within a 100-m length of

a stream is that of the ZT3 reach running through a spruce monoculture. The top of a spruce tree is often fragmented into many more pieces than the top of a beech tree of the same volume of organic matter. This fact can partly be attributed to a different habitus of coniferous trees characterised by high thin members and partly to worse mechanical properties of spruce wood (Peschel 2002), which is less resistant to water energy than beech wood in the case of increased stream flow. In the studied basins, there are 2.4 accumulations per 100 m of the stream length containing on average 6.2 wood pieces. If considering also 4.6 pieces of wood that are not part of an accumulation, it makes 19.4 pieces of LWD per 100 m of stream length and the average total volume of 12 m<sup>3</sup> of wood matter per 100 m of the length. The complete list of all measured parameters is presented in Tab. 3.

#### 4.2 Parameters of channel sediments

The research proved the impact of in-stream wood on the grain-size composition of the surface sediment layer. The sediments immediately upstream of accumulations show a higher ratio of sand fraction,

Tab. 3 Total number of wood pieces and relative proportion of wood aggregated in accumulations in studied stream reaches.

	Bučací potok	Mazák	ZT1	ZT2	ZT3	ZT4	Satina	Σ
No. of wood pcs in ACCU	112	456	260	59	99	38	241	809
ACCU volume (m <sup>3</sup> )	47.6	274.1	231.4	16.2	11.7	14.6	181.7	503.4
Max. No. of pcs in an ACCU	11	49	49	17	9	9	25	49
Mean No. of pcs in an ACCU	5.33	6	8.67	5.9	4.13	4.75	7.3	6.22
No. of identified ACCU	21	72	30	10	24	8	33	126
Mean No. of ACCU per 100 m	2.09	3.59	3.9	2.04	4.69	2.32	1.48	2.36

Data source: author's own measurement

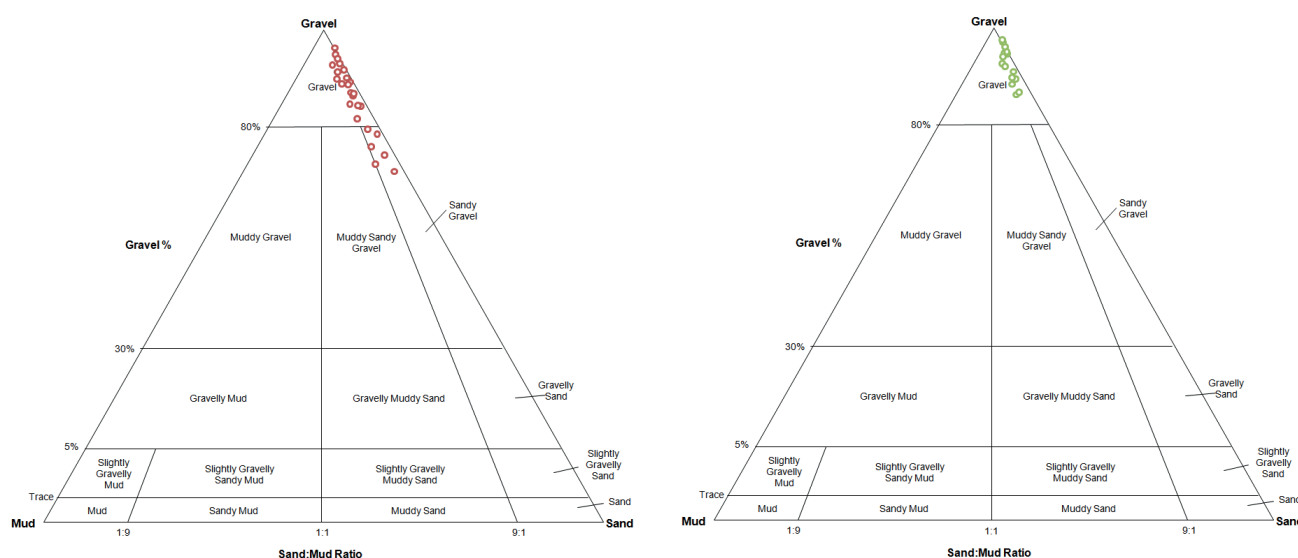


Fig. 5 Comparison of the grain-size composition of reaches containing wood accumulations (a – red circle) and channels unaffected by in-stream wood (b – green circle).



at the expense of gravel fraction, than the samples from reference segments unaffected by in-stream wood (Fig. 5). The differentiation is also observed in relation to pair samples, in the case of which mean grain size  $d_{50}$  downstream ( $X_p$ ) and upstream ( $X_N$ ) of wood accumulations ranged from 1.16 to 3.37 mm, while the sampling sites were only separated by a few decimetres.

Mean grain size  $d_{50}$  downstream of accumulations is 8.14 mm (Tab. 2), upstream of accumulations 6.17 mm (Tab. 3) and in reaches outside the impact of wood 6.94 mm (Tab. 4). Based on these parameters, we can suggest that in-stream wood retains fine-grained material in the direction upstream of accumulations, by which it temporarily increases the sediment roughness downstream of accumulations.

**Tab. 4** Grain-size analysis of forms affected by wood – pair sampling.

Sample ID	Samples from affected landforms – pair samples N, P					
	gravel (%)	sand (%)	silt (%)	$d_{50}$ ( $\mu\text{m}$ )	sorting	kurtosis
1 <sub>N</sub>	80.5	18.5	1.1	5613.7	1.495	4.458
1 <sub>P</sub>	92.1	7.0	0.8	7485.1	1.425	4.339
2 <sub>N</sub>	86.2	12.7	1.1	5320.2	1.261	4.544
2 <sub>P</sub>	97.0	2.3	0.7	6478.8	1.445	4.863
3 <sub>N</sub>	91.9	5.1	3.0	6386.7	1.679	6.570
3 <sub>P</sub>	97.1	2.2	0.7	8706.6	1.446	3.567
4 <sub>N</sub>	93.3	4.4	2.3	7140.5	1.562	4.934
4 <sub>P</sub>	86.6	10.4	2.9	9503.4	1.617	5.152
5 <sub>N</sub>	91.9	5.1	3.0	7118.0	1.679	6.57
5 <sub>P</sub>	96.1	3.2	0.7	9282.3	1.47	3.558
6 <sub>N</sub>	73.6	22.4	4.0	3330.5	1.771	6.54
6 <sub>P</sub>	83.6	13.5	2.9	6703.5	1.681	5.06
7 <sub>N</sub>	71.9	26.4	1.6	5240.6	1.627	4.049
7 <sub>P</sub>	89.1	9.4	1.5	8524.8	1.409	5.33
8 <sub>N</sub>	90.8	8.0	1.2	5795.5	1.364	5.314
8 <sub>P</sub>	91.3	8.0	0.7	8451.0	1.519	3.559
$\Sigma_p$	<b>85.0</b>	<b>12.8</b>	<b>2.2</b>	<b>5743.2</b>	<b>1.55</b>	<b>5.37</b>
	<b>91.6</b>	<b>7.0</b>	<b>1.4</b>	<b>8141.9</b>	<b>1.50</b>	<b>4.43</b>

Data source: author's measurement results

**Tab. 5** Grain-size analysis of landforms affected by wood – individual samples.

Sample ID	Samples from affected landforms – individual samples					
	gravel (%)	sand (%)	silt (%)	$d_{50}$ ( $\mu\text{m}$ )	sorting	kurtosis
9 <sub>N</sub>	98.3	1.4	0.3	5461.4	1.266	2.873
10 <sub>N</sub>	95.1	4.1	0.8	4301.3	1.117	7.398
11 <sub>N</sub>	75.7	22.6	1.6	4392.8	1.522	5.178
12 <sub>N</sub>	93.3	4.5	2.1	8478.8	1.589	5.124
13 <sub>N</sub>	93.7	5.7	0.6	8970.3	1.352	3.795
14 <sub>N</sub>	77.6	19.4	2.9	3893.6	1.561	6.918
15 <sub>N</sub>	81.5	16.7	1.8	3824.9	1.483	7.547
16 <sub>N</sub>	90.9	6.6	2.5	8529.4	1.591	5.341
17 <sub>N</sub>	88.4	10.1	1.4	7636.7	1.511	4.703
18 <sub>N</sub>	86.4	12.2	1.4	7494.1	1.559	4.345
19 <sub>N</sub>	88.9	10.0	1.1	8265.2	1.464	4.245
$\Sigma_N$	<b>88.2</b>	<b>10.3</b>	<b>1.5</b>	<b>6477.0</b>	<b>1.46</b>	<b>5.22</b>
	<b>86.8</b>	<b>11.4</b>	<b>1.8</b>	<b>6168.1</b>	<b>1.50</b>	<b>5.29</b>

Data source: author's own measurement

**Tab. 6** Grain-size analysis of landforms unaffected by wood – reference samples.

Sample ID	Samples from unaffected landforms					
	gravel (%)	sand (%)	silt (%)	d50 (µm)	sorting	kurtosis
1 <sub>R</sub>	98.1	1.6	0.3	4772.4	1.183	4.082
2 <sub>R</sub>	99.1	0.7	0.2	4527.8	1.138	4.110
3 <sub>R</sub>	99.5	0.4	0.1	5917.0	1.292	1.956
4 <sub>R</sub>	96.6	2.8	0.6	5109.5	1.247	4.650
5 <sub>R</sub>	94.6	2.8	2.6	5112.4	1.411	6.640
6 <sub>R</sub>	93.0	5.9	1.1	9008.7	1.401	4.657
7 <sub>R</sub>	88.2	8.8	2.9	8665.9	1.653	5.112
8 <sub>R</sub>	88.7	9.2	2.1	9694.3	1.503	5.377
9 <sub>R</sub>	96.9	2.1	1.1	4058.3	1.116	8.501
10 <sub>R</sub>	90.4	6.9	2.7	8829.1	1.707	4.678
11 <sub>R</sub>	91.5	7.0	1.5	9163.9	1.487	4.670
12 <sub>R</sub>	94.0	3.7	2.3	9194.5	1.624	4.670
13 <sub>R</sub>	91.8	6.2	2	9431.7	1.506	5.324
14 <sub>R</sub>	96.1	2.2	1.8	6207.5	1.474	4.988
15 <sub>R</sub>	97.1	2.5	0.4	4421.7	1.136	5.213
Σ <sub>R</sub>	94.4	4.2	1.4	6941	1.39	4.98

Data source: author's own measurement

The sorting analysis results show that the samples are poorly sorted, which is given by the character and length of sediment transport. The results also show that in-stream wood has no effect on the sorting of bed sediments in high-gradient streams.

By contrast, the kurtosis analysis points to the differences between the samples from stream segments containing in-stream wood and the reference segments. Although all the samples are extremely leptokurtic, the samples taken immediately downstream of wood accumulations show a higher degree of working than the samples from reference segments and pair samples taken immediately upstream of wood accumulations. This difference may be explained by the fact that wood accumulations slow down the progress of individual clasts through the stream basin, while the clasts immediately downstream of accumulations oppose the highest energy of water that is often carried over the accumulations by gravity.

### 4.3 Attributes of wood accumulations

*Number of wood pieces forming an accumulation* – The number of LWD pieces forming a wood accumulation is highly variable. Prevailing accumulations are those of up to 5 pieces that are prone to transformation, especially in reaches characterised by a higher channel gradient. On the other hand, large LWD accumulations of 11 and more pieces are not formed accidentally, but they are bound to structurally predisposed channel reaches. Large LWD accumulations of the studied areas are formed on large sandstone outcrops and in basin confluences.

Fig. 2 shows the distribution of wood accumulations in the study areas from the point of view of the number of wood pieces forming an accumulation. It is evident that the accumulations are formed outside spring areas as the streams need a necessary amount of kinetic energy. The largest and most voluminous known accumulation in the Moravskoslezské Beskydy Mts. consisting of 49 LDW pieces of the volume of 47.4 m<sup>3</sup> is found in ZT1.

*Site of the wood origin* – A characteristic feature of high-gradient streams is a high share of autochthonous wood, which can also be observed in the studied streams. Almost half (48.5%) of all accumulations is of autochthonous origin, while their share increases with decreasing drainage basin area. Combined accumulations hold a large share as well (41.5%) (Tab. 7) consisting of an autochthonous base in a form of wood fragments in the channel that becomes extended by smaller driftwood pieces brought by floods. Autochthonous accumulations can be identified all along the studied streams and their share slightly decreases with the drainage basin area. Allochthonous accumulations constituted of driftwood are considered rare in high-gradient streams with a share of about 10%. They only occur in the closing parts of the study areas where the streams are able to transport relatively large amounts of in-stream wood.

*Blocking, stabilising factor* – A dominant blocking factor (43%) causing the formation of accumulations in high-gradient streams is vegetation (Fig. 6), represented generally by pieces of uprooted trees. However, live standing trees may represent a blocking

Tab. 7 Types of accumulations according to the site of origin.

Accumulation types by the site of origin	Bučací potok	Mazák	ZT1	ZT2	ZT3	ZT4	Satina	Σ
ACCU total number (pcs)	21	76	34	10	24	8	33	130
autochthonous (pcs)	10	42	21	3	17	1	11	63
allochthonous (pcs)	3	7	3	1	2	1	3	13
combined (pcs)	8	27	10	6	5	6	19	54
autochthonous (%)	47.6	55.3	61.8	30	70.8	12.5	33.3	48.5%
allochthonous (%)	14.3	9.2	8.8	10	8.3	12.5	9.1	10%
combined (%)	38.1	35.5	29.4	60	20.8	75	57.6	41.5%

Data source: author's own measurement

factor in upper stream reaches. The blocking factor in erosion parts of streams is mainly boulders and rock steps (17%). The consistency and robustness of this blocking parameter enable the formation and long-term development of wood accumulations. Incidentally, three largest accumulations of the study areas are genetically conditioned by this factor. Blocking by streambed material (15%) can be observed in step-pool channel morphologies, where wood bunches up on steps during higher stream flow creating a base for accumulations.

*Morphological effect* – In-stream wood significantly diversifies the displays of the effect of water energy on the channel and banks of high-gradient streams in the study area. Erosion and accumulation forms (Tab. 8) of the effect of in-stream wood prevail in a form of distinct steps obstructing the

transport of material through the stream, decreasing its transport potential. This leads to material accumulating immediately upstream of wood accumulations and material deficiency immediately downstream of them. In other words, the presence of in-stream wood does not manifest itself solely by the presence of accumulation or erosion forms, but by the co-occurrence of both of these types in mutual interaction.

Although the main trend in the morphogenesis of high-gradient streams is channel deepening, an essential characteristic of the morphological effect of in-stream wood is different amount of retained sediments and increased channel ruggedness (Montgomery, Buffington 1998). In-stream wood thus often slows down the intensity of channel deepening, by which it becomes one of the basic eco-stabilising landscape factors helping to retain material and water in the landscape.

*Key member orientation* – The analysis results show (Fig. 7) that member orientation towards the stream's fastest flow is random. Both fluvial aspect (orientation around 0° and 180°) and slope aspect (orientation around 90° and 270°) can be observed. A fluvially modified orientation is typical of the Bučací potok brook and ZT1-4 of the Mazák stream, while a slope-conditioned orientation prevails in the Satina stream.

On the basis of the above, there is no universal key member orientation that would give rise to wood

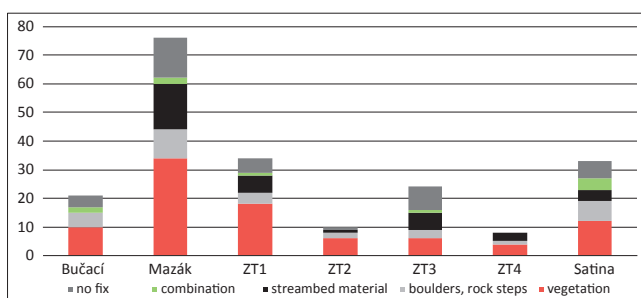


Fig. 6 Distribution of blocking mechanisms of wood accumulations.

Tab. 8 Morphological effect of in-stream wood.

Types of morphological effect	Bučací potok	Mazák	ZT1	ZT2	ZT3	ZT4	Satina	Share (%)
flow diversion, erosion	5	9	2	1	4	2	9	17.0%
backwater	1	4	3	0	0	1	3	5.9%
step	2	8	2	3	3	0	4	10.4%
step-pool	4	20	10	2	6	2	4	20.7%
sediments, accumulations	3	17	6	1	7	3	16	26.7%
no effect	6	17	7	3	7	0	3	19.3%
Σ	21	75	30	10	27	8	39	135 = 100%

Data source: author's own measurement

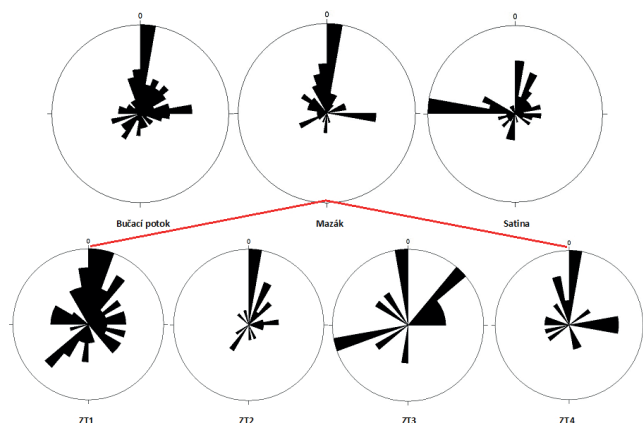


Fig. 7 Key member orientation.

accumulations. Whether an accumulation occurs in a given place depends rather on the morphometric parameters of wood and the given channel reach.

**Volume estimate** – Results of the analysis of wood accumulation volume characteristics show differences between individual streams (Tab. 9), especially when comparing ZT1 and other ZTs. ZT1 basin is characterised by a developed Carpathian primary forest with mid age of trees over one hundred years and therefore we can assume that the basin disposes of an extremely large amount of biomass, the volume of which is stable and maintained in constant values, considering the climax stage of the geosystem evolution. ZT1 basin contains 33.81 wood pieces per 100 m of the stream length stabilised in accumulations and 7.15 pcs of free woody material, which is almost 41 pcs of woody material of the minimum dimensions of 10 × 100 cm. Average total wood volume, including the pieces outside accumulations, is 36.6 m<sup>3</sup> per 100 m of the stream length.

If we accept one of the working hypotheses of this study that the natural state of geosystems guarantees a certain amount and volume of woody material in streams, then an average Carpathian stream running through the 4th to the 6th vegetation zone – altitudinal zonation: (4) beech, (5) beech-fir-spruce, (6) beech-spruce – should contain 30 to 40 m<sup>3</sup> of woody material per 100 m of the stream length. The fact that the summary wood volumes of the other streams are far

from the given hypothetical volume can be attributed, with regard to similar physical-geographical parameters of the channels, to the forest management prior to the proclamation of the streams as being under territorial protection.

#### 4.4 Multidimensional data analysis

Linear regression models combined with the ANOVA tool confirmed partial working hypotheses from correlation matrices (Tab. 10). Firstly, accumulation volume, at a confidence level  $\alpha = 0.001$ , has a significant impact on the accumulation width ( $r = 0.82$ ) and height ( $\alpha = 0.01$ ;  $r = 0.74$ ). These dependencies are common to both types of pair sampling (above/under accumulation) as they relate to the accumulation itself, not the sites of sampling immediately upstream or downstream of the accumulation. The models further confirmed the effect of woody material on sediment parameters which appears to be more significant downstream of an accumulation rather than upstream of it. The tests also showed a considerable impact on  $d_{50}$  parameter downstream of a wood accumulation ( $\alpha = 0.001$ ;  $r = -0.84$ ) and a less significant impact upstream of it ( $\alpha = 0.05$ ,  $r = -0.46$ ). Woody material has an impact also on gravel both upstream of an accumulation ( $\alpha = 0.05$ ,  $r = -0.48$ ) and downstream of it ( $\alpha = 0.05$ ,  $r = -0.67$ ). The impact of wood on the sandy fraction is also statistically significant, concretely in both the directions (upstream  $\alpha = 0.05$ ,  $r = 0.47$ ; downstream  $\alpha = 0.05$ ,  $r = 0.70$ ).

RDA analysis results show a distinct difference in the influence on the sedimentation zones downstream of a wood accumulation. Analysing the relation between the wood accumulation volume and other parameters we found that upstream of a wood accumulation the volume parameter can only explain 16.9% of the variability of the other morphometric parameters at a confidence level  $\alpha = 0.01$ . By contrast, the results are more revealing downstream of an accumulation, whereas 50.6% of the variability of morphometric parameters can be explained using the parameter of wood volume, namely at a lower confidence level  $\alpha = 0.001$ . Since wood accumulations act as sources of discontinuity in the transport of large clasts, an increase in accumulation volume leads to a decrease in  $D_{50}$  value. The bigger the accumulation

Tab. 9 Volume characteristics of wood accumulations.

Volume characteristics of the accumulations (m <sup>3</sup> )	Bučací potok	Mazák	ZT1	ZT2	ZT3	ZT4	Satina	Σ
min. accumulation volume	0.38	0.31	0.48	0.37	0.4	0.31	0.33	<b>0.31</b>
max. accumulation volume	5.37	47.44	47.44	7.5	2.11	2.98	20.15	<b>47.4</b>
average accumulation volume	2.26	3.61	7.71	1.62	0.49	1.86	5.51	<b>4</b>
total accumulation volume	47.56	274.12	231.4	16.19	11.7	14.87	181.68	<b>503.4</b>
average accumulation volume per 100 m	4.72	12.99	30.09	3.40	2.29	4.31	8.14	<b>9.40</b>
Σ in-stream wood volume per 100 m	<b>7.19</b>	<b>16.03</b>	<b>36.59</b>	<b>4.85</b>	<b>2.52</b>	<b>6.05</b>	<b>10.63</b>	<b>12.11</b>

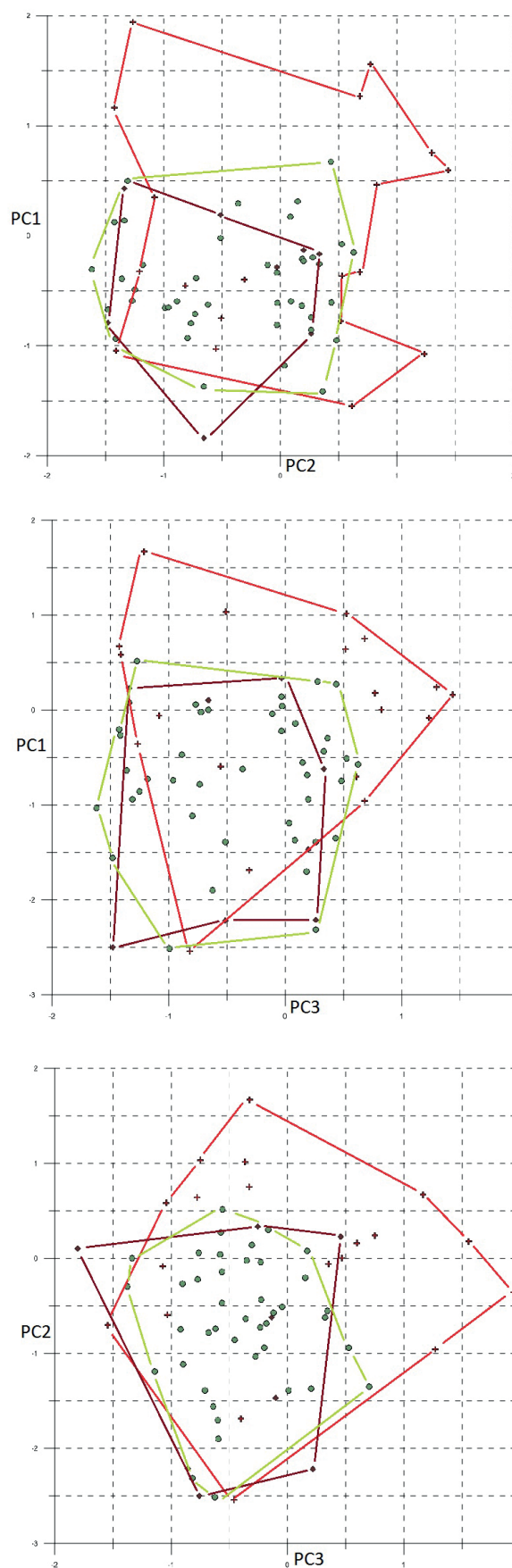
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**Tab. 10** Linear regression models + testing by means of ANOVA tool.

ACCU VOLUME n = 28	upstream of accu		downstream of accu	
	lm	glm.nb	lm	glm.nb
$d_{50}$	*		***	***
$d_{90}$		.		.
gradient				
sorting				
gravel	*		*	
sand	*	.	*	*
clay				
	common parameters			
	Lm		glm.nb	
height	**			
width	***			

lm – linear model; glm.nb – generalised linear model with negative binomial distribution; significance levels: 0 '\*\*\*', 0.001 '\*\*', 0.01 '\*', 0.05 '.', 0.1 ''

is, the wider the channel is and the finer the sediments are. This does not apply to absolute numbers, in the case of which  $d_{50}$  is smaller in sediments upstream of a wood accumulation, see Tab. 3, 4. The results of PCA analysis show (Fig. 8) that using the PC1, PC2 and PC3 components we can explain 77% of variability in the samples taken immediately upstream of an accumulation and this percentage is evenly distributed within all the three components (PC1 – 27.5%, PC2 – 23.3%, PC3 – 26.4%). PC1 component helps to identify similarity between  $D_{50}$  (0.83), gravel (0.61) and sand (0.63) within the n-environmental space. PC2 component reveals a relation between clay (0.88%) and sorting (0.57). PC3 component represents the gradient parameter (0.58). In the case of the samples taken immediately downstream of an accumulation, we can explain 89.5% of variability using the PC1, PC2 and PC3 components, whereas the distribution of samples within individual components is no longer even. The majority of the samples (gravel – 0.95; sand – 0.91; clay – 0.86; sorting – 0.93) falls within PC1 component, which explains the variability of 46.3% of samples. PC2 component explains 27.6% of sample variability with a significant representation of  $D_{50}$  parameter (0.92). PC3 component explains 15.6% of sample variability with a significant representation of gradient parameter only (0.93). With respect to reference samples, the PC1, PC2 and PC3 components can explain 86.8% of sample variability with a dominating PC1 component (61.2%), within which a significant representation is that of  $D_{50}$  parameter (0.81%), gradient (0.68), width (0.70), sorting (0.81), gravel (0.94), sand (0.87) and clay (0.69). The parameter of kurtosis (0.94) belongs to PC2 component (13.8%). The last PC3 component explains 11.8% of sample variability with a significant representation of the  $D_{50}$  parameter. Comparing the PC1 samples



**Fig. 8** Sampling within individual components: red – samples taken immediately upstream of an accumulation, brown – samples taken immediately downstream of an accumulation, green – reference samples.

taken immediately downstream of an accumulation and reference samples, we can identify factors that are correlated regardless of the presence of woody material. These factors are represented by the grain-size parameter and the sorting parameter. Apparent differences between the values of the samples taken downstream of an accumulation and reference samples in the case of  $D_{50}$ , gradient and width parameters can be attributed to the impact of woody material that takes on the role of a geomorphological factor, helping to create these parameters downstream of an accumulation. As for the samples taken immediately above an accumulation, there is a distinct correlation of  $D_{50}$  parameter, which supports the above conclusions of linear regression models. Also in PCA analysis  $D_{90}$  proves to be an independent variable parameter unaffected significantly by woody material or any other channel parameter. There is only a weak correlation between the gradient, showing a moderate correlation at the boundary of statistical significance  $<0.1$ , with the wood downstream of a woody accumulation.

## 5. Discussion

Many of the conclusions of this study are consistent with the results of scientific works published in foreign literature. Contradictions can mainly be found in some parameters of sedimentological analyses. Unlike the study of Máčka and Krejčí dealing with the Bílá Opava River (Máčka, Krejčí 2011), woody material showed no significant effect on sediment sorting. All samples are poorly sorted; a tendency towards better sorting can only be observed in the lowest reaches of the studied streams. This difference is partly attributed to the fact that our study is strictly aimed at high-gradient streams and partly at the specificities of flysch bedrock. On the other hand, the results fully confirmed the conclusion of the two above mentioned authors concerning the difference between sediments occurring upstream and downstream of accumulations, namely that the sediments upstream of accumulations were finer than those downstream of accumulations. Although the absolute size of grains is different (sediments in the study areas are 2.5 times coarser than those in the above-mentioned study), the size upstream of accumulations relative to that downstream of accumulations is in both studies almost identical, while the size of grains upstream of accumulations reaches 80% of the grain size downstream of accumulations.

In terms of wood quantity, the comparison with North American studies shows differences in long-term forest management in the study areas. Bragg (2000) states 24–118 pcs of in-stream wood per 100 m of the stream length. A similar wood distribution is presented in the study of Kaczky (1999) who states 26 pcs/100 m. Some authors (Gregory et al. 1993) state the value of around 40 pcs of LWD for

small natural streams, which is supported by the natural forest character in ZT1 and upper reaches of the Satina River, from where similar values are reported. The dimensions of individual wood pieces correspond to the parameters found in other studies (Gurnell 2002; Baillie, Davies 2002).

The research further indicates that the channels of the study streams contain 2–3 times smaller volume of in-stream wood than comparable streams abroad and this difference increases with the age of accompanying vegetation (Brooks et al. 2003) and rainfall totals in the basin (Bilby, Naiman 1988; Bragg et al. 2000). Brooks (2003) states that primary forest ecosystems contain 4 times bigger amount of in-stream wood than a 120-year-old forest with a natural species composition. The precipitation amount manifests itself by the differences in the volume of in-stream wood, namely in primary forest ecosystems. For example, the streams draining mountains in the state of Washington (USA) contain up to twice as high volume of in-stream wood in the channel (generally more than  $50 \text{ m}^3/100 \text{ m}$ ) as the streams draining the mountains in the state of Wyoming (USA), which contain less than  $50 \text{ m}^3$  of wood. The rainfall totals in Washington reach up to  $6000 \text{ mm/m}^2$ , while in Wyoming up to  $1800 \text{ mm/m}^2$ , which is comparable with the area of the Moravskoslezské Beskydy Mts. There are  $36.6 \text{ m}^3$  of wood in ZT1, which drains primary forest ecosystems, whereas the range of volume 30–40 ( $45 \text{ m}^3$ ) can be considered average maximum amount of in-stream wood in high-gradient streams in the Central European space (Herring et al. 2000).

The morphological effect of in-stream wood is enormous and the share of accumulations that affect the morphology reaches 80%, erosion-accumulation effect being predominant (37%). The research proved the assumption that in-stream wood grouped in wood accumulations increases the presence of stream pools in the channel (Ballie, Davies 2002). Dahlström and Nilsson (2004) state that 34% of pools evolved due to the presence of in-stream wood, whereas this share is even higher and exceeds 36% in the study areas. In reaches with a natural forest of the type of primary forest, the origin of as many as 46% of pools is related to the presence of wood accumulations and woody steps. It should be noted that the percentage of these pools is variable and there are major differences between individual studies (Ballie, Davies 2002).

In-stream wood actively participates in the morphogenesis of the study areas. It increases the roughness of the streambed producing related erosion-accumulation channel microforms and changing the sedimentological parameters of adjacent channel reaches. It can be assumed that the intensity of this impact will increase with gradual restoration of natural ecosystems to the original state typical of mountain forest communities of Central Europe.

## 6. Conclusions

In-stream wood is an important agent forming the character of high-gradient streams in the Moravskoslezské Beskydy Mts. Its amount and importance increase with increasing age of forests and in connection with the long-term forest management. The study areas contain 14.7 pcs of in-stream wood per 100 m of the stream length bound in accumulations and 4.6 pcs outside accumulations of the total volume of 12.11 m<sup>3</sup>/100 m. The volume of the wood in the studied streams is several times lower than in comparable streams abroad. Only ZT1 with its parameters is close to the natural state that would exist in the Moravskoslezské Beskydy Mts. if all anthropogenic activities were excluded from the area.

Sediment sample analysis indicates that in-stream wood changes sediment deposition. Pair sampling proved differences between sediments in the vicinity of accumulations with sediment fining immediately upstream of accumulations and sediment coarsening downstream of them. Measured  $d_{50}$  difference between samples upstream and downstream of accumulations is 1.97 cm. By contrast, sorting analysis failed to prove the impact of in-stream wood on sediment sorting; its influence on the character of sediment transport is also negligible.

Wood influences erosion-accumulation parameters of streams. A single accumulation gives rise to both erosion and accumulation landforms in 37% of the cases. Erosion landforms are generally found downstream of accumulations where they take the form of plunge pools, stream pools, eversion potholes and bank scours. Accumulation forms such as gravel bars and those of fine organic material of various origin are found upstream of wood accumulations.

The total of 90% of the wood accumulations in high-gradient streams are of the autochthonous or combined origin. Any stream is able to transport mainly FWD. The transport of LWD occurs especially during flood discharges. This is supported also by the analysis of blocking mechanisms revealing that the most frequent blocking elements are tree members fallen from slopes. A tree thus blocks the channel in the place where it grew without being transported to lower channel reaches.

The analysis of the orientation of key members failed to prove that a certain member orientation more than any other would lead to the formation and evolution of wood accumulations. The origin and development of wood accumulations are rather affected by the weight and dimensions of woody material and the morphological character of the channel in the vicinity of the fallen tree.

Statistical testing proved the impact of in-stream woody debris on the channel parameters. Being significant particularly downstream of a wood accumulation, the impact of in-stream wood is related to the  $d_{50}$  parameter, channel height and width, and changes

in the share of gravel and sand. In-stream woody has a minimum effect on sediment sorting and kurtosis as well as on the  $D_{90}$  parameter that acts as an independent variable.

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