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The Significance of Log and Boulder Steps for Diversification of Fluvial Sediments Characteristics in a Stream Channel in a Small Forest Catchment in the Polish Carpathians

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Abstract: The study presents the diversification of sediments deposited on log (LS), boulder (BS) and mixed-type (LBS) steps located in the channel of a stream in a small forest mountain catchment in the Polish Carpathians. The topic of sediment diversification in a stream channel is an important issue not only from the perspective of sediment transport process and shaping fluvial systems in forested catchments caused by woody or rock debris but also in the context of functioning of local ecosystems. We aimed to test the following hypothesis: the morphodynamic features of a stream channel and the type of steps therein significantly affect the diversification of the size and shape of mineral deposits and play an important role in the process of sediments transport and processing in the channels of small mountain streams. In order to verify the above hypothesis, sediments were sampled directly from the stream channel (Ch) in its longitudinal profile as well as upstream and downstream of steps (LS, BS and LBS) in the channel. The diversification of features of sediment grain size was analysed taking into account step type and sediment location in the longitudinal profile of the stream channel. The research was conducted separately for fine-grained sandstone (A) and coarse-grained sandstone (B). In addition, the basic sedimentological indicators and the shape parameter of the gravels, as described by the Zingg method, were determined. In order to determine the transport predisposition of the sediments in a specific load, an analysis of sediment distribution was performed on the C/M (C—first percentile and M—median) diagram. The PCA (Principal component analysis) analysis showed that the step type significantly affects the processing as well as the size and shape diversification of mineral deposits, which confirms our hypothesis. Therefore, this study is a contribution to the current knowledge on fluvial processes occurring in stream channels in small forest mountain catchments.

Keywords: forest; catchment; stream channel; log step; woody debris; sandstone; sediments; granulometric indicators

1. Introduction

The question of processes of erosion, transport and accumulation of mineral sediments in mountain river and stream channels is the focus of research for numerous researchers [1–4]. Analyses of alluvial sediment characteristics have mainly focused on reduction in bed material size downstream [5–7] because the granulometric composition of fluvial sediments is one of the most important factors which determine changes in stream and river morphology [8]. Downstream decrease in sediment size can be caused by many mechanisms, such as abrasion [5], flow regime (cumulative sediment transport during infrequent, high-magnitude floods) [9] and selective transport [10].

Among important factors involved in the differentiation of mineral material features is the occurrence of steps formed along a stream channel out of woody debris (LS) [6] and rock debris (BS) [11,12], which become the places of deposition of mineral sediments [13], large woody debris (LWD), fine woody debris (FWD) [14] and particulate organic matter (POM) [15]. There are many differences in the effect of woody debris (LWD and FWD) on fluvial forms and processes between lowland and mountain streams [16,17]. In forest mountain catchments, woody debris in the form of dead trees or their fragments is supplied to stream channels by windblow, rubble and mud downflow, landslides, avalanches, forest management activities or the activity of beavers [18,19]. It plays an important role in bedload transport [20]. Moreover, woody debris has strong control of the frequency of pools and bars and can create significant hydraulic roughness, influencing flow velocity, discharge, shear stress, bedload transport and a greater sediment fraction diversification [21]. Log steps increase channel roughness and hence reduce flow velocity [6], which means that the transported sediments of different fractions are introduced into the fluvial system gradually, mainly during high flows [22].

Numerous authors have emphasized the role of woody debris in the development of obstacles and traps for the transported mineral material [6,23–25]. In the case of small mountain catchments, the transport of sediments in stream channels usually takes place along short sections, the sediments are deposited mainly upstream of the steps [26], which results in local aggradation of the bed upstream of the steps [22]. Log steps influence the distribution of erosion and deposition reaches, armor the channels and form local base-levels [27]. The presence of woody debris in a stream channel also affects the functioning of local ecosystems [6,28]. FWD is an important habitat component of streams because it provides shelter for small fish. The growth of mid-channel bars around log steps as a result of sediment deposition may be important in the development of meandering stream channels and may constitute living space for some of the river benthos and insects.

Many mechanisms that determine the transport and processing of deposits in the fluvial system have been recognised and described [1,2,29]. However, the significance of log and boulder steps in mountain river and stream channels for sustainability remains a highly interesting research topic due to the complexity of the phenomenon. For this reason, the aim of the study is to provide a greater understanding of sediment indicator changes at a local scale within small mountain catchments in forests. Therefore, this study is a contribution to the current knowledge on fluvial processes occurring in stream channels in small forest mountain catchments.

2. Materials and Methods

2.1. Study Area

The research area is located in the Silesian Beskidy Mts. (Polish Carpathians) within the Wisła Forest District, Istebna Forest Range (Figure 1). The object of research is the Dupniański Stream, a right-bank tributary of the Olza River, flowing in a catchment area of 1.74 km^2. The maximum terrain elevation within the catchment is 882 m above sea level, the minimum is 493 m above sea level while the sources of the stream are located at an altitude of 805 m above sea level [30]. The stream flows in a V-shaped valley running north-southwards. In the geological structure of the catchment, there are sedimentary rocks of the Istebna and Godula layers, which were formed as syliciclastic formations, mainly Istebna and Godula sandstones built of quartz, feldspar and mica, connected by ferrous, quartz or clay binder [31]. These sandstones are characterized by low resistance to weathering processes.

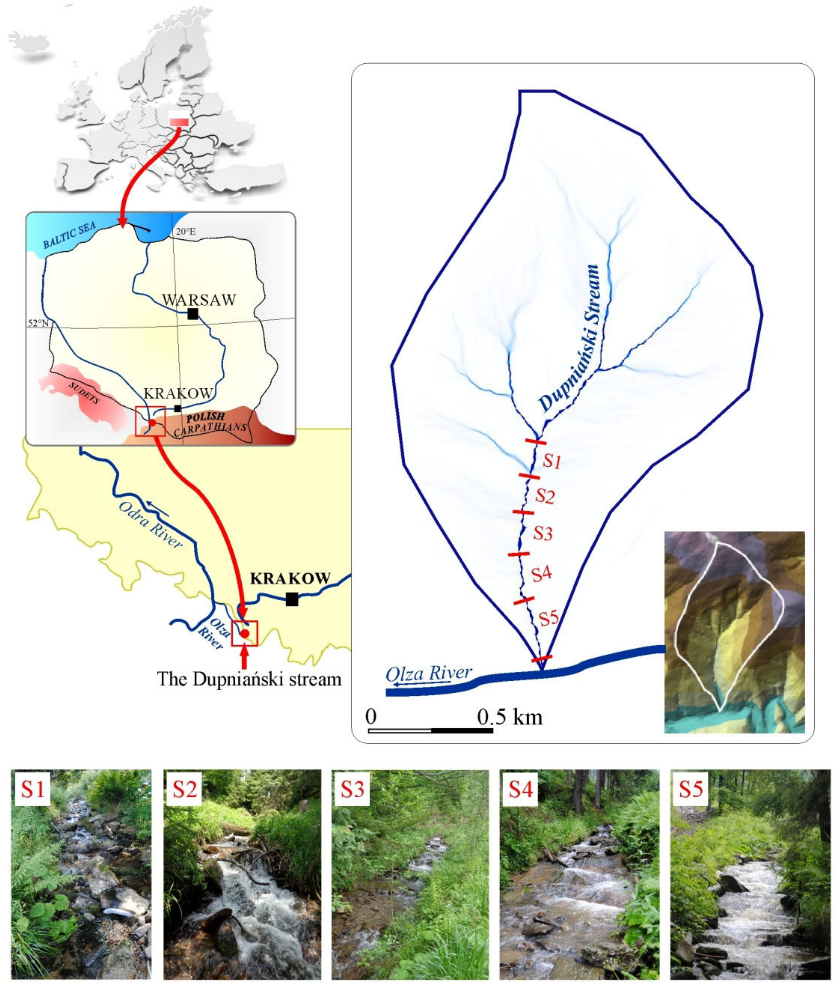


Figure 1. Location of the Dupniański Stream catchment with sections of the stream channel (**S1–S5**).

The stream catchment is located in the moderate climate zone affected mainly by polar maritime air masses. Due to its altitude, the area is located within two climatic zones: moderately warm and moderately cool. The average annual air temperature is 5.3 °C (min. 2.63 °C and max. 9.39 °C), and the total annual precipitation varies in the range of 1045–1250 mm (data for the years 1957–2006) [32]. The research area is characterised by a high share of forest cover (63%), with a negligible share of arable land (5%) and non-forest land (32%) (areas periodically devoid of forest due to pest gradation (*Ips typographus)*, but preserves the forest undergrowth layer as well as areas excluded from forest management because they have functions other than productive, i.e., meadows, pastures and spring areas). The main forest-creating species are spruce (*Picea abies*), beech (*Fagus sylvatica* L.), fir (*Abies alba Mill*) and pine (*Pinus sylvestris* L.).

2.2. Morphodynamic Characteristics of the Stream Channel Sections

The channel of the Dupniański Stream, for which the total length is 2080 m, is narrow and at its considerable length cut in the rock. The channel width ranges from 0.8 m to 3.5 m (1.7 m on average). Field measurements, made in accordance with the river channel mapping instructions [33], were performed to distinguish five research sections (S1–S5) (Figure 1), differentiated in terms of morphodynamic features [34].

The section located highest in the longitudinal profile of the analysed stream channel is section S1 with the length of 177 m and the terrain slope of 11%. In this section, the channel is narrow (up to 1.4 m) and deeper than in the other sections. Along the channel, within slope covers, there are lateral erosion undercuts with heights from 0.3 m to 1 m, which indicate evident contact between the slope system and the stream channel system. Slope covers are the effects of flysch rock weathering transformed in the upper part by soil processes, which undergo transport or splitting as a result of morphogenetic processes, such as landslides and linear erosion. Sandstone outcrops are also locally undercut. In the riverbed, there are scarce boulders and rock outcrops as well as several-meters-long local accumulation zones, formed above the steps. The study did not cover the stream channel section from S1 towards the stream sources due to the very narrow rock bed and the lack of steps and sediments in the channel. Section S2 is characterized by a length of 418 m, an average width of 1.7 m and a terrain slope of 8%. In the central part of this section, the channel is winding and its course is forced by the presence of colluvial deposits in the valley bottom, which are periodically undercut and constitute a source of mineral material supplied to the fluvial system. Colluvia form sharp-edged sandstone pieces with diversified fractions as well as clayey effects of the weathering of mudstones and shales. The channel has sharp-edged material as well as rounded gravel material. Part of the sharp-edged material is pieces of sandstones from the colluvia being cut. The channel bed in this section is based mainly on coarse fraction rock debris. At the convex edges, point bars with a length of 1.6 m and a width of 1.0 m were developed. Section S3 has a length of 156 m, an average width of 2.0 m and a terrain slope of 7%. Along this section, intensification of the lateral erosion process is clearly visible (older forms of fluvial accumulation are undercut), which results in an increase in the channel's meanders. Section S4 is the shortest section of the Dupniański Stream channel (86 m long), with undercuts of older alluvia. The channel with a 9% terrain slope and a width ranging from 1.2 m to 2.0 m is formed in thick-bedded Istebna sandstones. The last selected section is S5, for which the length amounts to 230 m while the terrain slope is 6%. In its horizontal dimension, the channel is straight with an average width of 1.6 m, cut in the bedrock. This is a consequent divergent channel section [35]. The lower part of the section is characterized by the lack of clear contact of the channel system with the slope system, while in the upper part, there are local undercuts of lateral erosion within older alluvia. In the case of the Dupniański Stream bed (as for other, similar streams in small Carpathian catchments), the presence of a real floodplain is rare. The valley bottom is formed by permanent bars, added to only rarely during high-water periods.

The source of supply of mineral material to the Dupniański Stream channel in the upper part of the catchment, i.e., along sections S1 and S2, are slope covers, including colluvia undercut by lateral erosion and rock outcrops. The remaining channel sections, i.e., S3 and S5, are characterized by the lack of direct contact on both sides between the slope system and the riverbed, and the fresh mineral material supplied to the channel system comes mainly from the riverbed or from undercuts of lateral erosion within older, permanent bars.

2.3. Inventory of Steps in the Longitudinal Channel Profile

As part of field measurements, a walking inspection was done along the longitudinal profile of the stream for the purpose of inventorying of log steps (LS), boulder steps (BS) and mixed-type, i.e., log-and-boulder steps (LBS) in the stream channel. Step is a channel section upstream of a weir formed out of woody or boulder debris. Step location in the profile was identified using a GPS device (Garmin GPSMAP (Olathe, Kansas, USA)). At the same time, measurements were taken of basic geometrical parameters of the steps, i.e., their height (H) and width (W). The measurements of elevation of the step were performed in the center of each step.

2.4. Mineral Material Sampling

Mineral material for testing was sampled from accumulation points upstream and downstream of steps (LS, BS and LBS) as well as from the channel bed between the steps. For the purpose of gravel shape analysis, five additional samples (P1–P5) were collected apart from the deposits (Ch). The deposits were collected by the handpicking method, belonging to surface methods [36], from an area of 1 m^2, using a frame. They were placed in containers and transported to the laboratory.

2.5. Mineral Material Analysis

2.5.1. Granulometric Composition

The starting point to characterize the sediment grain size was to conduct a granulometric composition analysis. In view of grain diversity of the sandstones present in the catchment, particles of fine-grained (A) and coarse (B) sandstone were selected in each sample prior to the analysis (Figure 2). Sieve analysis was used to determine the granulometric composition of sediments with the grain diameter greater than or equal to 2 mm [37], while the grain size of the sediments with a diameter smaller than 2 mm was determined by laser diffraction [38].

(A) (B)

Figure 2. Gravels consisting of **(A)** fine-grained sandstone and **(B)** coarse-grained sandstone

2.5.2. Determination of the Gravel Shape Parameters

During sediment transport in the stream channel, apart from changes in the diameter of grains [39], their shape changes as well [40]. Considering the above, the shape of gravels as three-dimensional solids was determined by the method proposed by Zingg [41,42], separately for fine-grained (A) and coarse-grained (B) sandstone. The length of each of the three axes was measured with calipers with an accuracy of 0.01 mm. Next, the following relationships were determined: 1) the ratio of the length of the medium axis (b) to the longest axis (a) (the so-called elongation measure) and 2) the ratio of the length of the shortest axis (c) to length (b) (the so-called flattening measure) in order to develop Zingg diagrams and to assign the gravels to one of 4 shape categories: spheroidal, discoidal, bladed and rod-shaped [41].

2.6. Basic Sedimentological Indicators of the Sediments

The basic sedimentological indicators were calculated according to [43], namely mean grain diameter (Mz), standard deviation (σ_1), skewness (Sk), kurtosis (Kg) and diameter d_{50}. The calculations were performed using the granulometric analysis software [44]. Also, the degree of sorting of the sediment and the type of grain size distribution were determined. The location of the samples was determined in the C/M diagram (C—first percentile and M—median) [45]. The differences in the grain size distribution of the sediment as well as the sedimentological indicators were analysed separately for steps (LS, BS and LBS) and for the stream channel (Ch) along the longitudinal profile.

2.7. Statistical Analysis of Sedimentological Indicators of the Mineral Material

The aim of this paper is to characterize sedimentological indicators and sorting trends and to compare sediments sampled from steps LS, BS and LBS and from the stream channel (Ch) in a small mountainous catchment. The sedimentological indicators were tested in terms of distribution normality using the Shapiro–Wilk test [46]. Next, it was examined whether differences in sediments in selected sections of the stream are significant for the analysed variables (Kruskal–Wallis test) and whether the differences between mixed-type steps (LBS) and the other types, LS and BS, are significant for these variables (Mann–Whitney U test). ANOVA variance analysis was carried out to investigate the differences between the means calculated for the variables. The variables were selected to represent the sediments collected upstream and downstream of the steps (LS, BS and LBS) as well as those sampled from the stream channel (Ch). In order to objectively select independent factors explaining differences between the variables, principal component analysis (PCA) was performed. Identification of the number of factors explaining the relationship between the analysed sediments and the type of steps (LS, BS and LBS) as well as their location in the longitudinal profile was carried out according to the Kaiser criterion [46], which states that the analysis was carried out only on factors for which eigenvalues (variances extracted by the factors) were greater than 1. Statistical significance assumed for analysis was 0.05 [47].

3. Results and Discussion

3.1. Characteristics of Steps Located in the Stream Channel

Field research done along the stream channel allowed for inventorying 11 LS steps formed on active dams [48], 6 BS steps and 3 mixed LBS steps, constituting a combination of LS and BS (Figure 3). Most step LSs were found in sections S1 and S2, characterized by small channel width. Deposition of thick woody debris in such channels occurs in a disorderly manner in places of direct supply of felled trees from banks and slopes [49]. LS steps are organic steps formed on dead logs anchored on both banks of the stream channel [6,50]. The average height of LS steps occurring in the channel is 0.4 m, and the width is 1.6 m (Figure 4).

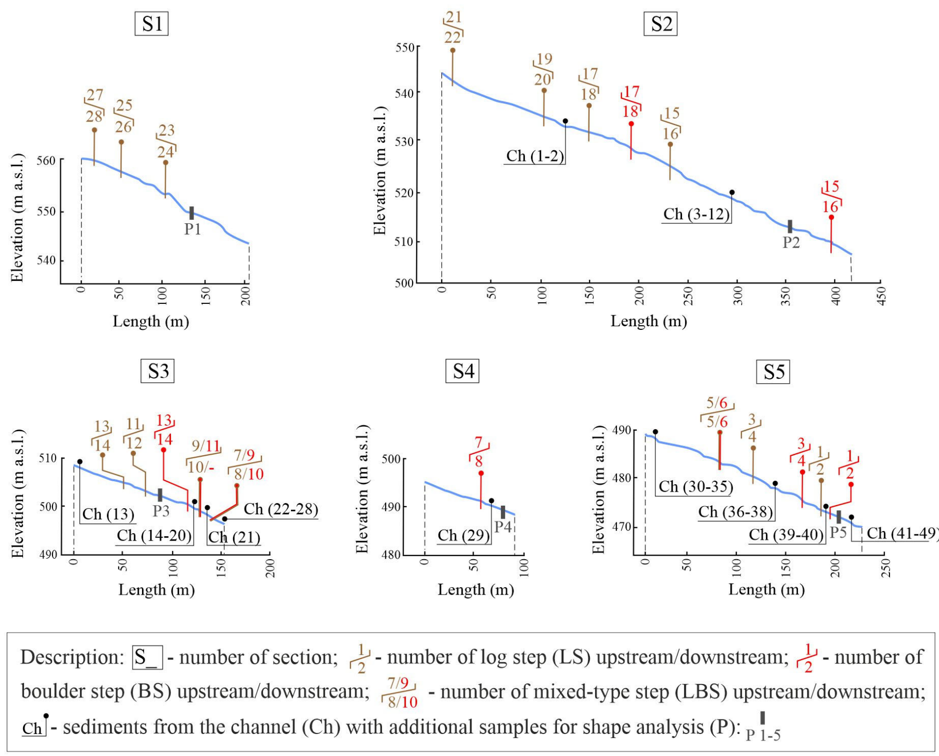


Figure 3. Location of steps in the channel's longitudinal profile in sections (**S1–S5**) together with marked places of sediment sampling from the steps (log step (LS), boulder step (BS) and mixed-type step (LBS)) and from the channel (Ch and P); (S–)—number of section, (1/2)—number of log step, (LS)—upstream/downstream, (1/2)—number of boulder step, (BS)—upstream/downstream, (7/9)/(8/10)—number of mixed-type step, (LBS)—upstream/downstream.

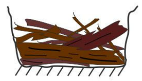
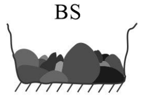
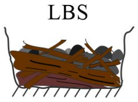
Type of the step	Number	H (m)	W (m)	d_{50} (mm) (u)	d_{50} (mm) (d)	Mz (phi) (u)	Mz (phi) (d)	σ_1 (u)	σ_1 (d)	Sk (u)	Sk (d)	Kg (u)	Kg (d)
 LS 	1/2	0.50	1.00	32.0	29.0	-4.84	-4.27	2.58	3.22	0.65	0.65	7.21	5.91
	3/4	0.45	1.30	25.5	13.8	-4.54	-3.35	2.58	1.66	0.58	0.50	9.81	1.23
	11/12	0.32	0.80	0.1	23.0	4.63	-3.66	2.76	3.17	0.13	0.78	0.85	3.50
	13/14	0.30	1.60	30.4	24.5	-3.48	-0.29	3.58	5.93	0.86	0.89	4.97	0.65
	15/16	0.35	1.60	1.0	-	2.57	-	4.63	-	0.69	-	0.48	-
	17/18	0.40	1.30	-	-	-	-	-	-	-	-	-	-
	19/20	0.36	1.28	31.5	18.4	-3.85	-3.29	3.51	3.35	0.78	0.73	3.42	2.18
	21/22	0.30	2.70	29.0	10.0	-4.86	5.40	1.54	4.34	0.40	-0.48	3.95	0.67
	23/24	1.10	2.10	1.5	36.0	1.67	-4.91	5.41	1.54	0.48	0.44	0.60	1.94
	25/26	0.44	1.30	0.1	0.1	5.57	5.12	4.32	4.48	-0.57	-0.45	0.50	0.51
	27/28	0.30	0.78	0.1	1.9	3.84	1.58	5.08	5.33	-0.13	0.57	0.54	0.64
 BS 	1/2	0.50	1.30	22.5	27.5	-3.95	-4.03	2.08	1.53	0.54	0.64	0.66	0.64
	3/4	0.35	2.45	26.0	59.5	-4.73	-5.73	1.54	1.10	0.36	0.52	5.96	2.05
	7/8	0.45	1.30	20.6	3.6	-3.69	-2.33	1.99	1.28	0.78	-0.58	0.56	1.97
	13/14	0.30	1.65	-	-	-	-	-	-	-	-	-	-
	15/16	0.40	1.60	24.0	39.0	-3.14	-3.27	2.01	1.58	-0.53	-0.15	0.58	0.57
	17/18	0.45	1.50	24.6	56.0	-3.27	-4.60	2.25	2.00	-0.22	0.74	0.57	0.52
 LBS 	5/6 - 5/6	0.20	1.80	31.5	30.0	-4.97	-4.97	0.42	0.53	0.05	-0.26	0.74	0.96
						-4.97	-4.97	0.42	0.53	0.05	-0.26	0.74	0.96
	7/8 - 9/10	1.30	2.30	10.0	60.0	2.46	-6.25	4.71	1.38	0.66	0.39	0.50	1.13
						-2.93	-4.67	1.94	1.41	-0.45	0.48	0.64	1.63
	9/10 - 11/12	0.90	1.65	25.0	33.0	-2.73	-3.29	4.12	3.70	0.87	0.84	2.56	3.35
						-2.91	-1.76	2.04	0.60	0.01	-0.19	0.50	1.20

Figure 4. Characteristics of step parameters (LS, BS and LBS) in the channel's longitudinal profile: H—height of the step, W—width of the step, d_{50}—mean diameter of mineral material, Mz—mean grain diameter, σ_1—sediment sorting, Sk—skewness, Kg—kurtosis, u—upstream of the step, d—downstream of the step and "–"—no deposits.

Boulder steps (BS), mainly in the form of boulder clusters and rock bars [51], were observed in sections S2, S3, S4 and S5 (Figure 3). These are steps with the average height of 0.45 m and width of 1.8 m, located mainly between the LS steps. In sections S3 and S5, three mixed-type steps (LBS), consisting of both boulder and log steps, were noted (Figure 3). These steps are characterized by the combined occurrence of rock outcrops or coarse rock debris, fragments of dead LWD [6] and accumulations of FWD in the form of large and small branches. Section S3 is characterized by marked intensification of the lateral erosion process, which is reflected in an increase in channel sinuosity, resulting in the accumulation of rock and woody debris, which facilitates the formation of steps in the channel. The shortest of the selected channel sections is S4, characterized by considerable terrain slope in the longitudinal profile. Only 1 rock step (BS 7/8) was noted in this section. S5 is the last channel section, with the lowest location. In this section, as in S3, 2 LS steps, 2 BS steps and 1 LBS step were noted. These steps are located interchangeably and thus form a stepped longitudinal profile of the channel [22].

The presence of numerous steps in the Dupniański Stream channel determines the formation of a stepped longitudinal profile, typical for mountain streams [22], which facilitates sediment retention and sorting. Upstream of the steps, there occurs mineral material deposition, while downstream, there is sediment leaching and the formation of overdeepenings or plunge pools [23].

3.2. Sediment Heterogeneity in the Longitudinal Profile of the Stream Channel

Sediments in the longitudinal profile of the Dupniański Stream channel are characterized by very high grain size variability and extremely varied degrees of sorting (Figure 5). The results obtained show evident differences between deposits related to different types of steps and deposits sampled directly from the stream channel. The PCA confirmed the diversification of values of the analysed features (Figure 6).

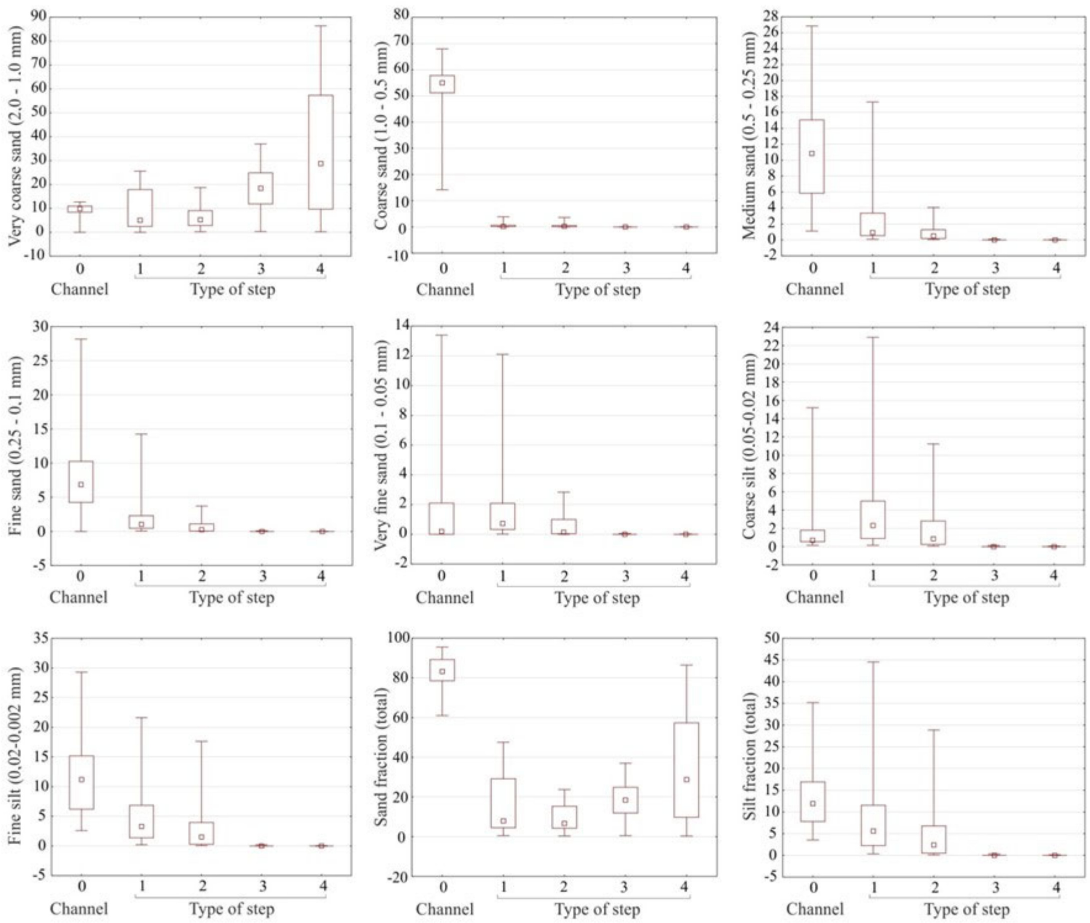


Figure 5. Differences between average values of standard deviations (σ_1) of fraction of sediments sampled from 0—stream channel (Ch), 1—LS (upstream of log step), 2—LS (downstream of log step), 3—BS (upstream of boulder step) and 4—BS (downstream of boulder step).

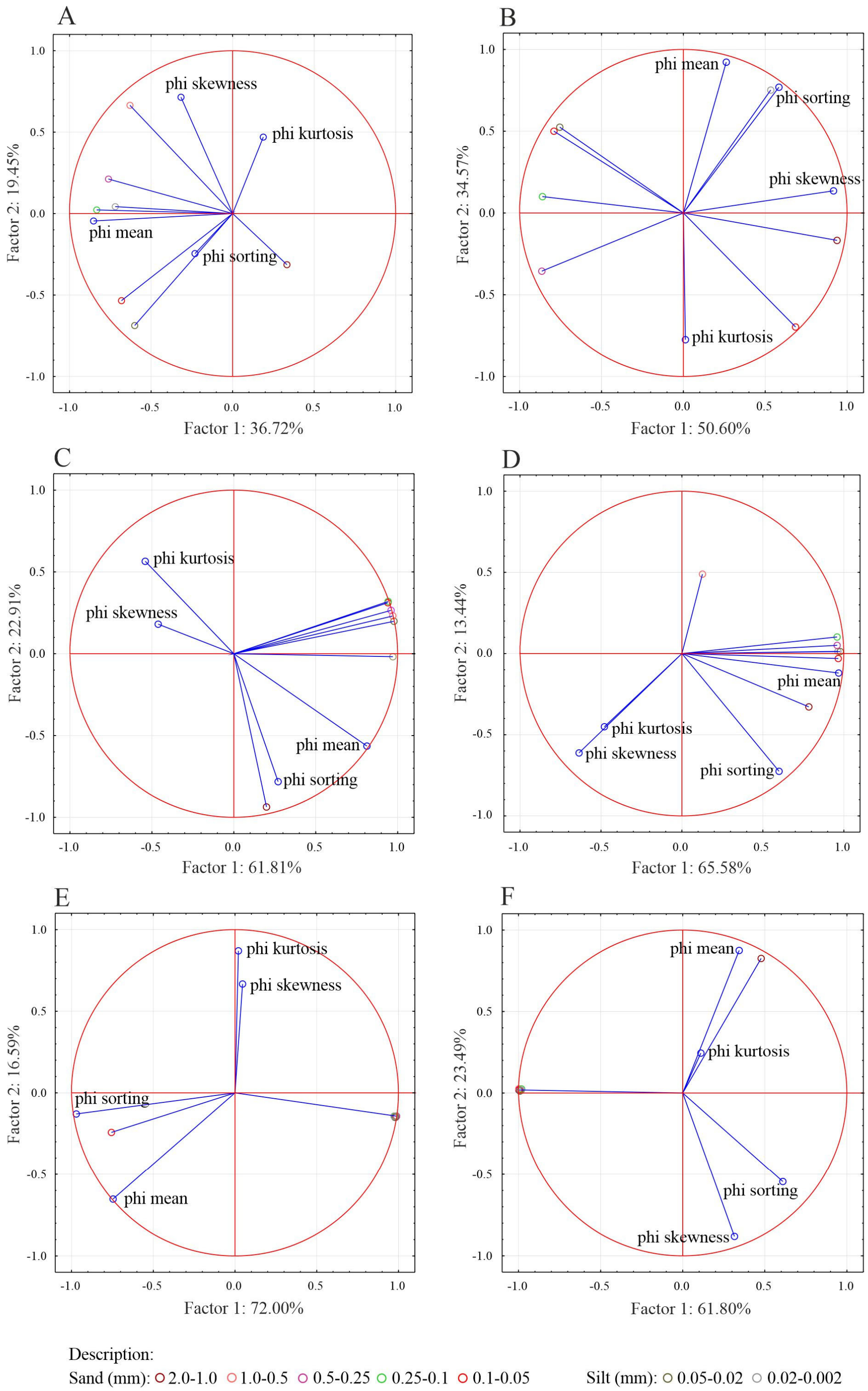


Figure 6. Projection of variables on the factor plane (Principal component analysis (PCA)): (**A**) all variables together (based on correlation); (**B**) sediments from the channel (Ch); (**C**) sediments from LS (upstream); (**D**) sediments from LS (downstream); (**E**) sediments from BS (upstream); (**F**) sediments from BS (downstream).

The most varied sediments—with poly-, tri-, bi- or unimodal grain size distribution—occur in the S1 upper channel section, where three steps of woody debris (LS) were identified. The diversification of the grain size distribution of these deposits is also confirmed by the range of skewness values (Sk = −0.57–(+0.57)). These deposits are usually extremely weakly sorted, and the average grain diameter (Mz) ranges from −4.91 to +5.57 phi (Figure 7). Relatively low values of kurtosis (Kg < 2) indicate pulsating energy changes during sediment deposition with a tendency to transport or erosion. The values of all sedimentological indicators point to short transport of sediments, their rapid deposition and periodic supply of fresh material [42]. The features of the mineral sediments clearly reflect the morphodynamic conditions in the upper channel section. The channel here is characterized by significant terrain slope; there are lateral erosion undercuts within the slope covers, which indicate a clear contact of the slope system with the channel system. All three LS steps located in this section of the channel are steps which retain mineral material of various fractions. The material retained upstream of these steps is extremely weakly sorted and is characterized by a much larger grain size variability than the sediments deposited downstream of the steps [42].

In the middle part of the longitudinal channel profile (S2, S3 and S4), mineral sediments are characterized by greater diversification of the degrees of sorting (from moderately good to extremely weak) than in the upper section. Extremely poorly sorted ($\sigma_1 > 4$) are the deposits associated with woody debris (LS and LBS). Relatively better sorting characterizes sediments associated with rock debris (BS and LBS) and most of the sediments sampled directly from the stream channel (Ch) (Figure 7). Sediments in the middle channel section are characterized by considerable grain size variability (Mz = −6.25–(+5.57) phi). These features reveal a clear distinction between deposits associated with particular step types (LS, BS or LBS) and deposits collected from the channel (Ch). The mineral material deposited upstream of the LS steps contains from 0% to 90.96% sediments with the fraction of ≥2 mm, and the average grain diameter (Mz) assumes values ranging from −4.86 to (+4.63) phi. Sediments upstream of the LS steps are weakly, very weakly or extremely weakly sorted. They are also characterized by diversified grain size distribution: usually unimodal but also bi- and trimodal. Sediments collected downstream of the LS steps contain 8.33–85.47% of deposits with the fraction of ≥ 2 mm, and the mean grain diameter assumes values in a fairly wide range (Mz = −3.66–(+5.40) phi). Sediments downstream of the LS steps are also characterized by weak, very weak or extremely weak sorting and usually uni- or bimodal grain size distribution as well as positive skewness (Sk) values in most samples (Figure 7).

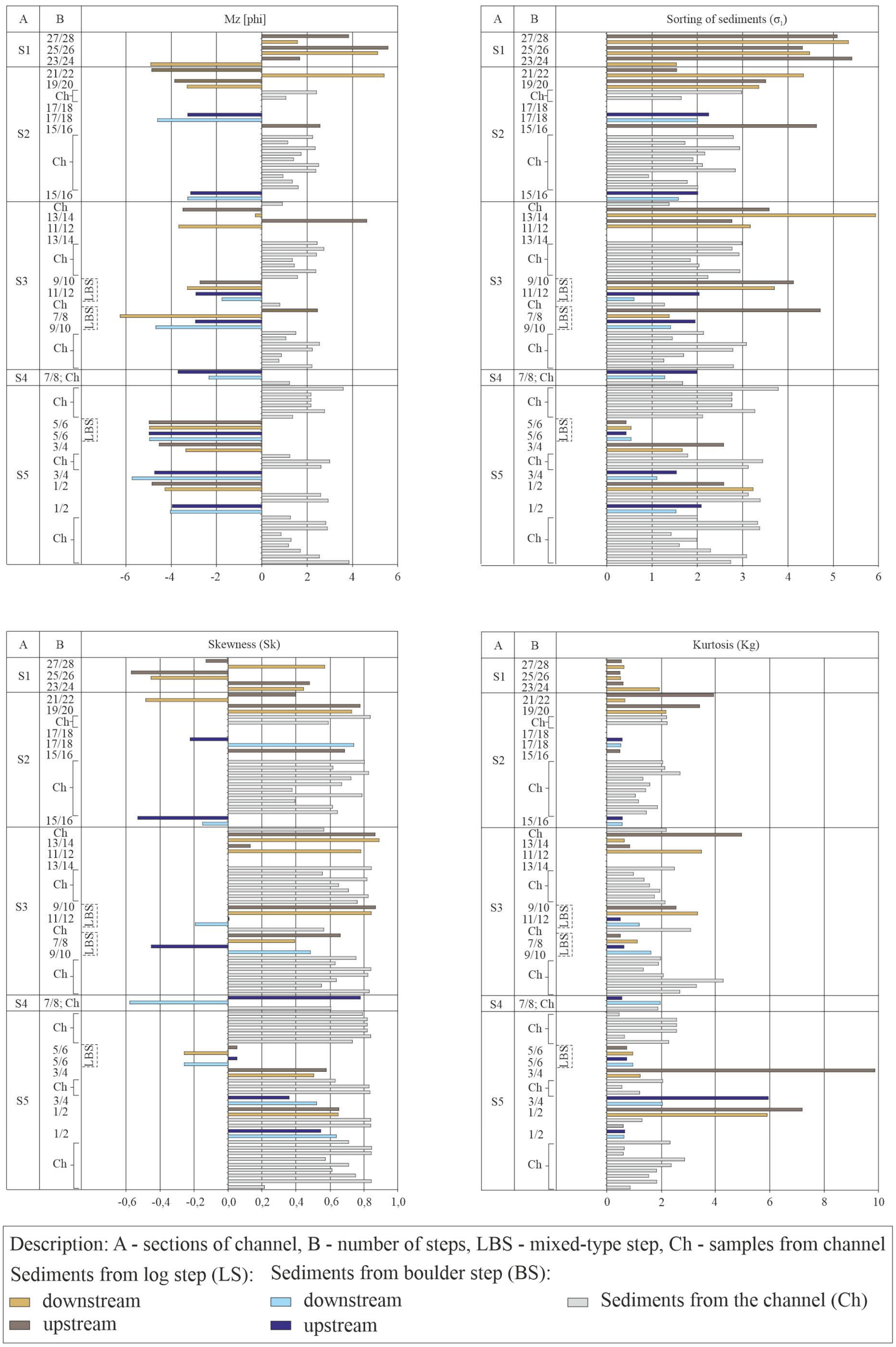


Figure 7. Variability of sedimentological indicator values in the longitudinal channel profile-; A—sections of channel; B—number of step; Mz—mean grain diameter, σ_1—sediment sorting, Sk—skewness, Kg—kurtosis.

Sediments associated with BS steps are more homogeneous in terms of grain size than sediments retained upstream or downstream of LS steps. They are also characterized by relatively better sorting. The mineral material retained upstream of the BS steps comprises from 74.83% to 88.13% of deposits with the fraction ≥ 2 mm, and the mean grain diameter assumes only negative values (Mz = −3.69–(−3.14) phi). The deposits are poorly and very poorly sorted (σ_1 = 1.99–2.25) and are characterized solely by bimodal grain size distribution. Sediments deposited downstream of BS steps comprise from 24.69% to 65.91% of deposits with the fraction ≥ 2 mm. They are characterized by uni- or bimodal grain size distribution, and the mean grain diameter also assumes only negative values (Mz = −4.60–(−2.33) phi).

Sediments deposited on mixed steps (LBS) in the S3 channel section (the rocky part of a step-BS) are characterized by better sorting and higher values of the mean grain diameter (Mz). This testifies to the retention of sediments that are thicker but also more differentiated in terms of grain size, upstream of mixed steps (the LS part of a step).

Grain size distribution is simpler in the case of sediments collected downstream of both the log parts and the boulder parts of LBS steps (uni- or bimodal distribution) as compared with the sediments accumulated upstream of the log parts and the boulder parts of steps, where there are also deposits with trimodal grain size distribution.

More homogeneous than sediments associated with the different types of steps are sediments sampled from the stream channel (Ch). These deposits are finer (Mz = +0.75–(+2.74) phi); they are also characterized by unimodal grain size distribution and only positive skewness values (Figure 7). Sediments sampled directly from the stream channel downstream of the LS steps have slightly higher average diameter values (Mz = +2.24–(+2.42) phi), which indicates a lower energy of the deposit environment. On the other hand, deposits sampled directly from the channel downstream of the BS steps are characterized by much larger fraction size differentiation (Mz = +0.90–(+2.44) phi); they are mostly thicker than channel deposits located downstream of the LS steps. This confirms the greater energy and dynamics of the deposit environment and indicates the possibility of sediment washing downstream of the BS steps. Also the deposits sampled directly from the channel downstream of the LBS steps are characterized by a larger fraction (Mz = +0.89–(+1.50) phi).

The S5 channel section is characterized by fine channel deposits (loamy sand) and coarse ones (Mz = −3.35–(−5.73) phi) as well as homogenous gravel deposits retained on various types of steps. Deposits sampled from the stream channel (Ch) as well as those deposited upstream and downstream of the various types of steps are characterized by uni- or bimodal grain size distribution. The deposits are usually weakly and very weakly sorted; only the sediments associated with the LBS step are characterized by good and moderately good sorting. In contrast, sediments associated with the LS steps are characterized by the largest differentiation of kurtosis values in the entire longitudinal channel profile (Kg = 1.23–9.88), indicating large changes in the energy of the stream current environment (Figure 7).

In the entire longitudinal profile of the Dupniański Stream channel, sediments associated with various types of steps as well as channel sediments (Ch) are characterized by a predisposition to transport in a highly dynamic environment (traction) with the absence of conditions for material deposition from the suspension (Figure 8). The only exceptions are sediments upstream of log step LS 11 / 12 (S3), and one sample of sediments collected directly from the channel bed in the final section (S5), which could have been deposited from a homogeneous suspension. The relationship between the values of kurtosis and skewness also indicate a higher energy environment (erosion and transport) (Figure 9). These regularities indicate the transport of material along the longitudinal channel profile mainly during high energy events [34]. The phased movement of the material along the longitudinal profile of the channel as well as features of the sediments are modified also by the presence of the various types of steps.

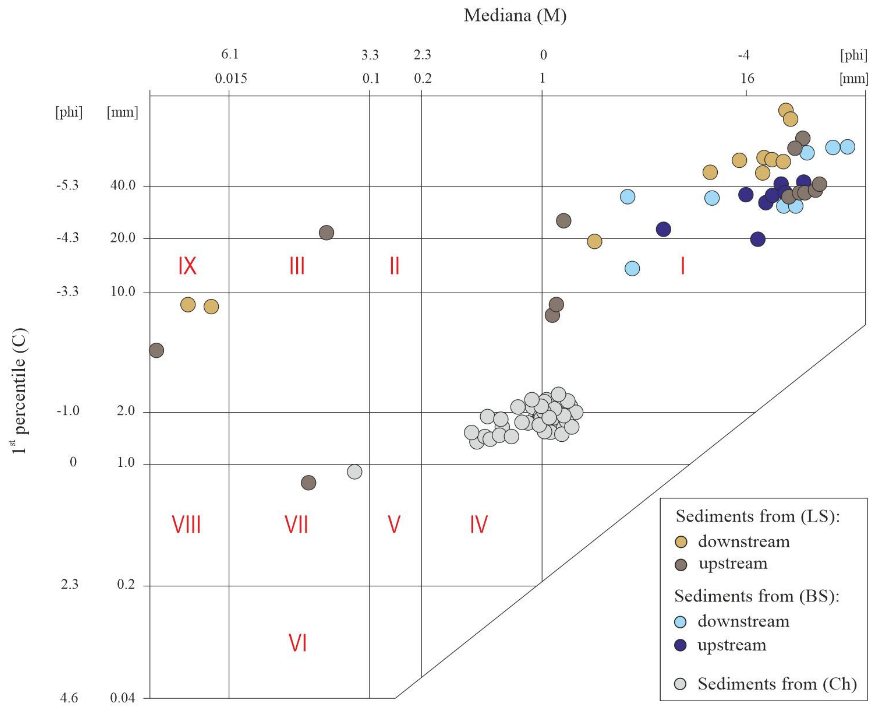


Figure 8. Location of samples on the C/M diagram (C—first percentile and M—median): I–IX—fast moving sediment (traction) without the right conditions for the deposition of suspended matter, IV—sediment deposited by gradation suspension transported under highly turbulent conditions and saltation with traction, V—sediment deposited by gradation suspension transported under moderately turbulent conditions, VI—sediment deposited by gradation suspension transported under weakly turbulent conditions, VII—sediment generated by homogeneous suspended matter, VIII—sediment produced under relatively non-turbulent conditions by homogeneous fine-grained suspended matter.

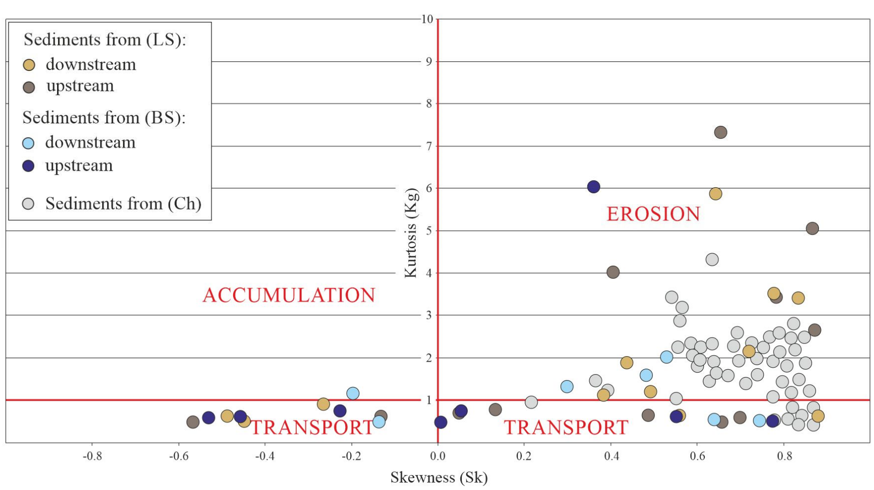


Figure 9. Relationship between skewness (Sk) and kurtosis (Kg) for sediments in the longitudinal channel profile.

The significance of steps in the modification of mineral sediment features in the longitudinal channel profile is very well emphasized by the differences between sediments sampled from various types of steps and sediments sampled directly from the Dupniański Stream channel (Figure 5). Sediments associated with the steps are characterized by much greater grain size diversification. This feature is reflected in the percentage of sediments in individual fractional sections and in the differences in sedimentological index values (Figure 7). This diversification is greater in the case of sediments retained on LS steps than on BS steps. Sediments associated with BS steps are much more homogeneous in terms of grain size than sediments retained on the LS steps. They are also characterized by relatively better sorting. In the longitudinal profile of the channel, the sediments located upstream of the steps are characterized by more diverse grain size distribution than sediments accumulated downstream of the steps. This regularity applies to both LS and BS steps. The reason for this larger diversification of sediment sizes on LS steps than on BS steps may be the weirs formed out of woody debris (of various kinds and sizes) which contribute to the selective transport of sediments, depending on hydrodynamic conditions in the channel. In the case of boulder steps, perhaps the very process of sediment transport and retaining proceeds in a different way. Perhaps larger particles are stopped at steps located in upstream sections due to water flow slowdown connected with longitudinal slope reduction.

In the longitudinal profile of the Dupniański Stream, the sediments collected directly from the stream channel (Ch) are smaller, much less diverse than the sediments associated with various types of steps and deposits upstream or downstream of a step (Figure 5). They are formed as sand or loamy sand; they are characterized by mostly unimodal grain distribution and by solely positive skewness values (Figure 7). As the mean grain diameter (Mz) decreases, the degree of sorting of these deposits also decreases (Figure 10). This relationship is characteristic for environments with a predominance of sorting processes within thicker fractions and periodic supply of weakly sorted material [42]. In the case of the fluvial environment, this is a feature of riverbed armoring or sediments related to deposition in the course of flood wave falling. This may also highlight a large significance of local, periodic material supply from lateral erosion undercuts. The relation between the average grain diameter (Mz) and the degree of sediment sorting also clearly distinguishes sediments associated with LS steps located in the S1 channel section (Figure 10), set S1.

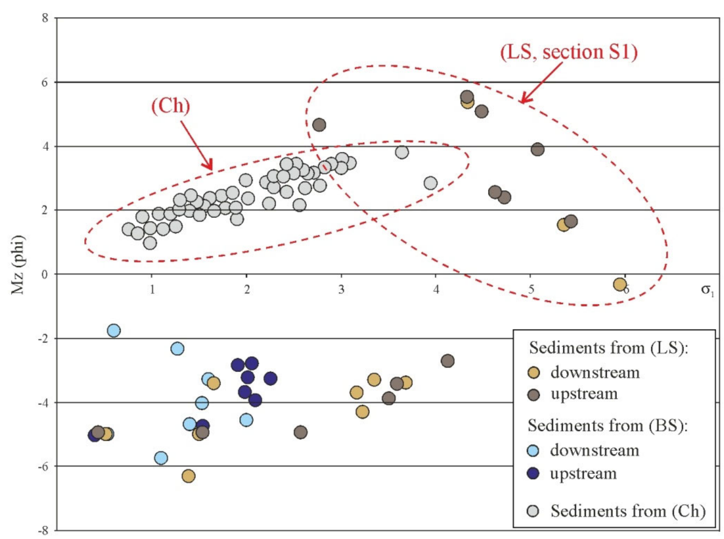


Figure 10. Relationship between mean diameter (Mz) and sediment sorting (σ_1).

3.3. Characteristics of Gravel Shape Parameters

An analysis of gravel sediment shapes was carried out for sediment samples collected from LS, BS and LBS steps and directly from the stream channel (Ch and P). In addition, two subgroups of gravel were distinguished in each of the samples, i.e., from sandstones (A) and (B). In the case of sediment samples collected from the steps (LS, BS and LBS), the shape parameter was determined for gravels collected both upstream and downstream of these steps.

3.3.1. Gravels from LS

In the upper channel section (S2), in fine sandstone gravels (A) sampled upstream of LS, the prevailing gravels are disc-shaped with a slight share of particles with intermediate shapes with a slight predominance of blades (Figure 11 and Figure 12). A comparable share of discs, spheres and blades was found in the gravel material collected downstream of LS. In section S3, discs and spheres predominate in sediments upstream and downstream of the steps. In section S5, in sediments upstream of LS, discs have by far the largest share, while downstream of the steps, there are discs and spheres with a small share of blades and rods.

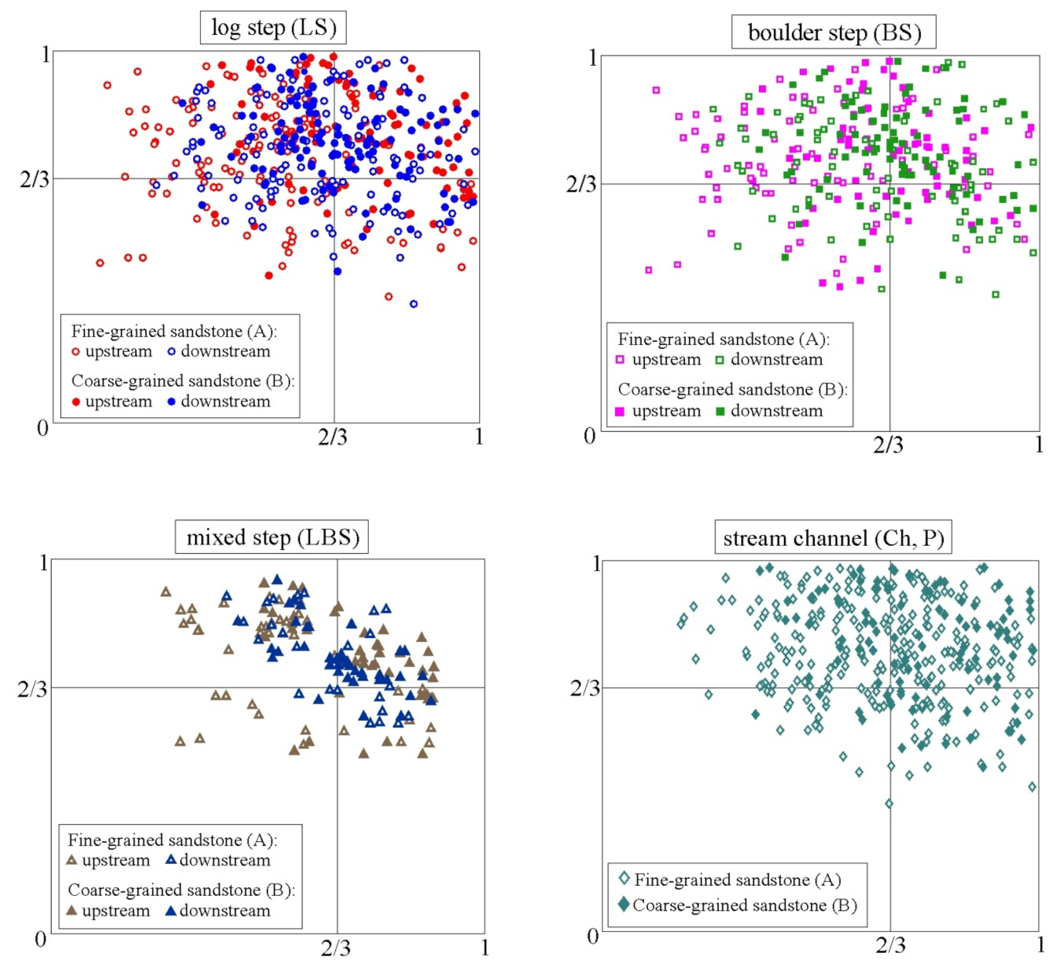


Figure 11. Zingg diagrams for gravels sampled from the steps (LS, BS and LBS) and the channel (Ch and P), taking into account sandstone grain-diversity: A—fine-grained sandstone; B—coarse-grained sandstone.

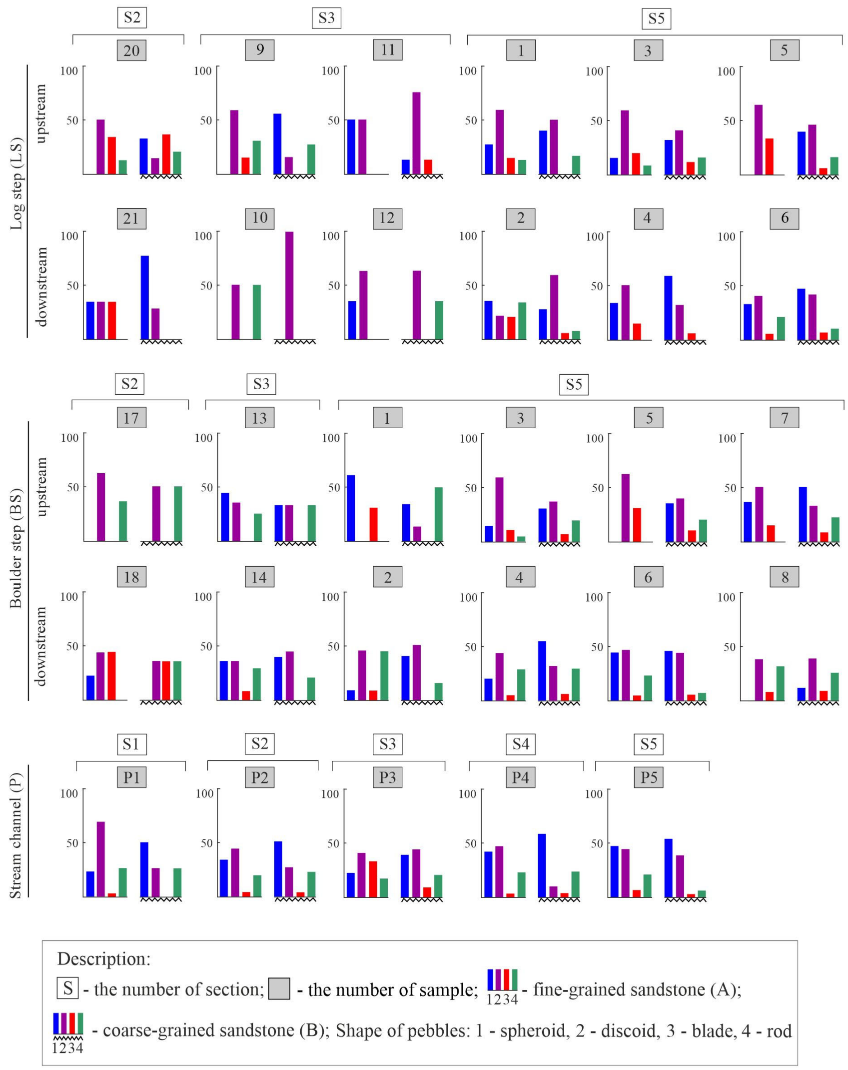


Figure 12. Share of gravels with a specific shape in sediments sampled from the steps (LS and BS) and the stream channel (P), taking into account sandstone grain-diversity: A—fine-grained sandstone, B—coarse-grained sandstone.

In coarse sandstone gravels (B) retained upstream of the LS steps in section S2, sphere- and blade-shaped particles predominate, while downstream of the steps, no spheres were found. Presumably, most of the spherical particles were retained in sediments accumulated upstream of the step. In section S3, in gravels upstream of the steps, a significant share of spherical gravels (P9) and discs (P11) was observed, with a small share of blades and rods. In contrast, in sediments downstream of the steps, the share of discs is dominant whereas spherical gravels are absent. Along section S5, discs and spheres predominate in gravels sampled both upstream and downstream of the steps, with a negligible share of blades and rods.

In general, the largest share of discs was found in sandstone sediments (A) collected upstream and downstream of the LS steps (Figure 11). In sediments collected upstream of LS from coarse-grained sandstone (B), spherical particles predominate whereas sediments collected downstream of the steps contain discs.

3.3.2. Gravels from BS

In the majority of the analysed samples, the gravel material from fine-grained sandstone (A) obtained upstream of BS has a dominant share of discs and spheres. The occurrence of disc-shaped particles was observed in gravels upstream of the steps located in sections S2, S3 and S5 (except P1, where spheres predominate). Rod-shaped particles occur only upstream of the steps in the upper part of the channel in sections S2 and S3. A small share of blades was found only in section S5. Discs predominate in gravels sampled downstream of the BS steps (S2, S3 and S5). Spherical particles occur in all sediment samples collected downstream of the steps, but their share is significantly smaller in comparison with the share of discs.

In the case of sandstone gravels (B) collected both upstream and downstream of the boulder steps, spheres and discs predominate and there is a small share of rods and blades.

3.3.3. Gravels from LBS

Along the longitudinal profile of the stream channel, 3 mixed-type log-and-boulder steps (LBS) were inventoried, within which mineral deposits were collected. The results of grain-shape parameter measurements indicate that, in gravels selected from sediments collected within LBS, there are mainly sphere-shaped particles and discs with a smaller share of blade-shaped particles and rods. This regularity applies to both fine and coarse sandstone particles. In the sediments collected upstream of the LBS steps, the dominant particles include fine-grained sandstone spheres and blades as well as coarse-grained sandstone spheres. On the other hand, sediments collected downstream of the LBS steps reveal a dominant share of disc- and rod-shaped gravels built of fine-grained sandstone as well as discs and spheres of coarse sandstone.

3.3.4. Gravels from the Stream Channel (Ch and P)

In sediments sampled from the stream channel (Ch and P) in section S1, fine sandstone gravels (A) contain a dominant share of discs (nearly 75%) and rods, while in coarse sandstone gravels (B), there are spheres (40%), followed by discs and rods (30% each). Similarly, in section S2, discs (sandstone A) and spheres (sandstone B) predominate in gravels. In contrast, in section S3 of the stream channel, sandstone gravels (A) contain discs (nearly 40%) and blades (30%), while sandstone gravels (B) have discs and spheres (40% each). Along S4, which is the shortest channel section, disc- and sphere-shaped gravels of fine-grained sandstone (A) are dominant (about 40% each), while spherical coarse-grained sandstone gravels (B) have a share of over 50%. Sediments sampled from the channel bed in section S5 are sphere- and disc-shaped gravels of sandstone A and B.

Essentially, discs, followed by spherical particles and rods, with a marginal share of blades predominate in fine-grained sandstone gravels. In contrast, in coarse sandstone gravels, a significant share of spheres and discs was observed, with a negligible share of blades and rods. These differences may be due to the higher susceptibility of coarse-grained sandstone particles to erosion processes in comparison with fine-grained sandstone. A significant role is played by both the share and the amount of cement. Coarse sandstone particles, transported in the stream channel, are therefore more susceptible to the process of abrasion and fragmentation, resulting also in the change of their size and shape.

4. Conclusions

Morphodynamic features of stream channels in small forest mountain catchments determine the type of sources of mineral material supply to the fluvial system by which these features affect the characteristics of alluvial deposits. These deposits are introduced into the fluvial system periodically, mainly during floods.

The presence of steps in the longitudinal profile of a stream channel affects the formation of local erosion and deposition zones and the creation of a stepped longitudinal profile of the stream channel. It also indirectly modifies the transport of sediments along the longitudinal channel profile: it is short and phased (in sections).

Our results suggest that the type of steps is significant for diversification of the size and shape of alluvial deposits. Deposits associated with steps are characterized by much greater diversification of the granulometric composition and shape than deposits collected from the stream channel. The circulation and diversification of mineral sediments in the longitudinal profile of the stream channel is mainly modified by steps formed out of woody debris, which retain sediments of various diameters and shapes.

Log steps in a stream channel cause hydrological regime modifications, the development of microhabitat diversity and the character of stream channel sediments, deciding on the diversity of the entire ecosystem. Woody debris, among others, constitutes a habitat with unique species of aquatic invertebrates, in particular some species of molluscs, mayflies, trichopterans as well as hygrophilous fungi. Thus, the preservation as well as artificial creation of log steps in stream channels of mountain forest catchments is beneficial to ecosystems as it reduces mineral material loss from the catchment, diversifies hydrodynamic conditions in the longitudinal profile of the stream channel and shapes biodiversity in local ecosystems.

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